FLOW-INDUCED VIBRATION ANALYSIS
AND TEST PLAN FOR GENERAL ATOMIC
GAS-COOLED FAST REACTOR CORE ELEMENTS

Battelle

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FOR
GENERAL ATOMIC
GAS-COOLED FAST REACTOR CORE ELEMENTS

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1. INTRODUCTION

Nuclear reactor core elements are subject to mechanical vibration due to the flow of coolant over them. The vibration, if excessive, can lead to component failure by wear, fretting, and fatigue.

It is generally accepted that flow-induced vibrations are caused primarily by the excitation of the normal vibrational modes of a core element-coolant system by the action of fluctuating fluid forces (flow noise, including vortex shedding). However, there is some disagreement on the primary source of the noise-exciting vibrations. It is believed by most investigators that noise generated in a rod itself (nearfield noise) is the primary source of excitation.^(1,2) Sources of nearfield noise include turbulence and vortex shedding behind rod supports and spacers. However, it has also been pointed out⁽³⁾ that the large discrepancies in existing vibration data can only be attributed to difference in flow system noise (farfield noise) such as generated by pumps and blowers, valves and vortex shedding from hardware remote from the elements.

A number of both theoretical and experimental studies have been performed on the flow-induced vibration of single rods in parallel flow and of fuel bundle configurations. Two distinct approaches have been used.⁽⁴⁾ The first is a deterministic approach^(5,6,7,8) involving postulation of the causes of self-excitation, cross flow, etc. Although complete solutions to the equations of motion were not presented, empirical correlations based on theory were developed and were found to be more or less successful in predicting selected data. In the second approach,^(4,9,10,11,12) random pressure oscillations were postulated as the cause of rod vibration and solutions of the equation of motion were performed using data describing the

fluctuating pressure field surrounding the rods. Although these methods were found to successfully predict trends and functional dependencies, their use in predicting maximum amplitudes of vibration is limited because of problems in accurately characterizing the forcing function in the application under consideration.

It is necessary to assure that excessive clad wear, fatigue or other undesirable effects will not occur as results of flow-induced vibration. Existing data and theories of flow-induced vibrations do not provide information of sufficient accuracy or level of confidence to provide this assurance. Therefore, it is necessary to employ experimentation to define the vibrational behavior of the GCFR core elements.

In this report, an experimental program to study and correlate flow-induced vibrations of the GCFR core elements over the anticipated range of operating conditions is described. This information will provide the required information on vibrational behavior of the core elements for design and licensing. Preoperational vibration testing of reactor internals, described in USAEC Regulatory Guide 1.20,⁽¹³⁾ is a requirement of the AEC Directorate of Licensing. That testing is not described herein but is shown on the schedule and program plan chart.

2. OBJECTIVES

The overall objective of this program is to provide analytic and experimental evidence to assure the absence of potentially damaging flow-induced vibrations in the GCFR fuel, blanket, and control elements.

To provide this evidence, experiments will be performed with instrumented single GCFR fuel and blanket rod models, multiple rod assemblies and instrumented full-scale elements. The objectives of these experiments will be to obtain the following information:

- a. Natural frequency(ies) and vibrational modes in air at ambient conditions.

- b. Maximum amplitudes and frequencies of flow-induced vibration. This information will be obtained for a range of coolant conditions and manufacturing tolerances anticipated for normal operation. Both nearfield and farfield noise associated with hydrodynamic behavior near the core entrance and exit will be considered.
- c. Damping coefficient with static and flowing simulated coolant.
- d. Visual evidence of unusual or unanticipated clad wear at supports, if present.
- e. Indication of impact forces on supports.

The information will be used with existing theory of flow-induced vibrations to develop an analytic model of the fuel and blanket element vibration and to provide theoretical validation of the experimental data.

3. DESCRIPTION OF GCFR CORE ELEMENTS AND FLOW CONDITIONS

The GCFR core elements include standard fuel elements, control fuel elements, and blanket elements. The present design for a fuel element calls for 270 fuel rods and one thermocouple rod, all 0.282-in. in diameter, about 7.5-ft long enclosed in a hexagonal duct (approx. 6.642-in. across flats) which has a 6.25-in. diameter cylindrical top section. Overall length of the elements is about 11.5 ft. A portion of each fuel rod is roughened to promote heat transfer. Fuel rods contain $(\text{Pu,U})\text{O}_2$ pellets.

