United States Nuclear Regulatory Commission

RESEARCH INFORMATION LETTER ON AN ASSESSMENT OF *RIAs*

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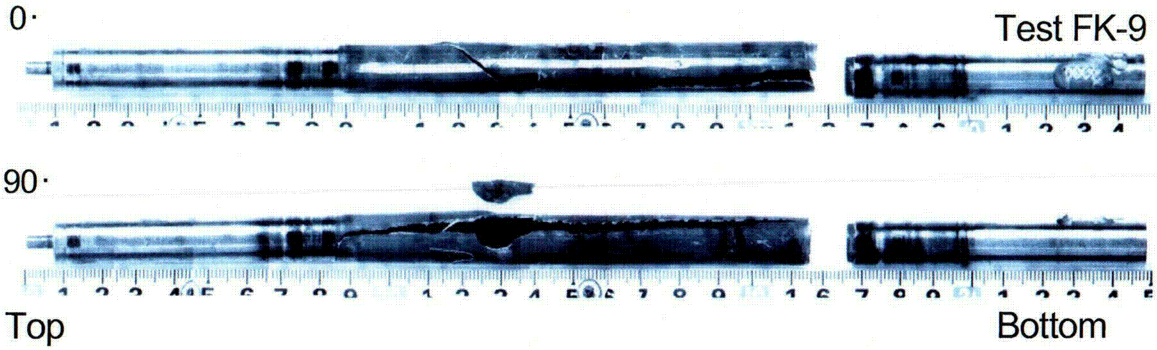
NSRR (Japan)

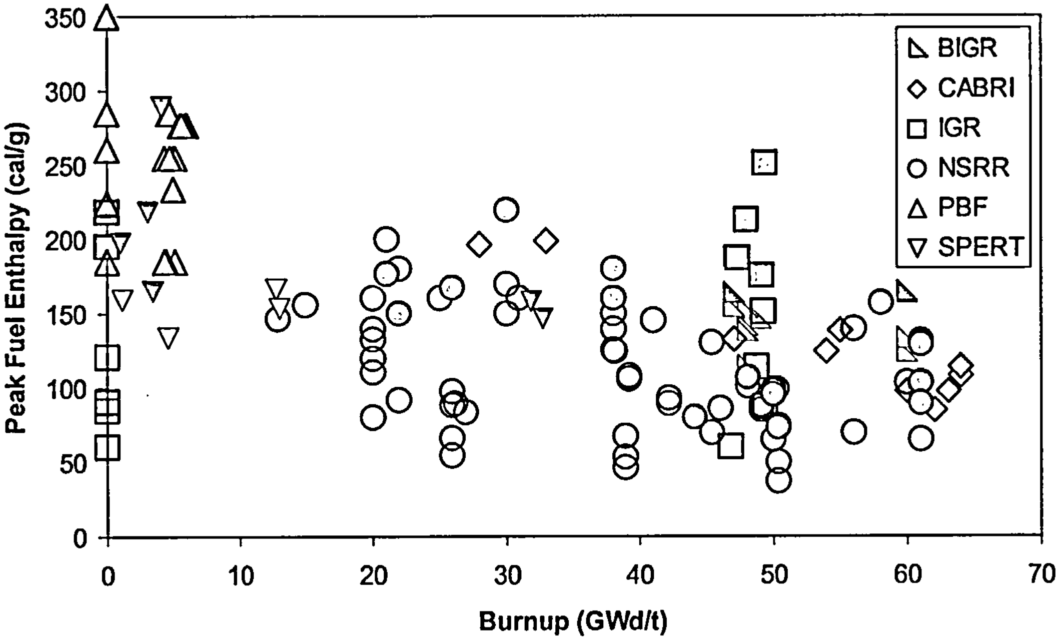


Partially brittle cladding failure in a reactivity transient test with a high-burnup Zircaloy-clad BWR fuel rod

