AREVA

Statistical Forum Meeting
Rockville, MD
March 4 & 5, 2009

RLBLOCA Methodology Review
Problems in Application

<u>**_RLBLOCA Methodology_**</u>
<u>**_Problems in Application_**</u>

Robert Martin
Bert Dunn

Others Attending
Phillipe Dias
Ken Carlson

March 4 & 5, 2009
Rockville, Maryland

Presentation Outline

- Introductions (Dunn, 5 min.)
- RLBLOCA Methodology Review (Martin, 40 min.)
- Problems in RLBLOCA Applications (Dunn, 15 min.)

Development Considerations of AREVA's Realistic LBLOCA Analysis Methodology

Robert P Martin
Advisory Engineer
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Outline

- AREVA's RLBLOCA Overview
  - Background
  - CSAU Compliance
- Methodology Aspects without Resolution
  - Defining "Best-Estimate"
  - Merits of Engineering Judgment
  - Convolution of Uncertainties
  - Data for Quantifying Uncertainties

Methodology Development History

> **Milestones**

Original Development (ANF, Siemens)	1989-1993
Revision Development (Siemens, Framatome)	01/98-08/01
Topical Report Submitted	08/01
Presentation to NRC	10/01
First Presentation to ACRS Subcommittee	01/02
NRC Issues Formal RAIs	04/02 - 8/02
AREVA Responds to RAIs	05/02 - 10/02
Draft Safety Evaluation Report by NRC	10/02
Final Presentation to ACRS Subcommittee	11/02
ACRS Full Committee Meeting	12/02
NRC Safety Evaluation Report for Rev 0	04/09/03
Plant Specific Applications	–> present
RLBLOCA for U.S. EPR	08/06

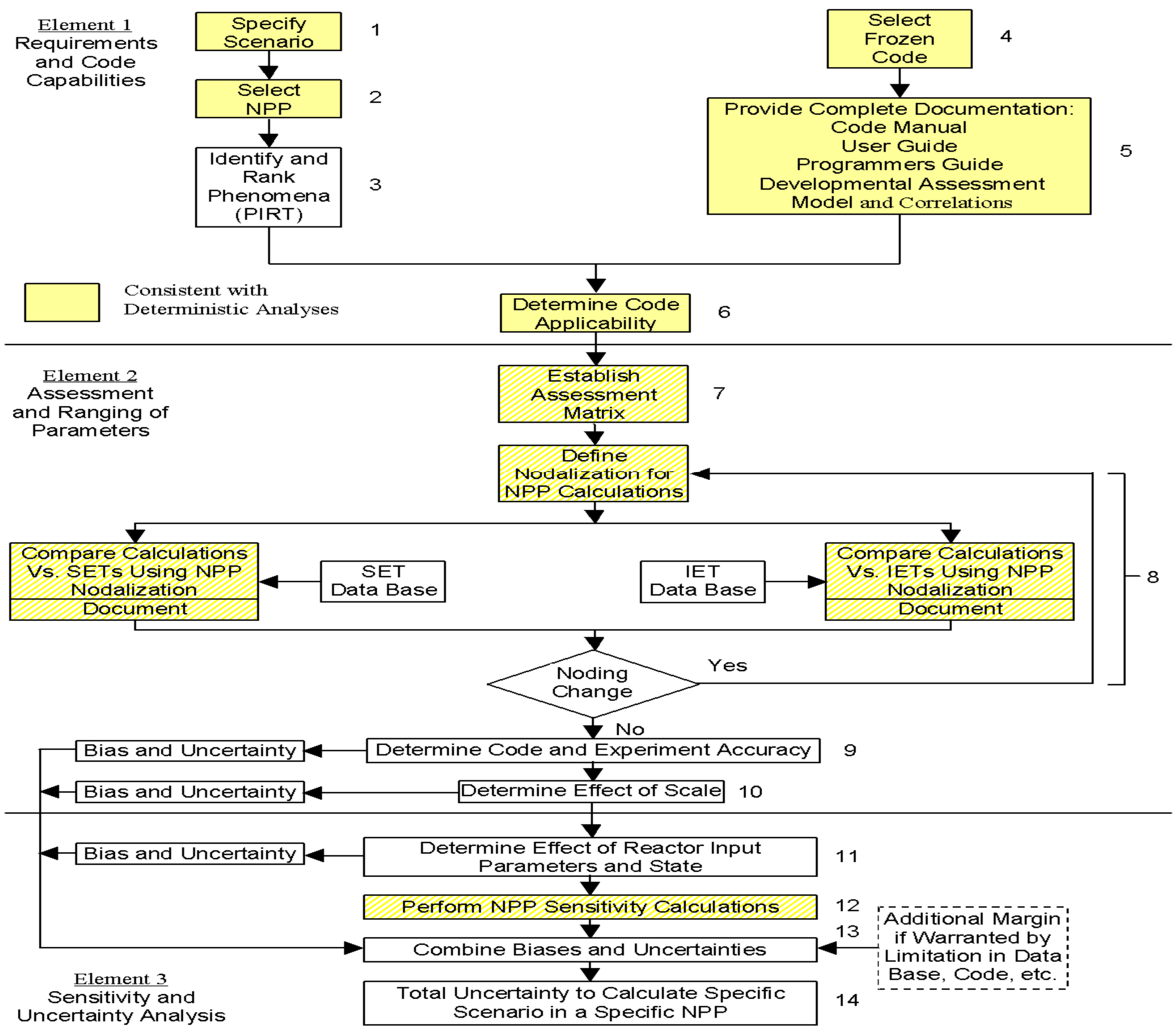
Background

> **Key Regulatory Documents**

- **10 CFR 50, Appendix K, 1974**
- **SECY 83-472, Emergency Core Cooling Analysis Methods, 1983**
  (permits many "best-estimate" methods and models to be used for licensee submittals, it retains those features of Appendix K that are legal requirements**)**
- **Development of NUREG-1230 - Compendium of ECCS Research, 1988**
- **TPG produces the Code Scaling, Applicability and Scaling (CSAU) methodology documented in NUREG-5249, 1989**
- **U.S. Regulatory Guide 1-157 prepared to provide guidance to industry as to the requirements for developing, 1989**
- **U.S. Regulatory Guide 1-203, evaluation methodology development and assessment process (EMDAP), 2005**

