Fuel Rod Vibration Due to Cross Flow Through Narrow Gaps

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SUMMARY

Flow in a reactor core consists of flow parallel to the fuel rods with small components of cross-flow due to turbulence and thermal mixing. Another source of cross-flow is the gaps between the baffle plates. These gaps are the result of tolerance stackups during fabrication, and thermal and gamma heating during reactor operation. During operation, the pressure drop across the baffle plate provides the driving force for cross-flow through the baffle gaps. In one configuration (skirting flow), the jet emerges from the gap and skirts along the edge of the fuel assembly. In the other configuration (impinging flow), the jet impinges directly on a fuel assembly. Local cross-flow impinging on or skirting the fuel rod may cause excessive fuel rod vibration which in turn may lead to fuel rod failures from wear, fretting, or fatigue.

Rod vibration is evaluated as a function of the cross-flow velocity through the gap between the baffle plates. The rod response to flow from the gap indicates two regions of high amplitude vibration. The first behaves somewhat similar to vortex shedding in that the vibration amplitude is limited to moderate values and it occurs only over a limited velocity range. Unlike classical vortex shedding, the frequency does not "lock-in". It increases steadily with the increasing flow. The second high amplitude vibration behaves like fluidelastic whirling. It has the rapid increase in amplitude which does not subside at higher flow rates.

The gap velocities that initiate the first and second high amplitude vibration mechanisms are a function of the size of the gap. Inspection of the data indicates that each mechanism is approximately a power function of the gap size. Both critical velocities decrease as the gap width increases.

In conclusion, the testing indicated that the large amplitude fuel rod vibration can be excited by flow through the baffle gap. The results were used to determine boundaries of the high amplitude vibration and to evaluate analytical predicting methods that can be used to determine the acceptable gap size between the baffle plates.

1. Introduction

This paper reports test results for flow-induced vibration (FIV) of a rod array subjected to cross-flow from a narrow gap. The centerline of the gap is parallel to the centerline of the rods in the array. Three gap configurations were tested:

1) With the gap centered on the centerline of a rod

2) With the gap centered on the lane between two rods

3) With the gap at the edge of the two perpendicular plates at the corner of the rod array

Testing was performed at several cross-flow and axial flow velocities for each of these configurations.

Figure 1 shows the normal flow in a reactor. The flow enters the reactor vessel, flows down the downcomer and up through the flow distributor plate with the majority of the flow going into the core and a small part of the flow going between the core barrel and the baffle plates. Due to the different flow paths, a differential pressure exists across the baffle plates. This differential pressure provides the driving force for the flow through the gaps between the baffle plates. Figure 2 shows the flow paths through the baffle gaps in the reactor. One baffle gap location provides a flow path along the edge of the fuel assembly ("skirting flow"). Another baffle gap configuration provides a flow path that impinges on the fuel assembly. Depending upon the fuel assembly position, the flow path may impinge on a fuel rod or on the lane between two fuel rods. When the baffle gap flow is centered on the fuel rod, it will be identified as "center-of-rod"; when it is centered on the lane, it will be identified as "center-of-lane".

2. Apparatus

The test facility that was used for the flow-induced vibration testing included a cross-flow chamber to provide flow through the baffle gap. Figure 3 illustrates the general arrangement of the facility and the cross-flow chamber. The cross-flow chamber provided baffle gap flows for reduced velocities from 0 to 1.4. Reduced velocity (V/fD) is defined as the velocity (V) in the gap divided by the frequency (f) of the rod and the diameter (D) of the rod.

The cross-flow chamber was designed with an adjustable baffle gap. The center of the gap was adjusted to three positions:

- Centered on the second rod from the corner of the rod array (center-of-rod)
- Centered on the lane between the first and second rods of the rod array (center-of-lane)
- At the edge of the rod array (skirting)

Five gap sizes were tested.

The top and bottom of the rod array were attached to the facility. The rod array was 17 rows wide x 17 rows deep, and had seven spans. At the end of each span was a spacer grid that provided support and spacing of each rod in the array. Biaxial accelerometers were installed in six of the fuel rods in the rod array. The pitch-to-diameter ratio of the rod array was 1.3. The rod array was located 0.4 rod diameters from the edge of the baffle gap. The skirting flow lane was also 0.4 diameters between the wall and the edge of the rod. The rod was 54 diameters long between the support at the bottom and the first spacer grid. The baffle gap was located opposite the lowest span of the rod array.

