CONF-72112--6

RECEIVED BY TIC JAN 10 1973

POTENTIAL FUEL FAILURE PROPAGATION DUE TO
FISSION-GAS RELEASE IN LMFBR
SUBASSEMBLIES

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Presented at:
The American Society of Mechanical Engineers
Winter Annual Meeting
November 26-30, 1972
New York, N.Y.

(ASME Paper No. 72-WA/NE-14)

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This paper deals with potential mechanisms for pin-to-pin failure propagation due to fission gas release in fuel subassemblies of liquid metal cooled fast breeder reactors, as a consequence of random failure of one or more fuel pins. Two distinctly different potential fuel failure propagation mechanisms associated with fission gas release are identified, viz., (a) temperature transients induced in the cladding of adjacent fuel pins, and (b) transitory mechanical loads on adjacent fuel pins. This paper deals solely with the former failure propagation mechanism, which is found to be linked with a number of different fission gas release modes. Out-of-pile experiments using both metallic and nonmetallic fluids are described and results are given regarding the various fission gas release modes. It is concluded that extensive and rapid pin-to-pin failure propagation in current-design LMFBF fuel subassemblies, due to thermal transients induced in the cladding of adjacent fuel pins by fission gas release from one or more randomly failed fuel pins, is unlikely.

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1 INTRODUCTION

The fission-gas inventory at end-of-life (burnup $\sim 10^5$ MWd/ton) of a fuel pin of a liquid metal cooled fast breeder reactor (LMFBR) of current design is approximately 2.5 g or 450 cc (STP). This fission gas consists predominantly of xenon which is stored in the fission gas plenum and within the central fuel void and the fuel matrix; it reaches at end-of-life a maximum pressure of 55 to 69 bar, abs. (800 to 1000 psia), depending on the power history of the fuel and the gas plenum size.

Release of fission gas in an LMFBF subassembly, due to rupture of one or more fuel pins, can potentially result in fuel failure propagation through two distinct mechanisms, viz.: (a) temperature transients in the cladding of adjacent fuel pins, exceeding the threshold temperature for failure at the operating conditions; and (b) transitory mechanical loads on adjacent fuel pins due to pressure pulses, causing deflection of the pins which could potentially result in brittle rupture of the cladding at high burnup of the fuel.

The importance of fuel failure propagation due to fission-gas release in LMFBF subassemblies was recognized early in view of its implications for both the safety and the economic viability of LMFBF's using mixed-oxide fuels (1).¹ A 1000-MWe LMFBF of current design contains $\sim 10^5$ fuel pins, resulting in a finite probability for occasional random failure of fuel pins.

The thermohydraulic transients induced by fission-gas release in LMFBF fuel subassemblies can be adequately studied by means of out-of-pile experiments at a lower cost than with in-pile experiments. Out-of-pile experiments will give the magnitudes of the temperature transients and the transitory mechanical loads resulting from the particular fission-gas release mode considered. Additional analyses, utilizing the information derived from out-of-pile experiments and taking into

account the mechanical properties of the cladding material at various burnup levels of the fuel, are then required to evaluate whether or not failure propagation would have occurred for the actual in-reactor case. Integral in-pile experiments, using irradiated fuel, may be required since such tests are expected to provide a more immediate answer as to whether failure will occur or not. However, the relatively high cost of such in-pile experiments necessarily limits the number of runs that can be made. No such limitations exist for out-of-pile experiments where a large number of data points can be obtained once the experimental facility is operative. Another point to be considered is that the difficulties encountered for obtaining an adequate degree of instrumentation within the test bundle are considerably larger for in-pile than for out-of-pile experiments, in particular if irradiated fuel is used for the former.

Even though gas release rates under actual conditions may be limited by the internal resistance due to the presence of the fuel pellets, the approach taken at Argonne National Laboratory (ANL) has been to investigate the full range of release rates which have the potential for failure propagation. Such an approach gives results which can be used no matter where the failure occurs (e.g., near the gas plenum, where the internal resistance is minimum, or removed from the gas plenum, where the internal resistance is higher) and can be easily extended to multiple-pin failures. It also allows consideration of different locations for the gas plenum.²

The present paper gives results of recent out-of-pile experiments using both metallic and non-metallic liquids.

² Most LMFBF designs of United States origin have the fission-gas plenum at the core outlet. However, LMFBF's of British, French, and German-Benelux design all appear to be designed with the main gas plenum at the inlet of the fuel subassemblies.

¹ Underlined numbers in parentheses designate references at end of paper.

