# ADVISORY COMMITTEE ON REACTOR SAFEGUARDS
# THERMAL HYDRAULIC PHENOMENA
# AND
# RELIABILITY AND PRA SUBCOMMITTEES
# GSI 189- "SUSCEPTIBILITY OF ICE CONDENSER AND MARK III CONTAINMENTS TO EARLY FAILURE FROM HYDROGEN COMBUSTION DURING A SEVERE ACCIDENT"
# ROOM T-2B3, 11545 ROCKVILLE PIKE, ROCKVILLE, MARYLAND

**November 5, 2002**

## - PROPOSED AGENDA -

| | SUBJECT | PRESENTER | TIME |
|---|---|---|---|
| I. | Introductory Remarks<br>Subcommittee Chair | T.S. Kress | 1:30-1:35 p.m. |
| II. | NRC Staff Presentation | | 1:35-3:15 p.m. |
| | A. Introduction and Overview | Allen Notafrancesco, RES | |
| | B. Benefits Analysis | John Lehner, BNL | |
| | C. Cost Analysis | James Meyer, ISL | |
| | D. Ice Condenser Combustion Issues | Allen Notafrancesco, RES | |
| | | ****BREAK**** | 3:15-3:30 p.m. |
| III. | NRC Staff Presentation (Continued) | | 3:30-4:30 p.m. |
| | E. MELCOR Analysis | Jack Tills, SNL | |
| | F. Summary/Recommendations | All | |
| IV. | Committee Comments and Discussion | | 4:30-5:30 p.m. |

BNL - Brookhaven National Laboratory
ISL - Information Systems Laboratories
SNL - Sandia National Laboratories

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ACRS CONTACT: Ms Maggalean W. Weston, mww@nrc.gov or (301) 415-3151.

Note: Number of copies of presentation materials to be provided to the ACRS - 35.

# ACRS Subcommittee Meeting on Thermal-Hydraulic Phenomena
# November 5, 2002
# GSI-189 RES Technical Assessment Summary
# Agenda

| | |
|---|---|
| **1:30-1:45pm** | **Introduction/Overview** (Allen Notafrancesco, RES TM) |
| **1:45-2:30pm** | **Benefits Analysis** (John Lehner, BNL) |
| **2:30-2:50pm** | **Cost Analysis** (James Meyer, ISL) |
| **2:50-3:15pm** | **MELCOR Analysis** (Jack Tills, SNL/JTA) |
| **3:15-3:30pm** | **Ice Condenser Combustion Issues** (A. Notafrancesco) |
| **3:30-3:45pm** | **BREAK** |
| **3:45-4:00pm** | **Summary & Recommendations** (Jack Rosenthal) |
| **4:00-5:00pm** | **Open Discussion** (All) |

# GSI-189 TECHNICAL ASSESSMENT SUMMARY

Recommendation: To cope with SBO events, pursue further regulatory action for both ice condenser and Mark III plants to provide back-up power to one train of the hydrogen igniter system

Ice Condensers-

- Calculations of averted costs with uncertainties- could pass cost-benefit considering back-up power to igniters (and even ARF in some cases)
  - Not recommending that back-up power be added to ARF

Mark IIIs-

- Calculations of averted costs with uncertainties- the cost-benefit of back-up power to igniters is marginal
  - Other important considerations

# ICE CONDENSER Averted Costs ($k)

| Plant | Case | | Source of SBO frequency used | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | Internal Events | | | | | External Events |
| | Cond Cntmt Failure Prob | Source Term | Pt Est | Uncertainty | | | Upper Bound Estimate of 95th combined (Lv1&Lv2) uncertainty | Pt Est |
| | | | | 5th | mean | 95th | | |
| **Sequoyah** | | | *NUREG-1150* | | | | | |
| 1 | EF =0.15 (N1150 mn) | 1150S (updated) | NA | 11 | 320 | 1,200 | | NA |
| 2 | EF =0.65 (N1150 95th) | | | 50 | 1,400 | 5,000 | 3,200 | |
| 3 | EF=0.97 (N/C 6427) | | | 74 | 2,100 | 7,500 | | |
| **Catawba** | | | *Duke PRA Rev 2b* | | | | | |
| 1 | EF=0.29 LF=0.71 (N/C6427 & Duke PRA range) | Duke | 180 | 11* | 220* | 750* | | 120 |
| 2 | | 1150S | 640 | 40* | 790* | 2,700* | 2,200* | 420 |
| 3 | | 1150S*1.8 | 870 | 54* | 1,100* | 3,700* | | 580 |
| | | | *Duke Rev 2b with RCP seal replaced* | | | | | |
| 4 | same as above | Duke | 120 | 6* | 150* | 530* | | NA |
| 5 | | 1150S | 420 | 22* | 540* | 1,900* | 1,500* | |
| 6 | | 1150S*1.8 | 570 | 31* | 740* | 2,600* | | |
| | | | *Duke Rev 2b w RCP seal replaced & flood wall installed* | | | | | |
| 7 | same as above | Duke | 14 | 2* | 31* | 100* | | NA |
| 8 | | 1150S | 52 | 7* | 110* | 370* | 310* | |
| 9 | | 1150S*1.8 | 70 | 9* | 150* | 500* | | |
| **McGuire** | | | *Duke PRA Rev 3* | | | | | |
| 1 | EF=0.26 LF=0.56 NF=0.18 (Duke PRA range) | Duke | 13 | 2* | 32* | 110* | | 98 |
| 2 | | 1150S | 44 | 8* | 110* | 380* | 320* | 340 |
| 3 | | 1150S*2.3 | 72 | 13* | 180* | 600* | | 540 |

* includes SBO frequency due to tornado

| MARK III- Averted Costs ($k) | | | | | |
|---|---|---|---|---|---|
| Plant & Case description | | Source of SBO frequency | | | |
| | | Internal Events | | | External Events |
| | | 5th | mean | 95th | |
| **Grand Gulf** | | *NUREG-1150* | | | |
| 1 | Mean NUREG-1150 CPEF<br>Split fractions from Figs 1&2 | <1 | 10 | 29 | NA |
| 2 | 95th NUREG-1150 CPEF<br>Split fractions from Figs 1&2 | <1 | 22 | 61 | |
| 3 | 95th NUREG-1150 CPEF<br>50% of sequences at low pressure, drywell always fails if containment fails | 2 | 60 | 170 | |
| | | *SPAR 3i* | | | |
| 4 | Mean NUREG-1150 CPEF<br>Split fractions from Figs 1&2 | <1 | 6 | 22 | NA |
| 5 | 95th NUREG-1150 CPEF<br>Split fractions from Figs 1&2 | <1 | 13 | 45 | |
| 6 | 95th NUREG-1150 CPEF<br>50% of sequences at low pressure, drywell always fails if containment fails | 2 | 36 | 120 | |
| **River Bend** | | *SPAR 3i* | | | |
| 1 | Mean NUREG-1150 CPEF<br>Split fractions from Figs 1&2 | <1 | 57 | 160 | NA |
| 2 | 95th NUREG-1150 CPEF<br>Split fractions from Figs 1&2 | <1 | 120 | 330 | |
| 3 | 95th NUREG-1150 CPEF<br>50% of sequences at low pressure, drywell always fails if containment fails | <1 | 320 | 880 | |

# Technical Assessment of GSI-189

# COST ANALYSIS

## Advisory Committee on Reactor Safeguards

### Subcommittee Meeting

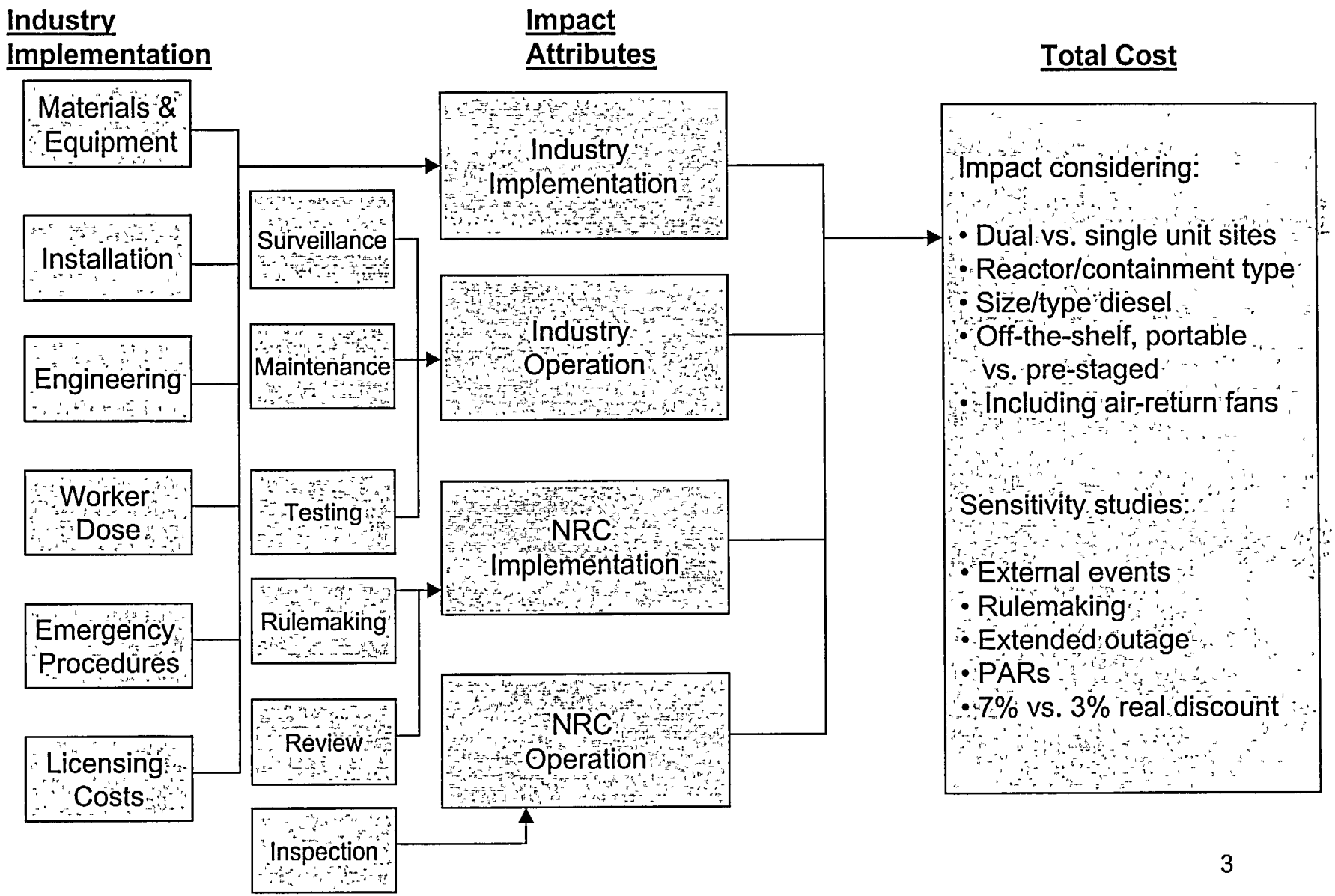
NOVEMBER 5, 2002

James Meyer, ISL

# OUTLINE

- Discussion of Cost Assessment Process
- Assumptions
- Cost Analysis Results
- Uncertainty Assessment
- Implications of System Reliability

