The Impact of Pellet-Cladding Interaction on Fuel Integrity - A Status Report -

February 1978

**by
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**Prepared for the
U.S. Nuclear Regulatory Commission**

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THE IMPACT OF PELLET-CLADDING INTERACTION
ON FUEL INTEGRITY
- A STATUS REPORT -

Prepared for
Core Performance Branch
Division of System Safety
U.S. Nuclear Regulatory Commission

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INTRODUCTION

There appears to be a general consensus that pellet/cladding interaction (PCI) is one of the principal limitations on reactor core power cycling. The economic importance of PCI, as fuel service limiting, is evidenced by the fact that all USLWR fuel suppliers impose some operating restrictions and/or recommendations on rates and magnitudes of power increases for both startup and demand load response modes of operation. In contrast to the economic aspects of PCI, there does not appear to be a similar attitude with regard to the safety significance of PCI in operating USLWRs. The apparent incidence of PCI failures accompanying a transient increase in core/rod power, however, provides a basis for some system safety concern and has prompted the following two fundamental questions:

- Will the existence of accumulated damage (e.g., incipient cracks in the cladding ID) or PCI fuel rod failures alter the course of transients and/or accidents so that these events are different than described in the safety analysis reports?
- Are radioactivity releases increased when PCI fuel rod failures are included in the safety analysis for abnormal operating transients (AOTs), anticipated transient without scram (ATWS) and/or design basis accidents (DBAs)?

The predominant role of the economics of PCI failures has led to the individual development, by USLWR fuel suppliers, of specific operating recommendations for minimization of PCI fuel failures under more or less normal operation. These operating recommendations do not generally apply

to hypothetical accidents and, therefore, do not appear to be adequate or appropriate for evaluating the PCI failure probabilities in AOTs, ATWS, and/or DBAs.

An assessment of the applicability of the AECL FUELOGRAM to PCI failures in USLWR fuel is currently well under way. The results of this assessment to date suggest that the FUELOGRAM is at best uniquely applicable to the on-line re-fueling transients in CANDU plants and not applicable generally to transients in USLWR plants without significant modifications. Furthermore, the statistical interrelationship between fuel assembly and fuel rod failure in the FUELOGRAM model appears to offer little promise for estimating the number of fuel rod failures in an AOT, ATWS and/or DBA. Preliminary efforts, however, suggest that a usable PCI failure model, using the operating parameters, the pre- and/or post-transient rod power, the transient increase in rod power and burnup can be developed. Unless there is some as yet unknown failure interaction between fuel rods in a single fuel assembly, it is expected that an adequate model will provide the methodology for estimating fuel rod failure as readily as fuel assembly failure. If not, there may be some basis to question whether such a model does indeed describe the PCI fuel rod failure phenomenon.

PCI FAILURE CHARACTERISTICS AND DETECTION

The substantial number of observations of experimental and operational fuel failures accompanying a ramp increase in fuel rod specific power provides the basis for categorizing these failures as PCI failures. It is generally acknowledged that a PCI failure is signaled by a relatively abrupt and distinct increase in the radioactivity in the primary coolant and which tends generally to occur within a few minutes to a few hours subsequent to the transient increase in power. Test reactor experiments, on-line refuelling operational experience in CANDU plants and operational experience in USLWR plants provide significant substantiation for the use of the abrupt and distinct increase in the primary coolant

radioactivity as a fuel failure indicator (See for example NUREG 0401, "Fuel Failure Detection in Operating Reactors," by B. L. Siegel and H. H. Hagen,⁽¹⁾ December 1977). There are, however, some post irradiation examination (PIE) observations which suggest that all PCI fuel rod failures may not be accompanied by a primary coolant radioactivity signal within a few hours subsequent to the transient in which the failure occurred. In USLWR plants, there are operating transients that seem to provide a low probability of causing PCI fuel rod failures, but which, nevertheless, are accompanied by a relatively abrupt and distinct increase in primary coolant radioactivity. This phenomenon is generally referred to as "iodine spiking" and tends to be observed during a slow approach to power from a "cold" shutdown, a transient decrease in core power or even shutdown. In a relatively short time following a slow approach to power from a "cold" shutdown, the "iodine spiking" tends to diminish to near previous radioactivity levels. There can be little doubt but that the "iodine spiking" is attributable to a breach in the cladding of one or more fuel rods and the thermal disequilibrium within the fuel pellet. As yet, there are no direct PIE observations, from USLWR fuel, to show whether the "leaker" resulted from a PCI or other cladding failure mechanism(s) during this transient or during some prior operating period. There is some speculation that the "iodine spiking" accompanying a slow rise to power following a cold shutdown may be attributable to in-leakage of water during shutdown and which is forced, by phase change expansions from the fuel rod, during the ascent to power. Such a hypothetical mechanism is not consistent with "iodine spiking" accompanying a transient decrease in power. There are, however, very limited experimental observations which suggest that gaseous fission products are released from the fuel during any transient power change (i.e., thermal disequilibrium in the fuel pellet) and very little release during steady state operation (see, for example, T. B. Burley and M. D. Freshley,⁽²⁾ "Internal Gas Pressure Behavior in Mixed Oxide Fuel Rods During Irradiation," Nuclear Applications and Technology, Vol. 9, pp. 233-241, 1970). There are very limited PIE observations which suggest that there are some PCI failures

