NUREG-0536

EVALUATION OF SIMULATED-LOCA TESTS THAT PRODUCED LARGE FUEL CLADDING BALLOONING

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ABSTRACT

A description is given of the NRC review and evaluation of simulated-LOCA tests that produced large axially extended ballooning in Zircaloy fuel cladding. Technical summaries are presented on the likelihood of the transient that was used in the tests, the effects of temperature variations on strain localization, and the results of other similar experiments. We have concluded that (a) the large axially extended deformations were an artifact of the experimental technique, (b) current NRC licensing positions are not invalidated by this new information, and (c) no new research programs are needed to study this phenomenon.

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I. INTRODUCTION

In May 1977, representatives from the United Kingdom Nuclear Installations Inspectorate (UKNII)* informed the NRC of a UKNII review of generic safety issues related to the future licensing of PWRs in the UK. Among the issues that were discussed was an implication from an unpublished British report (now published as Ref. 1) that coolability in a PWR core might be lost following a loss-of-coolant accident (LOCA). Core coolability following a postulated LOCA is a requirement in reactor licensing in the US (Ref. 2), and the cooling function in the plant is provided by the emergency core cooling system (ECCS). Such an implication, should it be well founded, would call into question the ECCS analyses approved by the NRC in licensing actions.

The implication about core coolability was based on cladding rupture tests that had resulted in greater deformations than the tests on which US licensing analyses are based. The British tests (Ref. 1) utilized a different experimental technique than the tests on which US licensing calculations are based, and the tests presumed core thermal-hydraulic conditions that heretofore have not been predicted to occur. Therefore, the significance of the coolability implication depends on the relevance of the experimental methods and accident assumptions employed by the investigator, E. D. Hindle.

*Abbreviations are defined in the Appendix.

To discuss the significance of the coolability implication in more detail, several followup meetings were attended by representatives from the NRC, the UKNII, the UKAEA (the agency from which Ref. 1 originated), and German (FRG) research and licensing agencies. The German participation in the discussions was included because Hindle's report had claimed confirming support from research conducted at Karlsruhe.

The first followup meeting was held in June 1977. NRC delegates presented technical arguments as to why the conditions of Hindle's ballooning tests would not be expected in a nuclear reactor (Refs. 3 and 4). Additionally, the German participants disagreed with Hindle's interpretation of their experiments and claimed that, to the contrary, their overall results corroborated the licensing analyses that are approved in the US and in the FRG (Refs. 3 and 4). After those discussions, the NRC reached a tentative conclusion that Hindle's tests were not relevant to licensing analyses, but it agreed to widen the debate and include input from more technical experts.

Subsequently two workshops were held on this subject. The workshops were held in conjunction with the 5th NRC Water Reactor Safety Research Information Meeting on November 11, 1977 and the 4th ASTM Zirconium Conference on June 30, 1978. A total of 25 technical presentations on this subject were made by participants from four countries. Summaries of these presentations (Refs. 5, 6 and 7) indicate widespread agreement that Hindle's observations are not relevant to LOCA analysis. In spite

of the majority opinion, some representatives from the UKAEA (including Hindle) remained unconvinced of the inapplicability of Hindle's tests. Because of the lack of unanimity among principal investigators, we will provide the technical considerations on which our conclusion on the atypicality of Hindle's experiments is founded.

II. SUMMARIES OF TECHNICAL CONSIDERATIONS

1. Effect of Temperature Uniformity on Ballooning

It is well known (Refs. 1, 8-14) that uniform temperature can promote extensive deformation (ballooning) in pressurized Zircaloy tubes, whereas local temperature variations lead to localized ballooning (see Fig. 1). The degree of temperature nonuniformity required for strain localization can be seen in Chapman's work (Refs. 8 and 14). His rod burst experiments have shown that, if cladding temperatures deviate more than ± 5°K over the heated length of tubing, then strain localization will occur. Such sensitivity of the bulge-growth dynamics to small temperature perturbations has been shown analytically for Zircaloy cladding (Ref. 12), and it has also been reported for stainless-steel cladding (Ref. 15). It therefore remains to compare the temperature uniformity that was present in Hindle's tests and that which could occur in actual fuel cladding during a LOCA with the observed value required to induce strain localization (i.e., ± 5°K).

