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REVIEW OF RECENT ORNL SPECIFIC-PLANT ANALYSES

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The Oak Ridge National Laboratory (ORNL) has been helping the Nuclear Regulatory Commission (NRC) develop the pressurized thermal shock (PTS) evaluation methodology since the mid-1970s. During the early 1980s, ORNL developed the integrated PTS (IPTS) methodology, which is a probabilistic approach that includes postulation of PTS transients, estimation of their frequencies, thermal/hydraulic analyses to obtain the corresponding thermal and pressure loadings on the reactor pressure vessel, and probabilistic fracture mechanics analyses. The scope of the IPTS program included development of the probabilistic fracture mechanics code OCA-P and application of the IPTS methodology to three nuclear plants in the U.S. (Oconee I, Calvert Cliffs I, and H. B. Robinson II). The results of this effort were used to help establish the PTS Rule (10CFR50.61) and Regulatory Guide 1.154, which pertains to the PTS issue.

The IPTS Program was completed in 1985, and since that time the ORNL related effort has been associated with long-term programs aimed at improving/updating the probabilistic fracture mechanics methodology and input data. In 1990, the NRC requested that ORNL review a vessel-integrity evaluation report submitted to the NRC by the Yankee Atomic Electric Co. for the Yankee Rowe reactor and that ORNL also perform an independent probabilistic fracture mechanics analysis. Details of the methodology and preliminary results are the subject of this paper/presentation.

Yankee Rowe is the oldest operating pressurized water reactor (PWR) plant in the U.S. and is somewhat unique. The primary-system pressure, the cold-leg temperature, and the vessel radius to wall-thickness ratio are relatively low (2000 psi, 500°F, and 7, compared to 2200, 550 and 10), and the cladding over the plate region is spot-welded sheet (cladding over the vessel welds is the usual weld-deposit type).

The beltline region of the vessel was fabricated from two rolled plates [A302 with low nickel (upper plate), A302 with high nickel (lower plate)], and thus there are two axial welds and one circumferential weld in the beltline region (welds are Linde 80, presumably with high nickel). The plates have unusually large grain size because of an unusually high austenitizing temperature.

Some surveillance data exist for the upper plate but not for the lower plate nor for the welds, and the concentration of copper in the welds is not known. There is, however, a substantial amount of chemistry data for typical Linde 80 welds, and, based on Regulatory Guide 1.99, Rev 2, a correction for the nickel in the lower plate can be estimated. The surveillance data were used to calculate ΔRT_{NDT} for the upper and lower plate sections, with the above mentioned correction for the nickel in the lower plate, and Reg. Guide 1.99, Rev 2, was used for the welds, with a correction of +50°F to account for the low irradiation temperature. Based on this approach and the

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present accumulated operating time (22 EFPY), all estimated values of RT_{NDT} were above the PTS-Rule screening-criteria values (270°F for axial flaws, 300°F for circumferential flaws).

Only surface flaws were considered for the particular analysis discussed herein. Flaws in the region of the plate where the cladding was not bonded (between spot welds) did not extend into and through the cladding and thus were "surface" flaws in the base material. Both axial and circumferential flaws were effectively infinitely long for initial initiation events (shallow flaws); circumferential flaws were continuous and axial flaws 120 in. long for subsequent events. Selection of infinite length for shallow flaws is based on the observation that at least in the absence of cladding the more-likely very short flaw propagates in length with the same potential as that of a long flaw of the same depth propagating in depth, thus generating a long flaw before the long flaw would propagate. Selection of the 120-in. length for subsequent events of an axial flaw is based on the fairly uniform embrittlement throughout the beltline region and the limitation in length extension imposed by the very steep attenuation of the fast neutron flux and thus embrittlement at the ends of the core.

The location of the initial (short) flaw was selected randomly, thus accounting for the axial and circumferential variations in fluence. The maximum fluence in the flaw plane was used for arrest and reinitiation, accounting, of course, in all cases, for the attenuation through the wall.

The mean flaw density (N) was assumed to be 45 flaws/m^3 in the seam welds and 4.5 flaws/m^3 in the plate beneath the unbonded portion of the cladding and also in the cladding spot welds. These mean values are based on best-estimate (mode) values of 1.0 and 0.1 flaws/m^3 and a log–normal distribution with $\sigma = 10^2\mu(N)$ and truncation at $500\mu(N)$. The flaw-depth distribution function was that suggested in the Marshall report.