which are not readily identified by visual examination and the usual (i.e., sipping) methods for failure identification, which are dependent upon the out-leakage of radioactive fission product gases without internal pressurization of the suspected fuel rod. There is some acknowledgment that in-core "sipping" may only identify up to about 80% of the fuel assemblies with failed and "leaker" rods. Based on some very limited PIE observations with CANDU fuels, there may well be reason to suspect that "sipping" methods may not identify all failed assemblies in storage basin examinations. In summary, there now appears to be a reasonable basis to suspect that all PCI failures:

- do not "leak off" gaseous fission products in at least a sufficient volume to signal their occurrence through a relatively abrupt and distinct increase in primary coolant radioactivity,
- do not exhibit visual evidence of failure or "leak-off" gaseous fission products without internal pressurization of the fuel rod, or
- that all fuel rod failures, by PCI or other mechanisms, are identified by current detection methods.

The foregoing, together with the more direct PIE observations of PCI failures, provides some basis to suggest that PCI failures in both LWRs and HWRs may be divisible into two fairly distinct categories with more or less the following general characteristics:

- A "pinhole" breach in the cladding which generally appears to be devoid of any significant local deformation (e.g., bulging). Strain (e.g., X or V band) markings may, however, be visible on the OD of the cladding.
- An "axial split" in the cladding which generally appears to be devoid of any significant local deformation, ranges upward in length from less than about 1/2 pellet length and may exhibit some "brittle fracture" characteristics.

Very few "pinhole" failures (e.g., Peach Bottom 8x8) have been observed in PIE of USLWR fuels. It may, therefore, be argued that a pinhole is a miniaxial split or that all PCI failures begin as a pinhole and enlarge during the remaining course of the transient. It is also conceivable that the pinhole may tend to be associated with the less severe ramp increases to rod powers which barely exceed the PCI failure threshold while the more catastrophic axial-split failure may tend to be associated with the most severe transient. The relative proportion of pinhole and axial split failures in light and heavy water reactors (LWR, HWR) fuels is currently unknown. There currently are no identifiable fuel rod design or reactor operating parameters which can be uniquely associated with either the pinhole or axial split type failures. Within the current state-of-the art, there appear to be no PIE or other observations to definitively suggest any link between failure types, as defined here, and

- specific fuel design parameters (e.g., cladding, fuel density, gap, etc.)
- specific operation parameters (e.g., P , ΔP , Bu , etc.)
- or the relative incidence of pinhole versus axial split failures.

The axial split in the cladding, frequently, but not always, coincides with a radial crack in the adjacent fuel pellet. In some instances, there appears to be some local clad wall thinning suggesting localized straining in the cladding. The axial split fracture surface morphology has been rather well characterized. By contrast, however, there are virtually no comparable PIE data and observations for pinhole failures. EPRI⁽³⁾ currently is sponsoring some PIE effort on "incipient" cracks in spent fuel rod cladding which, will provide some new information on PCI failures. Considering the safety concerns stated earlier, it can be concluded that the pinhole failure, as it has been defined, is equally as important as the axial split.

Virtually all PIE of PCI failures have been performed on fuel rods in which the failure was an axial split. One presumes that the reason for

this is that the axial split is generally more visible and therefore more readily located and identified in poolside examinations. Furthermore, it has only recently been generally acknowledged that pinhole failures are also very probably attributable to PCI.

PIE⁽⁴⁻¹⁴⁾ frequently shows the presence of a few-too-many part-through-wall axial cracks which appear to have started at or near the ID surface of the cladding. In most, but not all, instances, the cracks in the cladding are found to be coincident with a radial crack in the adjacent fuel pellet. In some cases, PIE shows the mid-length of the axial split to be roughly coincident with an adjacent pellet-pellet interface. Such observations provide some basis to presume that the axial split initiated at the pellet-pellet interface particularly if some clad "ridging" had also occurred at the same pellet-pellet interface. It is uncertain whether the clad ridging is evidence of more intense, localized thermal-mechanical interaction or whether the stress state and/or pre-strain in the cladding at a pre-existing ridge may have had a significant adverse effect on the failure threshold(s) for the cladding.

The PIE failure-fracture surface morphology of axial splits in fuel rods is reported to be generally similar to that in unirradiated zircaloy coupons (e.g., split rings from fuel clad tubing) which were statically loaded near or beyond yield in an iodine vapor environment at nominal fuel cladding temperatures.^(15,16,17) In these coupons, the failure-fracture mode tends to be intergranular and the failure-fracture surface exhibits "river patterns," "fluting" and localized "cleavage." In some cases, PIE reports suggest that the initial cracking at or near the I.D. surface of the cladding is transgranular and as the crack grows radially through the cladding wall, there is a change to the intergranular cracking mode.

