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Donna Post Guillen
Mark J. Russell

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ESTIMATION OF CRITICAL FLOW VELOCITY FOR COLLAPSE OF GAS TEST LOOP BOOSTER FUEL ASSEMBLY

Donna Post Guillen and Mark J. Russell
Idaho National Laboratory
Idaho Falls, Idaho 83415

ABSTRACT

This paper presents calculations performed to determine the critical flow velocity for plate collapse due to static instability for the Gas Test Loop booster fuel assembly. Long, slender plates arranged in a parallel configuration can experience static divergence and collapse at sufficiently high coolant flow rates. Such collapse was exhibited by the Oak Ridge High Flux Reactor in the 1940s and the Engineering Test Reactor at the Idaho National Laboratory in the 1950s. Theoretical formulas outlined by Miller, based upon wide-beam theory and Bernoulli's equation, were used for the analysis. Calculations based upon Miller's theory show that the actual coolant flow velocity is only 6% of the predicted critical flow velocity. Since there is a considerable margin between the theoretically predicted plate collapse velocity and the design velocity, the phenomena of plate collapse due to static instability is unlikely.

INTRODUCTION

A Gas Test Loop (GTL) system is currently being designed to provide a high intensity fast-flux irradiation environment for testing fuels and materials for advanced concept nuclear reactors. To assess the performance of candidate reactor fuels, these fuels must be irradiated under actual fast reactor flux conditions and operating environments, preferably in an existing irradiation facility [1]. The GTL system is being designed for operation in the northwest test lobe of the Advanced Test Reactor (ATR) at the Idaho National Laboratory. The Technical and Functional Requirements (T&FRs) for the GTL stipulate a minimum neutron flux intensity (10^{15} n/cm^2·s) and fast to thermal neutron ratio (>15) for the test environment [2]. Incorporation of booster fuel within the test lobe is necessary to achieve these neutron flux requirements.

The current design of the booster fuel assembly (BFA) for the GTL calls for 3 concentric rings of uranium silicide fuel plates clad with 6061 aluminum arranged in four quadrants (shown in Figure 1). The fuel plates are 0.1 inches (0.254 cm) thick, 4 foot (1.22 m) long, and separated by 0.078 inch (0.198 cm) water coolant channels.

PLATE COLLAPSE PHENOMENON

Long parallel plate fuel assemblies can experience static divergence and collapse at sufficiently high coolant flow rates. Such phenomenon has occurred at the Oak Ridge High Flux Reactor [3] in the 1940s and the Engineering Test Reactor at the Idaho National Laboratory [4] in the 1950s. When the coolant flow reaches a critical static divergent velocity, U_d, parallel plate fuel assemblies will buckle and collapse onto each other as a result of a flow-induced asymmetric pressure distribution in adjacent flow channels [5]. Analysis was performed herein to determine whether the GTL booster fuel assembly (BFA) is likely to collapse at the current design flow rate due to a flow-induced static-instability type of failure.

Fuel plate collapse stems from plate deformation, which can be caused by unbalanced channel pressures created by turbulence, pressure fluctuations produced by the primary coolant pumps, unequal flow in the channels due to assembly tolerances, etc. Pressure forces act to deflect the fuel plates. Excessive lateral deformation of long parallel plates subject to axial flow can occur due to unbalanced channel pressures when the pressure difference across the plates is too large for the plate to resist [6]. As the plates deform and the flow channel narrows, the flow velocity increases. By Bernoulli's equation, the pressure correspondingly decreases, and this causes an increase of the pressure differential across the plate with a corresponding increase in deformation. This deformation is resisted by elastic restoring forces developed in

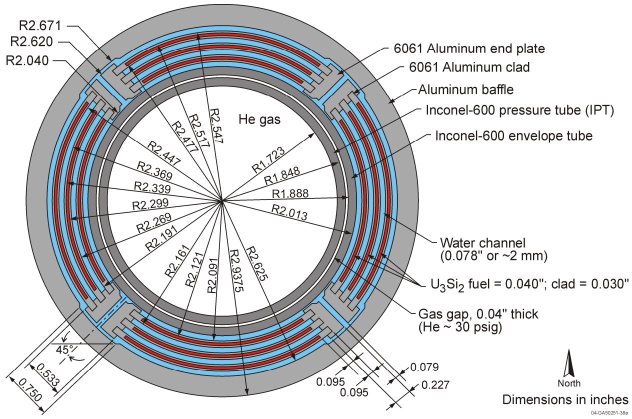

Fig. 1. Current booster fuel assembly configuration and dimensions.

the plate as a result of the deformation. As the flow velocity reaches the critical velocity, the relationship between pressure, flow and deflection becomes one of positive feedback, so that the pressure increase and lateral deflection increase without any further external increase of fluid flow. This effect can lead to large plate deflections and overheating of the fuel plates given critical fluid velocities.

