

## FLOW VELOCITY CALCULATION TO AVOID INSTABILITY IN A TYPICAL RESEARCH REACTOR CORE

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### ABSTRACT

Flow velocity through a research reactor core composed by MTR-type fuel elements is investigated. Core cooling capacity must be available at the same time that fuel-plate collapse must be avoided. Fuel plates do not rupture during plate collapse, but their lateral deflections can close flow channels and lead to plate over-heating. The critical flow velocity is a speed at which the plates collapse by static instability type failure.

In this paper, Critical Velocity and Coolant Velocity are evaluated for a typical MTR-type flat plate fuel element. Miller's method is used for prediction of Critical Velocity. The Coolant Velocity is limited to 2/3 of the Critical Velocity, that is a currently used criterion.

Fuel Plate characteristics are based on the Open Pool Australian Light Water Reactor (OPAL).

### 1. INTRODUCTION

A research reactor, as well as providing the research itself, can be a producer of radioisotopes for various uses, particularly for medicine. The demand for this product has grown, and it is interesting that a country like Brazil be self-sufficient in this regard, what is not true nowadays. The design and construction of a new reactor that enables self-sufficiency in radioisotopes production and expands the possibilities of research is a challenge that is worth to be faced. Australia recently, with the help of the Argentine company INVAP, designed and built the 20 MW reactor OPAL (Open Pool Australian Light Water Reactor), opening new prospects for that country. This work contributes technically to the development of new projects in Brazil presenting a discussion about the velocity of the coolant flow through a typical fuel element, the Materials Test Reactor (MTR) type, to avoid its instability. For this purpose, geometric characteristics of the OPAL fuel element [1] are used as a base for the hypothetical element studied.

The MTR-type is a fuel element that consists of a parallel arrangement of flat fuel plates. The velocity of water through the coolant channels of this element is an important parameter because there are limits beyond which instabilities can occur. The concern of this work is to establish a limit that prevents the occurrence of hydroelastic instability.

## 2. COOLANT FLOW VELOCITY THROUGH FUEL ELEMENT CHANNELS

The core of a typical pool type research reactor is cooled by light water. The influence of the coolant velocity through the core must be taken into account to prevent the collapse of the fuel plates at high speeds. The flow of the coolant at high speed through a channel made of parallel plates has the potential to cause deflections due to the interaction between fluid and structure. Deflections can produce severe local overheating or lead to blockage of the coolant flow.

For a given plate assembly, there is a critical flow velocity above which the plates become unstable. So, to avoid distortion of the channels and overheating of the fuel due to hydraulic instabilities of fuel plates, the maximum speed of the fluid flowing through the cooling channels should be less than this critical velocity.

The nominal velocity of the coolant ( $V_n$ ) should not endanger the hydraulic stability of the fuel plates. Daniel Miller [2] established the concept of the speed of collapse, that would be a speed at which any instability could lead the fuel plates to such a deformation that they could reach the point of touching one another, thus affecting the removing of heat from fuel elements. The speed so defined is known as Miller's Velocity or Miller's "Critical Velocity" ( $V_{cr}$ ). Later it was shown that, in the absence of any flow stabilizer, it would be possible to occur a collapse at a speed of  $0.9 \times V_{cr}$ . It was clear, thus, the need of having a safety margin for  $V_{cr}$ .

In this paper we set, as a design criterion, to limit the maximum speed of coolant flow in  $2/3$  of the critical velocity [3].

### 2.1. Fuel Element

In the present study, we have considered a fuel element similar to the one used for OPAL reactor [1]. It is a plate type fuel element with a square cross section. Each fuel element is composed of flat fuel plates fixed by their long edges on two support plates. The bottom part of the internal fuel plates is supported by a device in the form of a "comb", located in the middle of the width of the plates. Each fuel plate contains a central region called "meat", consisting of little particles of a uranium compound (in the case of OPAL,  $U_3Si_2$ ) dispersed in an aluminum matrix. The meat is hermetically sealed between two aluminum plates that form the cladding of the fuel plate. In this study, each fuel element is composed of sixteen fuel plates, fourteen internal and two external ones. The fuel elements are positioned vertically on the core matrix plate. The matrix plate has holes drilled in it where the mating parts of the elements are fitted. The coolant flows through the core, forced by the action of the Primary Cooling System pumps. Figure 1 shows a typical flat plate-type fuel element.

