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**FLOW-INDUCED VIBRATION
FOR LIGHT-WATER REACTORS**

**PROGRESS REPORT
(OCTOBER 1980 — DECEMBER 1980)**

SEPTEMBER 1981

M. R. TORRES

**GENERAL ELECTRIC COMPANY
NUCLEAR ENGINEERING DIVISION
175 CURTNER AVENUE
SAN JOSE, CALIFORNIA 95125**

**PREPARED FOR THE
U.S. DEPARTMENT OF ENERGY
ASSISTANT SECRETARY FOR NUCLEAR ENERGY
OFFICE OF LIGHT WATER REACTORS
UNDER CONTRACT DE-AC02-77ET34209**

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ABSTRACT

Flow-Induced Vibration for Light Water Reactors (FIV for LWRs) is a four-year program designed to improve the FIV performance of light water reactors through the development of design criteria, analytical models for predicting behavior of components, general scaling laws to improve the accuracy of reduced-scale tests, and the identification of high FIV risk areas. The program is managed by the General Electric Nuclear Power Systems Engineering Department and has three major contributors: General Electric Nuclear Power Systems Engineering Department (NPSED), General Electric Corporate Research and Development (CR&D) and Argonne National Laboratory (ANL). The program commenced December 1, 1976. This progress report summarizes the accomplishments achieved during the period from October 1980 to December 1980.

INTRODUCTION

The Flow-Induced Vibration for Light Water Reactors Program (FIV for LWRs) is being conducted for the Division of Nuclear Power Development, U.S. Department of Energy (DOE). The goal of the program is to increase nuclear plant availability and to reduce radiation exposure by substantially reducing downtime caused by FIV failure of components. It is a four-year balanced effort of fundamental studies, analyses, tests of idealized conditions, and realistic tests of reactor components, all leading to the preparation of design guides and criteria for LWRs. The program is broken into four major tasks:

- Task 1 - Fundamental Studies - General Electric Corporate Research and Development (CR&D) and Argonne National Laboratory (ANL)
- Task 2 - Model and Full-Size Tests - General Electric Nuclear Technology Department (NTD)
- Task 3 - Design Methods, Guides and Criteria - (NTD)
- Task 4 - Program Administration - (NTD)

A brief summary of the objectives of these tasks and a description of the technical progress achieved over the period from October 1, 1980, through December 31, 1980, is provided in the following sections. Additional background information can be obtained from other "Flow-Induced Vibration for Light Water Reactors Progress Reports" listed as follows:

1. December 1976 - May 1977, GEAP-24055, COO/4175-1.
2. June - September 1977, GEAP-24124, COO/4175-2.
3. October - December 1977, GEAP-24151, COO/4175-5.
4. January - March 1978, GEAP-24163, COO/4175-9.
5. April 1978 - December 1978, GEAP-24248, DOE/N/4175-14.

6. January 1980 - June 1980, GEAP-24926, DOE/ET/34209-16.
7. July 1980 - September 1980, GEAP-23468, DOE/ET/34209-17.

TASK 1 - FUNDAMENTAL STUDIES

The purpose of Task 1 is to develop a better fundamental understanding of FIV phenomena as related to light water reactors (LWRs). A combination of tests and analyses considers geometries and FIV mechanisms common to the LWR. Particular emphasis is given to characterizing the FIV forcing functions for use in establishing predictive models. The task is divided into four major areas:

Task 1.1 - External Flow over Tube Banks - Cross Flow (CR&D)

Task 1.2 - External Flow over Tube Banks - Parallel Flow (ANL)

Task 1.3 - Leakage Flow Mechanisms (CR&D)

Task 1.4 - Random Vibration Effects (ANL)

Progress has been achieved on Tasks 1.1 and 1.2 over the report period and is described on the following pages. Task 1.4 has been completed and the final results are documented in DOE report COO/4175-10, "Random High-Cycle Fatigue Analysis."

TASK 1.1 - EXTERNAL FLOW OVER TUBE BANKS - CROSS FLOW (CR&D)

Task 1.1, which is being performed by General Electric Corporate Research and Development, is designed to develop a better understanding of the response of tube arrays to fluid cross flow. It consists of six activities:

Task 1.1a - Preliminary Array Definition Experiments

Task 1.1b - Water-Based Tests at High Reynolds Numbers

Task 1.1c - Buffeting of Cylinder Arrays in Turbulent Cross Flow

Task 1.1d - Fluidelastic Instability Boundaries

Task 1.1e - Proof Test

Task 1.1f - Design Guides

Progress achieved over the report period on these activities is described as follows:

Task 1.1a - Preliminary Array Definition Experiments (S. D. Savkar, R.M.C. So)

Task Description

The objective of this task was to develop an experimental scheme capable of directly measuring the unsteady forces induced on cylinders immersed in a turbulent cross flow. The measurement scheme will be used in several of the Task 1.1 test programs.

Work Completed This Report Period

Task 1.1a, as previously reported, was successfully completed in an earlier report period. Work on this activity has been terminated.

Task 1.1b - Water-Based Tests at High Reynolds Number (S. Savkar/T. Litzinger/R. So)

Task Description

Task 1.1b consists of a series of experiments performed in water, using the Garfield Thomas Water Tunnel at Pennsylvania State University, to study the buffeting of a cylinder in a turbulent cross flow. The primary objective is to measure and correlate the unsteady forces induced by the cross flow on the cylinder as a function of Reynolds number and turbulence. The program is designed to complement the cross flow in air activities in Task 1.1c.

Work Completed This Report Period

The fluctuating lift data for two cylinders in tandem (spacing-to-diameter ratio of 6.7) have now been reduced. These have revealed several surprises. First, the interference increases the unsteady lift coefficients (C_L') of the downstream cylinder over the equivalent values (with or without turbulence grids) for isolated cylinders. Yet there was little or no measurable effect of the interference on the upstream cylinder; that is, the response continued to be essentially that of an isolated cylinder. In a similar manner, the spectra of the downstream cylinder remained more peaked (with a distinct Strouhal peak) over the whole range of Reynolds numbers (Re). The absolute values were not much different from the isolated cylinder values; in fact, the relative behavior with or without turbulence grids was about the same.

Perhaps the most significant feature of the above data is the correlation onto two curves by making use of the grouping previously suggested for isolated cylinder - $C_L' \cdot St \cdot \sqrt{L/\ell}$. Thus C_L' is the RMS value of the lift coefficient, St is the Strouhal number, and L is the active span. The remaining parameter ℓ is taken, as before, as the diameter for the Strouhal case (no grid) and the axial integral scale of turbulence for the buffeting case. This is illustrated in Figures 1.1-1 and 1.1-2. The choice of the scaling length ℓ in the buffeting data was made due to its success in the isolated cylinder experiments. Three distinctly different grids were used at that time and this choice of the scaling length worked the best. Therefore,

for consistency, the same parameter was picked for the tandem cylinders. It appears to work well here despite the "shadowing" effect of the upstream cylinder.

For the sake of completeness, the Strouhal number data are presented in Figure 1.1-3.

Task 1.1c - Buffeting of Cylinder Arrays in a Turbulent Cross Flow (S. Savkar/
T. A. Litzinger)

Task Description

Task 1.1c consists of a series of experiments performed in air to study the buffeting of single cylinders and cylinder arrays in a turbulent cross flow. The experiments characterize the forces exerted on the cylinder as a function of such parameters as Reynolds number, upstream turbulence, Strouhal number, and cylinder array geometry. The program utilizes the force measurement scheme developed in Task 1.1a to characterize the cylinder forces.

Work Completed This Report Period

During this reporting period a series of runs were made with a row of cylinders. In these runs the steady drag forces acting on a pressure tap instrumented cylinder were measured, and the vortex shedding frequencies were measured with a hot film immersed in the wake of the instrumented cylinder. The pitch-to-diameter ratio tested was 1.71.