RM1

Code Scaling, Applicability, and Uncertainty



Slide 8

RM1 Discuss contrast to App K

Also, "Top-Down, Bottom-Up" approach: Event, not symptom, focus; PIRT, phenomenon, separate-effects uncertainty, uncertainty convolution

Robert Martin, 4/5/2006

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CSAU Steps 1-6

Element 1: Requirements and Code Capabilities

PIRT STEP	AREVA Methodology
Specify Scenario	Large-break LOCA
Selection NPP	Westinghouse & CE PWRs with cold leg SI
Select Frozen Code	RODEX3A (fuel performance) S-RELAP5 (RCS and Containment Thermal-Hydraulics)
PIRT Results	Heat Transfer, Void Distribution, Axial Power Distribution, Entrainment, Spacer Effects, Break Flow, Cold Leg Condensation, Interfacial Heat Transfer, Upper Tie Plate CCFL, Core Multi-dimensional Flow, ECCS Bypass, Steam Binding, Accumulator Nitrogen Discharge
Provide Documentation	Evaluation Methodology Description Report, Code Programmers Guide, Code Verification and Validation Documents, Modeling and Analysis Guidelines, Theory and Models/Correlations Code Manuals
Code Applicability	Cross reference PIRT results with code models

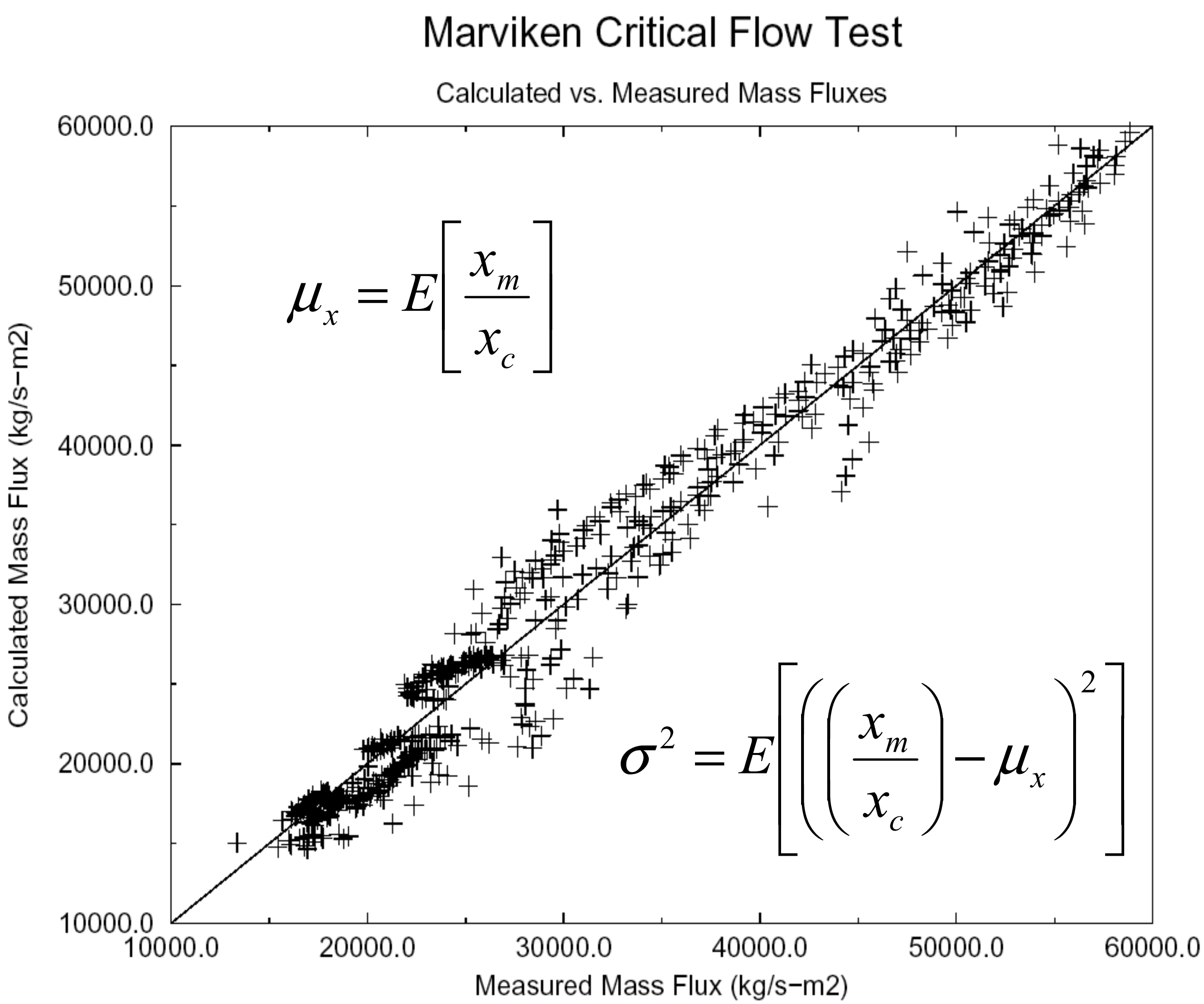
