UNITED STATES
NUCLEAR REGULATORY COMMISSION
ADVISORY COMMITTEE ON REACTOR SAFEGUARDS
WASHINGTON, D.C. 20555-0001

February 21, 2001

MEMORANDUM TO: ACRS Members

FROM: Paul Boehnert, Senior Staff Engineer
ACRS

SUBJECT: CERTIFICATION OF THE MINUTES OF THE ACRS JOINT METALLURGY & MATERIALS/THERMAL-HYDRAULIC PHENOMENA SUBCOMMITTEE MEETING, JANUARY 18, 2001, ROCKVILLE, MARYLAND

The minutes of the subject meeting, issued January 30, 2001, have been certified as the official record of the proceedings of that meeting. A copy of the certified minutes is attached.

Attachment: As stated

cc: via E-mail
J. Larkins
J. Lyons
S. Duraiswamy
R. Savio
ACRS Staff Engineers
ACRS Fellows

UNITED STATES
NUCLEAR REGULATORY COMMISSION
ADVISORY COMMITTEE ON REACTOR SAFEGUARDS
WASHINGTON, D. C. 20555

February 21, 2001

MEMORANDUM TO: P. Boehnert, Senior Staff Engineer
Technical Support Branch

FROM: W. Shack, Chairman
Materials & Metallurgy Subcommittee

SUBJECT: CERTIFICATION OF THE MINUTES OF THE ACRS JOINT METALLURGY & MATERIALS/THERMAL-HYDRAULIC PHENOMENA SUBCOMMITTEE MEETING, JANUARY 18, 2001 - ROCKVILLE, MARYLAND

I hereby certify that, to the best of my knowledge and belief, the Minutes of the subject meeting issued on January 30, 2001 are an accurate record of the proceedings for that meeting.

W. Shack, Chairman

2/21/2001

Date

UNITED STATES
NUCLEAR REGULATORY COMMISSION
ADVISORY COMMITTEE ON REACTOR SAFEGUARDS
WASHINGTON, D. C. 20555

January 30, 2001

MEMORANDUM FOR: W, Shack, Chairman, Joint Metallurgy & Materials/Thermal-Hydraulic Phenomena Subcommittee

FROM: P. Boehnert, Senior Staff Engineer

SUBJECT: MINUTES OF THE ACRS JOINT METALLURGY & MATERIALS/THERMAL-HYDRAULIC PHENOMENA SUBCOMMITTEE MEETING, JANUARY 18, 2001 - ROCKVILLE, MARYLAND

A Working Copy of the subject meeting minutes is attached. I would appreciate your review and corrections as soon as possible. Copies are being sent to all ACRS members, and the T/H Phenomena Subcommittee Consultants for their information.

Attachment: As Stated

cc: ACRS Members
V. Schrock
N. Zuber
R. Savio

cc via E-Mail:
J. Larkins
R. Savio
S. Duraiswamy
ACRS Staff Engineers
ACRS Fellows

DRAFT COPY - PREPARED FOR INTERNAL COMMITTEE USE

CERTIFIED BY: W. SHACK
FEBRUARY 21, 2001

CERTIFIED

JANUARY 30, 2001

ADVISORY COMMITTEE ON REACTOR SAFEGUARDS JOINT SUBCOMMITTEE ON MATERIALS & METALLURGY AND THERMAL-HYDRAULIC PHENOMENA - MEETING MINUTES: **PTS RULE SCREENING CRITERION REEVALUATION: DETERMINATION OF UNCERTAINTIES**

JANUARY 18, 2001
ROCKVILLE, MARYLAND

INTRODUCTION:

The ACRS Joint Subcommittee on Materials & Metallurgy and Thermal-Hydraulic Phenomena held a meeting on January 18, 2001 with representatives of the NRC staff. The purpose of this meeting was for the Subcommittee to hold discussions with representatives of the NRC staff concerning the treatment of uncertainties in the FAVOR probabilistic fracture mechanics code, including the treatment of uncertainties in the thermal-hydraulic codes. The FAVOR code is used in the Pressurized Thermal Shock (PTS) Technical Basis Reevaluation Project. The entire meeting was open to the public. Mr. P. Boehnert was the cognizant ACRS staff engineer and Designated Federal Official (DFO) for this meeting. The meeting was convened by the Subcommittee Chairman at 8:30 a.m., January 18, 2001, and adjourned at 4:35 p.m. that day.

ATTENDEES

ACRS Members/Staff:

W. Shack, Chairman
G. Wallis, Chairman
G. Apostolakis, Member
T. Kress, Member
M. Bonaca, Member
T. Kress, Member
V. Schrock, Consultant (part-time)
P. Boehnert, DFO

NRC Staff:

M. Mayfield, RES
N. Siu, RES
S. Malik, RES
W. Galyean, INEEL (Consultant)
K. Almenas, U. Md. (Consultant)
A. Mosleh U. Md. (Consultant)
M. Kirk, RES
M. Natishan, PEAI (Consultant)
M. Modarres U. Md. (Consultant)
P. Williams, ORNL (Consultant)
L. Abramson, RES

A list of public attendees is attached to the Office Copy of these Minutes.

The presentation slides and handouts used during this meeting are attached to the Office Copy of these Minutes. The presentations to the Subcommittee are summarized below.

CHAIRMAN'S COMMENTS

Dr. W. Shack, Subcommittee Chairman, convened the meeting. He had no specific comments, and turned the floor over to the Office of Nuclear Regulatory Research (RES) for their presentations.

RES PRESENTATIONS ON TREATMENT OF UNCERTAINTIES FOR THE PRESSURIZED THERMAL SHOCK (PTS) SCREENING CRITERION RE-EVALUATION PROJECT

Opening Comments

Mr. M. Mayfield, RES, provided an overview of the status of the PTS screening criterion re-evaluation project. He characterized this discussion as a status briefing to provide the Subcommittee with an in-progress summary of the work associated with the treatment of uncertainties. Mr. Mayfield said that RES is applying an integrated uncertainty analysis, pursuant to the (N. Siu, RES) approach specified in the RES White Paper on this matter. Specific discussion topics for today will include the uncertainty evaluation work for event sequence frequencies, thermal-hydraulic parameters, and fracture toughness parameters (K_{1c}, K_{1a}, RT_{NDT}). Mr. Mayfield characterized the uncertainty effort as a "work in progress" and, as such, said that the staff is not requesting a letter from the ACRS at this time.

RES Presentations

RES representatives and consultants made presentations on the following topics:

- Overview of Uncertainty Treatment for PTS (N. Siu)
- PRA Event Sequence Analysis (W. Galyean)
- Treatment of Thermal-Hydraulic Uncertainties (K. Almenas, A. Mosleh)
- Uncertainties in probabilistic fracture mechanics (PFM) analysis (M, Kirk, M. Modarres, P. Williams, M. Natishan)
- Uncertainties in Other PFM Variables (S. Malik, L. Abramson)
- Closing Remarks (N. Siu)

Subcommittee Comments

During the above discussions, Members of the Subcommittee noted the following points:

- In response to Dr. Shack, Dr. Siu said that T/H uncertainties are not formally treated in PRAs. The staff does not, at this time, know the magnitude of the T/H uncertainties. This is still under evaluation.

- Dr. Siu said that the end product of the PTS screening criterion re-evaluation project is the determination of a through-wall crack frequency (TWCF),

- Regarding the PRA event sequence analysis work, Dr. Apostolakis asked to see the results of this work to date, as it was applied to the Oconee plant analysis. RES indicated that they did not want to make this work public at this time, without reviewing it with the Oconee plant licensee to verify its accuracy.

- In response to questions from Dr. Apostolakis regarding the treatment of uncertainties in the PRA calculations, RES noted that they have structured the binning process to allow for insertion of aleatory uncertainty in the thermal-hydraulic analysis.

- In response to questions from Professor Schrock, RES noted that the testing at the Oregon State University "APEX" facility is to confirm the staff's assumption that the vessel azimuthal temperature can be modeled on a one-dimensional basis. If the test data shows otherwise, RES will have to re-think its approach here. As a result of further discussion on this matter, Mr. Mayfield indicated that RES hopes that the OSU data will confirm the staff's expectation that a three-dimensional fracture mechanics analysis will not be necessary for this project.

- Regarding the discussion of a proposed methodology for addressing thermal-hydraulic code uncertainties, Dr. Apostolakis noted that this approach essentially constitutes a sensitivity study, and is not an uncertainty analysis, per se, Dr, Almenas confirmed that his approach is a sensitivity study designed to identify the important uncertainties relative to T/H parameters. Dr. Apostolakis noted that the RES approach of combining both the aleatory and epistemic uncertainties is an issue that needs to be investigated. Following additional discussion on this point, Dr. Siu said that addressing epistemic uncertainties is still a "work in progress".

- RES has established a four-step process for estimating the epistemic uncertainties in $RT_{NDT.}$ In response to Dr. Shack, Mr. Mayfield noted that the fracture toughness curves had conservatism built into them, RES is trying to back-out this conservatism to be able to estimate the uncertainty.

- Regarding the characterization of uncertainty for fracture toughness, two model approaches were noted: the Master Curve Model and the Empirical Model (ORNL approach). In response to Dr. Shack, RES said they have elected use of the ORNL approach since the limitations of the Master Curve Model (no procedural agreement on determination of either the effect of flaw size and shape or computation of the indexing temperature, T-sub-zero) render its use impractical. RES is preparing a position paper that will form the basis for the recommended structure of the FAVOR PFM code.

NRC Closing Comments

Mr. Mayfield thanked the Subcommittee for its input on the status of the staff's work on this matter. Regarding the planned discussion of this topic before the full Committee during its February Meeting, he reiterated his position that the staff is not requesting a letter from the ACRS at this time, given the on-going nature of this work.

Subcommittee Caucus

The Subcommittee agreed that this matter should be brought to the full Committee for a briefing on the status of RES's progress. The Subcommittee also agreed with RES that a Committee letter on this matter is not necessary at this time. Dr. Shack and the Members of the subcommittee instructed the NRC staff relative to the issues that should be discussed during presentations to the ACRS.

BACKGROUND MATERIAL PROVIDED TO THE SUBCOMMITTEE PRIOR TO THIS MEETING

Memoranda dated January 5, 2001, from P. Boehnert, ACRS, to Joint M&M / T/H Phenomena Subcommittee Members:

- University of Maryland Paper: "TH Issues and System Code Uncertainties Relevant to PTS", K. Almenas, et al., University of Maryland, January 2001.

- University of Maryland Paper: "K_{ic}/K_{1a} Uncertainty Characterization", F. Li, et al., Center for Technology Risk Studies, University of Maryland, undated

- NRC White Paper: "Uncertainty Analysis and Pressurized Thermal Shock: An Opinion", N. Siu, dated September 3, 1999

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NOTE: Additional details of the open portions of this meeting can be obtained from a transcript of this meeting available for downloading or viewing on the Internet at "http://www.nrc.gov/ACRSACNW", or can be purchased from Neal R. Gross & Co., Inc., 1323 Rhode Island Ave., NW, Washington, D.C., 20005, (202) 234-4433 (Voice), 387-7330 (Fax), E-Mail: "nrgross@nealrgross.com".

ADVISORY COMMITTEE ON REACTOR SAFEGUARDS

SUBCOMMITTEE MEETINGS ON THERMAL-HYDRAULIC PHENOMENA AND METALLURGY AND MATERIALS

JANUARY 18, 2001
Today's Date

ATTENDEES - PLEASE SIGN BELOW

PLEASE PRINT

NAME	AFFILIATION
B. Richard Bass	Oak Ridge National Lab
Terry L. Dickson	Oak Ridge Nat'l Lab
Dr. Paul T. Williams	Oak Ridge Nat'l Lab
Robert Beaton	ISL, Inc.
Eric Thornsbury	RES/DRAA/PRAB
SHAH MALIK	RES/DET/MEB
MARK KIRK	RES/DET/MEB
Matthew A. Mitchell	NRR/DE/EMCB
Allen Hiser	NRR/DE/EMCB
ARTHUR BUSLIK	RES/DRAA/PRAB
WILLIAM R JONES	RES/DET/MEB
W Arcieri	ISL, Inc
Michael Mayfield	RES/DET
EDWARD D THROM	NRR/DSSA/SPSB
Marjorie Natishan	PEAI
KAZ CAMPE	NRR/DSSA/SPSB
NATHAN SIU	RES/DRAA
Frank Coffman	RES/DET
Frank Cherny	RES/DET
Lee Abramson	RES/DRAA/PRAB

ADVISORY COMMITTEE ON REACTOR SAFEGUARDS

SUBCOMMITTEE MEETINGS ON THERMAL-HYDRAULIC PHENOMENA AND METALLURGY AND MATERIALS

JANUARY 18, 2001
Today's Date

ATTENDEES - PLEASE SIGN BELOW

PLEASE PRINT

NAME	AFFILIATION
Edward D Throm	NRC/NRR
M. diMauro	NRC/RES
~~Atken Hiser~~	
W. J. GALYEAN	INEEL
Y. H. Chang	UMD
Kazys Almenas	U.M.D
David Bessette	NRC/RES
ANDRE DROZD	NRC/NRR

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NUCLEAR REGULATORY COMMISSION
ADVISORY COMMITTEE ON REACTOR SAFEGUARDS
MEETING OF THE ACRS JOINT SUBCOMMITTEE ON MATERIALS AND METALLURGY AND ON THERMAL-HYDRAULIC PHENOMENA

PTS RULE SCREENING CRITERION RE-EVALUATION
JANUARY 18, 2001
ROCKVILLE, MARYLAND

- PROPOSED AGENDA -

TOPIC	PRESENTER	TIME
I. Opening Remarks	W. Shack, ACRS	8:30-8:35 a.m.
II. Overview of PTS Re-evaluation Project	M. Mayfield (RES)	8:35-9:00 a.m.
III. Overview of Treatment of Uncertainties in Pressurized Thermal Shock (PTS)	N. Siu, (RES)	9:00-9:30 a.m.
IV. PRA Uncertainty Treatment	W. Galyean (INEEL)	9:30-10:15 a.m.
- BREAK -		**10:15-10:30 a.m.**
V. Thermal-Hydraulic Transients Uncertainties	K. Almenas (UMD) A. Mosleh (UMD)	10:30-12:00
- LUNCH -		**12:00-1:00 p.m.**
VI. Binning of PTS Transients	W. Galyean (INEEL)	1:00-1:30 p.m.
VII. Uncertainty in Fracture Toughness (K1c, K1a) and RT_{NDT}	M. Kirk, (RES) M. Natishan (PEAI) M. Modarres UMD) P. Williams (ORNL)	1:30-3:30 p.m.
- BREAK -		**3:30 -3:45p.m.**
VIII. Uncertainty in Other PFM Variables	L. Abramson (RES) S. Malik (RES)	3:45-4:15 p.m.
IX. Final Comments on Treatment of Uncertainties	N. Siu.(RES)	4:15-4:30 p.m.
X. Discussion	W. Shack, ACRS	4:30-4:45 p.m.
XI. Adjournment	W. Shack, ACRS	4:45 p.m.

NOTE:
Presentation time should not exceed 50 percent of the total time allotted for specific item. The remaining 50 percent of the time is reserved for discussion.
Number of copies of the presentation materials to be provided to the ACRS - 25.

INTRODUCTORY STATEMENT BY THE CHAIRMAN OF THE COMBINED SUBCOMMITTEES ON MATERIALS AND METALLURGY AND THERMAL-HYDRAULIC PHENOMENA
11545 ROCKVILLE PIKE, ROOM T-2B1
ROCKVILLE, MARYLAND
JANUARY 18, 2000

The meeting will now come to order. This is a meeting of the ACRS combined Subcommittees on Materials and Metallurgy and Thermal-Hydraulic Phenomena. I am Dr. William Shack, Chairman of the Materials and Metallurgy Subcommittee. Dr. Wallis is Chairman of the Thermal-Hydraulic Phenomena Subcommittee.

Other ACRS Members in attendance are: Drs. George Apostolakis, Mario Bonaca, and Thomas Kress.

The ACRS Consultant in attendance is Professor Virgil Schrock.

The purpose of this meeting is for the Subcommittee to hold discussions with representatives of the NRC staff concerning the treatment of uncertainties in the FAVOR probabilistic fracture mechanics code, including the treatment of uncertainties in the thermal-hydraulic codes. The FAVOR code is used in the Pressurized Thermal Shock (PTS) Technical Basis Reevaluation Project. The Subcommittee will gather information, analyze relevant issues and facts, and formulate proposed positions and actions, as appropriate, for deliberation by the full Committee. Mr. Paul Boehnert is the Cognizant ACRS Staff Engineer for this meeting.

The rules for participation in today's meeting have been announced as part of the notice of this meeting previously published in the *Federal Register* on December 28, 2000.

A transcript of this meeting is being kept, and will be made available as stated in the Federal Register Notice. It is requested that speakers first identify themselves and speak with sufficient clarity and volume so that they can be readily heard.

We have received no written comments or requests for time to make oral statements from members of the public.

(Comments from Drs Shack and Wallis -if any)

We will now proceed with the meeting and I call upon Mr. Michael Mayfield of NRC's Office of Nuclear Regulatory Research to begin.

Overview of Pressurized Thermal Shock Screening Criterion Re-evaluation Project

Michael Mayfield, Director

Division of Engineering Technology

Office of Nuclear Regulatory Research

Presentation to:

Advisory Committee on Reactor Safeguards

Joint Subcommittees

January 18, 2001

PTS Re-evaluation Project Introduction

- One of a continuing series of briefings to:
  - Provide in-progress summaries of key elements
  - Solicit committee feedback on key issues
- Key issue to be discussed today – *treatment of uncertainties*
  - Global picture – integrated uncertainty analysis
    - Application of uncertainty white paper approach
    - Links different technical disciplines
  - Specific snapshots
    - Event sequence frequencies
    - Thermal-hydraulics
    - Fracture toughness (K1c, K1a, RT_{NDT})

PTS Re-evaluation Project Background/Impetus

- Encouraging developments in materials area provided incentives. These are:
  - Improved NDE/DE flaw characterization
  - Revised embrittlement correlation
  - Improvement in fracture toughness models
- Additional developments in TH and PRA
  - Improvements in TH codes
  - Testing at APEX for flow stagnation/mixing
  - PRA RG-1.174 acceptance guidelines
  - HRA quantification tools

NRC/Industry PTS Re-evaluation Project

- Initiated in April 1999
- Fully participatory with input from stakeholders:
  - NRC (RES, NRR, Contractors)
  - Industry (MRP, EPRI, Vendors)
  - Public
  - ACRS Reviews (2/99, 7/99, 3/00, 5/00, 9/00)
- Four PWR plants to be analyzed – Oconee-1, Calvert Cliffs-1, Palisades, and Beaver Valley-1 (replacing HB Robinson-2)

PTS Re-evaluation Project
Current Status

- Work progressing in major technical areas
- Finalization of materials input and revision of PFM code (FAVOR) – March 2001
- TH code validation through testing in APEX facility -- completion in March 2001
- Progress in PRA aspects includes:
  - Explicit consideration of uncertainty in key input variables
  - Completed a Commission Paper on an approach for developing PTS risk acceptance criterion (SECY-00-0140, June 2000)

PTS Re-evaluation Project
Current Status (Contd.)

- Consideration for LERF and containment integrity has begun, and is a departure from the present PTS screening criterion
- Near-term PFM scoping study based on current developments is to be completed in January 2001 for Oconee-1
- Full-scale application of PFM methodology to first PTS re-evaluation plant expected to start in April 2001

PTS Re-evaluation Project Summary/Conclusions

- First major application of risk-informed methodology to revisit the tech. basis for a possible revision of an adequate protection rule
- Good progress thus far
- Schedule revised to accommodate newer developments in:
  - Fracture toughness modeling (K1c, K1a, RT_{NDT})
  - Embrittlement correlations
  - Generalized flaw distributions, ...
- Explicit consideration of uncertainties in key variables

PTS Re-evaluation Project
Summary/Conclusions (Contd.)

- Staff briefing goals for today:
  - Inform committee and obtain comments
  - Prepare for February 2001 full-committee information briefing
- No letter requested at this time

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United States
Nuclear Regulatory Commission

Overview: Treatment of Uncertainties in Pressurized Thermal Shock

N. Siu

Office of Nuclear Regulatory Research
U.S. Nuclear Regulatory Commission

Presentation to
ACRS Materials and Metallurgy Subcommittee
ACRS Thermal-Hydraulic Phenomena Subcommittee
January 18, 2001

Background

- A PTS analysis objective: consistent treatment of uncertainties
- White paper on aleatory and epistemic uncertainties in PTS developed to facilitate analysis
- ACRS Materials and Metallurgy Subcommittee briefings
  - March 2000: described overall approach
  - September 2000: Committee questions on details of application and consistency of approach
- Work is in progress
  - Consistent implementation of white paper philosophy
  - Development of results

Approach for Treating Uncertainties

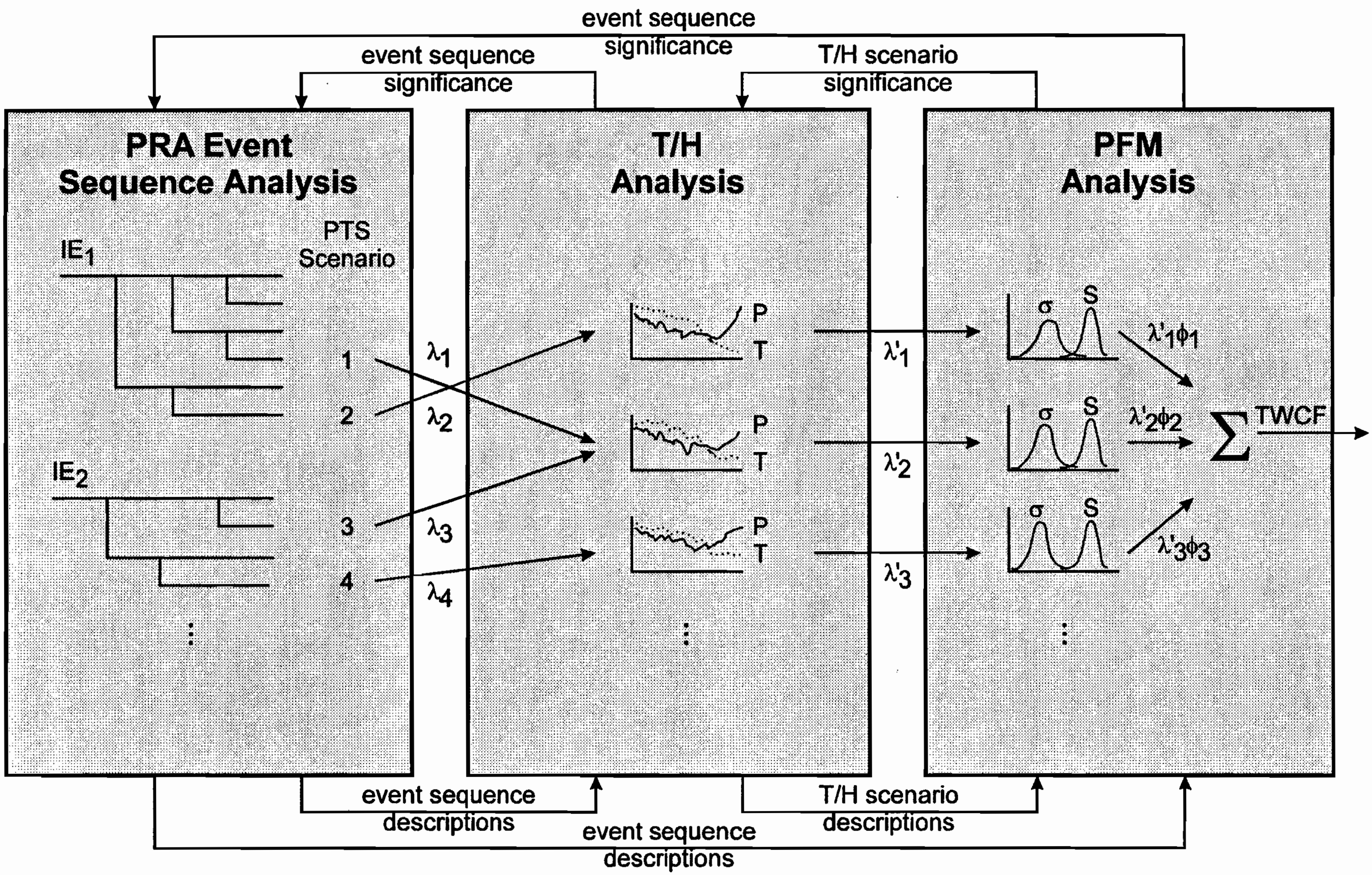
- Identify sources of uncertainty and categorize based on problem needs
  - Aleatory uncertainties: variables assumed to be the result of random processes (irreducible, given the model)
  - Epistemic uncertainties: variables treated as being deterministic (reducible, given the model)

- Aleatory uncertainties treated through T/H scenario frequencies and conditional probability of vessel failure, given the scenario

- Epistemic uncertainties treated through standard estimation and uncertainty propagation techniques

- Assemble results using FAVOR

Framework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PRA Event
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Uncertainties in PTS Sub-Analyses

- Event sequence analysis
  - Sequence frequencies quantify aleatory contribution
  - Uncertainties in hardware parameters treated conventionally
  - Treatment of HRA uncertainties being developed
- Thermal hydraulic analysis
  - Approach: address uncertainties using "probability of frequency" format
  - Boundary condition uncertainties dominate for 1-ϕ scenarios
  - Remaining issues: binning, 2-ϕ model uncertainties
- Probabilistic fracture mechanics analysis
  - Addresses aleatory uncertainties in crack initiation
  - Epistemic distributions for key parameters being developed
  - FAVOR code being modified

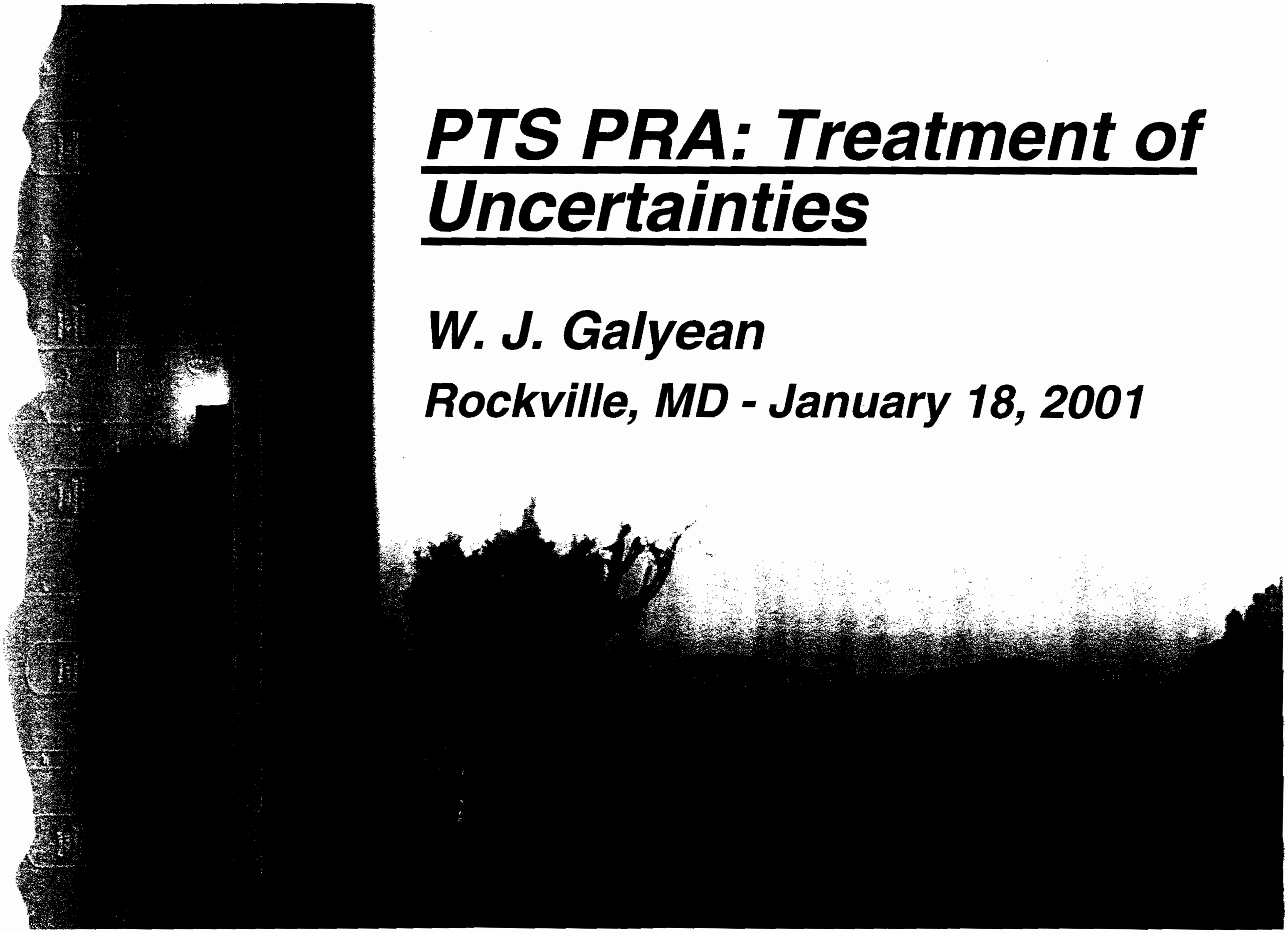
Following Presentations

- PRA event sequence analysis (W. Galyean)
- Thermal hydraulic uncertainties (K. Almenas, A. Mosleh)
- Event sequence binning (W. Galyean)
- Uncertainties in PFM analysis (S. Malik, L. Abramson, M. Kirk)
- Uncertainties in fracture toughness (M. Kirk, M. Modarres, P. Williams, M. Natishan)
- Closing remarks (N. Siu)

Closing Remarks

- **Ongoing technical development areas include:**
  - **HRA quantification**
  - **Treatment of 2-ϕ model uncertainties**
  - **Treatment of uncertainties in fracture toughness and RT_{NDT}**

- **White paper will be updated, published as a NUREG report**



PTS PRA: Treatment of Uncertainties

W. J. Galyean

Rockville, MD - January 18, 2001

Outline of Presentation

- Brief review of PTS PRA approach
- Types of PRA parameters
- Approach to treatment of uncertainties
- Quantification process
- Status

Overall Approach

- Use original Oconee PTS analysis as starting point
- Event trees used to model potential PTS sequence of events
- Update:
  - New event frequencies and probabilities
  - Reflect current plant designs
  - Incorporate current understanding of phenomena

PTS Sequence Event Trees

- Structure follows "original" Oconee ETs
  - Primary Integrity
    - LOCA, stuck open PORV/SRV, etc.
  - Secondary Integrity
    - steam line break, stuck open SRV/TBV, etc.
  - Secondary Feed
    - MFW, EFW, CBP, etc.
  - Primary Flow
    - HPI, RCPs, etc.