The flow through such a row does not appear to remain wholly stable. It appears to flip and flop between a vortex wake with a defined Strouhal frequency, and a "fully turbulent" wake. Since the flow appears capable of remaining in one or another mode for long periods, this appears to be an indication of bistability of the flow through a row of tubes. Steady drag data so obtained are illustrated in Figure 1.1-4.

Because of the above "peculiar" behavior, repeat runs were made to confirm the behavior. This time the static pressure upstream of the row was continuously monitored. It remained unaltered regardless of the particular mode of the flow through the cylinders. This would suggest that the gross flow through the row did not change in the observed flip-flops, but that either the flow became re-distributed between the passageways formed between the cylinders, or that the shedding process was unstable for the row itself.

Subsequent to these runs, the load cell instrumented cylinder was mounted in the test tunnel. Some difficulty was encountered in the assembly, and a certain amount of re-machining was required. Attempts were then made at measuring the steady drag forces with the load cells since the technique of measuring and integrating 33 static pressure taps was very time consuming (up to several hours for each flow setting versus a few minutes if the load cell technique could be made to work). To date these attempts have been unsuccessful. The main problems are repeatability and the drift in the load cell signal. Measure coefficients were off by as much as 25% from those obtained with static taps, which is unacceptable. Rather than lose any more time trying to perfect this technique, it was decided to revert to the older, albeit, slower technique for now.

Figure 1.1-1. Normalized Strouhal Lift Data for Tandem Cylinders (Pitch to Diameter Ratio: 6.77)

Figure 1.1-2. Normalized Buffeting Lift Data for Tandem Cylinders - Turbulence Grid of 2-in. Mesh Located 10 Mesh Dimensions Upstream of Leading Cylinder

Figure 1.1-3. Tandem Cylinder Strouhal Number Data

Figure 1.1-4. Bistable Drag Coefficients Observed with a Transverse Row of Cylinders
(Pitch to Diameter Ratio: 1.71)

TASK 1.2 - EXTERNAL FLOW OVER TUBE BANKS - PARALLEL FLOW (ANL)

Task 1.2, performed by Argonne National Laboratory, is designed to develop a better understanding of the response of tube arrays subjected to parallel flow. The specific objectives include the following:

- (1) Determine, by a systematic series of experiments, the dependence of amplitude of motion and forces on Reynolds number, upstream flow conditions, array geometry, and weak cross flow for tube arrays in essentially parallel flows;
- (2) Establish weak cross-flow-induced fluidelastic stability boundaries; and
- (3) Evolve design methodology to estimate the fluid forces and resulting vibration response.

The program is divided into five subtasks:

Task 1.2a - Review of Available Data from Flow-Induced Vibration Tests and Assessment of the State of the Art in Understanding/Modeling Parallel Flow-Induced Vibration Phenomena and/or Response

Task 1.2b - Experimental Study of Single Cylinders in Nominally Parallel Flows Typically Encountered in Channels and Reactor Plenums

Task 1.2c - Experimental Study of Fluidelastic Interaction that Can Result in Coupled Response and/or Instabilities in Rod/Shell Systems, Tube Bundles, Tubes in Asymmetric Flow Channels, and Systems with Nonuniform Cross Sections

Task 1.2d - Experimental Study of Tube Arrays in Parallel Flow

Task 1.2e - Development of Mathematical Models and Participation in Design Guides Evaluation (Task 3)

The primary test fluid will be water. Incoming flow conditions, together with a weak cross flow, will be used to establish the effects of the parameters of interest. The flow will be varied over a sufficient range to clearly establish the role of Reynolds number. Besides acquiring data of significance to the parallel flow FIV of tube arrays, analytical tools which can be evolved into design guides will be devised.

A description of the progress achieved on these subtasks over the periods from October 1980 to December 1980 follows.

Task 1.2a - State-of-the-Art Assessment

Task Description

Task 1.2a consists of a day-to-day review of available parallel FIV literature applicable to light water reactors in order to maintain a current knowledge of the state of the art.

Work Completed This Report Period

Other than continued general review of the FIV literature, no work was performed on this activity during the report period.

Task 1.2b - Single Cylinders in Nominally Parallel Flow (W. H. Lin, T. M. Mulcahy, W. P. Lawrence, B. G. Jones)

Task 1.2b consists of two complementary parallel FIV programs on isolated cylinders. Experiments are performed in water using the ANL Flow Induced Vibration Test Facility and in air using the University of Illinois at Urbana open cycle air loop at the Thermal Hydraulics Laboratory. Work performed on these programs is described as follows.

Activity 1 - Annular Region (Water)

Task Description

Parallel FIV experiments are performed on isolated cylinders in water to determine the cylinder response, wall pressure statistics, cylinder resonances, and fluid damping as a function of the independent parameters with the ultimate goal of developing an analytical response prediction model characterized by the test data. The independent test parameters include a wide range of Reynolds numbers, hydraulic diameters, cylinder structural boundary conditions, and, most important, upstream flow disturbances. The creation and characterization of upstream flow disturbances as a test parameter will be the unique contribution of this work.

The specific objectives are to:

- (1) Provide test data to develop an integrated analytical-experimental model for predicting response of a rod located symmetrically in a cylindrical region subjected to fully developed flow with and without upstream flow disturbances, and
- (2) Establish sensitivity (scaling) of wall pressures with respect to rod vibration, Reynolds number, hydraulic diameter, and upstream disturbances (turbulence).

Work Completed This Report Period

The experimental results from measurements of wall-pressure fluctuations on a circular rod concentrically located in three different circular channel flows with various upstream disturbances caused by flow spoilers are being reported in two parts. Part I was completed during the previous reporting period¹ and presents the results from tests with no flow spoilers. Part II was prepared during the current reporting to include tests with flow spoilers.

The experimental results are presented in the form of power spectral density (PSD) representations and mean-square values, and are compared with the results for the case without upstream disturbances. The three flow spoilers used in the study are shown schematically in Figure 1.2-1. The different types of spoilers create turbulences of different intensity and scale,² which in turn affect the wall-pressure fluctuations differently. The most apparent effect of the upstream flow spoiler is to increase the magnitude of the fluctuating wall pressures. Among the three types of flow spoilers, the grid is the most effective in creating high level turbulence, especially in the largest annulus.

The magnitude and shape of the spectra associated with the grid spoiler are quite different from those with other types of spoilers and with no spoiler (Figure 1.2-2). The oscillations shown in the PSD curves at high frequencies are believed to be associated with cavitation noise. The magnitude of the spectra for wall-pressure fluctuations at three axial locations increases with increasing hydraulic diameters (for example, see Figure 1.2-3). Additionally, the differences in the PSDs at the three axial locations for the three annuli are also comparable (Figures 1.2-4 - 1.2-6). These two trends are distinctly different from those observed in the data from the case of no upstream spoiler.

Scaling of the PSDs with dimensionless parameters was also studied extensively. In agreement with the no spoiler data, the results indicate the intensity of the spectra scales with the axial mean-flow speed to a power varying from 2.2 to 5.1, and the dependence of the spectra on hydraulic diameter is not well defined. An attempt to normalize the intensity using a dynamic head parameter is shown in Figure 1.2-7.

The rms values of wall-pressure fluctuations are obtained via integration of the power spectral density functions of pressure-difference signals over the frequency domain,

$$\langle p^2 \rangle = \int_0^{\infty} \phi_p(f) df ,$$

where ϕ_p is the wall pressure PSD and f is frequency.

In Figure 2.1-8, rms values of pressure fluctuations are plotted versus axial position for the three different flow annuli, with a grid spoiler and a mean flow speed of 8 m/s (26.2 ft/sec). Except for the region close to the entrance to the test section, the larger the hydraulic diameter of the annulus, the higher the rms value of wall-pressure fluctuations. RMS values of pressure fluctuations decrease with increasing axial distance. This decay of pressure fluctuations is especially apparent for the largest annulus.