The important fuel element dimensions for this study are:

- $h_p$  = Fuel Plate Thickness (0.135 cm)
- $h_c$  = Meat Thickness (0.061 cm)
- $t_c$  = Cladding Thickness (0.037 cm)
- $h$  = Thickness of the flow channel (0.245 cm)
- $b$  = Width of the flow channel (7.050 cm)

The aluminum currently used as cladding for the fuel plates is ASTM-6061. In the ASME Code [4], the material corresponding to ASTM-6061 is designated as SB-209 (6061 Alloy, UNS n°. A96061).



**Figure 1. Typical plate type fuel element.**

Considering that the coolant is light water, Table 1 shows the properties of aluminum (Young's modulus  $E$  and Poisson's ratio  $\nu$ ) and water (density  $\rho$ ) used in the calculations performed. To be conservative, the reference for the calculations was the internal plate, since its thickness ( $h_p$ ) is smaller than the external plate one.

**Table 1. Aluminum and water properties**

	<b>T (°C)</b>	25	100
<b>SB-209 [4]</b>	<b>E (10<sup>5</sup> bar)</b>	6.9	6.6
	<b><math>\nu</math></b>	0.33	
Light Water [5]	<b><math>\rho</math> (Kg/m<sup>3</sup>)</b>	997.0	958.4

## **2.2. Critical Velocity ( $V_{cr}$ )**

Miller's method uses the following assumptions [2]:

- The plates are homogeneous, isotropic, elastic, and initially flat, uniform in spacing and dimensions and free of unidentified sources of deformation;
- The coolant is incompressible; all channels have the same mass flow; at any cross section normal to the longitudinal axis the flow within any channel is uniform; leakage between channels is suppressed;
- Plates are broad enough (in comparison with their thickness) so that shear deformation is negligible, and are long enough (in comparison with their breadth) so that they can deflect locally without significant redistribution of flow among the coolant channels;
- Side plates or supports are rigid.

Miller's Critical Velocity [2],  $V_{cr}$  (m/s), is given by equation (1):

$$V_{cr} = \frac{[15 \times 10^5 E h_p^3 h]^{1/2}}{[\rho b^4 (1 - \nu^2)]^{1/2}} \quad (1)$$

In this formula, Miller considers that the two long edges of the plate are fixed, and that the entire section of a strip of unit width of the fuel plate works to resist to the loads.

As a first approximation, we have assumed that the plate is entirely homogeneous and performed the critical velocity calculation using only the aluminum properties ( $E$ ,  $\nu$ ) corresponding to the cladding of the plates (ASTM 6061). To evaluate how the velocity behaves with the coolant temperature, we have calculated it for the room temperature (25 °C), and for 100 °C, the temperature from which begins to occur the boiling of water and corrosion problems arise for the aluminum. Table 2 shows the results obtained for the calculations performed.

**Table 2. Calculated Miller's Critical Velocities**

<b>T (°C)</b>	25	100
<b><math>V_{cr}</math> (m/s)</b>	16.86	16.82

Virtually no influence of temperature is found in the calculations, so that it is reasonable to work with  $V_{cr} = 16.8$  m/s.