3. Results

The initial results from the baffle gap testing were X-Y plots showing the vibration of the rods as a function of the flow through the baffle gap. Figures 4A, 4B, and 4C respectively show the vibration of the rod as a function of cross-flow for the center-of-rod, center-of-gap, and skirting flow configurations with flow into the rod array. Figure 4D shows the vibration of the skirting flow configurations with flow out of the rod array. All four figures are for a gap-to-rod diameter of 0.13.

3.1 Center-of-Rod Configuration

Figure 4A shows the center-of-rod configuration with the cross-flow into the rod array. The recorded data is from an accelerometer located in the rod directly in front of the gap with its sensitive axis in the lift direction. The axial flow rate in this figure is zero. The figure shows that at very low cross-flow rates, there is very little vibration. At a reduced velocity of 1.9, the vibration increases significantly and continues at a high level up to a reduced velocity of about 6.3. This initial high amplitude vibration is sinusoidal and somewhat similar to vortex shedding. Between reduced velocities of 7 and 9.5, the vibration drops to a small value. At a reduced velocity of 9.5, the vibration increases sharply and continues to increase until the maximum cross-flow rate is reached. This vibration is also sinusoidal and may be fluidelastic whirling. At other baffle gap widths with the center of the gap still centered on the rod, the vibration as a function of cross-flow was similar to that shown in Figure 4A.

3.2 Center-of-Lane Configuration

The fuel rod response to slowly increasing and decreasing gap velocity for the center-of-lane configuration is shown in Figure 4B. The rod vibration for this configuration exhibits a sinusoidal response that resembles vortex shedding of a single cylinder. This is somewhat surprising since the flow is only on one side of the responding rods. The vibration shown on the figure is the rod acceleration in the stream-wise direction. This rod was the first rod adjacent to the jet emerging from the gap. The axial flow rate for the configuration shown was 11,000 lpm. The first high amplitude vibration occurs at reduced cross-flow velocities from 9.0 to 12.4. At lower axial flow rates (0, 3800, and 7600 lpm), the initiation of vortex shedding occurred at reduced cross-flow velocities of 5.2, 4.7, and 5.7, respectively.

3.3 Skirting Flow Configuration

Figure 4C depicts the rod vibration for skirting flow as a function of the cross-flow velocity. The figure shows the vibration in the lift direction of the accelerometer in the fourth tube from the corner of the rod array (the fourth tube down the lane). The axial flow velocity in this case is 3800 lpm. The rod vibration was low at reduced cross-flow velocities of 0 to 6.5, but became sinusoidal at reduced velocities of 6.5 and remained sinusoidal until a reduced velocity of 11.9. In the reduced velocity range from 11.9 to 16.7, the rod response is random. At other baffle gap widths, the rod vibration as a function of gap cross-flow was much different than that shown in Figure 4C. The number of variations are too numerous to include in this paper.

The skirting flow configuration was more difficult to test and analyze than the center-of-rod configuration. When the flow was centered on the rod, the rod opposite the gap had the largest vibration. With skirting flow, several rods could have the largest vibration. With a small baffle gap -- 0.4 rod diameters or less -- the baffle gap jet penetrated a long distance along the wall next to the rod array before expanding enough to excite the rods. Some qualitative measurements were taken that indicate that the seventh rod from the corner of the fuel assembly had the largest response. Only the first four rods were instrumented. At larger baffle gaps, the rod with the maximum vibration was closer to the corner of the fuel assembly.

With flow out of the skirting flow gap, the rod in the corner of the array had the maximum vibration. When the flow was out of the rod array, the initial high amplitude vibration (vortex shedding) was usually not seen. Figure 4D shows the rod vibration as a function of the reduced gap velocity for the skirting configuration described above, but with the flow directed out of the rod array. The axial flow rate in this figure is zero. High amplitude vibration occurs only at reduced cross-flow velocities above 14.