C01

SYNOPSIS

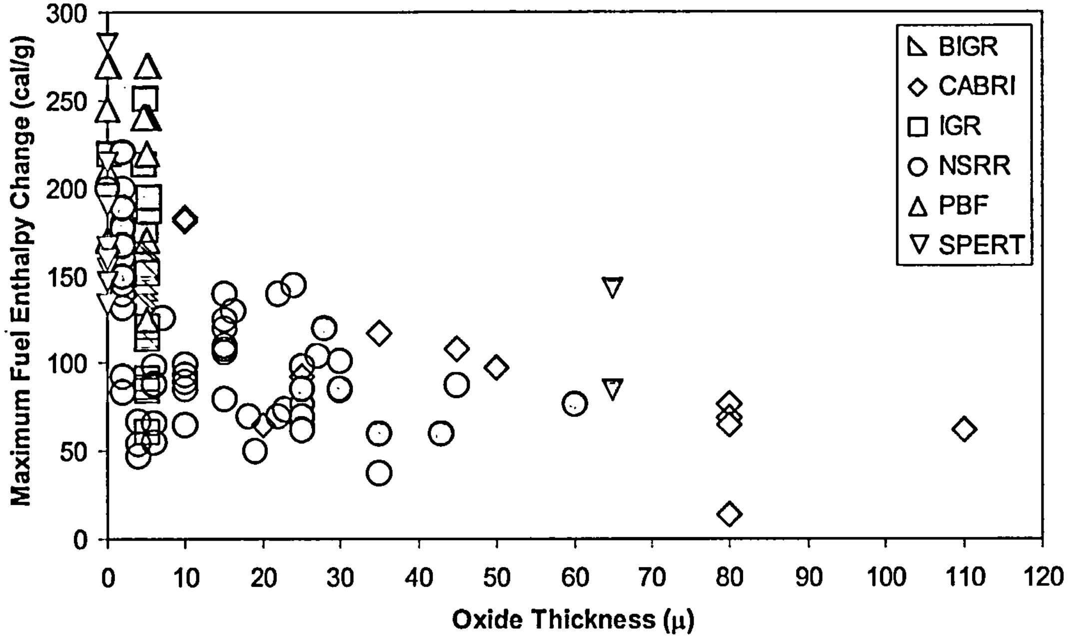
- The current body of data was reviewed
- Estimates were made of bias in data from atypical test temperatures and pulse widths
- An empirical cladding failure threshold was determined from data with bias correction
- Generic 3-D neutronic calculations were performed for reactivity accidents in PWRs
- For realistic reactivities, fuel rod enthalpy did not reach the failure threshold
- Therefore, General Design Criterion 28 is met for all U.S. power reactors



Test data, plotted as peak fuel enthalpy (total) as a function of burnup. Shaded symbols indicate cladding failure.

FIRST OBSERVATIONS

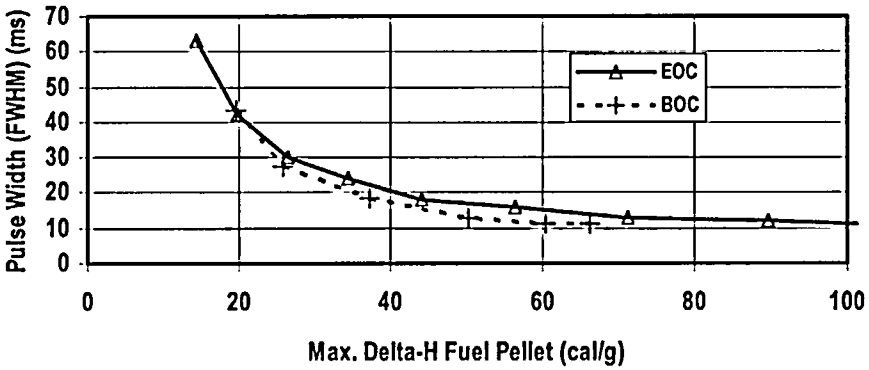
- Burnup is not as important as oxidation with regard to cladding failure
- Peak fuel enthalpy is not as important as maximum enthalpy change with regard to cladding failure
- The approach being taken relies on cladding failure, so the variables were changed



Test data, plotted as maximum fuel enthalpy change as a function of oxide (corrosion) thickness. Shaded symbols indicate cladding failure.