2 DESCRIPTION OF POTENTIAL FAILURE PROPAGATION MECHANISMS

A classification of the various potential fuel failure propagation mechanisms due to fission-gas release may be made as follows (Fig. 1):

Temperature Transients in the Cladding of Adjacent Fuel Pins

This potential mechanism of failure propagation can follow different modes for different clad breach sizes and different gas release rates. For purposes of easy reference, the different modes can be qualitatively subdivided as follows:

Slow Fission-Gas Release. For this release mode, the major part of the fission-gas inventory is released in time periods long enough to cause the clad temperature to exceed its threshold value for failure (release time $> \sim 0.25$ sec, see Section 3 of the present paper). This mode of fission-gas release can cause thermal transients of the cladding of adjacent fuel pins in five different ways:

- 1 Gas-jet impingement, resulting in gas blanketing and possibly dryout at, or in the immediate vicinity, of the area of impingement
- 2 Flow starvation due to increased (two-phase) frictional pressure losses affecting one or more coolant subchannels
- 3 Gas blanketing and possibly dryout immediately downstream of the point of release where the gas has not yet been radially dispersed
- 4 Flow stagnation in one or more coolant subchannels, immediately upstream of the point of gas release
- 5 Entrapment of gas bubbles in wakes of flow obstructions, such as partial or complete subchannel blockages or grid spacers.

Fast Fission-Gas Release. For this release mode, the major part of the fission-gas inventory is released in time periods $< \sim 0.1$ sec. The potential failure mode due to entrapment of gas bubbles in wakes of flow obstructions could occur also for fast gas release, though it may be less probable than for slow gas release. Furthermore, fast release of fission gas could result in severe flow transients, giving rise to the following potential fuel failure propagation mode — transient flow reversal, resulting in gas blanketing of fuel pins for time periods longer than the gas release time.

Transitory Mechanical Loads on Adjacent Fuel Pins due to Pressure Pulses

This potential mechanism for failure propagation is most probable for fast fission-gas release and for end-of-life fuel, when the ductility

Fig.1 Potential pin-to-pin fuel failure propagation mechanisms due to fission-gas release in LMFBR fuel subassemblies

of the cladding is considerably reduced. It is the subject of an on-going experimental program at ANL and will not be dealt with further in the present paper.

3 BOUNDING CONDITIONS AND EXPERIMENTAL STRATEGY

Two mechanisms exist for heating up the cladding of an adjacent fuel pin following the random rupture of one or more fuel pins, namely: (a) decrease of the heat-transfer coefficient between the cladding and the coolant, e.g., by (local) gas blanketing; and (b) increase of the coolant temperature, e.g., by (local) flow reductions.

An important bounding condition that must be fulfilled in order that failure propagation can occur is that the perturbation caused by the fission-gas release lasts long enough to allow the cladding of the adjacent fuel pin(s) to heat up to the threshold temperature for failure. For most gas-release modes, the foregoing perturbation time is approximately equal to the gas-release time; however, for rapid gas release, which may induce a severe transient flow reversal in the affected subassembly, the perturbation time can be longer than the gas-release time.

The minimum time length of the perturbation, required to make failure propagation potentially possible, is determined by the thermal time-response characteristics of the fuel pin (as de-

Fig.2 Mean cladding temperatures of LMFBFR fuel pins versus time, subsequent to complete thermal insulation at nominal power

terminated by heat capacity and conductivity of the fuel, heat conductance of the gap between fuel and cladding, etc.) and the mechanical properties of the cladding as a function of temperature. As to the latter, the threshold temperature for clad failure for short-term transients at end-of-life is often assumed to be between 850 and 900 C (2, 3). Regarding the thermal time-response characteristics of the fuel pins, Fig. 2 gives mean values of the clad temperature as a function of time, as calculated for a typical present-day design of an LMFBFR power plant at full power (maximum linear power rating 0.52 kw/cm; coolant temperatures 430 C and 615 C, respectively, at inlet and outlet), for the case of complete thermal insulation over a sector angle of 360 deg of the pin circumference. Table 1 summarizes the times required to reach clad temperatures of 850 and 900 C for the conditions stated in the foregoing, at the inlet, the midplane, and the outlet of the core. A minimum perturbation time of ~0.25 sec is thus required in the upper half of the core in order that failure propagation be potentially possible. Fission-gas release modes resulting in perturbation times <~0.25 sec need thus not be considered. The consequences of this conclusion will be discussed in Section 4 for each of the various fission-gas release modes.