# Cost (Impact ) Assessment Process: GI-189



# COST ASSESSMENT PROCESS
## (continued)

### COST ATTRIBUTES AND COST ELEMENTS CONSIDERED:

Industry Implementation
- Materials and equipment
- Installation (mainly labor)
- Engineering
- Occupational exposure (during installation)
- Emergency procedure - training
- Licensing costs - change to UFSAR

Industry Operation Over 40 Years
- Maintenance
- Testing
- Surveillance

NRC Implementation & NRC Operation
- Rulemaking costs
- Review of licensee documentation
- Inspection over 40 years

# COST ASSESSMENT PROCESS
(continued)

Physical Modifications Considered:

- Base case - pre-staged diesel to power igniters
- Alternative - portable diesel to power igniters
- Pre-staged diesel to power igniters and air return fans (ARFs require 20-30 kW)
- Passive autocatalytic recombiners (PARS)

Differentiated By:

- Type of reactor/containment/balance-of-plant
- Number of reactors on site (dual vs. single-unit)
- power requirements for igniters (5kW - 21kW)

# COST ASSESSMENT PROCESS
(continued)

## SENSITIVITY ANALYSIS

- External event qualification: variable and not quantified
- Extended outage: based on $300K/day
- Major rulemaking: separate from 10CFR50.44 rulemaking
- Alternative discount rate: compared 3% to 7%

# KEY ASSUMPTIONS

- Base case is a pre-staged diesel generator located near the auxiliary building.
- Activation of backup system is remote (located at the diesel generator) and manual.
- All costs are in 2002 dollars.
- 40 years of operation, starting in 2002.
- Backup power supply need not be safety grade.
- Powering one train of igniters is necessary & sufficient for mitigation.

# COST ANALYSIS RESULTS

## PER REACTOR COST (THOUSANDS OF 2002 DOLLARS)

| | Ice Condenser Best Estimate[1] | Mark III Best Estimate |
|---|---|---|
| Pre-staged/igniters – base case | 270 | 310 |
| Base case + external event qualified | 490 | 550 |
| Base case + major rulemaking | 290 | 330 |
| Base case + extended outage | 370 | 410 |
| Portable/igniters | 200 | 230 |
| Pre-staged/igniters/air return fans | 590 | N/A |
| PARs | 1700 | 1750 |

[1]The Best Estimate is an average of the estimates developed for each of the three categories of ice condenser plants.

# UNCERTAINTY ANALYSIS

Used a high, most likely, and low estimate to characterize uncertainty of the cost elements considered in the cost analysis and used Monte Carlo simulation software to propagate uncertainties.

- High, most likely, and low estimates based on industry input and engineering judgment.
- Most likely estimates were those assumed as "best estimate."
- Uncertainty analysis was applied only to pre-staged (w/ & w/o ARF) and portable diesel options.
- Statistics reported for 5th, 95th, and mean.
- Uncertainties are skewed toward the higher costs.

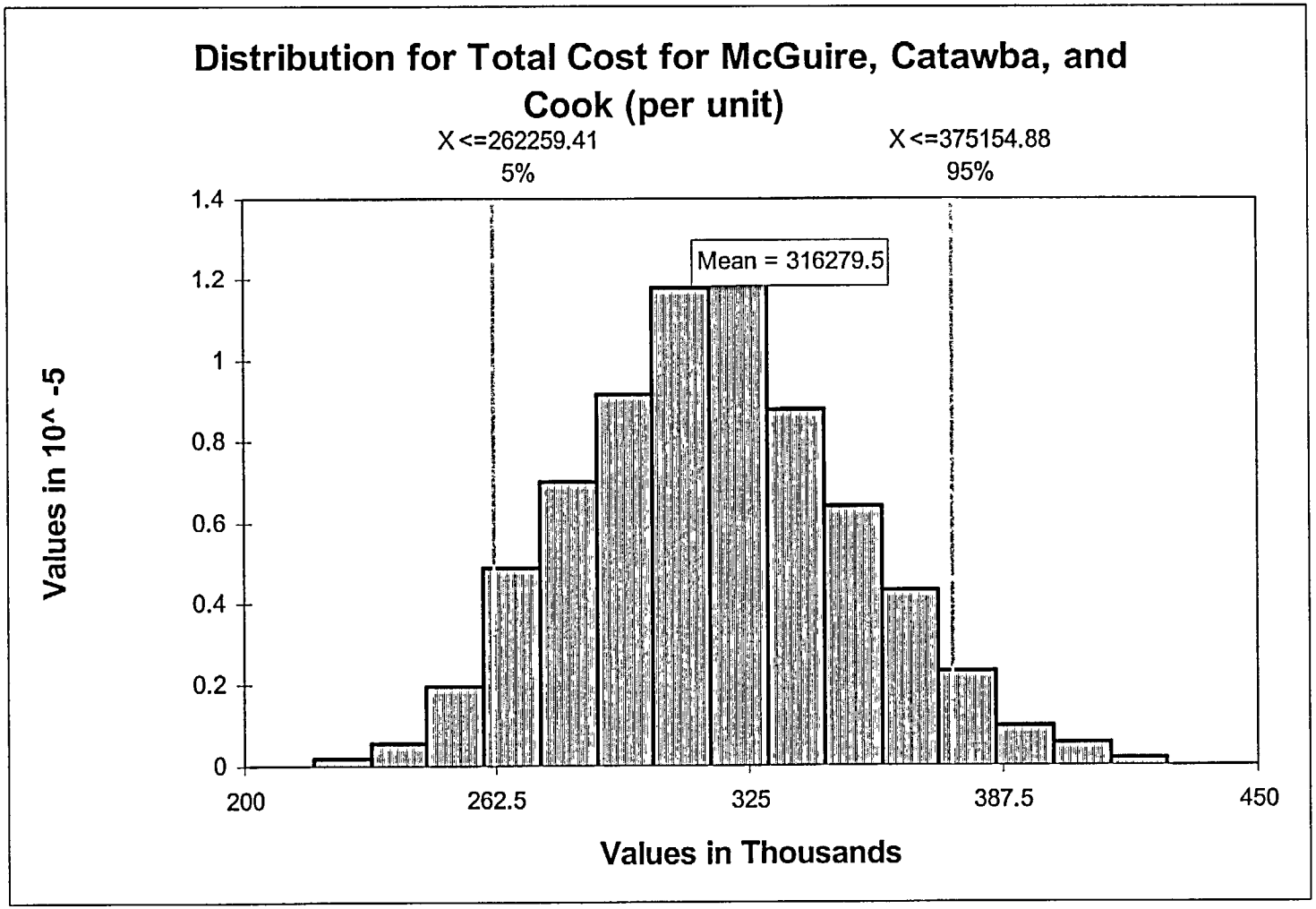
# COST ANALYSIS RESULTS: UNCERTAINTY ANALYSIS

## PER REACTOR COST (THOUSANDS OF 2002 DOLLARS)

| | Ice Condenser | | | Mark III | | |
|---|---|---|---|---|---|---|
| | Low 5% | Mean[1] | High 95% | Low 5% | Mean | High 95% |
| Pre-staged/igniters – base case | 260 | 330 | 460 | 310 | 380 | 460 |
| Portable/igniters | 180 | 230 | 330 | 220 | 270 | 330 |
| Pre-staged/igniters/air return fans | 510 | 640 | 830 | N/A | N/A | N/A |

[1]The Means are an average of the estimates developed for each of the three categories of ice condenser plants.

# UNCERTAINTY ANALYSIS (continued)




**Note: best-estimate = $260K**

# IMPLICATIONS OF BACKUP POWER SYSTEMS RELIABILITY ON COST BENEFIT ASSESSMENT

- Benefit assessment assumes that the systems are 100% reliable.
- No system has 100% functional reliability[1]. The impact of this assumption on the cost benefit assessment was addressed and determined to be insignificant.
- Backup power systems evaluated in this study should be able to have functional reliabilities greater than 0.95, values sufficiently close to 1.00 such that any adjustment would have a negligible effect on the cost-benefit assessment.
- Similar backup systems have estimated functional reliabilities in the range of 0.97 to 0.98[2].
- Conclusion: Backup power system functional reliabilities have a negligible impact on the cost-benefit assessment. Variations in functional reliabilities between systems also have negligible impact.

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[1] Functional reliability = {1 - (unavailability + hardware unreliability + human unreliability)}

[2] P. Moieni, et al., "A PRA-Based Design Change at San Onofre Nuclear Generating Station (SONGS) Units 2 & 3: Add Portable Gasoline-Powered Generators for Risk Reduction," PSA 2002, 10/02, pages 495 ff

# BENEFIT ANALYSIS FOR GSI-189

## Presentation to
## Advisory Committee on Reactor Safeguards
## (Sub-Committee)

## November 5, 2002

BROOKHAVEN
NATIONAL LABORATORY

John R. Lehner, Vinod Mubayi,
W. Trevor Pratt, Cheryl Conrad
Energy Sciences and Technology Department
Brookhaven National Laboratory

Asimios Malliakos
Probabilistic Risk Analysis Branch
Division of Risk Analysis and Applications
Office of Nuclear Regulatory Research

# OBJECTIVE

- Estimate the benefit obtained from enhancing current combustible gas control systems to make them operable during station blackout (SBO)

- Address previous ACRS comments by including additional assessment of the uncertainty in the benefit estimates

# BASIS FOR ANALYSIS

Benefit analysis carried out in accordance with the guidance provided in:

- NUREG/BR-0058, Regulatory Analysis Guidelines of the U.S. Nuclear Regulatory Commission, and
- NUREG/BR-0184, Regulatory Analysis Technical Evaluation Handbook.

Benefit consist of averted risk which includes:

- reductions in public and occupational radiation exposure,
- averted offsite property damage

# BASIS FOR ANALYSIS

Benefit = averted risk = risk reduction due to the enhancement

For combustible gas control in containment during station blackout (SBO):

Risk Reduction =
[SBO frequency] x
[Change in Conditional Probability of Early Failure (CPEF) due to enhancement] x
[Consequences of Early Failure]

Consequences consist of:

- exposure (person-rem) and
- property damage ($)

# APPROACH

Results from a Level 3 PRA are needed to estimate reduction in risk in terms of offsite person rem as well as offsite costs.