A residual stress of +6 ksi was included for the seam welds in the first 1.0 in. of the wall beneath the cladding and none elsewhere. Warm prestressing (WPS) effects were not included, although the specific PTS transient analyzed (small-break loss-of-coolant accident with low pressure and stagnation) exhibited characteristics consistent with Type-I WPS.

Seven parameters in the fracture-mechanics analysis were simulated: fluence, copper concentration, initial value of and increase in reference nil-ductility temperature, fracture toughness, and flaw depth. The Marshall distribution was used for the flaw depth, and normal distributions were used for the other simulated parameters.

Results of the preliminary analysis indicate that the plate contribution to P(F|E) is about five times that of the seam welds, the total value being 0.14. If Type-I WPS were included, P(F|E) would be reduced by a factor of ~30 to 5×10^{-3}.

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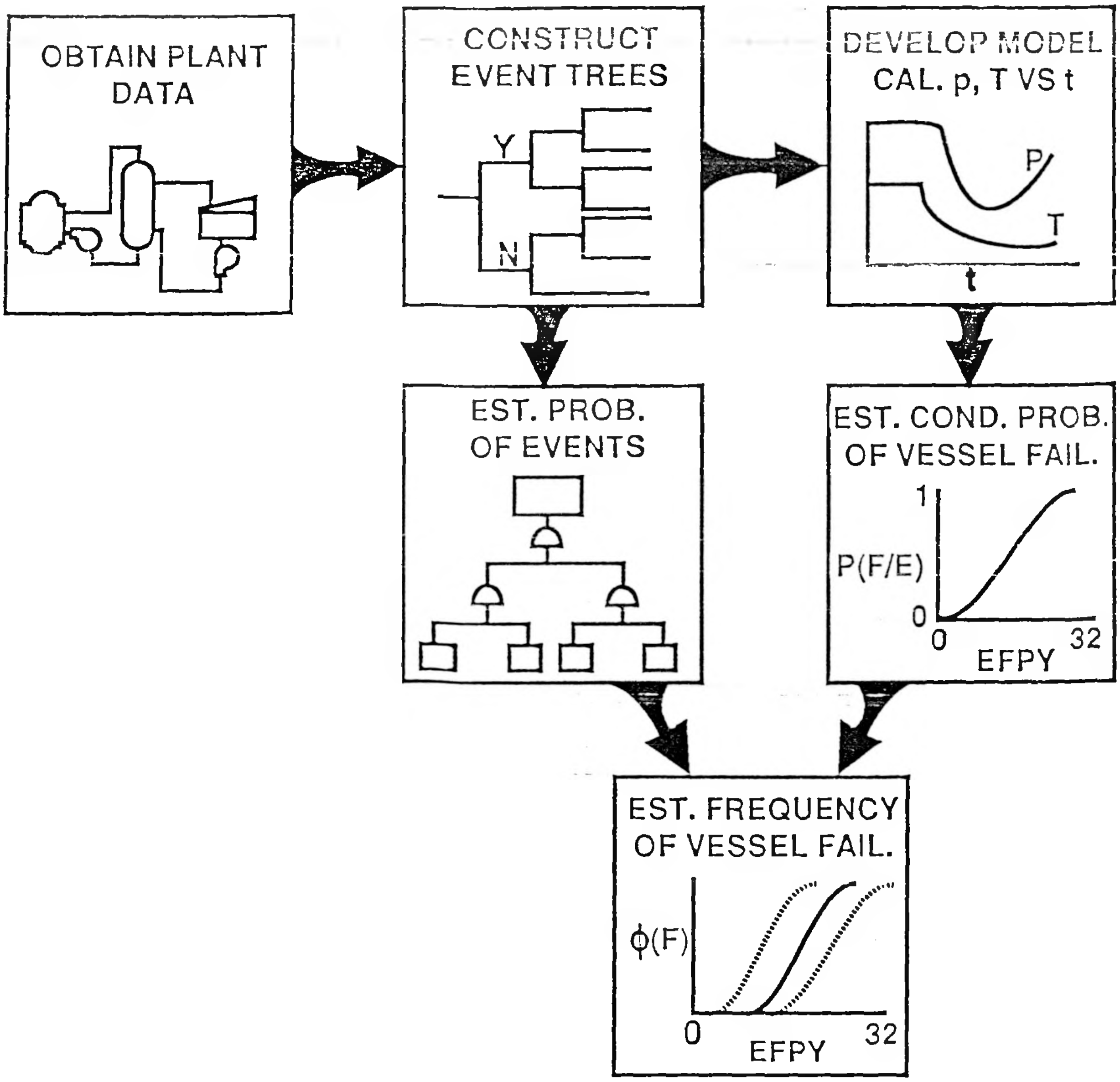
PROBABILISTIC APPROACH FOR EVALUATING INTEGRITY OF PWR VESSELS UNDER PTS LOADING DEVELOPED FOR NRC DURING EARLY 1980s