Typical PRA Parameters

- Initiating Event Frequencies
- Basic Event Probabilities
  - Hardware
    - component failures
    - component unavailability (TorM)
  - Human Errors
  - Common Cause Failures

Common PRA Models

- Event Probabilities
  - Binomial
    - $P\{r \text{ failures in } N \text{ trials } |\phi\} = \frac{N!}{r!(N-r)!} \phi^r (1-\phi)^{N-r}$
  - Poisson
    - $P\{r \text{ failures in } (0,T) \mid \lambda\} = \frac{(\lambda T)^r}{r!} e^{-\lambda T}$
  - Exponential
    - $P\{T_f < t \mid \lambda\} = 1 - e^{-\lambda t} \approx \lambda t$ (for small λt)
- Event occurrence rates (frequencies)
  - Probability density functions on estimates of ϕ and λ
  - Lognormal, Gamma, Beta

Treatment of PRA Uncertainties

- *Failure probabilities and sequence frequencies*
  - *Occurrence modeled as random process*
    - *Binomial or Poisson*
  - *Uncertainties treated as aleatory*
- *Event occurrence rates*
  - *Assumed to be time independent*
  - *Determined by specific boundary conditions on operation of component*
  - *Uncertainties treated as epistemic*

Probability Density Functions Reflect Confidence in Parameter Estimate

- *Estimate in "true" value of failure rate characterized using lognormal or gamma distribution*
- *Generated using*
  - *Engineering judgement*
  - *Bayesian methods*
- *Interpreted as representing degree-of-belief*

Individual Input Parameters Quantified Using a Variety of Sources

- *Oconee experience data*
- *Industry-wide experience data*
- *Oconee-PRA estimates*
- *Engineering judgement*

Uncertainty Propagated Step-wise

- *Event Tree top events quantified (with uncertainty)*
- *Event tree endstates (14,500) then quantified (with uncertainty)*
- *PTS-SIDs (2500) then quantified (with uncertainty)*
- *TH bins (31) than quantified (with uncertainty) using the results of the PTS-SID uncertainty analysis*
- *Used Monte Carlo sampling (2000 samples)*
- *Output is probability density represented by a histogram (19 bins)*

Status

- Oconee
  - Initial results completed - Dec. 4, 2000
  - Duke Power meeting - Jan. 23, 2001
  - External events analysis - Mar. 9, 2001
  - Model revised and requantified - Mar. 30, 2001
- Beaver Valley
  - Initial results (PTS-SIDs) - Jan. 26, 2001
    - T/H runs and mapping still pending
  - External events analysis - May 11, 2001
  - Model revised and requantified - May 31, 2001

TH issues and system code uncertainties relevant to PTS

Presentation to the ACRS (Jan, 18 2001)

K. Almenas and Y.H. Chang
M. Modarres, A. Mosleh
University of Maryland

Presentation Goals:

Provide a framework that encompasses all possible scenarios
(Move from an 'event space' to an 'energy/mass balance, relative time constants' space)

Categorize TH uncertainties
(Quantify RPV and system TH time constants. Quantify the importance of the SG heat sink. Separate that which is certain, from that which is not.)

Describe the propagation of uncertainties
(Show how initial + boundary conditions uncertainties are transformed into the uncertainties of the PTS relevant parameters. Classification: Damped, Proportional and Augmented propagation)

Outline methodology for evaluating the propagation of uncertainties
(Example of propagation for single variable PDF. Example for multi-variable PDF's)

Uncertainties for transients in which primary system becomes two-phase
(Classification of two-phase transients. Two-phase chocked flow uncertainties.)

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Impact of heat transfer coefficient on PTS relevant parameters

Effect of numerical flow anomalies

Inventory based two-phase flow states in OTSG NPP's

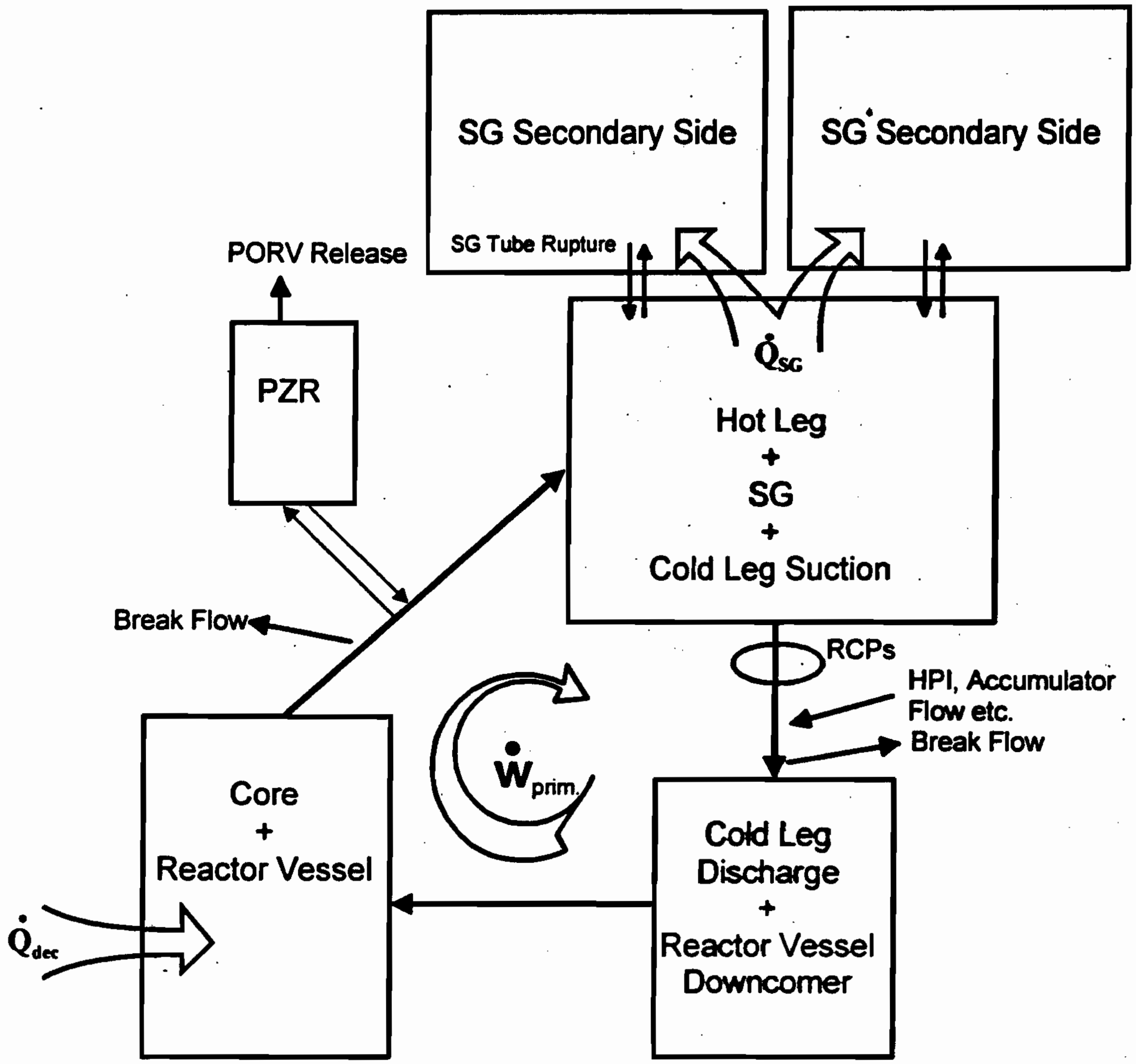

Figure 2.1 PWR Plant Schematic

End use of PTS relevant TH parameters by PFM analysis

1. Average RPV wall temperature

2. Temperature gradient in RPV wall

3. ΔP accorss RPV wall

   ('Crack propagation' or 'Driving crack through RPV wall')

Characteristics of $P(t)$, $h(t)$ and $T_{dc}(t)$

P(t) categories

1) P(t) controled or at PORV setting

2) $P(t) = P(T_{hot})$

With RCP's : $T_{dc}(t) \approx T_{av}(t) \approx T_{hot}(t)$

No RCP's : $T_{dc}(t) = T_{hot}(t) - \Delta T(t)$

TH uncertainty applies only to second category

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h(t) categories:

Low range – Flow stagnation. Internal circ. Ra number dependence

$h \approx 500$ to $1000\ W/m^2\ K$ (90 to 200 $BTU/hr\ ft^2\ s$)

$Bi_{RPV} \approx 2$ to 4

High range: RCP operating or system wide Nat-C.

$h \approx 30{,}000$ to 2000 (5300 to 400 $BTU/hr\ ft^2\ s$)

$Bi_{RPV} \approx 120$ to 8

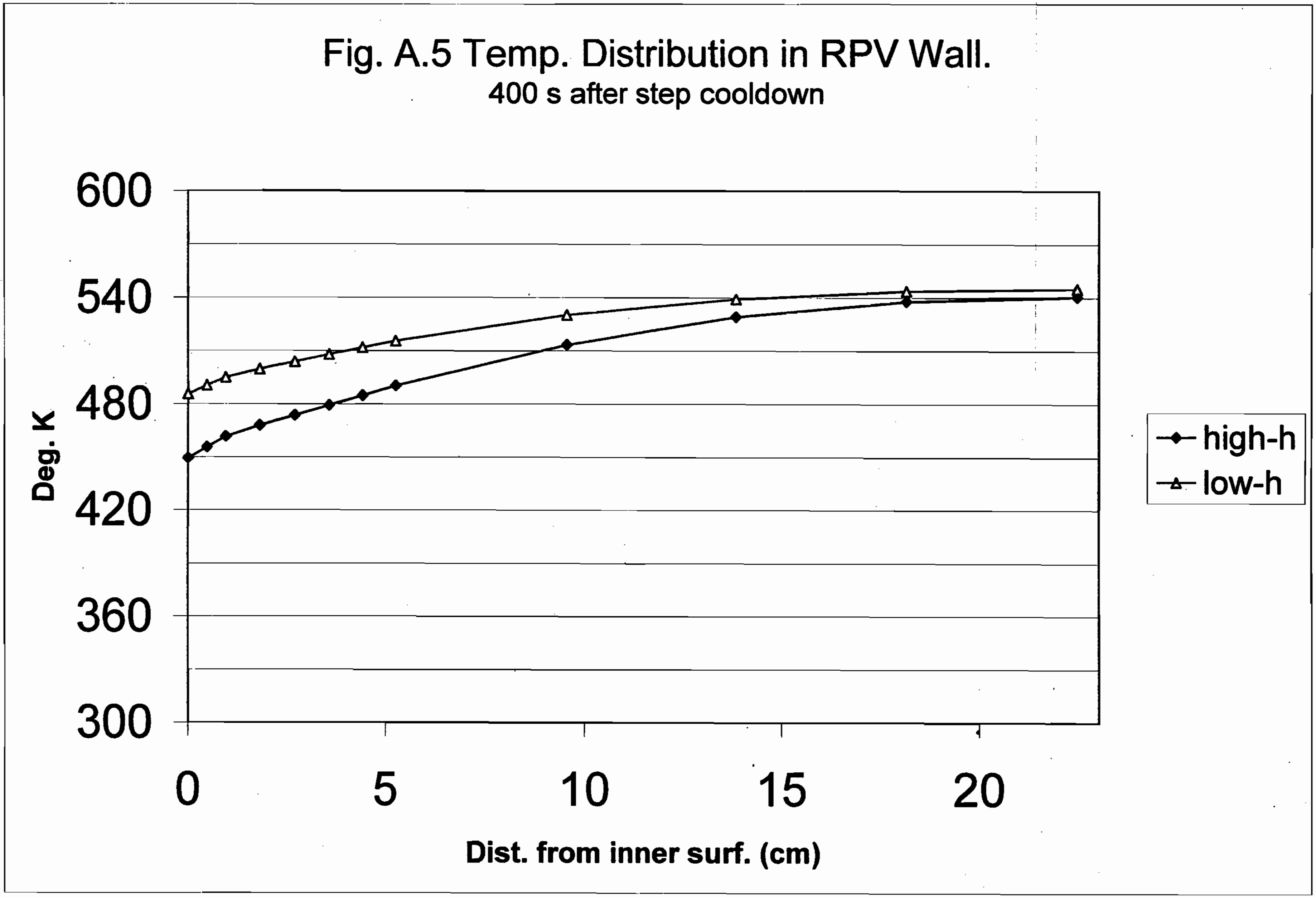


Fig. A.5 Temp. Distribution in RPV Wall.
400 s after step cooldown
600
540
480
420
360
300
Deg. K
0
5
10
15
20
Dist. from inner surf. (cm)
high-h
low-h

Table 4.1 Inventory and Heat Capacities of Oconee-1 Primary System

State of Primary	Liquid		Vapor			Combined Heat Cap (MJ/K)	
	Mass (kg)	Heat Cap. (MJ/K)	Mass (kg)	Heat Cap. (MJ/K)	Evap Energy (MJ)	Vapor + Liquid	Vapor + Liquid + Metal
Liquid Solid	2.57E5*	1360**	--	--	--	1360	1690
25% Steam	1.93E5	1080	3170	16	4760	1030	1360
50% Steam	1.29E5	680	6350	32	9520	710	1040

*Without pressurizer
**Evaluated at p = 71 bar (1043 psi), T_{SAT} = 560 °K, T_{CL} = 530 °K

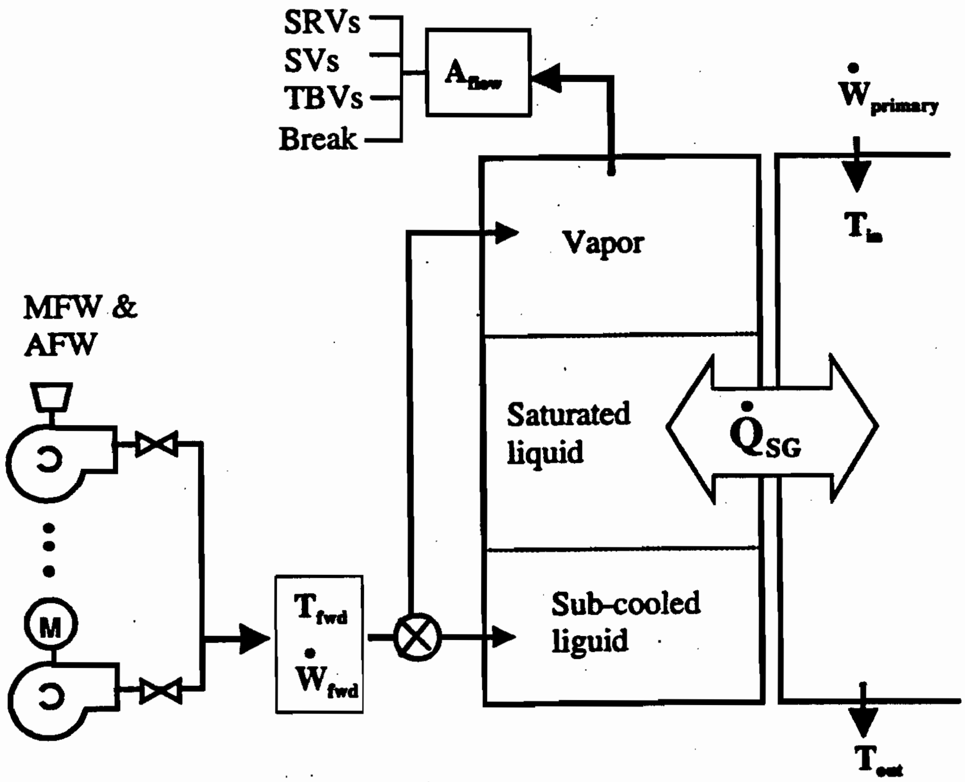
Table 4.2 Energy Source/Sink Magnitudes for Oconee

Time after trip (sec.)	System P* Bar (psi)	HPI flow rate (kg/s) 3 pumps	Energy source/sink (MW)		Downcomer + Cold Leg fill time (sec.)	SG en. rem. rate for δT=10 F, 5.5 K (MW)
			$\dot{Q}_{decay}$	$\dot{E}_{HPI}$*		
1000	60 (870)	67.	48	-70.	400.	150..
2000	46 (670)	71.	40	-74.	380.	125.
4000	20 (290)	77.	33	-81.	350.	115.
2000	170(2460)**	30.	40 + 22***	-31.	900.	325.

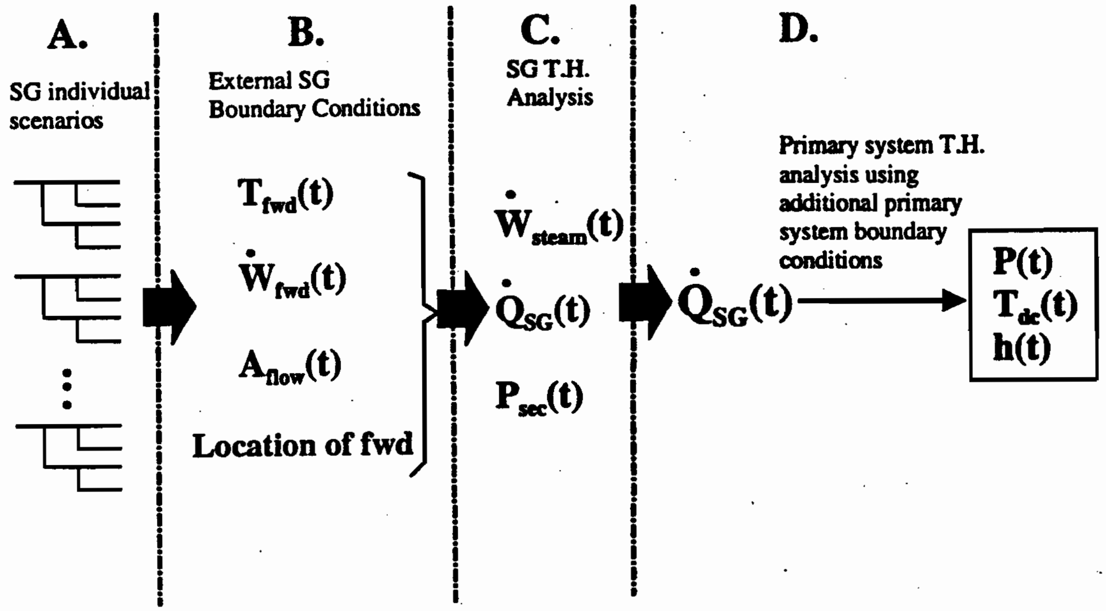
* $\dot{E}_{HPI} = \dot{w}_{HPI} \times [h_f(T_{SAT}) - h_f(T_{HPI})]$
**PZR PORV setting
***decay heat + pump power

Table 4.3 Fluid Circulation Time Constants for Oconee

	Flow Rate (kg/s)	System Exchange Time (without PZR)	V_{cl} (m/s)	V_{dc} (m/s)
RCPs Operating	17900	14 s	15.5	7.0
Nat. C. Single ph. Q_{dec} @ 1000 s 4000 s	 420. 290.	 610. 860.	 0.33 0.22	 0.15 0.11
Two-ph α = 0.25	83	40 min	0.06	0.3
Two-ph. α = 1 *BCM	24	95 min	0.02	0.008



Types and location of boundary conditions for OTSG



Effect Chain of SG TH conditions on PTS relevant output parameters

SG Impact summarized

The very large available heat-transfer area and the small thickness of the tube walls leads to a rapid equilibration of Q_{SG} to match the available heat source:

$$Q_{SG} = h_{eff} A \, (T_{prim,ex} - T_{sec})$$

This also leads to a relatively small δT across the SG tube walls:

$$T_{prim,ex} - T_{sec} = \delta T = \frac{Q_{SG}}{h_{eff} A}$$

Which implies that as long as the SG is available Tprim,ex closely follows the temperature of the fluid in the bottom region of the SG

$$T_{prim,ex} = T_{sec} + \delta T$$

Where δT ranges typically from ~0.5 to ~3.0 °C

Table 4.1

Classification of Uncertainties According to their Origin

1) Energy source/sink boundary condition uncertainties

Uncertainties arising from the variation of the decay heat source, HPI and Accumulator flow rate and fluid conditions, RCP's, PORV flow area and timing, break size.

2) Energy transfer rate to the secondary side uncertainties.

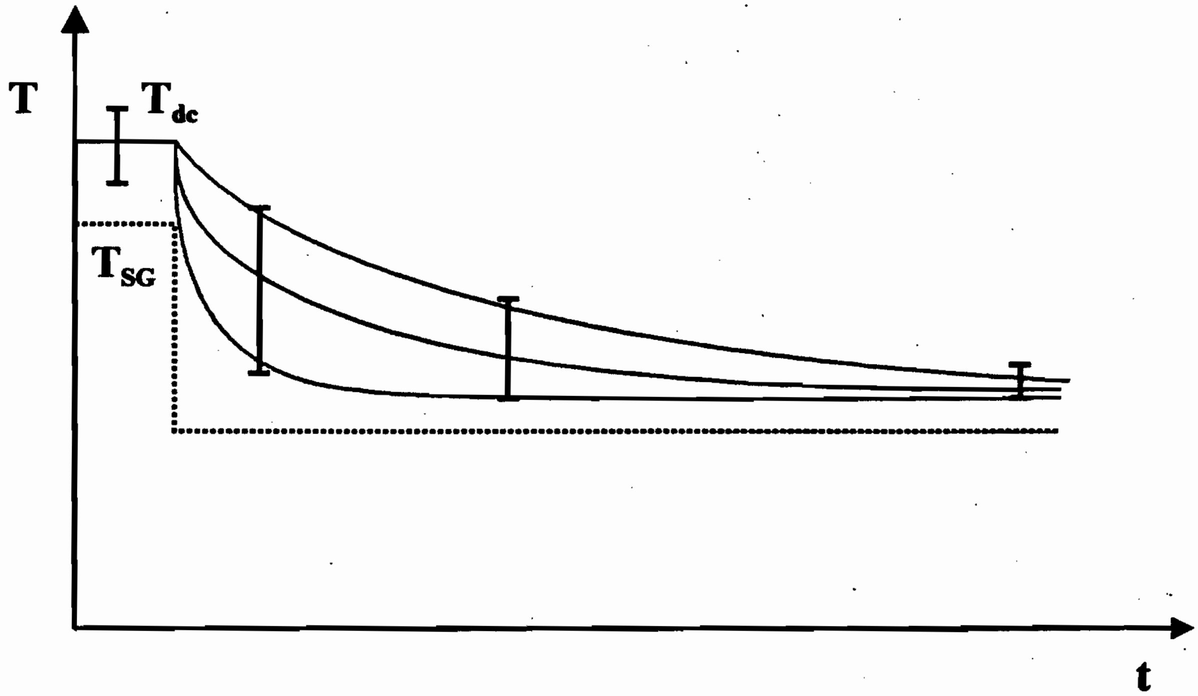
Uncertainties generated by P_{sat} variation in the SG's (TBV operation, MSL break, P_{sat} control), MFW and AFW flow rate, timing and T_f, SG tube break size.

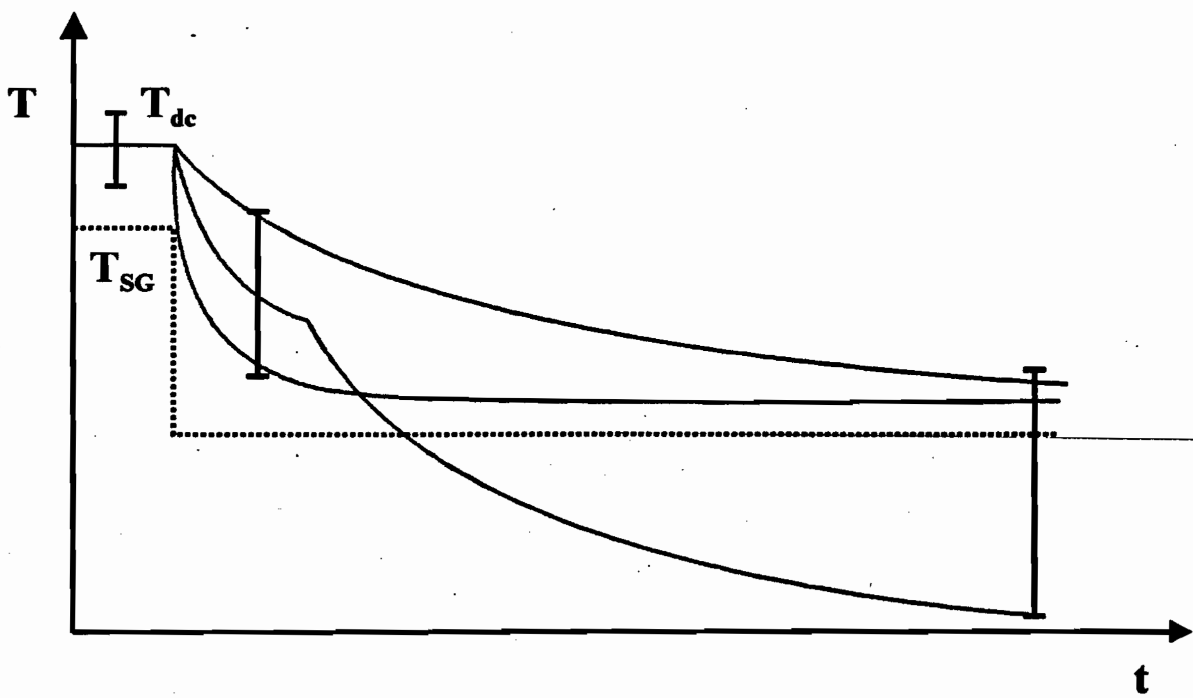
3) TH model and computational process imposed uncertainties.

Uncertainties due to inherent limitations of the 1-D, volume averaged system codes, empirical correlations, and nodding choices. Main computation types that are subject to code uncertainties:

Evaluation of out-flow rates, especially for two-phase chocked flows.
Evaluation of internal circulation.
Numerical mixing due to oscillations in parallel flow channels.