The benefit estimate is based on previously obtained PRA results from a number of existing studies.

Since a Level 3 PRA analysis was needed, the NUREG-1150 studies were used to:

- assess accident progression
- obtain base case benefit estimates

# APPROACH

Uncertainties associated with each part of analysis (no integrated uncertainty analysis available):

- SBO frequency
- CPEF
- consequences

To estimate uncertainty ranges, a number of sources with uncertainty and sensitivity information were considered:

- NUREG-1150 (SBO frequency, CPEF)
- Industry results (SBO frequency, CPEF, consequences)
- IPE ranges (SBO frequencies)
- SPAR models (SBO frequencies)

# ASSUMPTIONS

All benefit calculations carried out assuming:

- combustible gas control system is 100% effective
- gas combustion is principal cause of CPEF in SBO sequences
- late containment failures are not averted by the gas control system

# ASSUMPTIONS

- Public health from radiation exposure and offsite property impacts are examined over a 50-mile radius from the plant site
- A conversion factor of $2000 per person-rem is used to convert health effects attributable to radiological exposure to monetary terms
- All values and impacts are expressed on a present worth basis for lifetime benefits
- 40 years of plant life remain
- A 7% discount rate is used for the present value calculation (sensitivity analysis with a 3% rate)

# PWR ICE CONDENSER ANALYSIS

## Sequoyah NUREG-1150 study:

| Sequoyah Uncertainty Ranges for Internal Events | | | |
|---|---|---|---|
| | 5th | mean | 95th |
| SBO CDF frequency from NUREG-1150 (per reactor year) | 5.2E-7 | 1.5E-5 | 5.3E-5 |
| CPEF due to LOSP from NUREG/CR-4551, Vol. 5 | 1.3E-4 | 0.15 | 0.65 |

# PWR ICE CONDENSER ANALYSIS

| DUKE POWER PRA SBO CORE DAMAGE FREQUENCIES (per ry) | | | | | |
|---|---|---|---|---|---|
| Plant<br>Conditional Containment<br>Failure Probabilities | Internal Events | | | | External Events |
| | Pt Est | 5th | mean | 95th | Pt Est |
| Catawba | *Duke PRA Rev 2b* | | | | |
| Prob of early failure range:<br>0.16 to 0.21- slow SBO<br>0.16 to 0.34 - fast SBO | 1.5E-5 | 9.4E-7* | 1.9E-5* | 6.4E-5* | 1.0E-5 |
| | *Duke Rev 2b with RCP seal replaced* | | | | |
| | 9.8E-6 | 5.2E-7* | 1.3E-5* | 4.5E-5* | NA |
| Prob of late failure range:<br>0.72 to 0.84 - slow SBO<br>0.68 to 0.84 - fast SBO | *Duke Rev 2b w RCP seal replaced & flood wall installed* | | | | |
| | 1.2E-6 | 1.5E-7* | 2.6E-6* | 8.7E-6* | NA |
| McGuire | *Duke PRA Rev 3* | | | | |
| Prob of early failure range:<br>0.15 to 0.19- slow SBO<br>0.16 to 0.26 - fast SBO<br><br>Prob of late failure range:<br>0.34 to 0.56 - slow SBO<br>0.17 to 0.36 - fast SBO | 1.2E-6 | 2.2E-7* | 3.0E-6* | 9.9E-6* | 8.9E-6 |
| * includes SBO frequency due to tornado | | | | | |

# PWR Ice Condensers - Averted Costs ($k)

| Plant | Case | | Source of SBO frequency used | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Cond Cntmt Failure Prob | Source Term | Internal Events | | | | | External Events |
| | | | Pt Est | Uncertainty | | | Upper Bound Estimate of 95th combined (Lv1&Lv2) uncertainty | Pt Est |
| | | | | 5th | mean | 95th | | |
| Sequoyah | | | *NUREG-1150* | | | | | |
| 1 | EF =0.15 (N1150 mn) | 1150S (update) | NA | 11 | 320 | 1,200 | 3,200 | NA |
| 2 | EF =0.65 (N1150 95th) | | | 50 | 1,400 | 5,000 | | |
| 3 | EF=0.97 (N/C 6427) | | | 74 | 2,100 | 7,500 | | |
| Catawba | | | *Duke PRA Rev 2b* | | | | | |
| 1 | EF=0.29 LF=0.71 (N/C6427 & Duke PRA range) | Duke | 180 | 11* | 220* | 750* | 2,200* | 120 |
| 2 | | 1150S | 640 | 40* | 790* | 2,700* | | 420 |
| 3 | | 1150S* 1.8 | 870 | 54* | 1,100* | 3,700* | | 580 |
| | | | *Duke Rev 2b with RCP seal replaced* | | | | | |
| 4 | same as above | Duke | 120 | 6* | 150* | 530* | 1,500* | NA |
| 5 | | 1150S | 420 | 22* | 540* | 1,900* | | |
| 6 | | 1150S* 1.8 | 570 | 31* | 740* | 2,600* | | |
| | | | *Duke Rev 2b w RCP seal replaced & flood wall installed* | | | | | |
| 7 | same as above | Duke | 14 | 2* | 31* | 100* | 310* | NA |
| 8 | | 1150S | 52 | 7* | 110* | 370* | | |
| 9 | | 1150S* 1.8 | 70 | 9* | 150* | 500* | | |
| McGuire | | | *Duke PRA Rev 3* | | | | | |
| 1 | EF=0.26 LF=0.56 NF=0.18 (Duke PRA range) | Duke | 13 | 2* | 32* | 110* | 320* | 98 |
| 2 | | 1150S | 44 | 8* | 110* | 380* | | 340 |
| 3 | | 1150S* 2.3 | 72 | 13* | 180* | 600* | | 540 |

* includes SBO frequency due to tornado

# BWR MARK III ANALYSIS

Important considerations:

- need to fail both drywell and containment to get significant release
- NUREG-1150 accident progression indicates igniters only effective for sequences with low RCS pressure (about 40% of all sequences)
- No industry results available

# BWR MARK III ANALYSIS

## Grand Gulf NUREG-1150 Study:

| Grand Gulf uncertainty ranges for internal events | | | |
|---|---|---|---|
| | 5th | mean | 95th |
| SBO CDF frequency from NUREG-1150 (per reactor year) | 1.7E-7 | 3.9E-6 | 1.1E-5 |
| CPEF due to SBO from NUREG/CR-4551, Vol. 6 | ~1.E-2 | ~0.5 | ~1.0 |

## SPAR Models:

| SPAR 3i SBO CDF ranges for internal events (ry) | | | |
|---|---|---|---|
| | 5th | mean | 95th |
| Grand Gulf | 1.4E-7 | 2.4E-6 | 8.2E-6 |
| River Bend | 2.7E-8 | 1.0E-5 | 2.8E-5 |

# BWR MARK III ANALYSIS

## Grand Gulf NUREG-1150 Study:

| Conditional Containment and Drywell Failure Probabilities for Grand Gulf | | | | |
|---|---|---|---|---|
| RCS Pressure at Vessel Breach | Station Blackout, SBO (Igniters and Sprays unavailable) | | Non-SBO (Igniters and Sprays available) | |
| | Containment Fail | Containment and Drywell Fail | Containment Fail | Containment and Drywell Fail |
| High | ~ 0.5 | ~ 0.2 | ~ 0.5 | ~ 0.2 |
| Low | ~ 0.5 | ~ 0.2 | ~ 0.01 - 0.02 | ~ 0.01 |

# PWR Mark IIIs Averted Costs ($k)

| Plant & Case description | | Source of SBO frequency | | | |
|---|---|---|---|---|---|
| | | Internal Events | | | External Events |
| | | 5th | mean | 95th | |
| Grand Gulf | | *NUREG-1150* | | | |
| 1 | Mean NUREG-1150 CPEF | <1 | 10 | 29 | NA |
| 2 | 95th NUREG-1150 CPEF | <1 | 22 | 61 | |
| 3 | 95th NUREG-1150 CPEF 50% of sequences at low pressure, drywell always fails if containment fails | 2 | 60 | 170 | |
| | | *SPAR 3i* | | | |
| 4 | Mean NUREG-1150 CPEF | <1 | 6 | 22 | NA |
| 5 | 95th NUREG-1150 CPEF | <1 | 13 | 45 | |
| 6 | 95th NUREG-1150 CPEF 50% of sequences at low pressure, drywell always fails if containment fails | 2 | 36 | 120 | |
| River Bend | | *SPAR 3i* | | | |
| 1 | Mean NUREG-1150 CPEF | <1 | 57 | 160 | NA |
| 2 | 95th NUREG-1150 CPEF | <1 | 120 | 330 | |
| 3 | 95th NUREG-1150 CPEF 50% of sequences at low pressure, drywell always fails if containment fails | <1 | 320 | 880 | |

# COMPARISON OF RESULTS

- Comparison of the results for Sequoyah (PWR ice condenser) with results for Grand Gulf (BWR Mark III) shows that the estimated benefit of providing combustible gas control during SBO sequences differs significantly (a factor of roughly 30) for these two plants.

| Parameter comparison | | | |
|---|---|---|---|
| Parameter | Sequoyah value | Grand Gulf value | Sequoyah/ Grand Gulf |
| SBO frequency | 1.5E-5 | 3.9E-6 | 3.8 |
| Approximate averted CPEF | 0.15 | 0.09 | 1.7 |
| Off-site person rem 2000 estimate | 3.1E+6 | 6.1E+5 | 5.1 |
| TOTAL FACTOR | | | ~30 |

# Technical Assessment of GSI-189

## INTRODUCTION/OVERVIEW

## Advisory Committee on Reactor Safeguards
### Subcommittee Meeting

**NOVEMBER 5, 2002**

Allen Notafrancesco, Task Manager
Safety Margins and Systems Analysis Branch
Division of Systems Analysis and Regulatory Effectiveness
Office of Nuclear Regulatory Research

# TECHNICAL ASSESSMENT OVERVIEW

- BENEFITS ANALYSIS (PRAB/BNL)
  - Ice Condensers & Mark IIIs
- COST ANALYSIS (REAHFB/ISL)
  - System enhancements
- MELCOR Scoping Analysis (SNL/JTA)
- ICE CONDENSER COMBUSTION ISSUES (SMSAB)
- SUMMARY & RECOMMENDATIONS

# GENERIC SAFETY ISSUE 189: "SUSCEPTIBILITY OF ICE CONDENSER AND MARK III CONTAINMENTS TO EARLY FAILURE FROM HYDROGEN COMBUSTION DURING A SEVERE ACCIDENT"