The principal difference between the standard fuel element and the control elements is that the 37 fuel rods at the center of the control elements are omitted to allow space for the control rod and guide tube.

The blanket elements contain 126 blanket fuel rods and one thermocouple rod, all 0.504-in. in diameter. Blanket elements contain ThO_2 pellets.

Fuel-rod lattice spacing is maintained by 20% cold worked 316 SS spacers. The intermediate fuel rod spacers are at 10-in. intervals. The

elements themselves are initially spaced about 0.150-in. apart for the top 30 in. and 1/4-in. apart for the remainder of their length.

The basic structural material for the core element ducts and fuel rod and blanket rod cladding is 20% cold worked 316 stainless steel.

The fuel, control and blanket elements are secured by a locking mechanism at their upper end into a 2-ft thick grid plate. They are not otherwise restrained.

The elements are designed for a downflow of helium coolant. Total core coolant flow, at 100% load, provided by three circulators, will be 1550 lb/sec at an outlet pressure of about 1305 psia with a pressure drop of 42 psi across the core. Orifices at the outlet end of each element provide a maximum flow of about 17.32 lb/sec and minimum of about 5 lb/sec through the fuel elements and 1.5 to 2.5 lb/sec through the blanket elements. At 100% load, helium coolant inlet and outlet temperatures are about 613°F and about 1022°F respectively.

4. PROGRAM SUMMARY

To accomplish the objectives defined in Section 2, a combined analytic and experimental program consisting of the following principal tasks is proposed:

- Task I Analytic consideration of flow-induced vibrations
- Task II Single rod tests
- Task III Full-length partial element tests
- Task IV Full-scale assembly tests
- Task V Prototype verification tests

The sequence of these tasks, program logic and proposed schedule to meet assumed PSAR and FSAR completion dates of FY-78 and FY-83, respectively, are shown in Figures 1 and 2.

FIGURE 1

GCFR FLOW-INDUCED VIBRATION ANALYSIS AND TESTING PROGRAM PLAN

FIGURE 2. GCFR FLOW-INDUCED VIBRATION ANALYSIS AND TESTING SCHEDULE

▽ MILESTONE
 ▽ REVISION OR TENTATIVE

MILESTONES:

1. PROGRAM PLAN ISSUED	8. DECISION POINT - PROTOTYPE VERIFICATION TESTS
2. ANALYTICAL MODELS: SINGLE RODS, FULL-SCALE ELEMENTS	9. OBTAIN PROTOTYPE VERIFICATION DATA
3. ISSUE DETAILED TESTING PLANS, SINGLE RODS, MULT. ROD BUNDLES, FULL-SCALE ELEMENTS	10. INTERIM REPORTS - TEST RESULTS
4. START FABRICATION OF SINGLE RODS, MULTIPLE RODS AND FULL-SCALE ELEMENTS	11. FINAL REPORTS - TEST RESULTS
5. OBTAIN SINGLE RODS VIBRATION DATA	12. PSAR SUBMITTED
6. OBTAIN MULTIPLE RODS VIBRATION DATA	13. PRELIM. DESIGN OF ELEMENTS COMPLETE
7. OBTAIN FLOW VIBRATION DATA - FULL-SCALE ELEMENTS	14. FINAL DESIGN OF ELEMENTS COMPLETE
	15. FSAR SUBMITTED
	16. ISSUE DETAILED TESTING PLAN - PREOPERATIONAL VIBRATION TESTING

Task I, analytic consideration of flow-induced vibrations, will be initiated in FY-76. The principal objectives of the task are to provide pretest predictions of the vibrational behavior of the test assemblies for equipment and instrument system design, to analytically validate test results and to develop or adapt existing analytic techniques to describe rod vibration performance for future rod design enhancement or changes.

The experimental tasks (Tasks II, III, IV, and V) are sequentially arranged in order of increasing complexity to allow early definition and correction of potential problems. In general, experiments will be performed with full-length rod models using low temperature and pressure air as the simulated coolant. A verification test of a single fuel rod in helium at temperature and pressure will be performed. A general discussion of similitude principles and its applications to the modeling of the GCFR is presented in Sub-section 5.1.

Task II has two principal objectives: (1) to verify and calibrate instrumented model fuel and blanket rod(s) to be used later in Tasks III and IV and in parallel seismic studies; and (2) to determine the natural frequency(ies), amplitudes and mode shapes of single model fuel and blanket rods under static and flowing conditions. Data from these tests will show vibration amplitudes and an indication of support impact forces. Design changes, if necessary, can be recommended and the changes can be incorporated into following multiple rod tests.