2. Likelihood of a LOCA as Stylized by Hindle

During simulated-LOCA tests, Hindle subjected cladding specimens to stylized transients (see Fig. 2). The stylized transients were designed to simulate simplified pressure and temperature conditions that an average-rated PWR fuel rod might encounter during the post-blowdown

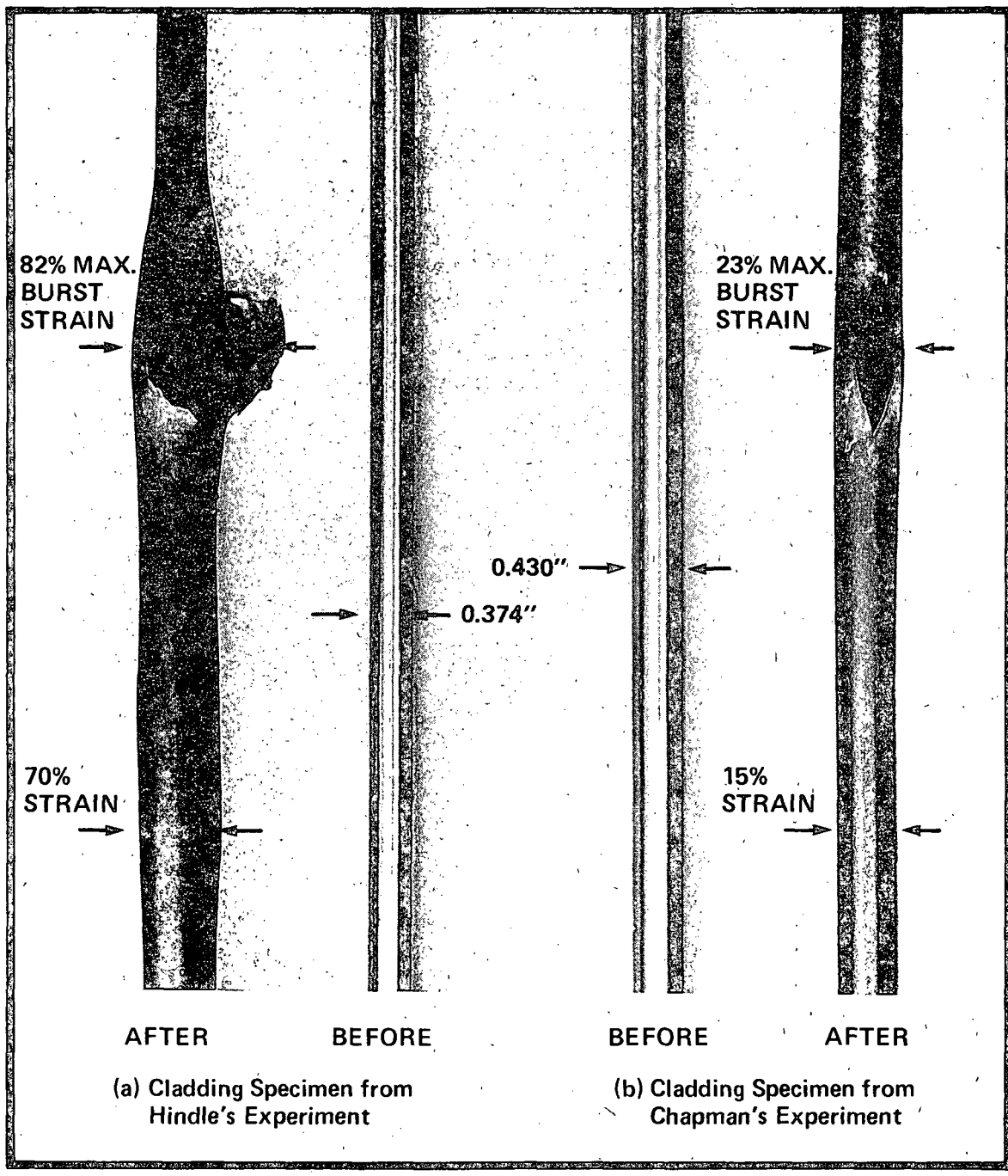


Fig. 1 Typical cladding specimens with (a) large axially extended deformation (see Ref. 1) and (b) smaller localized deformation (see Ref. 14)