Time Constant & Approach to Equilibrium





Classification of Uncertainties According to Their Impact

Transformation type	Relevant parameters & conditions
PROPORTIONAL $\delta BC\, I \Rightarrow$ [RELAP5 Transient Analysis] $\Rightarrow I\, \delta T_{dc}$	• Psec NOT controlled • Uncertainty of TBV flow area and timing • HPI flow & T_f for $\dot{Q}_{SG} \cong 0$
DAMPED $\delta BC\, I \Rightarrow$ [RELAP5 Transient Analysis] $\Rightarrow I\, \delta T_{dc}$	• $\dot{Q}_{dec}, \dot{W} \& T_f$ of MFW, AFW, HPI flow & T_f, SB LOCA flow for case where primary is liquid solid • for ~ constant Psec applies also reasonably well, if RCPs tripped
AUGMENTED $\delta BC\, I \Rightarrow$ [RELAP5 Transient Analysis] $\Rightarrow I\, \delta T_{dc}$	• $\dot{W}_{break}, \dot{W}_{HPI}$ & conditions for system status leading to flow stagnation

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<u>**Table 4.3 Classification of PTS Relevant Transients Based on Propagation of Uncertainties**</u>

TH Propagation of Uncertainty	Dominant Energy Sinks	Circl. Mode	Dominant Parameters Contributing to Uncertainty		Transients
			BC Unc.	Model Unc.	
T_{dc} - damped P - controlled	Q_{SG} – controlled (HPI-PORV)	RCP	Psec - Tsec		
$T_{sg,ex}$. damped P - controled $\Delta T_{SG\text{-}dc}$ proportional	Q_{SG} – controlled HPI-PORV	Nat-C	Psec – Tsec W_{HPI}, T_{HPI}	Wcirc	
T_{dc} - proportional P - proportional $\Delta T_{SG\text{-}dc}$ proportional	Q_{SG} – uncontrolled 1.-depressurized 2. - overcooled (HPI-PORV)	RCP (Nat-C)	1) $A_{SG\text{-}flow}$, Q_{dec} 2) W_{fd}, T_{wfd}, Q_{dec} (W_{HPI},T_{HPI})	W_{BRK}, Q_{BRK} Wcirc	PNACCCR PN011NCR
T_{dc} - augmented P - proportional	Q_{SG} –not avail. Q_{brk} > Q_{dec} HPI	Nat-C Potential Flow stag	A_{BRK}, Q_{dec} $A_{eff\text{-}VV}$ W_{HPI}, T_{HPI},	W_{BRK}, Q_{BRK} W_{VV}	

Fig. 4.4 PTS Sequence Identifier Definitions (From INEL PRA study)

1	2	3	4	5	6	7	8
Initial Power	Primary Integrity	Secondary Integrity	Main Feedwater Status	Emergency Feedwater Status	Condensate Booster Pumps	High Pressure Injection Status	Reactor Coolant Pump Status
Z – Hot Zero Power P – High Power	N – No leak Z – small LOCA (< 1.4 inches) L – LOCA (PTS size, >1.4 but <2.8 inches) P – PORV stuck open (1-inch) S – SRV stuck open (1.5-inch) I – PORV initially open, subsequently isolated R – RCP seal LOCA G – SGTR Y – Large LOCA (> 2.8 inches)	(# of TBV or SSRV stuck open) 0 1 A – 1/1 B – 1/2 C – 2/2 S – Small steam line break (<8") L – Large steam line break (>8") I – TBV (or SLB) initially open, subsequently isolated	C – Controlling level T – Tripped 1 – 1 S/G being overfed 2 – 2 S/Gs being overfed Overfed – exceed high level in S/G, or failing to isolate feed to a faulted S/G (i.e., any feed to an faulted S/G is overfeed)	C – Controlling level F – Failed N – Not demanded 1 – 1 S/G being overfed 2 – 2 S/Gs being overfed	C – Controlling level F – Failed N – Not demanded 1 – 1 S/G being overfed 2 – 2 S/Gs being overfed Overfed – implies concurrent excessive steam demand (operator induced).	N – not demanded C – Controlled running I – Full injection (operator error) F - Failed	R – Running T – Tripped U – Tripped and restarted

Case Study – Damped transformation of BC uncertainties

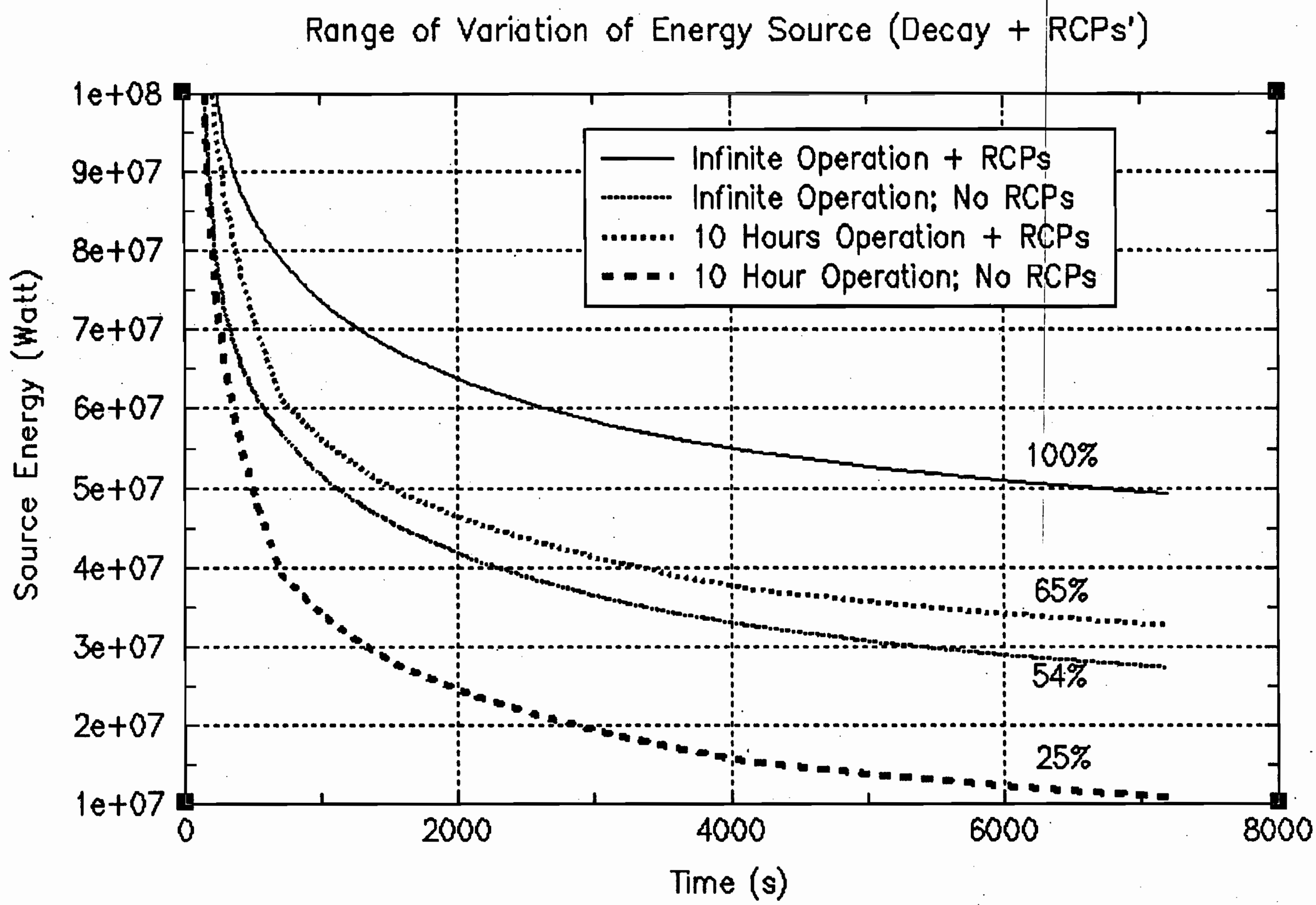
Reactor trip at a range of times after startup.

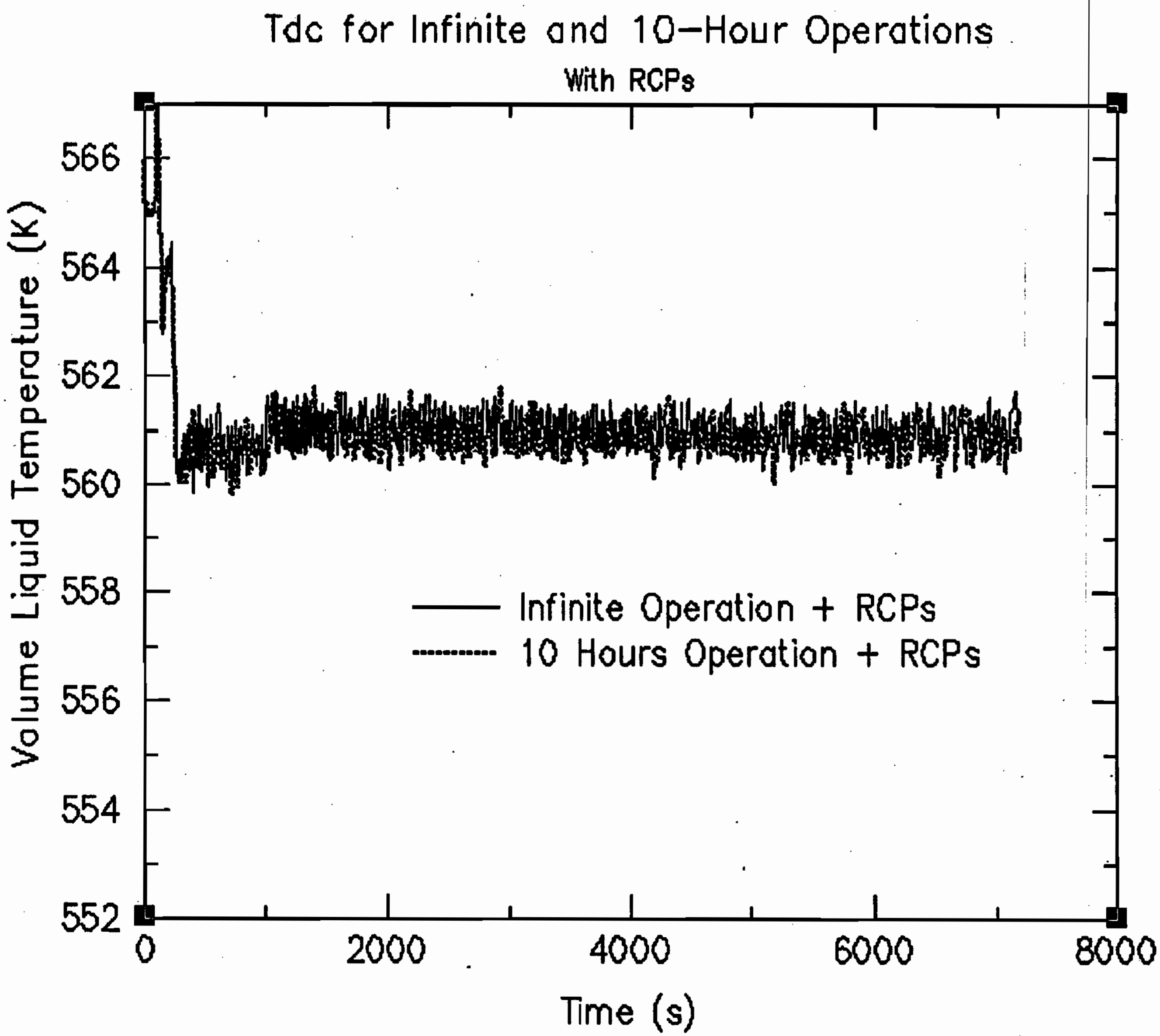
Inf. Operation with RCP's   Max en. input rate.

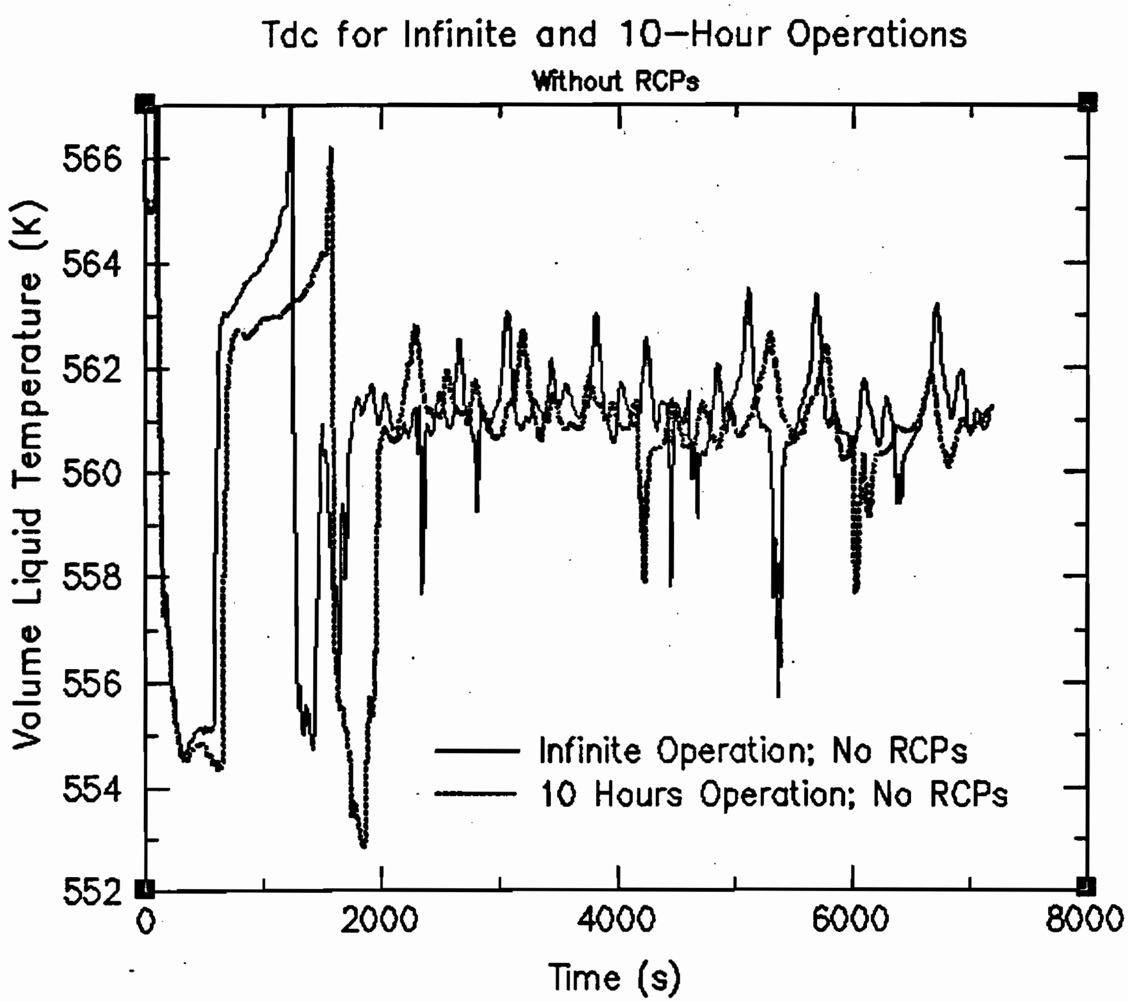
After 10 hrs. operation, with RCP's

After 10 hrs. operation RCP's tripped. Min en. input source

Other plant conditions nominal


Range of Variation of Energy Source (Decay + RCPs')
Infinite Operation + RCPs
Infinite Operation; No RCPs
10 Hours Operation + RCPs
10 Hour Operation; No RCPs
100%
65%
54%
25%
Source Energy (Watt)
1e+08
9e+07
8e+07
7e+07
6e+07
5e+07
4e+07
3e+07
2e+07
1e+07
0
2000
4000
6000
8000
Time (s)


Tdc for Infinite and 10-Hour Operations
With RCPs
Volume Liquid Temperature (K)
566
564
562
560
558
556
554
552
0
2000
4000
6000
8000
Time (s)
Infinite Operation + RCPs
10 Hours Operation + RCPs



Tdc for Infinite and 10-Hour Operations
Without RCPs
Volume Liquid Temperature (K)
566
564
562
560
558
556
554
552
0
2000
4000
6000
8000
Time (s)
Infinite Operation; No RCPs
10 Hours Operation; No RCPs

Case Study – Proportional transformation of BC uncertainties

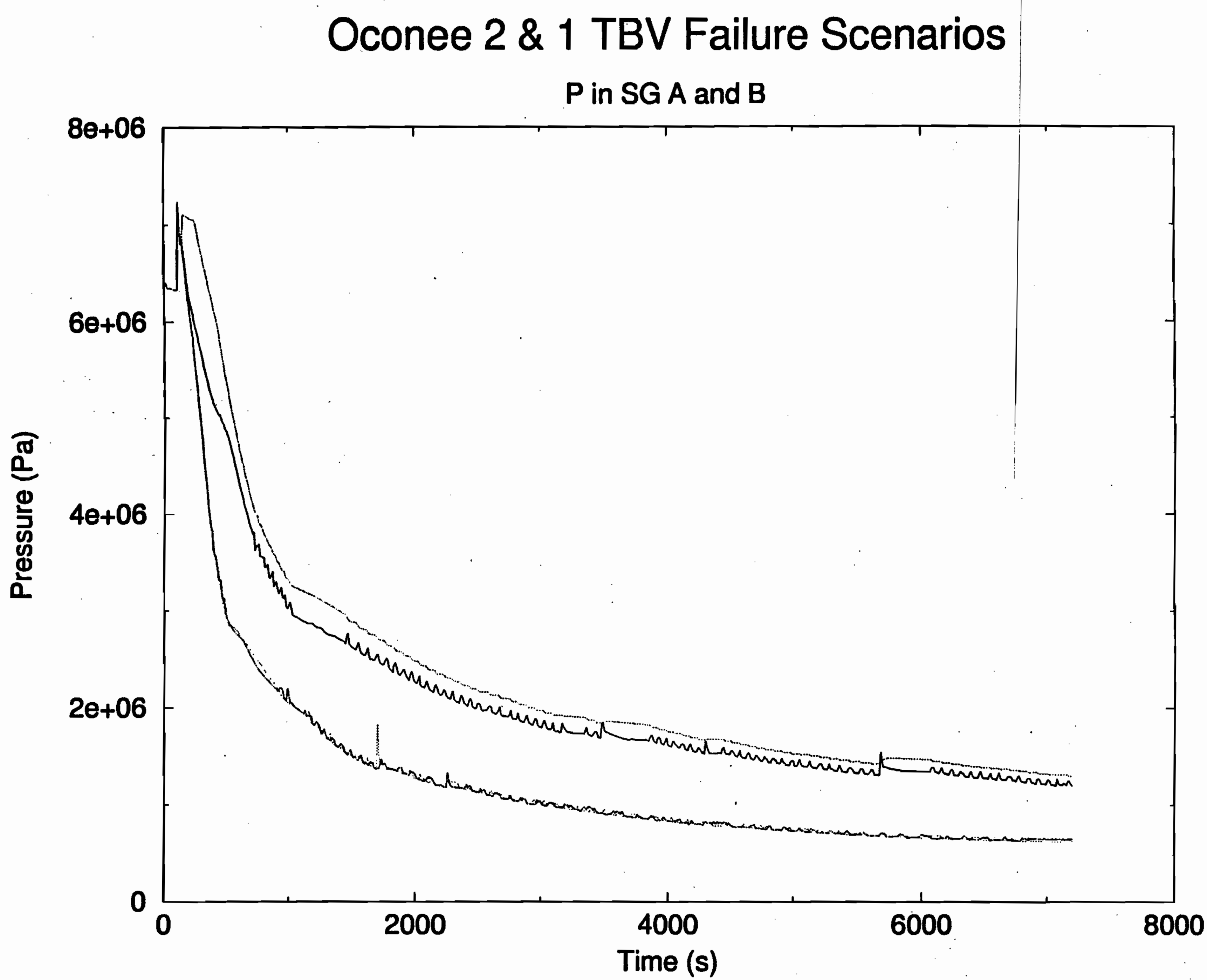
Reactor trip with TBV failures.

Single TBV fails to close

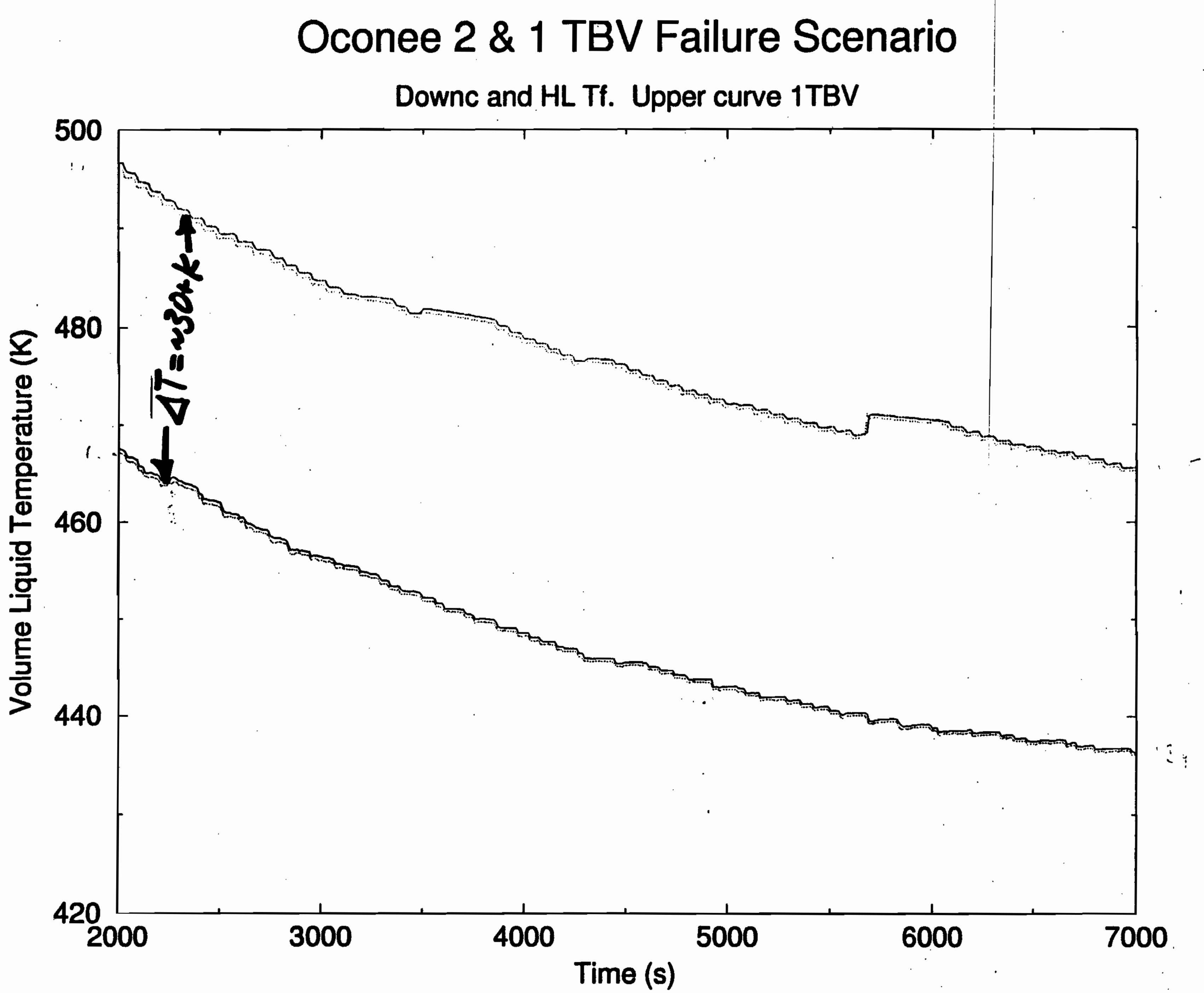
2 TBV's (one in each SG) fail to close

Transients lead to initiation of HPI and loss or pressurizer pressure control

Other plant conditions nominal

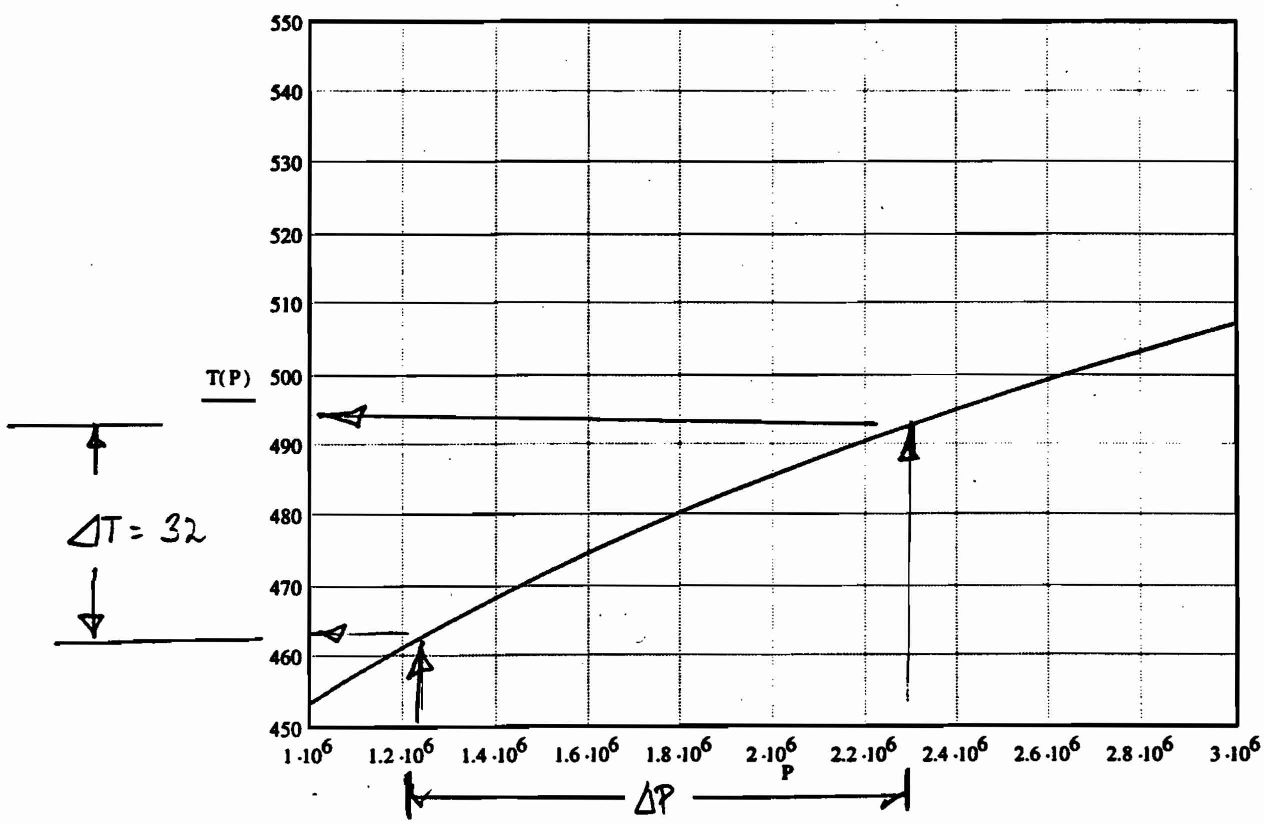


Oconee 2 & 1 TBV Failure Scenarios
P in SG A and B
8e+06
6e+06
4e+06
2e+06
0
Pressure (Pa)
0
2000
4000
6000
8000
Time (s)



Oconee 2 & 1 TBV Failure Scenario
Downc and HL Tf. Upper curve 1TBV
Volume Liquid Temperature (K)
500
480
460
440
420
2000
3000
4000
5000
6000
7000
Time (s)
ΔT=~30+K

P - T saturation line for water



P := 0, 25.. 2500

T(P) := (stm_tsatp(P))

Case Study – Augmented transformation of BC uncertainties

SB-LOCA in surge line.