The objective of Task III is to determine the flow-induced vibrational behavior of full-length partial fuel element models. These models will consist of 19-rod hexagonal sections of the standard fuel element cross-section and will be tested at simulated design conditions in air. Most of the rods in the test assembly will be full-scale rods supplied by GA. Several instrumented rods, weighted to achieve prototype mechanical behavior, will be placed at appropriate positions. The combinations of tests, amplitude of vibration, and post-test inspection will provide data on flow-induced vibration. Design refinements will be recommended and retesting performed if necessary. Upon completion of this task, the testing program will proceed to the Task IV full-size tests.

The objectives of Task IV will be to investigate the flow-induced vibrational behavior of full-size fuel elements, control elements and blanket elements containing instrumented fuel rods at appropriate positions to define frequency, amplitude and mode of the flow-induced vibration and impact at the supports. The test assemblies will be supported in prototypic manner and will include prototypic spacers and prototype element inlet and outlet configuration, including locking mechanism and control rod drive extension shaft, to allow simulation of potential far-field fluid dynamic noise from these sources. The full-scale duct will be instrumented to determine frequency, amplitude and shape of any vibration present. The results of these tests will be used to validate the design. If unanticipated problems are defined by these tests, design refinements will be recommended and retested if necessary.

In the event that uncertainties persist regarding the vibration behavior of the reactor fuel, control or blanket elements following the above program, Task V, Prototype Verification Tests, can provide additional test data. This program phase is included symbolically in Figure 1 and is a part of the GCFR development plan.

5. MODELING OF GCFR CORE ELEMENTS AND COOLANT

The direct measurement of element and rod vibration on a full-scale element in real coolant at temperature and pressure will undoubtedly produce the most valid information on the vibration performance of the GCFR core elements. However, because of the nature of the fluid and its temperature, this approach cannot be considered feasible. In this program, a similitude approach is proposed in which instrumented full-scale core elements and smaller rod assemblies are tested in air at conditions which simulate the fluid dynamic characteristic of the reactor coolant at temperature and pressure. The use of altered scale rods and elements was specifically avoided to reduce modeling distortions caused by attempts to model two situations (scale and fluid) simultaneously.

5.1 SIMILITUDE PRINCIPLES

According to the principles of similitude in flow, the behavior of two systems will be similar if the ratios of their linear dimensions, forces, velocities, etc., are the same. General flow is characterized by four dimensionless parameters. Their names and interpretations are:

$$\text{Reynolds Number, } N_R = \frac{LV\rho}{\mu} = \frac{\text{inertia force}}{\text{viscous force}} \quad (1)$$

$$\text{Strouhal Number, } N_S = \frac{\tau V}{L} = \frac{\text{inertia force}}{\text{force associated with period } \tau} \quad (2)$$

$$\text{Euler Number, } N_E = \frac{\Delta p}{\rho V^2} = \frac{\text{pressure force}}{\text{inertia force}} \quad (3)$$

$$\text{Froude Number, } N_F = \frac{V^2}{Lg} = \frac{\text{inertia force}}{\text{gravity force}} \quad (4)$$

In problems of vibrations of an elastic body, the important forces are the inertia forces and elastic forces. The criterion for similarity is the Cauchy Number.

$$\text{Cauchy Number, } N_C = \frac{\rho L^2}{\tau^2 E g} = \frac{\text{inertia force}}{\text{elastic force}} \quad (5)$$

In the above equations:

L = characteristic length, ft

V = velocity of flow, ft/sec

μ = viscosity, lb/ft-hr

τ = characteristic time, sec

Δp = pressure drop, lb/sec

g = gravity constant, ft/sec²

ρ = density, lb/ft³

E = Young's modulus, lb/ft²

Since there is no free surface in the reactor, the gravitational effects are negligible and the Froude Number may be neglected. Then for the study of flow-induced vibrations, equality of parameters defined by equation (1), (2), (3), and (5) assures similarity of flows in two systems.