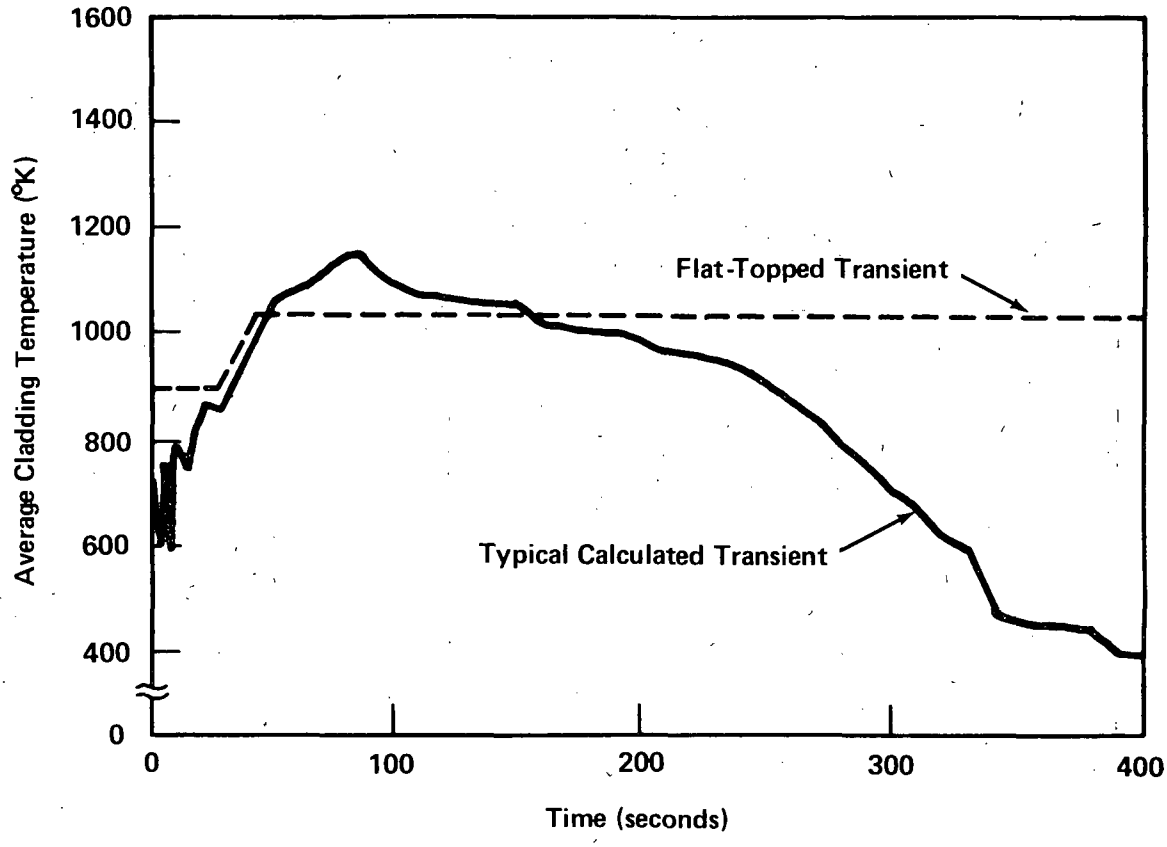


Fig. 2 Comparison of a typical calculated LOCA temperature transient (see Fig. 15.6-28 of Ref. 16) with a stylized "flat-topped" transient used in Hindle's experiment (see Fig. 6 of Ref. 1)

portion of a loss-of-coolant accident. Specifically, single rod specimens were thermally soaked at an elevated temperature of about 875°K, pressurized to a constant level, and then ramped at about 10°K/sec until a set temperature (in the range of 950 to 1100°K) was attained. The specimens were then allowed to isothermally creep-rupture in a quiescent condition during which the mid-wall cladding temperature over the specimen length of interest (370 mm) was maintained within ± 2 to ± 5°K.

We believe that stable thermal-hydraulic reflood conditions that would produce this type of stylized transient are very unlikely. Such "flat-topped" reflood temperature conditions have not been seen in analyses either performed by or reviewed by the NRC.*

A report (Ref. 13) by Rose (also of the same UKAEA Springfields laboratory as Hindle) addressed the likelihood of such "flat-topped" transients leading to axially extended ballooning with rod-to-rod contact. Rose reported on best-estimate calculations with the computer codes FRAP and RELAP and concluded that axially extended rod-to-rod contact on a core-wide basis would not be expected.

Additional insight on the likelihood of stable thermal-hydraulic conditions can be drawn from the Full Length Emergency Cooling Heat Transfer

*Both the stylized transient and the calculated transient illustrated in Fig. 2 were selected to represent a 4-loop Westinghouse PWR with a double-ended, guillotine, cold-leg break.

(FLECHT) tests. For the present consideration we refer only to the low-flooding-rate FLECHT tests (Refs. 17 and 18) since they produced the most stable thermal-hydraulic conditions in the series. There were two aspects in these tests that should have resulted in cladding temperatures more uniform than would be expected in a reactor with nuclear-heated fuel rods: (1) the lack of pellet-to-cladding gaps in the internal-conduction-heated simulators should lead to more uniform temperatures than in fuel rods (this aspect will be discussed further in Section 4), and (2) the FLECHT bundles were exposed to radially uniform temperatures because the rod simulators were operated at equal power ratings. The FLECHT data (Ref. 19) included both axial and radial cladding temperature measurements at the beginning of reflood and at the time that the hot rod attained its maximum temperature. In general, the observed temperature nonuniformities were substantial; the cladding temperatures recorded on the rods surrounding any one rod at a given elevation were never uniform to within 30°K. This observed nonuniformity of the temperatures of the surroundings suggests that the formation of axially extended balloons leading to coplanar blockage would not be possible for in-reactor conditions.