DETAILS OF METHODOLOGY MAY NEED UPDATING

IPTS METHODOLOGY RECENTLY APPLIED TO YANKEE ROWE

- PURPOSE OF ORNL PARTICIPATION: TAKE ADVANTAGE OF ORNL PTS-EVALUATION CAPABILITIES DEVELOPED OVER 20-YEAR PERIOD

- SCOPE OF ORNL PARTICIPATION
  - REVIEW UTILITY'S EVALUATION
  - QA PROBABILISTIC FRACTURE MECHANICS CODES
  - PERFORM INDEPENDENT PFM ANALYSIS

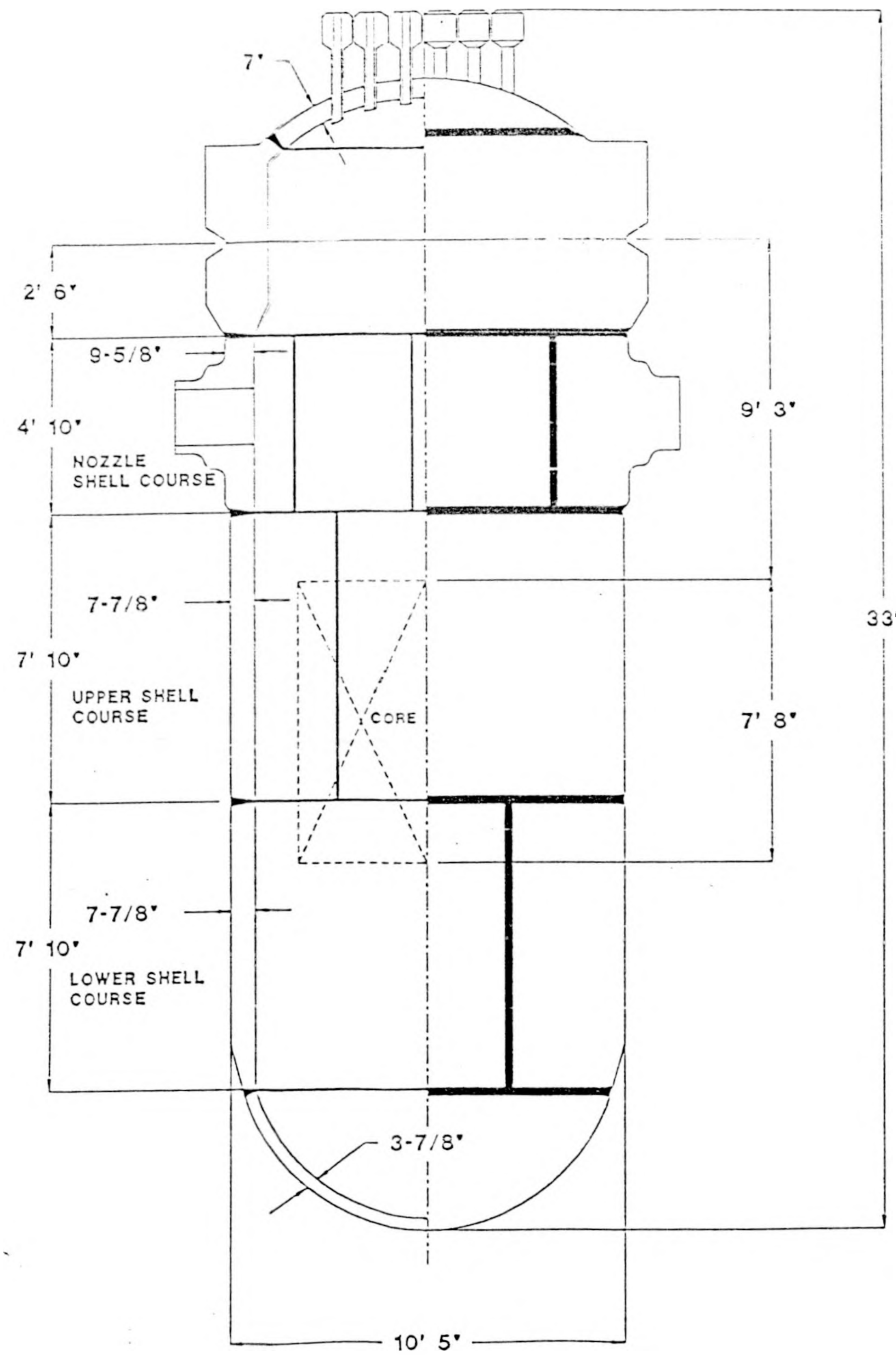
YANKEE ROWE OLDEST OPERATING PWR IN U.S. AND SOMEWHAT UNIQUE

- OPERATING TIME = 22 EFPY
- POWER (THERMAL) = 540 Mw
- PRESSURE = 2000 psi
- TEMPERATURE (INLET) = 500°F
- R/w = 7

YANKEE ROWE OLDEST OPERATING PWR IN U.S. AND SOMEWHAT UNIQUE (continued)

- VESSEL MATERIAL
  - — UPPER PLATE: A302 WITH LOW Ni
  - — LOWER PLATE: A302 WITH HIGH Ni
  - — WELDS: LINDE 80, HIGH Ni, Cu = ?
- CLADDING
  - — 0.25-in. WELD DEPOSITION OVER WELDS
  - — 0.109-in. SPOT-WELDED SHEET OVER PLATE
- SURVEILLANCE DATA
  - — UPPER PLATE: YES
  - — LOWER PLATE AND WELDS: NO
- RT_{NDT} “HIGH” FOR ALL REGIONS