5.2 FUEL AND FLOW MODELING

From the cost effectiveness viewpoint, the ideal test fluid is air at some nominal temperature and pressure. The working fluid in the reactor is helium at an average pressure of 1284 psia and an average temperature of 820°F. The significant properties of the respective fluids at a particular set of reference conditions* are:

$$\begin{array}{lcl} \text{air} & \left\{ \begin{array}{l} \mu_m = \text{viscosity, } 60^\circ\text{F} \\ v_m = \text{specific volume, } 60^\circ\text{F, } 70 \text{ psia} \end{array} \right. & \begin{array}{l} = 0.044 \text{ lb/ft-hr} \\ = 2.75 \text{ ft}^3/\text{lb} \end{array} \\ \text{helium} & \left\{ \begin{array}{l} \mu_p = \text{viscosity, } 820^\circ\text{F} \\ v_p = \text{specific volume, } 820^\circ\text{F, } 1220 \text{ psia} \end{array} \right. & \begin{array}{l} = 0.086 \text{ lb/ft-hr} \\ = 2.75 \text{ ft}^3/\text{lb} \end{array} \end{array}$$

Because of the large differences in the properties of the two fluids, air and helium, exact matching of all dimensionless parameters is impossible. As shown above, four dimensionless parameters are used to establish similitude of the model and prototype while only two fluid flow variables are independent, velocity and density. A study of the reactor and the test model conditions suggest, however, that excellent similarity between the reactor and the model conditions is possible by matching the Strouhal, Cauchy and Euler Numbers, and minimizing the difference in Reynolds Numbers.

In considering similitude of the reactor and test model flows, four mechanisms may be considered as sources of flow-induced vibrations in the reactor:

- 1) random pressure fluctuations due to the turbulent boundary layer,
- 2) periodic vortex shedding,
- 3) turbulent buffeting, and
- 4) farfield noise.

The vortex shedding may be due to the spacers in the fuel elements.

*Final test conditions will be based on actual reactor parameters.

In view of the foregoing, four properties may be used to characterize the system. They are:

- 1) inertia force of the rod (or the element),
- 2) inertia force of the fluid,
- 3) elastic force of the rod (or the element),
- 4) level of turbulence in the fluid.

Since full-scale and prototypic materials would be used, the Cauchy Number

$$N_{Cr} = \frac{\rho_r L^2}{\tau^2 E} ,$$

which represents the ratio of rod (or element) inertia force to the rod (or element) elastic force, is the same in the test model as in the prototype element. There is an error due to temperature dependence of E , not exceeding 25%. However, this error is well within the acceptable tolerances and will be considered qualitatively only. In order to properly account for the inertia of the fluid virtual mass, it is also necessary to establish similarity of the Cauchy Number,

$$N_{Cf} = \frac{\rho_f L^2}{\tau^2 E} ,$$

which represents the ratio of fluid inertia force to the rod (or element) elastic force. This requirement is essentially impedance matching and arises as a result of the coupling between fluid motion and rod motion. If the temperature dependence of E is assumed to be negligible, it requires that the density of the model fluid be the same as the density of the working fluid in the reactor, or

$$(\rho_f)_M = (\rho_f)_P = 0.363 \text{ lb/ft}^3.$$

To properly account for possible vortex shedding effects, it is necessary to duplicate the prototype Strouhal Number in the model,

$$\left(\frac{\tau V}{L}\right)_M = \left(\frac{\tau V}{L}\right)_P .$$

Since the lengths of the model and the prototype systems are the same and the natural frequencies are also the same, the flow velocities must be equal to maintain similitude:

$$V_P = V_M$$

The above choices of model scale, fluid type and flow parameters will result in similar:

- 1) rod inertia forces,
- 2) rod elastic forces, and
- 3) fluid inertia forces,

in the model and in the prototype.

The next property which must be matched is the flow turbulence level, a function described by the Reynolds Number. The choice of air as the working fluid, together with the necessity of satisfying the above similitude requirements, automatically specified the Reynolds Number. However, the Reynolds Number for the reactor is in the range of 10^5 at which the flow is fully turbulent and turbulence intensity is essentially independent of the Reynolds Number for $N_{Re} = O(10^5)$. Because the viscosity of the air ($\mu = 0.044$ lb/ft-hr) is nearly one-half the viscosity of the helium ($\mu = 0.086$ lb/ft-hr), the Reynolds Number in the test facility is higher by only a factor of two. This condition implies that the level of turbulence which the model rods will experience is slightly greater than that which they will be subjected to in actual operation and thus the model is slightly conservative relative to the prototype element.