It should be recalled that the turbulence inside the annulus is basically composed of freestream turbulence, turbulence caused by the abrupt contraction from a pipe to an annulus, and boundary-layer turbulence. In the largest annulus the "solidity" for the flow channel is 7% so that the turbulence associated with separation flow due to the blockage of the test element is minimal. On the other hand, the solidities are 51% and 82%, respectively, in the intermediate and smallest annuli. The transition from a circular pipe to such annuli causes an abrupt contraction in the cross-section of the flow channel. Consequently, the associated transition turbulence is apparent in these two annuli. At $x/\ell = 0.125$, the value of rms pressure in the small annulus is larger than that in the intermediate annulus. This implies that the turbulence caused by area contraction and flow blockage is most dominant in the smallest annulus. At and after $x/\ell = 0.375$, the turbulence is associated with area contraction and flow blockage decays and has less of an effect on wall-pressure fluctuations than it does near $x/\ell = 0.125$. By the same reasoning, at $x/\ell = 0.625$, all components of turbulence generated by upstream grid spoiler and channel transition have dramatically decayed, so that the pressure fluctuations at and after this position depend essentially on boundary-layer turbulence. It is also seen from Figure 1.2-8 that the turbulent pressure fluctuations in the intermediate and smallest annuli are essentially homogeneous (that is, invariant) with respect to the axial space for $x/\ell \geq 0.375$, and remain inhomogeneous in the largest annulus.

Activity 2 - Annular Region (Air)

Task Description

Two fundamental parallel FIV studies are being conducted; in one both the wall and fluid field fluctuating pressures will be measured simultaneously, and in the other both the wall fluctuating pressures and the turbulent velocity field will be measured simultaneously. The first will allow determination of the stochastic structure of the pressure field and a look for correlation relationships between the fluid stochastic pressure field and that at the wall. The second study will allow determination of the turbulent velocity field and examination of its relationship to the stochastic wall pressures. These studies will be conducted in air flows in which a simply supported central rod is mounted in a circular tube to provide a concentric annular flow field.

The research program is centered around four interrelated experimental objectives to be carried out in a concentric single pin annular geometry turbulent air flow:

- (1) Measure turbulent velocity intensity levels and mean velocity profiles in the flow region;
- (2) Measure pressure correlation in the flow region and compare with existing analytical data;
- (3) Measure the correlation between the fluctuating flow field pressure and wall pressure fluctuations on the rod; and
- (4) Measure the correlation between the fluctuating flow field velocity and wall pressure fluctuations on the rod.

The end result of this fundamental study should be a better quantitative and qualitative understanding of the flow phenomena which generate the wall pressure field.

Work Completed This Report Period

This activity has been completed and reported.

Task 1.2c - Fluidelastic Interaction in Parallel Flow (W. H. Lin,
J. A. Jendrzeczyk, B. G. Jones, W. Nagel)

Task Description

To develop a better understanding of the fluidelastic interaction that can result in coupled response and/or instabilities in parallel flow systems, a single rod asymmetrically positioned in a circular flow channel is being investigated. Wall pressure fluctuations and rod response will be measured for a range of Reynolds numbers, hydraulic diameters, reduced velocities, and damping in order to provide the basis for developing a mathematical model to predict response and scaling relations. As with the annular flow experiments of Task 1.2b, complementary studies performed in water in the ANL Flow Induced Vibration Test Facility and in air using the University of Illinois open cycle air loop will be carried out.

Work Completed This Report Period

Activity 1 - Water Tests (ANL)

The test model, designed for use in investigating the effect of eccentricity on the response of a rod asymmetrically positioned in a circular flow channel has been installed in the flow facility and testing has been initiated. The reference case, with the rod concentrically located in the flow channel, has been completed. Vibration response is measured as a function of mean axial flow velocity using a pair of internal mounted accelerometers located at the mid-span of the rod.

The result can be compared with previously reported² results for the case of a hydraulic diameter of 1 in. Comparison shows the present results to be smaller by a factor of two. This difference in response level is attributed

to the difference in free-stream turbulence as generated by the discontinuity in flow channel at the entrance to the test section. In the present test, there is an extension pipe of the same diameter as that of the test section located upstream of the test section inlet to condition the flow entering the test section. However, in the previous test², no extension was used and an abrupt discontinuity existed at the test section entrance. It is believed that the developing flow is responsible for the higher response obtained from the earlier test.

The test plan calls for testing with three different values of eccentricity. In addition to rod vibration response, damping and the two-dimensional spatial response at selected times will be measured.

Activity 2 - Air Tests (University of Illinois)

The subcontract with the University of Illinois was not in effect during the reporting period. Nevertheless, procurement of a replacement piezoelectric pressure transducer to match the failed one was accomplished. A full calibration of the transducer was required. This was also necessary for the other two wall transducers to insure matched behavior. Calibration is well underway, but it has been delayed by the failure of one transducer preamplifier which was returned to the manufacturer for repair. Since one of the bleed type pressure transducers had been damaged and was not repairable, a simultaneous series of delays was experienced in procuring a matched replacement.

Task 1.2d - Experimental Study of Tube Arrays in Parallel Flow (W. H. Lin, T. M. Mulcahy, J. A. Jendrzejczyk)

Task Description

Test 1.2d consists of an experimental study of the wall pressures and response of rods in a seven-tube array. As in Task 1.2b, the ultimate goal is to generate data for use in developing a vibration response prediction model. The independent test parameters include a wide range of Reynolds numbers and upstream flow disturbances.

Work Completed This Report Period

Efforts focused on the processing of fluctuating wall pressure data, analysis of results, and the performance of tests with the instrumented rod in a peripheral location in the seven-rod array. An improved, computerized data-processing method was developed for use with the spectrum analyzer to improve the low-frequency resolution of the spectra of wall-pressure fluctuations. In addition, an analytic waveguide mode was developed to compute the cutoff frequencies and attenuation lengths associated with the propagation of extraneous acoustic noise in the flow channel formed by the seven-rod array. The relatively high cutoff frequencies and short decay lengths substantiated the use of the pressure differencing technique to subtract out extraneous acoustic noise.

Typical results from measurements of wall-pressure fluctuations on a rod in the peripheral location at angular positions 0° and 90° (see Figure 1.2-9) is shown in Figure 1.2-10. The trends of the two sets of data at low frequencies are not much different in magnitude and shape, with the exception of the center frequencies occurring at the peaks in the two data sets. When the frequency is greater than 600 Hz, the magnitude and shape of the two spectra are quite different; the one associated with 0° rolls off fast and shows more oscillations at high frequencies.

The low frequency peaks are presumed to be associated with rod strain and to occur at the natural frequencies of the rod. The variance in the natural frequency is expected to be the result of fluid/structural coupling which is not the same in the two directions.

Figures 1.2-11 and 1.2-12 allow for comparisons of the PSD curves of fluctuating wall pressures on a circular rod in annular water flows with those from the same rod located in the center of a seven-rod channel at angular position of 0° . As shown in Figure 1.2-11, for frequencies less than 500 Hz, the magnitude of the spectrum of the wall-pressure fluctuations in the small annulus ($d_h = 1.17$ cm) is greater than that in the seven-rod channel without upstream disturbances. However, the result in the large annulus ($d_h = 3.71$ cm) matches

very well with that in the seven-rod channel in that frequency range. When the frequency is greater than 500 Hz, both spectra of wall-pressure fluctuations in the large and small annuli coincide and roll away from the spectrum of wall-pressure fluctuations in the seven-rod channel. The matching of the wall-pressure spectra in the low frequency range (i.e., $f \leq 500$ Hz) for the annulus with 5.08-cm O.D. and the rod array channel with 5.08-cm O.D. implies that the information on fluctuating wall pressures on tube array in parallel flow can be obtained from the test results for those in an annulus of the same O.D. as the array channel. From the viewpoint of flow-induced vibration of tube banks, the above observation can simplify the experimental studies on fluctuating wall pressure, which is responsible for the rod motion in parallel flow.