BELTLINE REGION OF YR VESSEL CONSISTS OF UPPER AND LOWER PLATES (ONE EACH), TWO AXIAL WELDS, AND ONE CIRCUMFERENTIAL WELD



PROBABILISTIC FRACTURE-MECHANICS ANALYSIS PERFORMED WITH OCA-P

- BASED ON MONTE CARLO METHODS
  - MANY VESSELS SIMULATED
  - DETERMINISTIC FM ANALYSIS FOR EACH
  - $P(F|E) = \frac{\text{NUMBER OF FAILURES}}{\text{NUMBER OF VESSELS}}$
- BASIC INPUT FROM SYSTEMS ANALYSIS:

  $T_C, p, h = f(t)$
- PERFORMS THERMAL, STRESS, AND FM ANALYSIS

SEVEN FM PARAMETERS SIMULATED IN IPTS STUDIES

- FLUENCE AT INNER SURFACE
- COPPER CONCENTRATION
- $RTNDT_o$
- $\Delta RTNDT$
- K_{Ic}, K_{Ia}
- FLAW DEPTH

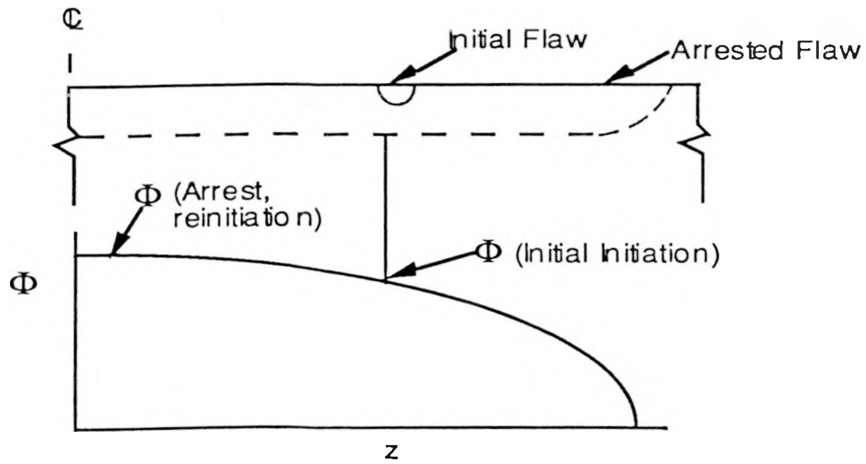
FLAW-RELATED DETAILS

- TYPE: SEMIELLIPTICAL SURFACE FLAWS
- SURFACE LENGTH:
  - INITIAL INITIATION: 2-D (2/1 $\rightarrow \infty$)
  - ARREST/REINITIATION: 120 in. (SUBSTANTIAL EMBRITTLEMENT IN ALL REGIONS)
- ORIENTATION
  - PLATE/AXIAL WELDS: AXIAL
  - CIRCUMFERENTIAL WELD: CIRCUMFERENTIAL
- FLAW-SIZE (DEPTH) DISTRIBUTION: MARSHALL