SECOND OBSERVATIONS

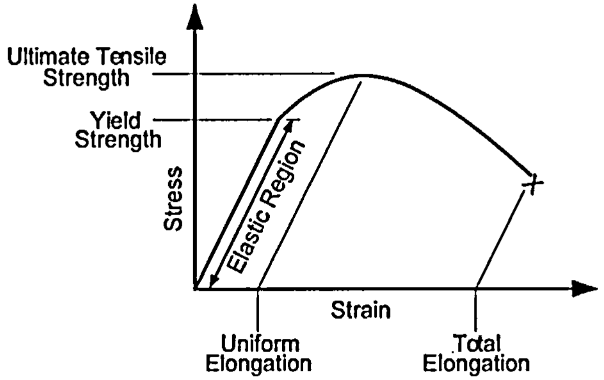
- Big reduction in scatter of data
- All cladding failures above 5μ corrosion result from PCMI
- REP-Na1 is an outlier and there is good reason to ignore it
- The tendency for moderately corroded (NSRR) rods to fail with a lower enthalpy change than heavily corroded (Cabri) rods does not seem realistic
- There are systematic differences between NSRR and Cabri test conditions



Dependence of pulse width on energy (fuel enthalpy change) for beginning-of-cycle (BOC) and end-of-cycle (EOC) conditions.

THIRD OBSERVATIONS

- Pulses must provide a fuel enthalpy change of 50-150 cal/g to cause cladding failure
- Corresponding pulse widths would be 18-10 milliseconds
- Cabri pulses (~30 ms) are too broad and NSRR pulses (~5 ms) are too narrow
- 20°C test temperature in NSRR is too low for hot PWR accident conditions of interest



Terms used to describe elastic and plastic properties of cladding.

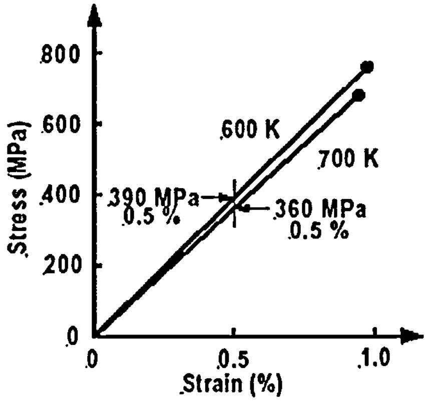
OUTLINE OF SCALING METHOD

Failures in Elastic Region

- Calculate hoop stress at reported time of failure (“failure stress”) for test pulse
- Note corresponding fuel enthalpy change
- Adjust code input for PWR conditions
- Calculate new failure time to reach this “failure stress”
- Note corresponding fuel enthalpy change
- Add the difference in fuel enthalpy change to test results

Failures with substantial plastic hoop strain

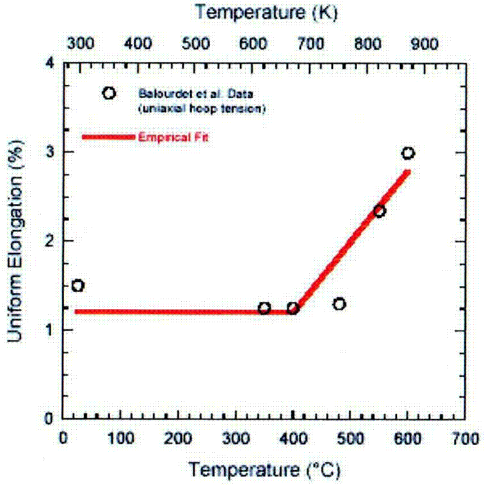
- Calculate plastic strain at reported time of failure (“failure strain”) for test pulse
- Note corresponding fuel enthalpy change
- Adjust code input for PWR conditions
- Calculate new failure time to reach this “failure strain”
- Note corresponding fuel enthalpy change
- Add the difference in fuel enthalpy change to test results



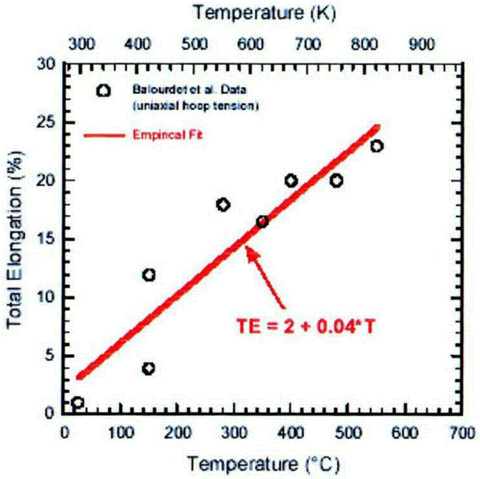
Stress versus strain in the elastic region from the elastic modulus in FRAPTRAN at two different temperatures.