...applies specifically for postulated SBO events

- Issue was raised as part of the effort to risk-inform 10CFR 50.44 (H2 Control):

- **GSI-189 resolution:**

  - Met with ACRS on June 6, 2002 on Technical Assessment
  - ACRS letter, June 17th; perform additional analysis to quantify uncertainties and brief ACRS again

  –RES completed a refined Technical Assessment

  - RES plans to transmit Technical Assessment with recommendations to NRR by end of CY02

# BACKGROUND

## AFFECTED DOMESTIC REACTORS

- **PWR Reactors with Ice Condenser Containments:**

  9 Reactors; four dual unit sites (McGuire, Catawba, D.C. Cook, and Sequoyah) and one single unit site (Watts Bar)

- **BWR Reactors with Mark III Containments:**

  4 Reactors; four single unit sites (Grand Gulf, Perry, Clinton & River Bend)

- **Common Attributes of these containments:**

Pressure Suppression with lower design pressures, 12-15 psig & relatively lower free volumes, ~1.1-1.5E6 cft

# GSI-189 Technical Assessment

**OBJECTIVE:**

Focused on susceptibility of early containment failure due to hydrogen combustion...for SBO events;

Determine whether providing additional/enhanced combustible gas control is justified (with a focus on considering uncertainties)

**APPROACH:**

- Use existing studies, e.g., NUREG-1150, IPEs, etc.
- Explore various options in performing cost analysis
- Focus on containment system performance improvement recognizing cost

# Technical Assessment of GSI-189

# Ice Condenser Combustion Issues

## Advisory Committee on Reactor Safeguards
### Subcommittee Meeting

NOVEMBER 5, 2002

Allen Notafrancesco, Task Manager
Safety Margins and Systems Analysis Branch
Division of Systems Analysis and Regulatory Effectiveness
Office of Nuclear Regulatory Research

# BACKGROUND

**Risk-Informing 10CFR50.44/GSI-189:**

- Several licensees (and public interest groups) currently state that back-up power to the igniters should also include back-up power to the air return fan (ARF) to effectively *mix* ice chest-
- Current evaluations reveal that igniters alone are sufficient
- Use of ARF would tend to accelerate ice chest melt-out during postulated core melt events-
    - Delaying melt-out of ice bed could extend fission product scrubbing and containment integrity
- ARF implementation/operational costs are much greater; cost-benefit becomes less favorable or does not pass

# GSI-189 PERSPECTIVES

- Recognize proposed enhancement would increase plant capabilities to deal with *low* frequency events

- Consider containment system performance improvement recognizing cost

- Best Estimate approach with consideration of uncertainties

# ICE CONDENSER DESIGN ATTRIBUTES

- Air Return Fans (ARF):
  - Part of original plant design
  - Two independent trains consisting of high capacity fans, i.e., about 40,000 cfm each train
  - Forces upper compartment atmosphere to the lower compartments
- Containment Sprays
- Ice Chest
  - Closely packed cylindrical baskets filled with ice

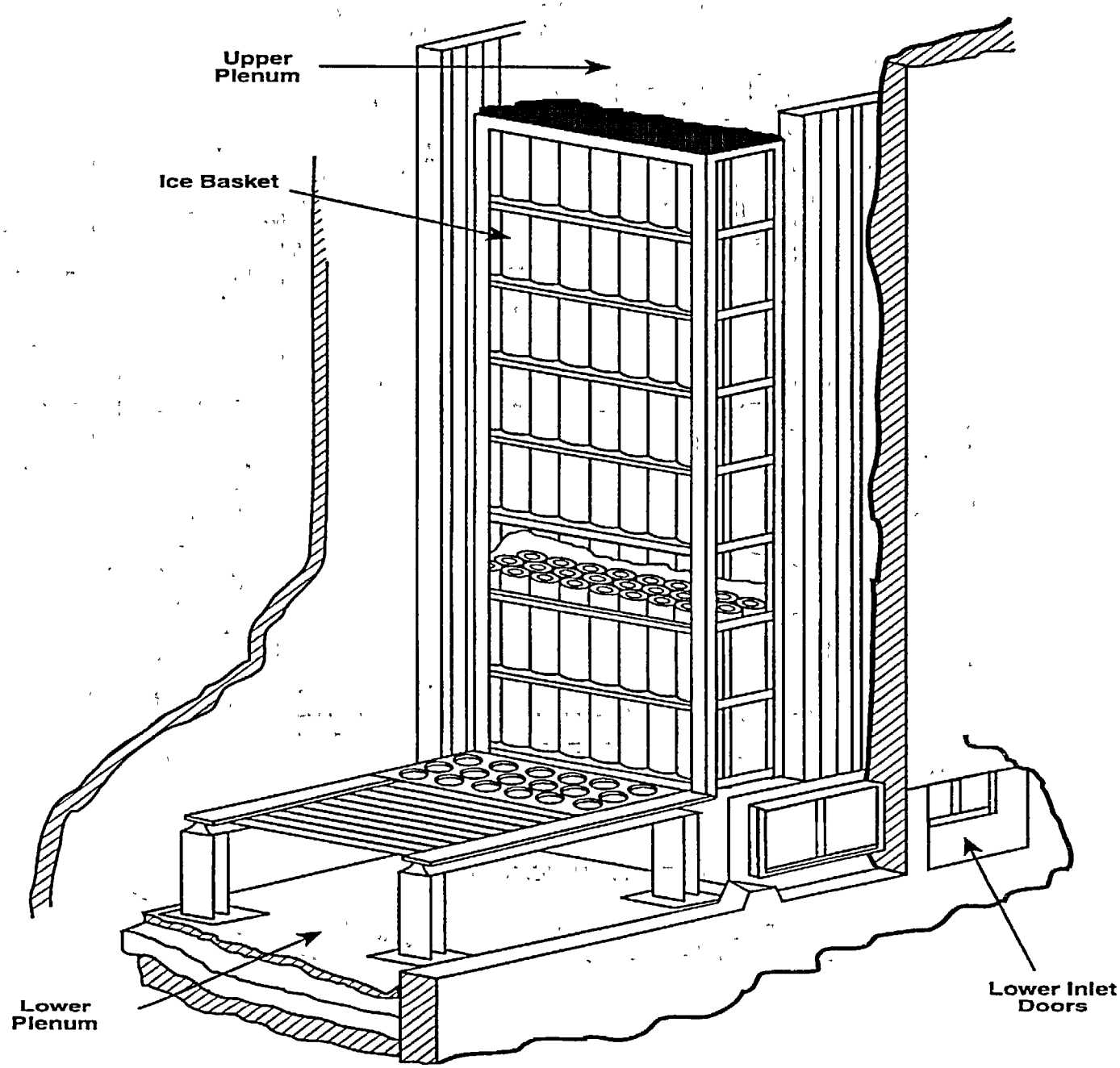
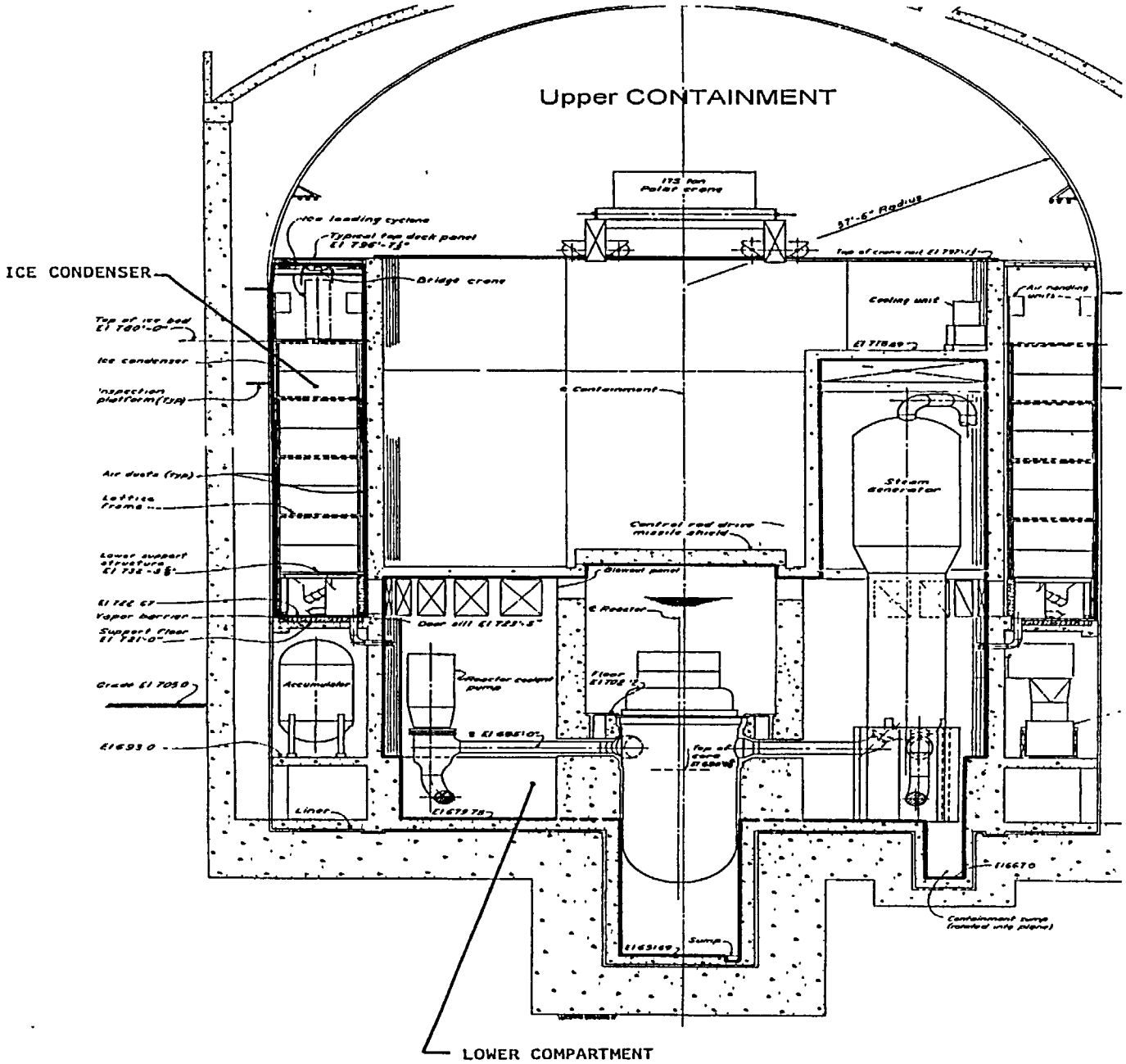