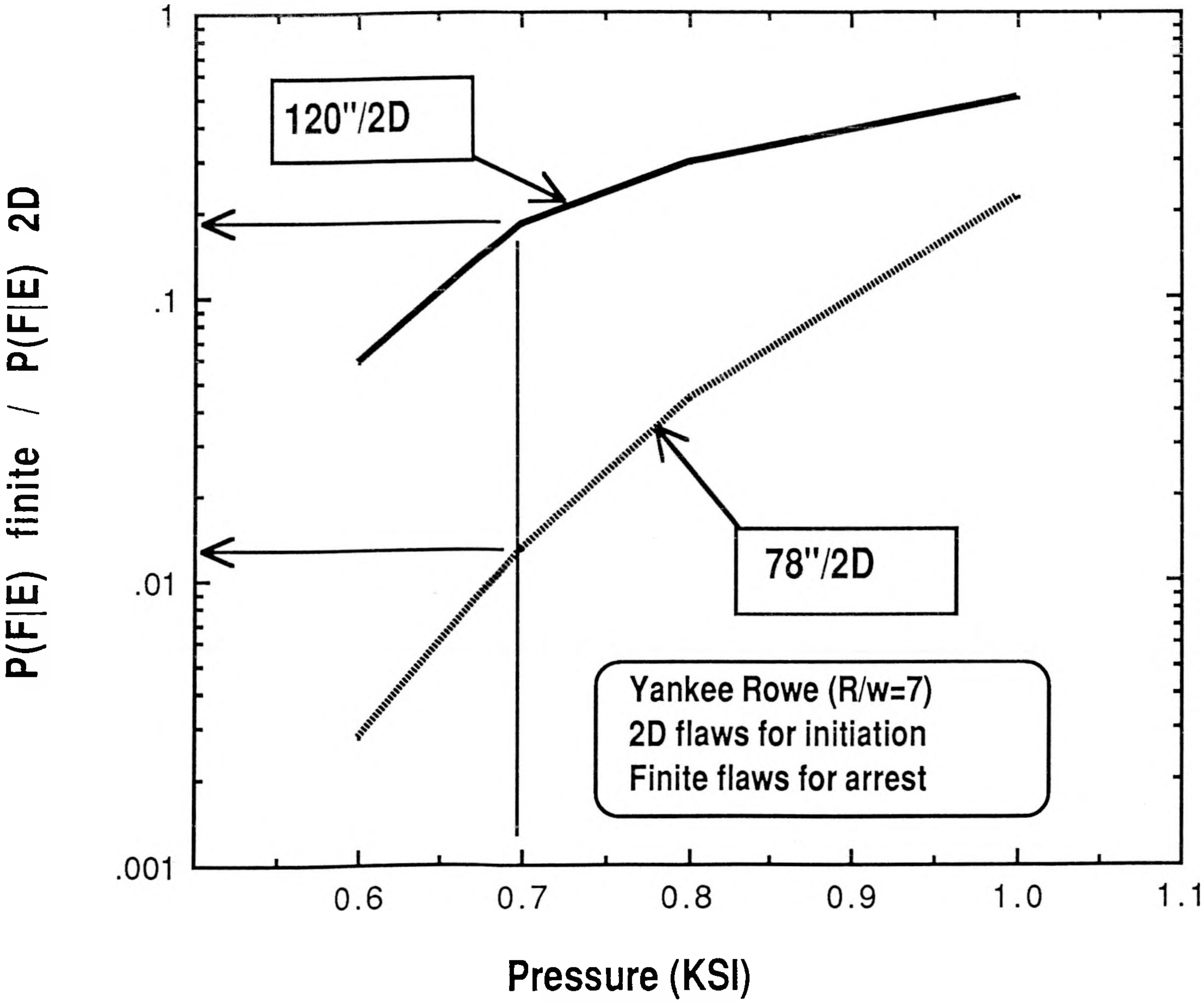
FLAW-RELATED DETAILS (continued)

- FLAW-DENSITY:
  - WELDS: 45 flaws/m^3 (mean value)
  - PLATE: 4.5 flaws/m^3 (mean value)