Figure 1.2-12 shows that the spectra of wall-pressure fluctuations in the large annulus and in the array channel with upstream grid turbulence match well in the frequency range of 60 Hz to 500 Hz, and the spectrum in the small annulus matches with that in the array channel for frequencies less than 30 Hz. For frequencies greater than 30 Hz, the spectrum of wall-pressure fluctuations in the small annulus is smaller than that in the array channel and becomes close to that in the larger annulus as the frequency passes 1000 Hz. Both spectra corresponding to the annulus flow cases drop off faster than the spectrum of the rod array. Further, the spectrum associated with the large annulus shows oscillations for frequencies larger than 1500 Hz. These high-frequency vibrations are probably caused by the cavitation of the grid in the upstream. Comparison of Figures 1.2-11 and 1.2-12 shows that the turbulence caused by the contraction of flow passage is more apparent in the small annulus than in other channels, and the grid turbulence in the cases of the large annulus and array channel has more affect on the fluctuating wall pressures than it does for the case of the small annulus.

Analysis and interpretation of the data will be continued. The results will be used in the evaluation and improvement of the prediction methods and design guides.

Task 1.2e - Development of Mathematical Models and Design Guides (W. H. Lin, T. M. Mulcahy)

Task Description

Experimental results from subtask activities 1.2b and 1.2d will be used to evaluate and improve prediction methods for parallel flow-induced vibration. The methods will be further evaluated via comparisons of predicted response with results from model and full-sized tests (Task 2). Critical flow velocities associated with the onset of fluidelastic instabilities will be expressed in terms of system parameters. Validated design guides will be developed for inclusion in an FIV Handbook.

Work Completed This Report Period

Wall-pressure fluctuations represent a force excitation mechanism for rod response. Subject to various modeling assumptions, including a spatially homogeneous pressure field, the mean-square value of the transverse displacement of the rod is related to the power spectral density of wall-pressure fluctuations as

$$\langle y^2 \rangle = \frac{(5.16 \times 10^{-5}) d^3 \theta_1^2}{(M + m)^2 f_1^3 \zeta_1} \phi_p(f)$$

Hence, if the modal damping factor, fundamental frequency and mode, dimensions and mass of the rod, and fluid added-mass are known, the level of the power spectral density of wall pressure required to excite rod vibration to the level $\langle y^2 \rangle$ can be computed as

$$\phi_p(f) = \frac{(1.94 \times 10^4) (M + m)^2 f_1^3 \zeta_1}{d^3 \theta_1^2} \langle y^2 \rangle$$

Based on the results for rod response reported previously², values of the PSDs of wall-pressure fluctuations at the fundamental frequency of the rod are calculated for the case of the grid-spoiler and are presented in Table 1.2-1.

In general, the calculated value (ϕ_c) at the fundamental frequency of the rod ($f \approx 30$ Hz) is lower than the corresponding measured value (ϕ_p) at $x/\ell = 0.125$ and higher than that measured at $x/\ell = 0.625$. This can be seen from Figures 1.2-4 and 1.2-6 for $U = 8$ m/s and $d_h = 3.71$ and 1.17 cm, respectively. This result is as expected since the model assumes a spatially homogeneous pressure field, that is, a flat distribution over the length of the test element. The results reported herein show the intensity to decay from a relatively high value immediately downstream from the entrance to the test section.

Plans for future work relating to the development of a mathematical model include accounting for the spatial decay of the single-point, wall-pressure PSD by assuming the exponential form

$$\phi_p(x, f) = A(f) \exp(-bx/\ell)$$

where A is a function of frequency f , b is a constant determined from a curve fit to the data, and ℓ is the length of the rod. An alternate approach that will be attempted involves the development of a bounding analysis that utilizes order of magnitude estimates of the single-point PSD levels and correlation lengths.

References

1. Mulcahy, T. M., Wambsganss, M. W., Lin, W. H., Yeh, T. T., and Lawrence, W. P., "Measurements of Wall Pressure Fluctuations on a Cylinder in Annulus Water Flow with Upstream Disturbance, Part I: No Flow Spoilers,"
2. Mulcahy, T. M., Yeh, T. T., and Miskevics, A. J., "Turbulence and Rod Vibrations in an Annular Region with Upstream Disturbances," GEAP-24173/ANL-CT-79-12/C00-4175-8, January 1979. (Also, J. Sound Vib. 69(1), 59-69 (1980)).
3. Wambsganss, M. W. and Chen, S. S., "Tentative Design Guide for Calculating the Vibration Response of Flexible Cylindrical Elements in Axial Flow," Argonne Natl. Lab. Rept. ANL-ETD-71-07 (1971).

Table 1.2-1

CALCULATED VALUES OF WALL-PRESSURE PSDS AT THE FUNDAMENTAL
FREQUENCY OF THE TEST ELEMENT AS OBTAINED
FROM MEASURED DISPLACEMENT RESPONSE

d_h (cm)	U (m/s)	$\langle y^2 \rangle$ (m ²)	ζ_1 (%)	ϕ_c (pa ² /Hz)
3.71	2	7.83×10^{-11}	1.20	8.17×10
3.71	4	3.27×10^{-10}	1.31	3.74×10^2
3.71	6	6.44×10^{-10}	1.72	9.68×10^2
3.71	8	2.24×10^{-9}	2.22	4.30×10^3
1.17	6	7.16×10^{-11}	1.72	1.36×10^2
1.17	8	1.81×10^{-10}	2.0	4.20×10^2
1.17	10	4.72×10^{-10}	2.0	9.99×10^2
1.17	15	2.35×10^{-9}	2.50	6.20×10^3
1.17	20	4.69×10^{-9}	3.00	1.48×10^4

Figure 1.2-1. Flow Spoilers

Figure 1.2-2. PSDs of Wall-Pressure Fluctuations for Measurements with Different System Spoilers versus Frequency; A (Grid), C (Ring), D (Propeller), N (No Spoiler), $d_h = 3.71$ cm, $X/\ell = 0.125$, and $U = 8$ m/s

Figure 1.2-3. PSDs of Wall-Pressure Fluctuations for Measurements in Three Annuli; $U = 8$ m/s, $X/l = 0.375$, Grid Spoiler

Figure 1.2-4. PSDs of Wall-Pressure Fluctuations at Three Axial Positions in 3.71-cm Annulus; $U = 8$ m/s, Grid Spoiler

Figure 1.2-5. PSDs of Wall-Pressure Fluctuations at Three Axial Positions in 2.44-cm Annulus; $U = 8$ m/s, Grid Spoiler

Figure 1.2-6. PSDs of Wall-Pressure Fluctuations at Three Axial Positions in 1.17-cm Annulus; $U = 8$ m/s, Grid Spoiler

Figure 1.2-7. Normalization of PSD Curves of Wall-Pressure Fluctuations with Dynamic-Head Parameter versus Wavenumber (f/U)

Figure 1.2-8. RMS Values of Wall-Pressure Fluctuations of Three Hydraulic Diameters and $U = 8$ m/s, as a Function of Axial Position; $d_h = 1.17$ cm (Δ), 2.44 cm ($\circ$) and 3.71 cm ($\square$)

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Figure 1.2-9. Positions of Instrumented Rod and Pressure Transducers

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Figure 1.2-10. Wall-Pressure PSDF from Three Axial Locations;
 $d_h = 3.71$ cm, $U = 8$ m/s, Grid Spoiler

