SPECIALIZED TOPIC WORKSHOP ON PRESSURIZED THERMAL SHOCK

POTENTIAL EFFECT OF FRACTURE TECHNOLOGY ON IPTS ANALYSIS (FRACTURE TOUGHNESS: K_{Ia} and K_{Ic} and Warm Prestressing)*

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CONF-9010196--2-Vugraphs
DE91 000396

SUMMARY

A major nuclear plant life extension issue to be confronted in the 1990's is pressure vessel integrity for the pressurized thermal shock (PTS) loading condition. Governing criteria associated with PTS are included in "The PTS Rule" (10 CFR 50.61) and Regulatory Guide 1.154: *Format and Content of Plant-Specific Pressurized Thermal Shock Safety Analysis Reports For Pressurized Water Reactors*. The results of the Integrated Pressurized Thermal Shock (IPTS) Program, along with risk assessments and fracture analyses performed by the NRC and reactor system vendors, contributed to the derivation of the PTS Rule.

The PTS rule established screening criteria in the form of limiting values of the reference nil ductility transition temperature (RT_{NDT}) of the reactor pressure vessel. The PTS rule requires that plant-specific safety analyses be performed for any plant that is intended to operate beyond the screening criteria. Regulatory Guide 1.154 provides guidance for utilities on how to perform the plant-specific safety analysis. It references the IPTS study as an acceptable method for performing the probabilistic fracture mechanics portion of the plant specific safety analysis.

The NRC IPTS study was initiated in 1981 and was completed in 1985. In the years since the IPTS studies were performed, the fracture toughness *initiation* and *arrest* data bases have been enlarged to include data with distinguishing characteristics that could potentially impact future PWR pressure vessel probabilistic assessments. It is anticipated that some plants will exceed the PTS screening criteria during this decade; therefore, evaluating the effect of the expanded fracture toughness databases on the results of IPTS-type probabilistic fracture mechanics analyses is appropriate and timely.

Over the last several years, the Heavy Section Steel Technology (HSST) Program at the Oak Ridge National Laboratory (ORNL) has

*Research sponsored by the Office of Nuclear Regulatory Research, U.S. Nuclear Regulatory Commission under Interagency Agreement 1886-8011-9B with the U.S. Department of Energy under Contract DE-AC05-84OR21400 with Martin Marietta Energy Systems, Inc.

performed a series of large-scale fracture-mechanics experiments. The Thermal Shock Experiments (TSE), Pressurized Thermal Shock Experiments (PTSE), and Wide Plate Experiments (WPE) produced K_{IC} and K_{Ia} data that suggest increased mean K_{IC} and K_{Ia} curves relative to the ones used in the IPTS study. Also, the PTSE and WPE have demonstrated that prototypical nuclear reactor pressure vessel steels are capable of arresting a propagating crack at K_I values considerably above 220 MPa$\sqrt{m}$, the implicit limit of the ASME Code and the limit used in the IPTS studies.

Deterministic and probabilistic fracture mechanics (PFM) analyses have recently been performed to evaluate the effect of the high K_{Ia} data on the cleavage fracture response of a nuclear reactor pressure vessel subjected to a PTS scenario. The results of these analyses have shown that the high K_{Ia} data do enhance the crack arrest potential; however, it appears that for high-pressure transients, the enhanced crack arrest potential will usually be negated by unstable ductile tearing. PFM analyses have shown that the high K_{Ia} data reduces the conditional probability of failure [P(F|E)]; however, the reduction appears to be insignificant for dominant high-pressure transients.

Warm prestressing (WPS) has been recognized as an important physical phenomena that can prevent the occurrence of cleavage fracture under certain conditions. The basic premise of Type I WPS, that a crack tip must have increasing plastic strain to propagate, was successfully demonstrated in the TSE and PTSE experiments. The basic premise of Type II WPS, that there can be an effective increase in fracture initiation toughness due to loading history, was successfully demonstrated in the Wide Plate Experiments (WPE). Regulatory Guide 1.154 presently states that the inhibiting effect of WPS should not be assumed.

The sensitivity of P(F|E) to the inhibiting effects of Type I WPS was considered in the original IPTS study; however, the effects were not included in the final results. The IPTS study concluded that the benefit of Type I WPS is transient dependent and in some cases could be quite significant. The primary reasons that Type I WPS was not included in the original IPTS is that the K_I vs. time curves are rather flat for the critical (shallow) flaws, making it difficult to identify the time at which $K_I = 0$. Also, this time is quite sensitive to slight variations in the postulated transient, and each transient calculated in detail represents a category of transients. Therefore, the time during the transient at which Type I WPS is effective is very uncertain. A methodology for including the beneficial effects of Type I WPS in IPTS-type PFM analyses is currently under review.

POTENTIAL EFFECT OF FRACTURE TECHNOLOGY ON IPTS ANALYSIS (FRACTURE TOUGHNESS: K_{Ic} AND K_{Ia} AND WARM PRESTRESSING)*

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HOLIDAY INN CROWNE PLAZA HOTEL, ROCKVILLE, MARYLAND
SEPTEMBER 27, 1990

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*Research sponsored by the Office of Nuclear Regulatory Research, U.S. Nuclear Regulatory Commission under Interagency Agreement 1886-8011-9B with the U.S. Department of Energy under Contract DE-AC05-84OR21400 with Martin Marietta Energy Systems, Inc.