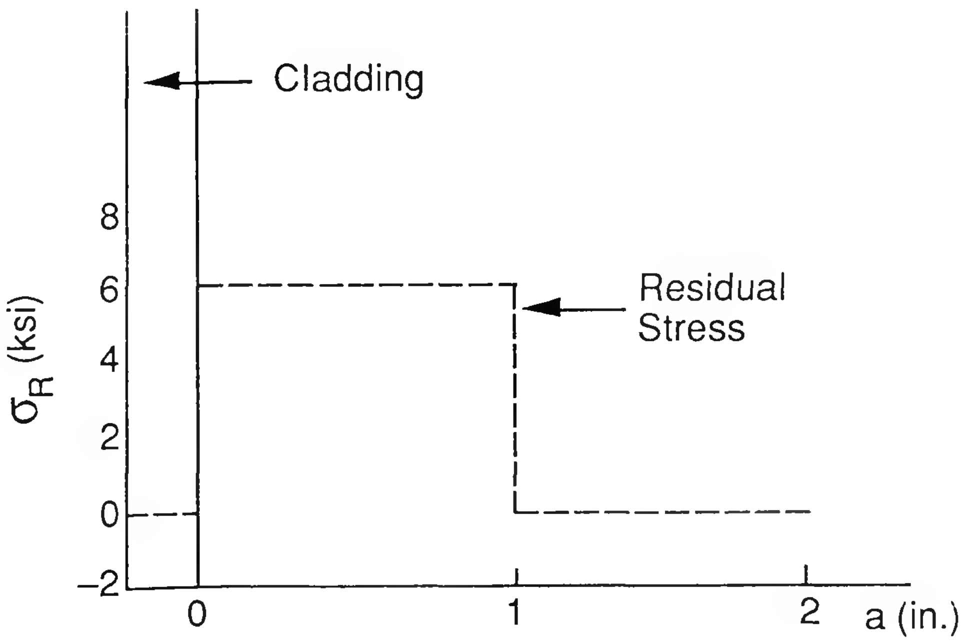
- FLAW LOCATION WITHIN REGION
  - INITIAL FLAW SHORT (SEMICIRCULAR)
  - RANDOM SELECTION OF LOCATION WITHIN REGION (ϕ,z GRID SYSTEM)
  - CORRESPONDING LOCAL FLUENCE FOR INITIAL INITIATION
  - CORRESPONDING MAX FLUENCE IN FLAW PLANE FOR ARREST AND REINITIATION



"BENEFIT" OF FINITE-LENGTH OF ARRESTED FLAW SENSITIVE TO PRESSURE



RESIDUAL STRESS INCLUDED FOR INITIAL INITIATION OF FLAWS WITH a ≤ 1.0 in.



