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

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**FINAL PROGRESS REPORT
(JULY 1981 — SEPTEMBER 1981)**

NOVEMBER 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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M. R. TORRES

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ABSTRACT

Flow-Induced Vibration for Light Water Reactors (FIV for LWRs) is a program designed to improve the FIV performance of light water reactors through the development of design criteria, analytical models for predicting behavior of components, and general scaling laws to improve the accuracy of reduced-scale tests, and through 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 final period from July 1981 to September 1981. This is the last quarterly progress report to be issued for this program.

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 the downtime caused by FIV failure of components. It is a 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 January 1, 1981, through March 31, 1980, are 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/4174-2.
3. October - December 1977, GEAP-24151, COO/4175-5.
4. January - March 1978, GEAP-24163, COO/4175-9.
5. April 1978 - December 1979, GEAP-24248, DOE/N/4175-14.

6. January - June 1980, GEAP-24926, DOE/ET/34209/16.
7. July - September 1980, GEAP-24368, DOE/ET/34209/17.
8. October - December 1980, GEAP-24369, DOE/ET/34209/18.
9. January - March 1981, GEAP-24370, DOE/ET/34209/19.
10. April - June 1981, GEAP-24385, DOE/ET/34209/22.

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, 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 Buffeting 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 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 studied in Task 1.1c.

Work Completed This Report Period

All work related to this activity is now completed.

Task 1.1c - Buffeting of Cylinder Arrays in a Turbulent Cross Flow (S. Savkar,
T. 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 are directed toward characterizing 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

All the staggered array testing was completed during this reporting period. Fluctuating forces, both lift and drag, were measured on three equilateral array configurations. The pitch-to-diameter ratios (p/d) tested were 1.2, 1.5, 1.71, with each array built up to four rows deep. The primary measurements were made with the load cell instrumented cylinders. The active span, over which the load was measured, was $3d$. The arrays were built up with

dummy (non-instrumented) cylinders arranged around the load cell cylinder. By suitably rearranging the array, the load cell cylinder was consecutively located in the first, second, third, and fourth row. This gives some measure of the fluctuating loads induced in the leading, trailing and intervening rows, although not all at the same time. Tests were run with both a uniform inflow and with the upstream rendered turbulent by means of a six-inch square mesh grid. The grid was located at a fixed distance of eight mesh dimensions upstream of the load cell instrumented cylinder. The nominal turbulence level at the instrumented cylinder site, in the absence of any cylinders, was an axial intensity of 8.5% and transverse fluctuations of 6.5%. The measured (average) axial scale, obtained from autocorrelations, under the same conditions was 2.6 inches. In the absence of the grid, the turbulence level in the tunnel was less than 1/2%. Some preliminary runs were also made with a three-inch mesh grid located 7.5 mesh dimensions upstream of the load cell cylinder. However, these results did not vary measurably from the six-inch mesh grid results. Consequently, very little testing with the three-inch mesh grid was done.

All force coefficients, Reynolds numbers, and Strouhal numbers reported herein will be based on the upstream (freestream) velocity U_∞ and cylinder diameter d . Thus the Reynolds number is $Re = U_\infty d/\nu$, with ν the kinematic viscosity; the Strouhal number is $St = fd/U_\infty$, with f the measured dominant spectral frequency;

and the force coefficients are (lift - C'_L , drag - C'_d) = $\text{force} / \left(\frac{\rho U_\infty^2}{2} \cdot S \cdot d \right)$ with S the active span ($S = 3d$).

A sample set of results obtained are illustrated in Figures 1.1-1 to 1.1-7. Figure 1.1-1 documents a set of results obtained on the 1.5 pitch array. Several features of these data are worth noting. For the 1.5 pitch array, the progression of the measured lift coefficients as a function of the row was more or less monotonic. This was not necessarily true for the other arrays. Indeed, the maximum lift coefficients measured for the 1.2 pitch were in the second row, whereas the 1.71 pitch array recorded the maxima in the third row. Maxima means the whole curve as a function of Reynolds number, not just individual points. Secondly, the flows through these arrays did not always behave predictably. Hence note the sudden drop in the 1.5 pitch second row lift coefficients at a Reynolds number of about 8×10^4 . This appears to