While neither of the studies that was discussed above completely rules out the possibility of a "flat-topped" LOCA as postulated by Hindle, they suggest that the stable thermal-hydraulic conditions that Hindle presumed are unlikely. Since the occurrence of large axially extended ballooning requires the presence of both stable thermal-hydraulic conditions and uniform local fuel rod conditions, and since we have not performed

an extensive thermal-hydraulic evaluation, we will turn our attention to the local fuel rod conditions. The next sections of this report will thus examine local Zircaloy cladding temperature variations, which would occur even if the thermal-hydraulic conditions were stable, and the effect of these temperature variations on ballooning shapes.

3. Effects that Lead to Uniform Cladding Temperatures

In addition to stable thermal-hydraulic conditions, local stabilizing heat-transfer effects are needed in the Zircaloy cladding to produce large balloons. A stabilizing effect that is of major importance in Hindle's work (see Discussion on page 9 in Ref. 1) is an effect that is generally recognized; when deformation begins, the local heat-transfer surface is enlarged and preferential cooling will occur in the deformed region. This locally enhanced cooling, which occurs for all heating methods, reduces the local temperature and hence the rate of local deformation thereby forcing the deformation to occur elsewhere and promoting the growth of large and uniform balloons.

Another feedback effect existed in Hindle's experiments, and this effect is unique to self-resistance heating methods (see Section II-4 for a further discussion of heating methods). The principle of the effect is as follows: the joule heat input per unit length of tubing is not affected by circumferential cladding strains, but it is affected by axial cladding strains. Consequently a short, nonconcentric bulge would

tend to grow azimuthally in a stabilizing manner, but a short, concentric bulge would tend to rupture. If this effect were pronounced, it would thus lead to ballooning instability and localized strains. The relative importance of this effect has not been evaluated rigorously, but it can be concluded from Hindle's work that this effect is overwhelmed by the increased heat-transfer effect that accompanies surface area increases in the ballooning process.

Picklesimer (Ref. 5) describes another heat-transfer effect that can lead to uniform deformation under some test conditions. He concludes that there was a heat-transfer condition in Hindle's alpha-phase* ballooning experiments that gave negative feedback to local ballooning behavior. This negative-feedback condition is said to be peculiar to directly heated Zircaloy tubes that are exposed to uniformly "cold" surroundings (i.e., when the temperature of the surroundings is uniform and more than 200°K colder than the ballooning cladding) as was the case in Hindle's experiments. This hypothesis may also explain differences between Hindle's tests and expected in-reactor results.

Healey, Clay, and Duffey (Ref. 10) have performed ballooning experiments and analyzed the coupled heat-transfer and creep-deformation mechanism in detail. In their directly heated experiments, they confirmed that ballooning stabilization can occur for isothermal creep-rupture at temperatures between 973 and 1073°K, provided that uniform cladding

*The metallurgically-stable structure of Zircaloy at temperatures less than 1098°K.

temperatures are maintained and that the initial tube hoop stresses are restricted to values less than 44, 62, and 72 MPa for the temperatures of 1073, 1023, and 973°K, respectively. For larger stresses, but otherwise identical test conditions, they found that the tubes rupture with a limited amount of circumferential expansion at all axial locations away from the locally bulged rupture location. They are able to predict the deformation response of directly heated Zircaloy tubes without accounting for joule-heating or cold-wall feedback effects mentioned above. It thus appears that Healey, et al., have included the important phenomena in their analysis and that the behavior of Hindle's ballooning tubes is understood. It is relevant to note that Healey, et al., whose work was cited to illustrate a general understanding of the deformation process, concluded that:

> "...it seems unlikely that the required axial and circumferential temperature uniformity needed to promote long balloons would be preserved during in-reactor heating."

In the next sections we will examine different effects that lead to temperature nonuniformities that are of sufficient magnitude to induce strain localization.

4. Effects of the Heating Methods that Lead to Temperature Variations

In addition to variations in fluid heat transfer that may lead to cladding temperature gradients, there are several significant phenomena in the fuel rod that also create local temperature variations in the cladding. Some of these sources of temperature variation are appreciably altered in out-of-reactor tests by the heating method. Other sources are not affected by the heating method and will be discussed separately.

It has been previously claimed (Refs. 10, 14, and 20-24) that the method of heating can have a dominant impact on the resultant cladding rupture strains. For the purpose of this discussion, three methods of heating Zircaloy cladding will be considered:

1. indirect heating of the cladding during a LOCA from the stored heat and decay heat in fuel pellets;

2. indirect heating of the cladding using internal ceramic-coated electrical-conduction heaters, which simulate fuel pellets; and

3. direct self-resistance heating* of the cladding as used in Hindle's tests.