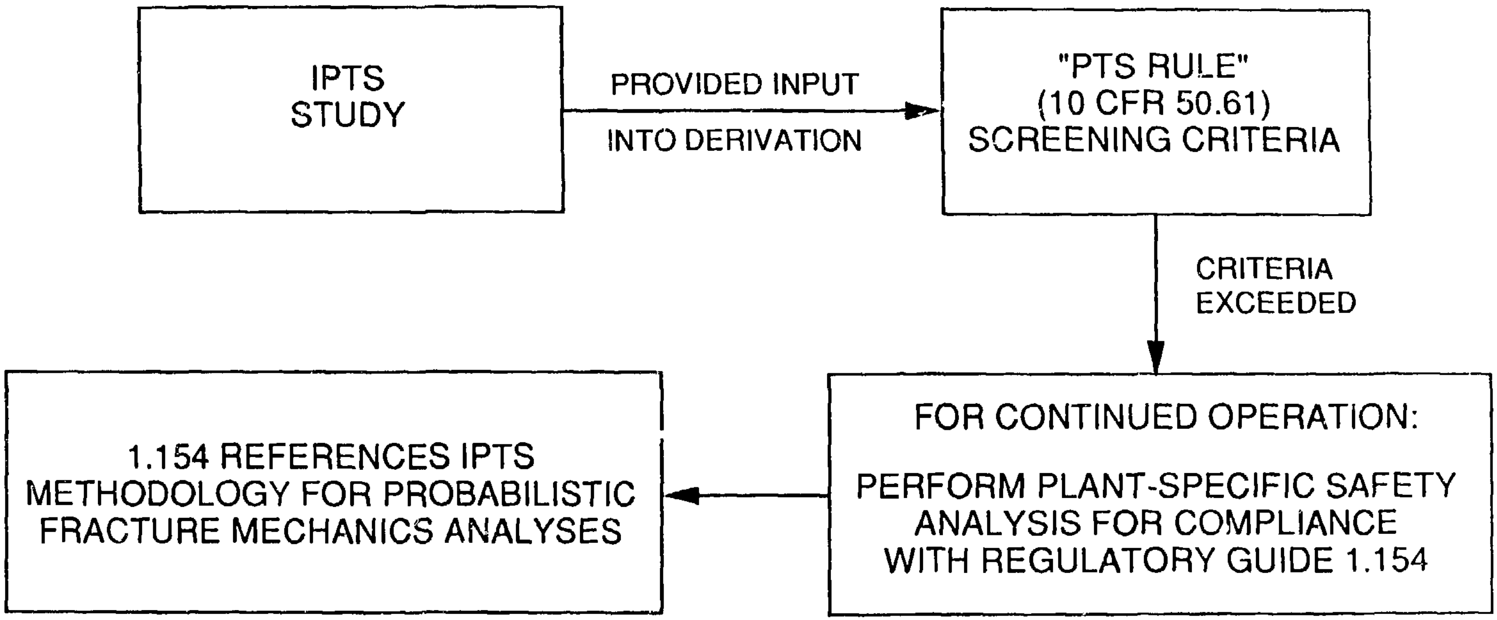
PRESSURIZED THERMAL SHOCK IS A MAJOR PLANT LIFE EXTENSION ISSUE FOR THE 1990's

GOVERNING CRITERIA FOR PTS:

- PTS RULE (10 CFR 50.61)
- NUCLEAR REGULATORY GUIDE 1.154

SOME U.S. PLANTS ANTICIPATED TO EXCEED PTS RULE SCREENING CRITERIA BEFORE THE END OF THIS DECADE

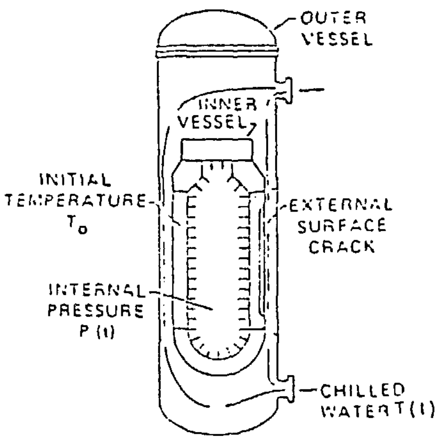
IPTS PROBABILISTIC METHODOLOGY COULD POTENTIALLY IMPACT FUTURE LICENSING DECISIONS



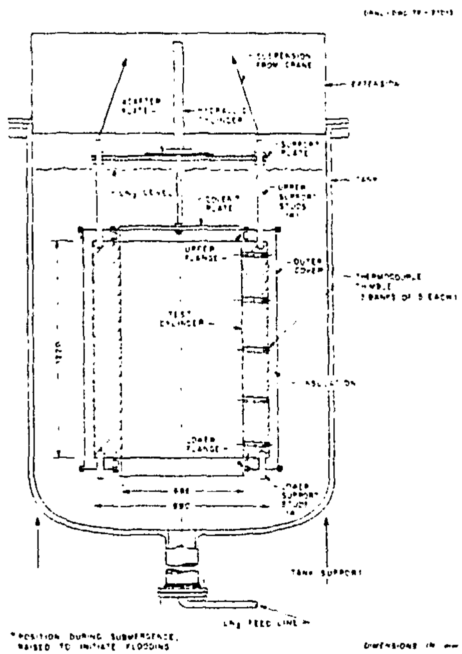
FRACTURE TECHNOLOGY DEVELOPMENT WHICH COULD IMPACT IPTS METHODOLOGY

- ENLARGED FRACTURE TOUGHNESS DATA BASES
  - LARGE SPECIMEN K_{Ic} DATA
  - LARGE SPECIMEN K_{Ia} DATA
- WARM PRESTRESSING
  - INCLUSION OF BENEFICIAL EFFECTS OF WPS WOULD REDUCE PROBABILITY OF FAILURE

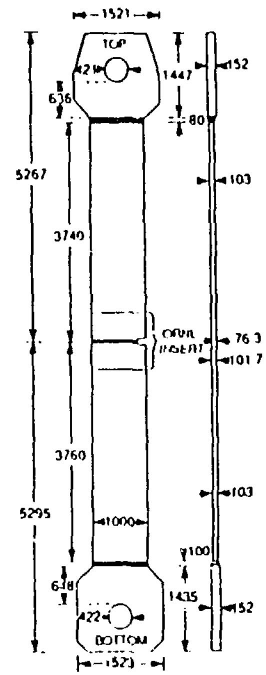
THE HSST PROGRAM HAS CONTRIBUTED TO FRACTURE TECHNOLOGY DEVELOPMENT BY PERFORMING LARGE-SCALE FRACTURE-MECHANICS EXPERIMENTS