Whether this failure-fracture behavior is characteristic of all axial split PCI failures or is influenced by the power ramping rate and/or magnitude of the power ramp is currently unknown. An EPRI⁽³⁾ sponsored PIE project is now under way and will examine the crack surface morphology of part-through-wall cracks in USLWR fuel designs. One expects that these

studies may provide some data which may relate the axial split failure-fracture mode(s) to specific fuel rod design and/or operating parameters.

The PIE reports regarding failure-fracture modes and fracture surface morphology and the "time delay" observed in CANDU⁽¹⁸⁾ PCI failures suggests that high strain rate failures may not exist in fuels subjected to power ramping. Considering the high strain-strain rate behavior in out-of-flux "expanding mandrel" tests, the absence of a high strain rate PCI fuel failure-fracture mode may be attributed to an inability to attain sufficiently large cladding strains during the ramp increase in rod power. Whether this is due to limited radial displacement in the fuel during the ramp increase in rod power and/or to an effect of irradiation on the "dynamic" behavior of the cladding is not yet known.

There are very few published reports of pinhole PCI failures in either experimental or commercial production fuels. Nevertheless, the occurrence of pinhole PCI fuel failures appears to be generally acknowledged and is beginning to be considered as the origin of at least some of the "iodine spiking" associated with some core power changes in USLWRs. There appear to be very few, if any, PIE observations relating to the failure-fracture mode and morphology of pinhole type PCI fuel rod failures.

Out-of-flux iodine stress corrosion cracking (I_2 SCC) has been studied fairly extensively by CRNL/AECL, ^(15,16,17) WAPD, ^(19,20) SRI/EPRI⁽²¹⁾ and others. WAPD and SRI/EPRI did I_2 SCC tests on zircaloy tubing stressed by internal pressurization with iodine-noble gas mixtures at temperatures prototypic of fuel cladding temperatures. In these I_2 SCC tests, the hoop stresses generally ranged from about the proportional limit to about the 0.2% offset yield strength. In all tests, the stored energy within the test specimen was minimized by limiting the volume of the compressed pressurizing gas mixture within the test specimen. In both the WAPD and SRI/EPRI I_2 SCC tests, the tubular test specimens were fully prototypic of commercial production zircaloy fuel clad tubing. In the WAPD experiments, the test specimens were prototypic of fuel clad tubing in the "as received"

condition. In the SRI/EPRI experiments, the tubular test specimens were "pre-defected" mechanically to produce a sharp V-like notch in the ID surface. The radial depth of this V-like notch was roughly 0.01 in. The length of the V-like notch was at least ten or more times the depth. In all of these I_2 SCC experiments, wherein the tubular specimen was stressed by internal pressurization, the failure-fracture was a pinhole. In the SRI/EPRI experiments, the pinhole coincided with the V-like notch defect. In the WAPD experiments, the pinhole was reported to coincide with ID surface pits with depths to 0.003 in. or some other minor surface scratches. Circumferential strains in the failed test specimens were measured only in the WAPD experiments. The measured circumferential strains ranged from about 1% to 3% and appeared generally to be uniform. It appears significant to note that there were no reports, in either the WAPD or EPRI/SRI experiments, of any localized deformation at the pinhole or any region of the tubular test specimens. The absence of any localized deformation is generally ascribed to the minimization of stored energy within the test specimen. It further appears significant to note that stress and temperatures, employed in these I_2 SCC experiments, can be expected to cause significant thermally activated creep. The uniform circumferential strains obtained from failed test specimens in the WAPD I_2 SCC experiments suggest that significant thermally activated creep did indeed occur. Reinoehl and Boyd⁽²²⁾ and Wearmouth et al.,⁽²³⁾ based on halogen stress corrosion cracking investigations, suggest that strain and strain rate may be key parameters in any stress corrosion cracking behavior in metal alloys. The role of creep strains and/or creep rates in either the WAPD or SRI/EPRI I_2 SCC experiments is as yet uncertain.

Pinhole failures, without significant localized deformation (e.g., bulging at the pinhole) have also been observed in room temperature burst tests done by internal pressurization on "as fabricated" zircaloy tubing. In these instances, the pinhole failures were associated with a fabrication defect in the tubing. By comparison, it appears that only the SRI/EPRI I_2 SCC test specimens contained a defect of sufficiently significant

dimensions to act as a stress riser and promote failure. The WAPD investigators contend that the shallow (≤ 0.003 in.) ID surface pits and scratches were the site of the I_2 SCC pinhole failure-fracture. However, if ID surface imperfections, shallow pits and superficial scratches indeed act as stress risers and promote pinhole failure-fracture, there should be some evidence of I_2 SCC action at several pits, etc., or even more than one pinhole failure-fracture. Based on the available data, the effect of ID surface imperfections, pits, scratches, etc., is as yet uncertain. One must acknowledge that at least a few nonductile (i.e., localized bulging) pinhole failure-fractures may be attributed to undetected tube fabrication defects.

FUEL DESIGN CONSIDERATIONS

As a starting point, it is worthwhile to review briefly some of the fuel design parameters for CANDU^(6,24) and USLWR^(25,26) fuels. Table 1 shows some of the fuel design parameters typical of those fuels for which much of the PCI fuel failure experience applies.