COMMENTS ON FAILURES IN THE ELASTIC REGION

- We assume that elastic properties respond instantaneously to temperature change during a millisecond transient because they are related to interatomic forces
- We assume that fracture toughness cannot change with temperature during a millisecond transient because a change would require diffusion (slow)
- Strain rate and strain hardening exponents have been fixed in FRAPTRAN such that they do not give unreasonable results for very rapid transients
- We rely on FRAPTRAN to handle all mechanical properties of the cladding that would be affected by pulse width and test temperature
- The PWR and test-pulse calculations are different primarily because the elastic properties are affected by temperature



Uniform elongation (UE) of irradiated Zircaloy as a function of temperature.



Total elongation (TE) of irradiated Zircaloy as a function of temperature.

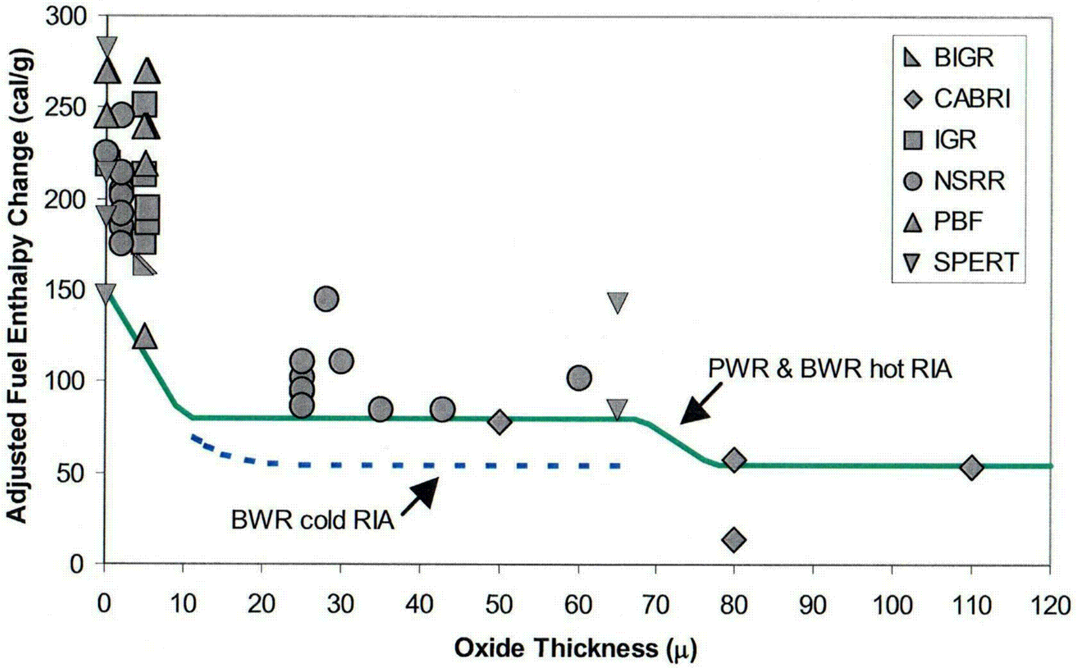
CO2

COMMENTS ON FAILURES WITH SUBSTANTIAL PLASTIC STRAIN

- All the above assumptions and observations about the elastic properties still apply
- We assume that UE and TE cannot change with temperature during a millisecond transient because a change would require diffusion (slow)
- We assume that UE and TE would be altered by the differences between NSRR pre-test temperatures and PWR pre-accident temperatures
- We were not sure whether to use the temperature dependence of UE or TE, so we tried both
- In the end, we chose the temperature dependence of UE
    - More consistent with FRAPTRAN, which calculates uniform strains
    - Produced better agreement between NSRR and Cabri results
    - Smaller correction with less uncertainty
    - More conservative result
- Over the temperature range of interest, the temperature variation of UE was zero
- The PWR and test-pulse calculations are different primarily because the elastic properties are affected by temperature

Results of scaling analysis for five selected tests

Test ID	Initial T (°C)	Pulse τ (ms)	Failure σ or ε	Reported ΔH_f (cal/g)	Calculated ΔH_f (cal/g)	Adjustm't ΔH_f (cal/g)	Adjusted ΔH_f (cal/g)
REP-Na10	280	31	230 MPa	65	59	-2	57
REP-Na8	280	75	130 MPa	62	63	-9	54
REP-Na7	280	40	0.49%	97	97	-19	78
HBO-1	18	4.4	0.52%	60	57	+23	80
TK-2	25	4.4	0.58%	60	59	+27	86