Scaling constitutes an important problem in fission-gas release studies, because experiments become prohibitively costly if full-size heated pin bundles (i.e., pin bundles having up to 271 pins) are used with sodium as coolant, and because it is not validly possible to scale down the amount of fission gas to be released per fuel pin with

Table 1 Typical Minimum Times Required to Reach Clad Failure for the Case of Complete Thermal Insulation of Fuel Pins at Nominal Power (Maximum Linear Power Rating, 0.52 kw/cm; Coolant Temperatures 430 and 615 C, Respectively, at Inlet and Outlet)

Assumed Value for Failure Threshold of Clad Temperature (Short-Period Transients), deg C	Time Period to Reach Clad Failure for Complete Thermal Insulation, at Nominal Power, sec		
	At Core Inlet	At Core Midplane	At Core Outlet
850	0.47	0.26	0.26
900	0.55	0.31	0.31

respect to the size of the bundle, since the local effects of gas release depend strongly on the total amount of gas released. The main problem is that fission-gas release induces coolant flow transients, which are, for most release modes (except for the rapid gas release mode), relatively small in full-size LMFBFR subassemblies but which can be substantial in test sections with small pin-arrays. The approach taken at ANL to overcome the scaling problem is the following: (a) perform tests, aimed at studying fluid-mechanics aspects solely, by means of relatively large pin-arrays using non-metallic fluids to simulate sodium; (b) perform tests, aimed at studying local heat-transfer phenomena, by means of small pin-arrays using sodium as coolant; and (c) perform tests, for those gas-release modes for which the induced flow transients in the test section are not negligible, at steady-state conditions (i.e., with prolonged constant gas-release rates), covering in separate runs the full range of gas-release rates which potentially can lead to failure propagation. This latter mode of testing is conservative and will yield data (e.g., local heat-transfer coefficients) which can be used in subsequent analyses of the actual transient case, with time-dependent gas release rates. A further discussion of this matter is given in Section 4.

Another experimental problem is due to the high cost of xenon, making an extensive test program in which it is used prohibitively costly, particularly if many runs are performed under prolonged steady-state conditions. For some tests, only the gas volume is of importance so that the xenon can be easily replaced by means of, e.g., argon or helium. However, for some aspects of the fission gas release problem (e.g., gas-jet impingement), the gas properties do play a role.

Fig.3 Xenon release rate from a failed fuel pin, $\dot{m}_g(t)$, versus time, for isothermal and adiabatic expansion in the gas plenum with sonic flow in the cladding breach, for various circular breach diameters, for various values of the equivalent discharge coefficient, C_{de} . Xenon release time, t_d , versus $C_{de}P_g(0)$, for isothermal and adiabatic expansion in the gas plenum

For this latter case, the approach taken at ANL to overcome the cost problem has been to run the experiments with argon (being an inert and easily available gas) and to develop a correlation which accounts for the gas properties, allowing to extend the results to the xenon case. Subsequently, a limited number of runs are to be made using xenon, providing, in this way, a method for checking the results already obtained semi-empirically.

4 EXAMINATION OF POTENTIAL FAILURE-PROPAGATION MECHANISMS

The various potential fuel failure propagation mechanisms, as described in Section 2, will now be examined, and results regarding pertinent experiments will be presented.

Gas-Jet Impingement

A jet of fission gas impinging on a fuel pin can potentially cause clad failure through local gas blanketing. In order that gas-jet impingement be able to lead to clad failure, at least two conditions need to be fulfilled:

- 1 The jet should be able to reach the opposite fuel pin and not be deflected excessively by the coolant stream through which it has to penetrate.
- 2 The jet should persist for a long enough time period ($> \sim 0.25$ sec, see Section 3).

A further limiting consideration concerning the potential for failure propagation is due to Judd, who pointed out in an early paper (4) that fuel failure propagation by gas-jet impingement, if at all possible, can be expected to be self-limiting, because the jets would preferentially cause failure of adjacent pins in such a way that the gas coming from subsequently failed pins would be directed mainly toward the pins which have already failed.

The deflection of a gas jet by a transverse flow can be derived from the following empirical relationship due to Ivanov (5, 6):

$$\frac{z}{d_0} = \left(\frac{\rho_c u_c^2}{\rho u^2} \right)^{1.3} \left(\frac{x}{d_0} \right)^3 \quad (1)$$

where x and z denote, respectively, the horizontal and vertical coordinates, d_0 denotes the diameter of the breach, u_c and u denote velocities, respectively, of the coolant and of the gas in the breach, and ρ_c and ρ denote densities, respectively, of the coolant and of the gas at the throat.