be the result of a sudden and early transition of the flow, during this run, from "subcritical" to "supercritical" (reminiscent of the isolated cylinder behavior reported in earlier reports). The transition phenomenon is also illustrated by the lift power spectra in Figures 1.1-2, 1.1-3 and 1.1-4. All three were obtained at approximately the same Reynolds number. The ordinates in the three spectra were not scaled to precisely the same number but are close enough for gross comparisons. Hence note that rows one and three show a strong peak at the Strouhal number of about 1.6, with a weaker peak at a Strouhal number of 1.1. This latter peak is a duct acoustic mode which is often seen occurring at about 138 Hz. The amplitude of this 138 Hz tone is about the same in all three figures. The amplitude of the Strouhal peak in Figure 1.1-3 is about the same as the 138 Hz acoustic mode, or well below the amplitude in Figures 1.1-2 and 1.1-4. Curiously, this sudden transition was unpredictable. In this series of tests, the sudden early transition occurred in both the second and fourth rows, but not during the runs when the load cell cylinder was in the first or third row.

Further evidence in support of the above transition is the turbulent flow run plotted in Figure 1.1-1. The transition occurs early in the first row lift coefficients when the upstream is made turbulent with a six-inch mesh grid. This answers the issue first posed by the author in an earlier paper¹ as to whether the flow over a cylinder in an array experiences flow transitions reminiscent of isolated cylinders². An additional comment to this will be made presently.

The effect of varying the array pitch on the measured fluctuating lift and drag are illustrated in Figures 1.1-5 and 1.1-6. Plotted in these figures are the maximum force coefficients measured, without regard to the row in which they were measured. (Again, these are whole curves as a function of Reynolds number, not individual points.) Thus, the drag in this investigation always peaked in the second row, whereas the lift peaked in the second row for the 1.2 pitch array, first row for the 1.5, and third row for the 1.71. The drag data were generally not as well behaved as the lift. Since the row-to-row variations of lift in the first three rows, as measured in this study, were not that large, this suggests that the peak fluctuating loads generally occur in the second row.

Three features of these data are worth noting. First, the dominant spectral peak for both lift and drag occurred at the same frequency (unlike an isolated cylinder). This suggests that the fluctuations measured are probably in the gross flow pattern rather than resulting from vortex shedding per se. Consequently to refer to the dominant peaks as "Strouhal" might be somewhat misleading. However, this issue can only be resolved by extensively and carefully studying the details of the flow through the array, a task which is beyond the scope of this program. The second feature is that all three arrays do show the presence of a "transition." The quotation marks have been added in light of the previous point made and to make the point that these transitions could be different from those seen with isolated cylinders. Again, the depth of investigation called for to settle the issue is beyond the scope of this study. The third feature is that as the array parameters are tightened, the measured force coefficients increase. While the increase is monotonic, it is not as large as measured by Richter and Naudascher³ in the study on the effect of tunnel blockage on vortex shedding.

The measured "Strouhal" or dominant frequencies are plotted in Figure 1.1-7. The data for the 1.5 array is in almost exact agreement with frequencies measured by Yeung and Weaver⁴, and the data for the 1.71 array is about the same as the data reported by Chen.⁵ The author is not aware of any data published for an array as tight as the 1.2. Moreover, none of the earlier studies covered as high a Reynolds number range, or have the fluctuating force data, as does the present study.

Task 1.1d - Fluidelastic Instability Boundaries (T. F. Balsa)

Task Description

A combined test and analysis program is directed toward establishing the nature and boundary of fluidelastic instability of arrays as a function of array geometry. A near-term objective is the numerical prediction of the forces on an oscillating single cylinder at high Reynolds numbers (10^4 to 10^7). These predictions should be useful in establishing whether the forces can produce a hydroelastic instability, or whether they simply excite cylinder motion through their fluctuating or unsteady component.

Work Completed This Report Period

Preliminary theoretical models were formulated and critical experiments were outlined in previous reporting periods. Activity on this task was terminated after the first contract suspension. No further work is planned.