CSAU Steps 7 - 10

Element 2: Assessment and Ranging of Parameters

Test Facility	Tests Used	Key Phenomena of Interest
THTF Heat Transfer	35	Heat Transfer
THTF Level Swell	3	Void Distribution
GE Level Swell	1	Void Distribution
FRIGG-2	27	Void Distribution
Bennett Tube	2	Heat Transfer
FLECHT & FLECHT-SEASET	9	Heat Transfer, Nodalization, Axial Power Distribution, Scalability, Entrainment
PDTF/SMART	4	Spacer Effects
Marviken	9	Break Flow
W/EPRI 1/3 Scale	9	Cold Leg Condensation, Interfacial Heat Transfer
Mini-Loop CCFL	3	Upper Tie Plate CCFL
Multi-dimensional Flow	3	Core Flow Distribution
UPTF	14	ECCS Bypass, Steam Binding, CCFL, Scalability, Nodalization
CCTF	4	Steam Binding, Nodalization, Scalability
SCTF	6	Nodalization
ACHILLES	1	Accumulator Nitrogen Discharge
LOFT	4	Overall Code Performance, Nodalization, Scalability
Semiscale	2	Blowdown Heat Transfer, Nodalization, Scalability, Compensating Errors

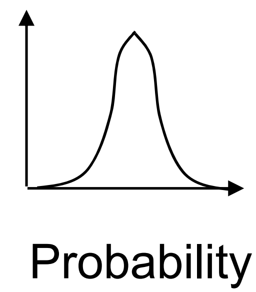
Nodalization validation (CSAU Step 8)
Code accuracy (CSAU Step 9)
Code/model scaling (CSAU Step 10)

Quantifying Bias and Uncertainty



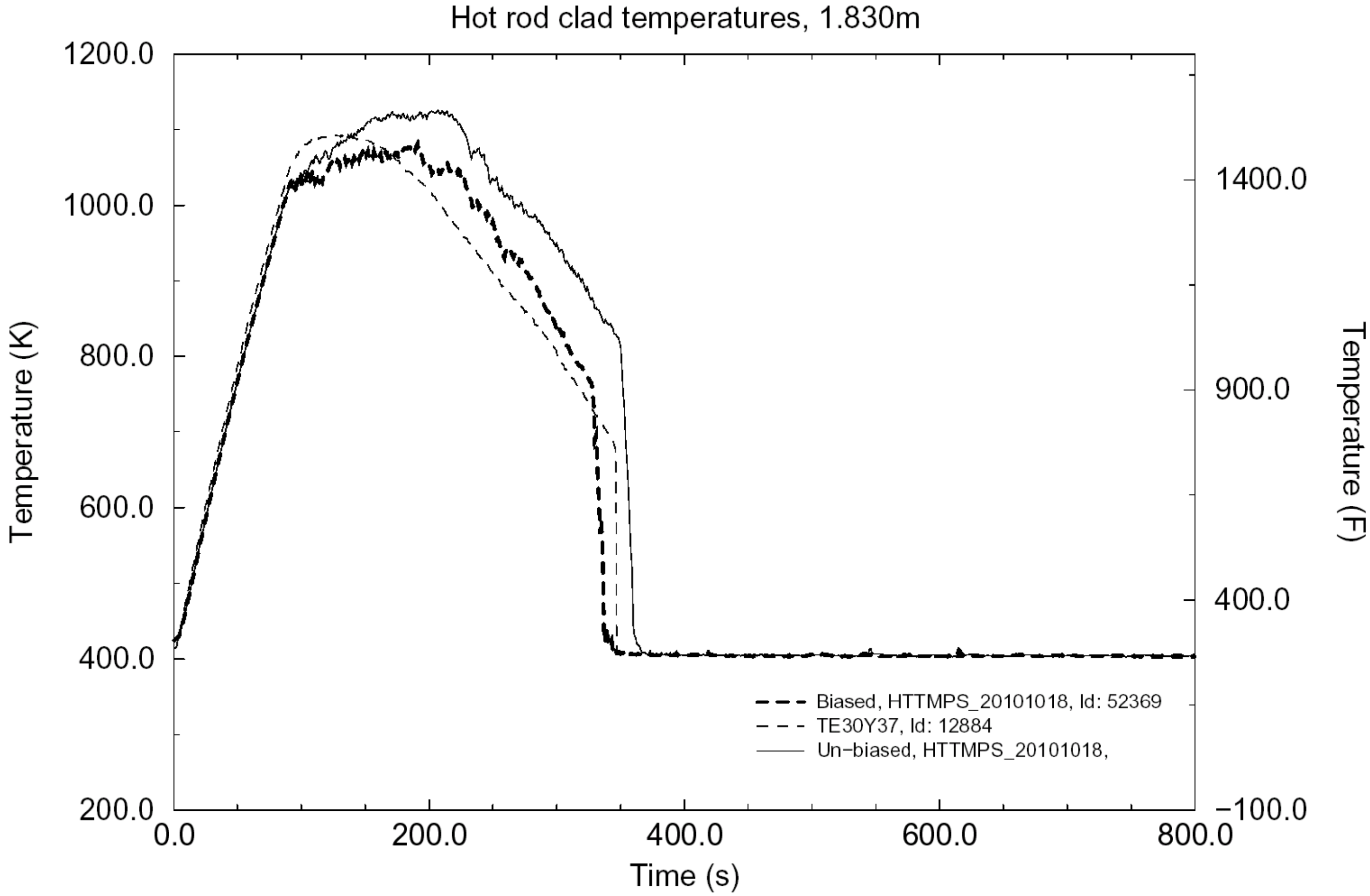
$$\mu_x = E\left[\frac{x_m}{x_c}\right]$$