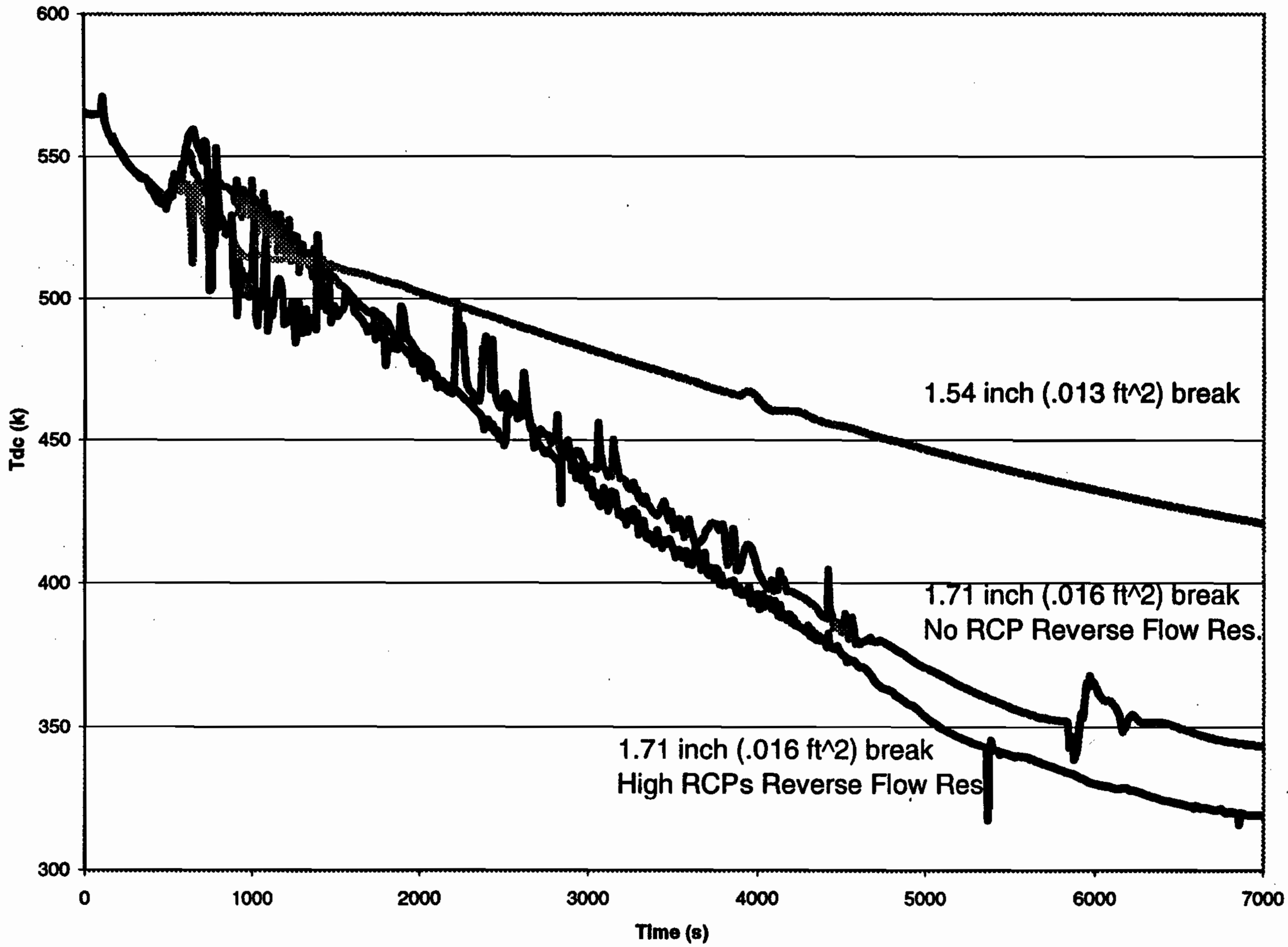
Break sizes differ by ~.000028 m^2 (20%)

Difference within the range of uncertainties for 2-phase chocked flow models

Other plant conditions nominal

Fig. C.6 Effect of numerical parallel channel flow on Tdc

Transients for break size .016 and .013 Ft^2



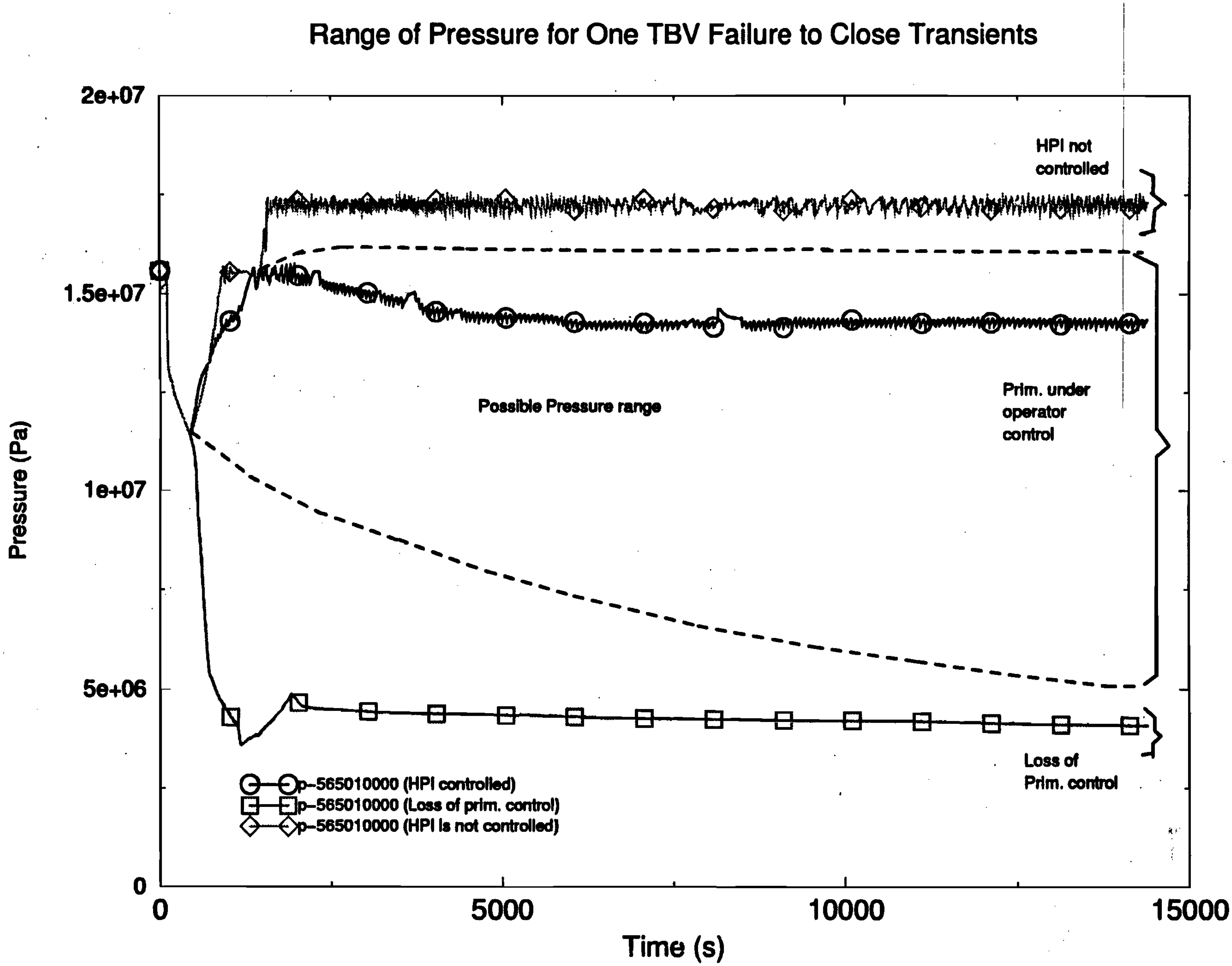
Steps in evaluating impact of uncertainties for 'proportional' propagation category.

Determine the BC which dominate the influence on P(t) and $T_{dc}(t)$

Obtain or define PDF and CDF relationships for the relevant BC's

Use RELAP5 to evaluate the proportionality factors

Using the CDF index choose BC values at specified probability limits (e.g. 5% and 95%) and evaluate the resulting spread in the values of P(t) and $T_{dc}(t)$



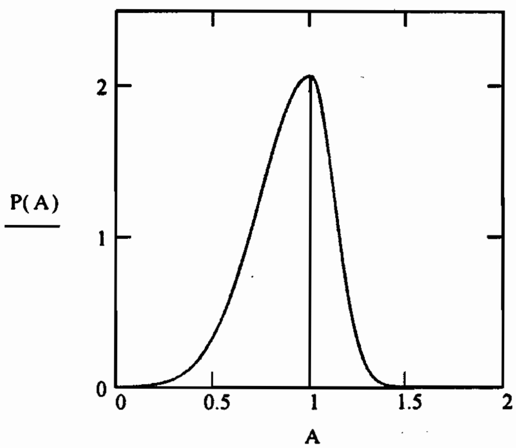
Range of Pressure for One TBV Failure to Close Transients
2e+07
1.5e+07
1e+07
5e+06
0
Pressure (Pa)
0
5000
10000
15000
Time (s)
HPI not controlled
Possible Pressure range
Prim. under operator control
Loss of Prim. control
p-565010000 (HPI controlled)
p-565010000 (Loss of prim. control)
p-565010000 (HPI is not controlled)

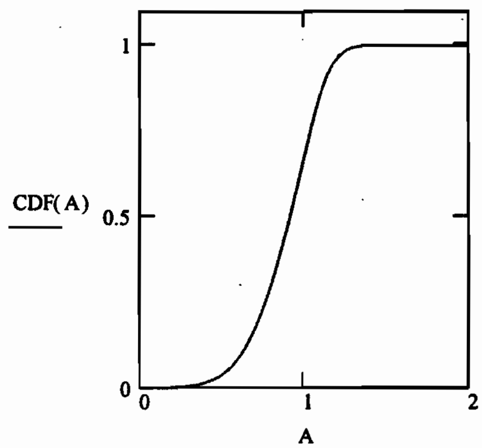
$$P(A) := \begin{cases} (Pl(A)) & \text{if } (A<1.) \\ (Pr(A)) & \text{if } (A>1) \\ 0 & \text{otherwise} \end{cases}$$

$$CDF(A) := \int_0^A P(x)\,dx$$

$CDF(2) = 1$

$A := 0, .001 .. 2$



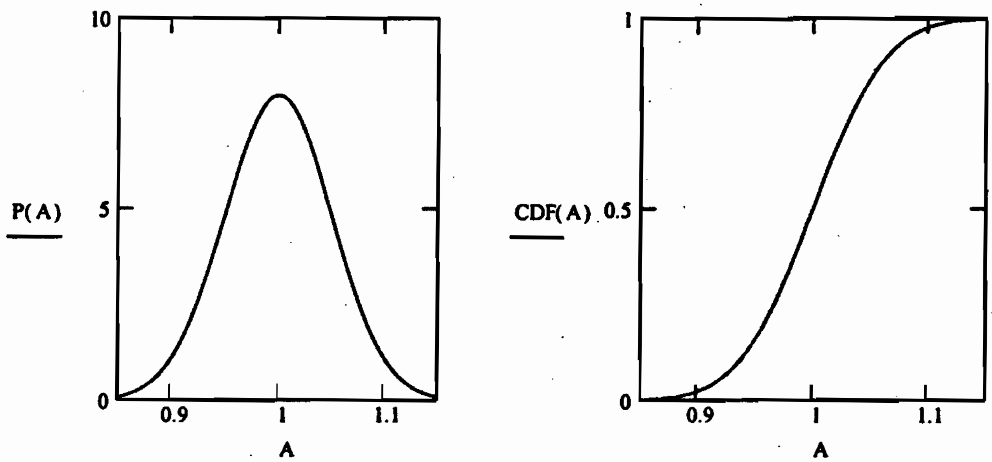


$CDF(.05) = 9.834 \cdot 10^{-5}$

$CDF(1.178) = 0.95$

PDF and CDF distributions of total energy source uncertainty.

(Normal dist. Nominal energy source value = 1.)



95 percentile factor
of the energy source

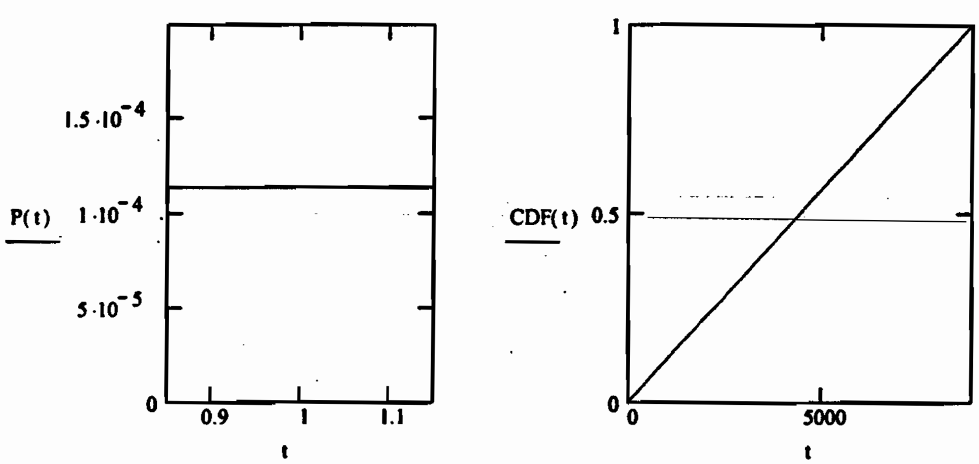
$CDF(av - 1.65 \cdot \sigma) = 0.049$

$av - 1.65 \cdot \sigma = 0.918$

PDF and CDF distributions of decay energy generation time

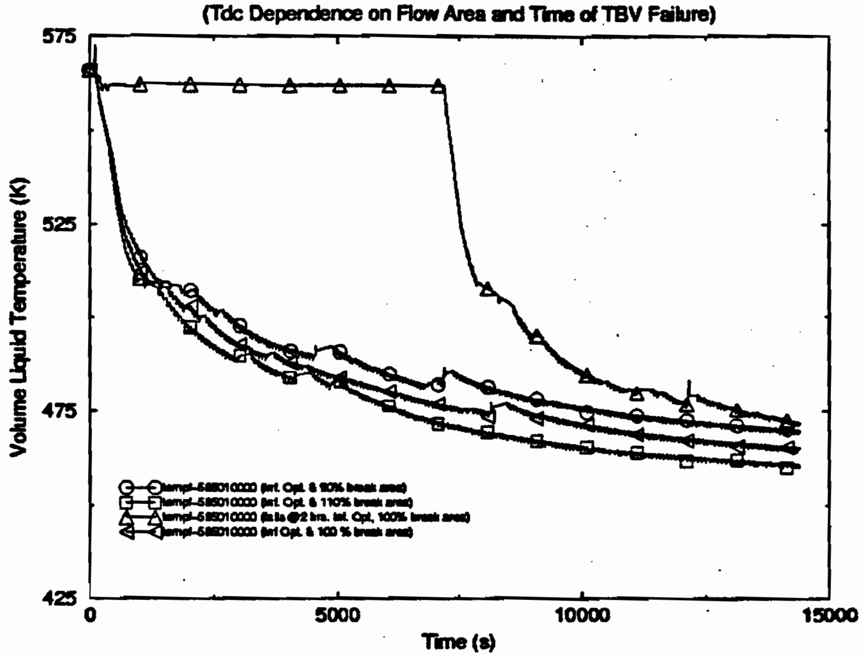
(total operation time = 1 year. In hours).

$yr := 24 \cdot 365$ $\quad t := 0, 1 .. yr$ $\quad P(t) := \frac{1}{yr}$ $\quad CDF(t) := \int_{0.}^{t} P(x)\,dx$



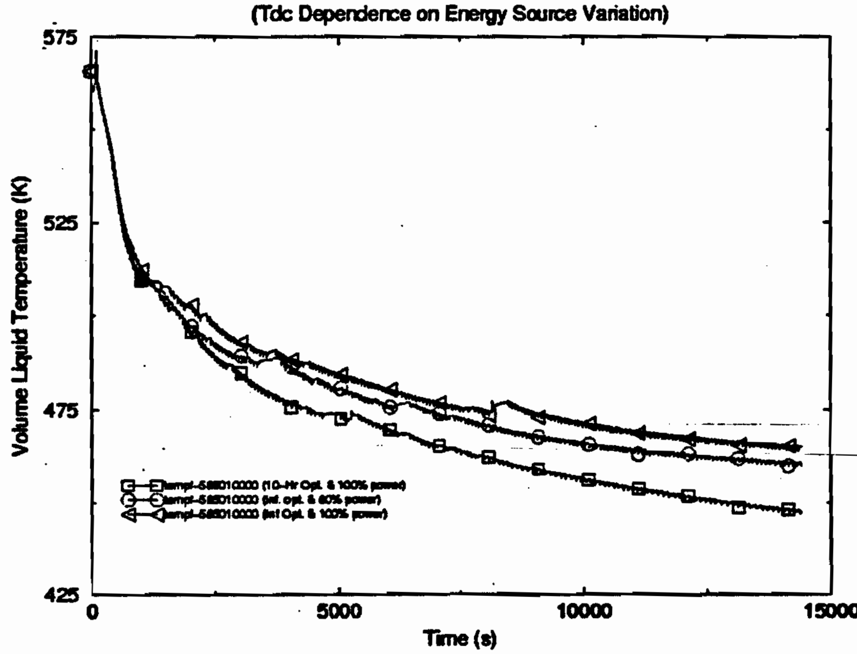
Single TBV Failure to Close Event

(Tdc Dependence on Flow Area and Time of TBV Failure)

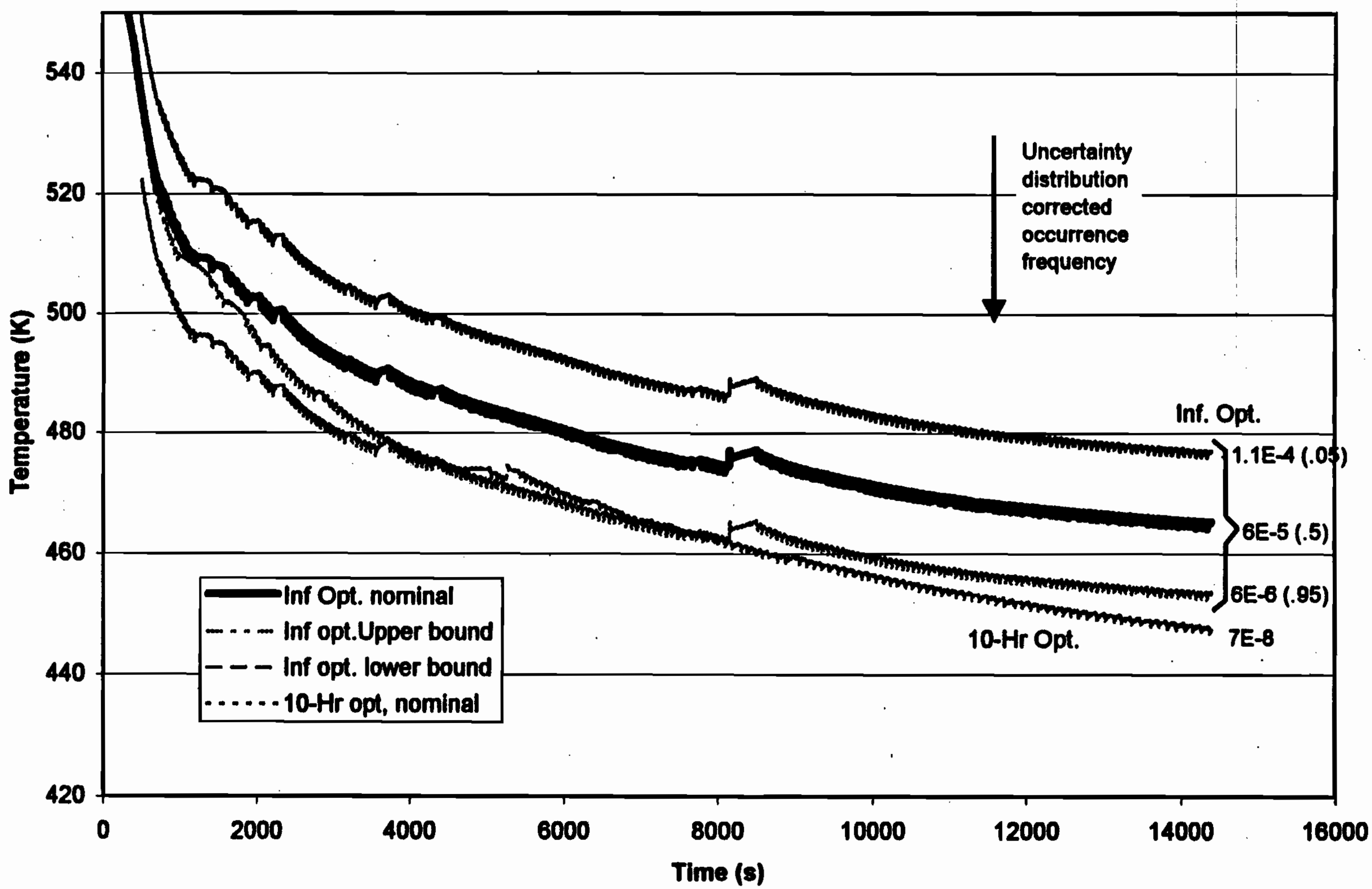


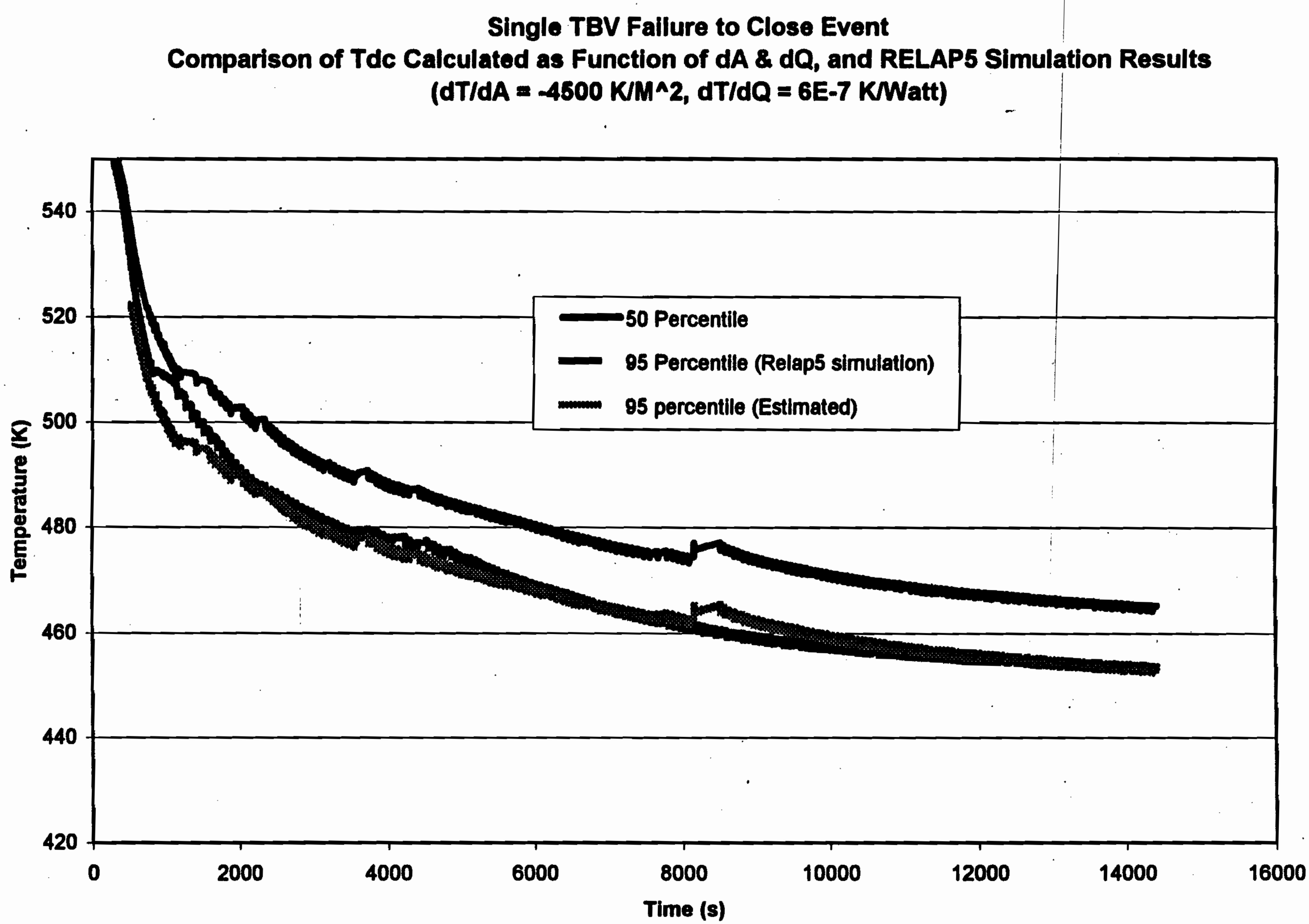
Single TBV Failure to Close Event

(Tdc Dependence on Energy Source Variation)



Single TBV Failure to Close Event
Tdc as a Function of TH and Boundary Condition Uncertainties
(dT/dA = -4500 K/M^2, dT/dQ = 6E-7 K/Watt)





Single TBV Failure to Close Event
Comparison of Tdc Calculated as Function of dA & dQ, and RELAP5 Simulation Results
(dT/dA = -4500 K/M^2, dT/dQ = 6E-7 K/Watt)
50 Percentile
95 Percentile (Relap5 simulation)
95 percentile (Estimated)
Temperature (K)
540
520
500
480
460
440
420
0
2000
4000
6000
8000
10000
12000
14000
16000
Time (s)

Table 6.2

Uncertainties associated with the evalutation of chocked two-phase flow rates

Physical (aliatory) causes of uncertainty Size of break Location in primary system (elevation, horiz. or vert. segment) Type of break Break shape Circuferential location (for horiz. pipes) Length of up-stream flow path (for sheared small pipes)
Modeling causes of uncertainty Uncertainties in the determination of break comp. fluid properties Uncertainties in the determination of break flow rate Boundig models of break flow rate: Lower – HEM (Homogeneous Eq. Model) Upper – Frozen (Constant up-stream fluid prop.)

Table 6.1

Classification of two-phase transients

Transient category	Break en/mass flow rate		En/mass sources	Flow stagnation probability
A	$Q_{BR} - Q_{HPI}$ W_{BR}	$<$ $<$	Q_{dec} W_{HPI}	No flow stagnation
B	$Q_{BR} - Q_{HPI}$ W_{BR}	$<$ $>$	Q_{dec} W_{HPI}	Flow stagnation possible, but intermittent
C	$Q_{BR} - Q_{HPI}$ W_{BR}	$>$ $>$	Q_{dec} W_{HPI}	Flow stagnation possible and could be prolonged
D	$Q_{BR} - Q_{HPI}$ W_{BR}	$\gg$ $\gg$	Q_{dec} W_{HPI}	Flow stagnation certain but P_{sys} decreases rapidly

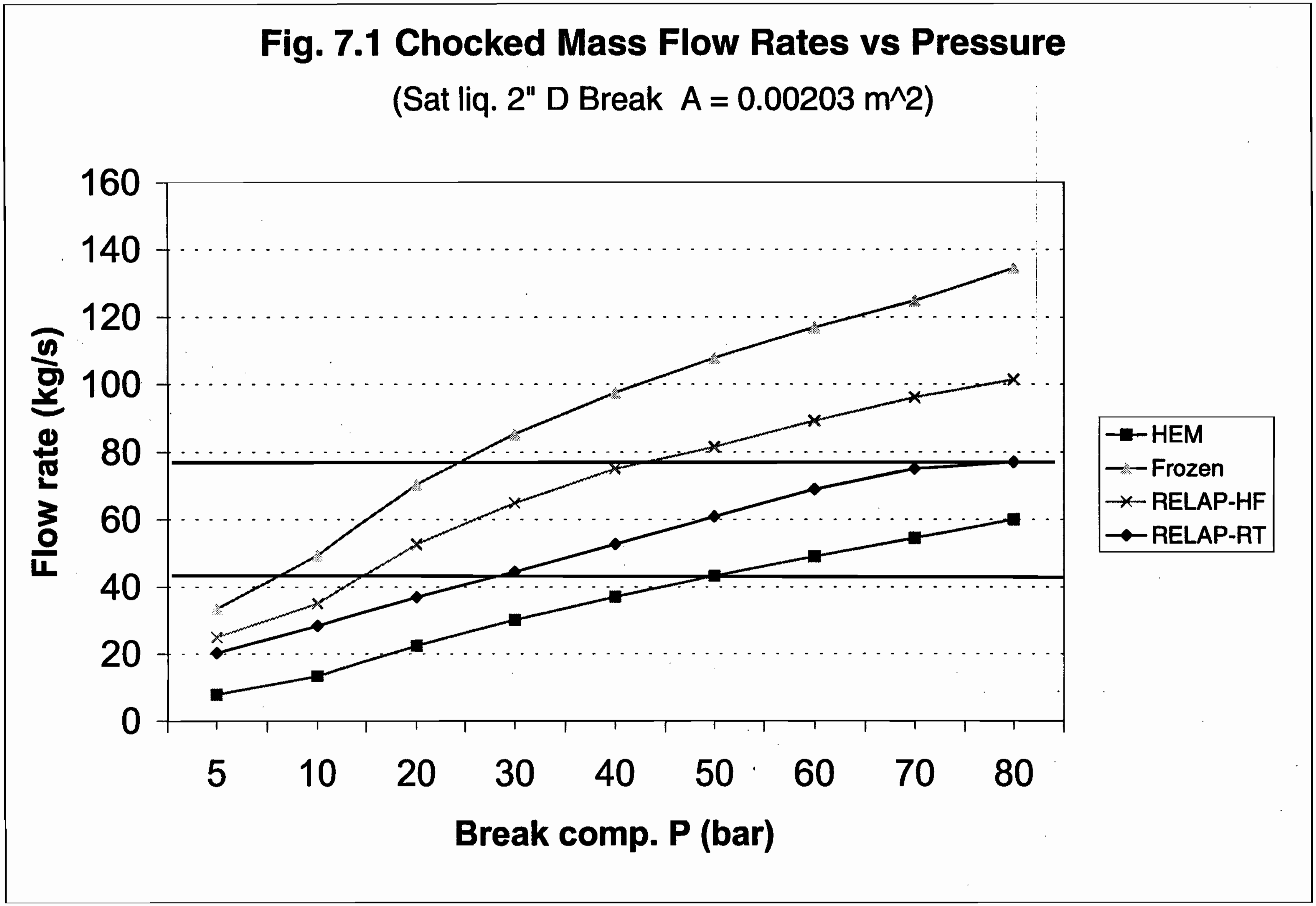


Fig. 7.1 Chocked Mass Flow Rates vs Pressure
(Sat liq. 2" D Break A = 0.00203 m^2)
160
140
120
100
80
60
40
20
0
Flow rate (kg/s)
5
10
20
30
40
50
60
70
80
Break comp. P (bar)
HEM
Frozen
RELAP-HF
RELAP-RT

Fig. 7.3 Chocked Mass Flow Rates as a Function of Break Area

Upstream cond: 70 bar (1028 psi); Tsat = 559K (546F)

