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Review of Key Aspects of the FAVOR Model Relevant to Small Surface Breaking Flaws

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Overview & Objective

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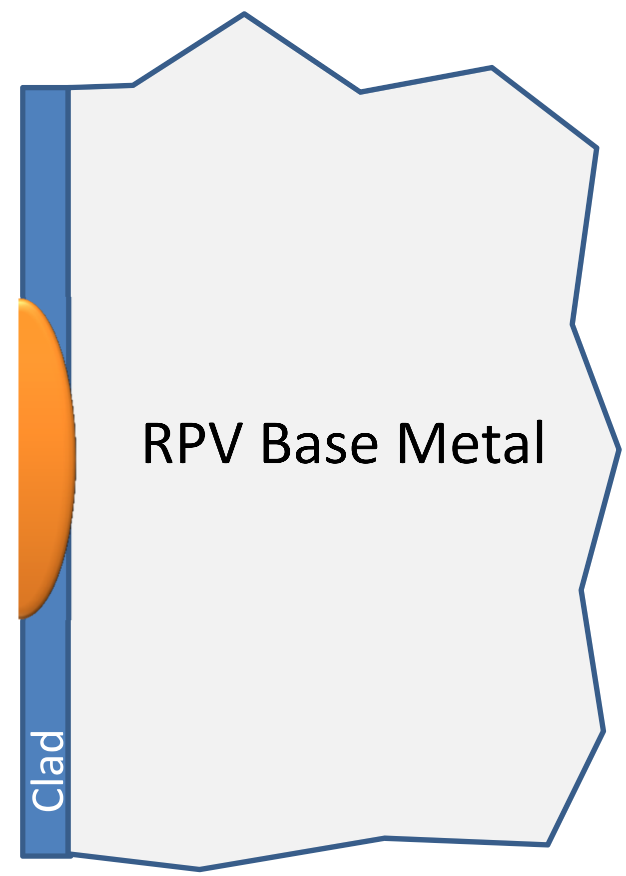
- Prediction of crack initiation / propagation from shallow surface flaws in the cladding may be influenced by by aspects of the FAVOR model
  - CTE mismatch
    - ***Addressed previously***
  - HAZ toughness not modeled
  - If the crack initiates it is modeled to instantly run long and then run deep
- This presentation reviews the adequacy and appropriateness of these latter two aspects of the FAVOR model



Key References

- **HAZ Toughness, or closely related measures**
  - Of structural welds
    - Troyer & Erickson, 2013
  - Of clad welds
    - McCabe, 1985-88
    - Iskander, 1992
    - Todeschini, 2013

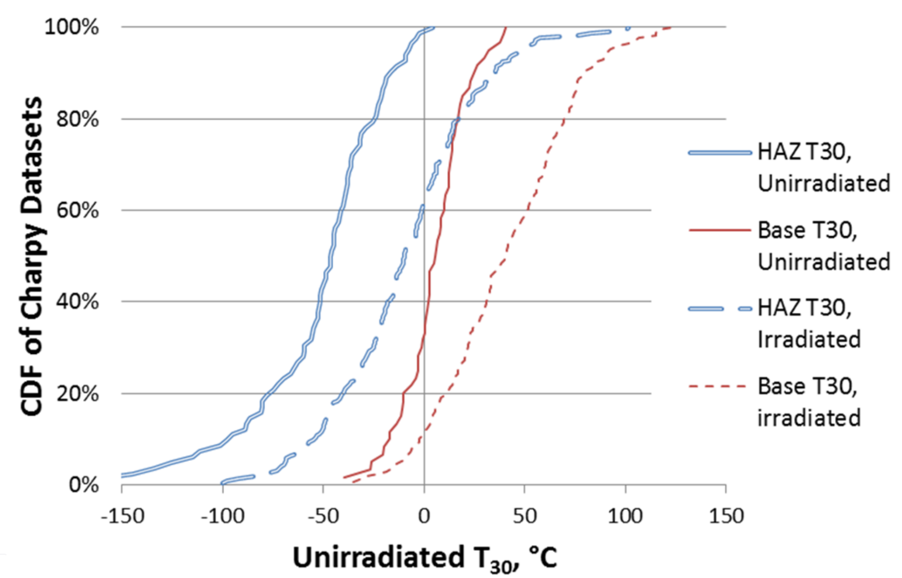
- **Crack / cladding / HAZ interaction behavior**
  - Iskander, 1992
    - Clad beams
  - Cheverton, 1990
    - Thermal shock experiments
  - Dickson, 1999
    - Analysis