References

1. S. D. Savkar, "A Survey of Flow Induced Vibrations of Cylindrical Arrays in Cross Flow," ASME Preprint 76-WA/FE-21, 1976.
2. R. M. C. So and S. D. Savkar, "Buffeting Forces on Rigid Circular Cylinders in Cross Flows," J. Fluid Mech., Vol. 105, 1981.
3. A. Richter and E. Naudascher, "Fluctuating Forces in Rigid Circular Cylinder in Confined Flow," J. Fluid Mech., Vol. 78, 1976.
4. H. C. Yeung and D. S. Weaver, "The Effect of Approach Flow Direction on the Flow Induced Vibrations of a Triangular Tube Array," ASME Preprint 81-DET-25, November 1981.
5. Y. N. Chen, "Flow Induced Vibration and Noise in Tube Bank Heat Exchangers Due to von Karman Streets," 1968 Trans. ASME, Series B, J. Eng. for Industry, Vol. 90, pp. 134-146.

Figure 1.1-1. Row by Row Data of the Fluctuating Lift Induced on an Equilateral Staggered Array of 1.5 Pitch-To-Diameter Ratio.

Figure 1.1-2. Power Spectrum of the Fluctuating Lift Induced in the First Row of 1.5 Fitch Array at $Re \approx 8 \times 10^4$.

Figure 1.1-3. Power Spectrum of the Fluctuating Lift Induced in the Second Row of 1.5 Pitch Array at Re app 8×10^4 .

1.1-10

Figure 1.1-4. Power Spectrum of the Fluctuating Lift Induced in the Third Row of 1.5 Pitch Array at Re app 8×10^4 .

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Figure 1.1-5. Peak Lift Coefficients Measured in an Equilateral Pitch Staggered Array.

Figure 1.1-6. Peak Drag Coefficients Measured in an Equilateral Pitch Staggered Array.

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1.1-13/1.1-14

Figure 1.1-7. Strouhal Frequencies Measured in an Equilateral Pitch Staggered Array.

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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 that can be evolved into design guides will be devised.

A description of the progress achieved on these subtasks over the periods from July 1981 to September 1981 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 a 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. The ultimate goal is to develop 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 diameters, and upstream disturbances (turbulence).

Work Completed This Report Period

This activity has been completed and reported.

Activity 2 - Annular region (Air)**Task Description**

Two fundamental parallel FIV studies are being conducted: in one the wall and fluid field fluctuating pressures will be measured simultaneously, and in the other 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 as follows:

- (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 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 and
J. A. Jendrzejczyk)

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, and reduced velocities, in order to provide the basis for developing a mathematical model to predict response and scaling relations.

Work Completed This Report Period

Internal review of the topical report presenting results of this study has been completed. The report is ready for publication.

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

Task Description

Task 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

A topical report presenting results of the seven-rod array tests has been submitted for publication. This subtask has been documented and completed.

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

With the exception of the work of Ohlmer et al.,¹ analytical models to predict the response of rods to axial flow excitation typically assume a spatially homogeneous wall-pressure field. The implication of this assumption is that the statistics describing the wall-pressure field are the same at every point on the rod. This would be expected to be the case in situations involving fully developed turbulent flow. However, in many practical situations upstream turbulence is caused by flow channel discontinuities and/or component support assemblies. Other sources of turbulence are internal support grids. Turbulence from these extraneous sources will influence the wall-pressure fluctuations.

Turbulence and rod vibrations in annular flows with upstream disturbances have been studied as part of Task 1.2b². As expected, the turbulence generated by upstream disturbances decays as it travels downstream. For the annular flow tests performed, with the largest hydraulic diameter, $d_h = 3.71$ cm, the grid turbulence governed the flow and did not decay out until the exit of the test section was reached; with the smallest hydraulic diameter, $d_h = 1.17$ cm, the grid turbulence decayed rapidly, disappearing after traversing one-fifth of the rod length.

In related studies³⁻⁵, also part of Task 1.2b, wall-pressure measurements were made at selected axial positions along a test element to evaluate the effect of upstream flow spoilers on wall-pressure and, in particular, the decay in intensity of the wall-pressure with distance from the entrance to the test section. In agreement with the turbulence measurements, the wall-pressure fluctuations with upstream grid turbulence (as represented by the root-mean-squared (rms) value) decay rapidly in the small annulus case, and for the large annulus require the entire test section length to decay.

Ohlmer et al., recognized the need for a model to account for the axial variation of the wall-pressure statistics (spatial nonhomogeneity). He proposed a model in which the rod, or beam-like structure, is divided up into discrete lengths over which the pressure field is assumed to be homogenous and the normal modes are taken as constant.¹ In the present study, axial decay in intensity of the wall-pressure power spectral density is modeled by an exponential decay function. To evaluate the model, results from wall-pressure measurements are used to determine the coefficients in the functional decay relationship, and predicted values of rms displacement response are compared with measured values. Two different cases are solved, in one the wall-pressure fluctuations are assumed to be uncorrelated in the axial direction, in the other, axial correlation is accounted for.