*Also referred to as a joule or skin heating.

Figures 3 and 4 illustrate the heat flow directions (neglecting axial heat flow) induced by these three heating methods during steady-state and temperature-ramped conditions.

For the steady-state condition (Fig. 3), all of the heat that is generated is transported away from the cladding outer surface by the coolant; this, by definition, is the steady state. With nuclear and internal-conduction heating, all of this heat flows across the pellet-to-cladding gap. If we assume that the effective power of the rod at the time of consideration is 5% of its rated full power, then the heat flux across the gap is about 900 W/m. With self-resistance heating, on the other hand, no heat flows across the gap and the rod is isothermal (not merely in a steady state).

For the temperature-ramping condition (Fig. 4), less heat is carried away by the coolant than is generated, and the balance goes into raising the internal energy (i.e., the temperature) of the cladding and pellets (or the pellet simulators). For nuclear and internal-conduction heating, if the effective rod power is again assumed to be 5% of its rated power and if the ramp rate is assumed to be 10°K/sec (both assumptions are representative of possible rod conditions during reflood), then the heat flux across the gap is 65 W/m. For self-resistance heating, the heat flux across the gap is reversed, large (90 W/m for a 10°K/sec ramp rate), and independent of the assumed effective rod power (the heat flux depends, to a first approximation, only on the ramp rate and the heat capacity of the pellet stack).

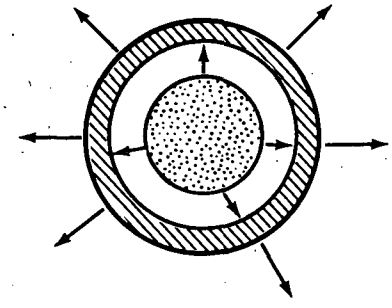
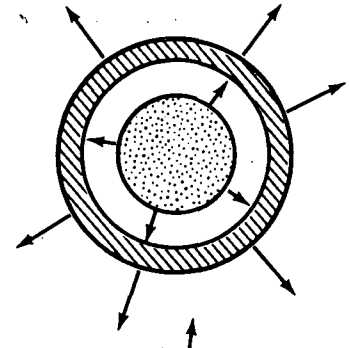
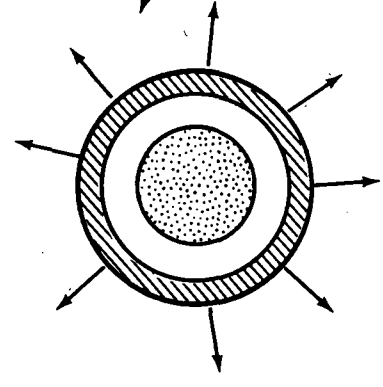
METHOD OF HEATING	RELATIVE TEMPERATURES	RADIAL HEAT FLOW
NUCLEAR	$T_{PELLET} > T_{CLADDING}$	
INTERNAL CONDUCTION	$T_{PELLET} > T_{CLADDING}$ SIMULATOR	
SELF-RESISTANCE	$T_{PELLET} = T_{CLADDING}$ SIMULATOR	

Fig. 3 Radial heat flow during steady state

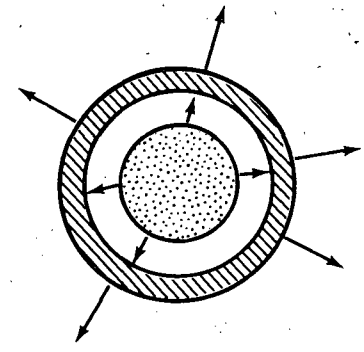
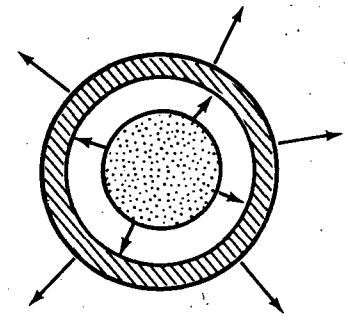
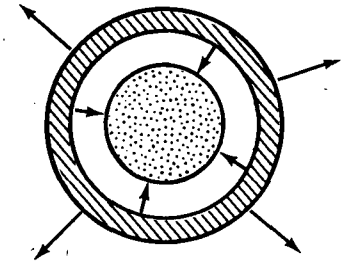
METHOD OF HEATING	RELATIVE TEMPERATURES	RADIAL HEAT FLOW
NUCLEAR	$T_{PELLET} > T_{CLADDING}$	
INTERNAL CONDUCTION	$T_{PELLET} > T_{CLADDING}$ SIMULATOR	
SELF-RESISTANCE	$T_{PELLET} < T_{CLADDING}$ SIMULATOR	

Fig. 4 Radial heat flow during the temperature-ramping phase of transient

Comparing the three different heating methods, fundamental differences are seen between Hindle's method and the nuclear-heated method, whereas the method that uses internal-conduction heaters is similar to the nuclear-heated method.

