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OVERVIEW OF IPTS STUDY*

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PRESENTED AT U.S.–JAPAN SPECIALIZED TOPIC WORKSHOP (STW) ON PRESSURIZED-THERMAL-SHOCK

HOLIDAY INN CROWNE PLAZA HOTEL
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OVERVIEW OF THE INTEGRATED PRESSURIZED THERMAL-SHOCK (IPTS) STUDY*

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SUMMARY

Postulation of a pressurized water reactor (PWR) large-break loss-of-coolant accident (LOCA) and the subsequent inclusion of provisions for injecting low-temperature emergency core coolant (ECC) in response to the LOCA eventually led to concern over a consequential thermal shock to the pressure vessel. This concern, plus the knowledge that (1) copper significantly enhances the radiation-induced reduction in fracture toughness, (2) "high" concentrations of copper probably exist in some vessel welds and heats of base metal, (3) low-temperature, primary-system coolant can result from transient-induced mechanisms other than injection of ECC, and (4) repressurization of the primary system during some overcooling transients can enhance the potential for vessel failure, set the stage for the pressurized-thermal-shock (PTS) issue.

By the early 1980s, PTS-related, deterministic, vessel-integrity studies sponsored by the U.S. Nuclear Regulatory Commission (NRC) indicated a potential for failure of some PWR vessels before design end of life, in the event of a postulated severe PTS transient. In response, the NRC established screening criteria, in the form of limiting values of the reference nil-ductility transition temperature (RT_{NDT}), and initiated the development of a probabilistic methodology for evaluating vessel integrity. This latter effort, referred to as the Integrated Pressurized Thermal-Shock (IPTS) Program, included development of techniques for postulating PTS transients, estimating their frequencies, and calculating the probability of vessel failure for a specific transient. Summing the products of frequency of transient and conditional probability of failure for each of the many postulated transients provide a calculated value of the frequency of failure.

The IPTS Program also included the application of the IPTS methodology to three U.S. PWR plants (Oconee-1, Calvert Cliffs-1, and HBRobinson-2)[1,2,3] and the specification of a maximum permissible value of the calculated frequency of vessel failure. With this information available, it was possible to evaluate, for the three specified plants, the adequacy of the screening criteria, that is, to determine whether the specified limiting values of RT_{NDT} corresponded to a calculated frequency of failure less than the maximum permissible.

Another important purpose of the IPTS study was to determine, through application of the IPTS methodology, which design and operating features, parameters, and PTS transients were dominant in affecting the calculated frequency of failure. This information can be used by the utility to direct efforts at reducing the probability of failure. In this regard, the IPTS studies were useful in evaluating the effectiveness of possible remedial measures such as design and operating changes that could reduce the frequency and severity of postulated transients, heating of the ECC, and annealing of the vessel.

The scope of the IPTS Program included the development of a probabilistic fracture-mechanics capability, modification of the TRAC and RELAP5 thermal/hydraulic

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codes,[4,5] and development of the methodology for estimating the uncertainty in the calculated frequency of vessel failure. This latter methodology involves the use of sensitivity studies and multidimensional response surfaces to relate frequency of failure to "all" parameters included in the analysis. In the "best estimate" analysis, which preceded the uncertainty analysis, only fracture-mechanics parameters were simulated.

The OCA–P code,[6] which makes use of Monte Carlo techniques, was used to perform the IPTS Program probabilistic fracture-mechanics analyses. Input to OCA–P includes the primary-system pressure, downcomer coolant temperature, and the fluid-film heat transfer coefficient at the vessel inner surface, all as functions of time in the transient (obtained from thermal/hydraulic analyses). One-dimensional thermal and stress analyses are performed, and unit point-load stress-intensity-factor (K_I) influence coefficients are used in conjunction with the one-dimensional stresses to calculate the K_I values. Fast neutron fluence, copper concentration, fracture toughness (K_{Ic} and K_{Ia}), initial value of RT_{NDT}, the radiation-induced increase in RT_{NDT}, and flaw depth were the only parameters simulated.