3.4 Statistical Evaluation of the Results

Figure 5 shows a statistical accumulation of the results from the testing reported in this paper. The stability boundaries for both the first and second high amplitude vibration responses were constructed using a confidence level of 99% and a failure level of 1%. In other words, we are 99% confident that there is less than a 1% chance of encountering a high amplitude response for gap widths and gap velocities that are below these boundaries.

4. Simple Analytical Calculations

Most of the rod vibration as a function of cross-flow curves (Figures 4A through 4D) show two high amplitude vibrations. The two best known mechanisms that cause high amplitude vibration in tube banks are vortex shedding and fluidelastic whirling. The following paragraphs assume that the high amplitude vibration can be defined by either the Strouhal Number:

$$S = \frac{V_s D}{f_s} \quad (1)$$

where:

S = Strouhal Number

V_s = Critical Vortex Shedding Velocity

f_s = Strouhal Frequency (Which is identical to the rod frequency at critical velocity)

D = Outside Diameter of the Rod

or Connors' Fluidelastic Equation [1]:

$$V_c = Cf_n \sqrt{\frac{W_e \delta_o}{\rho_s}} \quad (2)$$

where:

V_c = Critical Velocity for Fluidelastic Whirling

C = Instability Constant

f_n = Natural Frequency of the Rod

W_e = Weight Per Unit Length of the Rod

δ_o = Log Decrement of the Rod in Water

ρ_s = Water Density

The question as to whether vortex shedding can exist in a closely packed tube array, or whether fluidelastic whirling can exist with a fluid jet on only one side of the rod will not be addressed. We have assumed that whatever is happening can be described by these equations. Critical velocity (V_S) for vortex shedding can be obtained from the Strouhal Number. If the gap velocity is considered equivalent to the free stream velocity used in the Strouhal Equation, the calculated Strouhal velocities can be compared directly with the measured velocities. This assumes that flow around the rod will be similar to that obtained in a uniform cross-flow field. Chen [2] suggests using Strouhal Numbers from 0.31 to 0.46 for square pitch tube arrays with a pitch-to-diameter ratio of 1.3. Pettigrew [3] did not encounter vortex shedding with a square array at a pitch-to-rod diameter ratio of 1.3. At a ratio of 1.47, he obtained vortex shedding at Strouhal Numbers of 0.41 to 0.63.

For a Strouhal Number of 0.3, the critical Strouhal reduced velocity is 3.4; for a critical Strouhal Number of 0.63, the critical vortex shedding reduced velocity is 1.5. Even this wide range is not adequate to predict the Strouhal velocity (center of the first high amplitude vibration response). The comparably measured reduced velocities ranged from 3.3 to 7.2. Strouhal Numbers calculated from these velocities ranged from 0.14 to 0.31. A mean value of the calculated Strouhal Number for the center-of-rod configurations was 0.21, with the standard deviation of 0.06. This agrees very well with the single cylinder number of 0.2. For a Strouhal Number of 0.2, the critical Strouhal velocity is 5.1. Therefore, by using the single cylinder Strouhal Number we can predict the mean value of the center of the first high amplitude vibration.

The important velocity is not the Strouhal velocity but instead is the velocity at which high amplitude vibration is initiated. This velocity can be calculated from the Strouhal velocity and the frequency ratio. The range of the initial high amplitude vibration for the center-of-rod configuration extends to a frequency ratio of 0.45.

Frequency ratio (R) is defined by Franklin [4] as:

$$R = \frac{f_v}{f_r} = \frac{SV_r}{(f_r D)} \qquad (3)$$

where:

R = Frequency Ratio

f_v = Frequency of Vortex Shedding

f_r = Frequency of the Rod in Static Water

S = Strouhal Number

V_r = Velocity of the Initial Response

D = Rod Diameter

Using a frequency ratio of 0.45, this equation predicts an initial vortex shedding response at a reduced velocity of 2.3. This agrees well with the measured value (Figure 4A) of 2.4.