For large deflections of the gas jet, the force due to the momentum change on impingement of

the jet fluid will be small and may not displace completely the coolant from the pin, leaving a liquid film in the impingement area. No definite threshold value for clad failure can be given for the angle between the direction of the jet at impingement and the horizontal. However, we shall assume here, primarily for purposes of illustration, that this threshold value is ~ 45 deg.

Starting from equation (1), one finds that, at full coolant velocity (~ 8.5 m/sec) and neglecting the internal gas flow impedance, the angle between the direction of the jet at impingement and the horizontal is > 45 deg for circular clad breaches with diameters < 0.25 mm, for fission-gas pressures < 55 bar (abs.). Furthermore, if the internal flow impedance were accounted for, then the angle of impingement would still be larger for these breach sizes. It may thus be concluded that, under the foregoing assumptions and at full coolant velocity, small breach sizes do not constitute a problem with respect to gas-jet impingement. The second limiting condition is that the gas jet should persist in the sonic regime for a sufficiently long time, since the deflection becomes large shortly after the jet becomes subsonic, resulting in small temperature rises of the cladding of the opposite pin so that cladding failure can no longer ensue.

Fig. 3 gives xenon release rates, $\dot{m}_g(t)$, and release times, t_d , for isothermal and adiabatic expansion in the gas plenum with sonic flow in the breach, for an initial gas plenum pressure, $P_g(0)$, equal to 69 bar (abs.), accounting for the internal gas flow resistance due to the fuel by an equivalent discharge coefficient, C_{de} . This latter coefficient, C_{de} , is a function of fL/D_h , and is near-constant for high values of the Reynolds number at finite relative roughness, as was shown experimentally (7). It is found that the maximum release time occurs for $C_{de}P_g(0)$ equal to $eP_s \{(\gamma+1)/2\}^{\gamma/(\gamma-1)}$, and $P_s \{2\gamma^2/(\gamma+1)\}^{\gamma/(\gamma-1)}$, respectively, for isothermal and adiabatic expansion in the gas plenum, with P_s denoting the local system coolant pressure in the subassembly or test section and e being the base of the natural logarithm. For $P_s = 4$ bar (abs.), one finds that the maximum release time occurs for $C_{de}P_g(0)$ equal to approximately 22 and 25 bar (abs.), respectively, for isothermal and adiabatic expansion in the gas plenum.

In Fig. 3, $t < 0.25$ sec constitutes the safe region for the assumed failure threshold of 850 C for the cladding temperature in the upper half of the core. Thus, the maximum values to be considered for the release rate and the circular breach diameter are those for $t = 0.25$ sec and are found to be, respectively, ~ 4 g/sec and ~ 1.25 mm for

Fig. 4 Schematic representation of the flow regime in the gas impingement region

$C_{de}P_g(0) \approx 22$ bar (abs.). Testing at steady-state conditions (i.e., maintaining a persistent constant gas release rate for each run) up to the above maximum values for the release rate and the circular breach diameter, will result in conservative values for the measured cladding temperature rise in the gas-jet impingement area. By being able to limit the upper value of the fission gas release rate which needs to be considered to ~ 4 g/sec, rather than having to test for release rates as high as ~ 25 g/sec (Fig. 3), it is possible to make considerable cost savings in the experiments, since the test section required can be much smaller for the smaller release rates.

Fig. 4 gives a schematic representation of a gas jet impinging on a fuel pin. It is noted that the impingement area can be subdivided in the gas-cooled region, the spray-cooled region, and the region of the wall jets. Fig. 4 also gives a qualitative representation of the variation of the heat-transfer coefficient in the impingement area.

Hoglund et al. (8) performed gas-jet impingement experiments in a single-channel heated test section with water as coolant. He concluded that spray formation is an important feature of fission gas jet-impingement in LMFBR fuel subassemblies. The entrainment of liquid droplets at the gas-liquid interface of the jet was also confirmed in an excellent experimental study by Bell, Boyce, and Collier (9), in which radial profiles of the void fraction in the gas jet were measured at var-

Fig. 5 Schematic representation of the rectangular single-channel sodium test section

Fig. 6 Axial profiles of wall temperatures during gas-jet impingement for the rectangular single-channel sodium test section

ious axial locations of the jet. According to these latter authors, the central region of the jet with void fraction of 100 percent may extend to the impingement wall for jet lengths comparable to the distances existing between adjacent fuel pins in LMFBR subassemblies and for a relatively wide range of gas plenum pressures. If this were to be the case, then the cooling in the central

Fig.7 Schematic representation of the three-pin sodium test section

region of the impingement area, after dryout has occurred, is solely performed by the gas jet (neglecting tangential heat conduction in the cladding). Under these conditions, the gas temperature may be expected to have a non-negligible effect. If the fission gas were to heat up on its way from the gas plenum to the cladding breach and were to eject at high temperatures (> 850 C), then a localized hot spot could be formed on an adjacent fuel pin which could result in clad failure. This failure mechanism has also been recognized by Goffield and Wattlelet (2).