For ramped conditions, the heat flux with self-resistance heating is reversed but of the same magnitude as the nuclear case. Thus, heat flows across the pellet-to-cladding gap and produces a temperature gradient with all three heating methods. Chance variations in gap conductance introduce temperature variations in the cladding and lead to localized ballooning with all three heating methods.

For steady-state conditions, the heat flux is maximized with the internal-conduction and nuclear-heated methods, but the heat flux is zero with the self-resistance heating method. Pellet-to-cladding gap conductance thus plays no role in the isothermal creep-rupture phase of Hindle's test in determining cladding temperature gradients, and, consequently, nonuniform gap conductance effects are avoided. A major factor that contributes to local temperature variations in nuclear-heated fuel rods has thus been removed from the isothermal phase of Hindle's experiments, and it is only during the isothermal testing that large axially extended balloons are formed.

The circumferentially nonuniform gap conductance mentioned above arises because of eccentrically positioned fuel pellets, pellet cracks and

chips, irregular fission product deposits, and ovalized cladding. Several investigators (Refs. 25 and 26) have modeled the effects of asymmetrically positioned fuel pellets and found that even slight changes in the gap geometry will have a significant impact on fuel and cladding temperatures during normal power operation. In-pile experiments in the Halden Boiling Water Reactor were analyzed (Ref. 27) and found to substantiate this theory by showing that, for normal operation in the HBWR, the presence of eccentrically positioned fuel pellets resulted in circumferential temperature variations on the cladding inner surface of typically 15 to 20°K. This was a large temperature variation considering that all of the coolant was present and had not been lost as postulated in a large-break LOCA.

While the effect of eccentric pellets will be different under LOCA conditions, that has also been shown to be important (Refs. 11 and 28). Burman and Kuchirka (Ref. 28) tested randomly positioned eccentric pellets in out-of-pile ramp tests. Their measurements showed that, for a 14°K/sec transient, circumferential temperature variations of 22°K or more were common at any one axial position on the rod specimens.

It might be argued that hot spots that would be present in the cladding prior to deformation might dissipate during cladding deformation. This argument seems plausible, at first, since deformation at the location of the hot spot might lift the cladding away from the pellet, thus opening up the gap and decreasing the local gap conductance; the reduced gap

conductance would thus impede the flow of heat to the hot spot and it would cool. However, out-of-pile burst tests (Refs. 9, 14, 22, and 29-31), which were conducted in the same temperature region as investigated by Hindle, show that a hot spot on the cladding does not move away from the heat source; rod bowing occurs and moves the hot cladding region closer to the heat source. This bowing effect is attributable to the inherent strain anisotropy of Zircaloy in the alpha phase, so this effect would also be present in fuel rod cladding during a LOCA that induced ballooning in the alpha-phase temperature range.

It thus seems clear from Hindle's tests and the work of others that, in the presence of a heat flux, chance variations in gap conductance produce azimuthal temperature variations that are large enough to cause ballooning strain localization in Zircaloy clad fuel rods.

5. Other Effects that Lead to Cladding Temperature Variations

Another factor that leads to local temperature variations in fuel rod cladding is the randomly occurring variation (within manufacturer's specified tolerances) in pellet dimensions, density, and enrichment. Lowe (Ref. 32) investigated the effect of such permissible variations on pellet surface temperatures during a LOCA. The study utilized the Babcock & Wilcox LOCA fuel performance code SWEL-1 (Ref. 33), which is a combined analytical-numerical technique for evaluating the distribution of cladding failures during a LOCA. Two LOCA transients were investigated

for which the peak pellet surface temperatures were calculated to be 1060 and 1340°K. The results showed that temperature variations due to the combined contributions of randomly distributed variations in these three manufacturing parameters were normally ± 14 and ± 25°K, respectively. In light of the coupling between pellet surface temperatures and cladding temperatures, it is likely that such variations would be sufficient to cause cladding strain localization. (Lowe's study was performed prior to the current interest in cladding temperature variations and estimates of cladding temperatures were not included.)

A similar sensitivity study has also been reported by the Nuclear Power Company, Limited (Ref. 34). That study employed a transient fuel performance code called MABEL-1 (Ref. 35) which was developed by the UKAEA and applied by NPC to investigate the likelihood of large in-pile ballooning. It was stressed in the report (Ref. 34) that many reactor phenomena* were not represented in MABEL-1 and, therefore, the quantitative predictions should be viewed with some degree of caution. Nevertheless, analysis of the temperature variation sensitivity to local power perturbations resulted in the following comments.