$$\sigma^2 = E\left[\left(\left(\frac{x_m}{x_c}\right) - \mu_x\right)^2\right]$$



Code bias and uncertainty developed for 11 important phenomena

Validating Bias



Biased code studies showed improved clad temperature trending and magnitude predictions

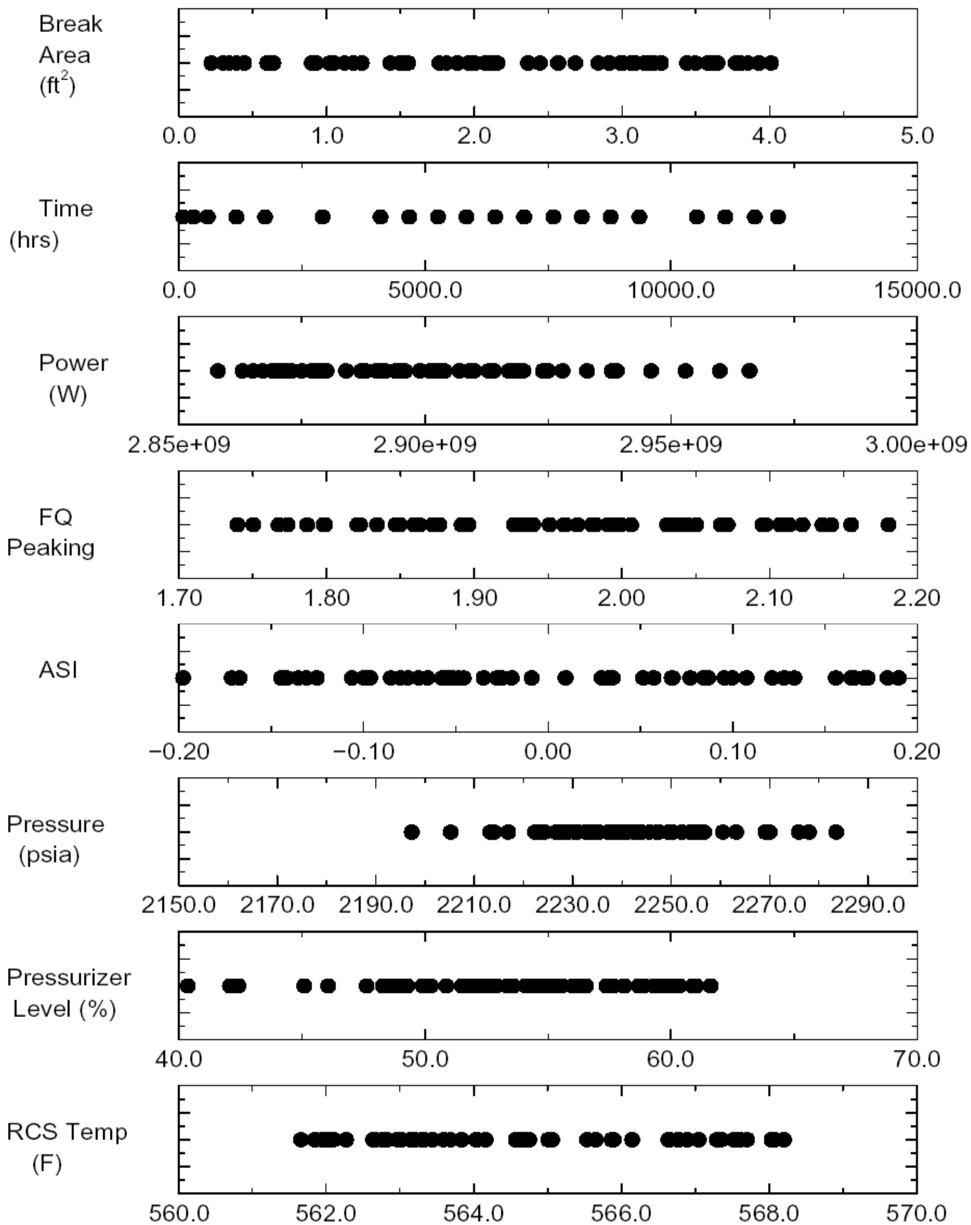
CSAU Steps 11 - 14

Element 3: Sensitivity and Uncertainty Analysis

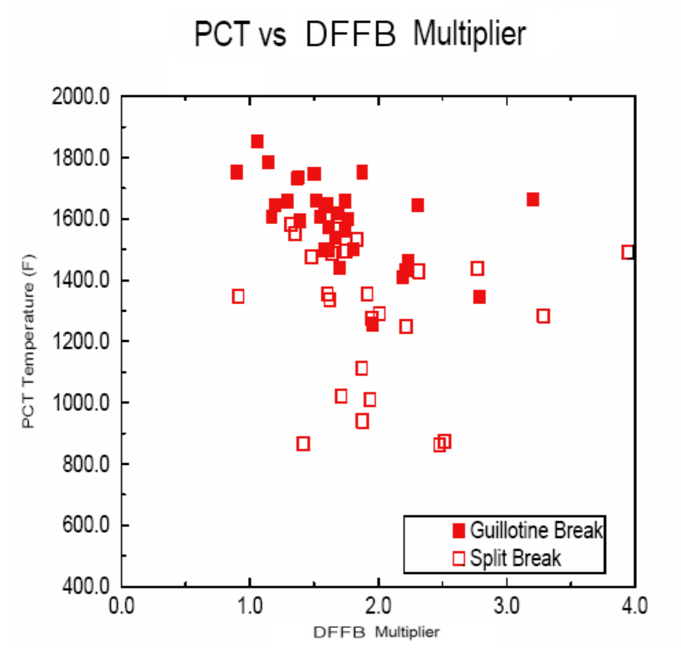
PIRT Parameter	Bias	σ
Break size	N/A	Uniform distribution
Break discharge coefficients	###	###
Critical heat flux	###	0.0
Film boling HTC	###	Custom distribution
Dispersed film boiling	###	Custom distribution
Tmin	###	###
Stored energy	###	###
Metal-water reaction constant	1	0.182
Metal-water reaction exponent	1	0.0134
Decay heat uncertainty	1	0.003
Condensation interface HTC	###	Uniform distribution
SG inlet interphase friction	###	0.0
Hot wall (CHF multiplier)	###	Binary distribution
Containment pressure (volume)	###	Uniform distribution