SOLUTION METHODOLOGY

The theoretical formulas outlined by Miller [3], based upon wide-beam theory and Bernoulli's equation, were used for the analysis. Although Miller's theoretical collapse velocity is a simplified model of a complicated system, it remains widely used due to its ease of use in predicting an approximate collapse velocity [6]. The method is applicable to plates with a length much larger than their width, with the long edges restrained by attachment to side plates, and assembled with uniform spacing. Plate assemblies with low aspect ratios, such as those considered here, are prone to lose stability by divergence whereas short, wide plate configurations are prone to flutter [7].

Assumptions made in the analysis include:

- Fuel plates are uniformly curved with the longitudinal edges hinged (pinned) to rigid side plates. Assuming pinned edge boundary conditions, rather than fixed edges, is conservative (i.e., yields a lower critical velocity) since a more flexible structure exhibits larger deflections in response to a given pressure differential. It is worth pointing out that the actual fuel plates will be attached to the side plates by crimping with a special jig, whereas the mockup fuel plates for the hydraulic flow test will be glued in place. If the hydraulic flow test model is to be used for vibration and/or plate collapse testing, this could affect the results since the boundary conditions are different.
- Coolant flow is incompressible and all channels have the same mass flow, which is uniform across any plate channel section.
- There is no flow across the channels. This is a conservative assumption since "windows" in the fuel side plates will allow flow between adjacent channels if there is a pressure difference to drive the lateral flow.
- There are no stabilization combs. In practice there will be stabilization combs at the leading and trailing edges (i.e., top and bottom) of the plates that will help steady the fuel plates from flow-induced vibration mechanisms, such as turbulence, vortex shedding and fluid-elastic instability. The presence of the combs will serve to increase the critical velocity.
- Material properties for aluminum are applicable for the plates since the outer surface (fuel cladding) is aluminum and this will dictate the buckling properties.
- This analysis does not include thermal elastic effects, growth of the fuel meat during irradiation, and transverse compressive loadings, which may also impose a negative stiffness on the fuel plates.

ANALYSIS

This calculation is based upon the method of Miller [3] for calculating the critical flow velocity of collapse to a pinned edge curved plate fuel assembly similar to the aluminum clad uranium silicide fuel for the GTL BFA.

The outer and inner radii of the silicide fuel element plates are

$$R_o := \begin{pmatrix} 2.547 \\ 2.369 \\ 2.191 \end{pmatrix} \cdot in \tag{1}$$

$$R_i := \begin{pmatrix} 2.447 \\ 2.269 \\ 2.091 \end{pmatrix} \cdot in \tag{2}$$

The individual plate thicknesses are

$$R_o - R_i = \begin{pmatrix} 0.1 \\ 0.1 \\ 0.1 \end{pmatrix} in \tag{3}$$

Assigning the variable, a, for plate thickness

$$a := 0.1 \cdot in \tag{4}$$

Fuel plate section parameters are defined on a "per unit width basis" with an arbitrary unit width

$$w := 1 \cdot in \tag{5}$$

The area of beam cross section per unit width of beam is

$$A := \frac{a \cdot w}{w} \tag{6}$$

and

$$A = 0.1\,in \tag{7}$$

The moment of inertia of the beam cross section per unit width of beam is given by

$$I := \frac{\frac{w \cdot a^3}{12}}{w} \tag{8}$$

and

$$I = 8.333 \times 10^{-5}\,in^3 \tag{9}$$

The minimum radius of curvature of fuel plate is used to minimize the critical velocity ratio

$$R := \min\left(\frac{R_o + R_i}{2}\right) \tag{10}$$

and

$$R = 2.141\,in \tag{11}$$

Half the curved plate arc between supports, α, is

$$\alpha := \frac{\pi}{4} \tag{12}$$

From Miller [3]

$$C(\alpha) := \frac{-2}{3} + \sin(2\cdot\alpha)\cdot\left(\frac{3}{4}\cdot\cot(\alpha) - \alpha\right) - \frac{4}{3}\cdot\cos(2\cdot\alpha) \ldots + \alpha\cdot\cot(\alpha)\cdot\left(1 - \frac{\cos(2\cdot\alpha)}{2}\right) \tag{13}$$

and

$$C(\alpha) = 0.083 \tag{14}$$

Miller [3] also defines the following variables

$$f_1(\alpha) := \frac{1}{2\cdot\sin(\alpha)^2}\cdot\left(\frac{\alpha}{2} + \frac{\sin(2\cdot\alpha)}{4}\right) \tag{15}$$