*Such as (a) cladding stress- or strain-to-failure criterion, (b) cladding surface radiation, (c) grid-to-cladding interactions, (d) eccentrically positioned pellets, and (e) nonuniform volumetric heat generation.

"As might be expected the results are very sensitive to the level of perturbation. For instance, if a perturbation of somewhat greater then 3% could be justified then it appears that there would be no incidence of "long balloons" at significant strain (above 30%). Conversely, if only a 1% perturbation could be justified it is predicted that there is a possibility of "long balloons" of 50% strain occurring.

"It may be reiterated that in this work, attention has been limited to local rating perturbations mainly because of current code limitations. There is no implication that many other perturbations are not equally possible."

One might expect that these predicted magnitudes of perturbation (i.e., 1 and 3%) will decrease when refinements (i.e., inclusion of additional phenomenological effects) are made to future versions of the MABEL code. Therefore, in light of typical PWR pellet-to-pellet power variations (the minimum occurs on the flux-flattened regions between grids) of around 2%, the current MABEL code predictions suggest that Hindle ballooning will not be possible under in-pile conditions.

Finally, there is a source of temperature variation that has not been widely discussed, and this source consists of "cold" objects in the core. Core shrouds, channel boxes, water rods, poison rods, thimbles, guide tubes, source tubes, and instrument tubes all have relatively cool

surfaces compared with that of the fuel rods. The presence of these neighbors will cause additional circumferential cladding temperature variations and promote the localization of ballooning strain.

6. Results of Other Ballooning Experiments

Many Zircaloy rod burst experiments other than Hindle's have been conducted, and most of these are publicly available (Refs. 8-11, 14, 21-24, 28-31, and 36-50). In-reactor rod burst experiments have been performed in three test reactors: TREAT (Refs. 44-46), PBF (Ref. 47), and FR-2 (Refs. 48-50). While these tests do not afford the best comparison with Hindle's work, they may be most representative of fuel rod behavior during a LOCA since they include realistic thermal-hydraulic and local fuel rod conditions.

Two experiments (FRF-1 and FRF-2) were performed in the TREAT reactor to determine fuel rod failure characteristics under LOCA conditions (Refs. 44-46). Each experiment was comprised of a seven-rod bundle in which the center rod of each bundle had been previously irradiated. Cladding ruptures occurred in flowing steam at ramp rates of 25 to 44°K/sec with burst temperatures ranging from 1015 to 1590°K at engineering burst stresses of 16.3 to 4.9 MPa. The resultant rod swelling was found to be localized (one or two lobes per rod) with the maximum circumferential burst strains varying between 26 and 44%. There were no rod deformations similar to those obtained in Hindle's tests.

One experiment has been conducted in the PBF reactor that resulted in cladding swelling (Ref. 47). In this experiment, four rods were subjected to a power-coolant-mismatch transient during which sustained operation in a film boiling regime occurred. One of the test rods, which had a large degree of prepressurization, ballooned and ruptured at 1100°K at an engineering burst stress of 37.6 MPa. Post-irradiation examination showed that this rod had incurred a centralized region of swelling with a maximum circumferential burst strain of 25%. Again, as in the previous in-pile experiments, the rod deformation was not similar to that observed in Hindle's tests.

A total of 18 single-rod burst tests have been conducted to date in the DK loop facility of the German research reactor FR-2 (Refs. 48-50). These experiments are being performed to investigate the influence of a nuclear environment on the mechanisms of fuel rod failure during a LOCA and to compare with electrically heated burst tests performed to study a LOCA. Cladding conditions are designed to simulate the pressure and temperature histories during the low-pressure phase of a LOCA. The test matrix includes both fresh and irradiated specimens. Cladding ruptures have been induced in stagnant steam at ramp rates of 6 to 10°K/sec with burst temperatures of 1080 to 1290°K at engineering burst stresses of 60.8 to 17.3 MPa. Measured rod swelling was found to be localized with the maximum circumferential burst strains ranging between 25 and 64%. There were no deformations similar to those observed in Hindle's tests.

Many out-of-reactor tests have also been performed, and recent experimental procedures tend to be more representative of in-pile behavior than those reported earlier. Chapman (Refs. 8, 14 and 29), Erbacher (Refs. 9, 30 and 31), Fiveland (Ref. 23), and Bauer (Ref. 36) have all used the more typical internal heating technique. Other important test parameters, however, have differed significantly (e.g., isothermal vs. transient temperatures, steam and water vs. argon and vacuum atmospheres, unconstrained vs. completely restrained specimens, BWR vs. PWR cladding geometries, unirradiated vs. irradiated cladding, and single vs. multiple rod geometries). Observations of all of these experimenters of the cladding conditions at rupture (i.e., temperature, strain, and stress) are consistent; differences in their observations are understandable and attributable to variations in test parameters. None of these experimenters observed large axially extended deformation of the magnitude that was seen by Hindle.