FRACTURE TOUGHNESS-RELATED INFORMATION

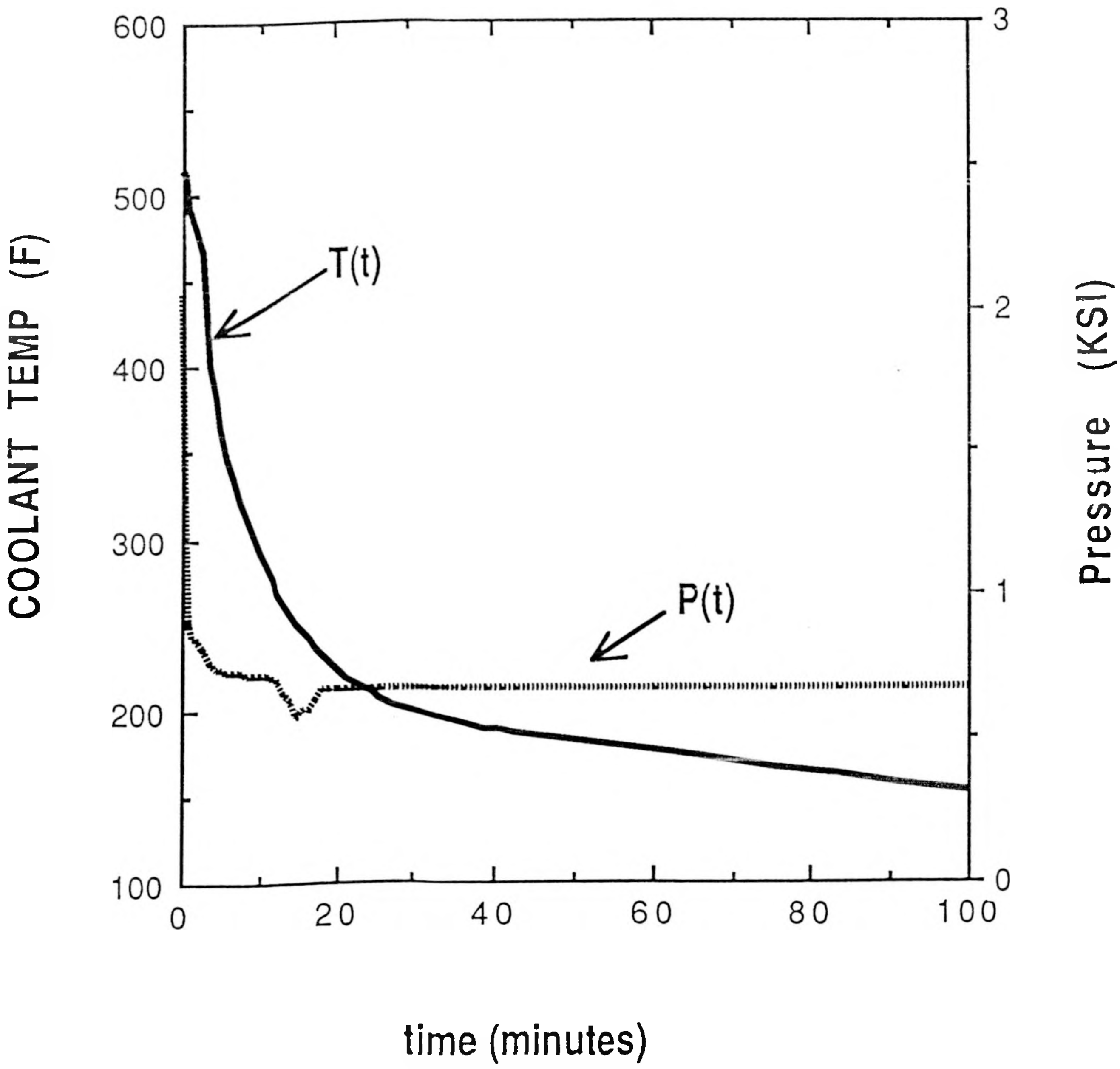
- ΔRT_{NDT}

  - WELDS:
    - R.G. 1.99, REV. 2 + LTCF (50°F)
    - Cu (MEAN AND DISTRIBUTION) OBTAINED FROM DATA ON NUMEROUS LINDE-80 TEST WELDS
  - UPPER PLATE: ODETTE (SURVEILLANCE DATA)
  - LOWER PLATE: ODETTE (UP SURVEILLANCE DATA +80°F FOR Ni)

- K_{Ic}, K_{Ia}: ASME LOWER BOUND CURVES CONVERTED TO MEAN CURVES WITH DISTRIBUTIONS

- FRACTURE TOUGHNESS OF CLADDING ASSUMED SAME AS THAT FOR BASE MATERIAL

HYPOTHETICAL PTS TRANSIENT (SBLOCA WITH STAGNATION), USED FOR ILLUSTRATION ONLY, CONSISTS OF LOW PRESSURE BUT SEVERE THERMAL SHOCK