### 2.2.1. Alternative critical velocity ( $V_{cr}^*$ )

$V_{cr}$  calculation done before includes the simplification of considering the section of the fuel plate of the elements as uniform and made only of aluminum. However, the existence of the meat may result in a lower resistance of this section and, consequently, lead to a lower critical velocity. At the limit, one can consider that the meat shows no structural strength, and only the cladding will work when the plate is loaded. In this situation, Miller offers the following expression (2) for the critical velocity  $V_{cc}$  [2]:

$$V_{cc} = \frac{[30 \times 10^5 E t_c^3 h]^{1/2}}{[\rho b^4 (1 - \nu^2)]^{1/2}} \quad (2)$$

Ultimately, to use this equation means to consider only the cladding as the resistant cross section, ignoring even the effects of shear and bending that would be transmitted by the meat. This procedure, however, is very conservative, and leads to very conservative critical velocities (3.4 m/s in the studied case).

Due to the manufacturing process of the fuel plates, even when neglecting the strength of the meat, it is reasonable to consider that there is sufficient continuity between the cladding and the meat in this sandwich-like configuration that the effects of shear and bending are still transmitted between them. Thus, despite the strength of the meat, everything happens as if the two sides of the cladding had been displaced from the medium plane of the fuel plate, and these displacements were taken into account when calculating the moment of inertia of the resistant section, with consequences on the critical velocity formulation. Let  $V_{cr}^*$  be the critical velocity so defined. This approach is the same as indicated by the IAEA in reference [3], which has the following expression (3) for the critical velocity:

$$V_{cr}^* = \frac{[15 \times 10^5 E h (h_p^3 - h_c^3)]^{1/2}}{[\rho b^4 (1 - \nu^2)]^{1/2}} \quad (3)$$

Using equation (3) to perform the calculation, we have that  $V_{cr}^* = 16.0$  m/s.

### 2.3. Maximum Flow Velocity

Taking a widely used design criterion [1], we stated that the maximum nominal speed of coolant flow through the reactor core in study ( $V_{n-max}$ ) can not exceed 2/3 of the Critical Velocity. Using the concept of critical velocity, as indicated by reference [3],  $V_{cr}^*$ , we have that:

$$V_{n-max} = 2/3 (V_{cr}^*) = 10.6 \text{ m/s} \quad (4)$$

The calculated value of 10.6 m/s, obtained for the maximum nominal speed of coolant flow through the core of a research reactor similar to the OPAL, is consistent with international experience for projects of similar characteristics. In fact, nominal speeds are generally below this limit (in the case of OPAL, the nominal coolant flow velocity is 8.2 m/s [1] and is, thus, consistent with this limit).

## 3. ADDITIONAL REMARKS

For more accurate assessments, the following works can be done: execution of thermal analysis (temperature distribution along the thickness) of the fuel plates for the evaluation of mechanical properties; characterization of bending stiffness properties of the fuel plates with the consideration of the heterogeneity along the thickness, by using experimental and analytical methods; collection of specific material data as a result of mechanical testing of

fuel plates, in hot and cold condition, in order to obtain more representative properties ( $E$ ,  $\nu$ ), to be used in the calculations.

#### 4. CONCLUSIONS AND COMMENTS

Using the properties  $E$  and  $\rho$  at a temperature of 100 °C, we obtained the values of 16.0 m/s for the critical velocity ( $V_{cr*}$ ), calculated similarly to the Miller's method and using the specific hypotheses and formulation from reference [3], and 10.6 m/s for the maximum nominal speed of coolant flow ( $V_{n-max}$ ) through the core of an OPAL-like reactor. This value is consistent with nominal speeds of fluid ( $V_n$ ) that are known by international experience for projects of similar characteristics.

Although Miller's method represents a simplification of a number of phenomena, it is well accepted and widely used, since it offers an easy way of knowing the flow velocity that could lead to the collapse of plates of MTR-type fuel elements. It should note that this formulation takes into account only the static-instability, or static divergence, as failure mode, what occurs at moderate speeds. Kim and Davis [6] and Smissaert [7] also studied the mechanism of dynamic instability, which occurs at high speeds, when there is coincidence of frequencies between flow and plates. The use of spacers between the plates (comb-like stabilizers) helps in controlling this phenomenon [8].

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