August 15, 2003

Steve Kraft
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SUBJECT: STAFF COMMENTS ON THE PROPOSED USE OF (CRITICAL STRAIN ENERGY DENSITY) CSED FOR PREDICTION OF CLADDING FAILURE FOR HIGH BURNUP FUEL

Dear Mr. Kraft

On October 23, 2002, staff from the Spent Fuel Project Office (SFPO) met with staff from the Nuclear Energy Institute (NEI), the Electric Power Research Institute (EPRI), Anatech, and industry representatives to discuss the proposed use of CSED as the measure most suitable for prediction of cladding failure for high burnup fuel rods. A representative from Anatech presented an overall approach to the CSED failure criterion.

During that meeting, SFPO staff stated that it would provide comments on the CSED failure criterion.

Based on the information presented at the meeting, the NRC Staff has a number of concerns with respect to the application of CSED to predicting fuel rod failure. These concerns are attached and focus on **six** broad areas that incorporate CSED into the methodology that will be used to predict fuel rod failure during a severe impact event.

We appreciate your effort to date on this difficult issue and look forward to continued interaction with you.

Sincerely,

/RA/
M. Wayne Hodges, Deputy Director
Technical review Directorate
Spent Fuel Project Office
Office of Nuclear Material Safety
and Safeguards

Attachment: Assessment of the Application of CSED
to Predicting High Burnup fuel Rod Failues

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Assessment of the Application of CSED
to
Predicting High Burnup Fuel Rod Failures

A most basic and useful description of a material's strength and toughness is its uniaxial stress-strain curve. The integrated area under a stress-strain curve is the total strain energy per unit volume (strain energy density, SED) absorbed by the material at failure. When SED is associated with failure criteria, it is commonly called the critical strain energy density (CSED).

At the joint NEI/NRC Meeting on 10/23/02, NEI proposed to use CSED as the measure most suitable for prediction of cladding failure for high burnup fuel rods. The NEI proposal (References 1 and 2) employs a set of assumptions and a first principles approach to develop equations that relate a CSED value for any material to its corresponding fracture toughness. Using a J-integral approach, an equation is developed that relates energy release rate to the SED in unflawed cladding. From this, it is concluded that failure of cladding with a longitudinal flaw can be predicted by calculating the SED of the cladding, without modeling the flaw or performing a fracture mechanics analysis, and comparing the calculated SED to the CSED determined from material tests.

Having established a relationship between CSED and fracture toughness parameters, the CSED data from ring tension tests, axial tension tests and burst tests are plotted against a cladding damage parameter (oxide thickness) in Figure 4 of Reference 2 (also included in Reference 1). A best estimate curve is drawn through the data. NEI proposes that this curve (or something similar) be used as the criteria to determine fuel rod failure by comparing CSED calculated from it, to SED values computed for fuel rods from finite element impact models.

Based on the information presented, the NRC Staff has a number of concerns with respect to the application of CSED to predicting fuel rod failure. These concerns are focused on six broad areas that incorporate CSED into the methodology that will be used to predict fuel rod failure during a severe impact event.

The six areas of concern are:

1. Development of a Stress-Strain behavior and Failure Database
2. Computation of CSED from the Stress-Strain / Failure Data
3. Accounting for Scatter in CSED Data
4. Accounting for Significant Physical Environmental Effects
5. Computation of SED in Finite Element Models
6. Validation of Finite Element Predictions of Cladding Failure

ATTACHMENT

Each of these concerns is discussed in further detail below.

1) Development of a Stress-Strain behavior and Failure Database

Stress-strain failure data must adequately reflect the effects of both the physical environment and damage environment to which the cladding is subjected during operation, transport and testing. The physical environment includes state of stress, temperature, strain-rate and test methods. The damage environment includes hydrogen content, hydride orientation, fast fluence and oxide thickness.

The Staff's specific concerns are focused on the effects on CSED of state of stress, strain rate, test methods and reporting of test data.