GEAP-24369

Figure 1.2-11. Wall-Pressure PSDF from Three Axial Locations;
 $d_h = 1.17 \text{ cm}$, $U = 8 \text{ m/s}$, Grid Spoiler

Figure 1.2-12. PSDF of Wall-Pressure Fluctuations on the Instrumented, Peripheral Rod with $\theta = 0^\circ$ and 90° , and No Upstream Spoiler; A (90°), B (0°), $X/l = 0.375$, $U = 12$ m/s

Figure 1.2-13. Comparison of Wall-Pressure Spectra for Measurements in Annuli and Array Channel without Upstream Grid Turbulence; A (Seven-rod Array), B ($d_h = 3.71$ cm) and C ($d_h = 1.17$ cm), $X/\ell = 0.125$ and $U = 8$ m/s

Figure 1.2-14. Comparison of Wall-Pressure Spectra for Measurements in Annuli and Array Channel with Upstream Grid Turbulence; A (Seven-rod Array), B ($d_h = 3.71$ cm), and C ($d_h = 1.17$ cm), $X/l = 0.125$ and $U = 8$ m/s

TASK 1.3 - LEAKAGE FLOW MECHANISMS (CR&D AND NED)

Task 1.3, performed by General Electric Corporate Research and Development and Nuclear Engineering Division, is designed to establish a better understanding of leakage-type flow-induced vibrations for geometries common to light water reactor. The technical objectives include the following:

- (1) Mathematically model and classify components involving leakage flows. Identify flow/geometric and structural features leading to an instability.
- (2) Experimentally illustrate the general classification with critically selected experiments.
- (3) Contribute input to design guides for critical reduced velocity $U/f_n L$ as a function of flow/geometric and structural features to eliminate or reduce possibility of self-induced vibrations. Proof test the design guide by application to a selected LWR component.

Task Description

Task 1.3 is divided into four subtasks:

Task 1.3a - Modeling and Classification of Classes of Components with Leakage Flow-Induced Vibration Susceptibility

Task 1.3b - Simple Experiments to Illustrate Concepts and Governing Parameters Identified by Mathematical Models

Task 1.3c - Proof Test of Evolving Design Guides on a Selected LWR Component

Task 1.3d - Leakage Flow-Induced Vibration Design Guide

Work Performed This Report Period

Activity on this task has not been initiated since it is not yet funded.

TASK 1.4 - RANDOM VIBRATION EFFECTS (ANL AND NED)

Task 1.4 consists primarily of a literature survey to review existing random vibration fatigue damage rules and experimental data related to interpretation of FIV data. Based on this review, suitable random fatigue damage criteria will be developed and recommended for application to LWR components subjected to flow-induced vibration.

Task Description

Task 1.4 is broken into three subtasks:

Task 1.4a - Survey of Literature

Task 1.4b - Derivation of Procedure/Criteria

Task 1.4c - Design Guides

Work Performed This Report Period

This task has been completed. There is no further progress to report.

TASK 2 - MODEL AND FULL-SIZE COMPONENT TESTS

Task 2 is devoted to the FIV testing of realistic model and prototypical geometries, rather than the idealized geometries studied in Task 1. Model and full-scale testing of several LWR components will be performed to extend the Task 1 results and provide input for the development and verification of empirical relations, scaling laws, and predictive models generated as part of Task 3. The components tested will, in general, be from General Electric's most recent boiling water reactor product line, the BWR/6. Task 2 is divided into five component test programs:

Task 2.1 - Lower Plenum

Task 2.2 - Fuel Assembly

Task 2.3 - Jet Pump

Task 2.4 - Low Pressure Coolant Injection Line

Task 2.5 - LWR Component (undefined)

Progress achieved for each of these component tests for the report period is described on the following pages.

TASK 2.1 - LOWER PLENUM (NED)

Task 2.1 is an experimental FIV study of tubes in an array. The array is a mix of tubes with different diameters. The flow environment combines regions of cross flow and parallel flows. The results from this task will be evaluated using results from the fundamental studies (Tasks 1.1 and 1.2) in order to highlight the important FIV mechanisms in real LWR components. The first steps in this study were to perform FIV tests on tenth-scale and quarter-scale models of a BWR lower plenum. This provided preliminary data and the experience necessary to run a productive full-scale model test. The final step in this process is to measure vibration in an LWR before power generation startup. This will verify the more extensive full-scale model results.

Task 2.1 consists of four subtasks:

Task 2.1a - Lower Plenum One-Tenth Scale FIV Test

Task 2.1b - Lower Plenum Quarter-Scale FIV Test

Task 2.1c - Lower Plenum Full-Scale FIV Test

Task 2.1d - Lower Plenum Operational LWR Field FIV Test

Progress achieved on Task 2.1 is described on the following pages.

Task 2.1a - Lower Plenum One-Tenth Scale FIV Test (M. A. DeCoster, S. L. Kushman)

Task Description

A one-tenth-scale model of a BWR lower plenum was constructed of clear cast epoxy to study the flow patterns in the lower plenum via flow visualization in 1974. Later, velocity probes were inserted into the flow stream to obtain quantitative measurements of the flow distribution. In 1976, flow-induced vibration tests were initiated to determine the vibrational characteristics of control rod guide tubes in the lower plenum. The tests were completed late in 1976.

Work Performed This Report Period

- I.S. X2AT

The one-tenth-scale lower plenum model test and analysis program was completed during a previous report period. Results were documented in GE report GEAP-24124, "Flow-Induced Vibration for Light Water Reactors Progress Report (June - September 1977)."

Task 2.1b - Lower Plenum Quarter-Scale FIV Test (M. A. DeCoster)

Task Description

A quarter-scale model of a BWR lower plenum was constructed by GE in 1974 to study flow distribution and vibration levels of lower plenum components. The model was situated at the Colorado State University Hydro-machinery Laboratory. Flow and shake tests performed in 1974, 1975, and 1976 yielded extensive flow distribution vibration data for various designs. The final tests were completed in the last quarter of 1976.

Work Performed This Report Period

The quarter-scale lower plenum model test and analysis program was completed prior to the commencement of the Flow-Induced Vibration for Light Water Reactors program. Results were documented in GEAP-24124.

Task 2.1c - Lower Plenum Full-Scale FIV Test (M. A. DeCoster)

Task Description

Task 2.1c consists of the FIV testing of prototype LWR components in the lower plenum of 60° sector model at the High Flow Hydraulic Test Facility (HF)². The test components were made at the same facility and to the same standards as actual reactor components. The components are full scale but the sector model contains one-sixth the number of components in a reactor. The components in the lower plenum are cylinders of various diameters in an array pattern. Water flows around the outside of these components.

The test program consists of a series of shake tests followed by flow tests. In the shake tests, a single component is forced to vibrate by an electromagnetic shaker or impact hammer. The input force and resulting motion are measured, and the information is processed to define the structural characteristics of the component. In the subsequent flow tests, the vibration response of the components, as well as certain aspects of the FIV forces, are measured for a variety of operational and nonoperational flow conditions.

Work Performed This Report Period

All work has been completed on this task with the exception of the topical report. The topical report will be completed in 1981.

TASK 2.2 - FUEL ASSEMBLY (NED)

Task 2.2 is designed to fully investigate the FIV characteristics of a prototype fuel assembly. The primary objectives are to:

- (1) Establish the FIV character of a typical fuel assembly including mode shapes, frequencies, character of response, and assessment of the stability margin as a function of system damping and flow;
- (2) Determine the relationship between the FIV characteristics and coolant properties; i.e., coolant temperature (ambient versus LWR operational conditions) and quality (single-phase water versus two-phase water-steam); and
- (3) Proof-test the concepts and forcing function estimates devised in Task 1.

Task 2.2 will be useful in verifying and extending the fundamental studies on parallel flow over tube banks of Task 1.1. It will provide input to the analytical model development of Task 3.1 and the scaling development (importance of temperature) of Task 3.2.