Gas-jet impingement tests, using a rectangular single-channel heated test section with sodium as coolant, were performed at ANL (10). Fig. 5 gives a schematic representation of the test section used which was heated on one side by means of quartz radiation lamps. The relatively simple geometry of the test section permitted a high degree of instrumentation, some 54 thermocouples allowed to gain rather detailed information regarding the axial temperature profiles existing under the various test conditions. Fig. 6 presents some of the experimental data which were obtained with argon at steady-state conditions (i.e., for persistent and constant gas release rates) and at relatively low heat fluxes ($\leq \sim 30$ w/sq cm). It is noted that for low gas plenum pressures, the jet did not penetrate far enough into the coolant stream to be able to reach the opposite wall. For the higher gas plenum pressure, the jet did impinge on the opposite wall. For this experiment, the gas plenum temperature was ~ 150 C. Adiabatic expansion of the gas could have resulted in a temperature drop of ~ 100 C, so that the gas jet temperature was considerably lower than the coolant temperature (321 C). The dip in the temperature profile in the impingement area can be attributed to this. From Fig. 6, a value of ~ 2.5 cm is obtained for the diameter of the impingement area under the particular test conditions. The wall temperatures downstream of the impingement area also show an increase, which is attributed to the effect of the high void fraction on the conductive component of the heat-transfer coefficient (11). This measured wall temperature increase in the downstream region is not representative of what will happen in an actual LMBFR subassembly, since the geometry for the latter case will be considerably less confining than for the single channel test section, so that the void fraction would be much lower for an actual LMBFR subassembly.

A second series of gas-jet impingement tests with sodium as coolant and argon as gas was performed at ANL making use of a three-pin test section (12). Figs. 7 and 8 give schematic representations of, respectively, the test section and the

TEST-SECTION CROSS-SECTION
AT GAS INJECTION POINT

GAS INJECTION
NEEDLE

THERMOCOUPLE LOCATIONS
AT GAS INJECTION POINT

Fig. 8 Schematic representation of a cross section of the three-pin sodium test section at the gas-injection point. (Thermocouples inside the heaters are numbered 72, 80, 88, 89, 90, 91; thermocouple inside the wire wrap is numbered 74)

cross section at the axial location of the gas-injection point. Electrically uniformly heated pins (O.D., 5.84 mm) (13) were arranged in an equilateral triangular configuration surrounded by a triflute shroud which, in turn, was surrounded by a cylindrical pressure chamber. Wire-spacers (O.D., 1.57 mm), wrapped around the heaters at a pitch of 30.48 cm (12 in.) were used for spacing the heater pins. The wire wraps, which each had seven internal thermocouples spaced axially 7.62 cm (3 in.) apart, were spot-welded onto the heaters at intervals of 5 cm to prevent movement. The heaters were provided with internal thermocouples, spot-welded at the junction onto the inside of the heater sheath, and located axially 15.24 cm (6 in.) downstream from the test section inlet. The angular orientation of the heaters was such that the internal thermocouples faced the central coolant subchannel. Argon, heated to 510 C, was released from a needle (I.D., 0.584 mm) protruding through the test section pressure chamber and the triflute shroud, in between two heaters. The end of the needle was adjusted to be at a distance of ~ 1.42 mm from the heater pin on which impingement took place.

The tests were performed at steady state so as to eliminate the effects of flow and temperature transients. The testing procedure was as follows: (a) gas was released at a predetermined constant rate, (b) the pump head was adjusted so as to maintain constant flow, and (c) temperature readings were taken after reaching new steady-state conditions. From the measured steady-state cladding temperature increase, it is possible to derive the heat-transfer coefficient in the im-

Fig.9 Cladding temperature rise from nominal, ΔT_w , and heat-transfer coefficient in the gas-jet impingement area, h^* , for the three-pin sodium section, as a function of the ratio of gas plenum pressure, P_g , and system coolant pressure, P_s

pingement area, h^* , with respect to the coolant bulk temperature in the central subchannel.