Process Parameter
Fuel State (Burnup and Power Peaking)
Core Power
Power Peaking, Axial Shape
Loop Flow Rate
Core Inlet Temperature
Upper Head Temperature
Pressurizer Pressure, Level
Accumulator Pressure, Temperature, Level
Containment Volume, Heat Transfer, Sprays
Steam Generator Feedwater Temperature
Offsite Power and Diesel Start Delay
(uniformly distributed, except core power)

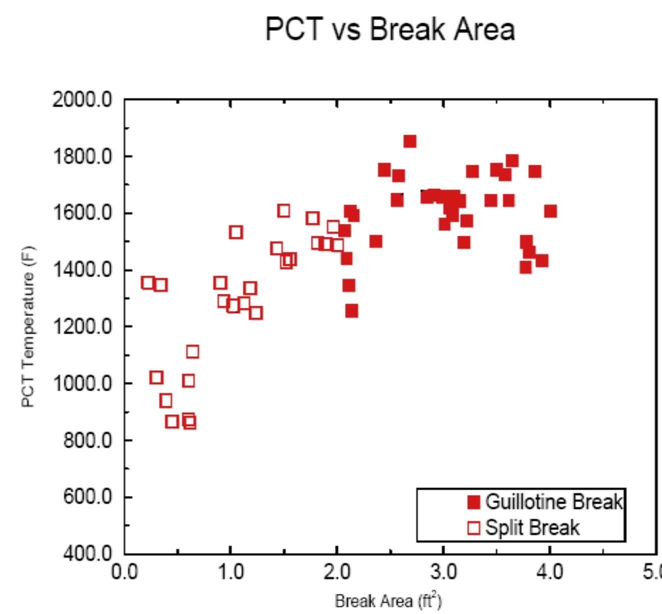
Determine/Combine biases and uncertainties (CSAU Steps 11, 12, 13)
Quantify total uncertainty (i.e., 95/95) (CSAU Step 14)



Break Area (ft²)
0.0 1.0 2.0 3.0 4.0 5.0
Time (hrs)
0.0 5000.0 10000.0 15000.0
Power (W)
2.85e+09 2.90e+09 2.95e+09 3.00e+09
FQ Peaking
1.70 1.80 1.90 2.00 2.10 2.20
ASI
−0.20 −0.10 0.00 0.10 0.20
Pressure (psia)
2150.0 2170.0 2190.0 2210.0 2230.0 2250.0 2270.0 2290.0
Pressurizer Level (%)
40.0 50.0 60.0 70.0
RCS Temp (F)
560.0 562.0 564.0 566.0 568.0 570.0