Task 2.2 is divided into three test programs:

Task 2.2a - Fuel Assembly Cold FIV Test

Task 2.2b - Fuel Spacer Preload FIV Test

Task 2.2c - Hot FIV Test

A description of progress achieved during this report period is given in the following pages.

Task 2.2a - Fuel Assembly Cold FIV Test

Task Description

Task 2.2a consists of the FIV testing of a prototype 8 x 8 fuel assembly over a wide range of hydraulic conditions using the General Electric Large Tank Hydraulic Loop. The assembly is heavily instrumented with accelerometers, pressure transducers, and strain gages to determine the dynamic characteristics of the fuel assembly components as well as to describe the forcing mechanisms. The test is performed at a water temperature of approximately 75°F.

The fuel assembly (Figure 2.2-1) is made up of 64 Zircaloy rods, each approximately 16-in. long, 1/2-in. in diameter, and 32-mils thick. The rods are spaced and supported in a square (8 x 8) array by a lower and upper tie-plate. The lower tieplate has a nosepiece which distributes coolant flow to the fuel rods. Seven spacers, evenly spaced along the rods, maintain rod-to-rod spacing. Each spacer provides a three-spring support for the fuel rod: two stiff springs contacting the rod at points azimuthally separated by 90 degrees, and a third flexible spring on the opposite side of the rod, azimuthally separated from the other two springs by 135 degrees. Three-point contact is maintained by establishing an initial preload (i.e., sizing the springs such that they are compressed when the fuel rod is first installed in the spacer). Finally, the fuel bundle is enclosed by a square channel box, causing the coolant flow to be almost exclusively parallel in nature.

Work Performed This Report Period

The cold flow-induced vibration testing of a prototypical 8 x 8 fuel assembly was completed early in the program and was substantially reported in previous progress reports. A final report on this work is being prepared.

Task 2.2b - Fuel Spacer Preload FIV Test

Task Description

These tests will investigate the effect of fuel spacer spring placed on the FIV characteristics of fuel rods. Specifically, the test results should indicate:

- (1) At what flow-preload conditions the fuel rod loses contact with the spacer springs and begins vibrating within the spacer.
- (2) The vibration levels (rod-spacer impact acceleration levels) that result when the conditions in (1) above are met.
- (3) The effect of spacer spring preload and stiffness on fuel rod FIV characteristics (frequency and amplitude).

Work Performed This Report Period

The test program will consist of the following elements:

- (1) single-rod flow test,
- (2) 3 x 3 rod bundle flow test.

Fuel preload flow-induced vibration tests were started at the end of 1980.

Single Rod Test

Preliminary observations show low level fuel rod vibration with full initial preload. This observation is for the single rod in annular flow. Instrumentation problems were encountered with the piezo-resistive force gages to measure spacer preload. The sensors were out of temperature specification so static load could not be measured electronically. Static load was measured manually.

3 x 3 Rod Bundle Flow Test

This test will utilize the same instrumented fuel rods described for the single rod test, surrounded by eight dummy (non-instrumented) rods. Actual fuel spacer equipment will be used, with the preload being adjusted by controlling the amount of spring deflection caused by rod insertion into the fuel bundle. Only the preload on the central, instrumented rod will be controlled.

The range of preloads to be tested is 0-3 pounds, which is inclusive of the preloads nominally encountered in present fuel designs. Testing will be performed on this 3 x 3 fuel assembly array in the first quarter of 1981.

Task 2.2c Hot FIV Test

Task Description

This is the final major test to be performed in San Jose under this contract. Flow tests will be performed on a 3 x 3 array of fuel rods under reactor temperature and pressure (550°F, 1050 psia) at the General Electric heat transfer test facility ATLAS. This is the final test in the fuel area. The primary purpose is to determine the effect of two-phase boiling conditions on fuel rod vibrations. The test will be run in four steps:

- (1) Single-phase water flow at 180°F to compare to results from Task 2.2b.
- (2) Single-phase hot flow at 550°F to determine any effect from temperature.
- (3) Two-phase hot flow with no heat input to the fuel rod (constant quality).
- (4) Two-phase hot flow with nucleate boiling from rod heating.

Work Completed This Report Period

Much of the preliminary preparation work has been completed. Hardware design and purchase of long lead time items is proceeding. Test support staff have been allocated for the prospective test period of July and August, 1981.

The ceramic fuel channel has been ordered. Two alternate dummy fuel pellet designs were evaluated. One design is a tungsten carbide pellet with flame sprayed insulation. The other possibility is die stamped uranium oxide. Either one will have the same weight as a real fuel pellet. The first design is preferred because radioactive safety measures will not have to be employed. The test specification has been written and is on review. All preparations are proceeding smoothly toward the July test start date.

Figure 2.2-1. Test Setup (Single-Rod Test)

TASK 2.3 - JET PUMPS

Task 2.3 is designed to fully investigate and quantify the FIV characteristics of a jet pump assembly. A typical jet pump assembly is shown in Figure 2.3-1. There are 20 jet pumps in the current BWR design. Jet pump primary components are a mixer and diffuser which are joined together at a thermal expansion slip joint. Approximately one-third of the reactor core flow is taken from the vessel, pumped through a piping manifold system, and returned to the vessel, where it is discharged from the jet pump nozzle at high velocity (≈ 200 ft/sec) into the initial stage of the jet pump mixer. The nozzle flow entrains surrounding water into the jet pump throat where the two flows mix and then diffuse, to be finally discharged into the lower core plenum at velocities up to 40 ft/sec. The jet pump has many characteristics that can contribute to flow-induced vibrations (e.g., high-velocity flow in small pipes, high-velocity flow in a pipe turning 180° within a small radius, and high-velocity jets exiting into a confined region). However, the two characteristics which are judged to be the most significant contributors are, in order of magnitude:

- Leakage flow through the mixer-diffuser slip joint interface.
- Mixing of the high-velocity drive flow with the entrained suction flow in the mixer.

Jet pump tests will be performed hot (550°F) and cold ($60 - 180^\circ\text{F}$), under operational and nonoperational conditions, at rated and above-rated flows. Specific goals include the following: (1) identify the vibration characteristics of a typical jet pump (natural frequencies, mode shapes, damping); (2) characterize the primary forcing functions; (3) establish a jet pump response map (i.e., response versus flow conditions); (4) relate jet pump stability to system damping, flow conditions, geometry, etc., and (5) determine the effect of fluid temperature on the FIV characteristics. This work will be directly tied to the fundamental studies performed in Task 1 (in particular, the leakage flow mechanisms work of Task 1.3) for input into the Design Guide Development work of Task 3.1. In addition, it will be utilized in developing temperature scaling relationships in Task 3.2.

Task 2.3 is divided into three subtasks:

Task 2.3a - Jet Pump Cold FIV Test

Task 2.3b - Jet Pump Hot FIV Test

Task 2.3c - Jet Pump Mechanistic Test

Task 2.3a - Jet Pump Cold FIV Test (M. A. DeCoster, M. R. Torres, T. Nakao)

Task Description

Four prototype BWR/6-238 jet pumps (two jet pump pairs) are flow-tested over a wide range of hydraulic conditions, using the High Flow Hydraulic Facility 60° Sector Test Stand (Figure 2.3-1). The jet pumps are heavily instrumented with accelerometers, pressure transducers, strain gages, and displacement sensors so as to determine the dynamic characteristics and vibration response, as well as to characterize the forcing function. Tests are performed at temperatures ranging from 60°F to 180°F.

Work Performed This Report Period

All testing and analysis of jet pumps at the High Flow Hydraulic Facility has been completed. Much of the vibration data has been reduced and analyzed. Topical reports documenting this work are in progress.