The critical velocity for fluidelastic whirling can be obtained from Connors' Equation [Equation (2)]. For flow centered on the rod, assume that the jet from the gap flows only down the lanes along either side of the rod. For an instability constant of 3.3, the corresponding predicted critical reduced velocity is 17.1 through the baffle gap. This calculated critical velocity is much higher (unconservative) than the measured critical reduced velocity of 9.5. To obtain a better analytical solution, we could modify Equation (2), reduce the 3.3 constant, or change our assumption on the velocity distribution. The most suspicious is the velocity distribution.

5. Conclusions

A rod array was tested with gap flow impinging on the centerline of one rod, jetting into the lane between two rods, and skirting the edge of the rod array. The conclusions drawn from this testing are:

- Jet flow from gaps can cause large amplitude rod vibration.
- The initial vibration appears to be a form of vortex shedding.
- The second high amplitude response appears to be related to fluidelastic whirling.
- For a constant gap size, the "center-of-rod" configuration encounters high amplitude vibration at lower gap velocities than do the "center-of-lane" or "skirting flow" configurations. Additionally, the center-of-lane configuration encountered high amplitude vibration before the skirting flow configuration.

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[3] M. J. PETTIGREW, Flow-Induced Vibration in Nuclear Components," AECL-6219, August 1980.

[4] R. E. FRANKLIN, "Results of the HTFS Questionnaire on Heat Exchanger Tube Vibration," AERE M 2932, November 1977.

