MASTER

TRANSIENT EFFECT ON LMFBR FUEL RODS
BY GAS BUBBLES ENTRAINED IN THE COOLANT (+)

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ABSTRACT

The effect of the intermittent passage of gas bubbles entrained in the sodium coolant on the integrity of the fuel rod cladding is examined for typical conditions of Liquid Metal Fast Breeder Reactors.

The maximum stable size of the bubbles is calculated to be of the order of 0.5 in. equivalent spherical diameter. The transient blanketing of the fuel rod due to the passage of the bubbles is studied for two extremely conservative geometrical configurations. The maximum calculated cladding temperature increase during the transient was found to be fairly limited, and the thermal fatigue effect due to the passage of a large number of bubbles was assessed. It appears that even in the most pessimistic conditions the fatigue effect is well below the failure limit. It has been concluded, therefore, that gas bubbles flowing through the core do not endanger the cladding integrity and do not reduce the fuel rod lifetime.

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1. INTRODUCTION

The effect of gas bubbles flowing through the core is one of the problems commonly investigated for Liquid Metal Fast Breeder Reactors (LMFBR). The phenomenon is not of real concern for the design since degassing devices are generally provided, but nevertheless it must be considered in safety analyses, since the possibility exists that bubbles emanating from a variety of plant components (sodium pumps, feed and purification systems, cover gas, etc.) remain entrained in the coolant.

The passage of large gas bubbles, with a volume up to the order of 100 liters and simultaneously voiding several assemblies, will of course have serious consequences, even the core disassembly, as several studies which have been conducted in the past indicated. However, there is no physical justification of the effective existence of bubbles having such dimensions; therefore, the first aim of this analysis has been to assess realistically the magnitude of the bubbles, determining their maximum stable size.

The thermal and mechanical analysis successively performed showed that the fuel rod behavior is very mildly affected by the passage of such bubbles. However, the possibility of a large number of bubbles passing through the core during the fuel rod lifetime cannot be ruled out completely, as the DFR experience suggests (even though the particular down flow arrangement of the DFR reactor highly enhances the chances of gas entrainment from the cover gas system). Thus, the useful life of the fuel element could be shortened due to a thermal fatigue effect. This analysis clearly indicates that for the current design specifications of LMFBRs, no fatigue problem arises both for unvented and vented fuel elements, even employing the most conservative assumptions.

2. TRANSIENT BLANKETING OF THE FUEL ROD

2.1 Maximum Stable Size of the Gas Bubbles

The consequences of the passage of the bubbles are critically dependent on their stable size; larger bubbles than the stable size would break up and smaller bubbles may coalesce into the stable size.

The maximum stable size of the bubbles was found to be dependent on a critical value of a modified Weber number:

$$We_{crit} = \frac{D_{max} V_r^2 \Delta \rho}{\sigma} \quad (1)$$

Both theoretical and experimental studies (see for example Ref. [2-5]) are in good agreement indicating a value of We_{crit} approximately equal to 4, for gas bubbles rising in a quiescent liquid contained in a circular tube; if it is $We > We_{crit}$ large oscillations in the bubble take place and break-up could occur. A quick calculation, considering the equilibrium between hydrodynamic and surface tension forces and using experimental values of the drag coefficient reported in the literature, has confirmed the above value of We_{crit} .

The relative velocity between the liquid and the gas bubble was taken equal to the so-called "terminal velocity" of the bubble, which is nearly independent of the bubble size and is in the order of 0.8-1 ft/sec. There is, in fact, experimental evidence^[6] that the relative velocity of the bubble in a moving system is similar to its rise velocity in a quiescent system and it is independent not only of the bubble size, but also of the Reynolds number of the system.