Pressure Transducer Data Reduction

In a previous quarterly report (GEAP-24926) vibration response data was described. During this report period extensive investigation of dynamic pressure transducer data was performed.

Pressure Distribution

The pressure fluctuations along the inner surface of the mixer and diffuser were measured by pressure transducers shown in Figure 2.3-1. Root mean squares

(RMS) of the pressures are plotted in Figure 2.3-2. Pressure fluctuations were found to be quite large in the mixer, especially just downstream from the mixer inlet. It is hypothesized that these large fluctuations are the direct result of high turbulence caused by the unsteady mixing between suction and drive flow in this mixer region. In the diffuser, the fluctuations were found to be quite small (less than 1 psi).

Differential Pressure Distributions and their PSDs

Fluid force, which vibrates jet pumps, can be presented by differential pressures in radial and tangential directions. Differential pressures can be calculated by subtracting pressure signals from diametrically opposite sensors at the same axial location. Figure 2.3-2 shows differential pressure distributions on the mixer and diffuser in radial and tangential directions. Again, the differential pressures are largest in the mixer region with maximum 8 psi RMS (Root Mean Square of signal) and decreases through the mixer until at the lower elevation near the slip joint where the differential pressure is less than 1 psi through the diffuser. Again, the high turbulence just downstream of the mixer inlet is observed as previously stated. As to the force directions, differential pressure measurements in radial direction on the mixer were found to be larger than those in tangential direction.

The PSD of the differential pressure transducer was found to decrease almost linearly on a log-log plot with the frequency. The slope of this decrease is 20 dB per a decade. This relation can be described analytically as (PSD) $\propto f^{-1}$. This relation can be seen in the mixer and diffuser, and agrees well with past measurements and theories on turbulence spectra. Again, this observation alone is an extremely important and new contribution to the understanding of the nature of the predominate (turbulent) forcing function acting on jet pumps.

Task 2.3b - Jet Pump Hot FIV Test

Task Description

Flow tests are performed on single prototypical jet pumps under reactor temperature and pressures (550°F, 1050 psia) at the Pacific Gas & Electric Moss

Landing Power Station where the GE Steam Water Test Facility is located. The test program is designed to establish a better understanding of the relationship between the vibration response of the component and the key fluid and geometric parameters, particularly in the slip joint region. The program is separated into two activities, each described below.

- (1) The first activity consists of the thorough FIV testing of a BWR/5 201-in. jet pump. This jet pump is of interest to the FIV for LWR Program because its geometric and fluid characteristics (lower fundamental frequency and higher slip joint pressure drop than other designs) make it more susceptible to slip joint-type vibration stabilities. Sufficient vibration instrumentation will be utilized to characterize the natural frequencies, mode shapes, primary forcing functions, and system response for various flow conditions.
- (2) The second activity consists of the very limited FIV testing of BWR 218-in. and 251-in. jet pumps. The data, consisting primarily of vibration response as a function of flow condition, are acquired through the addition of several vibration sensors to jet pumps scheduled for hydraulic performance testing at the Moss Landing facility. The additional data will provide significant information concerning the effect of geometry (diffuser length, slip joint geometry, etc.) on the dynamic response of this LWR component.

Work Performed This Report Period

All flow-induced vibration testing of single prototypical jet pumps under reactor temperature and pressure in the Pacific Gas & Electric Moss Landing Steam Water Test Facility has been completed. Much of the vibration data has been reduced and analyzed. Topical reports documenting this work will be issued.

Figure 2.3-1. Jet Pump 2 Pressure Sensors

Figure 2.3-2. Pressure Distribution (RMS) in Mixer and Diffuser

Figure 2.3-3. Differential Pressure (DP) Distribution in Mixer and Diffuser

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Figure 2.3-4. Power Spectral Density (PSD) of Differential Pressure

Figure 2.3-5. Jet Pump Pairs

TASK 2.4 - LOW PRESSURE COOLANT INJECTION COUPLING

The low pressure coolant injection (LPCI) system is part of the boiling water reactor emergency core cooling system. Not used during normal operation, its sole purpose is to restore and maintain the desired water level in the reactor vessel after a loss-of-coolant accident (LOCA). The overall system is shown in Figure 2.4-1; the internal coupling hardware is shown in Figure 2.4-2. The coupling hardware consists primarily of two 10-in.-ID elbows, joined together by a 26-in.-long sleeve. Collars with thread on the two elbows capture the sleeve during installation and hold it in place (to accommodate differential thermal expansion, the sleeve is not welded to the elbows). A nominal gap of 8 mils exists between the sleeve and each collar.

The LPCI is subject to FIV under both normal plant operation and emergency (LOCA) modes. Under normal operating conditions, when there is no flow through the LPCI, downcomer annulus flow buffets the LPCI coupling. In addition, a steady-state pressure drop across the collar-sleeve slip joints induces leakage flow which can result in fluid-elastic coupling. In the LOCA mode, the high flow velocities through the coupling produce turbulent buffeting of the inner walls. Also, as in the normal operating mode, slip joint differential pressures exist which can induce some leakage flow.

Task Description

Task 2.4 consists of flow-testing a prototypical BWR/6 238-in. LPCI coupling in the High Flow Hydraulic Facility's General Purpose Test Tank. The coupling is heavily instrumented with a combination of accelerometers, pressure transducers, and strain gages, as well as many thermal-hydraulic sensors to ascertain the vibration characteristics and leakage flow through the collar-sleeve slip joints as a function of the following parameters:

- (1) Slip joint differential pressure;
- (2) Internal (LOCA) flow;
- (3) External (normal plant operation) flow;

(4) LPCI cooling alignment; and

(5) Slip joints sealing (none, labyrinth seal, and piston ring).

This test program should provide some fundamental understanding of the flow-induced vibration characteristics of large piping configurations with slip joints.

Work Performed This Report Period

All test activities have been completed, and efforts are now directed toward data reduction and analysis, as well as final test documentation. Preliminary results from data analysis were reported in GEAP-24248. Data analysis is continuing and a final report is being prepared.

- ① CONTAINMENT
- ② DRYWELL
- ③ RPV
- ④ SYSTEM PUMP
- ⑤ SUPPRESSION POOL
- ⑥ HEAT EXCHANGERS

Figure 2.4-1. Residual Heat Removal System, Low Pressure Coolant Injection Function

Figure 2.4-2. Low Pressure Coolant Injection System

TASK 3 - LWR FIV DESIGN METHODS, GUIDES AND CRITERIA

The primary purpose of Task 3 is the development of FIV guides and criteria which can be utilized by engineers for the design of LWR components. This is accomplished through the generation of analytical models and empirical relations, using the results of the fundamental studies, full-scale component tests, and actual plant vibration data generated in Tasks 1 and 2. Additionally, Task 3 is designed to establish scaling laws for FIV testing of reactor components, as well as to provide analytical support for the model testing of Task 2. The technical objectives are to:

- (1) Develop analytical methods and computer codes for predicting the FIV response of reactor components;
- (2) Develop empirical relations, scaling laws, and practical design guides for reactor design utilizing the information generated in Tasks 1 and 2; and
- (3) Verify analytical methods by comparison with full-scale development tests and actual plant vibration data as available.

Task 3 is divided into three separate activities:

Task 3.1 - Predictive Model Development

Task 3.2 - Scaling

Task 3.3 - Correlation with Full-Scale Tests and Plant Data

Task 3.1 will develop the analytical methods and computer codes for predicting the FIV response of reactor components. Task 3.2 will indicate which parameters are critical (i.e., must be duplicated or accounted for) when performing scale-model testing of reactor components. Task 3.3 will verify the results of the predictive models and scaling laws, using vibration data from prototype LWR tests.

Progress achieved on these activities is described on the following pages.

TASK 3.1 - PREDICTIVE MODEL DEVELOPMENT (NED)

Task 3.1 is devoted to the generation and verification of analytical methods for predicting the FIV response of reactor component structures. The desired output from the task is one or more FIV design guides.