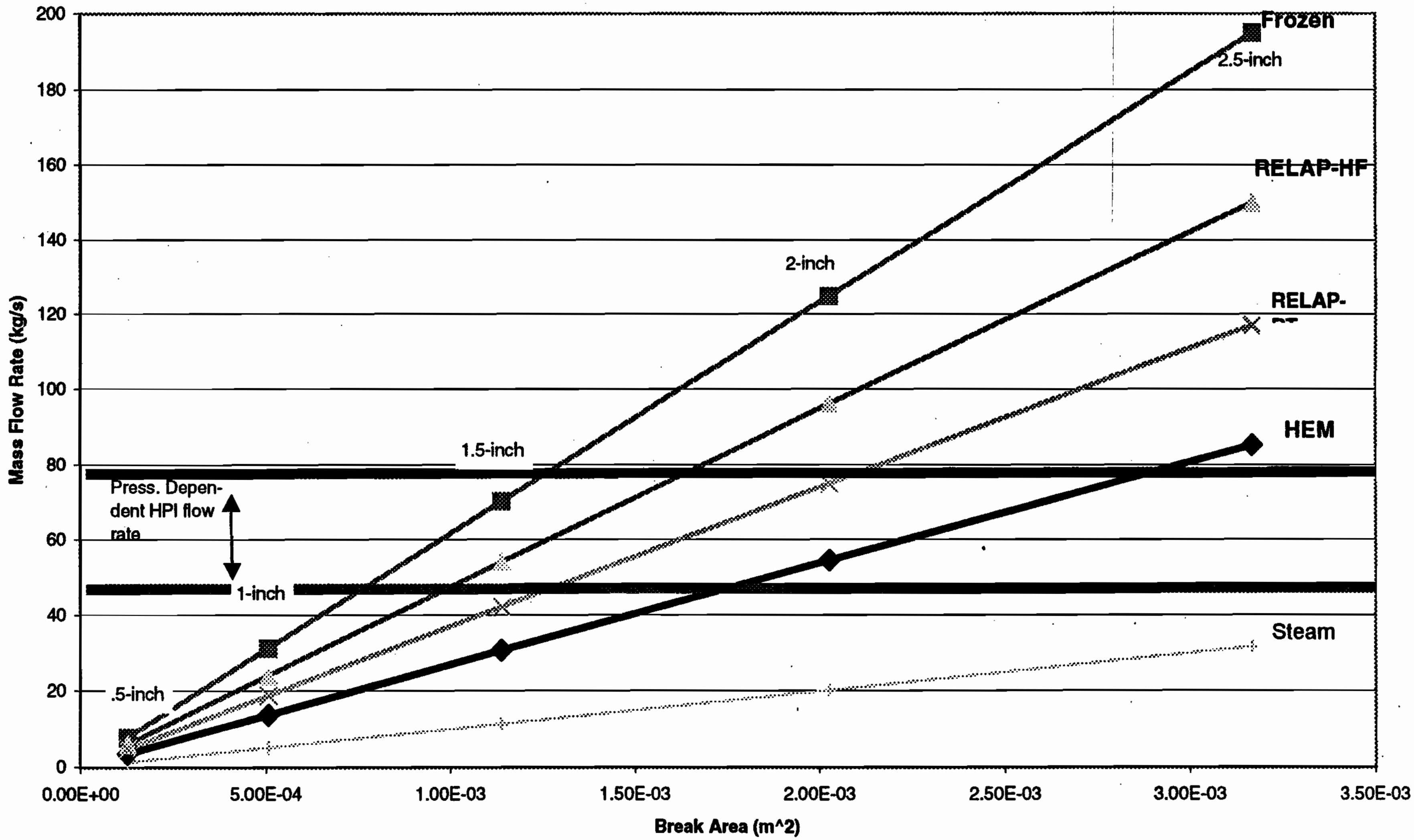


Fig. 7.4 Chocked Enthalpy Flow Rates as a Function of Break Area

Upstream cond.: 70 bar (1028 psi); Tsat = 559K (546F)

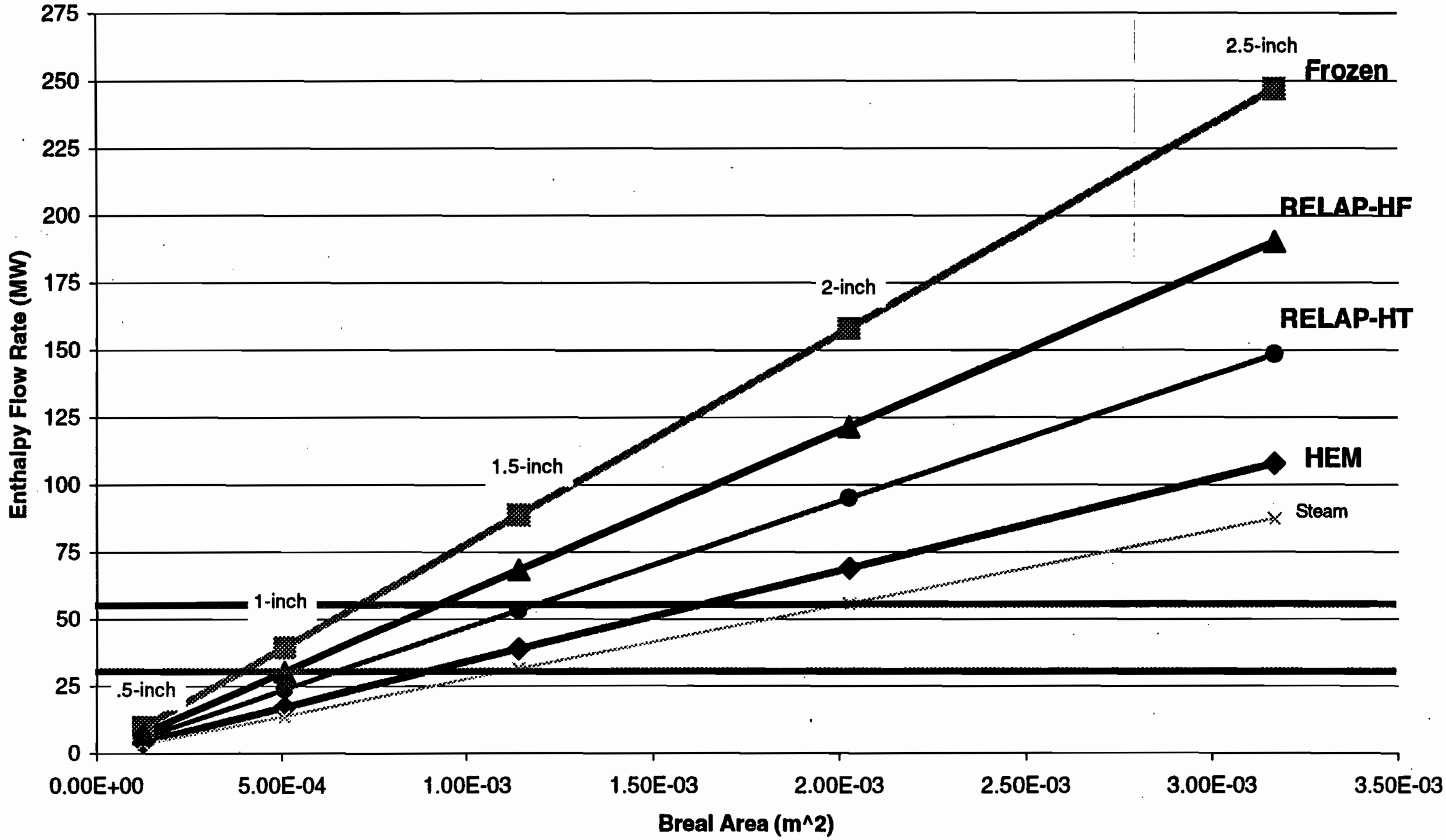


Fig. 7.5 Chocked Mass Flow Rates as a Function of Break Area

Upstream cond: 20 bar (290 psi); Tsat = 486K (414F)

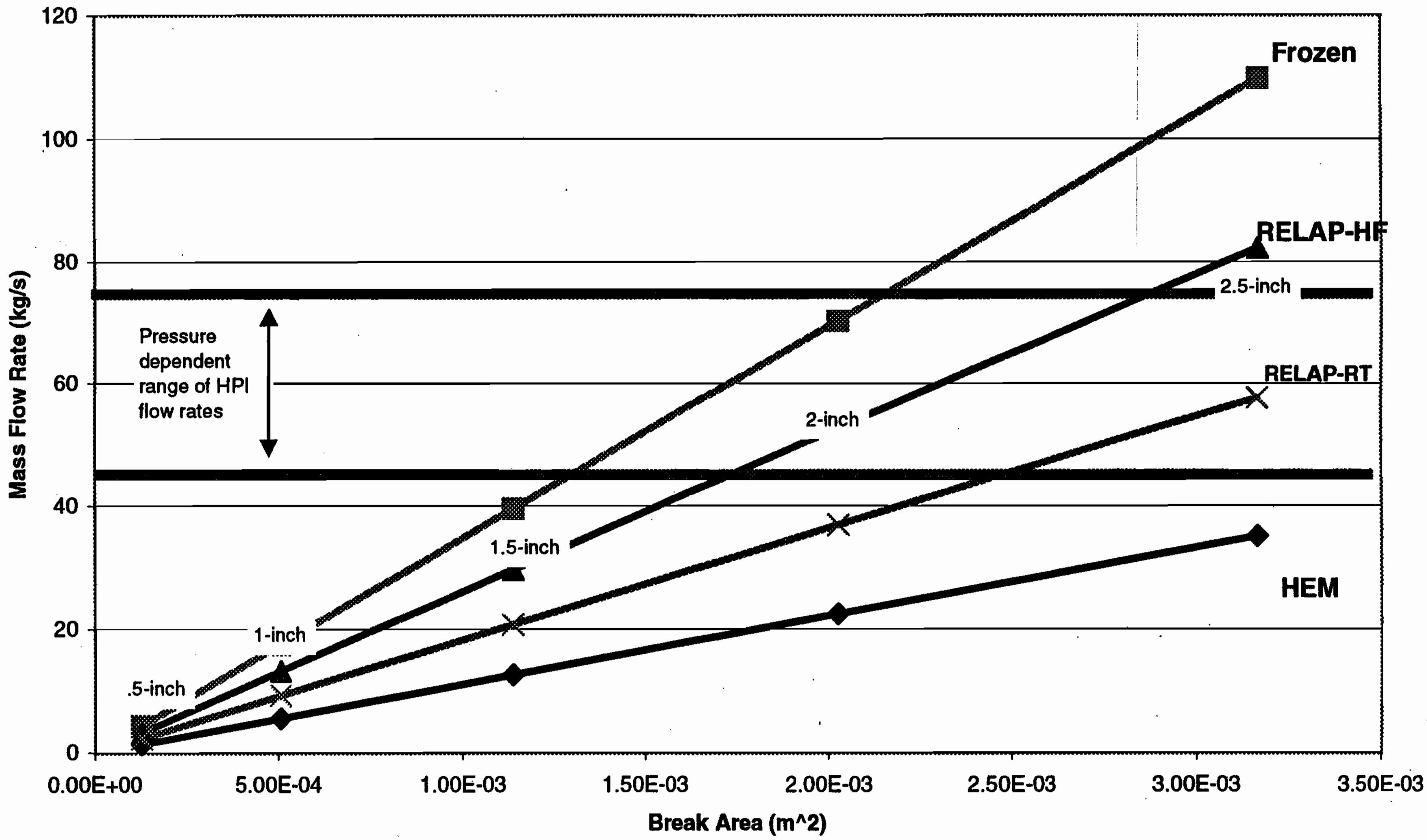


Fig. 7.6 Chocked Enthalpy Flow Rates as a Function of Break Area

Upstream cond: 20 bar (290 psi); Tsat = 486K (414F)

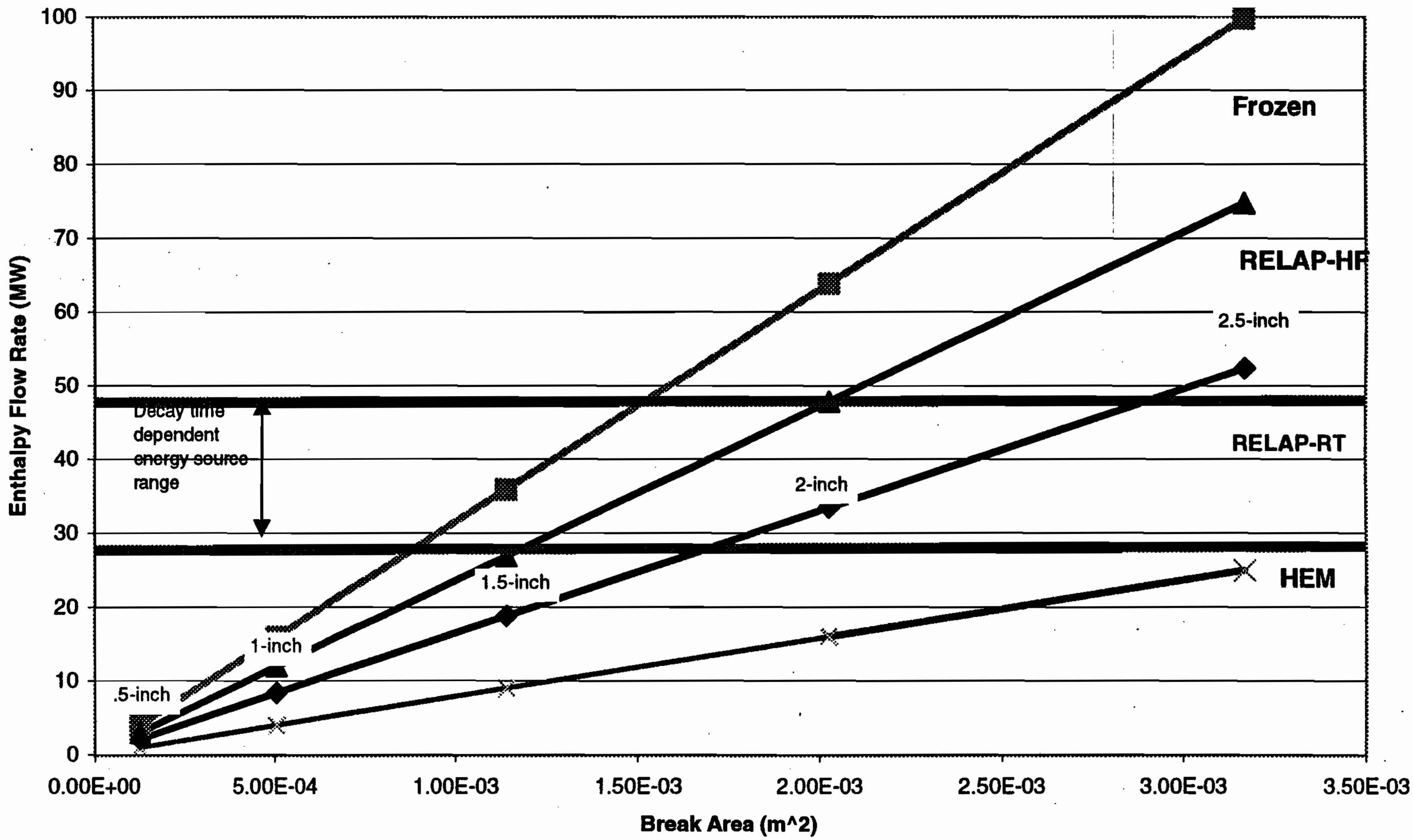
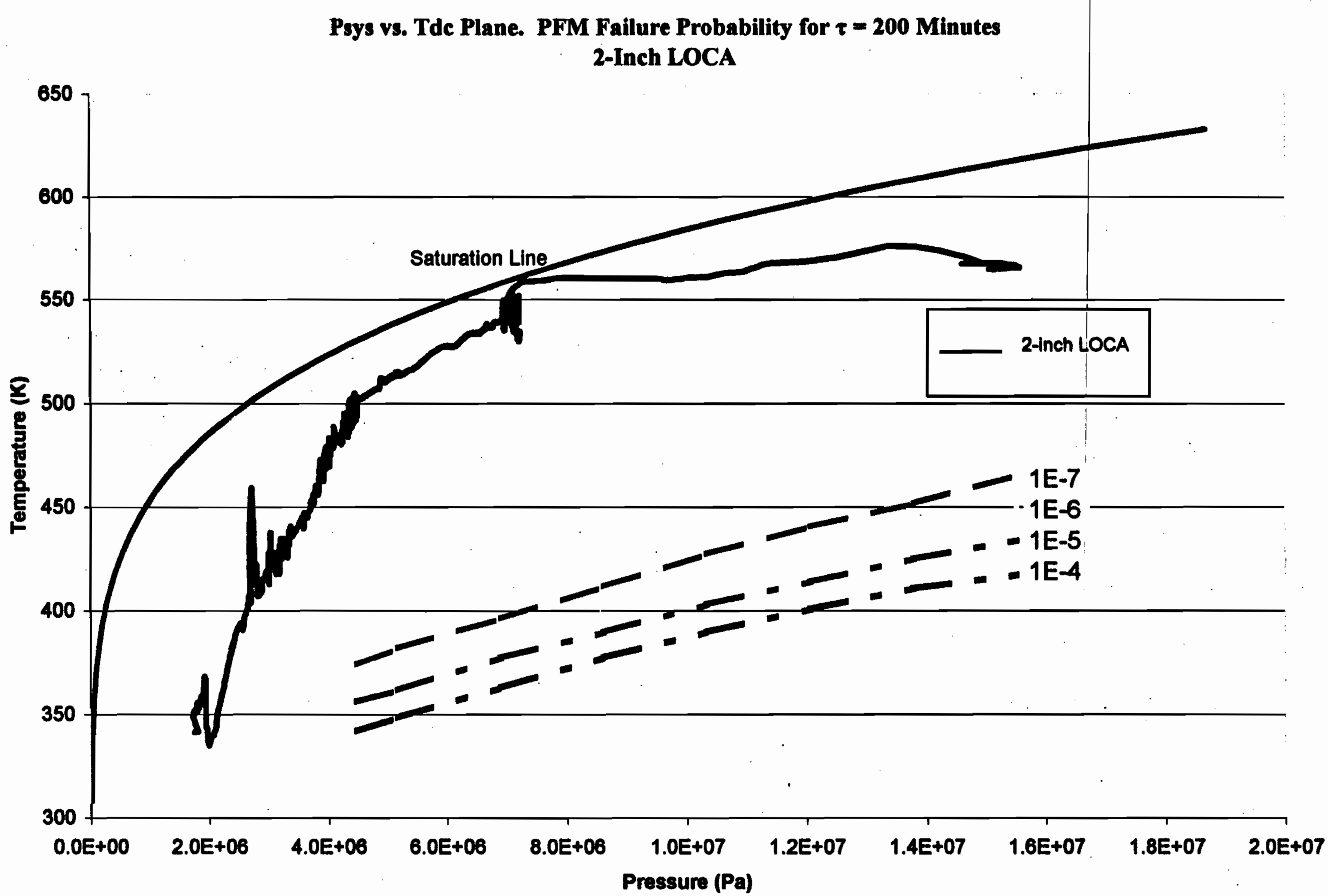


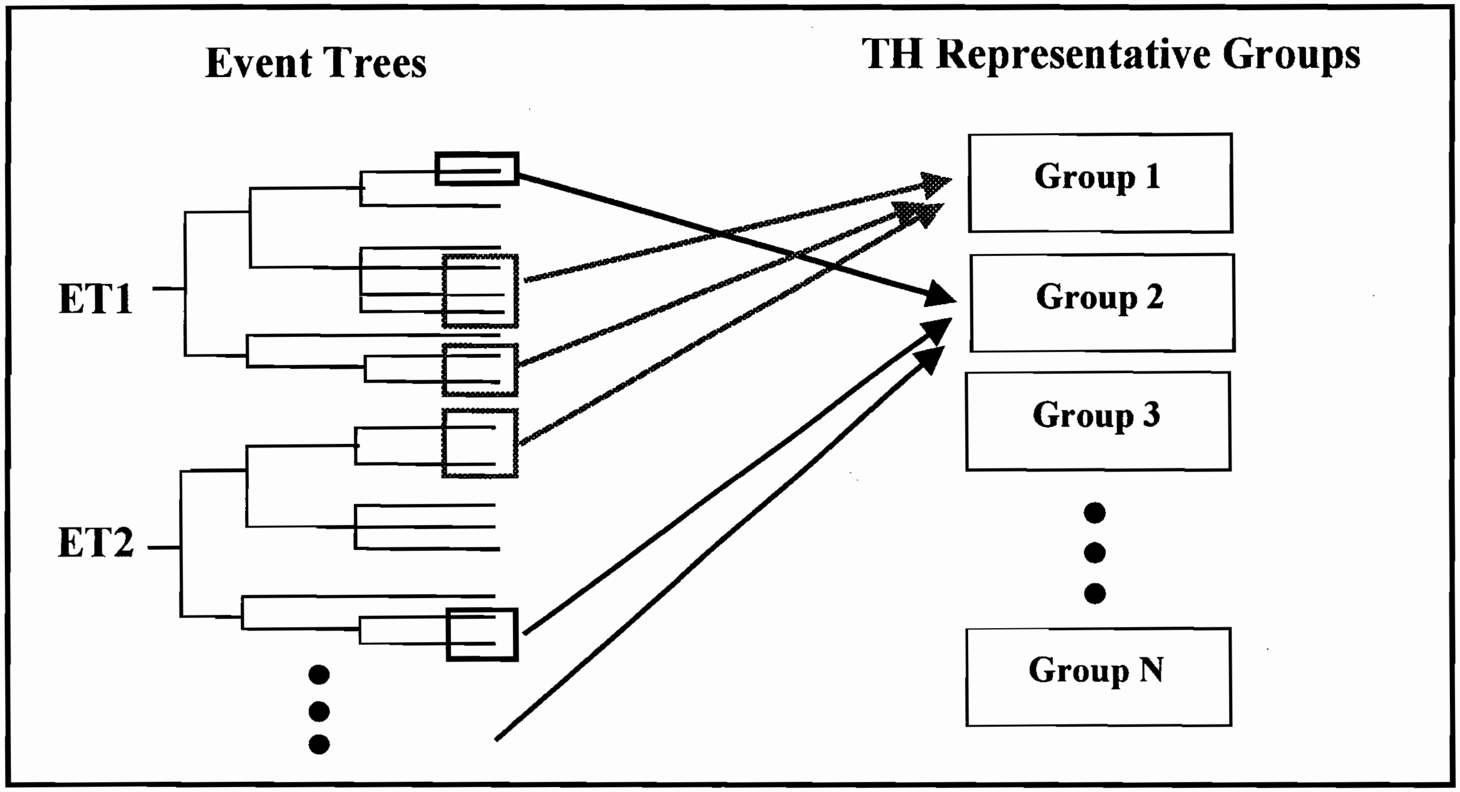
Table 7.3 Bounding Range of Break Sizes for Two-Phase Chocked Flow

		Low flow lim. HEM		High flow lim. 'Frozen'	
		Mass flow $W_{BR} > W_{HPI}$	En. flow $W_{BR} > Q_{HPI}$	Mass flow $W_{BR} > W_{HPI}$	En. flow $W_{BR} > Q_{HPI}$
70 bar	Area (cm^2)	30 – 17	17 – 10	12 – 8	7 - 4
	Eq D (in)	2.4 – 1.4	1.4 - .8	1 - 0.65	0.6 – 0.4
20 bar	Area (cm^2)	40 - 36	21 -18	21 - 18	14 - 9
	Eq D (in)	3.2 - 2.9	1.7 - 1.4	1.7 - 1.4	1.2 - 0.7

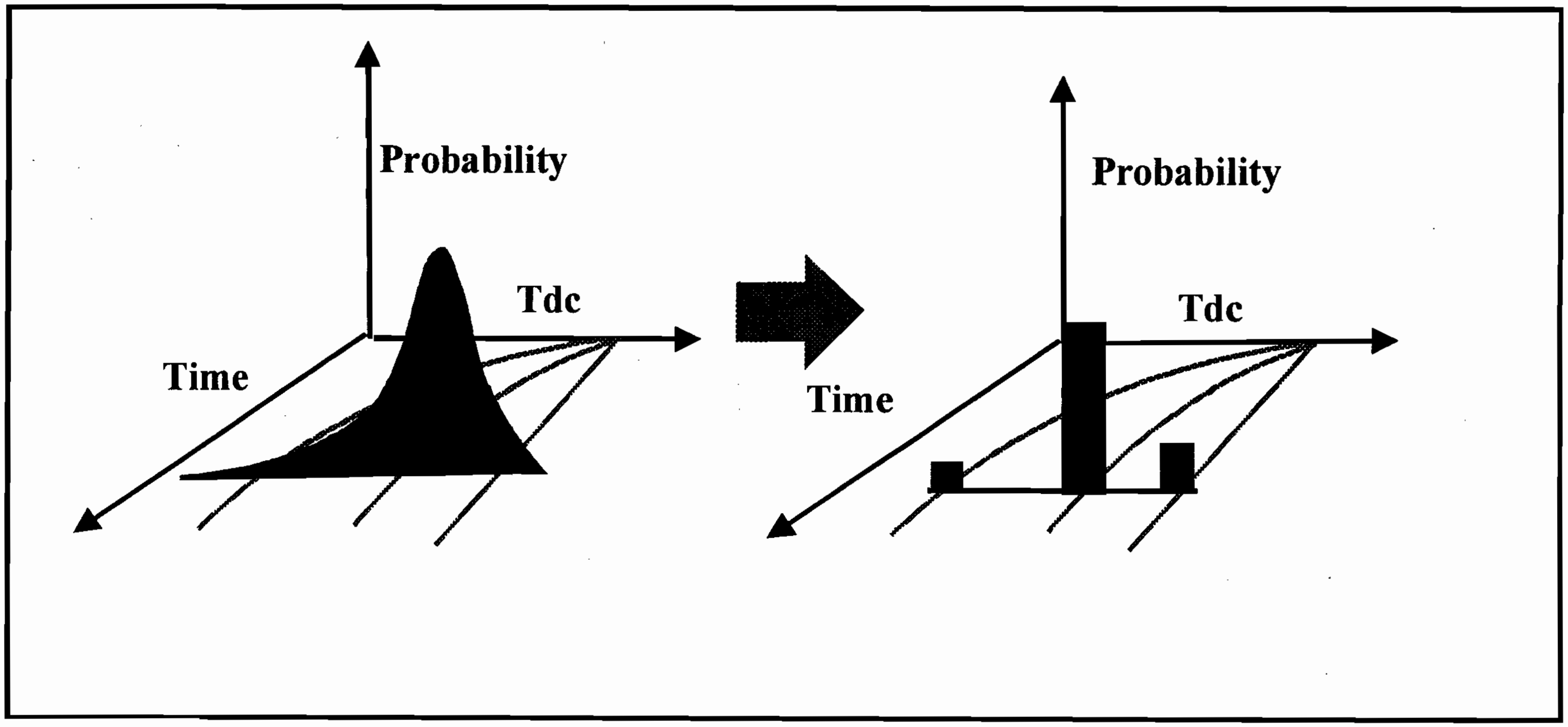


Psys vs. Tdc Plane. PFM Failure Probability for τ = 200 Minutes
2-Inch LOCA
Temperature (K)
Pressure (Pa)
Saturation Line
2-inch LOCA
1E-7
1E-6
1E-5
1E-4
650
600
550
500
450
400
350
300
0.0E+00
2.0E+06
4.0E+06
6.0E+06
8.0E+06
1.0E+07
1.2E+07
1.4E+07
1.6E+07
1.8E+07
2.0E+07

Grouping PRA Event Tree Scenarios According Similarity in Key TH Relevant Parameters



Discrete Representation of Parameter Trends



The Discretized Probabilities of Key Parameters Uncertainty of AFW Overfeed Scenarios

- **Time at which overfeed is terminated**
  - 10 minutes (.99*)
  - 30 minutes (.009*)
  - - Not controlled (.001*)
- **Feedwater flow rate**
  - Motor driven + Turbine driven AFW pumps (62 kg/s per SG; .9955*)
  - Motor driven AFW pumps only (31 kg/s per SG; .0045*)
- **Feedwater temperature**
  - 21 C (70 F; .5**)
  - 38 C (100 F; .5**)
- **HPI state**
  - Not activated (Nominal; .999*)
  - Activated (.001*)
- **RCP state**
  - Not tripped (Nominal; .999*)
  - Tripped (.001*)
- **Decay heat** (Damped effect; Not considered)

*ATHEANA data

**Engineering estimate

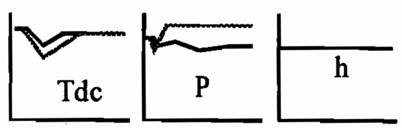
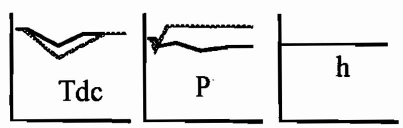
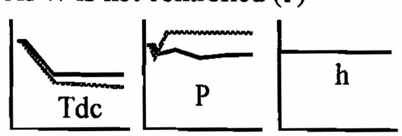
UNIVERSITY OF MARYLAND 1856