Finally, the relative density between the liquid and gas phases is practically equal to the sodium density. Thus, the maximum stable size of the bubbles in a typical LMFBR environment was calculated on the basis of

Equation (1) and resulted to be in the order of 0.3-0.5 in. equivalent spherical diameter. This value compares well with the maximum size (in the order of 1.5 cm) reported in an independent study.^[7] Higher values cannot, of course, be excluded but they relate to unstable bubbles. Moreover, in the real case of a nuclear core environment the bubble stable size will be smaller than for bubbles rising very quietly in a quiescent unobstructed liquid experiment, owing to the presence of obstacles like the support and spacer grids and the rods themselves and also owing to variations in the coolant velocity distribution. Thus, a bubble diameter of 0.5 in. has to be regarded as a conservative upper limit.

2.2 Thermal Analysis

The transient rise in the cladding temperature at the time of passage of the gas bubbles has been calculated. Other conservative assumptions, besides considering bubbles having the maximum stable size, were: the fuel rod is completely blanketed over 360°, the slip ratio between the two phases is very close to 1 (a bubble velocity of 30 ft/sec has been considered), and the examined fuel rod is the hot rod.

Clearly all these assumptions will give the maximum extent, in space and in time, of the disturbance to the fuel rod which experiences a perturbation in the heat transfer conditions and will give the maximum increase in the temperature (hence in the thermal stresses) of the cladding.

Two limiting cases of blanketing configurations were analyzed (see Fig. 1):

1. Type A - The gas bubble will spread around the rod; for a typical LMFBR geometrical arrangement (triangular pitch; rod diameter = 0.25 in.; ratio pitch/diameter = 1.26) the length of the insulated section will be 0.6 in. for the maximum bubble size considered, and the time during which a point on the cladding will be blanketed by the bubble will be approximately 1.7 msec.

CASE A
 ONE BUBBLE SPREADS AROUND THE ROD
 BUBBLE LENGTH = 0.6 in.
 TIME OF PASSAGE = 1.7 msec

CASE B
 SIX BUBBLES SIMULTANEOUSLY
 SURROUND THE ROD
 BUBBLE LENGTH = 3.5 in.
 TIME OF PASSAGE = 10 msec

Figure 1. Scheme of Two Different Configurations of Bubble Blanketing

2. Type B - This is the most pessimistic case which can be conceived. Six bubbles, each having the maximum size, simultaneously surround the fuel rod and elongate in each of the six subchannels adjacent to it, thereby causing a more prolonged blanketing. In this case the length of the blanketed section is 3.5 in. and the time of passage approximately 10 msec.

The conservatism of this second configuration is evident because the bubbles so elongated will not remain stable and their break-up is very probable, especially if grids are used as rod spacers. The results of the analysis conducted for bubbles of the B type will give therefore the upper limit of the thermal (and mechanical) perturbation caused by the bubble passage.

The reactivity insertion due to the passage of bubbles 3.5 in. long was calculated^[8] and found to be negligible, less than 1c , even assuming passage of the bubble at the core location having the maximum reactivity worth. Therefore, the effect of the reactivity insertion on the fuel rod temperature was disregarded; moreover, such an insertion may have a slight effect on the fuel temperature, but it would not affect the cladding temperature, which is the parameter of interest in this analysis.

The heat transfer degradation effect due to the transient blanketing of the rod was analyzed by means of a two-dimensional model, taking into account the heat conduction both in the axial and in the radial direction (no heat conduction in the peripheral direction, since the rod is blanketed over 360°). The bubble movement along the rod was followed by changing, for each axial location at the time of passage of the bubble, the value of the convective heat transfer coefficient. Values assumed were $25,000 \text{ Btu/hr-ft}^2\text{ }^\circ\text{F}$ for full sodium flow and $1,000 \text{ Btu/hr-ft}^2\text{ }^\circ\text{F}$ (calculated on the basis of the Dittus-Boelter correlation) when the gas bubble was present. The analysis was carried out by the use of the TOSS code^[9]; this code calculates the transient and/or steady state temperature distribution, solving the three-dimensional heat conduction equation by means of a finite difference technique.