Many thousands of PTS transients were postulated, using event trees and eight categories of event initiators. Frequencies of the event-tree end points (PTS transients) were estimated, those below 10^{-7}/reactor year were relegated to the residual category, and the remaining were categorized for the thermal/hydraulic and subsequent fracture-mechanics analyses.

Results of the IPTS study indicated that the dominant transients were different for each of the three plants, and that small differences in plant design and operating procedures can make a big difference in the calculated frequency of failure. The results also indicate that with RT_{NDT} equal to the NRC screening-criteria limiting value, the mean value of the calculated frequency of vessel failure for Calvert Cliffs and HBRobinson is about equal to the maximum permissible value specified in NRC Regulatory Guide 1.154, but for Oconee it is larger. Thus, it appears that generic IPTS evaluations are not appropriate, and that the NRC screening criteria (10CFR50.61) may not be valid for all PWR vessels in the U.S.

The NRC IPTS study was completed in 1985, and since that time there have been discoveries and improvements that should be considered in an update of the IPTS methodology. These include cladding effects; improvements in K_{Ic} that are the result of an enlarged data base and consideration of shallow-flaw effects and out-of-plane strain; ductile tearing and tearing instability; and azimuthal variations in temperatures that can result from flow channeling in the downcomer. Each of those features is being investigated and evaluated for inclusion in the NRC IPTS methodology.

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PURPOSE OF IPTS PROGRAM

- DEVELOP PROBABILISTIC METHODOLOGY FOR EVALUATING INTEGRITY OF PWR VESSELS
- DETERMINE DOMINANT FEATURES/ PARAMETERS/TRANSIENTS AFFECTING CALCULATED FREQUENCY OF VESSEL FAILURE
- EVALUATE EFFECTIVENESS OF POSSIBLE REMEDIAL MEASURES
- EXAMINE ADEQUACY OF NRC PTS-RULE SCREENING CRITERIA (10CFR50.61)

SCOPE OF IPTS PROGRAM

- DEVELOPMENT OF A PROBABILISTIC FRACTURE-MECHANICS METHODOLOGY

- MODIFICATION OF TRAC AND RELAP-5 THERMAL/HYDRAULIC CODES

- DEVELOPMENT OF METHODOLOGY AND ACQUISITION OF DATA FOR POSTULATING PTS TRANSIENTS AND ESTIMATION OF THEIR FREQUENCIES

- DEVELOPMENT OF METHODOLOGY FOR AN UNCERTAINTY ANALYSIS OF FREQUENCY OF VESSEL FAILURE

- APPLICATION OF IPTS METHODOLOGY TO SEVERAL U.S. PWR PLANTS

THREE PWR PLANTS, REPRESENTING THREE U.S. NSSS VENDORS AND EXPECTED TO HAVE RELATIVELY HIGH CALCULATED FREQUENCY OF VESSEL FAILURE, WERE SELECTED FOR INCLUSION IN THE IPTS STUDY