While there are basic dimensional differences between fuel designs, there does not appear to be any obvious link between these design parameters and PCI failure probability. There are several design parameters that have been identified as possible contributors toward influencing the PCI failure probability. Those parameters that have been most frequently identified include:

- fuel cladding gap
- fuel pellet density
- fuel pellet geometrical designs which minimize and/or eliminate cladding ridging at pellet-pellet interfaces (e.g., chamfering)
- fuel pellet/cladding interfacial lubricants which minimize and/or eliminate cladding strain localization
- cladding thickness.

TABLE 1. Typical Fuel Design Parameters

Parameter	CANDU	BWR	PWR
Cladding			
Material	Zry	Zry	Zry
Outside diameter	~0.60"	~0.56"	~0.42"
Wall thickness	~0.015"	~0.037"	~0.024"
R/t	~20	~7	~9
Fuel Pellet			
Material	UO ₂	UO ₂	UO ₂
Density	~95%	~95%	~95%
Diameters	~0.56"	~0.48"	~0.36"
Fuel Rod			
Pellet-cladding gap	~0.006"	~0.009"	~0.007"
Active fuel length	~20"	144"	144"

The above list is not intended to be exhaustive. The effects of the above fuel rod design parameters have only been investigated in exploratory experiments with the exception of pellet-cladding interfacial lubricants (e.g., CANLUB). AECL⁽²⁷⁾ is currently using CANLUB--a graphite pellet/cladding interfacial lubricant--on a production scale with significantly beneficial results. CANLUB, however, is no panacea for PCI failures and, at best, appears to raise the PCI failure threshold(s) by a modest amount(s).

The fuel pellet-to-cladding gap appears to be of significance only during the early life of the fuel. With continued burnup, both cladding creepdown, fuel expansion and fuel pellet cracking operate to functionally eliminate the mechanical effects of the as-fabricated fuel-cladding gap. This appears to occur from within a very few days of effective full power operation to perhaps as much as 1 to 1-1/2 GWd/MTM burnup exposure. It may be more than coincidence that, within the range of about 1 to 1-1/2 GWd/MTM burnup, there is a sufficient accumulation of fission products

(e.g., iodine) within the fuel pellet and "radiation hardening" of the cladding to "set-the-stage" for iodine stress corrosion cracking (I_2 SCC) of the cladding. These considerations, substantiated by laboratory experiments, suggest that PCI failures, at very low burnup (i.e., ≤ 1 GWd/MTM), are very probably attributable to fuel pellet/cladding mechanical interaction only whereas at higher burnup the PCI failures appear to be attributable to some combination of fission product/cladding chemical and fuel pellet/cladding mechanical interactions.

It has become more or less normal operating procedure to "pre-condition" fuel at the beginning of each operating campaign. In essence, the "pre-conditioning" consists of a slow rise to a predetermined power shape such that subsequent operations do not exceed the established pre-conditioned rod power "envelope." It is generally presumed that pre-conditioning provides in a mechanical sense some fuel pellet to cladding gap tolerance that would otherwise result in "hard" contact between the fuel pellet and cladding and thereby promote mechanical interaction at smaller ramp increases in fuel rod power. While there appears to be some general beneficial effect of pre-conditioning, one must still question whether the beneficial effect is indeed due to the pellet-to-cladding gap effects per se or additional skill and care to avoid substantial ramp increases in fuel rod power. Until shown otherwise, the pre-conditioning will probably need to be taken into account in any PCI fuel failure model(s) based on the operating parameters of pre- and/or post-transient, the ramp increase in rod power, and burnup.

It has been postulated that fuel density and the densification phenomenon may have played a significant role in the Maine Yankee PCI failures.^(14,15) There appear to be some exploratory observations which suggest that lower density fuel pellets cause lesser cladding strains, particularly with regard to ridging at pellet-pellet interfaces. These observations would appear to be somewhat contradictory to the postulated densification role in the Maine Yankee PCI failures. It may be significant to note that other instances of more obvious densification (e.g., R. E. Ginna, etc.) were apparently unaccompanied by any significant incidence of PCI failures. Based on

these observations, it is, as yet, uncertain what, if any, role fuel density plays in PCI failures.

The extent of fuel clad ridging at pellet/pellet interfaces is generally attributed to the pellet length to diameter ratio (L/D) and/or end dishing fuel pellet design parameters. PIE reports for axial split PCI failures generally imply that failure initiated in the "ridged" region of the cladding. These PIE observations have often served as a basis to conclude that PCI failures may be linked to the L/D and/or end "dishing" fuel pellet design parameters. Based on Maine Yankee PCI failures, Cubicciotti et al.⁽²⁹⁾ showed the role of radial pellet cracking in the release, transport and localized deposition of potentially detrimental fission products (e.g., I_2 , Cs, Cd, Te, etc.) on the ID surface of the cladding. In more recent exploratory experiments with LMFBR fuel rods, Wilson et al.⁽³⁰⁾ demonstrated the role of the pellet/pellet interface in the release, transport and localized deposition of potentially deleterious fission products (Cs in particular) on the ID of the fuel cladding. In short, Wilson's experiments suggest that a pellet/pellet interface is as, or perhaps even more, effective in the release, transport and localized deposition of fission products than is a radial crack extending only partially through the pellet radius. Based on these considerations, a pertinent question is:

Does the PCI failure--axial split or pinhole--occur at the pellet/pellet interface because of:

- a. the function of the pellet/pellet interface in the release, transport, and localized deposition of detrimental fission products?
- b. the stress and/or "pre-strain" state existing in the cladding ridge immediately prior to and/or as a result of a transient rod power increase?
- c. combination of a. and b.?