In Figure 2, the temperature profile in three different radial locations of the cladding (outer surface, midpoint, inner surface) is shown at the time when the bubble has travelled to the indicated position which corresponds to the middle of the core. As mentioned before, the blanketing effect has been studied for the case of the hot rods (assumed power rating = 16 kw/ft), again yielding the most conservative results. The principal conclusions obtainable from an examination of the Figure are:

1. The maximum increase in the outer surface cladding temperature is 53°F, which reduces to 25°F at the cladding midpoint.
2. The temperature increase due to bubbles of Type A is practically negligible, except at the very outer surface of the cladding where it is 28°F.
3. The maximum cladding temperature occurs at the bottom of the bubble, as would be expected because it is the point which has remained uncooled for the longest time. As the bubble passes up the cladding, this temperature perturbation in the cladding moves up with the bubble as a ripple on the existing cladding temperature.
4. The outside diameter and midpoint temperature gradients are very steep at the interface between the blanketed section and the section not yet affected by the bubble.
5. The passing bubble develops a long temperature tail behind it, due to the good thermal conductivity of the stainless steel. However, even for the longest 3.5 in. bubble, significant changes in temperature do not extend much beyond the coverage of the bubble.
6. The effect of the cladding thermal inertia is clearly visible if the transient temperatures at the three radial positions are compared. Moving inwards from the outer surface to the inner surface the temperature increase sharply decreases, the position of maximum temperature lags with respect to the location of the bubble and the temperature tail increases in length.

Figure 2. Cladding Transient Temperature Profile Generated by the Passage of Gas Bubbles at Middle of the Core

The results reported in Figure 2 refer to passage of the bubble at a position corresponding to the midcore, where the power rating is maximum, therefore yielding the maximum temperature increase. On the other hand, the maximum cladding temperature will be reached at the top of the core, where the steady state coolant and cladding temperatures are the highest. A similar analysis has been therefore performed for bubble passage at the latter position, considering a fuel power rating equal to 8 Kw/ft. The transient temperature profile is quite similar to that reported in Figure 2 and an almost linear relationship between power rating and cladding temperature increase was found (see Table 1). Thus, the transient behavior for intermediate conditions may be easily inferred.

3. THERMAL FATIGUE ANALYSIS

The results of the thermal studies indicated that in no case does the passage of the gas bubble have a significant effect on the temperature attained by the cladding and in no case is the integrity of the fuel rod threatened by a single bubble. Nevertheless, it is necessary to calculate the thermal fatigue effect produced by the intermittent passage of a large number of bubbles during the fuel rod lifetime in order to assess the condition of the cladding during the plant lifetime and verify if the target burnup can be attained.

The thermal stresses induced in the cladding during the transient passage of the bubble are due to:

1. The axial temperature rise in the cladding.
2. The change in the radial temperature gradient through the cladding.

The expressions for the shear and circumferential hoop stress due to the axial temperature rise are respectively^[10]:

TABLE 1

CLADDING MAXIMUM TEMPERATURE DURING GAS BUBBLE PASSAGE

Bubble	Axial Location in Core	Radial Location in Cladding	Cladding Maximum Temperature and Change From Steady State Conditions	
Type A 0.6 in. long	Core Midplane	Outer Surface Midpoint Inner Surface	1062°F 1082°F 1125°F	$\Delta T = 28.4^{\circ}\text{F}$ 4.4°F 3.0°F
	Top of the Core	Outer Surface Midpoint Inner Surface	1230°F 1240°F 1260°F	$\Delta T = 13.5^{\circ}\text{F}$ 2.4°F 1.6°F
Type B 3.5 in. long	Core Midplane	Outer Surface Midpoint Inner Surface	1087°F 1102°F 1143°F	$\Delta T = 53.3^{\circ}\text{F}$ 25.0°F 21.5°F
	Top of the Core	Outer Surface Midpoint Inner Surface	1242°F 1250°F 1269°F	$\Delta T = 25.8^{\circ}\text{F}$ 12.6°F 11.0°F

$$\sigma_s = \frac{\alpha E \Delta T}{4 \beta r} \quad (2)$$

$$\sigma_c = \pm \frac{\alpha E \Delta T}{2(1 - \mu)} \quad (3)$$

$$\text{where } \beta = 4 \sqrt{\frac{3(1-\mu^2)}{r^2 t^2}} \quad (4)$$

Considering an average ΔT at the cladding midpoint of 25°F and conservatively idealizing the temperature distribution as constant over the region covered by the bubble and equal to its maximum value, the shear stress resulted in a nearly negligible 400 psi and the hoop stress was equal to ± 4200 psi.