Figure 4-3 Cross-sectional sketch of a typical PWR ice condenser showing the inlet doors, lower plenum, ice bed with ice baskets, and upper plenum


Upper CONTAINMENT
ICE CONDENSER
LOWER COMPARTMENT
Ice loading cyclone
Typical top deck panel
Bridge crane
Top of ice bed
Ice condenser
Inspection platform (typ)
Air ducts (typ)
Lattice frame
Lower support structure
Vapor barrier
Support floor
Grade El 705.0
El 693.0
Liner
Accumulator
Reactor coolant pump
Door sill El 723'-5"
Blowout panel
Reactor
Control rod drive missile shield
Containment
Steam generator
Cooling unit
Air handling units
Floor
Sump
Containment sump (rotated into plane)
57'-6" Radius

## Post-TMI requirements:

- Plants Retrofitted with AC Powered Igniters to deal with large quantities of hydrogen (equivalent to 75% MWR of active cladding) for postulated recoverable degraded core events
  - Separate igniter units are located throughout the containment airspace (except ice chest and lower plenum)
  - Igniters to "burn" hydrogen at lean gas mixture concentrations
  - Maintain containment integrity
  - TMI-type sequences for ice condensers, ARF and containment spray are available

# EXAMINE CONTAINMENT PERFORMANCE

## For Ice Condensers, combustion issues during SBO-
**...focusing on the importance of ARF**

- Previous Assessments/Experiments
  - Post-TMI assessments & Staff SERs
  - IPE treatment of igniters & ARF
  - Relevant Hydrogen experiments
- Recent Plant Analysis
  - MELCOR scoping study with new hydrogen release profiles
- Summary & Conclusions

# HYDROGEN COMBUSTION BEHAVIOR

- Possible combustion modes inside containment
  - Flame front propagation characteristics
    - Slow Speed; deflagrations & diffusion flames
      - ~ 1 - 10 m/sec
      - ~ 4 - 10% H2 (dry) concentration
      - Intent of deliberate ignition system is to burn hydrogen in this range
    - Fast Speed; flame acceleration (FA) & deflagration to detonation transition (DDT)
      - ~ 100 - 1000 m/sec

# POST-TMI ASSESSMENT

## Key Ice Condenser Evaluation:

McGuire Units 1 & 2, Atomic Safety & Licensing Board (ASLB) Hearings for Operating License-

Extensive discussions relating to hydrogen control inside an ice condenser containment

- A team of combustion experts
  - Most notables; Dr. Bernard Lewis & Bela Karlovitz to review issues surrounding hydrogen combustion

- **Combustion issues associated with the ice chest, Experts:**
  - Continuous diffusion flame at the top of the ice condenser.
  - The geometry and flow conditions inside the ice condenser region are not conducive to producing a transition to detonation.
  - Even without air return fans nor containment sprays, "then the hydrogen stream emerging from the ice condenser will mix slower with the air under the dome, and will be ignited and will burn as a slow-burning diffusion flame."
  - "... don't have a strong sideways confinement."..."Any expansion that takes place during the deflagration phase of the propagation will hold back the transition to detonation..."

(Reference: Transcript of ASLB Operating License Hearing for McGuire Units 1 & 2, dated February 26, 1981)

# ICE CONDENSER IPE TREATMENT

- Generic Letter No. 88–20 (Supplement No. 3) July 1990; Completion of CPI program and forwarding insights for use in IPEs

  - Evaluate interruption of power to igniters

- Survey of several licensee's evaluation on the response to this GL supplement: cost benefit small, no identification by licensees that ARF are necessary. Moreover, some discussion on restoring igniters as part of accident management program.

- Survey of several IPEs:

  - Event trees indicates that continuous operation of igniters is sufficient

# HYDROGEN COMBUSTION EXPERIMENTS

- Since 1981, numerous hydrogen combustion testing programs were performed
- RES played an active role in hydrogen behavior research
- Generally, during the 1980s most of the testing focused on slow speed combustion to evaluate efficacy of igniters (summary in NUREG/CR-5079)
- During the 1990s, greater emphasis on high speed combustion testing....NEA/CSNI State-of-the-Art Report, August 2000, "Flame Acceleration and Deflagration-to-Detonation Transition in Nuclear Safety"
- Deliberate ignition of H2-Air-Steam mixtures in condensing steam environments (NUREG/CR-6530)

# SUMMARY OF TEST RESULTS

- Igniters reliably initiate combustion at lean mixtures
- Exhibit low flame speeds
  - Confirms tendency for H2 to burn, where conditions permit, as diffusion flames
- No opportunity for flame acceleration in covered regions
- Smooth transition in steam condensing environment
- Besides burning locally & efficiently...induces bulk circulation currents which promotes mixing

# MELCOR SCOPING ANALYSIS

- Using new ice condenser plant response uncertainty study to obtain H2/steam source terms

  - At Vessel Breach H2 released about 50-60% MWR

- Code sensitivities reveal relatively small differences between the use of igniters only versus igniters and ARF

# OVERALL CONCLUSION

**For Ice Condensers, during postulated SBO sequences back-up power to the igniter system *only* is sufficient:**

- **Collectively, past findings and relevant combustion testing provides adequate basis**
  - Use of ARF would tend to accelerate ice chest melt-out during postulated core melt events-
    - Delaying melt-out of ice bed could extend fission product scrubbing and containment integrity

# Hydrogen Control Calculations for the Sequoyah Plant

## Reference and Uncertainty Calculations

Presentation By:
Jack Tills, JTA. Inc.
Contracted to Sandia National Laboratories, Org 6415

To:
ACRS
NRC Headquarters
Rockville, MD

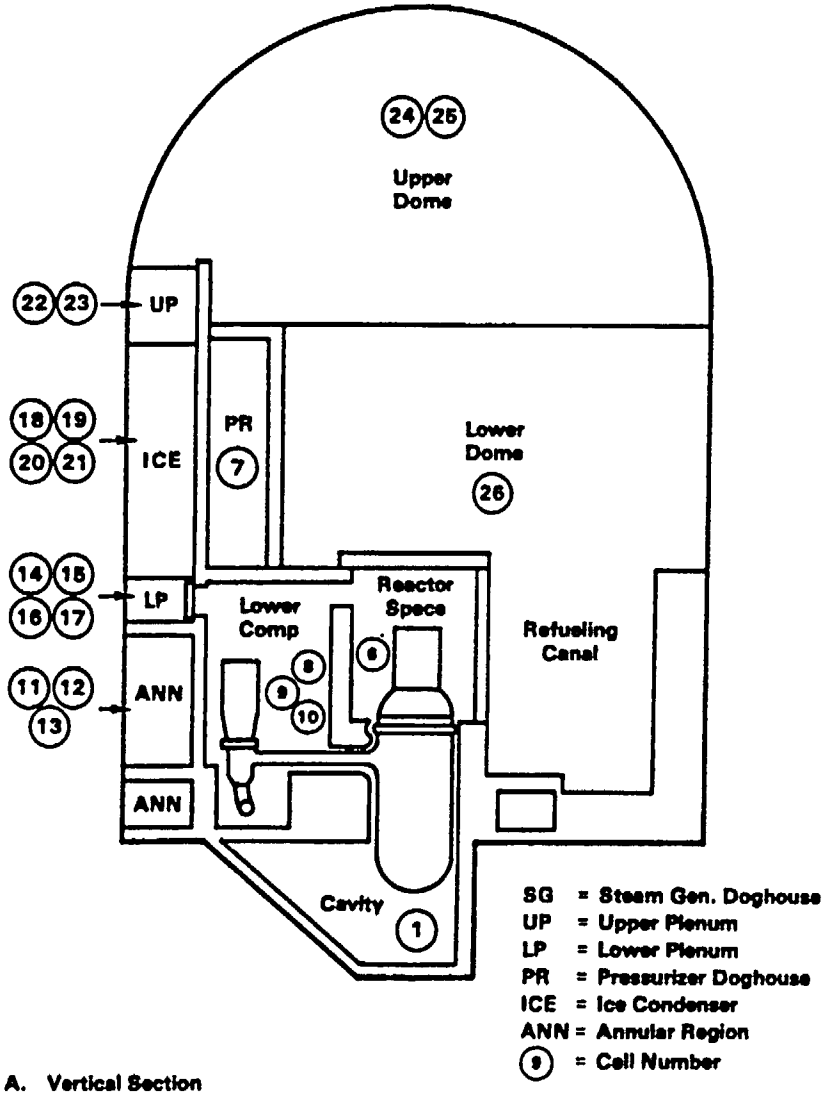
5 November 2002

# Hydrogen Control Issues Addressed

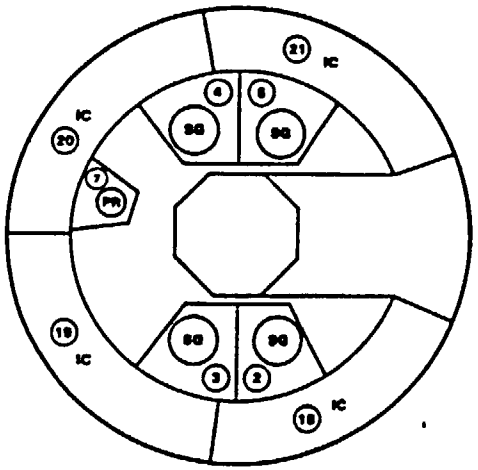
- Multi-cell MELCOR input for evaluation of ice condenser plant performance during SBO-type events (standalone containment analysis)
- Selection of hydrogen source terms based on MELCOR uncertainty calculations for short term SBO with pump seal leakage
- Relative comparison of thermal-hydraulic and hydrogen control results involving auxiliary power options:
  - No Power
  - Power to Igniters only
  - Power to Igniters and Single Fan Train

- Uncertainty/Sensitivity study for containment model and hydrogen burn parameters

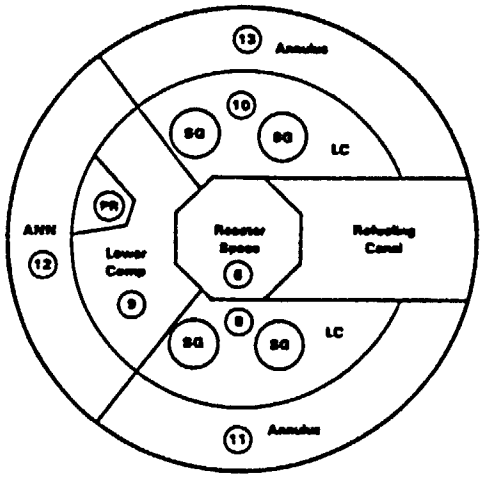
# MELCOR 26-Cell Model of the Sequoyah Containment