Considering that there really are few PCI fuel rod failures for each of the three typical fuel designs, under more or less normal operation, it may be more pertinent to know whether:

- a. Fission product/cladding thermal-chemical interaction or
- b. Pellet/cladding thermal-mechanical interaction contributes most to the PCI failure probability.

The experience with CANLUB - a graphite pellet/cladding interfacial lubricant - appears to have been generally good in CANDU fuels at burnup exposures to about 10 GWd/MTM. It is generally acknowledged by those with CANLUB experience that the graphite interfacial lubricant effectively increases the threshold(s) for PCI failure but does not eliminate the probability of PCI failure in the more severe transient increases in fuel rod power. To what extent interfacial lubricants may minimize the PCI failure probability in AOTs, ATWs and/or DBAs is currently unknown. The effects of interfacial lubricants have not yet been included in PCI failure models such as the AECL FUELOGRAM. Ontario Hydro apparently is accumulating PCI failure statistics on CANDU fuel incorporating CANLUB for use in a PCI failure modeling effort. When and/or if such PCI failure statistics may become publicly available is uncertain.

MATERIALS CONSIDERATIONS

Pinhole and axial split type PCI failures tend invariably to be devoid of substantial local bulging deformation. There are, however, a notable number of PIE observations wherein the cladding at the breach exhibits local wall thinning and/or OD surface X and V shaped shear band marks indicating that, in these instances, there were significant inelastic deformations preceding failure. It is, as yet, uncertain whether there are any PCI cladding failures which are essentially devoid of any inelastic deformation preceding fracture and which thereby may be categorized as "brittle" fractures and amenable to analysis by linear elastic fracture mechanics methods.

It is generally acknowledged that the fracturing phenomenon in metals is a multi-stage process (see, for example, Zackay et al.,⁽³¹⁾ "Structural Modes of Fracture," FRACTURE, H. Liebowitz, ed., Chap. 6, pp. 395-440, 1969, Academic Press). The stages in the fracturing phenomenon may be generally categorized as follows:

- Crack nucleation, followed by
- Crack extension (e.g., slow growth) to a critical size, followed by
- Separation by net section yielding or rapid and catastrophic crack propagation.

There are a number of mechanisms^(31,32,33) by which crack nucleation (often referred to as micro-cracking or void formation) may occur:

- The intersection of two or more shear-slip bands.
- The intersection of shear-slip bands and grain boundaries at grains where crystallographic orientations are unfavorable for continuous shear-slip through adjacent grains.
- The intersection of a shear-slip band and a second phase particle resulting in either fracture of the second phase particle or separation at the metal matrix-second phase particle interface.
- Separation at grain boundaries.

With the exception of separation at grain boundaries, all of the above mechanisms only function after the onset of some critical inelastic deformations. Grain boundary separation may occur either as the result of chemical action or inelastic deformation or perhaps both. While there is ample experimental evidence to support the existence of the above mechanisms, there are no experimental data to quantify precisely the critical strain at which crack nucleation occurs. At best, it can only be said that the crack nucleation strain is greater than the elastic limit and very probably substantially less than the so-called "uniform" strain which corresponds to the strain at maximum load in a simple uniaxial tensile test. The critical strain for crack nucleation is very probably variable and dependent upon such metallurgical

parameters as: strain hardenability, strain rate sensitivity, grain size, second phase particle characteristics and distribution, "radiation damage/hardening," etc. The stress and/or strain state is also likely to be a factor in the critical strain at which cracks may nucleate.

Cox and Woods⁽¹⁶⁾ at CRNL have demonstrated experimentally that Zry is susceptible to stress corrosion cracking in an iodine environment and that susceptibility is enhanced after irradiation to fluences in the range of about 5×10^{19} to 1×10^{20} nvt. [It is perhaps only coincidental, but this is also the fluence range wherein the reduction in ductility and the increase in yield and ultimate strength, as determined in PIE tensile tests, begins to approach "saturation."] As a result of these and other experimental investigations, it is now generally acknowledged that iodine stress corrosion cracking (I_2 SCC) of the Zry cladding and perhaps embrittlement by other fission product species (e.g., Cs, Cd, Ag, etc.) plays a significant, if not dominant role, in PCI failures. Over the past several years, considerable effort has been applied by CRNL/AECL,⁽¹⁵⁻¹⁷⁾ WAPD and SRI/EPRI⁽²¹⁾ in independent experimental studies to define the threshold stress conditions for I_2 SCC. The results of these independent investigations appear to be at some significant variance with one another and have prompted some speculation that there may be a range of threshold stresses for I_2 SCC in the zircalloys commonly used for fuel cladding.