PTSE SPECIMEN



TSE SPECIMEN

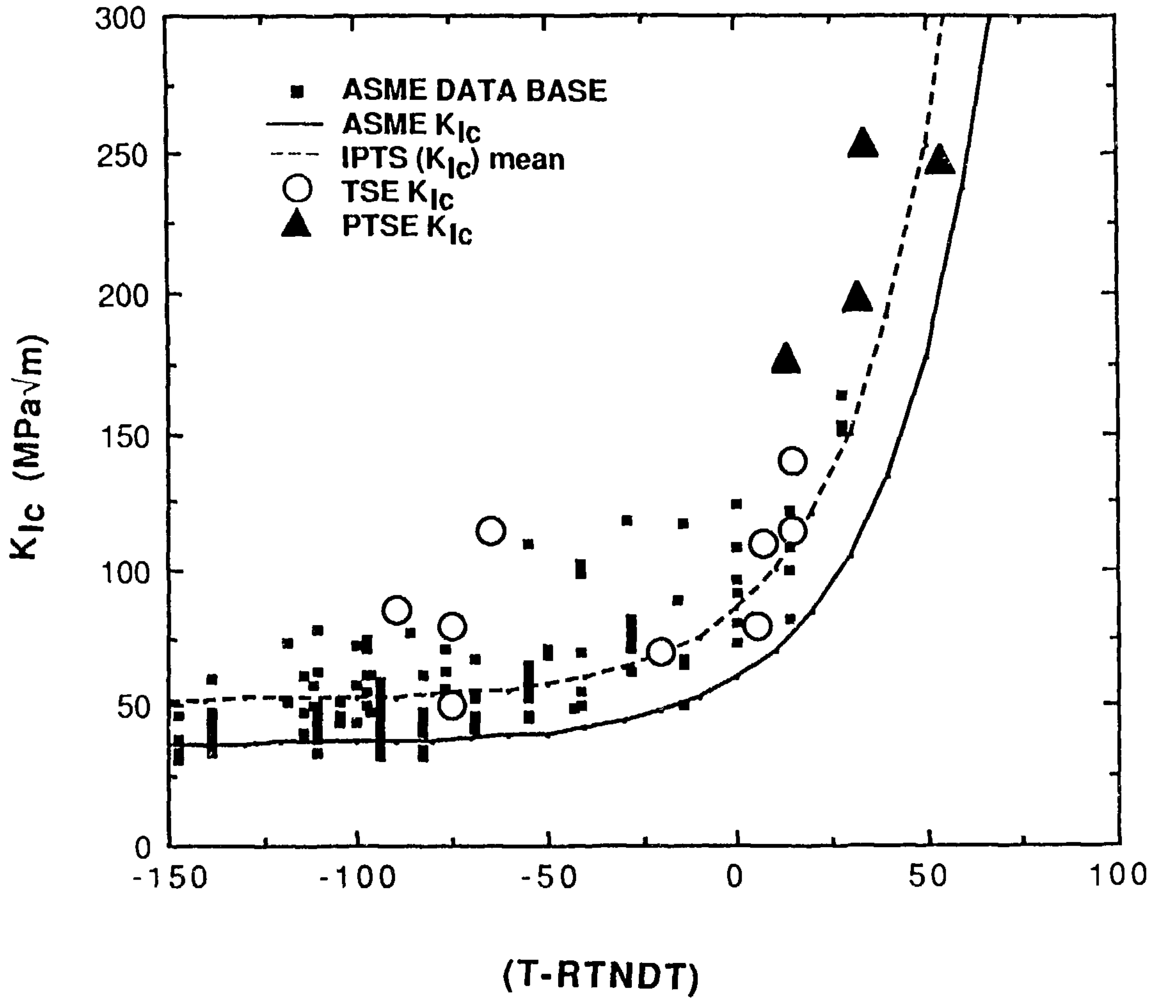


(a) SPECIMEN WP 2 5

WIDE-PLATE EXPERIMENT (WPE) SPECIMEN

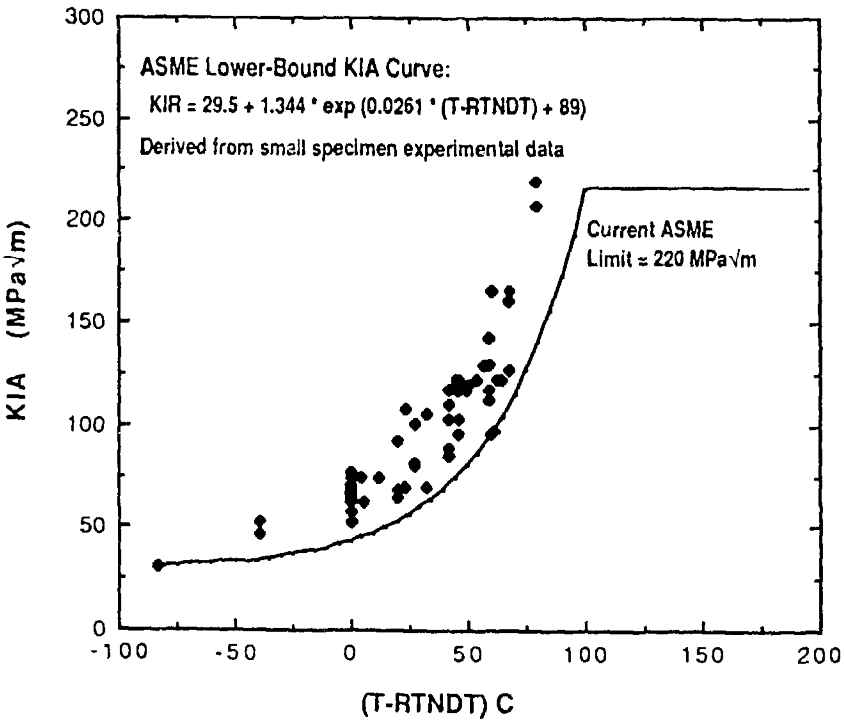
- GENERATED K_{Ic} FOR PROTOTYPIC SCENARIOS
- GENERATED K_{Ia} FOR PROTOTYPIC SCENARIOS