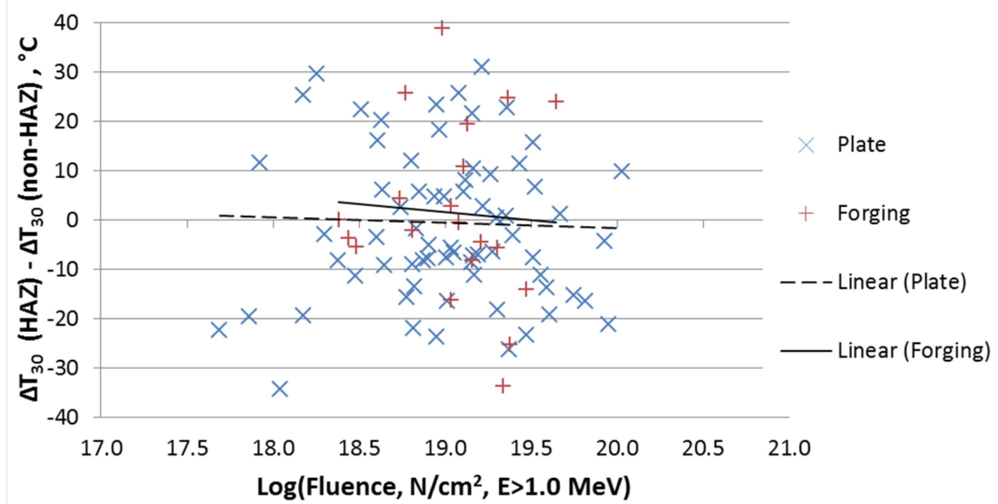
Many more citations reviewed, these were the most pertinent.

HAZ of Structural Welds

Troyer & Erickson, 2013

- Comprehensive summary based on USA surveillance testing
  - Data from PR-EDB
- HAZ T_{30} values compared with T_{30} values for companion plate or forging
- Key findings
  - T_{30} of HAZ < T_{30} of plate or forging in virtually all cases
  - Embrittlement behavior (ΔT_{30}) of HAZ, plates, and forgings very similar





Troyer, G., and Erickson, M., *"Empirical Analyses of Effects of the Heat Affected Zone and Post Weld Heat Treatment on Irradiation Embrittlement of Reactor Pressure Vessel Steel,"* 26th ASTM Symposium on Radiation Effects, Indianapolis, IN, 2013

HAZ of Cladding

- **Iskander 1992, NUREG/CR-5785 &/etc.**
  - Test block for mechanical specimens: 3 layer cladding
  - $T_{30(HAZ)} < T_{30(BASE)}$