PLANT	NSSS VENDOR	VESSEL FABRICATION
• OCONEE UNIT 1	B&W	B&W
• CALVERT CLIFFS UNIT 1	CE	CE
• H.B.ROBINSON UNIT 2	W	CE

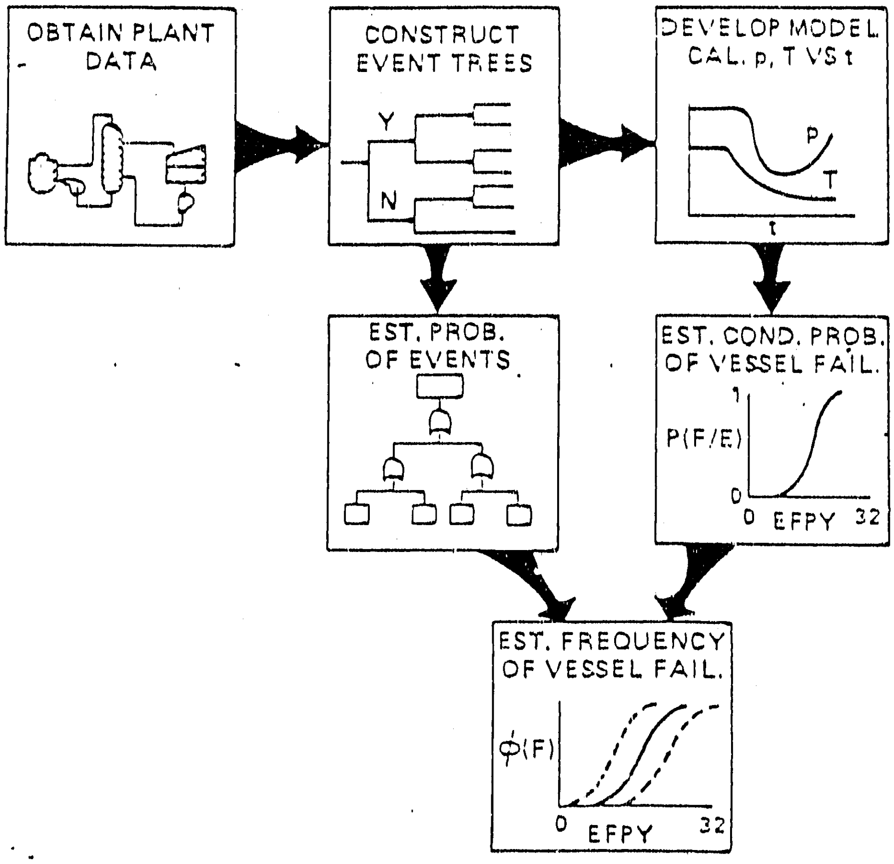
THE THREE IPTS-STUDY PWR PLANTS HAVE SEVERAL SIGNIFICANTLY DIFFERENT BASIC FEATURES

- OCONEE-1
  - VENT VALVES
  - LOW FLUENCE RATE
  - HIGH Cu AND Ni

- CALVERT CLIFFS-1
  - LOW-HEAD HPI
  - HIGH FLUENCE RATE
  - LOW Cu
  - LOW $RTNDT_0$

- H. B. ROBINSON-2
  - LOW-HEAD HPI
  - THREE LOOPS
  - HIGH FLUENCE RATE
  - LOW Cu AND Ni
  - LOW $RTNDT_0$
  - STEAMLINE FLOW RESTRICTORS