In all of the above experimental studies, the stress and temperature conditions were very conducive for thermally activated creep. In no case, however, were creep rate and strains measured during the tests and in only one case were total strains measured and then only after the tests were terminated (WAPD experiments). In that instance the total strains sustained by the I_2 SCC test specimens ranged from about 1% to 3%. In halogen (i.e., fluoride and chloride) SCC testing of a rather large number of alloys, Reinoehl and Boyd⁽²²⁾ observed that consistent and predictable SCC results could only be achieved when the test specimens were strained, during the SCC testing, at a "critical" strain rate. Considering these experimental results, as a whole, it is uncertain whether the observed variability in the stress

threshold for I_2 SCC could be realistically attributable to the variability in the strength and/or metallurgical condition of the test materials or whether strain and/or strain rate may have been a better "characteristic" parameter to define the I_2 SCC threshold(s).

As stated previously, crack nucleation is very probably the first stage process in the "fracturing" phenomenon. There are no data to show whether or not the crack nucleation stage may be bypassed in an aggressive-thermal, chemical, irradiation, etc. environment. Assuming that PCI failures do indeed occur by the aforementioned multi-stage processes, crack nucleation would then appear to be a key and perhaps controlling mechanism. In biaxially stressed coupons, exposed to iodine vapor at 300°C, Cubicotti and Jones⁽²⁷⁾ found that cracks in the Zry metal were associated with second phase particles at or near the metal surface after the surface oxide had been removed by ion milling. The test coupon had sustained significant inelastic deformation--ranging from about 1% to 6%--but the exact strain at the cracks was not determined. There were no metallographic examinations to determine whether or not the cracks may have arisen from shear-slip band-second phase interaction. It is noteworthy, however, that Wood and co-workers at CRNL/AECL have always emphasized that some inelastic deformation must precede or at least accompany I_2 SCC.

There is currently appreciable speculation that the I_2 SCC occurs at cracks in the Zry oxide surface film. The presumption is that when the cladding is critically strained the oxide surface film cracks and exposes the metal substrate to I_2 SCC. This has been generally demonstrated^(34,35) in both plane-stress and plane-strain type pre-irradiated tensile specimens. Zebroski and Roberts⁽³⁶⁾ have reported that the critical strain for "cracking" the oxide surface film was about 0.4%. It was not reported whether this critical strain was determined from pre- or nonirradiated Zry test material. It was implied, however, that the presence of second phase particles at the surface appeared to increase or perhaps even be required for I_2 SCC susceptibility. An alternate hypothesis is that the crack nucleation occurs at the intersection of the shear-slip bands and second phase particles at the surface

of the metal and in turn promotes "cracking" of the oxide film. This coincidental "cracking" of the metal and oxide may be the combination that makes the Zry susceptible to I_2 SCC. It has been well established experimentally that irradiation to fluences in the range of $5E19$ to $1E20$ nvt enhances "dislocation channelling" in Zry.⁽³⁷⁾ There can be little doubt but that "dislocation channelling" will very significantly increase the probability for shear-slip band/second phase particle interaction and thereby crack nucleation in the metal substrate. It is perhaps more than coincidental that irradiation of Zry to fluences in the range of $5E19$ to $1E20$ nvt not only enhances the occurrence of "dislocation channelling" but also the susceptibility to I_2 SCC as compared to nonirradiated Zry. In this same vein, it is perhaps noteworthy that it is very difficult to produce both "dislocation channelling" and I_2 SCC in nonirradiated Zry.

Considering the foregoing, one may speculate that the absence of a unique I_2 SCC stress threshold for the CRNL/AECL,⁽¹⁵⁻¹⁷⁾ WAPD^(19,20) and SRI/EPRI⁽²¹⁾ investigation may be due to a failure to separate the crack nucleation process(es) from the crack growth process(es) and a failure to take into account the thermally activated creep that must have occurred in all tests. Until the stress, strain, strain rate dependencies for crack nucleation and subsequent growth by I_2 SCC have been identified and quantified, it is virtually impossible to establish a reliable analytical PCI fuel rod failure criterion.

OPERATING CONSIDERATIONS

PCI failures have been modelled (e.g., AECL FUELOGRAM⁽¹⁸⁾ PCI failure model) empirically in terms of the following operating parameters.

- A post-transient rod power
- A delta increase in rod power
- A delay between the transient and failure
- A minimal burnup

Significant exploratory and experimental efforts have been undertaken to identify and quantify mechanisms by which PCI failures occur. Although these

exploratory and experimental efforts have not yet been fully successful, there appears to be but little doubt that stress corrosion cracking by fission product iodine plays a key role in the PCI failure phenomenon. All factors considered, there now appear to be rational, although still undemonstrated, mechanisms which are corollary to the operating parameters comprising the AECL empirical PCI failure model.⁽³⁸⁾ In some cases there may be multiple or alternative mechanisms contributing to the PCI failure phenomenon. The postulated mechanistic corollaries are described as follows:

- The mechanistic corollary to the minimum critical or threshold post-transient rod power-- P_C --is postulated to be the "threshold" fuel temperature for fission product (i.e., I_2 , Ca, Cd, Te, etc.) release.