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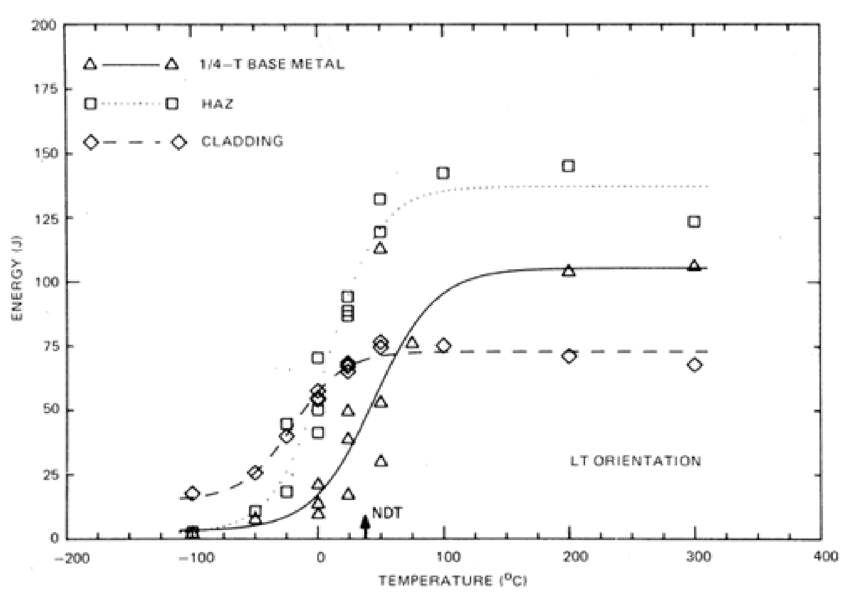

- **McCabe 1985-89, various NUREG/CRs**
  - Results qualitatively similar to those reported by Iskander, i.e.:
    - $T_{30(HAZ)} < T_{30(BASE)}$
  - However, HAZ specimens smaller than base metal specimens, so loss of constraint may have also reduced the HAZ transition temperature

HAZ of Cladding

Todeschini et al., 2013

HAZ of Cladding

Todeschini et al., 2013

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HAZ of Cladding

Summary

- Structural welds have many passes, which improves HAZ toughness properties relative to the base metal
  - More passes →
    - More opportunities for grain refinement
    - Smaller regions of coarse grains
    - Tempering of martensite

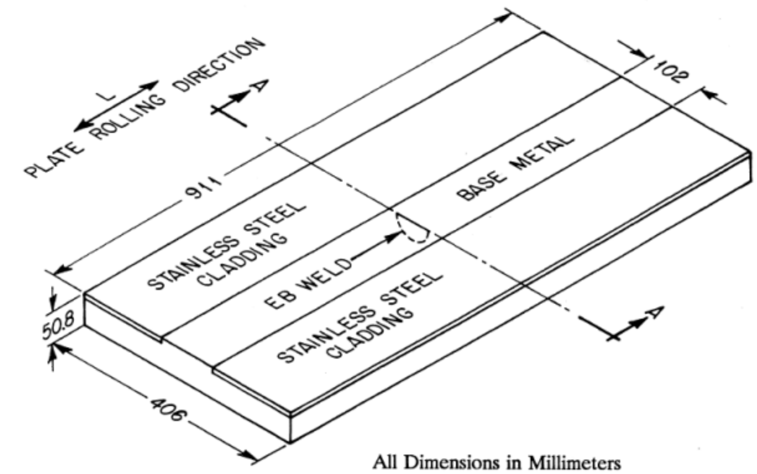
    all of which tend to increase toughness

- HAZ under cladding does not experience as many thermal cycles (especially single layer cladding)
    - Less tempering
    - Less grain refinement
  - Recent toughness measurements by Todeschini indicates potential for HAZ toughness to be (sometimes) lower and (sometimes) higher than the base metal
    - Modeling of the HAZ is therefore not expected to alter the "late peaking" behavior that leads to the risk-dominance of shallow surface breaking flaws in FAVOR

Crack/Clad/HAZ Interaction

Iskander

- Experimental details
  - 4-point bending
  - Thermally embrittled plate material
  - H_2 charged cracks
- Results
  - Once initiated, cracks run long but do not rupture cladding
  - However
    - Propagating flaws tunnel, even without the cladding & HAZ, probably due to the max value of K_I/K_{Ic} occurring below the surface.
    - Load-bearing capacity of the clad plates enhanced by compressive stresses due to bending