IPTS APPROACH CONSISTS OF SIX BASIC STEPS



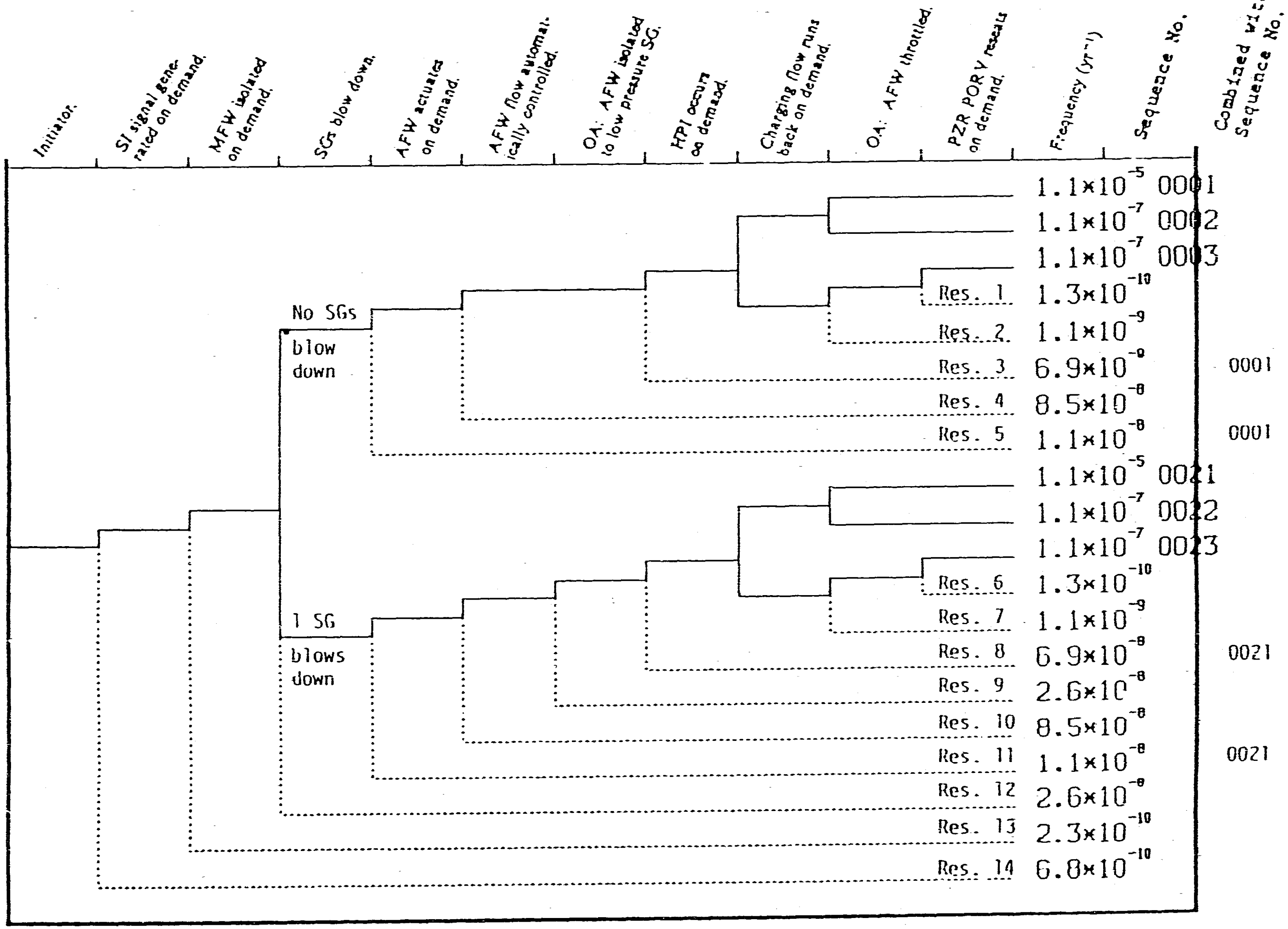
"INTEGRATION" OF TRANSIENT-INITIATOR FREQUENCY [Φ(I)] EVENT-TREE BRANCH PROBABILITIES [P(B)] AND [P(F|E)] PROVIDES ESTIMATE OF FREQUENCY OF VESSEL FAILURE

$$\Phi(F) = \sum_i \Phi_i(E) P_i(F|E)$$

$$\Phi_i(E) = \Phi_I(I) \pi_i P_{ij}(B)$$

POSTULATION OF PTS TRANSIENTS ACHIEVED THROUGH USE OF EVENT TREES

(EVENT TREE FOR LARGE STEAMLINE BREAK AT HOT 0% POWER)



EIGHT CATEGORIES OF EVENT INITIATORS CONSIDERED

- DIRECT INITIATORS

  - LOCA
  - STEAMLINE BREAKS
  - OVERFEED (SG SECONDARY)
  - TUBE RUPTURE (STEAM GENERATOR)

- INDIRECT (INITIATION FOLLOWED BY FAILURE OF REACTOR COMPONENT)

  - REACTOR TRIP
  - ELECTRICAL-SYSTEM FAILURE
  - INSTRUMENT-AIR SYSTEM FAILURE
  - COMPONENT AND SERVICE-WATER SYSTEM FAILURE