This temperature appears to be the temperature at which thermally activated solid state reactions, diffusional processes, knockout-recoil mechanisms, etc., begin to occur at significant rates and may also correspond approximately to the fuel recrystallization temperature (i.e., $\sim 1300^\circ\text{C}$). Based on GAPCON⁽³⁹⁾ estimates for USLWR fuel designs, the rod power, roughly corresponding to a volumetric average fuel temperature of 1200°C to 1300°C is about 9 to 10 kW/ft. The Maine Yankee PIE results tend to support the idea that a "threshold" fuel temperature may be a rational mechanistic corollary to the minimum critical fuel rod power postulated in the AECL empirical PCI failure model.

- The mechanistic corollary to the threshold increase in fuel rod power-- ΔP_C --may be severalfold.
 - a. a critical or threshold stress, strain or strain rate for crack nucleation and crack growth through stress corrosion by, for example, iodine and/or perhaps embrittlement or other chemical attack by, for example, cesium, cadmium, tellurium, etc.

The differential thermal expansion of the fuel and cladding provides the thermal mechanical interaction forces to produce the threshold levels of stress, strain and/or strain rate in the cladding.

- b. the thermal-stress effect in promoting radial cracking in the fuel pellet.

Radial cracking, combined with pellet/cladding interfacial friction is generally considered to promote stress and strain localization in the cladding and thereby enhances the probability for failure by mechanical and/or chemical interaction(s).

- c. the thermal-transient effect on the "relatively prompt" release of the potentially objectionable fission products (e.g.: I_2 , Cs, Cd, Te, etc.)

In pressure-monitored oxide fuels, Freshley and Burley⁽²⁾ found that fission product gas releases, as indicated by increases in internal pressure in the fuel rod, appeared to accompany changes in rod power rather than steady state (i.e., constant power output) operation.

This mechanism would, therefore, be expected to contribute primarily to thermal-chemical interactions.

- The mechanistic corollary to the burnup parameter may also be severalfold.
 - a. the accumulation of a fission product inventory for thermal-chemical interactions (e.g. I_2 SCC)
 - b. cladding "creepdown" and perhaps fuel swelling, causing "hard contact" between the fuel pellet and cladding and thereby maximizing the thermal-mechanical interaction forces accompanying a specific transient increase in fuel rod power.

This mechanism may provide a basis for special considerations in defining the pre-transient rod power for USLWR fuels. The basis for a special pre-transient rod power definition, when applying, for example, the AECL empirical failure model, stems from the fact that USLWR fuels are generally "pre-conditioned" at specified operating intervals. Inasmuch as the "pre-conditioning" rod power exceeds the subsequent operating power the "hard contact" rod power may lie somewhere between the "pre-conditioned" and "de-conditioned" rod power.

- c. The accumulation of substantial radiation hardening and the attendant reduction in uniform elongation and strain hardenability which

may promote crack nucleation and/or otherwise "sensitize" the cladding to SCC by iodine or other fission product species (e.g.: Cs, Cd, etc.). As hypothesized in a preceding section, irradiation of the Zry cladding to fluences of about $1E20$ nvt, or greater, will enhance the probability for crack nucleation via "dislocation channelling" and thereby increase the susceptibility for I_2 SCC.

- d. The accumulation of some as yet undefined "cumulative damage" which may reduce either the post-transient rod power "threshold" and/or the critical delta power increase for PCI failure. There are data which suggest that the PCI failure threshold may be dependent upon fission product (eg: I_2 , Cs, etc.) "availability" which in turn is dependent upon burnup. As cited previously, the release of gaseous fission products has been shown to be enhanced by either increasing and/or decreasing power transients (ie: thermal disequilibrium in the fuel pellet). These considerations suggest that burnup may be the best parameter to define "cumulative damage" because it combines exposure and severity of the fuel duty. The Scandpower "POSHO"⁽⁴⁰⁾ failure model, however, suggests that the total power history may be required to adequately define "cumulative damage" and the basis for estimating PCI failure probabilities.
- e. In a more speculative vein, there may be changes in U-O stoichiometry with increasing burnup which may significantly influence the oxygen potential at the pellet/cladding interface.
- The mechanistic corollary to the time delay parameter appears to be the "reaction rates" for thermal-mechanical and/or thermal-chemical interactions.

There appear to be several rate phenomena which probably play a role in PCI failures, and may therefore be considered as mechanistic corollaries to the time delay parameter postulated in the AECL PCI failure model. Some of the more important may be:

- Iodine stress corrosion cracking

- Other, as yet unidentified fission product/cladding chemical reaction(s) probably stress/strain and/or strain rate related.

There are some data which suggest that the "time-to-failure" following a ramp increase in fuel rod power may be inversely proportional to the severity of the transient.⁽⁴¹⁻⁴²⁾ Further analyses of these data are needed to establish whether there is indeed an interdependence on "time-to-failure" and severity of the transient. These analyses may provide some further insight relative to failure type--"pinhole" versus "axial split" and "iodine spiking."