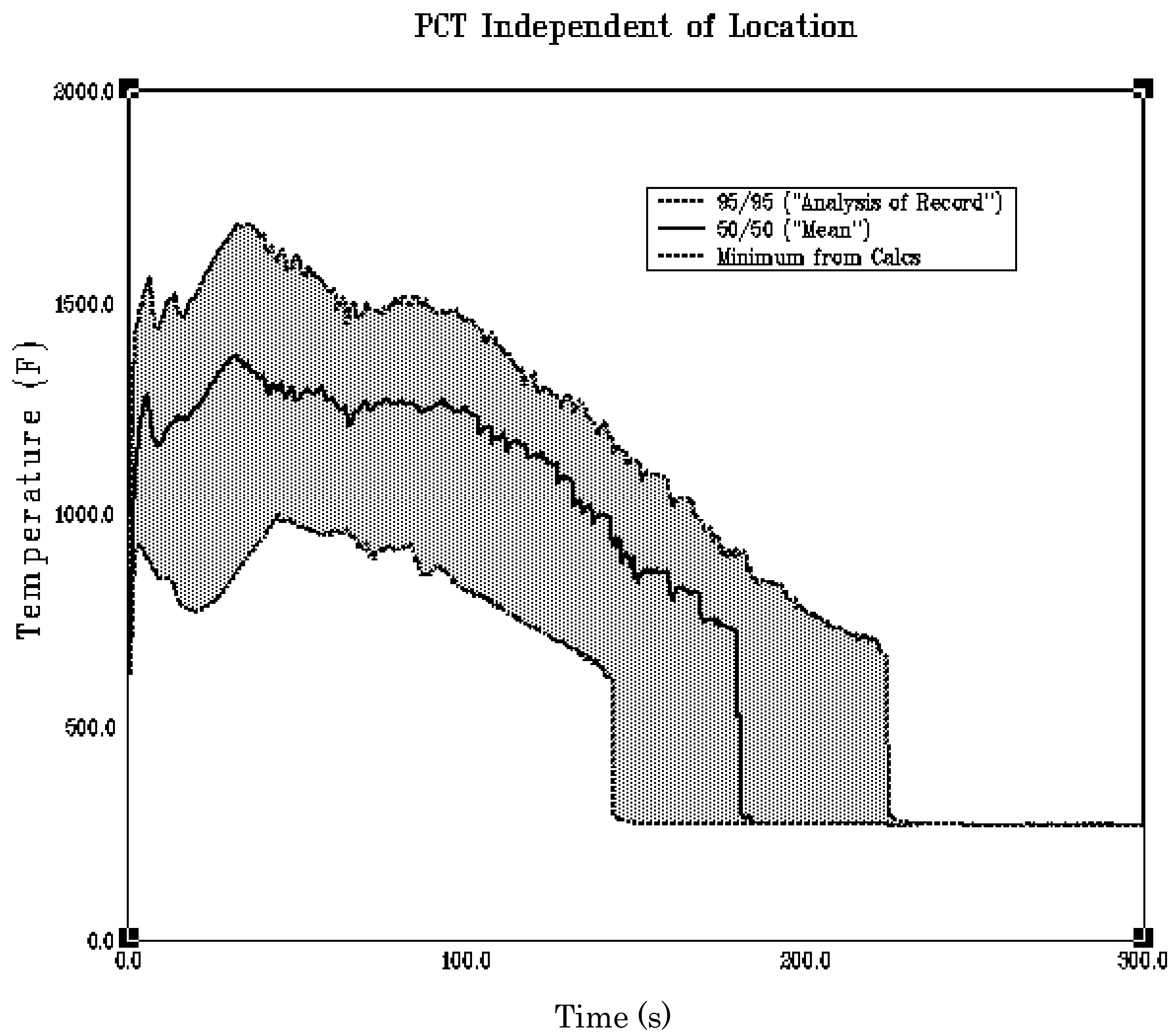


PCT vs DFFB Multiplier
PCT Temperature (F)
2000.0 1800.0 1600.0 1400.0 1200.0 1000.0 800.0 600.0 400.0
0.0 1.0 2.0 3.0 4.0
DFFB Multiplier
Guillotine Break
Split Break



PCT vs Break Area
PCT Temperature (F)
2000.0 1800.0 1600.0 1400.0 1200.0 1000.0 800.0 600.0 400.0
0.0 1.0 2.0 3.0 4.0 5.0
Break Area (ft²)
Guillotine Break
Split Break

PCT Tolerances vs. Time



RLBLOCA Components Providing Improvements over Appendix K

- Core Heat Transfer – “No” restrictions on applicable heat transfer correlations, e.g., no CHF-lockout
- Power Distribution – Bounding-Realistic power shapes acceptable (must incorporate Licensing Limits)
- Breaksize – May incorporate best-estimate understanding of likely breaksizes

Lesser, but notable gains

- Containment Pressure (downcomer boiling)
- Stored Energy – not penalized by BOL conditions (large gap)

Definition of "best-estimate" methods

> **Definitions/Uses:**
- **RG 1.157,**
  - "A best-estimate calculation uses modeling that attempts to realistically describe the physical processes occurring in a nuclear reactor. "
  - "...to predict realistic reactor system thermal-hydraulic response;" **"...not used in the statistical sense"**
- **NUREG-5249,** "...more realistic estimates of plant safety margins"

> **Inputs**
- **RG 1.157,**
  - "...the assumed initial conditions ... calculated in a best-estimate manner"
  - "Best-estimate models will be considered acceptable provided their technical basis is demonstrated with appropriate data and analyses"

> **Outputs**
- **RG 1.157,** "A best-estimate model should provide a realistic calculation of the **important** parameters associated with a particular phenomenon to the degree practical."
- **10 CFR 50.46, term not used; however,** "... a high level of probability that the criteria would not be exceeded. "
- **NUREG-5249,** "...best-estimate value of the peak cladding temperature for the specified scenario and the uncertainty in the peak cladding temperature associated with a high probability (95%)."

Definition of “best-estimate” methods

> **Constraints/Criticisms**
- Database is not sufficiently populated to avoid conservatisms in some areas
- Licensing is granted for the Tech Spec and Limiting Condition of Operation boundary – not best-estimate

> **RG 1.157, conservatism may be introduced:**
- The model simplification or conservatism has little effect on the result, and therefore the development of a better model is not justified.
- The uncertainty of a particular model is difficult to determine, and only an upper bound can be determined.
- The particular application does not require a totally best-estimate calculation, so a bias in the calculation is acceptable.