State of Stress: CSED is a scalar quantity and is not uniquely related to the state of stress from which it is derived. As such, there are an infinite number of states of stress that can produce the same value of CSED. Thus, axial tension, hoop tension, biaxial tension due to internal pressure, and other states of stress can each produce the same value of CSED. On-the-other-hand, because cracks, flaws and defects generally have an orientation associated with them, the failure of high burnup fuel cladding dependents directly on the state of stress in the cladding (i.e., an axially oriented crack is not susceptible to fracture from axial tension, but is from hoop tension).

Figure 4, presented by NEI, clearly shows that state of stress significantly affects the computed value of CSED. Therefore, separate curves that adequately account for the effect of state of stress on cladding failure are necessary.

Strain Rate: In general, as strain rate increases, material strength increases and ductility decreases. Since both strength and ductility are directly related to CSED, it would be expected that CSED would not be as greatly affected by strain rate, as rupture strain would be. Nevertheless, uncertainty exists, and as cladding becomes more and more brittle due to high burnup, the effects of strain rate on CSED may become more severe. Testing programs currently underway will hopefully be able to address this issue.

Test Methods and Reporting of Test Data: Procedures for conducting tests on fuel rod cladding and the methods for reducing and reporting data must be standardized and rigorous. Figure 4, presented by NEI, clearly shows that the CSED computed from ring tensile tests is significantly higher than the CSED computed from the axial tensile tests. Since irradiated Zircaloy cladding exhibits isotropic or near-isotropic behavior, as explained in Reference 2, one might conclude that the dramatic differences in calculated CSED are related to flaw orientation. But are they? Clearly the different values relate to the state of stress in the two types of specimens.

Figures 5-51 and 5-58 (and Figures 5-48 and 5-55) from Reference 3 provide a clue to explain these differences. Figure 5-51 shows a stress-strain curve of a tube (axial) tensile specimen from a high burnup fuel rod. Figure 5-58 shows a stress-strain curve of a ring tensile specimen taken from the same rod at a location only a couple of inches from the tube tensile specimen. Both the tube test and the ring test are uniaxial tension tests. What is observed from these figures is that the rupture strain in the ring test is almost an order of magnitude greater than in the tube test, and that the CSED is almost six times greater. This begs the question as to whether strain in the cladding material is actually what is being represented in the ring test stress-strain curve?

Round robin ring tensile testing performed by ANL, CEA, and the Russians have shown that ring tension test data are not a good measure of material strain capability, because measured strains from this test depend on test specimen size and the test apparatus, and are not a measure of cladding strain. The ring test tends to measure artificially high strains and, therefore, artificially high CSEDs, when these erroneous strains are used. This suggests that the currently proposed CSED correlation may seriously under predict the probability of failure. More importantly, it is obvious that greater care must be exercised in the methods used to extract and report test data.

There are additional concerns that place Figure 4 data in conflict with other sources. A methodology for determining fuel rod failure during a cask impact event was developed in Reference 4. The NEI presentation focused attention on modifying aspects of this methodology to accommodate high burnup fuel rod cladding. However, a discrepancy exists between information contained in Reference 4 and information presented by NEI. In Figure III-30 of Reference 4, rupture strain (which is directly proportional to CSED) is plotted against the cumulative probability of cladding failure for three different ratios of hoop stress to axial stress. This plot shows that as hoop stress increases, rupture strain (and CSED) dramatically decreases. This is exactly the opposite of the trend reflected in Figure 4, which shows CSED increasing as hoop stress increases. This discrepancy needs to be resolved.

2) Computation of CSED from the Stress-Strain / Failure Data

The concerns enumerated above lead directly to the concern for how CSED is calculated from test data.

- What is the precise methodology used to calculate CSED in the tube tensile test, the ring tensile test, the burst test and the bending test?
- What does the calculated CSED actually represent, and is it a true expression of the SED in the cladding alone?
- What is the volume over which CSED is calculated? Is it measured at a point, or, is it measured over a smeared volume by computing the total elongation over some gage length, as would be expected in the development of a typical stress-strain curve?