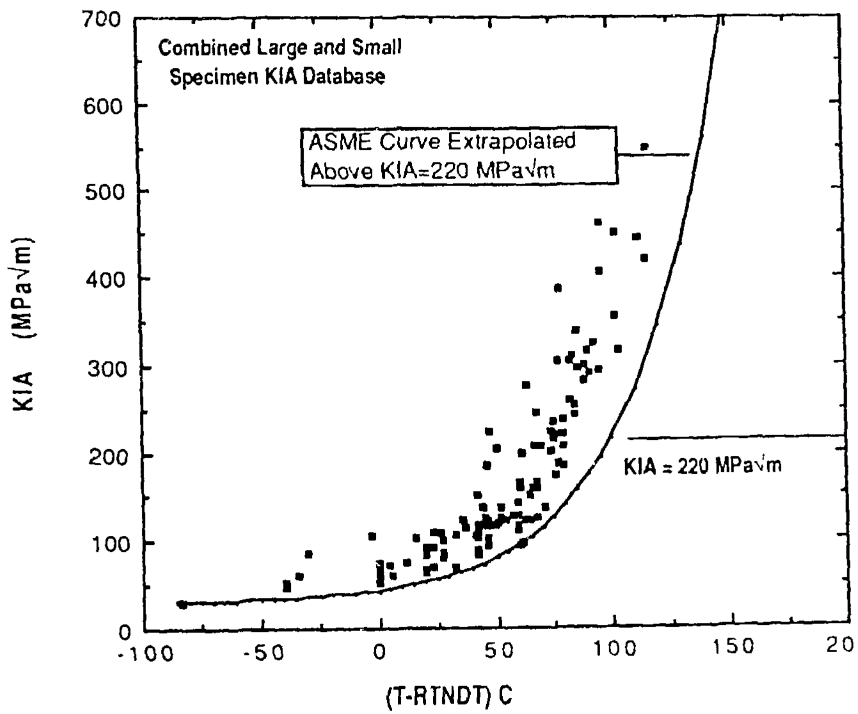
HSST LARGE SPECIMEN K_{Ic} DATA SUGGEST INCREASED MEAN CURVE RELATIVE TO IPTS MEAN K_{Ic} CURVE



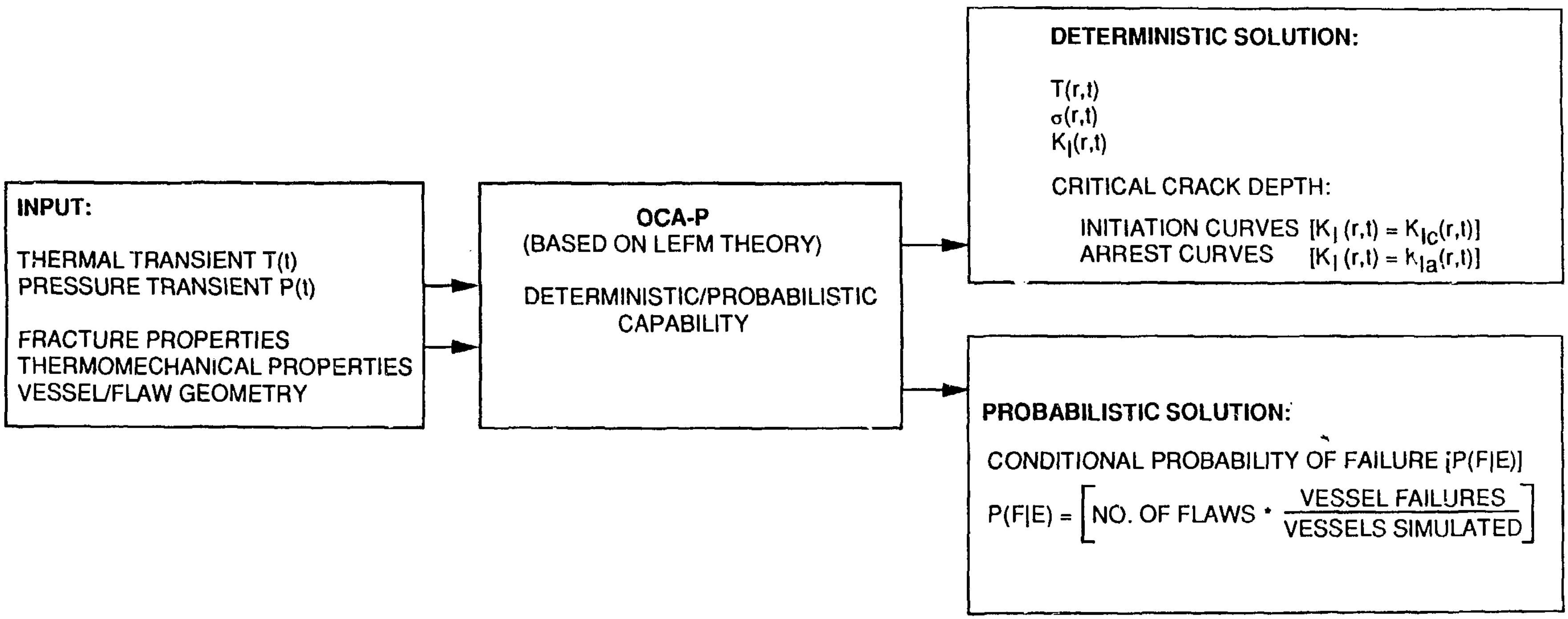
HSST DEMONSTRATED CRACK ARREST WELL ABOVE ASME LIMIT OF 220 MPa√m