The basic approach used in Task 3.1 is to characterize the FIV problem into two categories, one to determine the amplitude of response, and the other to establish critical stability parameters and their range of influence. For response problems, the approach taken is to stochastically model the excitation and random response. Wherever possible, existing analytical tools, as well as special analytical techniques developed through the fundamental studies, are used for the generation of predictive FIV methodology. For the stability problem, reliance will be placed primarily on empirical results. Computer results are written to calculate the FIV response of structures, knowing structural and damping characteristics. Empirical formalisms and predictive models are verified against experimental results from Task 2. Stability curves are generated for structures to aid in safe-point operations.

Task 3.1a - Random Decrement Method (M. A. DeCoster)

Task Description

Damping is a very important parameter in evaluating the response of any vibrating structure. Unfortunately, it can be difficult to quantify, particularly for some of the complex reactor components under operational conditions. Therefore, methods are being sought to accurately measure the damping of structures in the actual reactor environment (i.e., after plant installation). The method presently under consideration is called random decrement. It is designed to identify model parameters such as frequencies and damping for any component from a simple vibration response time history obtained during normal operations. This is accomplished by time-averaging specifically chosen blocks of data to form a randomdec signature, and then fitting one or more damped sinusoids to the signature via the modified difference Levenberg-Marquardt algorithm.

Task 3.1b - Slip Joint Mechanistic Model (M. R. Torres)

Task Description

The internal flow velocities required to incur detrimental levels of flow-induced vibration in pipes are usually quite high for most practical applications. However, if submerged piping structures are coupled with annular slip joints to accommodate static load deflections or thermal growth, a practice utilized quite freely in industry, a geometry is created which is very susceptible to high-level FIV. This was demonstrated during the early stages of the FIV for LWR Program through small-scale experiments on a pair of submerged cantilever pipes joined at their free end with internal flow (documented in "FIV for LWR Progress Report, June-September 1977," Document No. C00/4175-2).

An in-depth investigation of existing technical literature has been performed which reveals extensive information exists on the dynamic stability of pipes with internal or external flow, as well as on the dynamic characteristics of submerged structures (e.g., virtual mass, stiffness, frequency mode shape). However, sparse technical reporting on the subject of slip joint geometries is available, revealing that more fundamental-work is warranted, particularly as related to the development of analytical models to predict the response of reactor components with slip joints. Therefore, it is the objective of this task to generate a mathematical model which can be used to predict the level and onset of slip joint vibration as a function of piping structural parameters, details of the slip joint geometry, and hydraulic parameters.

Work Performed This Report Period

A mathematical model is under derivation. The approach taken is to solve the Navier-Stokes equation within the annular slip joint and determine the interaction force between the two cantilever pipes as a function of the motion of the pipes at the slip joint. The equations of motion of each cantilever pipe are coupled with this interaction (slip joint) force. Solution of these fluid-structure equations is underway.

TASK 4 - PROGRAM ADMINISTRATION

Task Description

The purpose of Task 4 is to provide the overall management of the program, including coordination, reports, and reviews. In addition, it ensures that the program's fundamental studies, model and full-size component tests, and analytical method development are responsive to the PWR as well as the BWR needs in the area of flow-induced vibrations.

Work Performed This Report Period

The fiscal year 1981 budget was increased to 1.25 million and the contract period was extended to December 31, 1981.

DISTRIBUTION LIST

Dr. M. K. Au-Yang
Babcock & Wilcox
Nuclear Power Generating Division
P.O. Box 1260
Lynchburg, VA 24505

Dr. Thomas Balsa
Engineering Mechanics Programs
Corporate Research & Development
General Electric Company
P.O. Box 8
Schenectady, New York 12301

Mr. Jon Borg
Reactor Programs Division
9800 South Cass Avenue
Argonne, Illinois 60439

Mr. J. N. Calvin
C-E Power Systems
Combustion Engineering, Inc.
1000 Prospect Hill Road
Windsor, Connecticut 06095

Chief
Mechanical Engineering Branch
Division of System Safety
U.S. Nuclear Regulatory Commission
Washington, D.C. 20555
Mail Stop P-1114

Mr. Thomas N. Rodeheave
Division of Naval Reactors
U.S. Department of Energy
Washington, D.C. 20545
Mail Stop H-404

Mr. R. W. Curtis, Manager
Design and Development Laboratory
Alliance Research Center
Babcock & Wilcox Company
Alliance, Ohio 44601

Mr. Dominic Dilanni
Engineering Branch
Division of Operating Reactors
U.S. Nuclear Regulatory Commission
Washington, D.C. 20555
Mail Stop P-1030

Mr. William Farmer
Division of Reactor Safety Research
U.S. Nuclear Regulatory Commission
Washington, D.C. 20555
Mail Stop 1130SS

B. Fritz
General Electric Company
Box 1072
Schenectady, NY 12301

Dr. Donald R. Harris
Department of Nuclear Engineering
Rensselaer Polytechnic Institute
Troy, NY 12181

Professor Barclay G. Jones
Nuclear Engineering Program
University of Illinois at
Urbana-Champaign
214 Nuclear Engineering Laboratory
Urbana, Illinois 61801

Jefferey Hangst, Project Manager
Office of Light Water Reactors
Div. of Fuel and Components
U.S. Department of Energy
Washington, D.C. 20545
Mail Stop B107

Mr. R. P. Letendre
C-E Power Systems
Combustion Engineering, Inc.
1000 Prospect Hill Road
Windsor, Connecticut 06095

Dr. M. Levenson, Director
Nuclear Power Division
Electric Power Research Institute
3412 Hillview Avenue
P.O. Box 10412
Palo Alto, California 94304

Dr. W. Loewenstein, Director
Safety and Analysis Department
Electric Power Research Institute
3412 Hillview Avenue
P.O. Box 10412
Palo Alto, California 94304

DISTRIBUTION LIST (Continued)

Mr. Barry J. Lubin
C-E Power Systems
Combustion Engineering, Inc.
1000 Prospect Hill Road
Windsor, Connecticut 06095
Mail Code 9485-1027

Ms. Jane Monhart/Mr. Lou Parys (2)
Contracts Management Office
U.S. Department of Energy
Chicago Operations Office
9800 South Cass Avenue
Argonne, Illinois 60439

Dr. T. M. Mulcahy
Vibration Analysis Section
Components Technology Division
Argonne National Laboratory
9700 South Cass Avenue
Argonne, Illinois 60439

Professor M. P. Paidoussis, Chairman
Department of Mechanical Engineering
McGill University
817 Sherbrook Street West
Montreal, P.W., Canada H3A2K6

Professor Robert Plunkett
Department of Aerospace
Engineering & Mechanics
University of Minnesota
107 Aeronautics Engineering Building
Minneapolis, Minnesota 55455

Mr. Joseph A. Prestele
Assistant Department Director
Nuclear Engineering & Operations
Department
Electric Power Research Institute
3412 Hillview Avenue
P.O. Box 10412
Palo Alto, California 94304

E. Ruggiero
Code 08
Department of the Navy
Naval Sea Systems Command
Washington, D.C. 20362

Dr. Sudhir Savkar
Engineering Mechanics Programs
Corporate Research & Development
General Electric Company
P.O. Box 8
Schenectady, New York 12301

Mr. Norman Singleton
Westinghouse Electric Corp.
P.O. Box 355
Pittsburgh, PA 15230

Dr. Ronald So
Engineering Mechanics Programs
Corporate Research & Development
General Electric Company
P.O. Box 8
Schenectady, New York 12301

Dr. Martin W. Wambsganss
Vibration Analysis Section
Components Technology Division
Argonne National Laboratory
9700 South Cass Avenue
Argonne, Illinois 60439

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