A. Vertical Section

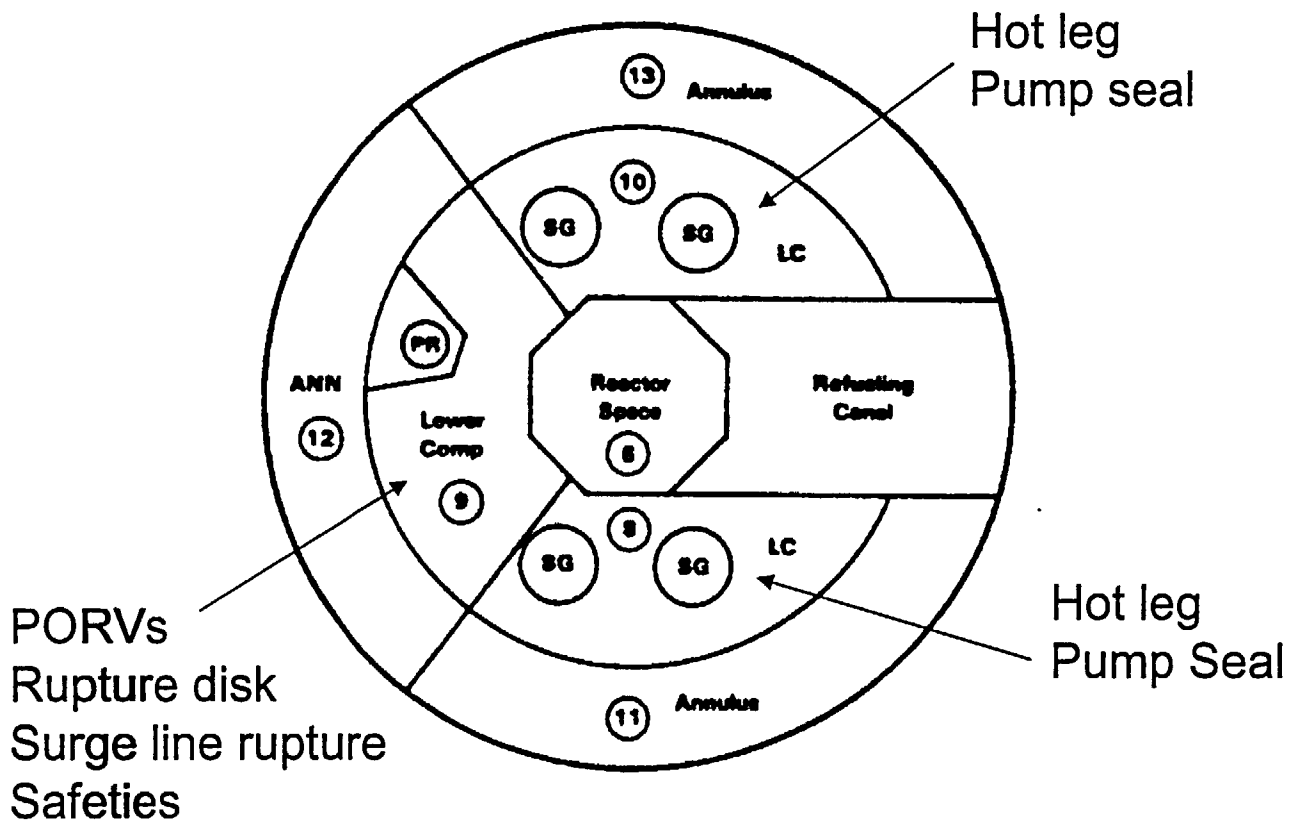



B. Top View of Ice Condenser Nodalization

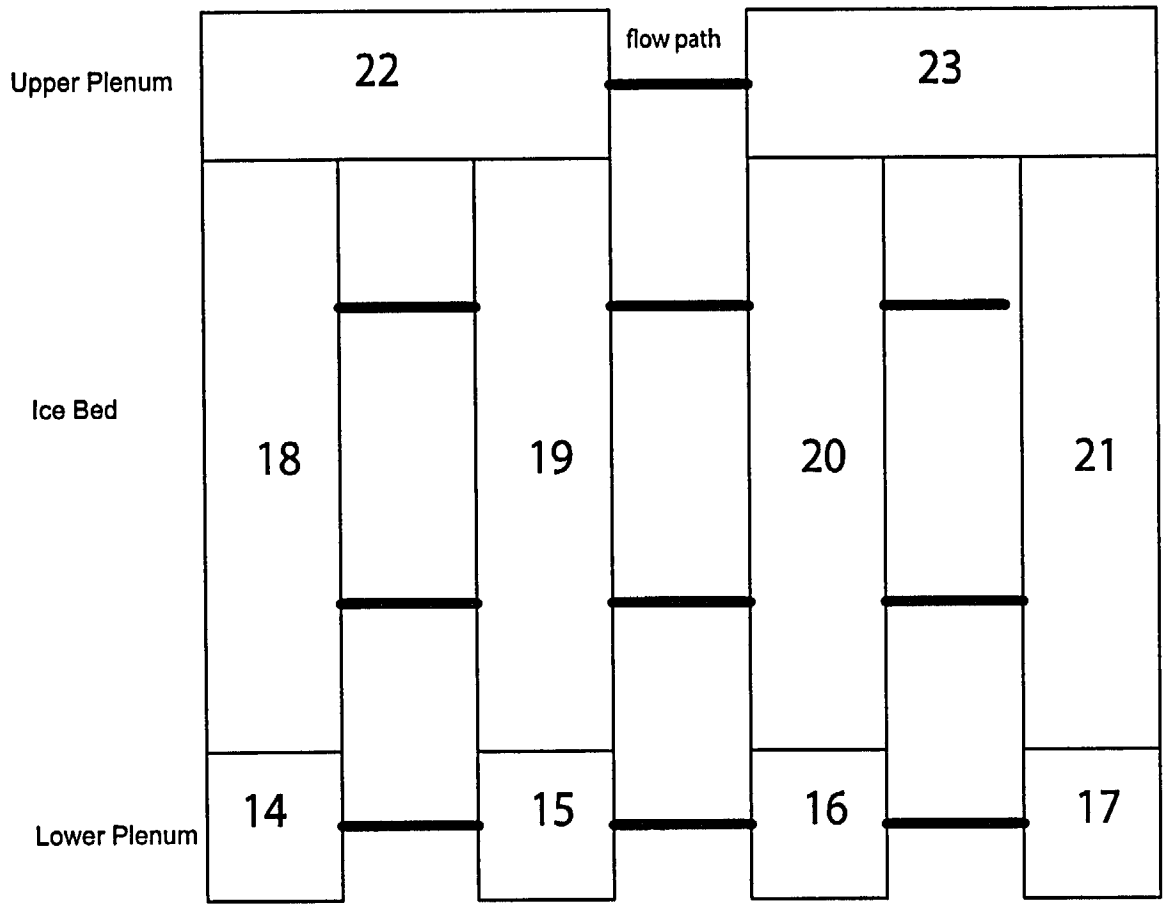



C. Nodalization of Lower Compartment

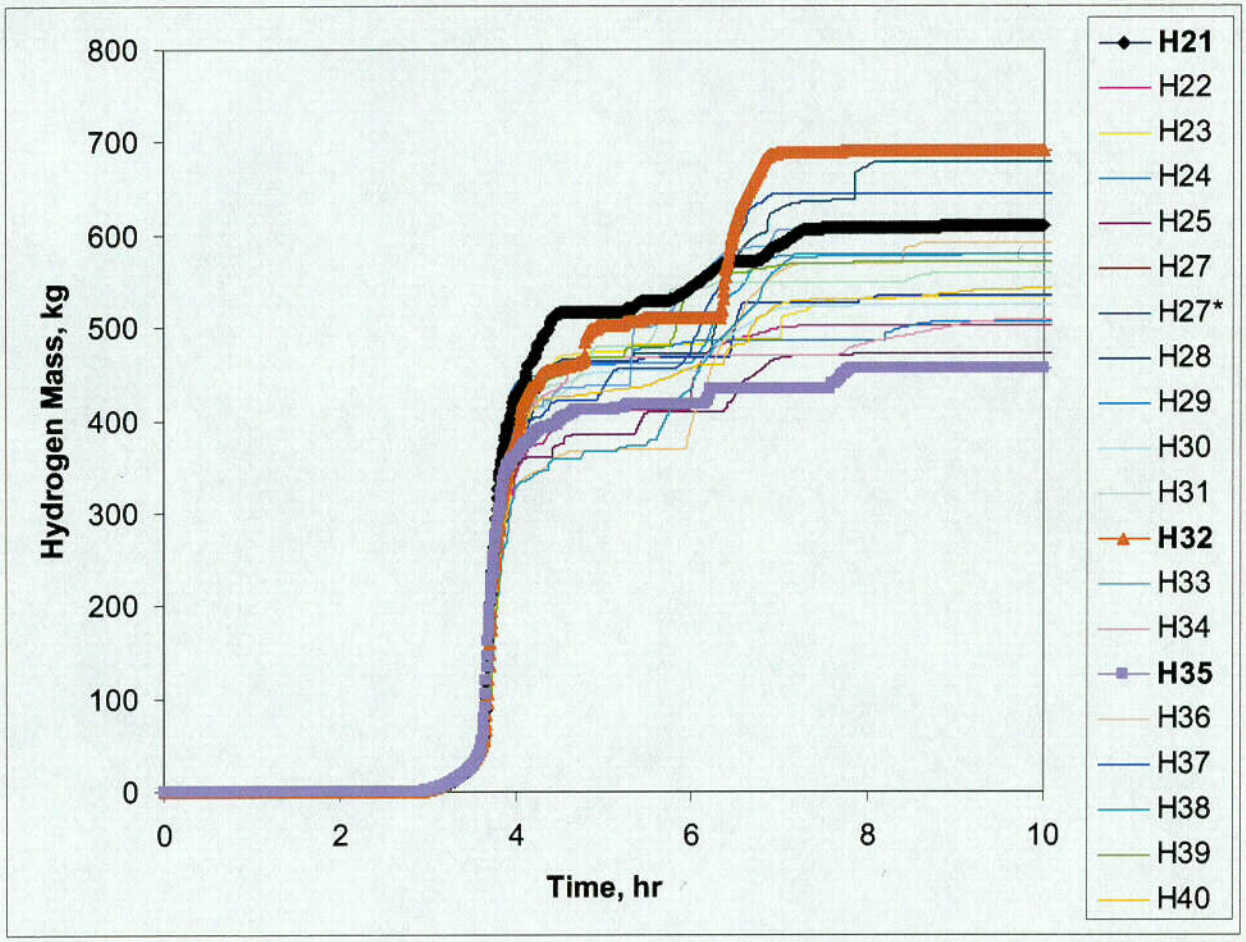
## Lower Compartment Source Locations for Sequoyah 26-Cell Model STSBO w Pump Seal Leakage