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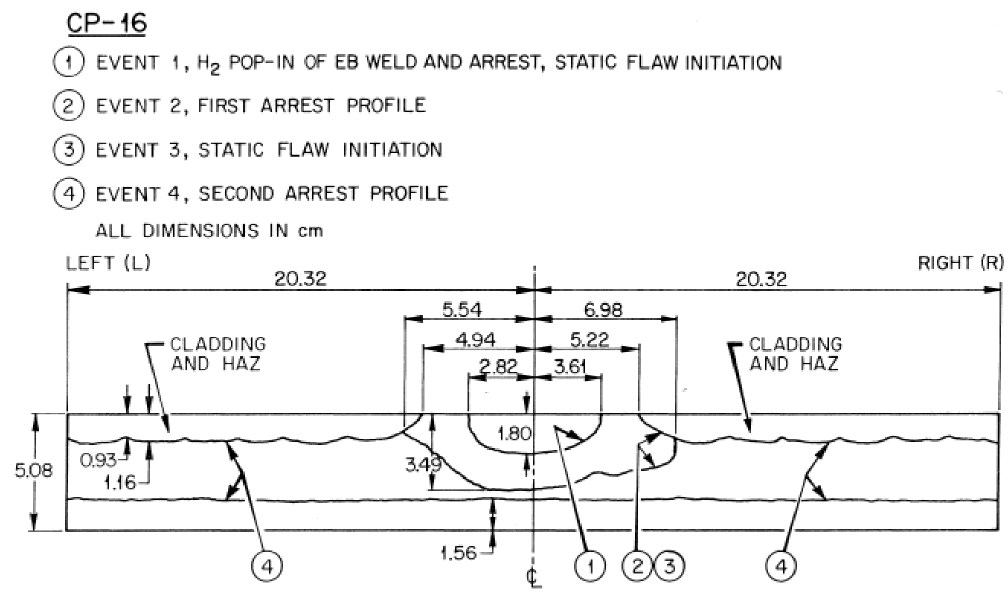
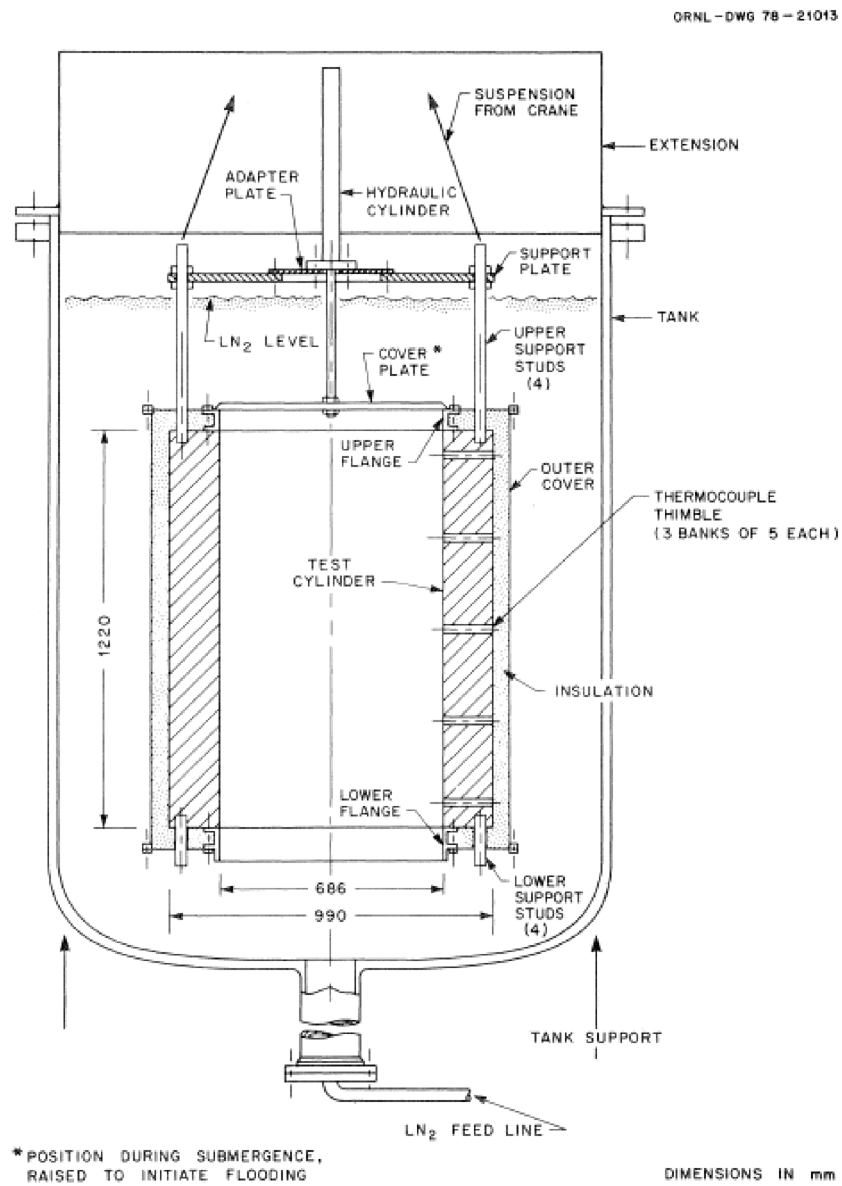