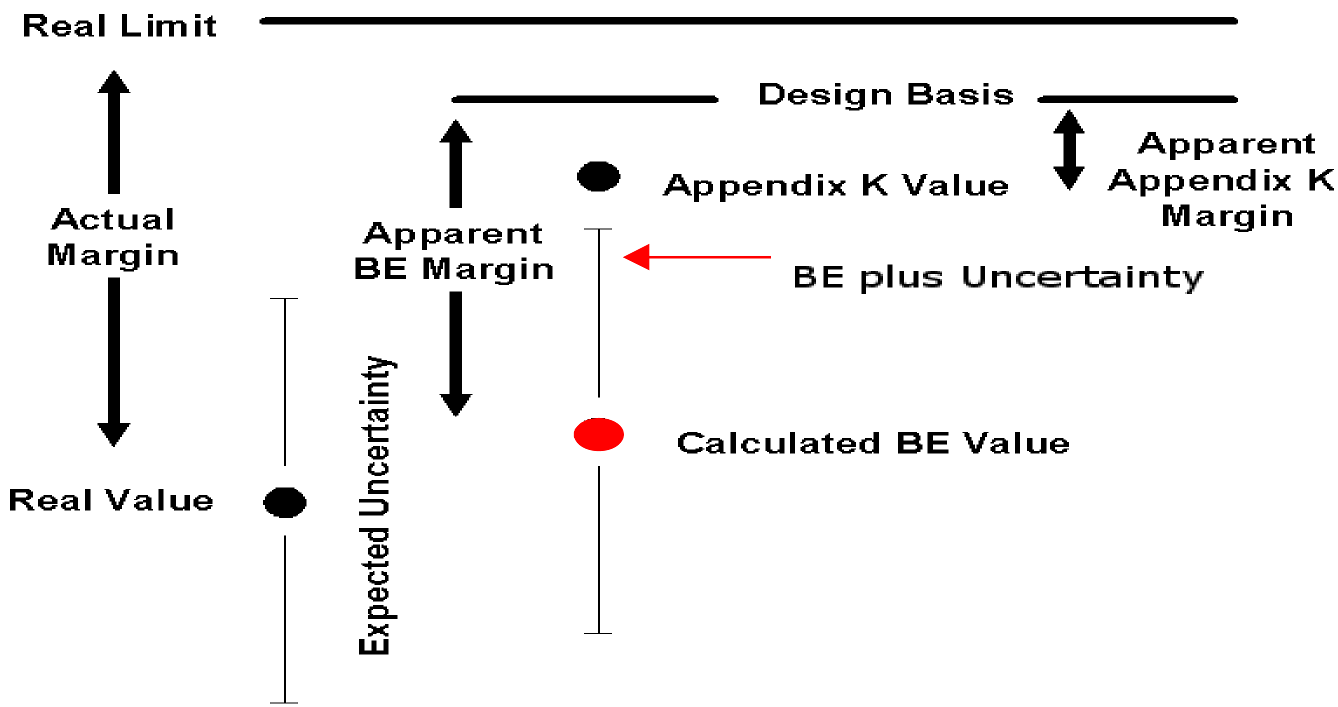
> **RG 1.203,** “The intended results of an analysis can be conservative due to a combination of code input and modeling assumptions.”

> **Conservatisms in best-estimate EM should not result in calculations that are unrealistic**

Focus must be on Uncertainty Management (BEPU methods)

AREVA NP's BEPU Paradigm

- Margin is characterized by the separation between the design or licensing limit and the nominal operation point
  - Goal is not to identify the "nominal" condition; but, rather provide an estimate of margin assured by a high degree of confidence
  - Requires acceptance of "realistic conservatism"



Merits of Engineering Judgment (i.e. role of PIRT)

> **Engineering judgment is unavoidable**

> **Engineering judgment is formalized for NPP safety analysis with Phenomena Identification and Ranking Tables (PIRT)**

- **Provide decision-making direction in the development of evaluation methodologies**
- **Provide baseline for evaluation methodology review by licensing authorities**

> **Regulatory statements**

- **NUREG 5249 – presents the PIRT concept and defines its roles**
- **RG 1.157 – makes no mention of PIRT; however, frequently uses "important parameters/variables/phenomena"**
- **RG 1.203 – acknowledges PIRT and its role as a basis for a proper review**

PIRT Questions

- PIRT criticisms
  - Who is qualified to be a part of a PIRT team?
    - Experts vs. Egos
  - How do PIRT teams deal with differences of opinion?
    - All agree important – High
    - All agree unimportant – Low
    - Debate – Medium
  - Should uncertainty with the ranking process be incorporated into the PIRT?
    - What is the impact of an incorrect ranking?
    - Even after the PIRT is developed, engineering judgment is required to use the results.
    - How can the absence of knowledge (i.e., unmodeled parameters) be treated in this context?
  - What is the correct number of important parameters?
    - For LBLOCA, the TPG identified a minimum list of important parameters
    - Since NUREG-5249, more have been added with every application

Building Confidence in the PIRT Process

Complementary CSAU/EMDAP steps provide complete event and analysis characterization

> **Qualitative reinforcement**
- Code documentation
- Assessment of code model applicability
- Code validation exercises

> **Quantitative reinforcement**
- Model uncertainty studies
- Scaling studies
- Plant sensitivity studies

> **Recent innovations**
- Scaling analysis and similarity criteria (IMHO, lose information)
- Correlation coefficient-based "Importance Analysis"

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Methods for the convolution of uncertainty

- Over the last 20 years, the number of phenomena considered important has increased
- Practical constraints limit the number of uncertainty parameters with parametric methods
- Non-parametric methods allow an unlimited number of uncertainty parameters
- What is the value of identifying the best-estimate result and total uncertainty?