# Ice Condenser Nodalization for 26-cell MELCOR Model



# In-vessel Hydrogen Generation for MELCOR Runs #21 - #40




C01

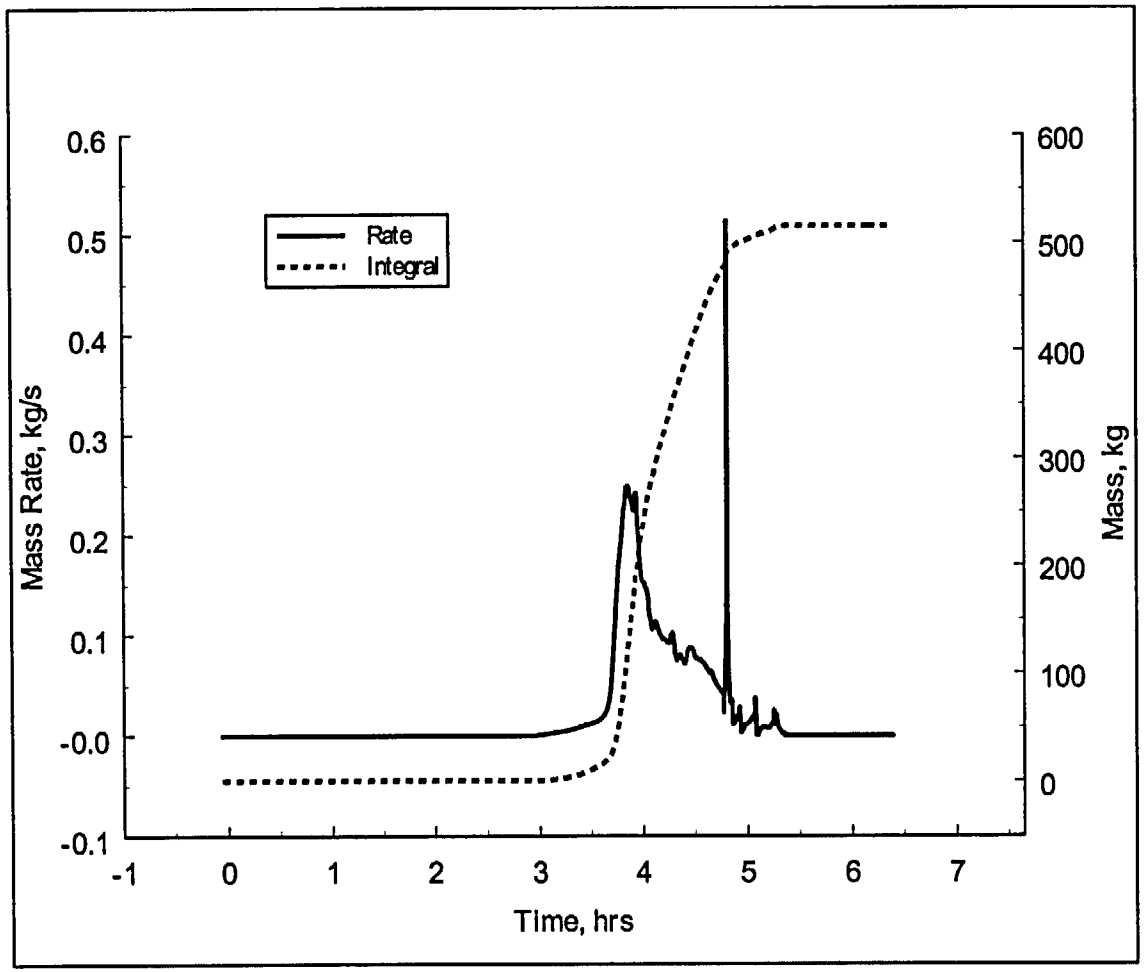
# Selected MELCOR Sequoyah Sensitivity Runs

## (High and Low Total Release including variability associated with hot leg failure)

| Run # | Primary System Failure Times (Hours) | | Hydrogen Cumulative Mass (Kg) | | |
|---|---|---|---|---|---|
| | Vessel | Hot Leg | Generated in Core* | Core to Containment | |
| | | | | Hot Leg | Pump Seals |
| 21 | 6.37 | 5.57** | 570 | 55.6 | 515.2 |
| 32 | 6.3 | ---- | 510 | ---- | 508.9 |
| 35 | 7.57 | 6.38 | 434.5 | 13.9 | 420.2 |
| Rev 1 Rpt*** | 5.45 | 3.99 | 476 | 170 | 305 |

* At time of vessel failure
** (triple loop, single loop not failed)
*** "Hydrogen Control Calculation for the Sequoyah Plant: Station Blackout Scenario," April 2002 draft report.

# Hydrogen Injected Through Pump Seals
# Run #21 (Reference $H_2$ Source Term)



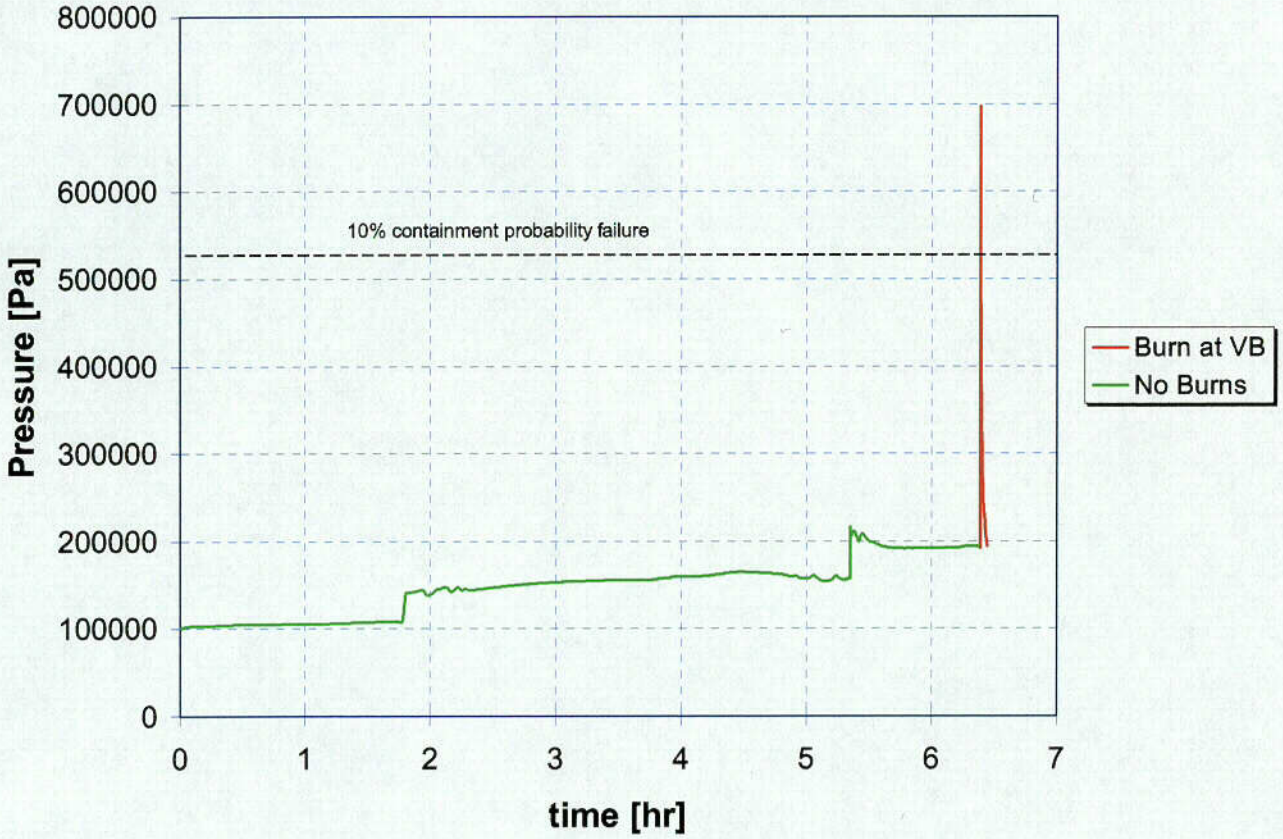
## Ignition and Propagation Limits used in MELCOR (default)

| Limits | X (H2)* | X (O2) | X (steam) |
|---|---|---|---|
| Ignition | >= 0.05 | >= 0.05 | <= 0.55 |
| Upward propagation | >= 0.041 | >= 0.05 | <= 0.55 |
| Horizontal propagation | >= 0.06 | >= 0.05 | <= 0.55 |
| Downward propagation | >= 0.09 | >= 0.05 | <= 0.55 |

## Igniter Locations used in the Sequoyah Containment Analysis

| Location | Igniters |
|---|---|
| Cavity | No |
| Steam Gen. Doghouses | Yes |
| Upper Reactor Space | Yes |
| Pressurizer Doghouse | Yes |
| Lower Containment (Inside Crane Wall) | Yes |
| Lower Annulus (Between Crane Wall and Shell) | Yes |
| Lower Plenum | No |
| Ice bed | No |
| Upper Plenum | Yes |
| Upper Dome | Yes |
| Lower Dome & Operating Floor | Yes |