Iskander, S.K., et al., *"Experimental Results of Tests to Investigate Flaw Behavior of Mechanically Loaded Stainless Steel Clad Plates,"* NUREG/CR-5785

Crack/Clad/HAZ Interaction

Cheverton – TSE Experiments

- Experimental details
  - Thermally embrittled cylinders
  - Insulated on OD
  - Dunked in LN_2 → thermal shock only (no pressure)
  - Tests performed both with and without cladding



Crack/Clad/HAZ Interaction

Cheverton – TSE-7 (no cladding)

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- Experimental results
  - Significant bifurcation on ID
  - Cracks run long
  - Cracks run deep
  - Series of 3 initiation / run / arrest events predicted reasonably well by FAVOR precursor software

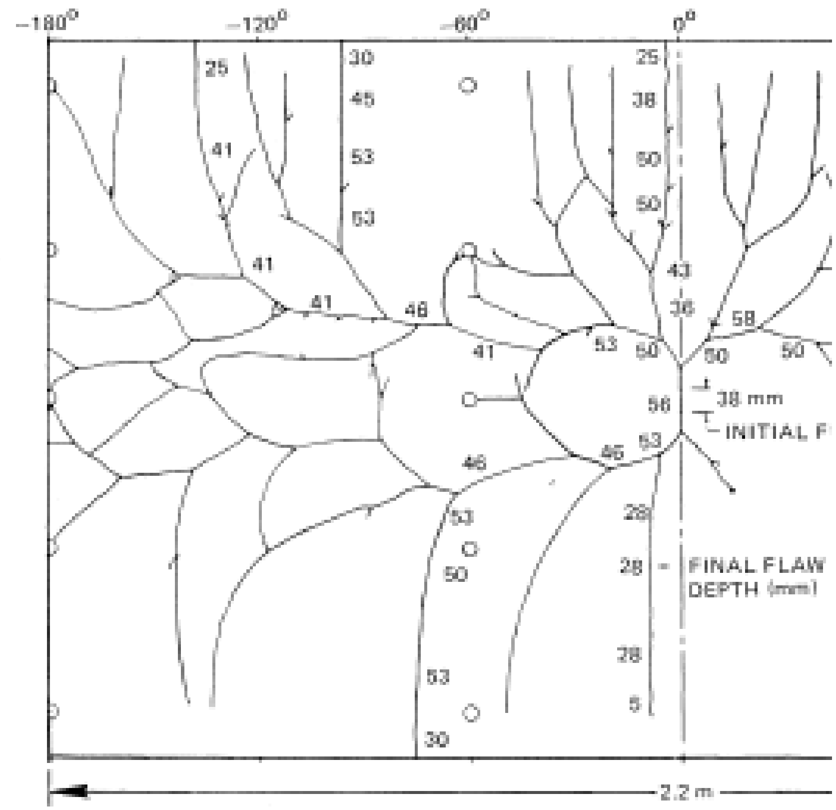

Fig. 8.12. Developed view of inner surf: showing final crack pattern and UT estimates selected locations.