Cladding failure data with adjustments from the scaling analysis and lower-bound failure correlations

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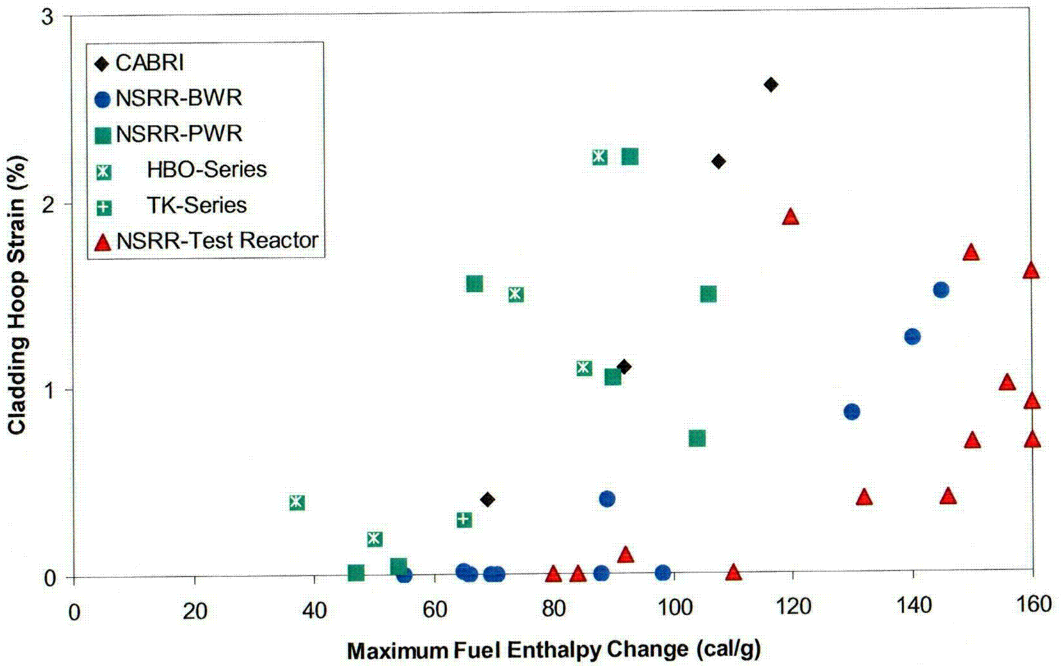
COMMENTS ON *FRAPTRAN* CALCULATIONS

- Thermal expansion model was modified to describe edge-peaked temperature distributions (permanent code change)
- Strain rate and strain hardening exponents have been fixed in FRAPTRAN such that they do not give unreasonable results for very rapid transients (permanent code change)
- Initial cold gap size was adjusted to get agreement with measured strain data for Cabri and NSRR (different adjustments were required)



Plastic strain measured from non-failed cladding as a function of maximum fuel enthalpy change for tests in Cabri and NSRR.

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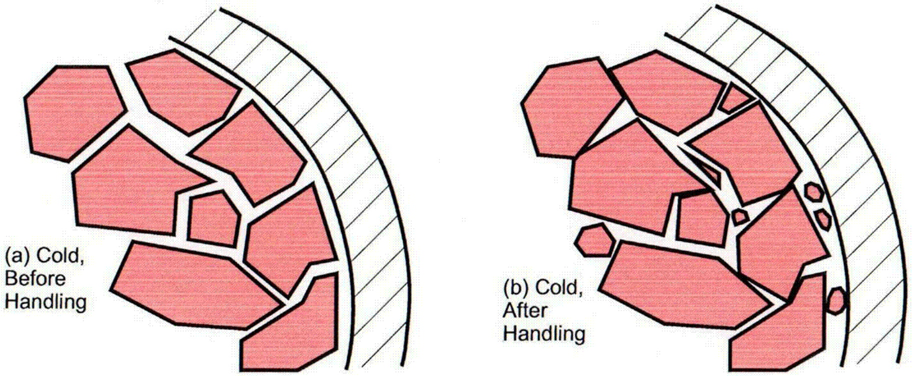
COMMENTS ON MEASURED PLASTIC STRAIN