To establish Euler Number similarity,

$$\left(\frac{\Delta p}{\rho V^2} \right)_M = \left(\frac{\Delta p}{\rho V^2} \right)_P$$

it is necessary to examine the level of turbulence and the friction factor in the flow of the working fluid over the fuel rods. As noted above, the Reynolds Number, which defines the friction factor, is in the range of 10^5 for flow in the reactor and is equal to approximately 2×10^5 in the test facility for the specified conditions of density and velocity. In this

range, the turbulence intensity and, hence, the friction factor are nearly independent of the Reynolds Number. Thus the friction factors for flow in the reactor and in the test model are nearly equal and, hence, the pressure drops associated with the flows are equal:

$$\left(\Delta p \right)_P = \left(\Delta p \right)_M$$

Since the velocities and densities of the model and the reactor were equated a priori, Euler similitude is established. There is a possible problem with modeling of the blanket elements, however, since some will operate in the laminar range, so that this argument is no longer strictly valid. This will be corrected analytically.

The maximum required model flow rate for this similitude scenario is

$$Q_M = Q_P = 17.32 \text{ lb/sec}$$

for the fuel elements since all densities, velocities and cross-sectional areas are identical. The average pressure of the working fluid is

$$p_M = 72 \text{ psia.}$$

To summarize the above similitude scenario, the test model will match the full-scale element in velocities and in densities. Since the flow cross-sectional areas will be made identical, the flow rates will also be similar. Furthermore, full-scale fuel rods and elements will be used. This allows the matching of Strouhal, Cauchy, and Euler Numbers and reproduces the effects of turbulence, providing nearly exact similitude.

6. TASK DESCRIPTIONS

6.1 TASK I - ANALYSIS AND PREDICTIONS OF FLOW-INDUCED VIBRATION

6.1.1 Task Objective

The principal objective of this task is to develop analytic and/or semi-empirical methods to describe flow-induced vibrations in the GCFR fuel,

control, and blanket elements. It is also the objective of this task to provide analytic support as required for test planning and validation of results.

6.1.2 Description of Work

This task will start in FY-76 and proceed in parallel with Task II, III, and IV through FY-79. The initial efforts will be directed at predicting vibrational frequencies, modes, and amplitude of the GCFR fuel rods using existing methods described in Section 1. The objective of this initial effort is to define instrumentation requirements and sensitive parameters (variables) which must be given special attention in the design and construction of the test assemblies for the experimental tasks. Initially, calculated and assumed values of rod stiffness damping characteristics and end conditions will be used in these predictions. As experimental evidence is acquired in the experimental tasks, these assumptions will be replaced by more realistic information. The end product of this task will be an analytic method (or computer code) which is capable of describing the flow-induced vibrational behavior in the GCFR under all anticipated operational conditions. This method or code will be valuable in future fuel rod design enhancement or correction of problem areas defined in this program or elsewhere.

The exact methods to obtain values of the parameters mentioned above from the experimental data will be developed as a part of this task. However, it is anticipated that the following conventional approach will be used: The natural frequencies, stiffness and damping coefficients for the test assemblies will be obtained by direct measurements. Once these factors are established, the responses of the fuel can be computed analytically using methods referenced in Section 1, and these responses can be compared with experimental results.

6.2 TASK II - SINGLE ROD TESTS

6.2.1 Task Objectives

Task II has the following objectives:

- To design, construct, and calibrate instrumented fuel and blanket element rods for use in Tasks III and IV and in parallel seismic studies.
- To measure the natural frequency(ies) amplitudes and mode shapes of single fuel and blanket rod models under static and flowing conditions.

6.2.2 Description of Work

This task will provide information necessary for satisfactory progress in Task I and for initial work in Tasks III and IV. Therefore, Task II must be initiated early in FY-77 to assure maintaining the schedule described in Figure 2.

Instrumented vibration rods will be developed and constructed for application in fuel and blanket element models. The rods will consist of a full-length, full-diameter clad tube in which are placed pellets of depleted UO_2 , lead, or tungsten. The surface of the fuel rods will be appropriately roughened to simulate prototype fuel, and the pellet weight and pellet-clad gap will be also prototypic for both fuel and blanket rods. The pellet-clad gap will simulate the hot condition. These vibration rods will be provided with the following instrumentation:

- Miniature strain gages will be attached to the outside of the clad tube. Two gages at 90° will be installed at a minimum of two axial positions on each rod. The surface roughness will be removed from fuel rods at the point of attachment. The leads will go through small holes in the clad to the central cavity produced by the cored pellets and out the downstream end of the rod through a special end cap.
- Miniature biaxial accelerometers will be provided in each rod at the location of a support and between two supports. The instrument leads will be brought out of the rod through the center of the cored pellets.