Subdividing TH Groups Based on Important of The Key Parameters Within The Group

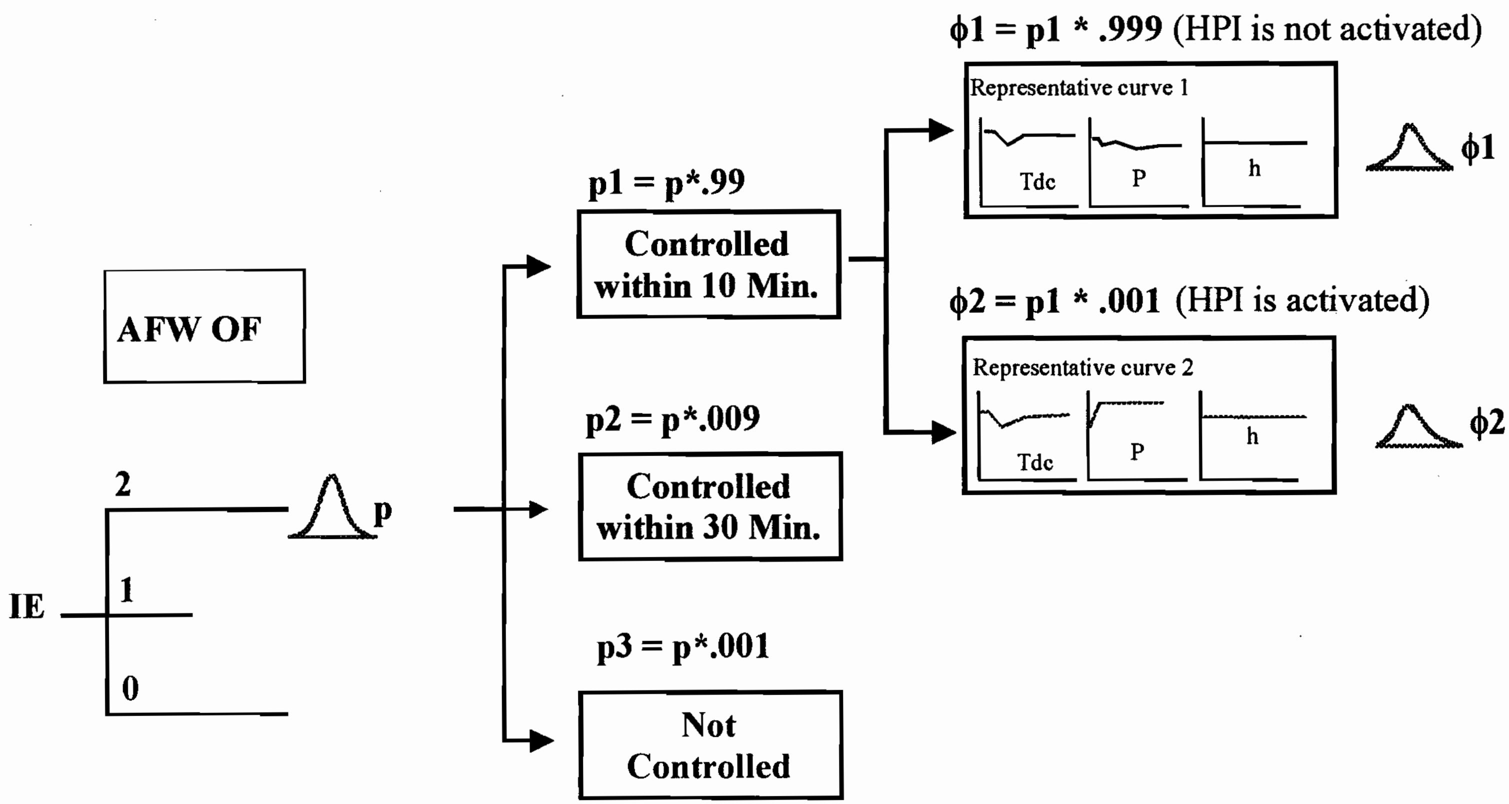
2 SGs Overfed Example

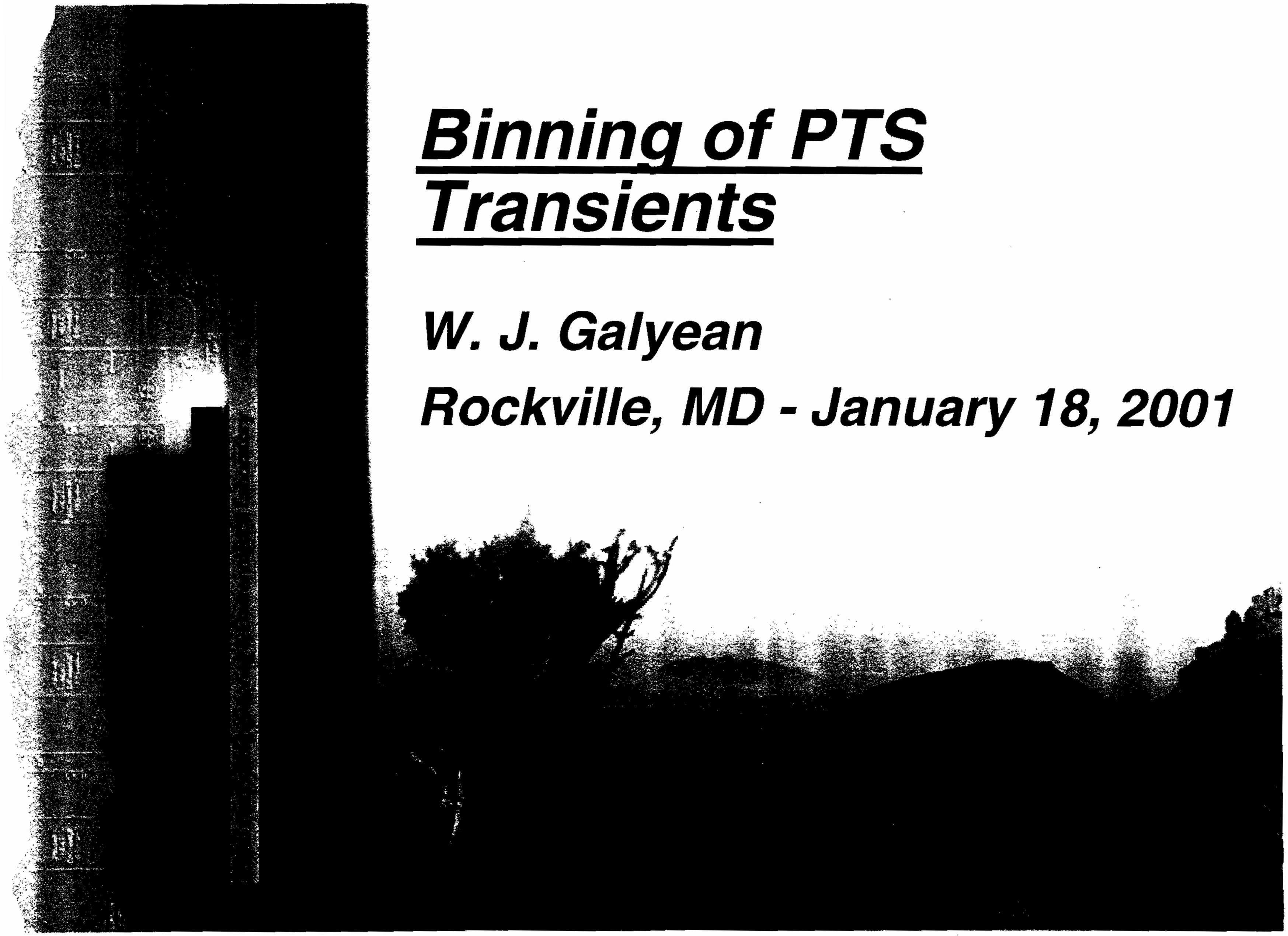
Feedwater Flow Rate

Time at Which Overfeed Is Terminated

	AFW Overfeed	MFW Overfeed
10 min.	AFW is controlled at 10th min.(**p**) 	NA
30 min.	AFW is controlled at 30th min.(**q**) 	NA
Not controlled	AFW is not controlled (**r**) 	MFW is not controlled 

Quantification Process





Binning of PTS Transients

W. J. Galyean

Rockville, MD - January 18, 2001

PTS Event Trees Generate Sequence of Events (PTS Transients)

- System and operator responses listed as event tree top events
- Individual branch points dependent on preceding path through the event tree
  - Specifics of event can vary
  - Probability can vary
- Each event tree end state represents a single unique path through the event tree (unique sequence of events)
  - Approximately 14,500 unique sequences generated

Each Event Tree Endstate Sequence Mapped into SID

- Sequence Identifier (SID) mapping used to group similar sequences
  - Eight character vector
  - Captures most relevant information (with respect to T/H response)
  - Developed in interactively with T/H analysts and T/H-uncertainty analysts
- Approximately 2500 unique PTS-SIDs
  - Each SID maintains link to member sequences

Eight Character SID

1 - Initial Power

2 - Primary System Integrity Status

3 - Secondary System Integrity Status

4 - Main Feedwater Status

5 - Emergency Feedwater Status

6 - Condensate Booster Pump Cooling of S/Gs

7 - High Pressure Injection Status

8 - Reactor Coolant Pumps Status

Each PTS-SID Mapped into TH Bin

- Second stage processing maps each PTS-SID into one of the available Thermal-Hydraulic cases
- 45 Available TH bins
  - 40 TH case
  - 4 "other" bins (CD but not PTS, or OK's)
  - 1 residual bin
- 31 TH bins actually used

Example Rule for Binning (TH24)

If both primary and secondary systems are intact, overfeeding S/Gs, HPI full (not throttled) then map into TH24

if

"PTS-PN01??I?" + "PTS-PN0?1?I?" +

"PTS-PN0??1I?" + . . .

then

GlobalPartition = "TH24-PN02NNIR";

PTS-SIDs Contributing to TH24

TH24-PN02NNIR

Total Frequency = 5.4E-5

PTS-SID	Frequency	Contribution
PTS-PN02NNIR	2.7E-5	51%
PTS-PN0T2FIT	1.7E-5	32%
PTS-PN0T1FIT	6.2E-6	12%
PTS-PN0T2NIR	1.0E-6	2%
PTS-PN01NNIR	9.3E-7	2%

Final Binning Process Relies on Engineering Judgement

- Binning of event tree sequences into PTS-SIDs, relatively straight-forward
  - If EFW successful, then "C" in 5th position
- Binning of PTS-SIDs into THxx-SIDs somewhat subjective
  - E.g., is PTS-ZS0T2NIR closer to
    TH17-ZZ1TCNIR or
    TH34-PS0TCNIR
- Final review of Binning process will be done once conditional (on THxx) PFM results are available

Current Analysis More Focused Compared to Original IPTS Study

- *Many details of original IPTS unavailable*
- *Original work was a series of separate almost independent analyses*
- *Original IPTS analysis for Oconee resulted in residual (un-binned) group as dominant risk contributor*
- *Better understanding of most key issues*
- *Fully integrated analysis*

Uncertainty in the Fracture Toughness Characterization

Mark Kirk
NRC

Marjorie Natishan
Phoenix Engineering Associates, Inc

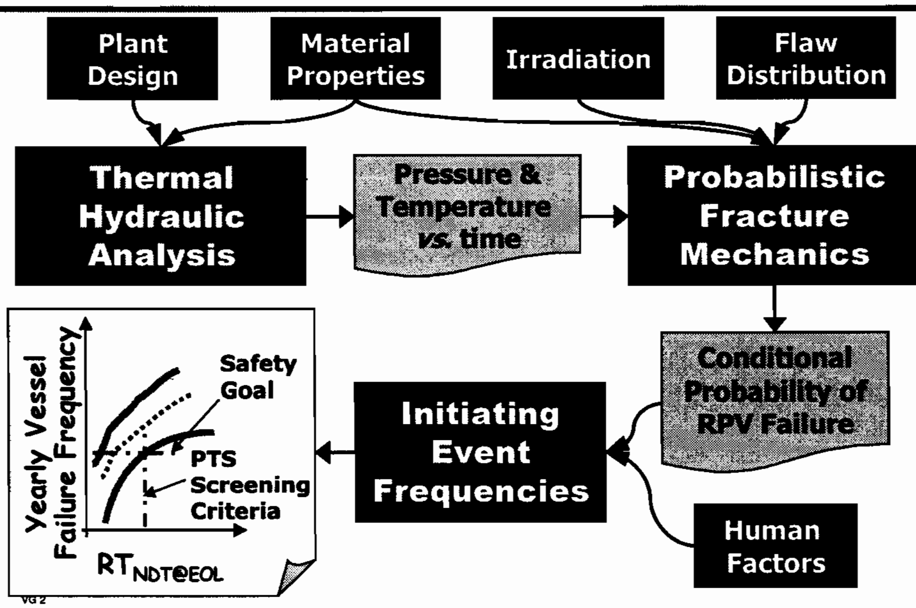
Paul Williams, Richard Bass, Terry Dickson
Oak Ridge National Laboratory

Mohammad Modarres, Fei Li
University of Maryland

ACRS Materials and Metallurgy Subcommittee Briefing
USNRC Headquarters – Rockville, MD – January 18, 2001

VG 1

Analysis Framework



VG 2

Nathan Siu's 1999 White Paper

Outside FAVOR[a]
- weld residual stresses
- cladding thickness
- stress-free temperature
- flaw size distributions[b]
- flaw density[b]
- T/H pressure-temperature curve[b]

Inside FAVOR[a]
- copper content
- nickel content
- neutron fluence
- flaw size
- flaw location
- RT_{NDT} margin
- reactor vessel temperature
- reactor vessel stress
- K_I
- K_{Ic} scatter

Table 2 - Recommendations for Categorization of Uncertain Variables and Parameters in PFM

Variable/Parameter	Recommended Uncertainty Category[a]
copper content	epistemic
nickel content	epistemic
neutron fluence	epistemic
flaw size	epistemic
flaw location	epistemic
RT_{NDT} margin	epistemic
reactor vessel temperature	deterministic[b]
reactor vessel stress	deterministic[b]
K_I	deterministic[b]
K_{Ic} scatter	aleatory and epistemic
weld residual stresses	epistemic
cladding thickness	epistemic
stress-free temperature	epistemic
flaw size distributions	epistemic[c]
flaw density	epistemic
T/H pressure-temperature curve	aleatory and epistemic

[a]Underline indicates a change from the current PFM approach.
[b]Variable is a deterministic function of other, uncertain variables; no additional treatment of uncertainty is required.
[c]Uncertainties in flaw size distribution should be addressed as part of the uncertainty analysis for flaw size.

VG 3

PFM: Treatment of Uncertainty

- Flaw characterization
  - Density
  - Size distribution
  - Fracture toughness
  - $RT_{NDT} - K_{Ic}$
    - ✓ Embrittlement correlation
      - Fluence
      - Chemistry
  - $RT_{NDT} - K_{Ia}$

Today's focus. An example Implementation of Dr. Siu's overall uncertainty framework.

VG 4

The Question

How is the characterization of fracture toughness uncertainty being treated in a manner that is methodologically consistent with the risk-informed framework being employed in the PTS re-evaluation project?

VG 5

A PTS Re-Evaluation Constraint

Need to stay within context of existing 10CFR50.61 methodology so licensees need not make new measurements.

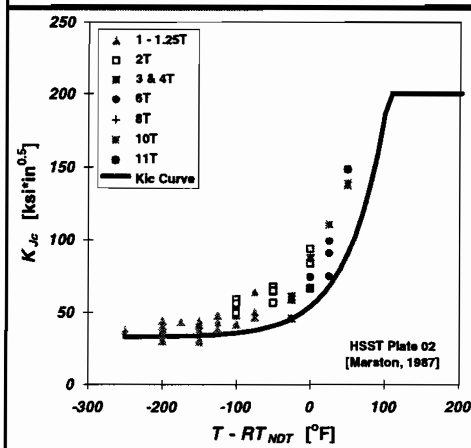
A Constraint

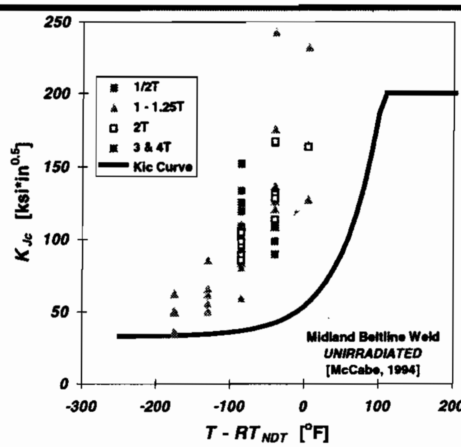
Therefore, need to re-cast the K_{Ic}-RT_{NDT} & K_{Ic}-RT_{NDT} processes, which are known and intended to be conservative, as a best-estimate.

A Requirement

VG 6

So, We have to Address this:



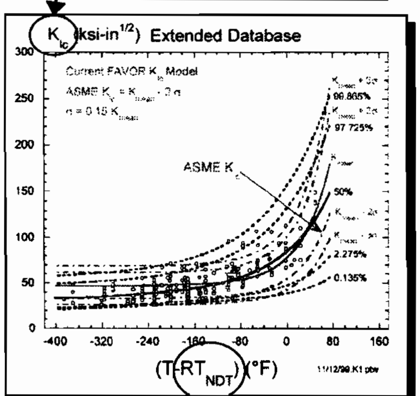


☞ **The 10CFR50.61 process contains considerable, inconsistent, uncertainties.**

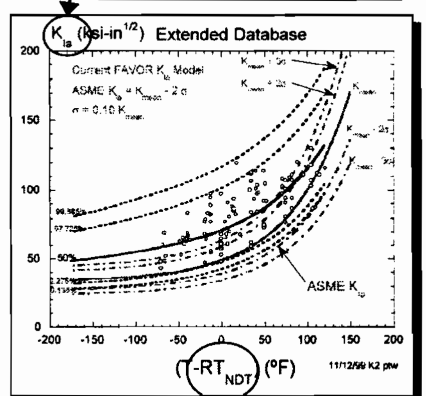
VG 7

We Have 3 Parameters for Uncertainty Characterization

K_{IC}: *Crack Initiation*



K_{IA}: *Crack Arrest*

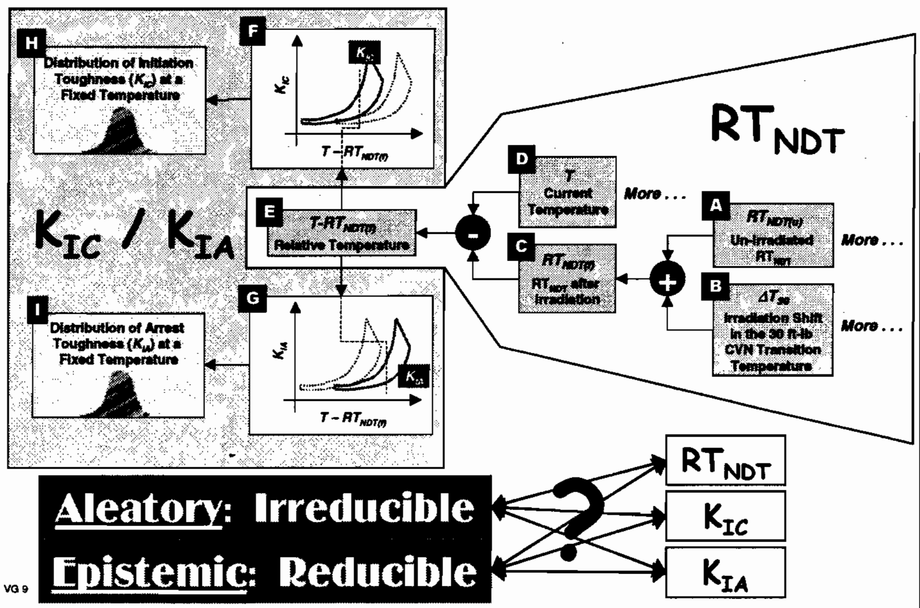


RT_{NDT}
Index Temperature Intended *to* Normalize Material Differences

VG

10CFR50.61 Toughness Estimation

→ The Challenge ←



VG 9

Outline

- **Overview**
  - Existing fracture toughness characterization
  - Uncertainty definitions
- **Uncertainty characterization and classification**
  - The 10CFR50.61 RT_{NDT} process
  - A physical understanding of K_{IC}
  - A physically motivated proposal
- **Domain expert agreement on adjustment factors**
  - $RT_{ADJUSTMENT}$ factor
  - K_{Ic} distribution to sample
- **Treatment of uncertainties**
  - Methodological consistency with a risk informed framework
  - Quantification framework
- **Summary and remaining work**

VG 10

Accounting for Fracture Toughness Uncertainty in the PTS Analysis

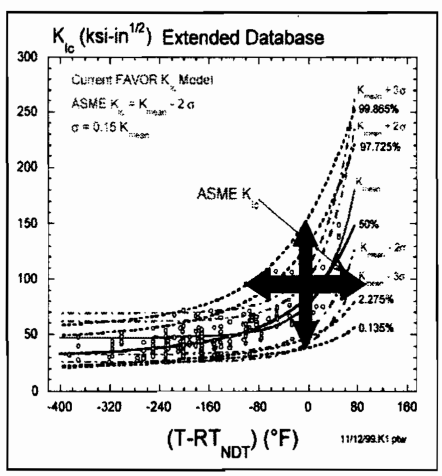
Background:

- EPRI and NRC involved in development of technical basis for revision to PTS rule and screening criteria to take advantage of technological developments
- PRA methods are used to account for uncertainty in a consistent manner within FAVOR to result in more risk-informed and close to best-estimate computations
- PRA methodologies depend on identification, and development of appropriate methods to account for, of all sources of uncertainty in a process
  - **Material variability and model uncertainty**
  - **Aleatory and epistemic uncertainty**

MARYLAND EPRI

Motivation

Identify sources & nature of uncertainties in RT_{NDT}-indexed K_{IC} to provide guidance in development of a model to quantify these uncertainties in FAVOR computations



MARYLAND EPRI

Structure of the Program

- **Develop framework to decompose process**
  - ***Identify sources of uncertainty***
    - $RT_{NDT(u)} - K_{Ic}$
    - ΔT_{30}
    - $RT_{NDT} - K_{Ia}$
  - ***Describe uncertainties***
    - Data & material variability
    - Model uncertainty
    - Expert judgements/ appropriateness of criteria
- **Establish physical basis for parameters classification**
  - ***Aleatory (irreducible)or***
  - ***Epistemic (reducible)***
  - *Quantify degree of uncertainty in RT_{NDT} - K_{Ic}*
    - Relative to current method of accounting for uncertainty
      - Implicit conservatisms
      - Explicit margins
    - Relative to state-of-the-art
- **Provide information to UM-CTRS for development of a model to account for these uncertainties**

Product — **Procedure to treat parameter and model uncertainty in FAVOR**

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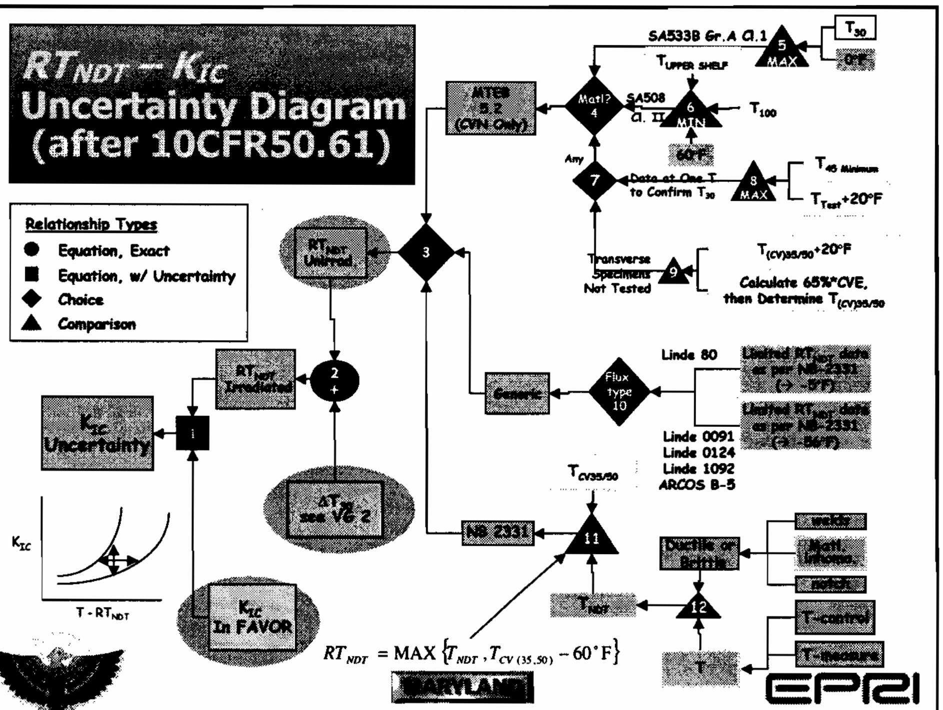
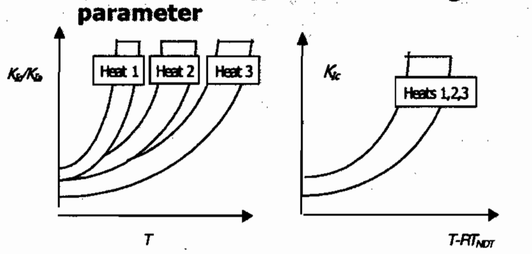
$RT_{NDT} - K_{IC}$ Uncertainty Diagram (after 10CFR50.61)



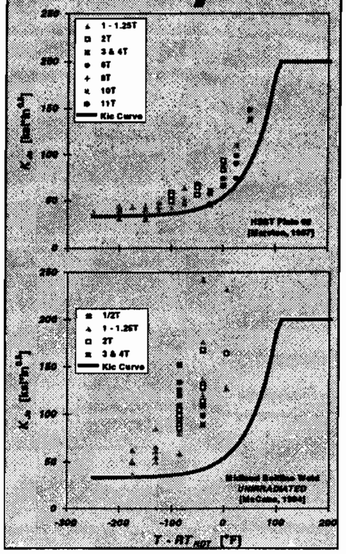
$RT_{NDT(u)}$ Uncertainty

Intent

- $RT_{NDT(u)}$ intended to represent fracture toughness transition temperature
  - ✓ Collapse K_{Ic} data onto single curve
  - ✓ Characterize K_{Ic} transition using one parameter



Reality



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$RT_{NDT(u)}$ Uncertainty Quantification

- **Goal: to define uncertainty in $RT_{NDT(u)}$ by comparing to current state-of-art "best estimate" T_{trans}**
  - Characterize how well $T\text{-}RT_{NDT(u)}$ places K_{Ic} model relative to K_{Ic} vs T data
- **Issues to be addressed:**
  - Define "truth." What is the value most representative of T_{trans}?
  - How should this best estimate be applied to "adjust" $RT_{NDT(u)}$?
  - Where in the 10CFR50.61 process are adjustments required
- **Proposal: We believe that T_0 (Master Curve method) best represents the "true" T_{trans} of a material**
  - Strong empirical basis
  - Physically based method
  - Accounts explicitly for cleavage process using weakest link statistics
  - Consistently defined for all materials as T@ 100 MPa√m
    - Corresponds to the position of the data instead of a representation of data

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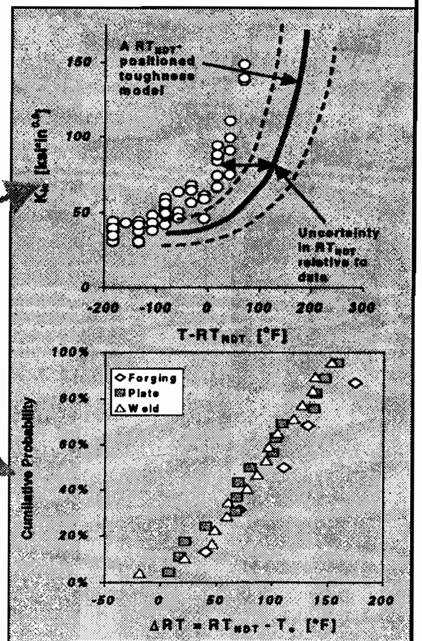
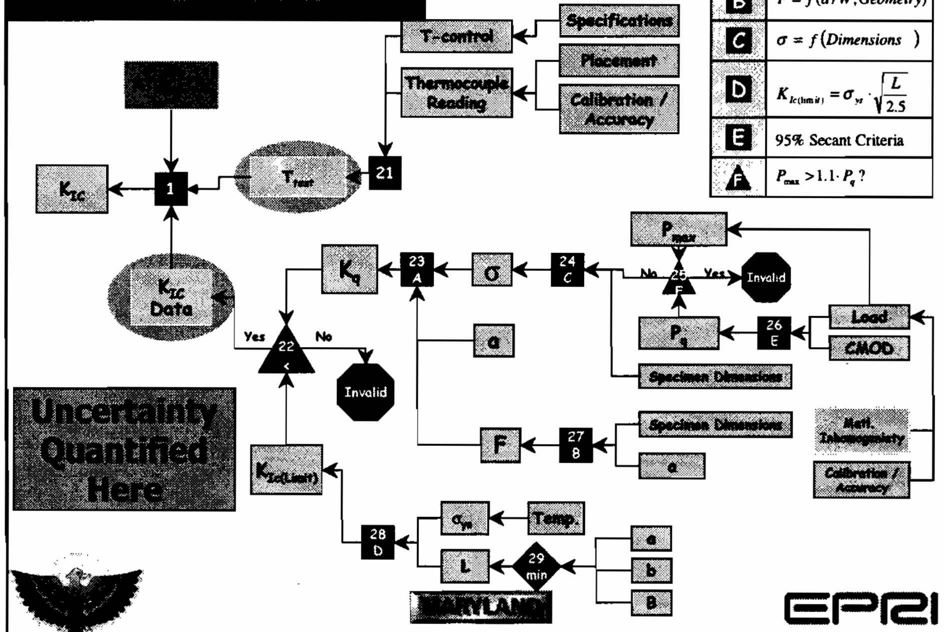
Proposed $RT_{NDT(u)}$ Adjustment

- Goal is to quantify uncertainty in $RT_{NDT(u)}$
  - Quantify how far off RT_{NDT} is from more accurate representation of the real toughness data
  - Using a consistent representation of that data
- T_o best represents "true" fracture toughness transition data
- Adjustment Factor based on CDF of $\Delta RT = RT_{NDT(u)} - T_o$
- ΔRT accounts for KNOWN epistemic uncertainties
- Brings $RT_{NDT(u)}$ closer to a best estimate in a PFM calculation



K_{Ic} Decomposition

A	$K = \sigma\sqrt{\pi a} \cdot F$
B	$F = f(a/W, Geometry)$
C	$\sigma = f(Dimensions)$
D	$K_{Ic(limit)} = \sigma_{ys} \cdot \sqrt{\frac{L}{2.5}}$
E	95% Secant Criteria
F	$P_{max} > 1.1 \cdot P_q$?