SAFETY CONSIDERATIONS

The potential for PCI failure accompanying plant startup, fast recovery from a scram or following a moderate core power transient is rather well demonstrated. In attempts to minimize the occurrence of PCI failures, all USLWR fuel manufactures have developed operating criteria in the form of a set of operating recommendations. These criteria and recommendations are not generally useable as analytical or empirical models to assess the probability of PCI failure in an AOT or more severe core power transient. On the basis of on-line-refuelling experience in CANDU's, AECL⁽¹⁸⁾ has developed an empirical model which appears to reliably predict the probability for PCI failures when the reactor core as a whole is operating in a steady-state mode. Whether this model can be used or modified to estimate the PCI failure probability for USLWR fuel in a BWR or PWR core in a transient state has not yet been established.

Safety concerns tend to center on factors such as:

- the total number of failures and the concomittant release of radioactivity in a single event and/or the additional release from prior failed rods.
- secondary fuel rod damage that may occur during operation subsequent to failure and which may potentially result in further significant damage and/or radioactivity release.

- the effect of a prior failure on the behavior of a fuel rod in an ATWS or DBA.

Based on operating experience it is relatively well established that PCI failures tend to occur only during or very shortly after a significant reactivity insertion. At present PCI failure criteria are not yet well defined. Current evaluation of the AECL FUELOGRAM⁽¹⁸⁾ suggests that the model is not adequate for a core wide estimation of the number of PCI failures that may occur in a moderate to severe reactivity insertion accident (RIA). There appears, however, to be some hope yet that a model, employing the same operating parameters--P(pre- and/or post-transient), ΔP and Bu--may be developed. If a fuel rod PCI failure model can be developed in terms of P, ΔP and burnup, a method for core wide fuel rod power estimation will also be required.

Preliminary considerations of PCI failures with regard to ATWS and DBAs does not suggest any severe secondary effects on fuel rod behavior during the ATWS or DBA transient other than the relatively prompt release of gaseous and perhaps some particulate fission/fissile products to the primary coolant system.

On the basis of operating experience to date the secondary damage, which may be directly related to a concurrent (eg: Peach Bottom) or a prior PCI failure, does not appear to be critical with regard to normal operation. It should not, however, be inferred from the experience to date, that PCI failed fuel can generally continue to operate to design burnups or even the next scheduled outage. The existence of "iodine spikes" suggests, however, that some prior failed fuel may have operated beyond scheduled outages. These situations add emphasis to the need for a core-wide method for evaluating RIAs to provide assurance that the number of failures prior and RIA caused--and the attendant fission product release--is within the handling and retention capabilities of the plant.

There may be some basis for greater concern regarding the secondary damage effect concurrent with or following a prior PCI failure. In the

CIRENE^(7,11) fuel experiments, two of seven rods exhibited end cap failure concurrent with an apparent PCI failure even though the PCI failure responsible for the actual cladding penetration was not found. Secondary damage effects of this nature could conceivably be rather critical if they occur to "tie" rods in BWR fuel assemblies.

In non-RIA events, the effect of a prior PCI failure, on the behavior of a fuel rod through an ATWS or DBA, does not generally appear to be significant. An "axial split" type of prior PCI failure may subject the cladding to simultaneous I.D./O.D. oxidation. Current cladding oxidation limits, however, take I.D./O.D. oxidation into consideration. The prior "axial split" PCI failure is expected to alleviate the potential for ballooning and flow blockage. There does appear, however, to be some basis for greater concern when the prior PCI failure is of the "pinhole" type. In this case, entrapped water, as it flashes to steam could conceivably cause ballooning in regions away from the "pinhole" and/or cause a more gross failure. Some consideration must also be given to the escapement of fission product gases which may further aggravate the local heat transfer which may already be at a critical state.

There is, at this time, some contention that the PCI failure probability is minimal and perhaps nonexistent for RIA's, wherein the time at the peak transient power is very short (e.g., <15 minutes). The basis for this contention is that the AECL FUELOGRAM⁽¹⁸⁾ model suggests a minimum "hold-time" of approximately 18 minutes for failure by I_2 SCC. There are, however, a few data⁽⁴¹⁻⁴⁴⁾ suggesting an inverse relationship between peak fast transient power and time-to-failure. These data show failures occurring in significantly less than about 15 minutes at the peak fast transient power and further suggest almost instantaneous failures at sufficiently high fast transient powers.

With perhaps the exception of severe RIAs, PCI failures do not appear to present any new and/or unique safety problem. Perhaps, the most nagging current concern is the uncertainty in estimating core-wide, the probability

and number of PCI failures in slight to moderate upset operation. Operating experience, however, shows that the number of PCI failures occurring in an AOT is a small ($\sim 1\%$) fraction of the fuel in an LWR core and therefore any PCI failure analysis model of value will need to be quite precise or supported by significant amounts of failure statistics. Concerning ATWS and DBAs, there appears to be a basis for some concern as to the most severe RIA and perhaps secondary damage effects in non-RIA events.

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