The mean-square vibration response is determined by integration of the vibration response power spectral density function over frequency, as follows:

$$\langle y^2 \rangle = \int_0^{\infty} S_y(z, \omega) d\omega \quad , \quad (1.2-1)$$

$$S_y(z, \omega) = \sum_i \frac{R^2 \phi_i^2(z)}{\omega_i^4 [(1 - \Omega_i^2)^2 + 4\Omega_i^2 \xi_i^2]} \int_0^L \int_0^L \phi_i(z_1) \phi_i(z_2) \quad .$$

$$\int_0^{2\pi} \int_0^{2\pi} S_p(z_1, z_2, \theta, \theta', \omega) \cos \theta \cos \theta' d\theta' d\theta dz_2 dz_1 \quad , \quad (1.2-2)$$

and

$R \equiv$ rod radius

$\phi_i \equiv$ i th normal mode

$\omega_i \equiv$ i th natural frequency

$\Omega_i = \omega/\omega_i$

$\omega \equiv$ frequency

$$\xi_i \equiv \frac{c}{2\omega_i(M + m)}$$

$c \equiv$ damping constant

$M \equiv$ added mass of fluid per unit length

$m \equiv$ rod mass of fluid per unit length

$l \equiv$ rod length

$z_1, z_2 \equiv$ axial positions along rod

$\phi', \phi \equiv$ angular positions

$S_p \equiv$ cross-spectral density of the wall-pressure field

Solution of Equation 1.2-1 requires mathematical characterization of the cross-spectral density representation of the convecting wall-pressure field. Corcos⁶ proposed the following phenomenological model to describe the cross-spectral density of the wall-pressure field

$$S_p(z_1, z_2, \theta, \theta', \omega) = \psi_p(\omega) A\left(\frac{\omega\eta}{U_c}\right) B\left(\frac{\omega\xi}{U_c}\right) \cos\left(\frac{\omega\eta}{\pi c}\right) \quad (1.2-3)$$

where, ψ_p is the wall-pressure PSD at a point; $\eta = z_2 - z_1$ and $\xi = \theta' - \theta$ are separation distances in the longitudinal and circumferential directions, respectively; and A and B are functions describing the longitudinal and axial decay of the correlation. Corcos' model, as given in Equation 1.2-3, assumes a spatially homogeneous field; the model is a function of the separation distances η and ξ (not axial position z) and the wall-pressure PSD $\psi_p(\omega)$ is the same at every point on the surface.

To account for the axial decay in the intensity of the wall-pressure field, as observed in the related experimental program³⁻⁵, and as expected in many practical cases in which the flow is developing, a modified version of Corcos' model is proposed here. It is assumed that the local convection is a function of the separation distances η and ξ as given by Equation 1.2-3. However, the wall-pressure PSD is taken to be a function of position z , that is

$$\psi_p(\omega) = \psi_p(z, \omega) \quad (1.2-4)$$

As a first approximation, an exponential decay of the form

$$\psi_p(z, \omega) = \phi(\omega) \exp \left(- \frac{bz}{l} \right) \quad (1.2-5)$$

is assumed where ϕ and b are determined from experimental data, and l is the length of the rod.

Two cases are studied. In the first case the wall-pressure field is assumed to be uncorrelated in the axial direction. The second case assumes axial correlation. Predicted values of response are computed and compared with experimental data. All predicted values are within a factor of 6 or better of the corresponding measured value.

Application of the model still requires experimental data to evaluate the empirical coefficients and to define a functional relationship for the axial variation of the intensity of the wall-pressure field that is inherent in practical cases involving developing flows. Nevertheless, it is felt to be an advancement as it accounts for, in a mathematically tractable way, yet another feature of the complex buffeting excitation mechanism.