K_{Ic} Uncertainty Classification

- Uncertainty in K_{Ic} is aleatory
- **A physical understanding of the cleavage fracture process demonstrates that non-coherent particles (& other crack initiating features) are, alone, responsible for the scatter in K_{Ic}**
- **This physical understanding coupled with the ideas that:**
  - K_{Ic} does not exist as a point property (associated length scale)
  - Both non-coherent crack initiating particles and postulated flaws are ***randomly*** distributed throughout the vessel

suggests that K_{Ic} uncertainty should be treated as aleatory

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Appropriate Distribution for K_{Ic}

Use of a Weibull model to describe the distribution of K_{Ic} data follows from the physical phenomena of the cleavage fracture process (i.e. weakest link).

Physical Process	Weibull Model Parameters
1. Accumulation of strain to some critical value required to initiate a microcrack	1. Gives us K_{min}: a minimum value below which cleavage fracture will not occur
2. High enough stress triaxiality to inhibit crack blunting by dislocation motion	2. Implies SSY conditions that give us a Weibull shape parameter of 4 (next slide)
3. A crack tip stress that exceeds the fracture stress of the material	3. K_{med}: the median value (from measurements) of critical stress intensity for fracture

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Weibull Shape Parameter of 4

Shape Parameter of 4 describes how the volume involved with the fracture process scales only with K_I

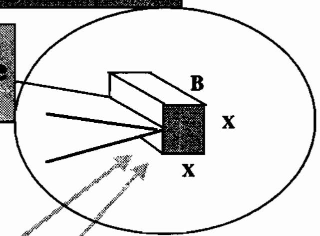
Maximum triaxiality occurs under SSY

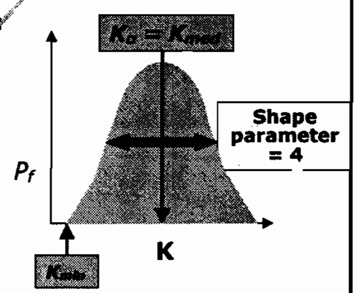
- **When crack tip stress field is not effected by the specimen boundaries,**
- **Dislocations are fully contained within a finite volume at the crack tip**

This allows us to describe the volume in which dislocations are moving (the plastic zone) relative to a ratio of $(K_I/\sigma_y)^2$

- **$X^* = X/(K_I/\sigma_y)^2$ where X^* describes some location within the plastic zone**
- **Crack tip vol. elem. = $X^2B = X^{*2}(K_I/\sigma_y)^4 B$**

Probability of failure depends on the sampling volumes, thus- probability scales with K_I^4 and the appropriate shape parameter is 4





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Summary of Uncertainty in RT_{NDT}/K_{Ic}

- **$RT_{NDT(u)}$ uncertainty is epistemic**
  - Can be accounted for by use of an adjustment factor based on Master Curve
- **K_{Ic} uncertainty is aleatory**
  - As it describes the physical process of cleavage fracture which is a weakest link statistical competition based on random distributions of crack initiators in a crack tip stress field
- **The distribution of K_{Ic} is appropriately described using a 3-parameter Weibull distribution**

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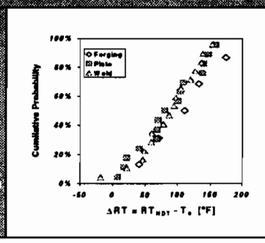
EPRI

Proposed Method for Quantifying Uncertainty in K_{Ic}

Simulate $RT_{NDT(u)}$ per 10CFR50.61

Epistemic

Simulate ΔRT

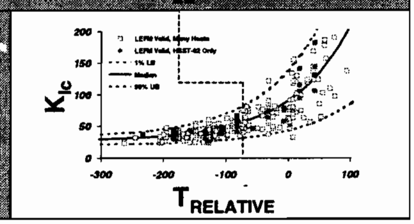


$$RT_{NEW} = RT_{NDT(u)} - \Delta RT$$

$$T_{RELATIVE} = T_{VESSEL} - RT_{NEW}$$

Determine K_{Ic} Distribution

Aleatory



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Proposal Implementation Issues

Proposed Method

- ΔRT_{new} is found by comparing relative positioning of the toughness curve by RT_{NDT} versus a consistently defined position in the real data.
- Here we use MC positioning of T_o
- We could just as easily use another point
- Experts agree that this is the best technical resolution

Issues

- No agreed procedure to convert straight flaw size to curved crack fronts analyzed within FAVOR using MC method
- This keeps us from taking full advantage of state-of-the-art "best estimate" methodology
- We need to develop another data-positioning method that implicitly addresses size effects (LEFM-based method)

MARYLAND

EPRI

Estimation of Epistemic Uncertainties in RT_{NDT} : Quantifying Adjustment Terms

B. R. Bass
P. T. Williams
T. L. Dickson
Computational Physics and Engineering Division

J. G. Merkle
R. K. Nanstad
Metals and Ceramics Division

Oak Ridge National Laboratory
Oak Ridge, Tennessee

ACRS Materials and Metallurgy Subcommittee Briefing
USNRC Headquarters – Rockville, MD – January 18, 2001

Oak Ridge National Laboratory
U.S. Department of Energy

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Separating epistemic uncertainty in RT_{NDT} involves several steps.

$$RT^* = RT_{NDT(0)} - \Delta RT$$

where

RT^* = *resampled replicate*
$RT_{NDT(0)}$ = *measured value*
ΔRT = *adjustment term*

K. O. Bowman and P. T. Williams, *Technical Basis for Statistical Models of Extended K_{Ic} and K_{Ia} Fracture Toughness Databases for RPV Steels*, (ORNL/NRC/LTR-99/27), Oak Ridge National Laboratory, February 2000.

Step 1: K_{Ic} vs (T-$RT_{NDT(0)}$) database and statistical model were developed without adjustment term (ORNL 99/27).

Step 2: Statistical cumulative distribution functions (*CDFs*) were developed for RT_{NDT} adjustment term (ΔRT) from ORNL 99/27 database.

Step 3: Weibull K_{Ic} statistical models (based on re-sampled ORNL 99/27 RT_{NDT} data) were created using a statistical re-sampling method.

Step 4: Evaluation of methodology with implementation into FAVOR (to be done)

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2

Step 1

Construct statistical model from ORNL 99/27 K_{Ic} extended database. (no uncertainty adjustment).

K. O. Bowman and P. T. Williams, *Technical Basis for Statistical Models of Extended K_{Ic} and K_{Ia} Fracture Toughness Databases for RPV Steels,* (ORNL/NRC/LTR-99/27), Oak Ridge National Laboratory, February 2000.

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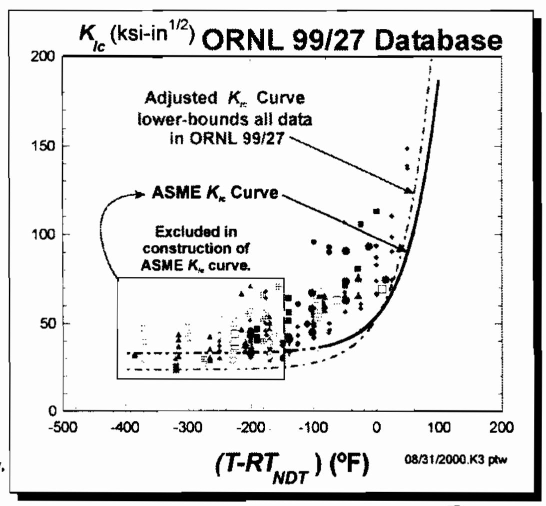
3

This study was confined to the ORNL 99/27 K_{Ic} database of ASTM E399 data.

18 RPV Steels
plate
forging
weld

254 data points
ASTM E399
K_{Ic}



R. K. Nanstad, J. A. Keeney, and D. E. McCabe, *Preliminary Review of the Bases for the K_{Ic} Curve in the ASME Code,*(ORNL/NRC/LTR-93/15) Oak Ridge National Laboratory, July 12, 1993.

K. O. Bowman and P. T. Williams, *Technical Basis for Statistical Models of Extended K_{Ic} and K_{Ia} Fracture Toughness Databases for RPV Steels,* (ORNL/NRC/LTR-99/27), Oak Ridge National Laboratory, February 2000.

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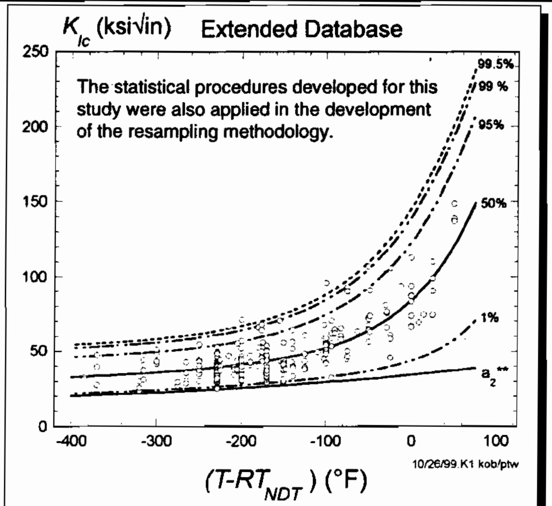
4

ORNL Weibull model (99/27) of K_{Ic} fracture toughness *vs* normalized temperature ($T - RT_{NDT}$) was developed using a strictly statistical analysis.

Epistemic uncertainties for K_{Ic} and RT_{NDT} were not quantified in this analysis.

The three parameters of this Weibull model are temperature dependent.

ASME K_{Ic} curve played no role in the model development.



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5

Step 2

Generation of cumulative distribution functions *(CDFs)* for uncertainty adjustment term Δ*RT*

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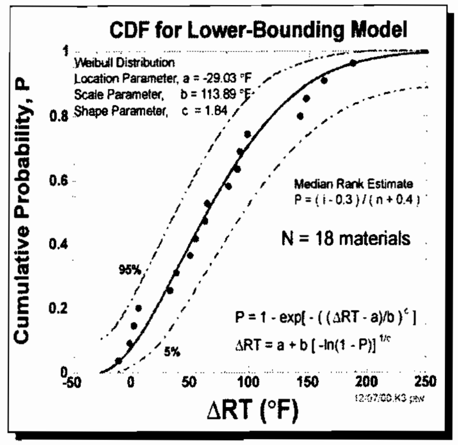
Data point samples of ΔRT were fitted with a 3-parameter Weibull distribution.

- ΔRT data points were determined by applying adjustment methodology to measured $RT_{NDT(0)}$ data.

- Parameters *a, b,* and *c* in *CDF* were determined from method of moments and maximum-likelihood point-estimation procedures.



Several strategies for quantifying ΔRT were investigated.

- $\Delta RT = RT_{NDT(0)} - T_0$

  Proposed by M. Modarres (U. of Maryland) and M. Natishan (PEAI)

- ΔRT = Lower-bounding shift of adjusted ASME K_{Ic} curve

  Proposed by J. G. Merkle/R. K. Nanstad (ORNL)

Apparent bias in $RT_{NDT(0)}$ relative to T_o is evident for 15 unirradiated RPV materials.

Proposed by M. Modarres (University of Maryland)

M. Natishan (PEAI)

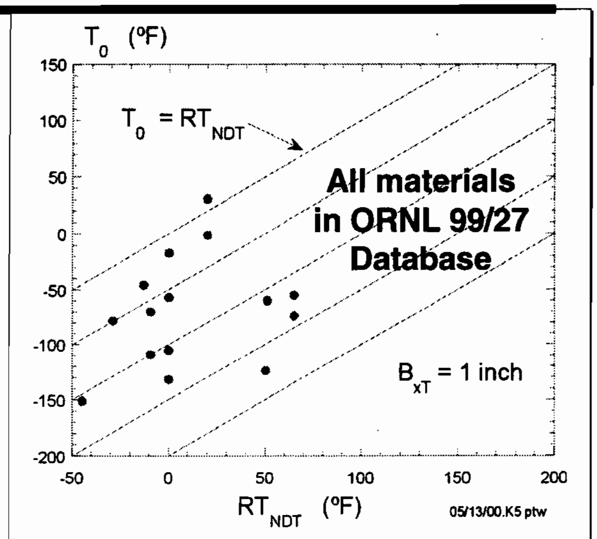
ΔRT is sampled from a statistical distribution developed from ($RT_{NDT(0)} - T_0$) data.

Application

$P = \text{RAND}(0,1)$

$\Delta RT = a + b \ln[-(1-P)]^{1/c}$

$RT^* = RT_{NDT(0)} - \Delta RT$



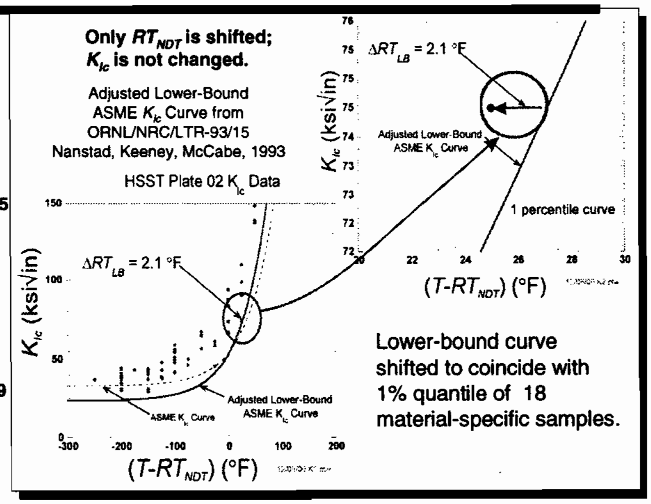
Lower-bounding methodology is consistent with original intent of RT_{NDT}

Proposed by J. G. Merkle and R. K. Nanstad (ORNL)

ASME Code K_{Ic} curve does not lower-bound ORNL 99/27 database.

Adjusted curve from ORNL 93/15 does lower-bound ORNL 99/27 database and is assumed to represent a 1 % quantile curve.

LB adjustment is intended to *CONSISTENTLY POSITION* bounding curve relative to E-399 data for 18 materials in ORNL 99/27 database.

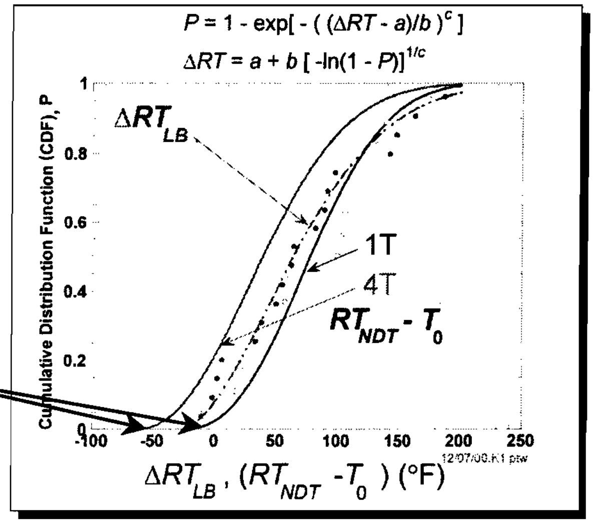


LB adjustment quantifies the ability of $RT_{NDT(0)}$ to position K_{Ic} data relative to a lower-bounding curve.

Comparison of *CDFs* for ΔRT

Lower-bounding *CDF* represents an intermediate distribution relative to the expected spread between 1T and 4T for $RT_{NDT} - T_0$.

B_{xT} size adjustment affects only location parameter, *a*.



Step 3

Generation of Weibull K_{Ic} statistical models (based on ORNL 99/27 database) using a statistical resampling method.

Parametric procedure produces a large set of resampled K_{Ic} models that include the effects of RT_{NDT} uncertainty.

Step 1. Create replicate data set by resampling on ΔRT.

$$RT^* = RT_{NDT(0)} - \Delta RT_{NDT}$$

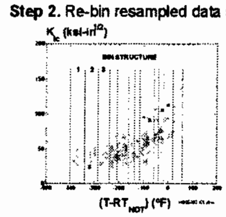
for 18 material groups

$$\Delta RT = a + b\ \ln(-(1-P))^{1/c}$$

for $0 < P < 1$

Re-sampled 18 times

Step 2. Re-bin resampled data set



Step 3. For each of NBIN data bins:
Calculate average bin temperature, T_r.
Calculate (a,b) parameters using modified shape parameter c from ORNL 99/27 K_{Ic} model.

a = location parameter
b = scale parameter
c = shape parameter

$$T_{bin} = \overline{(T - RT^*)}$$

$$\Pr(K_{Ic} < K_I) = 1 - \exp\left[\left(\frac{K_I - a}{b}\right)^c\right]$$

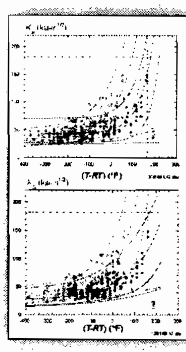
Step 4. Carry out nonlinear regression to produce location, scale, and shape parametric functions of normalized temperature (T-RT^*).

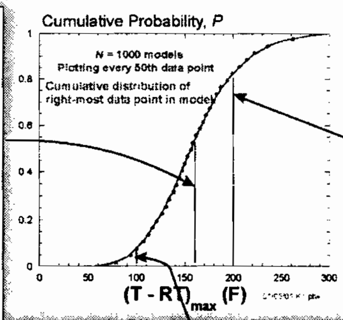
$aKIc$ = A1 + A2 exp[A3(T-RT*)]
$bKIc$ = B1 + B2 exp[B3(T-RT*)]
$cKIc$ = C1 + C2 exp[C3(T-RT*)]

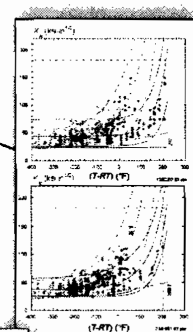
$$Q = 1 - \exp[-((K_{Ic} - aKIc)/bKIc)^{cKIc}]$$

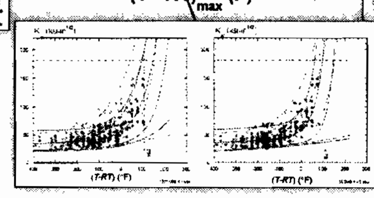
Resampled K_{Ic} Models

Snapshots of Resampled K_{Ic} Models









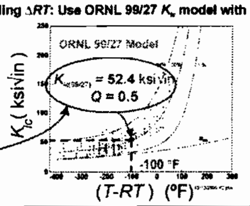
Resampling using Lower-Bound CDF for ΔRT.

Look-up table should include how many (100, 1000, 10000,..) K_{Ic} models? (To be determined)

Example Case: Resampling both ΔRT and K_{Ic} Model

Let the following data be fixed:
T = 50 °F
$RT_{NDT(0)} + \Delta RT_{irrad}$ = 150 °F
$T - (RT_{NDT(0)} + \Delta RT_{irrad})$ = -100 °F
K_I = 54.2 ksi in

(1) No resampling ΔRT: Use ORNL 99/27 K_{Ic} model with $\Delta RT = 0$



Q = cumulative probability of exceeding K_{Ic} for a given value of applied K_I and a resampled value of (T-RT^*).

where
$RT^* = RT_{NDT(0)} + \Delta RT_{irrad} - \Delta RT$

(1) Resample ΔRT, given T, $RT_{NDT(0)}$, ΔRT_{irrad}:

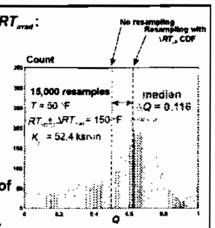
P = RAND(0,1)
$\Delta RT = a + b[-\ln(1-P)]^{1/c}$
$RT^* = RT_{NDT(0)} + \Delta RT_{irrad} - \Delta RT$
$\Delta T = T - RT^*$

(2) Resample K_{Ic} model :

$aKIc$ = A1 + A2exp[A3 ΔT]
$bKIc$ = B1 + B2exp[B3 ΔT]
$cKIc$ = C1 + C2exp[C3 ΔT]

(3) Calculate cumulative probability of exceeding K_{Ic} given applied K_I:

$Q = 1 - \exp\{-[(K_I - aKIc)/bKIc]^{cKIc}\}$



K_{Ic} model completely defined by the set of coefficients (A1,A2,A3,B1,B2,B3,C1,C2,C3)

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Steps to be Completed

Step 4: Multi-step Evaluation Process

Step 4a - ***QA verification*** **of K_{Ic} model lookup table**
Step 4b - **Determination of number, (*N = 100, 1000, 10000?*), of resampled models in K_{Ic} model lookup table required to produce acceptable statistics.**
Step 4c - **Implementation into FAVOR**
Step 4d - ***QA verification*** **of FAVOR implementation**
Step 4e - **Execution of a representative sample of dominant transients in FAVOR to estimate PRA impact**
Step 4f - **Development of a rational basis for bounding (T-RT^*) and K_{Ic}, since model is limited to cleavage initiation only.**

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16

Fracture Toughness Uncertainty Characterization

M. Modarres
F. Li
University of Maryland
Center for Technology Risk Studies

Presentation
To
Advisory Committee on Reactor Safeguards
Subcommittees on Materials & Metallurgy and T-H Phenomena
January 18, 2001

VG 1

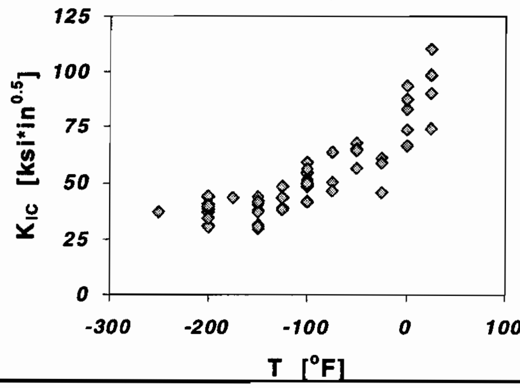
Uncertainty in Models

- Models are partial representations of reality thus involve uncertainties
- A distinction can be made between practically "irreducible" (often random) and "reducible" (often deterministic) estimates thus leading to the *aleatory* and *epistemic* types of uncertainty
- These two types of uncertainty influence the choice of uncertainty propagation procedure (in this case in the computation of fracture toughness, vessel fracture, arrest toughness and vessel failure)

VG 2

Uncertainty in Fracture Toughness

- Cleavage fracture in steels is well represented by the weakest link theory and microscopic size distribution of carbides leading to the uncertainty of K_{Ic} at any fixed temperature
- K_{Ic} uncertainty can be assumed purely aleatory at a fixed temperature since K_{Ic} distribution is completely driven by the irreducible distribution of microscopic carbides



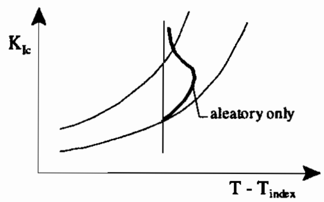
VG 3

Indexing Temperature

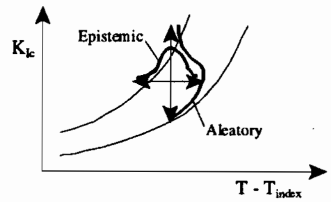
- To account for heat-to-heat variability, an indexing temperature should be devised
- The indexing procedure (model) inevitably introduces uncertainty since the indexing temperature can't be determined exactly in almost all cases
- Indexing temperature uncertainty is epistemic
- Depending on the approach used, the resulting K_{Ic} model involves uncertainty

VG 4

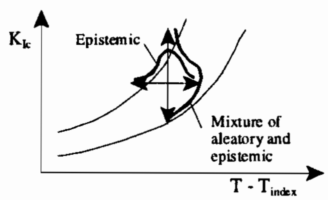
Recognize Three Possible Cases



(A) physically driven K_{Ic} model with exact T_{index}



(B) physically driven K_{Ic} model with uncertain T_{index}



(C) empirically driven K_{Ic} model with uncertain T_{index}

VG 5

Two Possible Approaches to Account for Uncertainties in K_{Ic}

1) Master Curve model
- ✓ Advantages
  - ➢ Physically-based (assumes one universal indexing exists)
  - ➢ K_{Ic} uncertainty is a pure reflection of the weakest link model applied to a distribution of microscopic carbides (assumed purely aleatory at a fixed temperature since K_{Ic} distribution is dictated by the irreducible distribution of microscopic carbides)
  - ➢ The community accepts the weakest link and carbide fracture assumptions as a reasonable model of fracture
- ✓ Issues
  - ➢ Need to account for the effect of flaw size and shape explicitly for which no agreed upon procedure exists yet (but is within reach)
  - ➢ No generally agreed upon procedure for computing indexing temperature T_0 for reactor vessels exist at this time (this issue can be reasonably addressed as discussed later)

VG 6

Two Possible Approaches to Account for Uncertainties in K_{Ic} (Cont.)

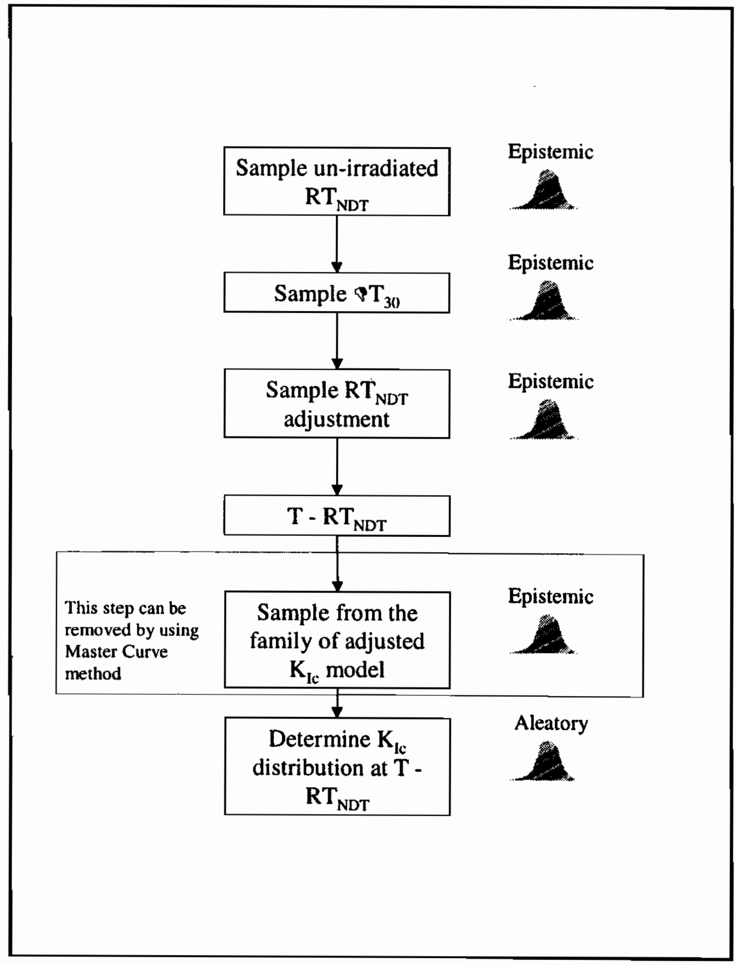
2) Empirical model (ORNL Approach)
   - ✓ Advantages
     - ➢ Size effect not as significant as the Master Curve approach
     - ➢ K_{Ic} model is based on actual observed data
     - ➢ The procedure is well understood and compatible with the past NRC practices
   - ✓ Issues
     - ➢ The resulting model is not purely aleatory but use of a temperature dependent Weibull model and adjustment of the LEFM data to correct for indexing conservatisms make aleatory distribution assumption possible
     - ➢ Extrapolation beyond data points involves epistemic modeling uncertainties

VG 7

Procedures for Computing Fracture Toughness

- Master Curve Procedure
  - Sample distributions of RT_{NDT}, and RT_{NDT} bias relative to T_0
  - Compute adjusted RT_{NDT}
  - Obtain the Weibull distribution corresponding to T – adjusted RT_{NDT} (aleatory uncertainty)
  - Correct for the flaw size and shape
- Empirical Procedure (Modified Traditional ORNL Approach)
  - Sample RT_{NDT} and RT_{NDT} bias based on lower-bounding model
  - Adjust the LEFM data (samples) and empirically generate a new "adjusted" K_{Ic} distribution that is fit into the data (repeat the process to get a family of such distributions)
  - Compute an adjusted RT_{NDT}
  - Obtain a Weibull distribution from a sample of the adjusted K_{Ic} distributions at (T – adjusted RT_{NDT}) which is assumed aleatory

VG 8


Sample un-irradiated RT_{NDT}
Epistemic
Sample ΔT_{30}
Epistemic
Sample RT_{NDT} adjustment
Epistemic
$T - RT_{NDT}$
This step can be removed by using Master Curve method
Sample from the family of adjusted K_{Ic} model
Epistemic
Determine K_{Ic} distribution at $T - RT_{NDT}$
Aleatory

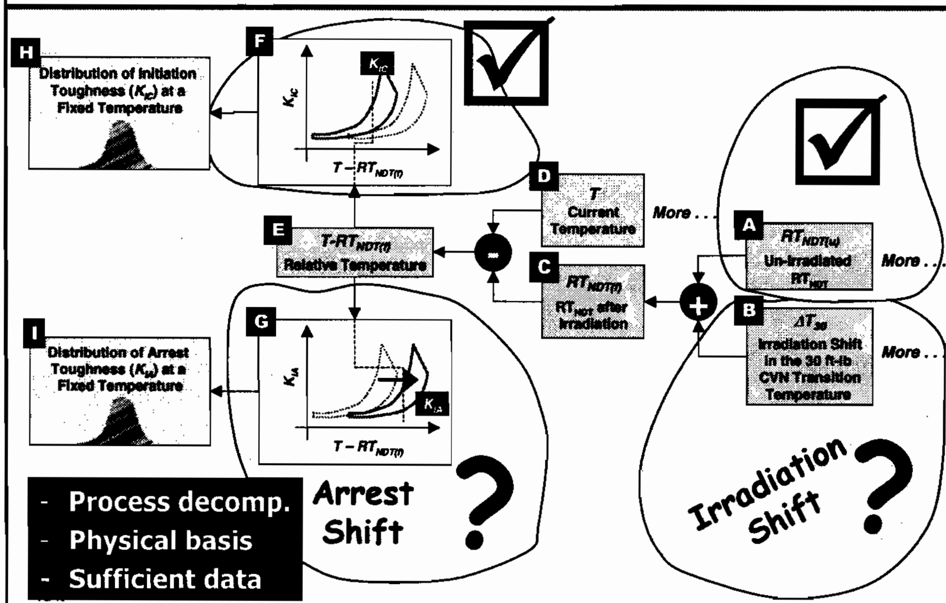
Summary of Work to Date

A physical understanding of fracture toughness for RPV steels and an examination of the 10CFR50.61 toughness estimation process → →

- **RT_{NDT} is treated as epistemic**
- **K_{IC} is treated as aleatory**
- **2 step procedure to adjust RT_{NDT} to obtain a "best estimate" value has been developed**
  - **$RT_{ADJUSTMENT}$ factor agreed upon**
  - **Aleatory distribution for K_{IC} sampling being developed**

VG 14

Areas of Work Remaining



Fracture Toughness Uncertainty

→ Status and Closure ←

- Details being wrapped up following 19th Dec 2000 public meeting
- Position paper being prepared
- Paper will form the basis for recommended structure of FAVOR

VG 16

Uncertainties in Other PFM Variables

L. Abramson, S. Malik
Office of Nuclear Regulatory Research

Presentation to:
ACRS Joint Subcommittees
January 18, 2001

Uncertainties in Other PFM Variables

- Generalized Flaw Distributions
  - L. Abramson, D. Jackson, PNNL
- Neutron Fluence
  - W. Jones, BNL
- Material Chemistry
  - D. Kalinousky, L. Abramson, C. Santos
- Irradiation Embrittlement Correlations
  - M. Kirk, M&CS, UMD, PEAI

Generalized Flaw Distribution Methodology and Uncertainties

- Flaw densities
- Volumes or areas
- Distributions of crack depths

Generalized Flaw Distribution Methodology (contd.)