Crack/Clad/HAZ Interaction

Cheverton – TSE-8&11 (with cladding)

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- Experimental results
  - Significant bifurcation on ID
  - Cracks run long
  - Cracks run deep
    - Significant through-thickness propagation even in the absence of pressure
  - Cladding not severed by underlying crack
- Analytical results
  - Dickson, 1999
  - Accounts for effect of pressure
  - Cladding rupture predicted by action of pressure

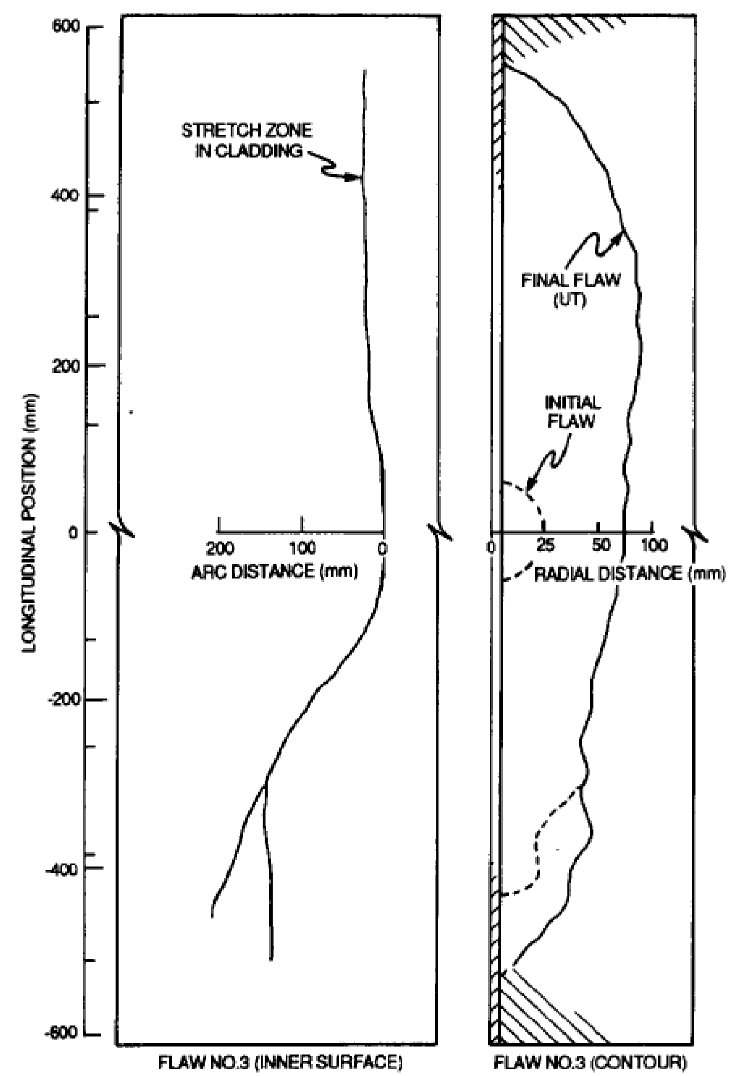

Fig. 8. Stretch-zone and UT indication of flaw 3 TSE-8 extension.

Crack/Clad/HAZ Interaction

Summary

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- Both clad beams (bending) and clad cylinders (thermal shock only) show
  - Cracks run long
  - Cracks run deep
  - Cladding (& perhaps HAZ) not severed by underlying crack

    Note: Max $K_{APPLIED}$ being sub-surface could also rationalize this tunneling behavior

- Effect of pressure in addition to thermal loading in cylinders
  - Could cause rupture of cladding