The conversion of strain into displacement requires the assumption of mode shape. The mid-span accelerometers and proximity gages will provide the additional information required on which to base this assumption and to verify the results.

Each rod will be tested to define its vibrational characteristics, calibrate the instrumentation and verify similitude requirements. To test these rods, each will be placed in a flow tube which is sized to provide a hydraulic diameter equivalent to the prototype. The flow tube will contain means to support the rod at prototypic positions and clearances. The flow tube will also be equipped with proximity gages (capacitance or variable reluctance type) at numerous locations to define the position and motion of the instrumented rod. The following tests or procedures will be performed:

- The proximity and strain gages will be statically calibrated by displacing the rod by means of a micrometer adjusted probe inserted through holes in the flow tube. This test will also provide information on the rod stiffness.
- The natural frequency and mode shapes will be determined by exciting the rod by means of an electrodynamic shaker and noting vibrational amplitudes as indicated by means of the strain and proximity gages. This test will be performed in static air.
- The damping characteristics will be determined by perturbing the rod and recording the subsequent decay of vibrational amplitude.
- The rod will be tested in flowing air at prototypic flow conditions to verify the operation and calibration of instrumentation under dynamic conditions. Flow rates will correspond to minimum, maximum, 1-1/4 times maximum, and selected rates less than maximum which show by experimentation that they may induce resonance or higher than normal vibrational amplitudes.
- For verification of the air test results, a fuel rod will be tested in helium at about 800°F and 1280 psia. The flow rate will be the maximum reactor flow rate for a single fuel rod. Measurement of vibrational amplitudes will be done by optical methods. Comparisons

will be made of amplitudes obtained in air at 60°F and 72 psia and in the helium at temperature and pressure from the same amplitude measuring devices. If air test similitude is verified, continued testing in air will be justified. It is expected that the helium test at reactor temperature and pressure will show good correlation with the air test results.

6.3 TASK III - FULL-LENGTH PARTIAL ELEMENT TASKS

6.3.1 Task Objective

The objective of this task is to determine the flow-induced vibrational behavior of full-length 19-rod assemblies of GCFR fuel element rods. The data from this task will provide preliminary information on the vibration of GCFR rods in a rod bundle environment, and enable the early definition of necessary design changes required to improve undesirable behavior, if encountered.

6.3.2 Description of Work

The test assembly configurations to be considered in this task will consist of 19-rod hexagonal sections of standard fuel elements enclosed within full-length hexagonal flow ducts. The 19-rod configuration was selected since it will be less difficult to construct than a full assembly, but will still provide instrument rod locations surrounded by several "rings" of similarly vibrating rods to provide a prototypic acoustic environment for rod vibration measurement. Because of the difficulties of simultaneously modeling duct stiffness and mass in the smaller duct, some distortions in similitude will be required. However, duct vibrations will be investigated later in Task IV with undistorted models.

The test assembly rods will be either actual fuel rods or model rods that will simulate the mechanical and dynamic characteristics of the rods. Model supports which provide the type of support and nominal clearances of actual elements will be installed at the appropriate locations. Three to six rods in each assembly will be replaced by instrumented rods developed

in Task II. The rod positions in the assemblies will be different from test to test to enable measurement of their vibrational characteristics at various locations throughout each bundle.

By comparing the vibrational characteristics of the instrumented rods with prototypic fuel and blanket rods in the same test assembly, the ability of the instrumented rods to simulate prototypic behavior will be further verified.

Each assembly will be tested by placing it in a flow fixture in which the element is prototypically supported and which is provided with volumes simulating the upper and lower plenums. This fixture will be appropriately mounted to prevent the transmission of extraneous vibration from the environment, building structure and piping to the test assembly.

Air at low temperature and pressure will be supplied to the inlet plenum by the flow apparatus described in Section 7. The discharge from the exit plenum will go to the atmosphere and will avoid downstream obstructions. Experiments will be performed at various air flowrates ranging from minimum reactor flow to 125% of the flow required to simulate maximum reactor flow as described in Section 6.2 for single rod tests. The similitude considerations defining the required air flows are discussed in Section 5.