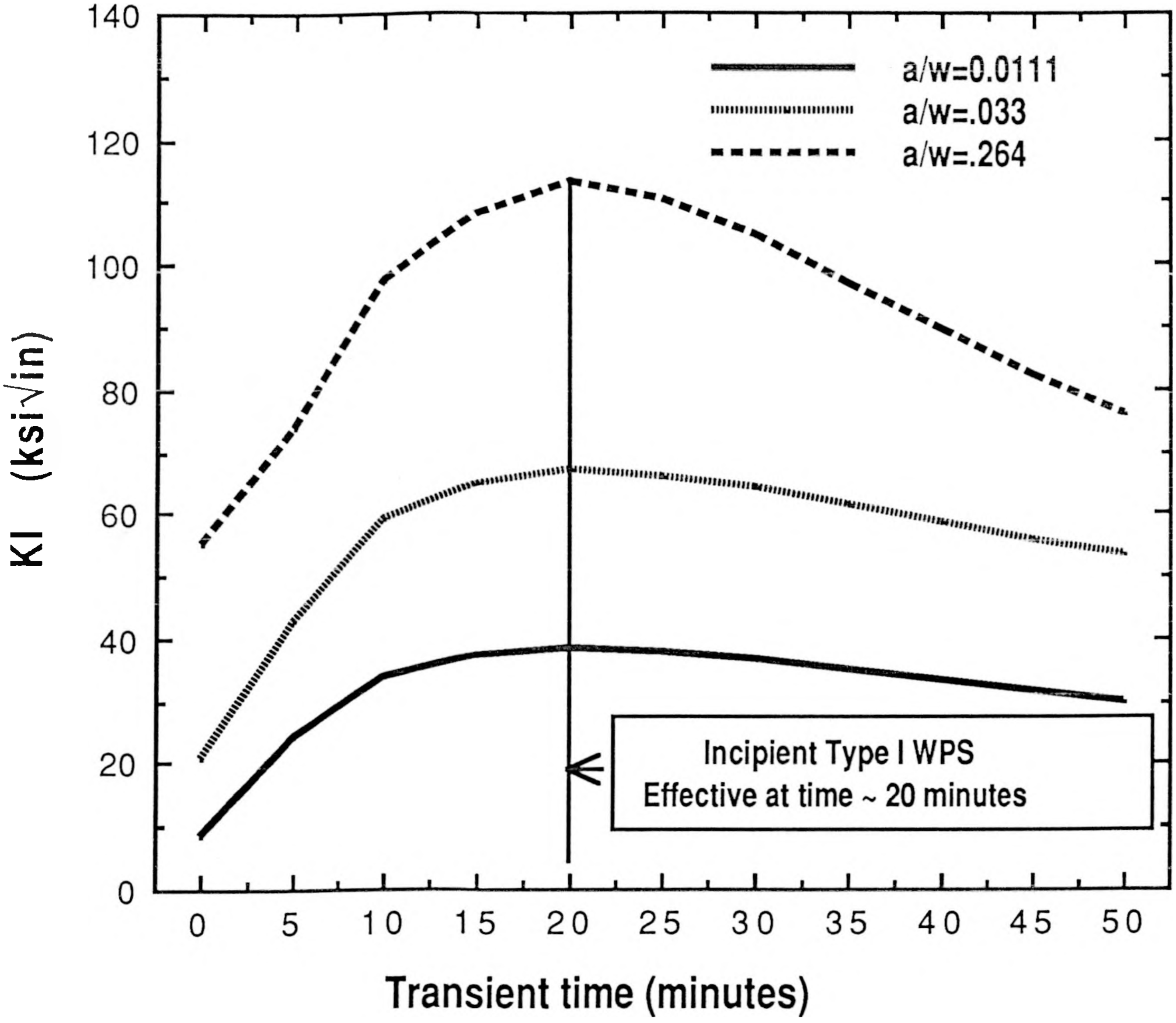


RESULTS OF ORNL ANALYSIS INDICATE THAT PLATE CONTRIBUTION TO P(F|E) FIVE TIMES THAT OF WELDS, AND LOWER PLATE IS DOMINANT REGION (HYPOTHETICAL SEVERE PTS TRANSIENT)

Region	Fluence (maximum)[a] (n/cm^2 E19)	RT_{NDT} (maximum)[a] (°F)	Flaw density (flaw/m^3)	Number of flaws	$\hat{P}(F\|E)$[b] (2D flaws)	$P(F\|E)$[b] (2D flaws)	$P(F\|E)$[b] (finite flaws)
UAW[c]	1.13	274	45	0.86	0.068	0.058	0.0117
LAW[d]	1.13	274	45	0.38	0.045	0.017	0.0034
CW[e]	2.44	316	45	3.48	0.0021	0.0073	0.0073
						Subtotal	0.0224
UP (ASW)[f]	2.74	281	4.5	9.5	0.020	0.190	0.038
UP (BSW)[g]	2.74	281	4.5	8.8	0.0035	0.031	0.0062
LP (ASW)[h]	2.44	352	4.5	4.2	0.070	0.294	0.059
LP (BSW)[i]	2.44	352	4.5	3.9	0.018	0.070	0.0140
						Subtotal	0.117
			Total	31			0.140

[a]Space-wise maximum of mean values
[b]Ignores warm prestressing
[c]Upper axial weld
[d]Lower axial weld
[e]Circumferential weld
[f]Upper plate, at spot welds
[g]Upper plate, between spot welds
[h]Lower plate, at spot welds
[i]Lower plate, between spot welds

INCLUSION OF WPS (TYPE I) IN YR SBLOCA7 ANALYSIS REDUCES P(F|E) BY FACTOR OF ~30



INCLUSION OF WPS (TYPE I) IN YR SBLOCA7 ANALYSIS REDUCES P(F|E) BY FACTOR OF ~30 (continued)