$$f_3(\alpha) := \frac{1}{2\cdot\sin(\alpha)^2}\cdot\left(\alpha - \frac{3}{4}\cdot\sin(2\cdot\alpha) + \frac{\alpha\cdot\cos(2\cdot\alpha)}{2}\right) \tag{16}$$

$$\beta_2 := \frac{A\cdot R^2}{I}\cdot f_3(\alpha) + f_1(\alpha) \tag{17}$$

The ratio of pinned edge curved plate to pinned edge flat plate critical velocity is

$$V_{rh} := \left(\frac{8\cdot\beta_2\cdot\sin(\alpha)^5}{15\cdot C(\alpha)}\right)^{\frac{1}{2}} \tag{18}$$

and

$$V_{rh} = 14.9 \tag{19}$$

Now, the pinned edge velocity to which the above ratio applies is calculated. The gravitational acceleration constant is

$$g = 386.089\,\frac{in}{sec^2} \tag{20}$$

Young's Modulus for the fuel plate using room temperature data for aluminum (1000 series) is [8]

$$E := 10\cdot10^6\cdot psi \tag{21}$$

Poisson's ratio of the fuel plate is taken to be that of aluminum [9]

$$\upsilon := 0.33 \tag{22}$$

The fuel element channel widths, h_{el}, are

$$h_{el_i} := R_{i_i} - R_{o_{i+1}} \tag{23}$$

which results in an initial flow channel thickness, h, of

$$h := \min(h_{el}) \tag{24}$$

and

$$h = 0.078\,in \tag{25}$$

The average density of the water coolant is

$$\rho := 62.24\cdot\frac{lbf}{ft^3} \tag{26}$$

The dimension of end plate is

$$ep := 0.533\cdot in \tag{27}$$

The width of the flat plate is taken as arc length of curved plate minus end plate

$$b := 2\cdot\alpha\cdot R - ep \tag{28}$$

and

$$b = 2.83\,in \tag{29}$$

The critical velocity of pinned edge flat plate is

$$V_s := \left[\frac{5\cdot g\cdot E\cdot a^3\cdot h}{2\cdot\rho\cdot b^4\cdot\left(1-\upsilon^2\right)}\right]^{\frac{1}{2}} \tag{30}$$

which yields

$$V_s = 50.39\ \frac{\text{ft}}{\text{sec}} \tag{31}$$

The critical static divergent velocity for the curved plate GTL booster fuel assembly is the product

$$U_d := V_s\cdot V_{rh} \tag{32}$$

which yields

$$U_d = 749.2\ \frac{\text{ft}}{\text{sec}} \tag{33}$$

The total cross-sectional flow area of the four fuel channels is

$$XA := 2.50379\cdot 10^{-3}\cdot m^2 \tag{34}$$

The total coolant flow rate necessary to produce plate collapse is the product of the cross-sectional flow area and the critical static divergent velocity

$$Q := U_d\cdot XA \tag{35}$$

which results is a critical flow rate of

$$Q = 9.062\times 10^3\ \text{gpm} \tag{36}$$

DISCUSSION OF RESULTS

The theoretical collapse velocity for flat plates with simply supported edges was calculated first. Then, the ratio of the critical velocity of hinged curved plates to that of hinged flat plates was calculated. The critical velocity for the hinged curved plate assembly was calculated by multiplying the predicted collapse velocity for hinged flat plate assemblies by this critical velocity ratio. Due to the higher stiffness of the curved plate assembly, the critical velocity is approximately 15 times higher than that for a long flat plate assembly with identical dimensions.

The predicted plate collapse velocity, U_d, for the GTL booster fuel assembly is 228 m/s (749 ft/s). This would occur at a total coolant flow rate around 9100 gpm. Preliminary calculations performed using RELAP5-3D using a fuel plate surface roughness of 1.31 microns, predict an average coolant flow velocity of approximately 10.5 m/s (34.4 ft/s) with the snubber tube included and 13.4 m/s (44.0 ft/s) without the snubber tube. The total coolant design flow rate without the snubber tube is 533 gpm [10]. The snubber tube is part of the original ATR design intended to hydraulically slow the control rod as it reaches the bottom of its travel path.

Miller states "in some fuel-plate assemblies collapse has occurred at velocities on the order of one-half of that predicted by the formulas here" [3]. In the absence of a considerable margin between the theoretically predicted plate collapse velocity and the design velocity, a test program would be warranted. However, since the coolant design flow velocity is only 6% of the predicted critical flow velocity based upon Miller's theory, the phenomena of plate collapse due to static instability is unlikely. However, this does not rule out the possibility of plate collapse caused by other mechanisms, such as thermoelastic instability, creep, radiation-induced fuel meat distortion, etc., which may need to be investigated.

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