References

1. E. Ohlmer, S. Russo, and R. Schwemmler, "Investigation of an Analytical Model for Parallel Flow Induced Rod Vibrations," Nucl. Eng. Des. 22, 272-289 (1972).
2. T. M. Mulcahy, T. T. Yeh, and A. J. Miskevics, "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. T. M. Mulcahy, M. W. Wambsganss, W. H. Lin, T. T. Yeh, and W. P. Lawrence, "Measurements of Wall-Pressure Fluctuations on a Cylinder in Annular Water Flow with Upstream Disturbances; Part I: No Flow Spoilers," GEAP-24310/DOE-N-4175-15/ANL-CT-81-11, January 1981.

4. W. H. Lin, T. M. Mulcahy, M. W. Wambsganss, T. T. Yeh, and W. P. Lawrence, "Measurements of Wall-Pressure Fluctuations on a Cylinder in Annular Water Flow with Upstream Disturbances; Part II: Flow Spoilers," GEAP-24340/DOE-ET-34209-17/ANL-CT-81-11, January 1981.
5. W. H. Lin, M. W. Wambsganss, and J. A. Jendrzejczyk, "Wall-Pressure Fluctuations within a Seven-rod Array," ANL-CT-81-33 (To be published).
6. G. M. Corcos, "Resolution of Pressure in Turbulence," J. Acoust, Soc. Am. 35, 192-199 (1963).

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 reactors. 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

This task was never 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.

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**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 in late 1976.

Work Performed This Report Period

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

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

Task Description

Task 2.1c consists of the FIV testing of prototype LWR components in the lower plenum of the 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 with the exception of a topical report which is currently underway.

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-stream); 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 fuel assembly was instrumented with accelerometers, pressure transducers, and strain gages to measure the dynamic characteristics of the fuel assembly components.

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 reported in previous progress reports.

Task 2.2b - Fuel Spacer Preload FIV Test (C. G. Hayes)**Task Description**

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

- (1) At what flow-preload conditions and 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).

The test program will consist of the following elements:

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

The tests will be performed at the General Electric High Flow Hydraulic Facility.

Single Rod Flow Test

The single full-scale fuel rod is supported by segments of actual lower and upper tie plates. The inside diameter of the test cylinder has been sized to approximate the hydrodynamic mass and hydraulic diameter of a single rod in an actual fuel assembly. The simulated fuel spacer location and preload adjustment fixture will allow for easy adjustment of spring preloads. The locations of both the preload fixture and hard supports will match the spacer locations of actual fuel assemblies.

Several different instrumented rods will be used to determine fuel FIV characteristics.

3 x 3 Rod Bundle Flow Test

These tests utilized the same instrumented fuel rods described for the single rod test, surrounded by eight dummy (non-instrumented) rods. Actual fuel spacers were 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 was controlled. The range of preloads tested is 0-3 pounds, which is inclusive of the preloads nominally encountered in present fuel designs.

Work Performed This Report Period

The final topical report on this subtask was completed during this report period. The final report is in internal review. It will be published soon. This completes all activity planned for this subtask.

Task 2.2c Hot FIV Test (C. G. Hayes, M. R. Torres)

Task Description

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

Vibration instrumentation of the four fuel rods with acceluometus was completed. The fuel channel box and fuel bundle were assembled into the ATLAS test vessel. The data acquisition system was completed and installed at the test site. Both the test plan and the procedure, and the computer program for thermal hydraulic test set points were written, reviewed and approved. The test started on schedule August 1, 1981.

Several difficulties were initially encountered during flow testing. Two phase flow testing was initially not possible due to a hydraulic instability in the steam-water supply. A bypass line was installed between the two steam drums and the problem was resolved. In addition, in order to acquire data during boiling the vibration sensor ground had to be floated as leaks developed between the sensor and fuel clad.

Fuel rod vibration testing in single-phase (water), two-phase (steam-water) and boiling was completed during this report period. Data was successfully acquired for several fuel rods, for all three hydraulic conditions at various flow rates and heat fluxes. Preliminary observations or conclusions are:

- (1) Vibration levels of the fuel rods for all tests are extremely small.
- (2) Fuel rod vibration increases with mass flux and steam quality as expected,

(3) Fuel rod vibration was fairly insensitive to changes in coolant temperature.

(4) Vibration levels during the two-phase (steam-water) and boiling tests were substantially larger than the single-phase (water) flow tests.

A draft topical report of this important test series is being prepared. Completion of the draft report is expected on November 30, 1981. Upon completion of this report, all work planned for Task 2.2 - Fuel Assembly will have been completed.