It is expected that the tests will be performed to determine the following information:

- Natural frequencies of the rods and test assembly. These tests will be performed with no flow with excitation provided by an electromagnetic shaker.
- Damping factors for rods and test assemblies with no and full flow.
- Vibration behavior of rods at interior bundle positions, adjacent to the hexagonal duct and at various axial locations. These data will be determined for the simulated flowrates specified above.
- Peak lateral rod accelerations at the support locations for interior rods and rods adjacent to the duct.

The data will be recorded on FM magnetic tape for later processing and analysis. Following each test, sample rods will be examined microscopically at the areas of support contact to determine the extent of damage or wear.

If the results of the data analysis suggests potential fuel damage, design refinements will be suggested and verified by retesting if necessary.

6.4 TASK IV - FULL-SCALE ASSEMBLY

6.4.1 Task Objective

The objective of this task will be to investigate the flow-induced vibrational behavior of full-scale fuel elements, control elements, and blanket elements. The results of this task will provide final verification of element design with regards to flow-induced vibrations.

6.4.2 Description of Work

The test assemblies that will be tested in this subtask will be full-scale assemblies of GCFR fuel, control, and blanket elements in which selected rods will be removed and replaced with instrumented rods developed in Task II. In addition, proximity gages will be used to determine the frequency, amplitude and mode shape of flow duct vibration, if present. Each element will be tested by placing it in a flow fixture which simulates the inlet plenum (including nearby flow obstructions such as control rods, control rod drives, etc.), element support members, outlet plenum and other structures which may contribute to nearby "farfield" noise generation. Damping of the fuel assembly elements will be determined for the hot pellet-clad gap condition by perturbing the assembly and recording the subsequent decay of vibrational amplitude. The other details of testing, such as test fixture details, simulated flowrates, types of tests, and method of data collection and analysis are the same as Task III.

If unanticipated problems are defined by this subtask, design refinements will be recommended and retesting performed if required.

6.5 TASK V - PROTOTYPE VERIFICATION TESTS

In the event that uncertainties or unknowns persist following the analytic and experimental program described above, additional prototype verification testing is planned on the GCFR Development Program. Such uncertainties may involve questions of similitude, interactions between elements, possible excitation from vibrations transmitted through the reactor building and structure, etc.

7. TEST FACILITY REQUIREMENTS

The purpose of this section is to describe the required general features of test facilities required to perform the experimental work described in Subsections 6.2, 6.3, and 6.4.

It is envisioned that two separate facilities would be required for this work. Because of the developmental and calibration type of work in Task II and III, a test rig capable of providing a continuous supply of simulated coolant to the test assembly would be required. On the other hand, Task IV requires extremely large flowrates which may be difficult to supply economically. For this task a "blowdown" facility capable of providing quasi-steady flowrates for reasonable periods of time (up to 1 hr) may be the most adequate solution. For these reasons, requirements for two separate facilities will be described in this section.

7.1 FLOW SYSTEM REQUIREMENTS

7.1.1 Task II and III Flow Facility

The general requirements for the facility for the Task II and III experiments are as follows:

- Type Flow System: Continuous flow open system; for Task II, test assembly discharges to atmosphere; for Task III, upper and lower plenum volumes are provided.
- Maximum Flowrate: ~0.0825 lb/sec for Task II;
1.55 lb/sec for Task III (1-1/4 times actual)

- Test Assembly Inlet Conditions: $P \approx 90$ psia; $60 < T < 100^\circ\text{F}$ (air)
Prototypic temperature and pressure
(Task II, single rod, helium)
- Instrumentation: Flowmeter upstream of test assembly, static temperature upstream of test assembly, pressure upstream at midpoint and downstream of test assembly.
- Test Assembly Isolation: Suitable flexible piping connection and acoustic attenuators shall be provided to prevent the direct or acoustic transmission of vibration to the test assembly in the range of frequencies between 1 and 500 Hz.

7.1.2 Task IV Flow Facility

The general requirements for a flow facility suitable for Task IV are as follows:

- Type Flow System: Continuous flow open system or blowdown system.
A blowdown system shall be capable of up to 1-hr steady flow operation.
- Maximum Flowrate: ~ 21.6 lb/sec (1-1/4 times actual)
- Test Assembly Inlet Conditions: $P \approx 90$ psia
 $60 < T < 100^\circ\text{F}$
- Instrumentation: Same as Task III Facility.
- Test Assembly Isolation: Same as Task III Facility.