TRANSIENTS CATEGORIZED FOR THERMAL/HYDRAULIC AND FRACTURE-MECHANICS CALCULATIONS

- THOSE WITH $\Phi(E) \leq 10^{-7}$ ASSIGNED TO "RESIDUAL" GROUPS

- ~200 TRANSIENTS WITH $\Phi(E) > 10^{-7}$

- DURATIONS OF ALL TRANSIENTS = 2 H

THERMAL/HYDRAULIC CALCULATIONS PERFORMED TO OBTAIN T, p, h VS TIME

- RELAP-5 AND TRAC MODIFIED TO INCLUDE DETAILS OF SECONDARY SYSTEM

- COMPLETE MODEL USED FOR 12–14 TRANSIENTS (VERY EXPENSIVE)

- SIMPLIFIED MODEL AND INTERPOLATION USED FOR OTHERS (MUCH LESS EXPENSIVE)

- MIXING CONSIDERED
  - PURDUE REMIX CODE AND 1/2-SCALE PTS FACILITY
  - CREARE 1/5-SCALE FACILITY

SCOPE OF PROBABILISTIC FRACTURE-MECHANICS ANALYSIS

- P(F I E)
- SENSITIVITY OF P(F I E) TO SIMULATED PARAMETERS
- EFFECT OF WARM PRESTRESSING (WPS)
- EFFECT OF REMEDIAL MEASURES
  - REDUCTION IN FLUENCE RATE
  - IN-SERVICE INSPECTION
  - LIMIT ON REPRESSURIZATION
  - ANNEALING