TASK 2.3 - JET PUMPS

Task 2.3 is designed to 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 ($\sqrt{200}$ ft/sec) into the initial stage of the jet pump mixer. The nozzle flow entrains the 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 have been performed hot (550°F) and cold ($60 - 180^\circ\text{F}$), under operational and nonoperational conditions, at rated and above-rated flows.

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**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. 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 has been completed. Topical reports are in progress.

Task 2.3b - Jet Pump Hot FIV Test**Task Description**

Flow tests are performed on single prototypical jet pumps under reactor temperature and pressure (550°F, 1050 psia) at the Pacific Gas and 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 and Electric Moss Landing Steam Water Test Facility has been completed. Draft reports have been completed.

Figure 2.3-1. 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 coupling hardware consists primarily of two 10-in.-ID elbows, joined together by a 26-in.-long sleeve. Collars which 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).

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.

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, as well as final test documentation. Preliminary results from data analysis were reported in GEAP-24248. A draft final report has been completed.

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

Work Performed This Report Period

No significant time or funds were used during this reporting period on Task 3. There is no progress to report.

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 is to ensure 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

This report, the last quarterly progress report, was completed and submitted to reprographics to be prepared and issued during this final quarter.

The following reports were issued or are in the process of being issued under this program over the past several years. Extensive program management time was spent during this report period handling final program documentation.

DOCUMENTATION FOR DOE FIV PROGRAM

Contract DE-AC02-77ET34209

<u>Report</u>	<u>Contributor</u>	<u>Number</u>	<u>GEAP</u>
"FIV for LWR Progress Report (12/76-5/77)"	NTD	4175-1	24055
"FIV for LWR Progress Report (6/77-9/77)"	NTD	4175-2	24124
"On the Buffeting Response of a Cylinder in a Turbulent Cross Flow"	CR&D	4175-3	24149
"Two-Phase Flow-Induced Vibrations of Rods in Parallel Flow; A State-of-the-Art Review"	ANL	4175-4	24148
"Prediction Methods of High-Cycle Fatigue Life of LWR Components under Random Vibrations: A State-of-the-Art Review"	ANL	4175-5	24152
"FIV for LWR Progress Report (10/77-12/77)"	NTD	4175-6	24151
"Preliminary Design Handbook for Flow-Induced Vibrations of Light Water Reactors"	NTD	4175-7	24158
"Turbulence and Rod Vibrations in an Annular Region with Upstream Disturbances"	ANL	4175-8	24173
"FIV for LWR Progress Report (1/78-3/78)"	NTD	4175-9	24163
"High Cycle Fatigue Analysis"	ANL	4175-10	24152
"Turbulence and Rod Vibrations in an Annular Region with Upstream Disturbances"	ANL	4175-11	24173
"Circular Cylinder in Cross Flow"	CR&D	4175-12	24176

"Measurements in Annular Turbulent Flow"	ANL	4175-13	
"FIV for LWR Progress Report (4/78-12/79)"	NTD	4175-14	24248
"Measurements of Wall Pressure Fluctuations"	ANL	4175-15	24310
"FIV for LWR Progress Report (1/80-6/80)"	NPSSED	34209-16	24926
"FIV for LWR Progress Report (7/80-9/80)"	NPSSED	34209-17	24368
"FIV for LWR Progress Report (10/80-12/80)"	NPSSED	34209-18	24369
"FIV for LWR Progress Report (1/81-3/81)"	NPSSED	34209-19	24370
"Wall Pressure Fluctuations Within a Seven Rod Array"	ANL	34209-20	24375
"Response of Tube in Eccentric Flows"	ANL	34209-21	24382
"FIV for LWR Progress Report (4/81-6/81)"	NPSSED	34209-22	24385
"FIV for LWR Final Progress Report (7/81-9/81)"	NPSSED	34209-23	24386
"Analytical Modeling of the Buffeting of a Rod in Axial Flow"	ANI.	34209-24	24383

Topical reports completed in draft form as part of this program were:

<u>Title or Subject</u>	<u>Subcontractor</u>
Tube Arrays in Cross Flow	CR&D
Fuel Rod Vibration with Reduced Spacer Spring Preload	NPSSED
Fuel Rod Vibration in Two Phase Flow	NPSSED
Flow Induced Vibration of Jet Pumps	NPSSED
Flow Induced Vibration of LPCI	NPSSED
Lower Plenum Flow Induced Vibration	NPSSED

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