- LARGE-SCALE FRACTURE-MECHANICS EXPERIMENTS
- PROTOTYPICAL NUCLEAR REACTOR PRESSURE VESSEL STEELS

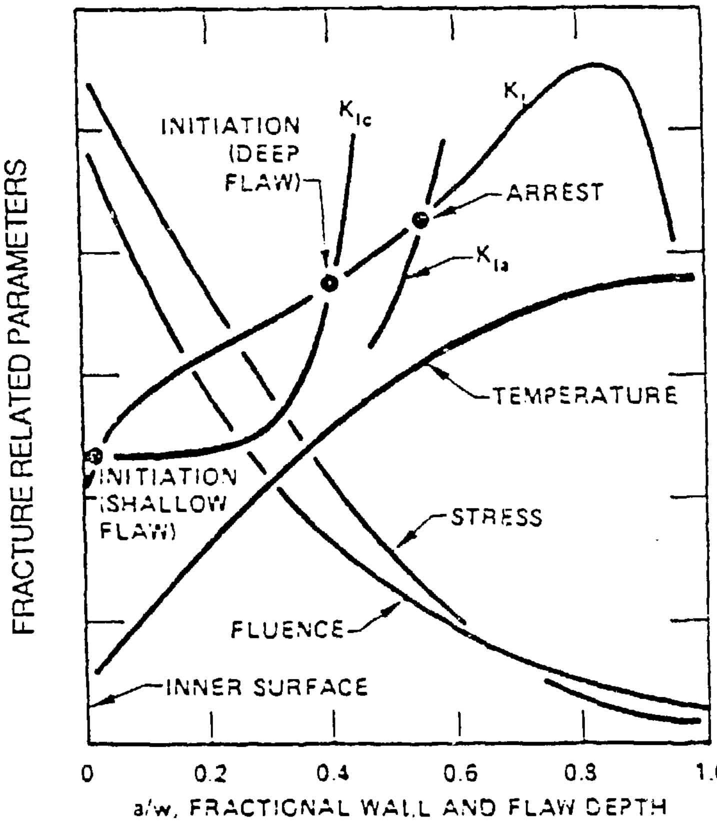




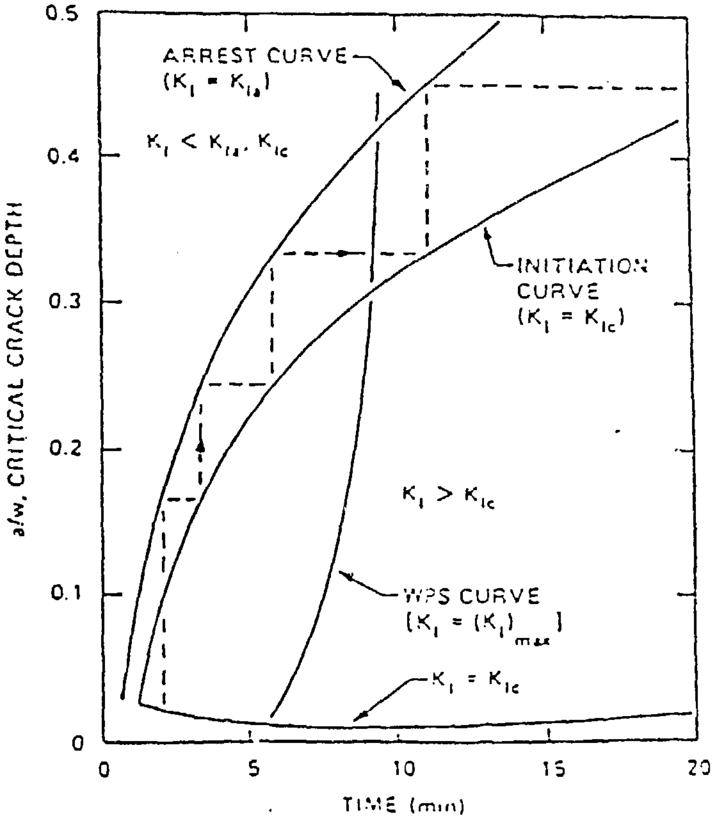
DETERMINISTIC AND PROBABILISTIC FRACTURE MECHANICS ANALYSES WERE PERFORMED TO EVALUATE EFFECT OF HIGH K_{Ia} ON CLEAVAGE RESPONSE OF RPV SUBJECTED TO PTS LOADING



CRITICAL-CRACK-DEPTH CURVES PREDICT CLEAVAGE FRACTURE RESPONSE OF FLAW DURING PTS



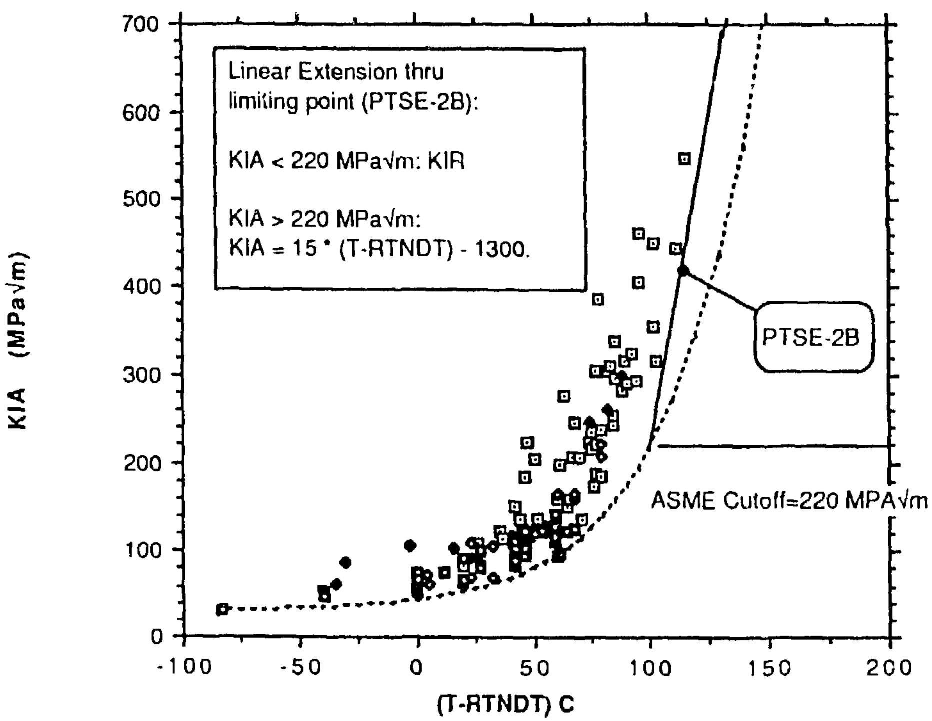
FRACTURE RELATED PARAMETERS IN A REACTOR PRESSURE VESSEL WALL AT A GIVEN INSTANT IN TIME DURING A PTS TRANSIENT

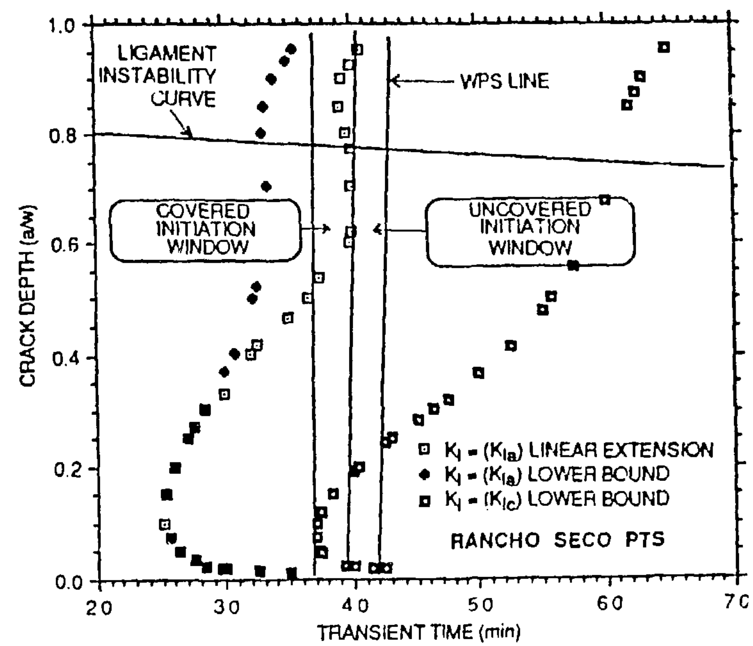


CRITICAL-CRACK-DEPTH CURVES DEFINED BY PLOTTING THE LOCUS OF CRACK-INITIATION AND CRACK-ARREST VALUES AS A FUNCTION OF TIME DURING A PTS TRANSIENT