- The strain=0 intercept corresponds to the enthalpy change required to close the gap and expand the cladding through the elastic region — then plastic strain begins
- The Cabri data points (including CIP0-1 and CIP0-2, which are not plotted) have a small amount of scatter and a well-defined intercept
- The NSRR data points have a large amount of scatter and poorly defined intercepts
- The three NSRR test groups (PWR, BWR, and JMTR) are in the right order, with the PWR rods having the smallest gaps and the JMTR rods (no creep down) having the largest gaps
- However, the PWR data from NSRR should be to the right of the Cabri data in the figure because cold gaps are larger than hot gaps — the order is reversed
- Something important is going on, and it cannot be explained by pulse width or MOX

CHIPS & FINES



Open gap (actually, distributed cracks) after cooldown from power, (a) before handling and (b) after handling and specimen preparation.

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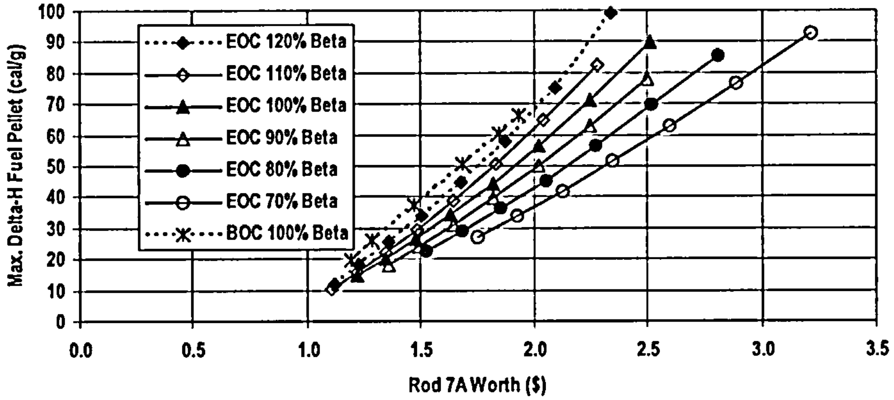
THE CHIPS & FINES HYPOTHESIS

- Test rods for Cabri and NSRR all look like Fig. (b)
- Cabri rods are preconditioned >300°C for many hours, permitting local deformation or movement such that the effective gap increases
- An unrealistic cold gap of 95µ is needed in FRAPTRAN for the Cabri rods to get predicted strains in agreement with the measured strains (modified expansion model probably too aggressive)
- All PWR calculations were also done with a 95µ cold gap because they are effectively preconditioned
- NSRR tests are run without preconditioning such that chips & fines act as wedges that create a smaller effective gap
- A cold gap of 10µ was needed to get agreement with the HBO series (same gap used for TK series)
- The Chips & Fines hypothesis is not modeled and is only used as a plausible explanation of the need for gap size adjustments

FUEL ENTHALPY LIMITS

No damage to pressure boundary or significant impairment of core coolability (GDC-28)
↘
No steam explosions
↘
Keep fuel inside the cladding
↘
No cladding failure

N.B. At low burnup, fuel melting is necessary to promptly disperse fine fuel fragments into the coolant. At high burnup, fission-gas-bubble expansion can disperse fuel provided the cladding is breached.



Maximum fuel enthalpy change for a PWR rod ejection accident from hot zero power as a function of control rod worth for various values of delayed-neutron fraction (beta).

PWR CONCLUSIONS
FOR A ROD-EJECTION ACCIDENT

- For moderately corroded fuel rods, a control rod worth of more than $2 would be needed to reach the cladding failure threshold (80 cal/g)

- For heavily corroded fuel rods, a control rod worth of at least $1.75 would be needed to reach the cladding failure threshold (55 cal/g)

- Based on available data, it is very unlikely for a rod worth to exceed $1.5

- A rod-ejection accident in a PWR would not result in cladding failure and therefore would meet the requirements of General Design Criterion 28

BWR CONCLUSIONS
FOR A ROD-DROP ACCIDENT

- No specific analyses were done
- BWR calculations that have been done generally result in lower values of fuel enthalpy change than for PWRs
- BWRs have broader pulse widths because of slow rod drop and therefore may have less of a tendency to disperse fuel if there were a cladding failure
- The probability of a BWR rod drop is significantly lower than the probability of a PWR rod ejection
- Taken together, these factors indicate that a BWR would not result in cladding failure and therefore would meet the requirements of General Design Criterion 28