The instantaneous stress due to the radial temperature gradient through the cladding at a point having an instantaneous temperature T during the transient is expressed by: [10]

$$\sigma(T) = \frac{E \alpha (T_{avg} - T)}{(1 - \mu)} \quad (5)$$

Thus, the maximum change in the hoop stress level due to the change in the radial temperature distribution indicated in Figure 2 was -10,600 psi at the cladding outer surface and +3,000 psi at the inner surface. Combining the effects of the changes in the axial and radial temperature distributions caused by the passage of the bubble, an alternating stress range of 14,800 psi results, which corresponds to a mean stress of 7,400 psi. From a modified Goodman diagram (see the solid line in Figure 3), the resulting equivalent alternating stress intensity is approximately 8,500 psi.

The fatigue curves shown in Figure 4, which take temperature and irradiation effects into account, indicate that such a stress is safely below both the failure and design fatigue curves, even for 10^6 cycles, which is generally the asymptotic limit for the fatigue curves S-N (fatigue stress vs. number of cycles to failure). On the other hand, a number of bubbles equal to 10^6 corresponds to an average frequency of approximately 1 bubble/minute for a three year life of the fuel element, a value which is felt to be very much larger than any expected frequency of small entrained gas bubbles.

Figure 3. Modified Goodman Fatigue Diagram

Figure 4. Design and Failure Fatigue Curves for Stainless Steel 316

The conclusion reached is valid for the case that no mean stress is present in the rod, that is, it applies to unpressurized rods without any fuel swelling or fuel cladding interaction considered. Under operating conditions the rod will be pre-stressed by the fission gas pressure (unless the fuel element is of the vented type) and by swelling and thermal stresses.

Using the modified Goodman diagram (see, as an example, the dotted lines in Figure 3) the equivalent alternating stresses corresponding to various mean stresses in the rod are determined. Successively, the equivalent alternating stresses are related to the number of cycles to failure according to the curves reported in Figure 4 and finally the relationship between the mean stress in the rod and the maximum allowable number of gas bubbles was calculated. The results are reported in Figure 5, which shows that even in the case of 10^6 bubbles, fatigue failure would occur only when the mean stress exceeded 40,000 psi. This is larger than the yield strength (20,500 psi), which is, therefore, a more restrictive limit than the thermal fatigue effect.

It may be concluded from this conservative analysis that entrained gas bubbles, irrespective of their number or of the steady state stress on the cladding, do not give rise to any safety problem when passing through the core of LMFBFR reactors.

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Figure 5. Allowable Number of Gas Bubbles for Prestressed Rods

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NOTATION

$D_{\max}$	maximum diameter of equivalent spherical bubbles
E	elastic modulus
r	radius
T	temperature
t	cladding thickness
V_r	relative velocity between liquid and gas phases
We	Weber number
α	coefficient of thermal expansion
β	defined by equation (4)
ΔT	temperature rise
$\Delta \rho$	relative density between liquid and gas phases
μ	Poisson ratio
σ	cladding stress, surface tension
σ_c	cladding hoop stress
σ_s	cladding shear stress
σ_t	cladding tensile strength

FIGURES CAPTIONS

FIGURE 1 - Scheme of Two Different Configurations of Bubble Blanketing.

FIGURE 2 - Cladding Transient Temperature Profile Generated by the Passage of Gas Bubbles at Middle of the Core.

FIGURE 3 - Modified Goodman Fatigue Diagram.

FIGURE 4 - Design and Failure Fatigue Curves for Stainless Steel 316.

FIGURE 5 - Allowable Number of Gas Bubbles for Pre-stressed Rods.