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# Industry Justification for Post-Quench Impact Tests for LOCA

(for use in cladding embrittlement criteria development)

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# Cladding Embrittlement Criteria

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- Primary Objective of Criteria
  - Ensure fuel rod damage is limited during LOCA event
  - Maintain a coolable fuel rod geometry following the LOCA event
- 10 CFR 50.46 Specifications
  - (b)(1) Peak cladding temperature shall not exceed 1204°C (2200°F)
  - (b)(2) Total oxidation shall not exceed 17% ECR
- Basis for Current Criteria
  - Original ECCS Rulemaking Hearing 1971 – 1973
  - NRC established revised basis in 1988 rulemaking

# Historical Perspective – 1973 ECCS Hearings

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- As expressed in “Opinion of the Commission” (RM-50-1)
  - Limits are required to preclude conditions leading to zero residual ductility following thermal shock quench
    - » Maintain some level of post-quench ductility to ensure survival during quench
    - » Retention of residual ductility will ensure a coolable core geometry amenable to long term cooling
  - Ductility and strength of oxidized zirconium depend upon the oxygen content and thickness of the prior beta phase
    - » Establish limit on oxidation temperature
    - » Establish limit on extent of oxidation

# Historical Perspective – 1973 ECCS Hearings

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- Cladding Embrittlement Criteria - 1973
  - PCT criterion of 1204°C (2200°F) was established to further assure survival during thermal quench and guarantee some remaining post-quench ductility
    - » Minimize solid solution hardening (embrittlement) of the beta-phase caused by an increase in oxygen diffusion above 1200°C
    - » Influenced by Hobson ring-compression tests at 1315°C (2400°F) for 2 to 4 minutes (Commissioners Opinion Exhibit 1113)
  - 17% total oxidation limit was established to limit embrittlement below the PCT
    - » Consensus among the regulatory, industry, and intervenor participants that the limit on total oxidation should be around 17%
    - » Influenced by thermal quench tests and some mechanical property tests
- Oxidation calculated by the Baker-Just equation per Appendix K

# Historical Perspective – 1973 ECCS Hearings

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- PCT and ECR criteria incorporate conservatisms
  - Commissioners considered the database concerning oxidation embrittlement to be insufficient at that time
  - The criteria were established to contain margin to the best-estimate cladding fragmentation threshold
- Commissioners recognized that future data could be used to relax the requirements

## Historical Perspective – 1980's Review

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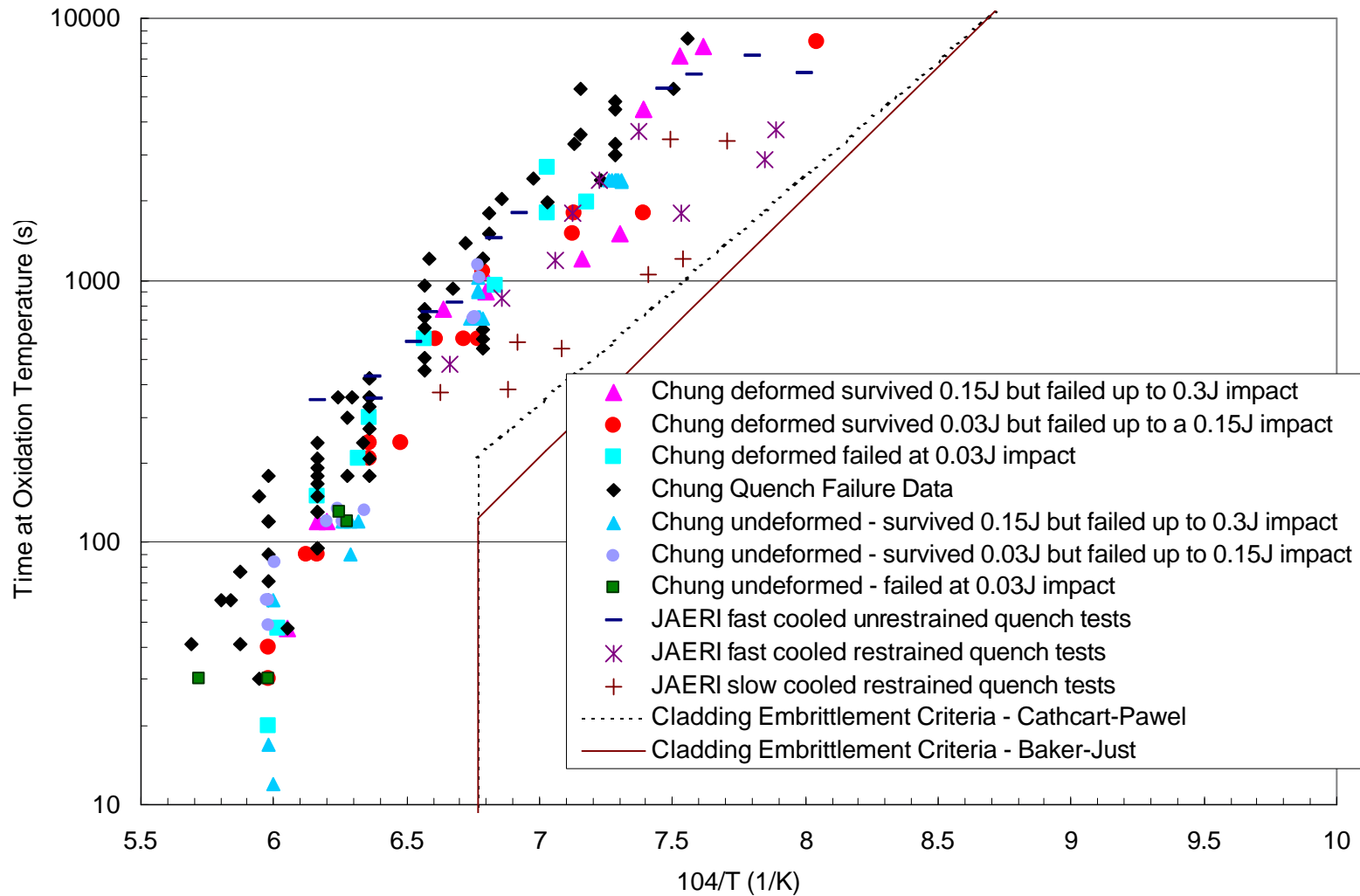
- NRC staff reviewed the large amount of experimental and analytical research on LOCA ECCS behavior
  - Primary focus was to establish a basis for the use of best-estimate evaluation models including uncertainties
  - Sufficient experimental data was available to evaluate the degree of conservatism in the cladding embrittlement criteria
    - » Experiments at ANL, JAERI, INEL, and others
  - Staff review summarized in “NUREG-1230 – Compendium of ECCS Research for Realistic LOCA Analysis”