Uncertainty Methods

> The CSAU methodology does not strictly specify a particular approach to quantifying uncertainty
  - Parametric vs. Nonparametric
  - Integral vs. Separate Effects-based
  - Local or Average Properties

> Originally, both Westinghouse and Siemens submitted a Parametric "Integral Uncertainty Approach"
  - Multi-variant pdf for PCT evaluated from many parametric sensitivity calculations
  - Monte-Carlo sampling of the pdf used to identify 95/95
  - Uncertainty bias added based on code performance against integral test data

> Integral Uncertainty method reject by US NRC based on insufficient breadth of database

> Westinghouse received approval for a response surface approach in 1996

Nonparametric Statistics

- AREVA (Siemens) changed nonparametric in 1998
- Derived from fundamental Bernoulli Trials (combinatorial analysis)

$$P[G(x_k) > \beta] = \gamma = \frac{n!}{(k-1)! \cdot (n-k)!} \cdot \int_{\beta}^{1} \xi^{k-1} (1-\xi)^{n-k} d\xi$$

- When $k=n$, (i.e., largest value in sample set), this relationship reduces to (Wilks formula):

$$\gamma = 1 - \beta^n$$

- Solve for number of cases for a desired uncertainty coverage(β)/confidence(γ) (e.g., n = 59 for 95/95):

$$n = \frac{\ln(1-\gamma)}{\ln(\beta)}$$

- Extensions to the method provide alternatives to determine the 95/95 condition
  - 93 cases: second highest value calculated is the 95/95
  - 124 cases: third highest value calculated is the 95/95
  - etc.

Data for quantifying uncertainties

- Is statistics enough to declare the LBLOCA issue resolved? (re: Theofanus, 1992)
- If data is limited, derived uncertainties will reflect that condition. If the uncertainty is too penalizing, then new test programs need to be performed.

Code Accuracy

> **Uncertainty Evaluation**

- **Uncertainty quantification begins with a clear qualitative understanding of the assumptions associated with measured values – consideration necessary for data that has been filtered for global vs. local variable or the convolution of multiple effects**

  Example: Core heat transfer

$$HTC = fct\left(\dot{m},\ geometry\ ,\ fluid\ \ properties\ ,\ design\ assumptions,\ measurement,\ data\ reduction\right)$$

- **Results of SET evaluations used to develop uncertainties and distributions for important PIRT phenomena ("Bottom-Up" approach)**
- **Integrity of statistics requires the demonstration of sufficient density and breadth of data within the range-of-applicability**
- **Validation of uncertainty ranges provided by reserving "control sets" of data and reevaluating statistics**
- **Conservatisms are necessary to overcome limitation in database**

Problems in RLBLOCA Applications

Bert Dunn
Advisory Engineer
AREVA NP Inc.

- Listing of Specific Identifiable Issues from AREVA
- Identification of Probable Causes
- Recommendation for Forum Activity

Problems in RLBLOCA Applications

> Technical Issues with the Base Methodology
- Fuel Rod Quench
- DFFB Correlation
- Rod to Rod Radiation

> SER Issued Approved these Models
- "The report is acceptable for referencing in licensing applications to the extent specified and under the limitations delineated in the report and in the associated NRC staff's safety evaluation …"
- The SER raises no issues relative to the above technical approaches

> Same Rejected by NRC on First Application

> Root Cause
- Inadequate Review by NRC
- Process Based Strong Arm Approach by AREVA

> Ancillary Issue:
- NRC Review Statements are Not Upheld

Problems in RLBLOCA Applications

- Issues with Containment Modeling
- Difficulties with First Application
- Root Cause
  - Poor Documentation by AREVA
  - Inadequate Review by NRC
    - Review Did Not Involve Containment Branch

Problems in RLBLOCA Applications

> Sampling of Core Power

- Approved in SER – Rejected Later Applications

> Root Cause

- Inadequate Review by NRC

> Ancillary Issue:

- NRC Review Statements are Not Upheld

Problems in RLBLOCA Applications

- Sampling of Off-Site Power (GDC-35)
  - Approved in SER – Rejected Later Applications
- Root Cause
  - Inadequate Review by NRC
- Ancillary Issue:
  - NRC Review Statements are Not Upheld

Problems in RLBLOCA Applications

> Order Statistics with 59 Cases
- Approved in SER – Rejected Later Applications

> Root Cause
- Inadequate Internal NRC Agreement
- Process Based Strong Arm Approach by AREVA

> Ancillary Issue:
- NRC Review Statements are Not Upheld

Problems in RLBLOCA Applications

> **Sampling of Decay Heat**
- **Approved in SER – Rejected Later Applications**

> **Root Cause**
- **Inadequate NRC Review**

> **Ancillary Issue:**
- **NRC Review Statements are Not Upheld**

Problems in RLBLOCA Applications

- NRC Reviewers Do Not Understand Statistical LOCA Methodologies
  - Continuous Re-Education of Reviewers by Applicant
  - Sporadic and Inconsistent Review Decisions
- Root Cause
  - Inadequate NRC Dissemination of Decisions
  - Inadequate Internal NRC Agreement
- Ancillary Issue:
  - NRC Review Statements are Not Upheld

Problems in RLBLOCA Applications

> **Recommended Forum Activity**

- **Review and Clarify Licensing Requirement Statement**
  - **Establish Nature of BE Level**
    - Complete as we can get
    - Some retained margins applied after BE determination
    - Internally maintained retained conservatisms
  - **Use NuReg/Reg. Guide to Phrase Requirement Statistically**
  - **Establish Domain (Range) of Requirement**
- **Re-Consider Order Statistics Case Set Requirement**
  - **Univariate / Multivariate**
- **Establish Range of Sampling Opportunities**

Problems in RLBLOCA Applications

> Open Discussion

Revision 2 Status Meeting - Conclusions

> **Backup Slides**