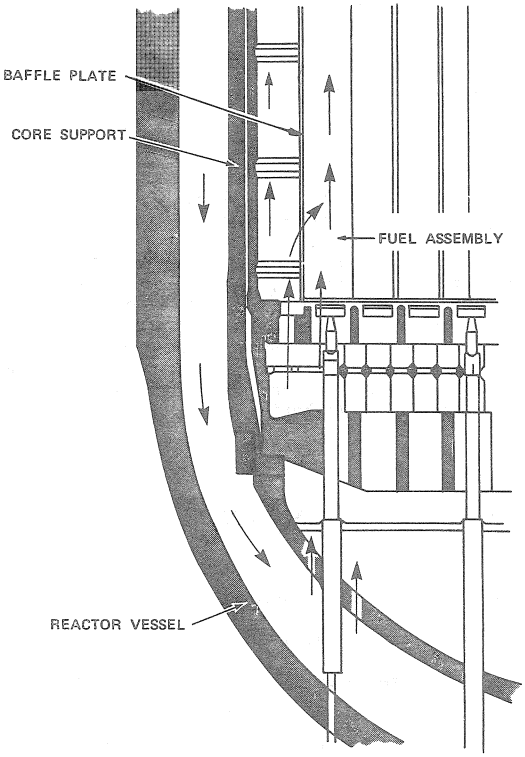

Figure 1 Reactor Flow

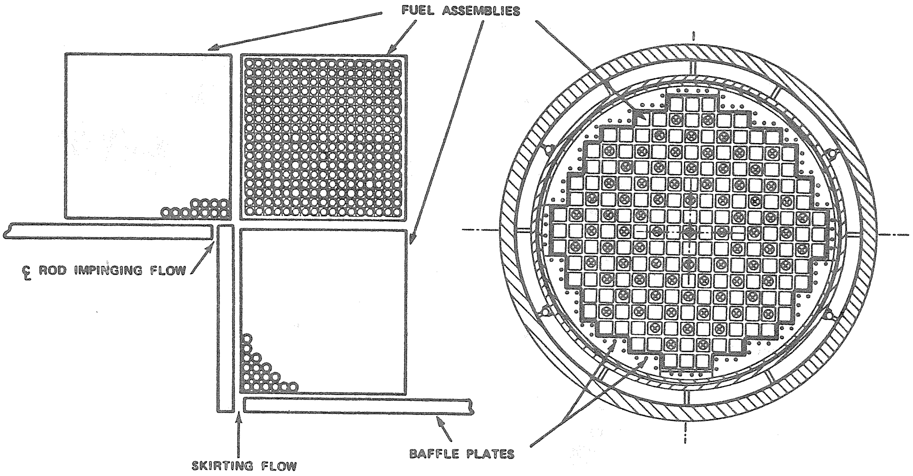

Figure 2 Baffle Gap Configurations

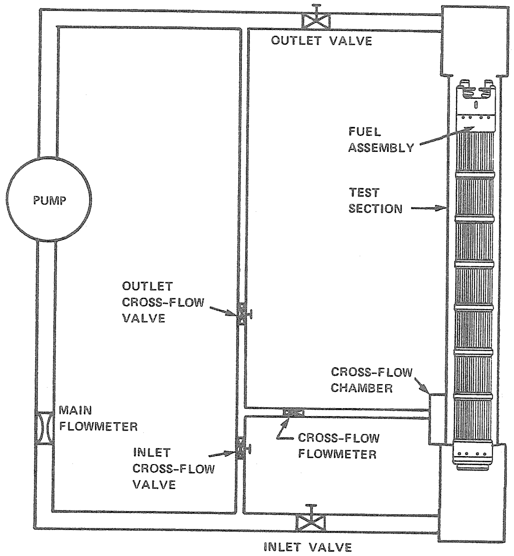

Figure 3 Test Facility

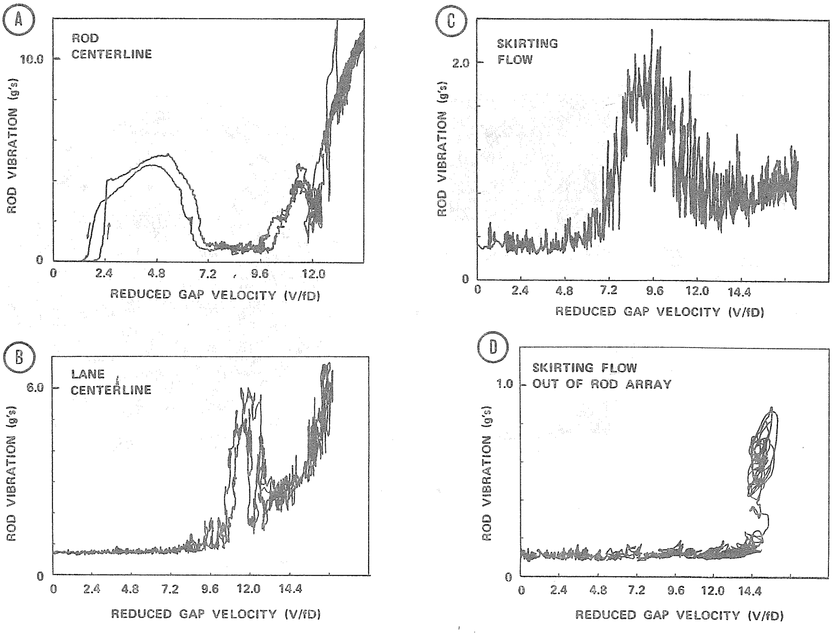

Figure 4 Rod Vibration as a Function of Cross-Flow

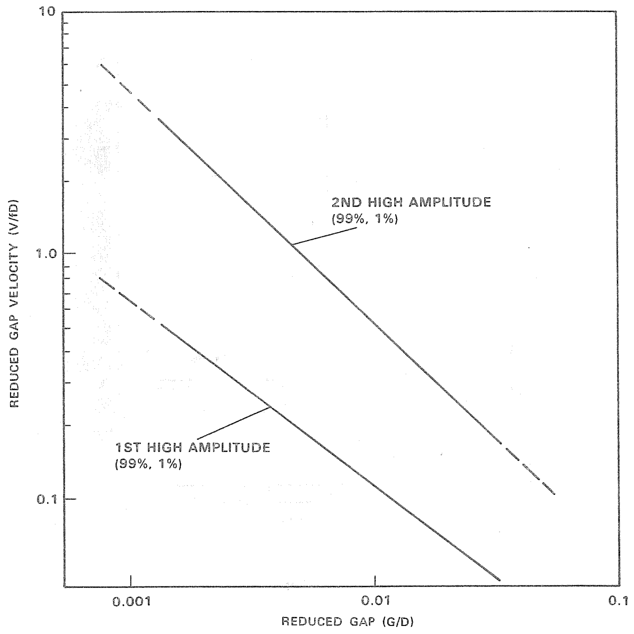

Figure 5 Statistical Stability Boundaries