7.2 MODEL MOUNTING FIXTURE

A model mounting fixture shall be provided to provide ample support for the test assemblies described above and to isolate them from vibration in the range from 1 to 500 Hz transmitted through the supporting structure.

7.3 INSTRUMENTATION

All transducers and associated instrumentation will be selected to produce a goal accuracy of 5% when calibrated against NBS traceable standards.

The data gathering system will be designed to continuously record the outputs from the various transducers on FM magnetic tape for subsequent data analysis by digital or analog processes. The interface between the transducers (strain gages, proximity gages, and accelerometers) and the

recording equipment will consist of appropriate signal conditioning, amplification and filtering circuits. The FM magnetic tape recorders will be provided with voice and time marker channels to enable the identification and synchronization of all data records for each run. Sufficient number of channels will be provided to simultaneously record all transducer outputs during the full-scale bundle tests described in Section 6.4. The exact requirements will be defined during detailed program planning.

The instrumentation system will be provided with means of electrical or electronic calibration. This calibration will consist of determining the gain, frequency response and distortion (if present) for each channel by providing a simulated transducer signal of known characteristics and monitoring the output using an oscilloscope and voltmeter.

A recorder-computer interface will be provided to allow digital or analog computer analysis of results. Suitable software will be provided to allow data scanning for preliminary identification of specified events or occurrences, detailed analysis, and display of results.

REFERENCES

1. M. W. Wambsganss and P. L. Zaleski, "Measurement, Interpolation and Characterization of Nearfield Noise," Proc. Conf. on Flow Induced Vibrations in Reactor System Components, ANL-7685 (1970).
2. S. Fabric, "Investigation of Methods for Coupled Structural-Hydrodynamic Analyses of Reactor Internals," Proc. Conf. on Flow Induced Vibrations in Reactor System Components, ANL-7685 (1970).
3. A. K. Addae and H. Fenech, "Experimental Determination and Analysis of Vibrations Induced by the Near-field Flow Noise in Tubes," Proc. Conf. on Flow Induced Vibrations in Reactor System Components, ANL-7685 (1970).
4. S. S. Chen and W. M. Wambsganss, "Response of a Flexible Rod to Near-Field Flow Noise," Proc. Conf. on Flow Induced Vibrations in Reactor System Components, ANL-7685 (1970).
5. M. P. Paidoussis, "An Experimental Study of Vibration of Flexible Cylinders Induced by Nominally Axial Flow," Nucl. Sc. and Engr., vol. 35, pp. 127-138, 1969.
6. M. P. Paidoussis, "Vibration of Flexible Cylinders with Supported Ends, Induced by Axial Flow," Proc. Instn. Mech. Engrs., vol. 180, pp. 268-278, 1966.
7. D. Burgreen, J. J. Byrnes, and D. M. Benforado, "Vibration of Rods Induced by Water in Parallel Flow," Trans. Am. Soc. Mech. Engrs., pp. 991-1003, 1958.
8. E. P. Quinn, "Vibration of Fuel Rods in Parallel Flow," USAEC Report GEAP-4059, General Electric Company, July 1962.
9. J. R. Reavis, "WVI-Westinghouse Vibration Correlation for Maximum Fuel Element Displacement in Parallel Turbulent Flow," Trans. Am. Nucl. Soc., vol. 10, no. 1, pp. 369-370, 1967.
10. D. J. Gorman, "The Role of Turbulence in the Vibration of Reactor Fuel Elements in Liquid Flow," Atomic Energy of Canada Limited, Chalk River, Ontario, AECL-3371, May 1969.
11. M. W. Wambsganss and B. L. Boers, "Parallel-Flow-Induced Vibration of a Cylindrical Rod," Presented at ASME Winter Annual Meeting and Energy Systems Exposition, NY, NY, Dec. 1968, ASME Paper No. 68-WA/NE-15.
12. R. M. Kanazawa and A. P. Boresi, "Calculation of the Response of Rods to Boundary Layer Fluctuations," Proc. Conf. on Flow Induced Vibrations in Reactor System Components, ANL-7685 (1970).

13. Regulatory Staff, U.S. Atomic Energy Commission, Regulatory Guide 1.20 (formerly Safety Guide 20), "Vibration Measurements on Reactor Internals," Washington, D.C., December 29, 1971.

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