Finally and of particular significance to the deformation responses of different heating techniques are the results from recent low-heating rate and creep-rupture tests reported by Chapman, et al., (Ref. 14). Their creep-rupture tests were designed to replicate Hindle's flat-topped LOCA-simulation tests, but heating was provided by internal heaters rather than direct-electrical heating. They found that (1) local temperature variations control the deformation behavior in low-heating-rate and creep-rupture tests much the same as in their 28°K/sec transient tests (Ref. 29), (2) local strain was more uniform and somewhat greater in the

low-heating rate and creep-rupture tests than in the transient tests, (3) no large differences occurred in the burst strains for any of their tests, and (4) no large balloons of the kind seen by Hindle were produced.*

*Chapman's cladding specimen labeled (b) in Fig. 1 was chosen for illustration because its rupture conditions were most similar to Hindle's specimen labeled (a). Specimen (a) ruptured after 90 seconds at 973°K in stagnant steam. Specimen (b) ruptured after 103 seconds at 1035°K in gently flowing steam.

III. CONCLUSIONS

We have reviewed the experimental work of an investigator who suggested that large axially extended cladding strains might occur in some LOCA transients. The extended deformations accompanied by large diametral strains that he observed in laboratory tests are substantially greater than those assumed in safety analyses for power reactors licensed in the US. Such deformations, if they existed during a LOCA, could threaten the coolability of the core; we have concluded, however, that such large axially extended deformations will not occur.

Our conclusion is based on a general understanding of the phenomenon. Large axially extended deformations can be achieved with pressurized Zircaloy cladding if the cladding temperature is very uniform. This fact is demonstrated in Hindle's tests and was known previously. Uniform cladding temperatures can exist only if core thermal-hydraulic conditions are stable, and then only if local fuel rod conditions are suitable.

The existence of stable thermal-hydraulic conditions during a LOCA is, at most, doubtful. Furthermore, we have examined local fuel rod conditions carefully and concluded that Hindle's method of testing was ideal for achieving very uniform local temperatures, but it differed in fundamental ways from the heating mode that would occur in nuclear-heated fuel rods during a LOCA. Several arguments have been presented that suggest that such uniform temperatures cannot occur in-reactor. The few in-reactor tests that have been performed fail to exhibit large ballooning deformations.

And, finally, tests have been performed using heating methods that simulate the in-reactor mode much more closely than Hindle's direct-electrical heating technique, and these tests do not show such large deformations even for controlled "flat-topped" transient conditions.

It is our conclusion that (a) the large axially extended deformations observed by Hindle were an artifact of the experimental technique, (b) current NRC licensing positions are not invalidated by this new information, and (c) no new research programs are needed to study this phenomenon. The NRC has made small changes in on-going research programs to ensure their accountability for the sensitivity to the effects of temperature variation.

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V. APPENDIX (List of Abbreviations)

BWR	boiling water reactor
CEGB	Central Electricity Generating Board
ECCS	Emergency Core Cooling System
FLECHT	Full Length Emergency Cooling Heat Transfer
FR-2	Forschungszentrum Reaktor-2
FRAP-T	Fuel Rod Analysis Program-Transient
FRF	Fuel Rod Failure experiment
FRG	Federal Republic of Germany
HBWR	Halden Boiling Water Reactor
LOCA	Loss-of-Coolant Accident
NBS	National Bureau of Standards
NPC	Nuclear Power Company
NRC	Nuclear Regulatory Commission
PBF	Power Burst Facility
PWR	pressurized water reactor
RELAP	Reactor Leak and Power Safety Excursion
SNPDL	Springfields Nuclear Power Development Laboratories
TREAT	Transient Reactor Test
UKAEA	United Kingdom Atomic Energy Authority
UKNII	United Kingdom Nuclear Installations Inspectorate

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A description is given of the NRC review and evaluation of simulated-LOCA tests that produced large axially extended ballooning in Zircaloy fuel cladding. Technical summaries are presented on the likelihood of the transient that was used in the tests, the effects of temperature variations on strain localization, and the results of other similar experiments. We have concluded that (a) the large axially extended deformations were an artifact of the experimental technique, (b) current NRC licensing positions are not invalidated by this new information, and (c) no new research programs are needed to study this phenomenon.

17. KEY WORDS AND DOCUMENT ANALYSIS
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