## Conclusions from NUREG-1230

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- NRC concluded the cladding embrittlement criteria are sufficiently conservative to avoid cladding fragmentation by both thermal shock and post-LOCA impact loads
  - Based on thermal shock quench tests and post-quench impact tests
  - The database of tests include the effects of ballooning, burst, and hydrogen uptake
- Recognized that ring compression tests were conservative with respect to thermal shock quench and post-quench impact tests
  - Original PCT limit apparently based on results of ring compression tests
  - Retaining the 1204°C limit would be conservative with respect to the cladding ductility required to survive both thermal shock quench
  - Technical basis for ECR limit sufficiently established using thermal shock quench and post-quench impact tests

# Thermal Shock and Impact Tests





# 1988 Rulemaking

- 10CFR50.46 Revisions Based on NUREG-1230 Review
  - Allowed the use of more realistic evaluation models
    - » Combined with uncertainty evaluation
  - NRC Position from forward in NUREG-1230

*“However, in keeping with the admonition by the Commission in its 1973 issuance of Appendix K, we propose to retain a margin of safety by a requirement that calculational uncertainties be explicitly taken into account. This together with the demonstrated safety margin that will be retained in the 10 CFR 50.46 limits will provide a suitably conservative regulatory posture.”*

- Cladding embrittlement criteria paragraphs (b)(1) and (b)(2) remained unchanged (PCT:1204°C, ECR:17%)
  - » Redefined technical basis with newer thermal shock quench and impact tests

Provides appropriate margin to conditions leading to significant core damage

# Basis for Cladding Embrittlement Criteria

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- Current regulations are based on 1988 rulemaking
  - Provide a clear assessment of the margin to fragmentation threshold
  - Based on thermal shock and post-quench impact loads
- Approach to Evaluate Burnup Impact on Cladding Embrittlement Criteria (ANL LOCA Program)
  - Use thermal shock quench tests and post-quench impact tests on irradiated and unirradiated pre-hydrated material
    - » Same technical basis as the 1988 rulemaking
  - Compare with earlier database to evaluate change (if any) in the;
    - » best-estimate fragmentation threshold caused by irradiation effects
    - » margin to cladding embrittlement criteria