$N_S(x)$ = number of small flaws > x, for $x \leq b$

$N_L(x)$ = number of large flaws > x, for $x > b$

x = crack depth

b = bead thickness

PF = Product Form (Weld Metal, Cladding, Plate, Ring Forgings)

WP = Weld Process (SMAW, SAW, ESW; Strip, Single & Multi Wire)

R = Repair State (Unrepaired, Repaired)

Generalized Flaw Distribution Methodology (contd.)

ρ_S(PF, WP, R) = density of small flaws per unit volume or area

ρ_L(PF, WP, R) = density of large flaws per unit volume or area

V(PF, WP, R) = volume or area of material.

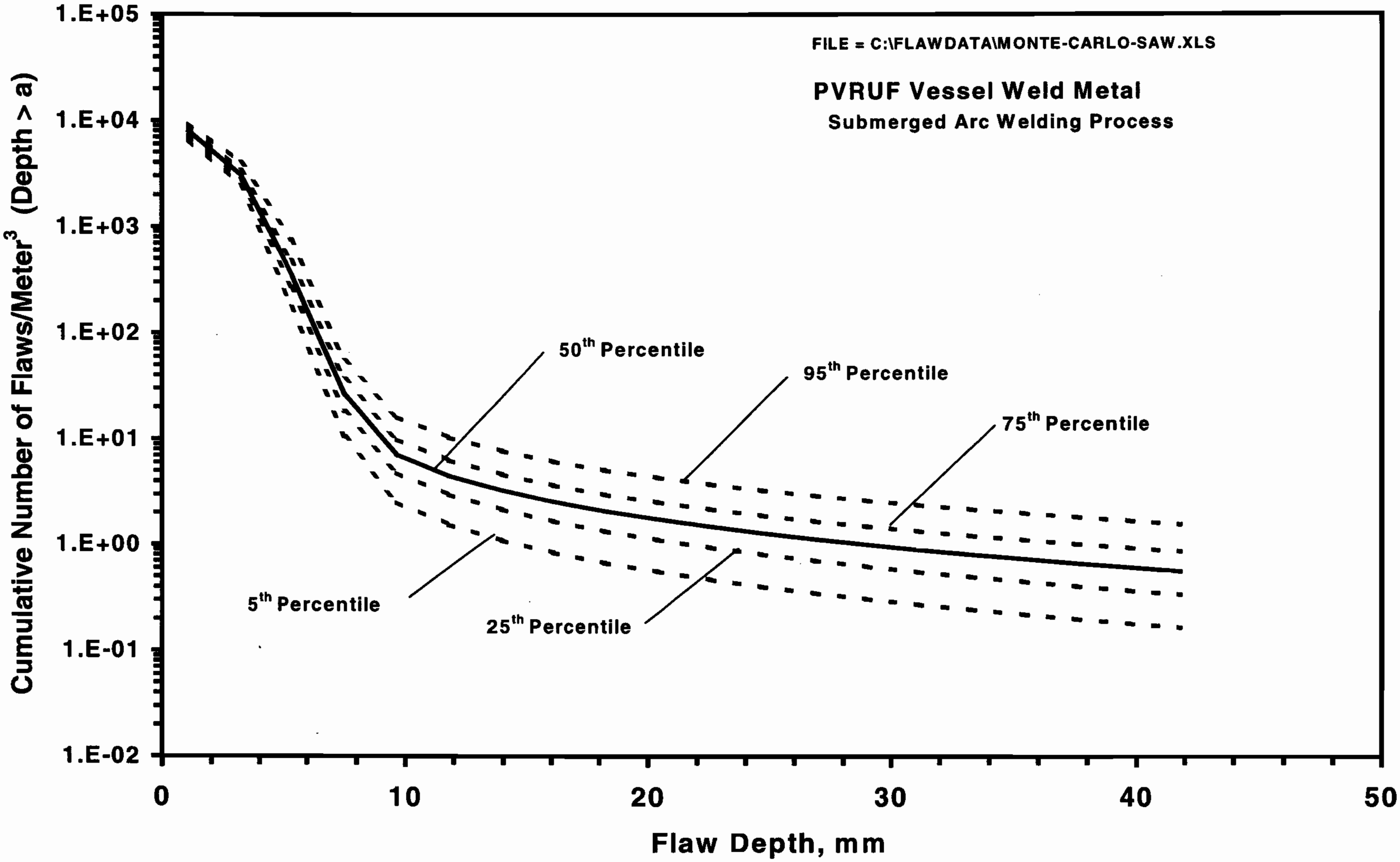
$G_S(x)$ = ccdf for small flaws = Prob {crack depth > x}, where $x \leq b$

$G_L(x)$ = ccdf for large flaws = Prob {crack depth > x}, where $x > b$.

$N_s(x) = \Sigma\, \rho_S(PF, WP, R) \bullet V(PF, WP, R) \bullet G_S(x; PF, WP, R)$

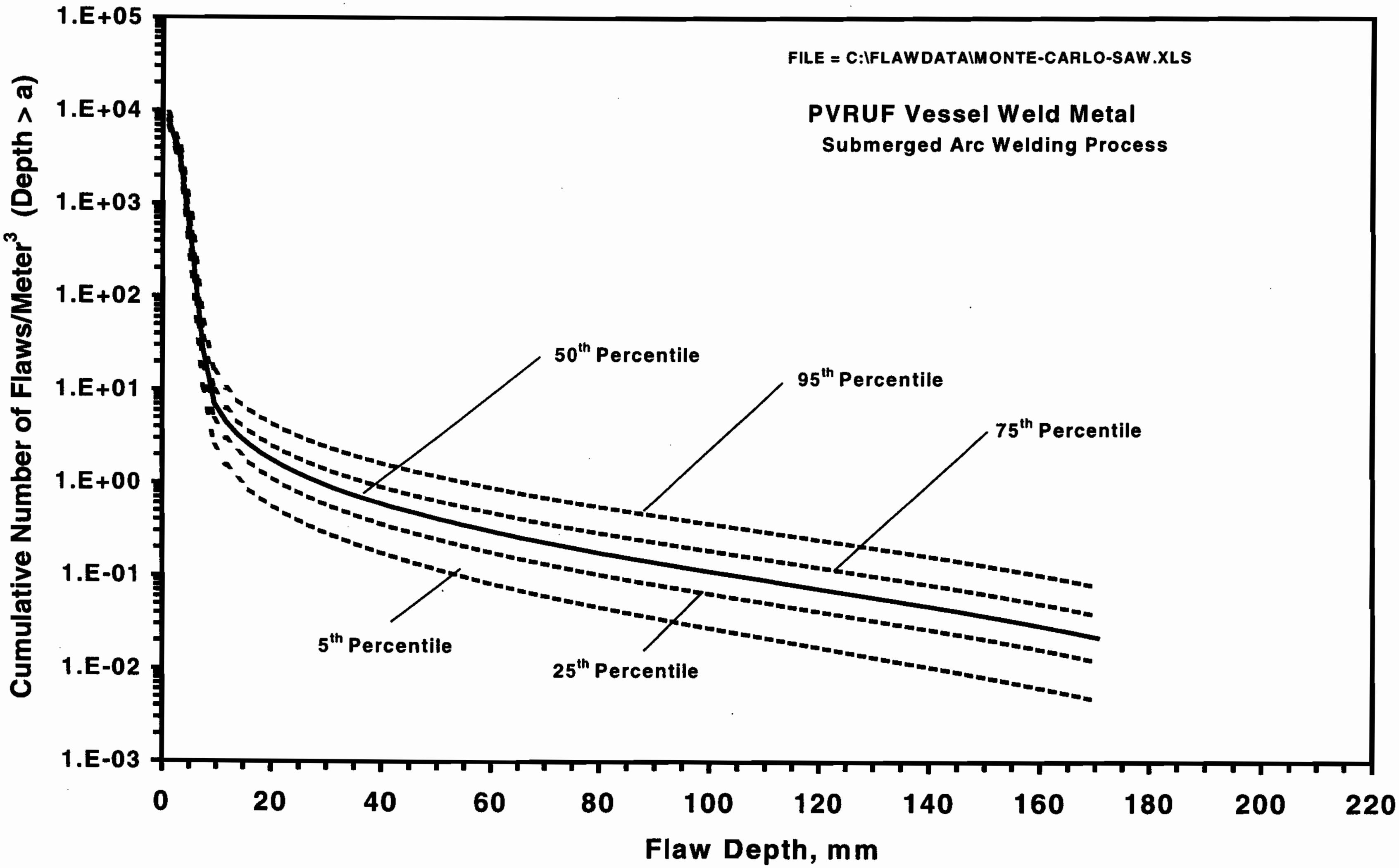
$N_L(x) = \Sigma\, \rho_L(PF, WP, R) \bullet V(PF, WP, R)\,] \bullet G_L(x; PF, WP, R)$

Generalized Flaw Distribution Uncertainties Submerged Arc Welding (SAW) Process



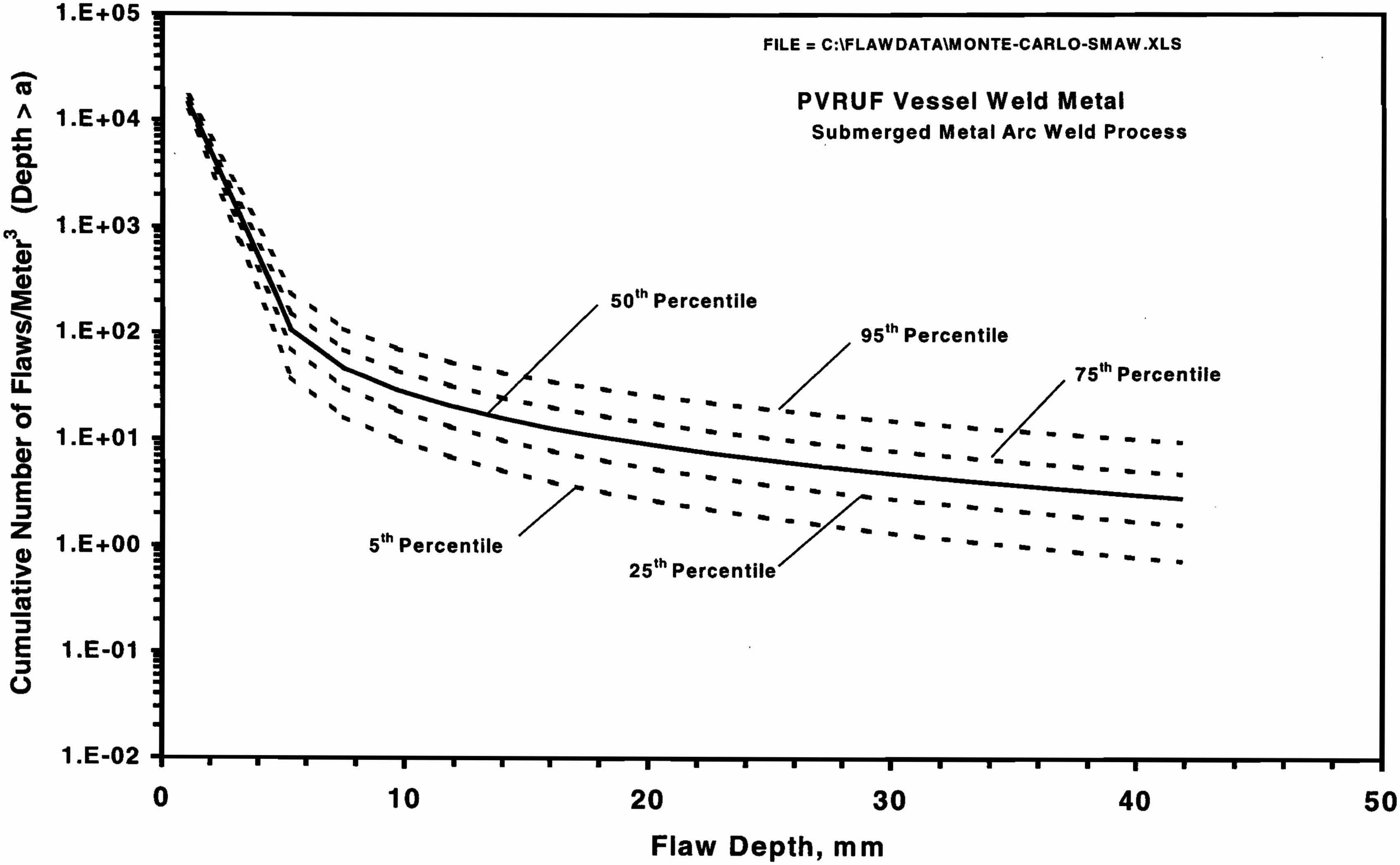
Generalized Flaw Distribution Uncertainties

Submerged Arc Welding (SAW) Process



Generalized Flaw Distribution Uncertainties

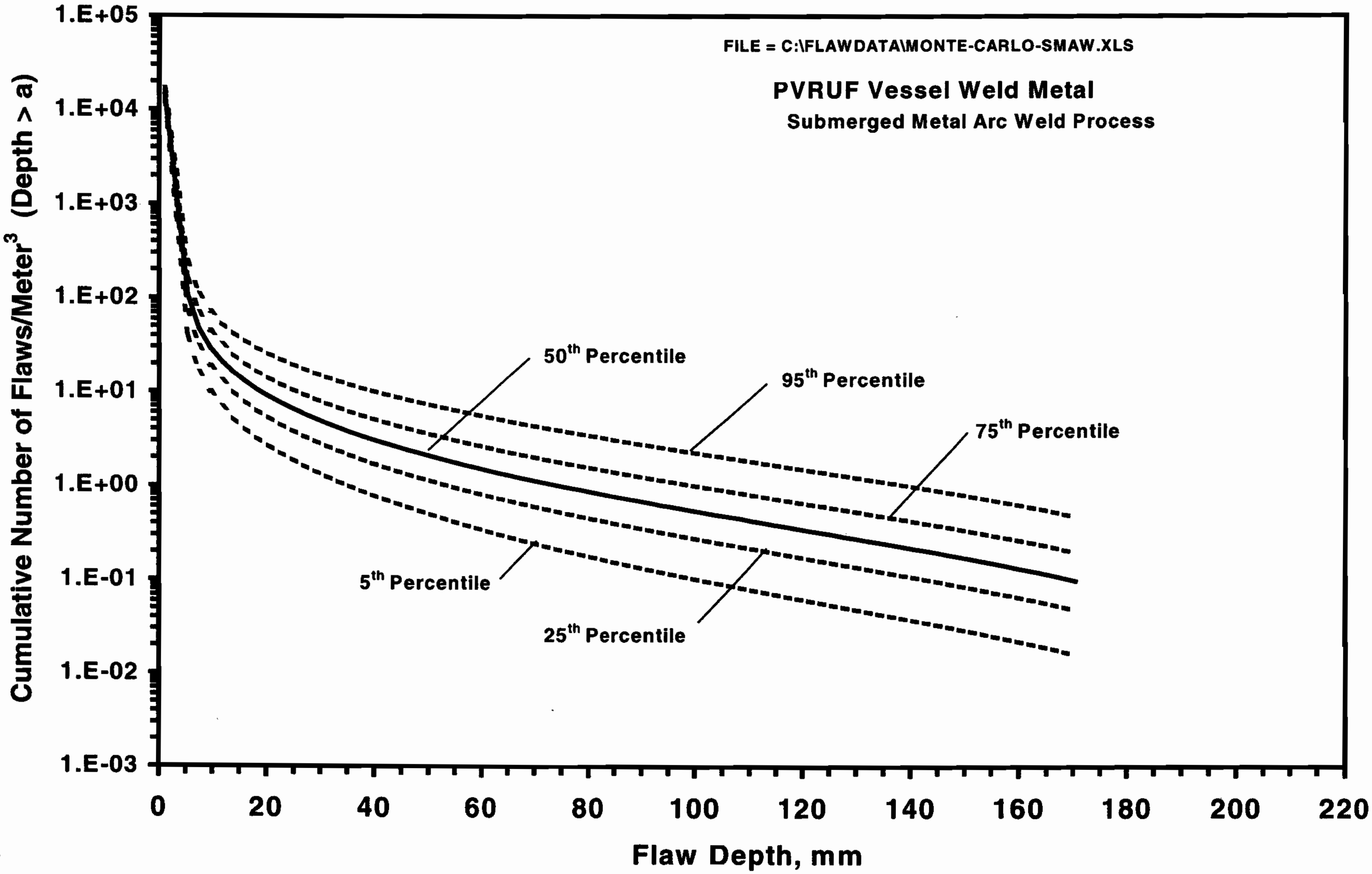
Submerged Metal Arc Welding (SMAW) Process



VG 8

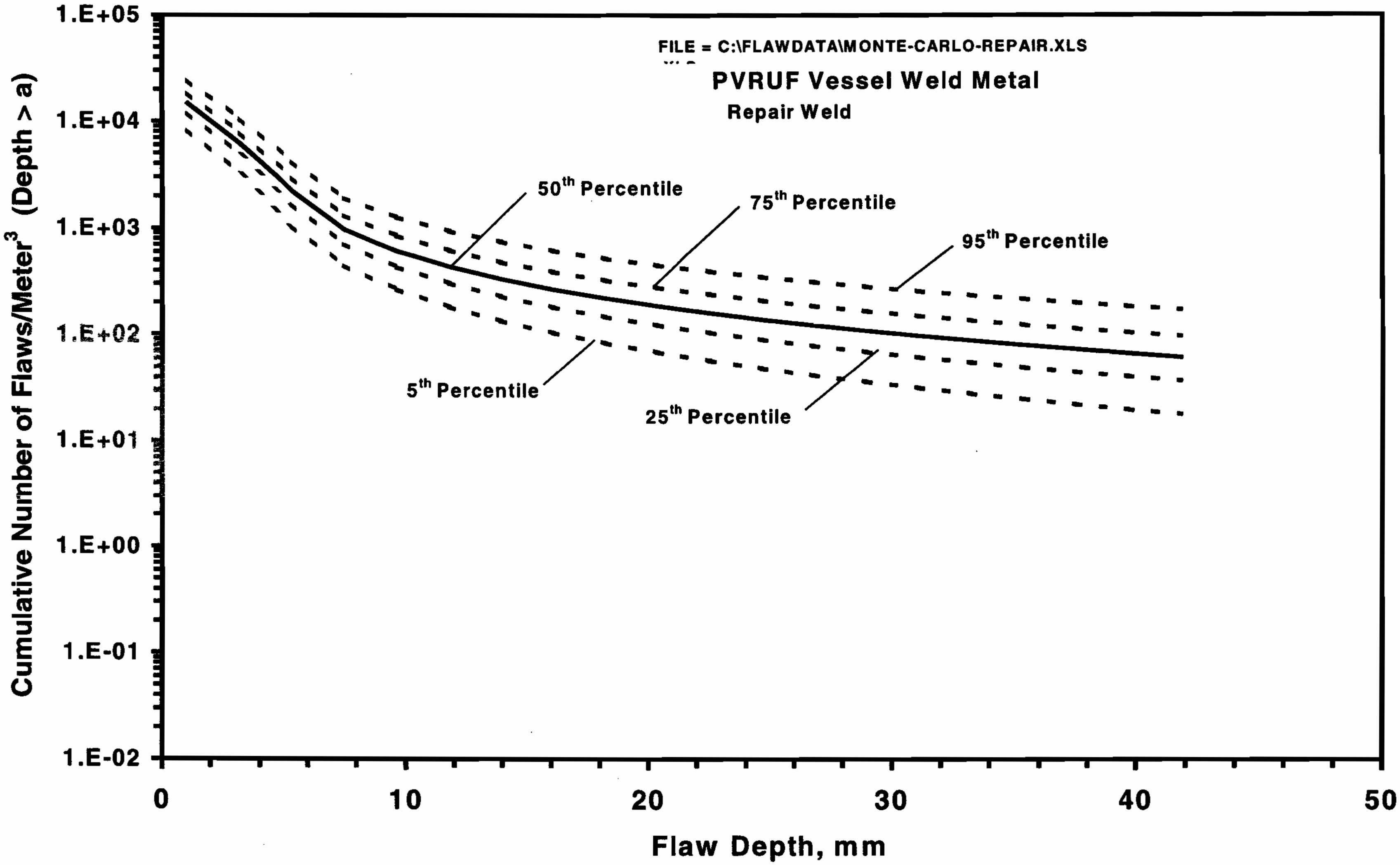
Generalized Flaw Distribution Uncertainties

Submerged Metal Arc Welding (SMAW) Process



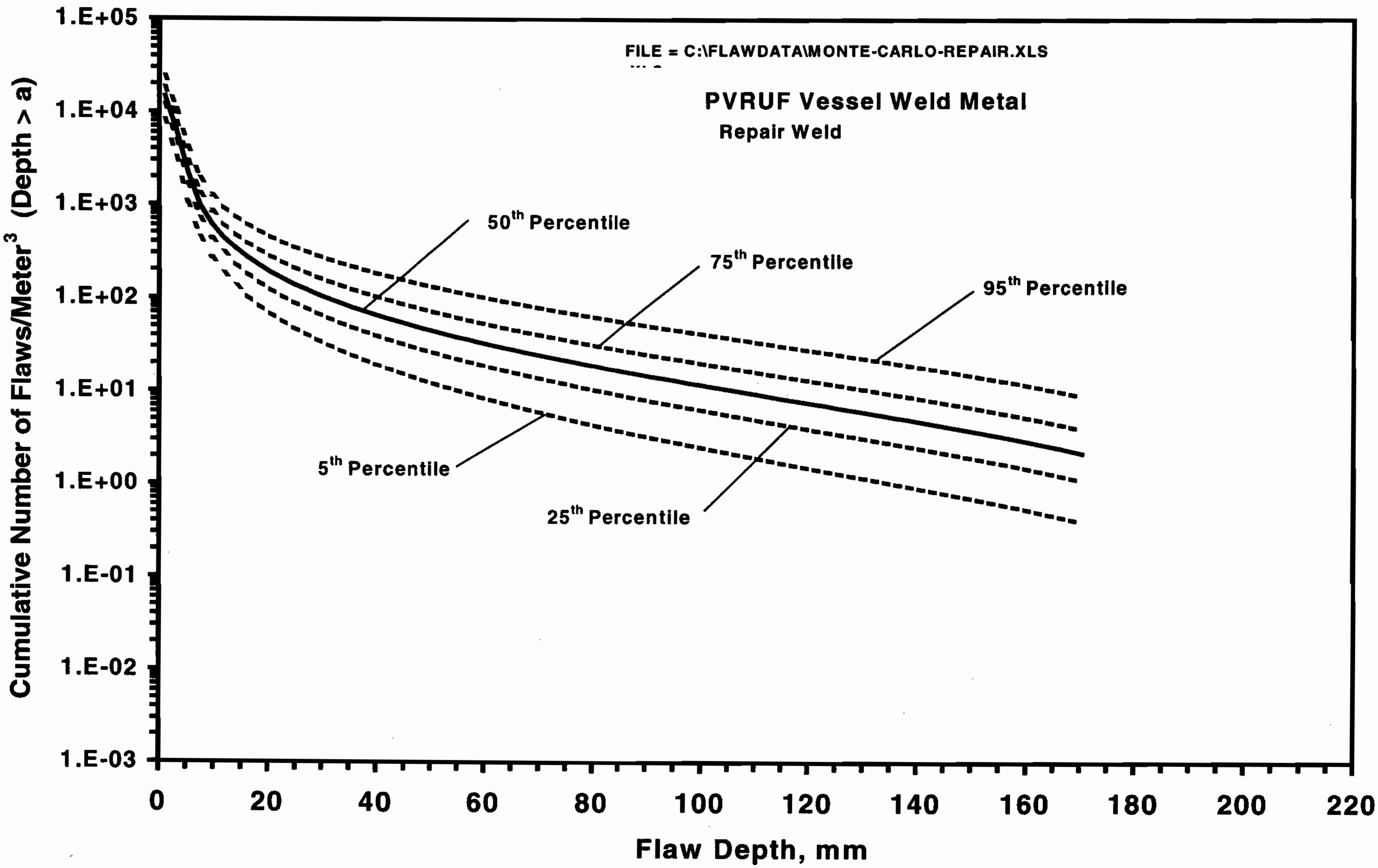
Generalized Flaw Distribution Uncertainties

Repaired Welds (SMAW)



Generalized Flaw Distribution Uncertainties

Repaired Welds (SMAW)



Beltline Neutron Fluence

- Determined fluence maps for 3 PTS re-evaluation plants using
  - cycle-by-cycle fuel loading histories
  - Beltline plant geometry data
- Estimated uncertainty in computed fluence
- Used dosimetry draft Reg. Guide 1053 and draft NUREG/CR-6115 methodology

Sources of Fluence Uncertainties

- Major sources of uncertainties
  - Reactor Vessel diameter
  - Core neutron source
  - Core inlet temperature
  - Nuclear cross-section
  - Method's errors
  - Other un-quantified
- Uncertainty in calculated fluence is about 15% (1σ) for each of the 3 plants analyzed
- Potential interaction between the uncertainty sources is planned for investigation

Material Chemistry Distributions

- Weld heat-specific distributions
  - Normal (for Copper, Nickel, Phosphorus)
- Weld local variability
  - Logistic for Copper and Nickel
  - Normal for Phosphorus
- Plates
  - Limited data for the heats in PTS plants
    - ✓Chemistry values taken as Heat Estimate
- Plate local variability – limited data from CE
  - Normal distribution

Embrittlement Trend Curve

→ *Uncertainty Status* ←

- Data assembled and curve fit developed (MCS / UCSB)
- Nature of uncertainties understood, framework for mathematical model developed (PEAI)
- Mathematical model developed consistent with PRA (UM)
- Need NRC inputs on
  - Treatment of surveillance data
  - Thru wall attenuation