Fig. 9 gives the measured cladding temperature increase as well as the calculated heat-transfer coefficient for three different operating conditions, corresponding approximately to those obtaining at the core-outlet region of a typical LMFBF for, respectively, 100, 75, and 50 percent of nominal power and flow. These data are in good agreement with the data on gas-jet impingement, obtained at lower heat fluxes by means of the previously described rectangular single-channel test section.

Analysis of the gas-jet impingement problem (14, 15) led to the following general expression:

$$Nu = hD_s/k = C_0 (\dot{W}_L D_s / A_j)^m (P_g/P_s)^{-mn}, \quad (2)$$

where P_g and P_s denote, respectively, the gas plenum pressure, and the system coolant pressure at the injection point, A_j denotes the cross-sectional area of the clad breach, D_s denotes the droplet size, $\dot{W}_L$ denotes the liquid entrainment rate, and C_0 is a constant. D_s and $\dot{W}_L$ are obtained from an analysis of the Kelvin-Helmholtz

Fig.10 Correlation for the heat-transfer coefficient for liquid-metal spray cooling in the impingement area

instability at the gas-liquid interface between the gas jet and the coolant (15).

Fig. 10 shows the correlation of the heat-transfer coefficient on the basis of the non-dimensional parameters of equation (2). From Fig. 10, it is seen that the values of the Nusselt number, based on the measured values of the heat-transfer coefficient as presented in Fig. 9 and the droplet size, D_s , as obtained from the analysis described in reference (15), "collapse" approximately around a single mean curve with $C_0 = 0.831 \times 10^{-15}$, $m = 3.44$, $n = 0.193$, obtained by a least square fit. It is clear from Fig. 10 that the coolant velocity, having been varied in the experiments over a wide range, does not have a significant effect on the heat-transfer coefficient.

Experimental and analytical work on gas-jet impingement relative to fission gas release in LMFBF subassemblies is continuing at ANL. Among the parameters that will be further explored are the breach size and the gas type (xenon). This work is expected to further narrow down the uncertainties in the evaluation of gas-jet impingement. The conclusion in the present state of knowledge is that fuel failure propagation due to gas-jet impingement is not very likely and is probably self-limiting.

Flow Starvation

Release of fission gas into an LMFBF fuel

subassembly may potentially cause flow starvation in a limited number of coolant subchannels, due to increased (two-phase) frictional pressure losses and dilution of the coolant. The degree of flow starvation will, all other things being equal, be more serious for small than for large values of the radial dispersion rate of the gas inside the fuel subassembly. Due to the decrease of the coolant mass flow rate in the affected subchannels, the local coolant temperatures will increase, resulting in higher clad temperatures which potentially could exceed the failure threshold. If the gas would not disperse radially, i.e., would remain confined to a few subchannels, and if coolant crossflow would not take place between the subchannels of the subassembly, then the worst conditions (highest coolant and clad temperatures) would occur at the exit of the affected subchannels. However, with radial dispersion of the gas and with coolant crossflow, the worst conditions will, in general, occur at some intermediate position in between the point of gas release and the subassembly outlet.

In order to obtain an insight into the magnitude of the available safety margins against flow starvation, it is useful to first determine qualitatively the allowable local flow reduction in a subchannel. The evaluation is here limited to the case in which the flow starvation extends radially over a limited part of the cross-sectional area of the subassembly, so that the overall subassembly flow does not change much. It is furthermore conservatively assumed that no crossflow takes place along the length of the flow-starved region (i.e., no coolant from surrounding colder regions enters the flow-starved region), and also that no radial heat transfer through conduction from the flow-starved region into the colder surrounding regions occurs. By neglecting, in this way, all radial heat transfer, the radial dimensions of the flow-starved region do not enter the results (provided, as mentioned in the foregoing, that the overall subassembly flow is not changed much). A simple heat balance performed over the affected subchannels with the foregoing conservative assumptions shows that, for an LMFBF with a core height of 80 cm and inlet and outlet temperature of the core region of, respectively, 444 and 604 C, a flow reduction of 90 percent (i.e., the remaining flow is 10 percent of nominal) can extend over an axial distance of ~20 cm and ~12 cm, respectively, at the inlet and outlet of the core region prior to reaching a coolant temperature of 850 C. These values are, of course, only approximate. The exact values will depend on the particular reactor design considered and on the degree of crossflow existing between the subchan-

nels. However, it may be concluded that relatively large safety margins do exist, and that severe flow starvations can be tolerated, even under steady-state conditions, over relatively large axial heights.