# Post-Quench Ductility Tests

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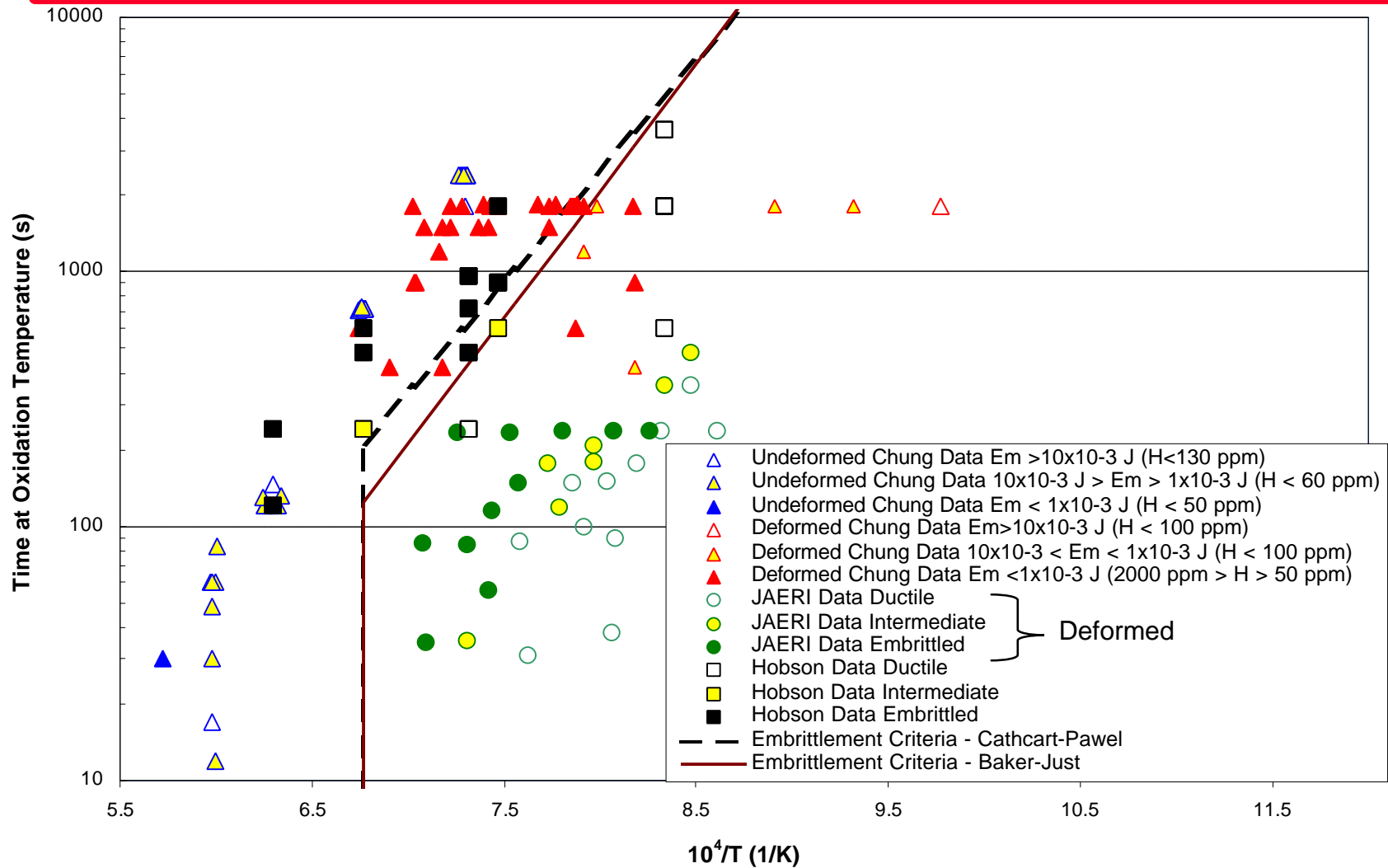
- Use of post-quench ductility tests is problematic
  - No clear method to relate ring compression or 4-pt/3-pt bend tests to define ECR criterion
    - » Original 17% criterion was based on a consensus between different approaches (or bases)
    - » In 1980's rulemaking, margin to fragmentation threshold was demonstrated using thermal shock quench and post-quench impact tests – **Not ring compression tests**

# Post-Quench Ductility Tests

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- Use of post-quench ductility tests is problematic (cont'd)
  - Results from post-quench ductility tests are qualitative and subject to interpretation
    - » Embrittlement is a complex function of oxygen content, hydrogen content and beta layer thickness
    - » Looks only at local effects – not structural behavior
    - » No consensus on the method to define ductile/brittle behavior
  - Use of post-quench ductility tests requires complete reassessment of ECR criterion
    - » New basis for unirradiated material ECR
    - » Comparison of irradiated material with the new basis

# 1988 Rulemaking was not based on ring compression data



# Industry's Position on LOCA Research Needs

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Position expressed in 9/9/03 Letter (Modeen to Thadani)

- Current regulations are based on the 1988 rulemaking which relied on thermal shock quench and post-quench impact tests
- Impact tests on irradiated fuel are necessary to provide a tie-in to the reference for current regulation
  - Irradiated vs. unirradiated (reference)
  - Irradiated vs. pre-hydrated (unirradiated)
  - Deformed vs. undeformed
- Impact tests are more representative of postulated post-LOCA loads