APPLICATION OF LARGE-SPECIMEN K_{Ia} DATA ENHANCES CRACK-ARREST POTENTIAL

- DETERMINISTIC FRACTURE MECHANICS ANALYSES
- RANCHO SECO (HIGH PRESSURE) PTS EVENT





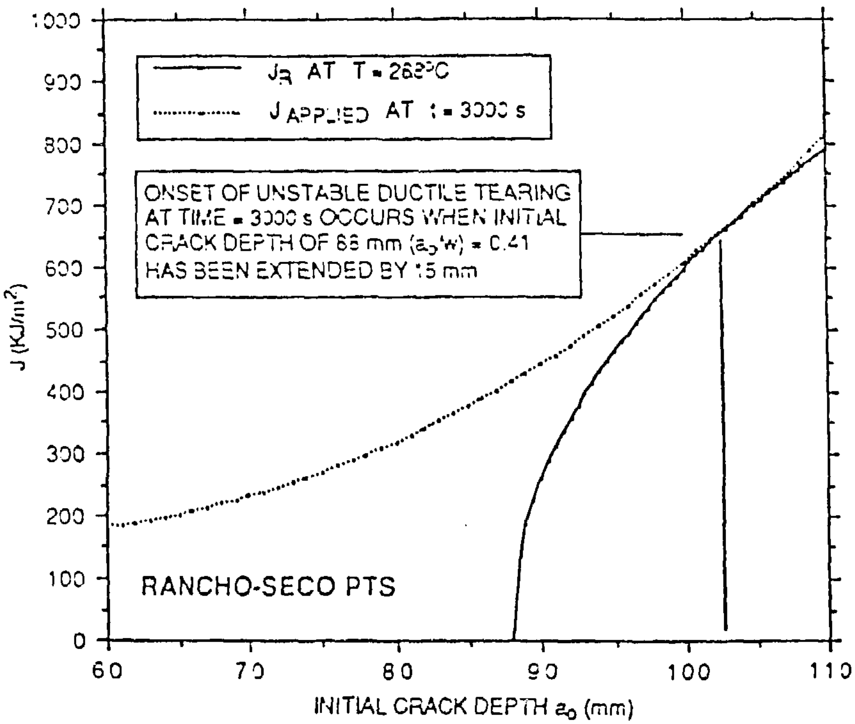
DUCTILE TEARING CONSIDERATIONS

- MANY OF THE CRACK ARRESTS THAT OCCURRED AT VALUES OF $K_I > 220$ MPa$\sqrt{m}$ WERE FOLLOWED IMMEDIATELY BY A FRACTURE MODE CONVERSION TO UNSTABLE DUCTILE TEARING LEADING TO FAILURE

- UNSTABLE DUCTILE TEARING MUST BE CONSIDERED BEFORE CONCLUDING THAT ENHANCED CLEAVAGE CRACK-ARREST POTENTIAL DECREASES THE PROBABILITY OF FAILURE

- DERIVED CRITICAL CRACK DEPTHS THAT APPROXIMATE THE ONSET OF UNSTABLE DUCTILE TEARING, i.e., THE CRACK DEPTH BEYOND WHICH DUCTILE TEARING BECOMES UNSTABLE

UNSTABLE DUCTILE TEARING CRITICAL CRACK DEPTHS CORRESPOND TO POINT OF TANGENCY BETWEEN TEARING RESISTANCE (J_R) CURVE AND $J_{APPLIED}$ CURVE