Analytical treatment of the problem of flow starvation due to fission gas release has been hampered mainly by the lack of data on both the radial dispersion rate of the gas and the degree of coolant crossflow (16, 17). Experiments were performed at ANL making use of 19-pin (heated and unheated) test sections with wire-wrap spacers (18). In one experiment, high-speed motion pictures were taken which showed that the gas disperses radially relatively fast: Some gas bubbles did spread to the periphery of the cross section of the 19-pin array over a distance of 8 to 14 in. downstream of the point of gas release. This particular experiment used a test section with 18 Lucite pins and one central stainless-steel pin from which the gas was released. Subsequent experiments used a 19-pin heated test section. Thermocouples were mounted inside the test section at various axial locations, allowing measurement of both coolant temperatures (with time constant ~2 msec) and pin wall temperatures in a number of subchannels. Gas was injected through a hole in the central pin. Test runs were made for different hole sizes at various pressure differences across the hole and at various coolant flow velocities. It was found that the rise of the local coolant temperatures was highest for large clad breach sizes at relatively low-pressure differences across the hole. For these latter conditions, a relatively high release rate is attained combined with a low velocity in the gas jet at the breach, so that the initial radial gas dispersion caused by the jet is small. The gas is then initially confined to a limited number of coolant subchannels, causing these subchannels to be more affected than for the case where the jet disperses the gas immediately over a larger number of subchannels. However, even for these worst conditions the maximum coolant temperature increase, extrapolated to full LMFBF power, was found to be less than 100 C under steady-state conditions at gas release rates up to ~1000 cc (STP)/sec. The occurrence of a small pressure drop across the clad breach is most probable if the clad failure occurs in the fuel region of the pins, in which case considerable pressure drop may occur over the length the gas flows inside the fuel pin.

On the basis of the foregoing experimental studies and related analyses performed at ANL (19) and elsewhere (20), it seems justified to conclude that flow starvation due to fission gas release in an LMFBF fuel subassembly is an unlikely mechanism

for fuel failure propagation.

Downstream Gas Blanketing

This second mode in which gas blanketing may occur (the first mode being due to gas-jet impingement) is most probable if the gas is released at a relatively large volumetric rate in combination with a low velocity in the gas jet, i.e., for a large breach size combined with a small pressure drop across the breach. As mentioned earlier, the gas tends, under those conditions, to remain initially confined to a limited number of coolant subchannels, and may, if the volumetric rate of release is large enough, cause gas-blanketing in the immediate vicinity of the gas-release point through displacement of the coolant. Persistence of a coolant film in the affected region would, however, tend to limit the temperature rise of the cladding.

British fuel irradiation experiments (3), performed in the Dounreay Fast Reactor (DFR), indicate the formation of "tear-stains" on some fuel pins and the occurrence of "paired events" (i.e., failure of the cladding of one pin and failure of, or formation of a "tear stain" on, the cladding of an adjacent pin at a location opposite to the failure location of the first pin). Furthermore, cracks in the cladding of fuel pins were found to be surrounded by tear stains. These events may, perhaps, be related to gas blanketing as described in the foregoing. It should be kept in mind, however, that the fact that the coolant flow in the DFR core is downward (rather than upward, as is usually the case for current design LMFBR's) could have influenced the outcome of the foregoing fuel irradiation experiments, inter alia, because of the possibility of gas entrainment from the free surface in the upper coolant plenum and the buoyancy forces on the gas bubbles.

Experiments carried out at ANL using a 19-pin heated test section with water as coolant (18) did show a tendency toward downstream gas blanketing for large breach sizes and low-pressure drops across the breach. These experiments are, however, not conclusive as to whether or not this gas release mode could in an LMFBR subassembly lead to clad failure, since the heat fluxes in the experiments were low (~ 25 w/sq cm), and since the difference in properties of water and sodium are expected to have an important effect. Experiments with sodium as coolant at heat fluxes comparable to those encountered in LMFBR's are necessary and will be performed.

The tentative conclusion at this time is that downstream gas blanketing, if it can lead to clad failure, is expected to be self-limiting and will not lead to extensive and rapid fuel failure propa-

gation.

Upstream Flow Stagnation

Experiments at ANL, using a heated 19-pin test section with water as coolant (18), as well as Japanese experiments (21), indicated coolant temperature increases immediately upstream of the point of gas release. The region affected in the ANL experiment did not extend more than 5 cm upstream, and the temperature rise was small (< 1 C at heat fluxes up to 25 w/sq cm). The Japanese experiments showed somewhat higher temperature increases in the upstream region; it is felt, however, that this is attributable to the confined geometry of the test section used (single pin, annular coolant channel), which probably caused the coolant to stagnate considerably more in the upstream region than would be the case in a 19-pin test section or in an actual LMFBR fuel subassembly.