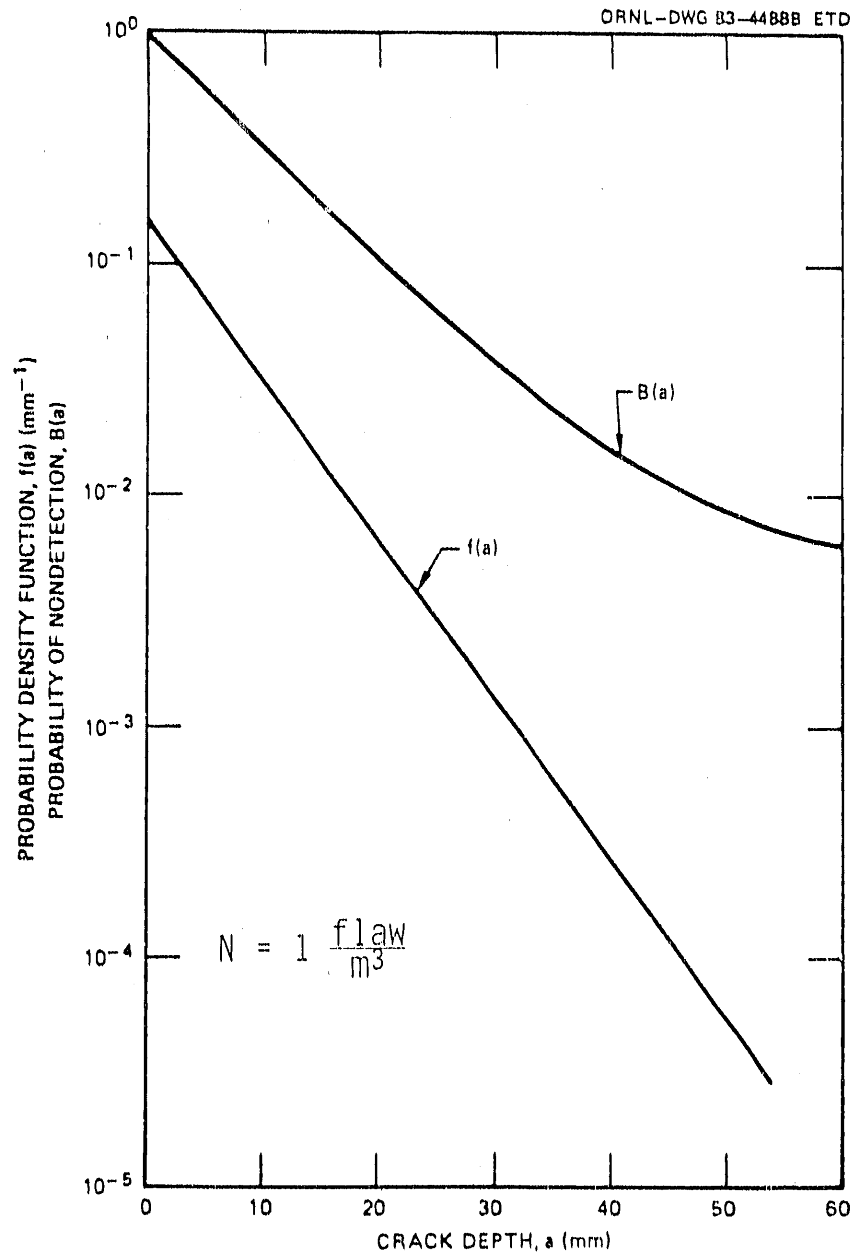
PROBABILISTIC FRACTURE-MECHANICS ANALYSIS PERFORMED WITH OCA-P

- BASED ON MONTE CARLO METHODS
  - MANY VESSELS SIMULATED
  - DETERMINISTIC FM ANALYSIS FOR EACH
  - $P(F|E) = \frac{\text{NUMBER OF FAILURES}}{\text{NUMBER OR VESSELS}}$
- 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 DENSITY AND FLAW SIZE DISTRIBUTION FUNCTION TAKEN FROM MARSHALL REPORT



DOMINANT TRANSIENTS DIFFERENT FOR THREE PLANTS

- EVENT FREQUENCIES AND BRANCH PROBABILITIES SENSITIVE TO PLANT DESIGN AND OPERATIONAL DETAIL

- VESSEL FLUENCES AND MATERIAL CHEMISTRY DIFFERENT

- CONCLUSION: GENERIC EVALUATION NOT ADEQUATE

UNCERTAINTY ANALYSIS PERFORMED TO ACCOUNT FOR PARAMETERS NOT SIMULATED IN "BEST ESTIMATE" ANALYSIS

- PTS TRANSIENT PROBABILITY
  - INITIATING-EVENT FREQUENCY
  - BRANCH PROBABILITY
- THERMAL/HYDRAULICS
  - TEMPERATURE (COOLANT IN DOWNCOMER)
  - PRESSURE (PRIMARY SYSTEM)
  - RESPONSE SURFACE USED TO GENERATE IMPACT
- FRACTURE MECHANICS
  - FLAW DENSITY
  - RTNDT (mean value)
  - $\Delta RTNDT_0$ (mean value)
  - K_{Ic} (mean value)
  - RESPONSE SURFACE USED TO GENERATE IMPACT

RESULTS OF UNCERTAINTY ANALYSIS

- FLAW DENSITY SINGLE LARGEST UNCERTAINTY

- Φ(F) (mean) >> Φ(F) ("best estimate")

- NRC SCREENING CRITERIA MAY NOT BE APPROPRIATE FOR ALL U.S. PWR PLANTS

IMPROVEMENTS IN FRACTURE-MECHANICS METHODOLOGY, DATA, AND MODELING ARE BEING INVESTIGATED

- CLADDING EFFECTS
- K_{Ic} AND K_{Ia} REFINEMENTS
  - UPDATE OF DATA BASE
  - SHALLOW-FLAW EFFECTS
  - OUT-OF-PLANE STRAIN EFFECTS (CIRCUMFERENTIAL FLAWS)
  - K_{Ia} AT "UPPER-SHELF" TEMPERATURE
- DUCTILE TEARING AND TEARING INSTABILITY
- AZIMUTHAL VARIATIONS IN TEMPERATURE (FLOW CHANNELING)

- END -

DATE FILMED

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