These questions are related to how the calculated CSED is actually used in failure prediction for cladding and is discussed again in Item 5 below.

3) Accounting for Scatter in CSED Data

There is significant scatter in the data presented by NEI correlating CSED with the cladding damage parameter (oxide thickness). The single, best-fit curve drawn through the data presented in Figure 4 does not adequately describe the failure probability of high burnup fuel cladding because of the large uncertainty in any estimate of CSED. Best estimate and lower bound (mean minus one standard deviation, or 84% non-exceedance probability) curves need to be constructed to quantify uncertainties in order that a probabilistic fuel rod failure evaluation can be performed, as intended in Reference 4.

[Comment: The CSED in Figure 4 appears to be based on total elongation strains at failure as opposed to uniform elongation strains. Use of uniform elongation strains from burst and axial tensile tests typically reduces the scatter in the CSED data by a factor of 3 to 4 as compared to use of total elongation strains from the burst and axial tensile tests. However, using uniform elongation strains will generally under predict CSED.]

4) Accounting for Significant Physical Environmental Effects

The failure mechanisms for fracture have sometimes proven to be too numerous and complex to trust the accuracy of empirical correlations, other than over narrow ranges of materials and test conditions prototypical of the intended application. For example, in the case of ferritic steels the existence of a transition temperature for ductile versus brittle fracture has complicated the efforts to develop correlations. In the case of zirconium alloys the complicating effects of temperature are further compounded by the effects of hydride orientation and total content on fracture toughness.

Indeed, further complexity is encountered as the state of damage in the cladding becomes more severe due to high burnup. In these circumstances it is important to develop empirical correlations within ranges of variables that more precisely reflect the physical conditions (state of stress, strain rate, etc.) to which the cladding is subjected. If cladding is subjected to axial tension at high strain rates, a correlation between CSED and the damage parameter for those specific physical conditions will produce far more meaningful results than a correlation between CSED and the damage parameter that includes all states of stress and low strain rates. Clear delineation among states of stress is necessary to develop better correlations with failure data and to minimize uncertainty.

5) Computation of SED in Finite Element Models

This concern addresses the need for guidance and consistency in computing SED results from finite element models and in using these results to make proper comparisons with CSED test data. There are two issues. The First concerns the choice of constuitive model used to represent the stress-strain behavior of the cladding from which SED is calculated. The Second concerns the element volume over which SED is computed in finite element models and how SED, so computed, relates to CSED calculated from test data.

Choice of Constuitive Model: As mentioned in Item 1, CSED is a scalar quantity and is represented by a single number. It contains the integrated information of the stress strain curve from which it was derived. The integration process is not reversible, and given only CSED, there are an infinite number of stress-strain curves that can be constructed to yield the same CSED.

Once the general characteristics and scale of the finite element model have been determined, the analyst makes a number of choices that include: (1) the types of elements to represent the various components and the interaction between components, (2) the size of elements and the mesh refinement necessary to achieve desired accuracy, and (3) the representation of material properties. To represent the elastic-plastic properties of high burnup fuel rod cladding, the analyst must decide on a constuitive material model to represent the material behavior of the cladding. Generally three properties are required to characterize behavior in order to calculate plastic strains. They are a yield function, a flow rule, and a hardening rule. Analysts will do their best to construct a reasonable material model. But of what? Zircalloy from a handbook? Moderately irradiated Zircalloy? High burnup Zircalloy from an axial tension test at low strain rate, 300 degrees C and 700 ppm hydrogen? Each of these material models will calculate SED, but they will all be quite different. Clearly analysts need guidance to develop an adequate material model to ensure a level of consistency

among the numerous finite element models that may be constructed to address this issue on a cask by cask basis.

Volume over which SED is computed: In a typical finite element, stress and strain are computed at integration points within the element. From the integration points, stress and strain are extrapolated to the surface of the element, where they achieve their maximum values, or they can be integrated over the element volume to produce an average value of stress and strain over the element. Each of these three computations of stress and strain produces a different value of SED. And, if the element is located within a region of high stress gradient, each of these values can be significantly different and could easily be an order-of-magnitude apart. What then is the proper value of SED to report and use?