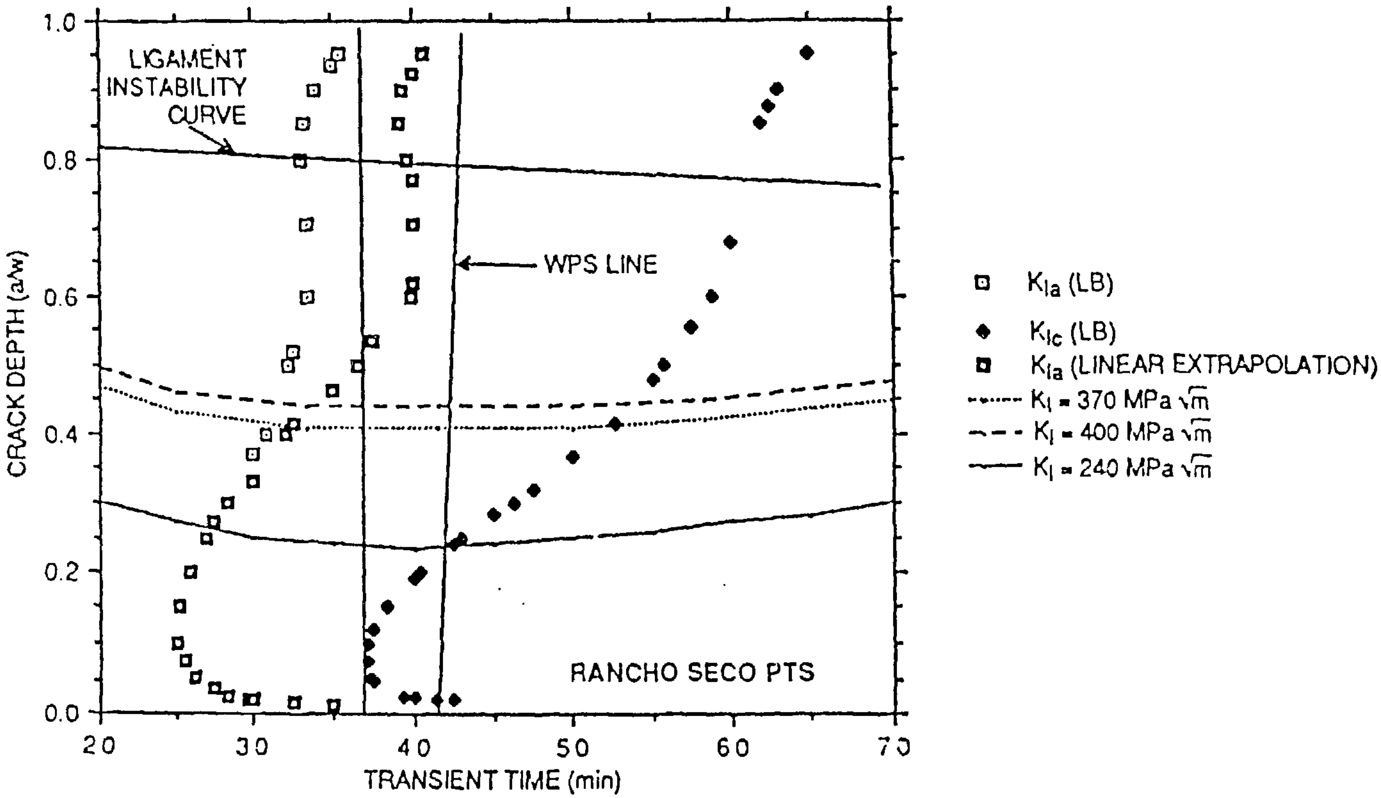


POINT OF TANGENCY REPRESENTS INITIAL FLAW DEPTH (a_o) PLUS CRACK EXTENSION (Δ) DUE TO TEARING UP TO POINT OF INSTABILITY

APPROXIMATIONS FOR THE ONSET OF UNSTABLE DUCTILE TEARING WERE DERIVED

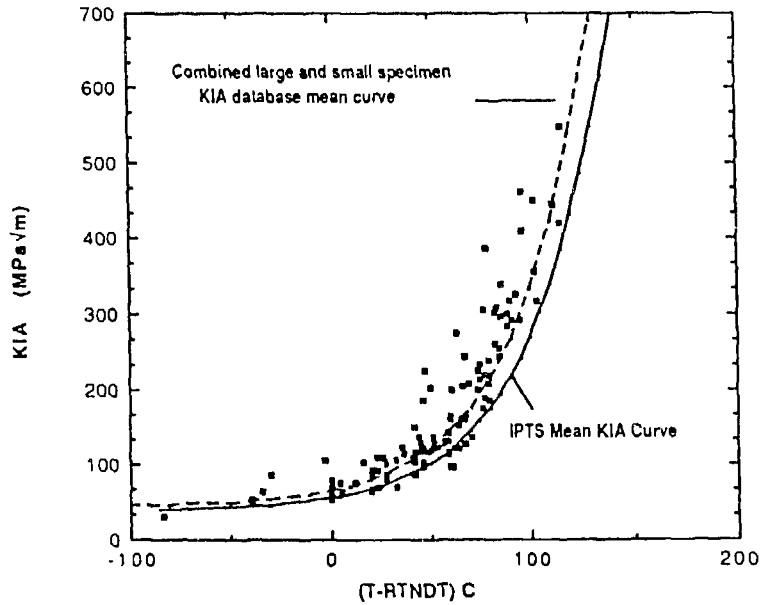
- ~240 MPa$\sqrt{m}$ FOR LUSW MATERIAL
- ~370 MPa$\sqrt{m}$ FOR A533-B STEEL

FOR RANCHO SECO (HP PTS EVENT), THE ENHANCED CRACK-ARREST POTENTIAL IS NEGATED BY THE INCLUSION OF UNSTABLE DUCTILE TEARING



APPLICATION OF HIGH K_{Ia} DATA HAS THE POTENTIAL FOR DECREASING P(F|E) RELATIVE TO VALUES CALCULATED IN ORIGINAL IPTS

- ORIGINAL IPTS ANALYSES ASSUMED:
  - $(K_{Ia})_{max} = 220\ MPa\sqrt{m}$
  - $(K_{Ia})_{mean} = 1.25 * K_{IR}$
  - ONSET OF UNSTABLE DUCTILE TEARING = $220\ MPa\sqrt{m}$



- POTENTIAL PRIMARILY EXISTS FOR:
  - LOWER PRESSURE TRANSIENTS
  - NON-LUSW MATERIALS

ENHANCED K_{Ia} DATA DOES NOT APPEAR TO SIGNIFICANTLY DECREASE P(F|E) FOR HIGH PRESSURE TRANSIENTS

CASE	P(F|E)	$P(F\|E)_{WPS}$	$\frac{P(F\|E)_{WPS}}{P(F\|E)}$	% FAILURES DUE TO REINITIATIONS
BASE (IPTS PFM MODEL)	2.1 E-2	4.4 E-3	.21	0.2%
ENHANCED K_{Ia}	1.9 E-2	3.1 E-3	.16	6.0%