In the earlier mentioned three-pin sodium experiment, the test section was not instrumented in the region upstream of the gas-release point. (Current technology of heaters for LMFBR fuel pin simulation imposes still severe limitations on the number and location of internal thermocouples.) However, visual observation of the heaters subsequent to termination of the experimental runs did not show any signs that high temperatures had existed in the upstream region.

It is concluded that upstream flow stagnation in an LMFBR subassembly due to fission gas release does not constitute a mechanism for fuel failure propagation.

Gas Bubble Entrapment in Wakes of Flow Obstructions

Experiments at ANL showed a tendency for gas bubbles to become entrapped in the wakes of flow obstructions. The length of time for which the bubbles remain entrapped depends, as would be expected, on the coolant velocity and the degree of turbulence. For relatively low Reynolds' numbers ($Re \leq 20,000$) the bubbles can remain entrapped indefinitely, long after the gas release is terminated. At higher Reynolds' numbers, the bubbles will still collect in large concentrations in the wakes of flow obstructions during the gas release, but will remain entrapped for shorter times after the gas release has been terminated. This phenomenon could have an important effect on the cooling conditions downstream of partial or complete subchannel blockages. It also may have to be considered if grid spacers were to be used in LMFBR fuels. A need for further research seems to be indicated in this area. There appears, however, to be no problem for fuel subassemblies with

Fig. 11 Schematic representation of a fuel subassembly of the Fast Flux Test Facility (FFTF)

wire-wrap spacers.

Transient Flow Reversal Due to Rapid Gas Release

For rapid gas release to occur, it is necessary that the clad breach size be relatively large and that the resistance encountered by the gas flow inside the fuel pins be small. The most likely location for a rapid gas release is thus at or near the gas plenum.

Early work regarding rapid gas release was performed by Hori and Friedland (22) and Kondo et al. (21). Subsequently, experiments regarding coolant flow transients, induced by rapid gas release in a 19-pin test section, were performed at ANL (23). On the basis of these experiments, a mathematical model (23, 24), was developed which treats the gas as a single "slug-type" bubble. Relatively good agreement was found between experimental and calculated values of the displacements of the upper and lower gas-liquid interfaces. The model permits extrapolation to full-size subassemblies, provided the gas-injection rate is sufficiently high to justify treatment as a single "slug-type" bubble.

An example of the application of the model

Fig. 12 Lower and upper gas-liquid interface inside an FFTF fuel subassembly versus time, subsequent to simultaneous rupture of 10 or more fuel pins at the outlet region of the core, assuming zero gas flow resistance

is given using an FFTF fuel subassembly (Fig. 11). Simultaneous rupture in the upper part of the core region of 10 or more fuel pins is considered, neglecting the flow resistance inside the fuel pins as well as that due to the breach. Under these assumptions, the gas-release rate is solely limited by inertial effects due to acceleration of the coolant inside the fuel subassembly and in the lower and upper coolant plenums. The results are given in Fig. 12, where the interrupted and full-line curves represent, respectively, the lower and upper gas-liquid interface as a function of time. It follows from Fig. 12 that simultaneous rupture of up to 30 fuel pins in the upper core region will not lead to a gas-blanketing time exceeding ~ 0.1 sec. This gas-blanketing time is less than the minimum required time of 0.25 sec for cladding failure (Table 1).

It is thus concluded that rapid gas release, even for simultaneous failure of a large number of fuel pins, does not lead to fuel failure propagation due to temperature transients in the cladding.

CONCLUSION

On the basis of the various experiments and analyses performed to date at ANL and elsewhere, it is concluded that extensive and rapid pin-to-pin failure propagation in IMFBR fuel subassemblies, due to thermal transients induced in the cladding of adjacent fuel pins by fission gas release from a limited number of randomly failed fuel pins, is unlikely.

ACKNOWLEDGMENTS

The authors wish to acknowledge their indebtedness to J. F. Marchaterre and B. M. Hoglund, under whose guidance the study program at Argonne National Laboratory on fission gas release in LMFBF fuel subassemblies was started a number of years ago. Thanks are due to H. K. Fauske for his help and constructive criticism in the various phases of the program. E. L. Kimont and R. P. Carter were instrumental in solving many design and testing problems associated with the various test loops and test sections. C. Fiala provided support in the various computer studies. Last, but not least, thanks are due to C. J. Roop and R. D. Baldwin for their valuable assistance in running the experiments and in the data reduction.

The experiments and analyses, performed at ANL and reported on here, were carried out under the auspices of the U. S. Atomic Energy Commission.

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