The proper value is the one that best compares to the way in which CSED was computed from test data, which is directly linked to the questions raised in Item 2. For example, integration point estimates of SED may significantly over predict the probably of cladding failure when compared to CSED data, if the CSED was computed over a smeared volume containing a tensile stress gradient. On-the-other-hand, CSED data computed at the location of maximum strain in a bending test would produce a severe under prediction of failure if compared to SED derived from the integration of stress and strain over the element, whereas for uniform axial tension this would be appropriate. Thus it must be clearly understood by the analyst how CSED data was computed so that SED can be properly calculated before comparisons are made.

6) Validation of Finite Element Predictions of Cladding Failure

One way to begin to address the concerns raised in Item 5 is to develop general finite element modeling guidelines based on direct comparisons of results from finite element models of test specimens to the results of the actual test. This approach is taken in Reference 5.

> "The Expansion Due to Compression (EDC) test has been developed for the study of irradiated and hydrated cladding failure, under conditions of pellet cladding mechanical interaction, which are expected during a reactivity initiated accident (RIA). A finite element simulation of the EDC test is presented. The objective of the study is (i) to understand the deformation of the cladding during the experiment, including the effect of cladding material properties, and (ii) to provide information necessary for the development of failure criteria."

Demonstrating that finite element models can reasonably duplicate the results of simple controlled static tests will develop confidence in the results from complex models used to predict fuel rod cladding failure during an accident event.

The CSED method presented by NEI brings a new approach to the problem of predicting cladding failure and is perhaps a better predictive tool that alternative empirical correlations such as critical strain level. As stated earlier, the concerns enumerated here, not only address the CSED method proposed by NEI, but also include concerns for the details of incorporating the CSED method into the entire methodology that will be used to predict fuel rod failure during a severe impact event. NEI and the NRC Staff will continue to work together to address these concerns. In this regard, it may be advisable to approach ASTM Committee E8 to obtain views on the use of CSED for this application and to develop a standard test method the takes into account the significant variables.

Some Recent Test Information

A public meeting was held at Argonne National Laboratory on July 16-17, 2003, to review research in an NRC program that is being performed in cooperation with EPRI and other industry representatives. Highlights included a presentation on a high burnup fuel specimen that failed. It was stated that several medium-burnup and high-burnup cladding specimens in creep furnaces were brought down in temperature under full pressure to roughly simulate conditions of vacuum drying in a cask. The two medium-burnup specimens exhibited remarkable redistribution of their hydrides, with some now in the radial orientation, which can lead to cracking. The high-burnup specimen failed about half way through the cooldown and has not been examined yet. All initial temperatures were 400^{o}C or less (ISG-11, Rev. 2 limits temperature to 400^{o}C).

Although no additional information has been provided concerning this failure, staff offers that this test and data might provide some useful information for validating whether or not CSED would be an appropriate failure criterion for hydrided fuel cladding.

1. "Analysis of High-Burnup Spent Fuel Subjected to Hypothetical Transportation Accidents, Part I and II,", presented by Joe Rashid and Albert Machiels, NRC-Industry Meeting, Washington, DC, October 23, 2002.

2. "A Cladding Failure Model for Fuel Rods Subjected to Operational and Accident Transients," Progress Report, J. Rashid, R. Montgomery and W. Lyon of ANATECH, and R. Yang of EPRI.

3. "Hot Cell Examination of Extended Burnup Fuel from Calvert Cliffs-1," EPRI TR-103302-V2, July 1994.

4. "A Method for Determining the Spent Fuel Contribution to Transport Cask Containment Requirements," SANDIA Report, SAND90-2406, November 1992.

5. "Elastic-Plastic Deformation of a Nuclear Fuel Cladding Specimen under the Internal Pressure of a Polymer Pellet," Dufourneaud, et.al., Fifth World Congress on Computational Mechanics, July, 2002.