P(F|E) – CALCULATED CONDITIONAL PROBABILITY OF VESSEL FAILURE WITHOUT INCLUDING TYPE I WARM PRESTRESS

$P(F|E)_{WPS}$ – CALCULATED CONDITIONAL PROBABILITY OF VESSEL FAILURE INCLUDING TYPE I WARM PRESTRESS

HSST HAS DEMONSTRATED WPS CAN PREVENT THE OCCURRENCE OF CLEAVAGE FRACTURE UNDER CERTAIN CONDITIONS

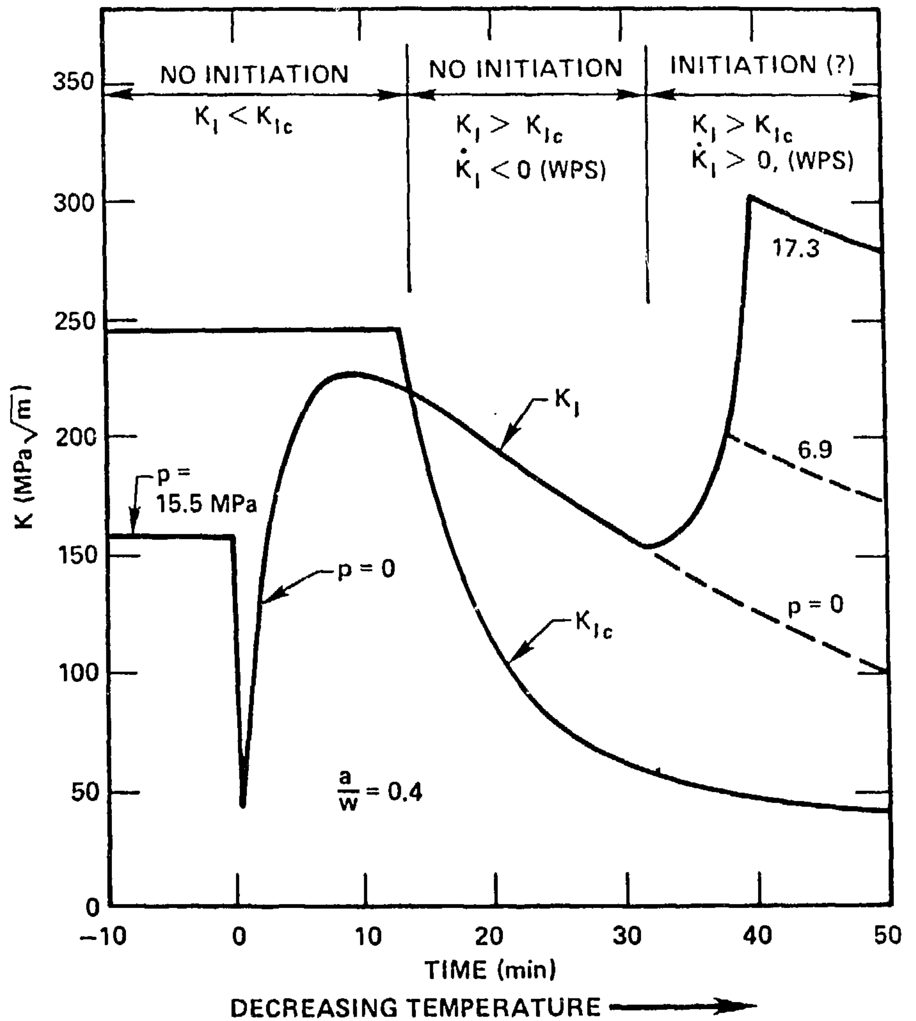
TYPE I WPS:

- CLEAVAGE FRACTURE CANNOT INITIATE WHEN K_I IS DECREASING WITH TIME ($\dot{K}_I < 0$)
- CRACK TIP MUST HAVE INCREASING PLASTIC STRAIN TO PROPAGATE
- DEMONSTRATED EXPERIMENTALLY (PTSE, TSE)

TYPE II WPS:

- EFFECTIVE TOUGHNESS ELEVATION DUE TO LOADING HISTORY, i.e., CRACK-TIP CONDITIONING
- DEMONSTRATED EXPERIMENTALLY (WPE)

WPS CAN PREVENT CLEAVAGE INITIATION (TYPE I) AND CAN EFFECTIVELY INCREASE THE FRACTURE TOUGHNESS (TYPE II)



THE EFFECTS OF WPS WERE CONSIDERED IN THE CALCULATION OF P(F|E) IN THE IPTS

HB ROBINSON TRANSIENTS

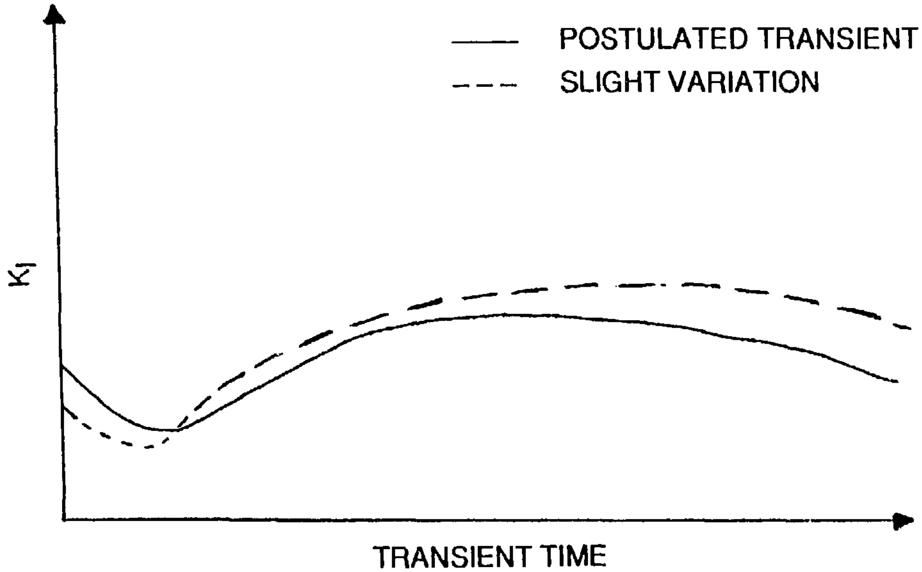
Transient	$P(F\|E)_0$[a]	Time of WPS (min)	$P(F\|E)_{w/WPS}$[a] / $P(F\|E)_0$
9.41	9E−7	26	$<2 \times 10^{-3}$
9.33	2E−7	48	0.01
9.19B	9.5E−5	26	$<3 \times 10^{-3}$
9.43	1.2E−5	54	0.2
9.20B	1.0E−4	26	$<3 \times 10^{-3}$
9.22B	5.5E−4	50	0.2

[a] $P(F|E)_0$ is the original mean value at 32 EFPY; $P(F|E)_{w/WPS}$ is the value of $P(F|E)$ with warm prestressing included in the analysis.

- BENEFIT OF WPS CAN BE LARGE
- BENEFIT IS TRANSIENT DEPENDENT

THE EFFECT OF TYPE I WPS WAS NOT INCLUDED IN THE FINAL RESULTS OF P(F|E) IN THE IPTS

- K_I VS TIME CURVES FOR CRITICAL (SHALLOW) FLAWS ARE RELATIVELY FLAT
- EACH TRANSIENT REPRESENTS A CATEGORY OF TRANSIENTS. THE TIME WHEN $\dot{K}_I = 0$ IS SENSITIVE TO SLIGHT VARIATIONS IN THE POSTULATED TRANSIENT.



- LARGE UNCERTAINTY FOR PRECISE DETERMINATION OF TIME WHEN TYPE I WPS IS EFFECTIVE

A METHODOLOGY FOR INCLUDING THE BENEFICIAL EFFECTS OF TYPE I WPS INTO IPTS-TYPE ANALYSIS COULD BE DEVELOPED

- INCLUDE TYPE I WPS FOR MONOTONICALLY DECREASING K_I VS TIME
- DEVELOP ANALYTICAL CRITERIA FOR DEFINING TIME AT WHICH $\dot{K}_I = 0$