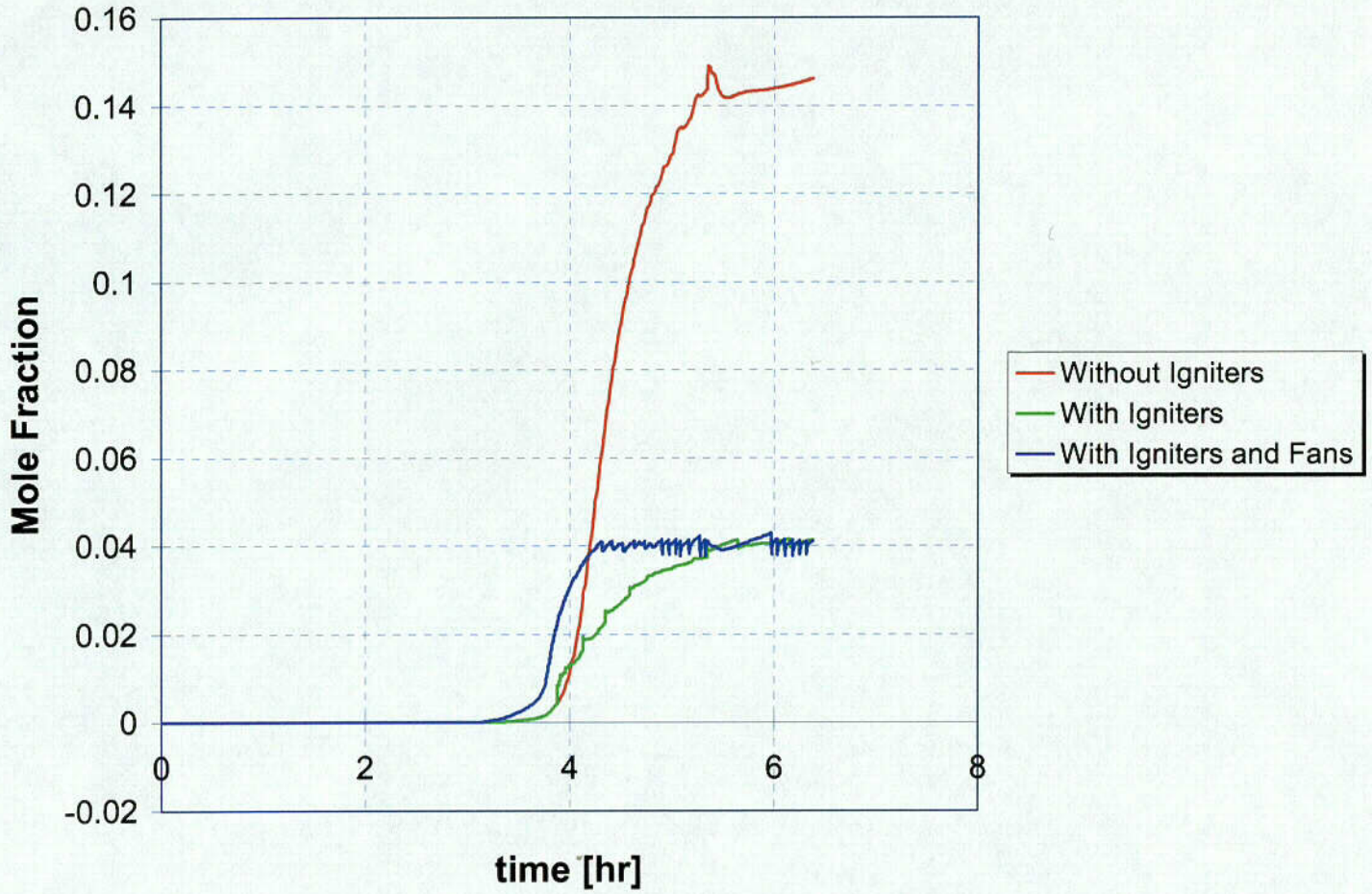
# Containment Pressure for Delayed Deflagration at Vessel Failure
# No Aux Power (Reference, Run #21 $H_2$ Source Term)






C02

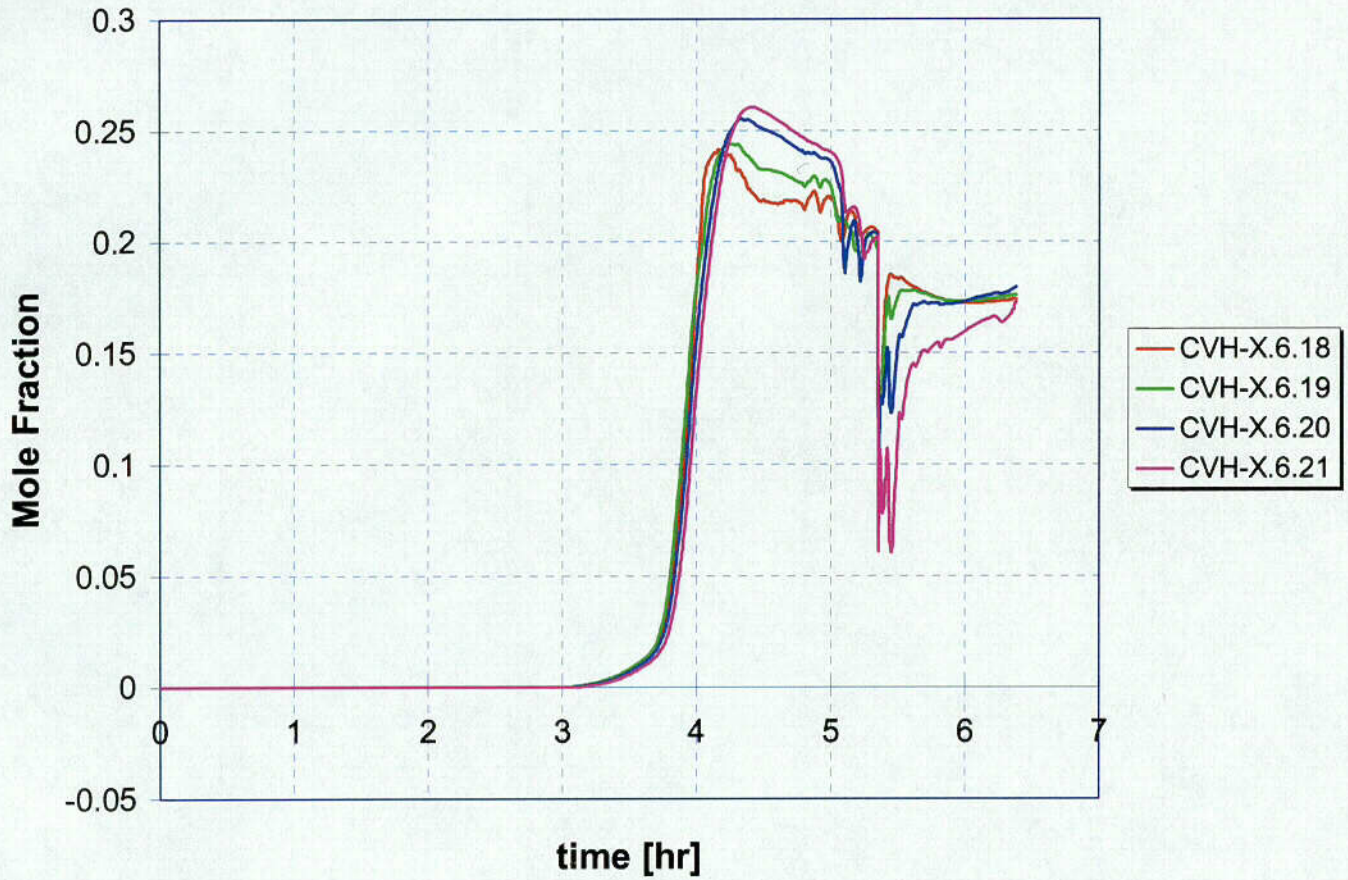
## Upper Containment Hydrogen Control for Aux. Power Options (Reference $H_2$ Source Term, Run #21)






C03

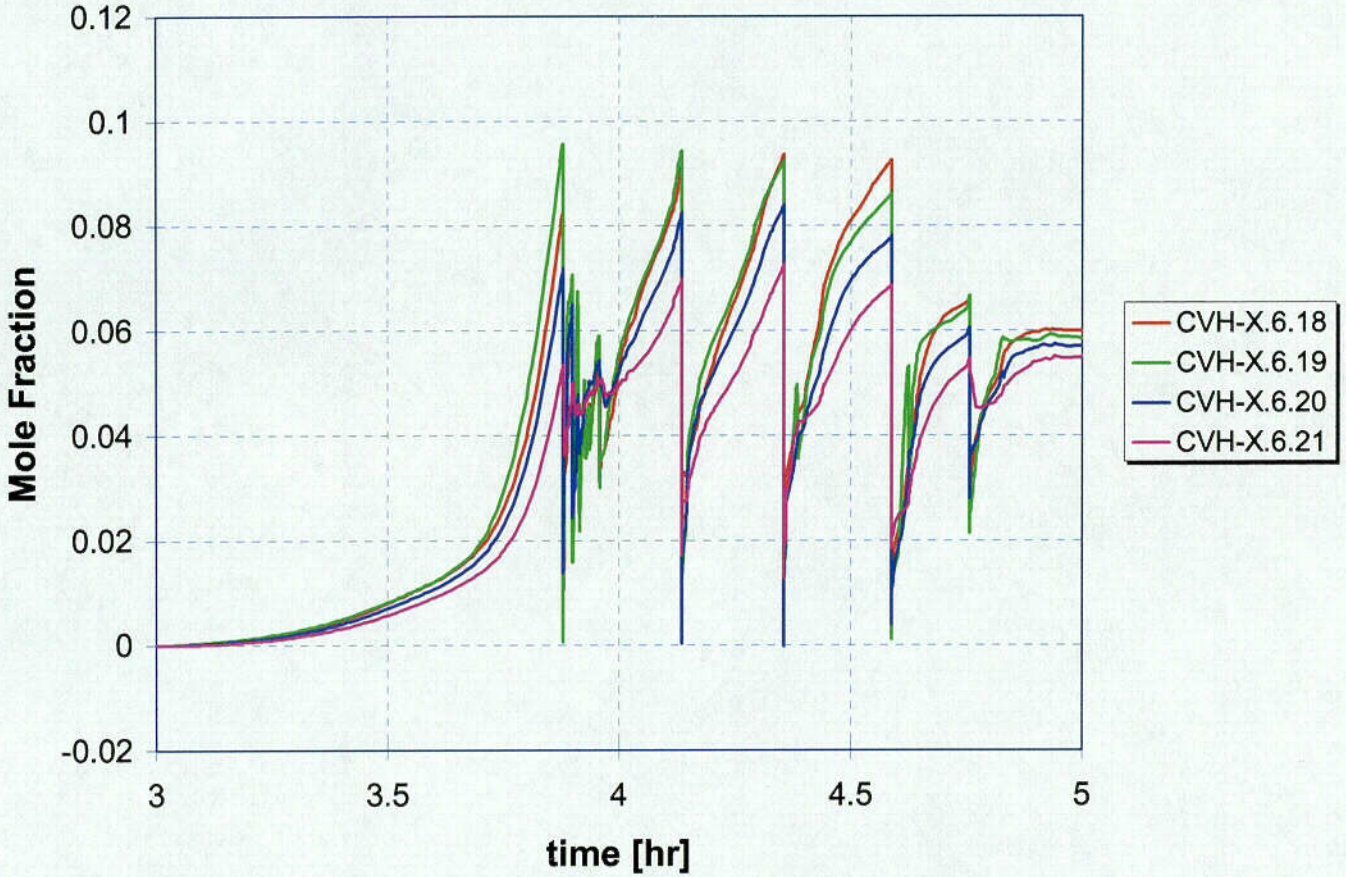
# Hydrogen Conc. in Ice Bed without Aux Power (Reference $H_2$ Source Term, Run #21)






C04

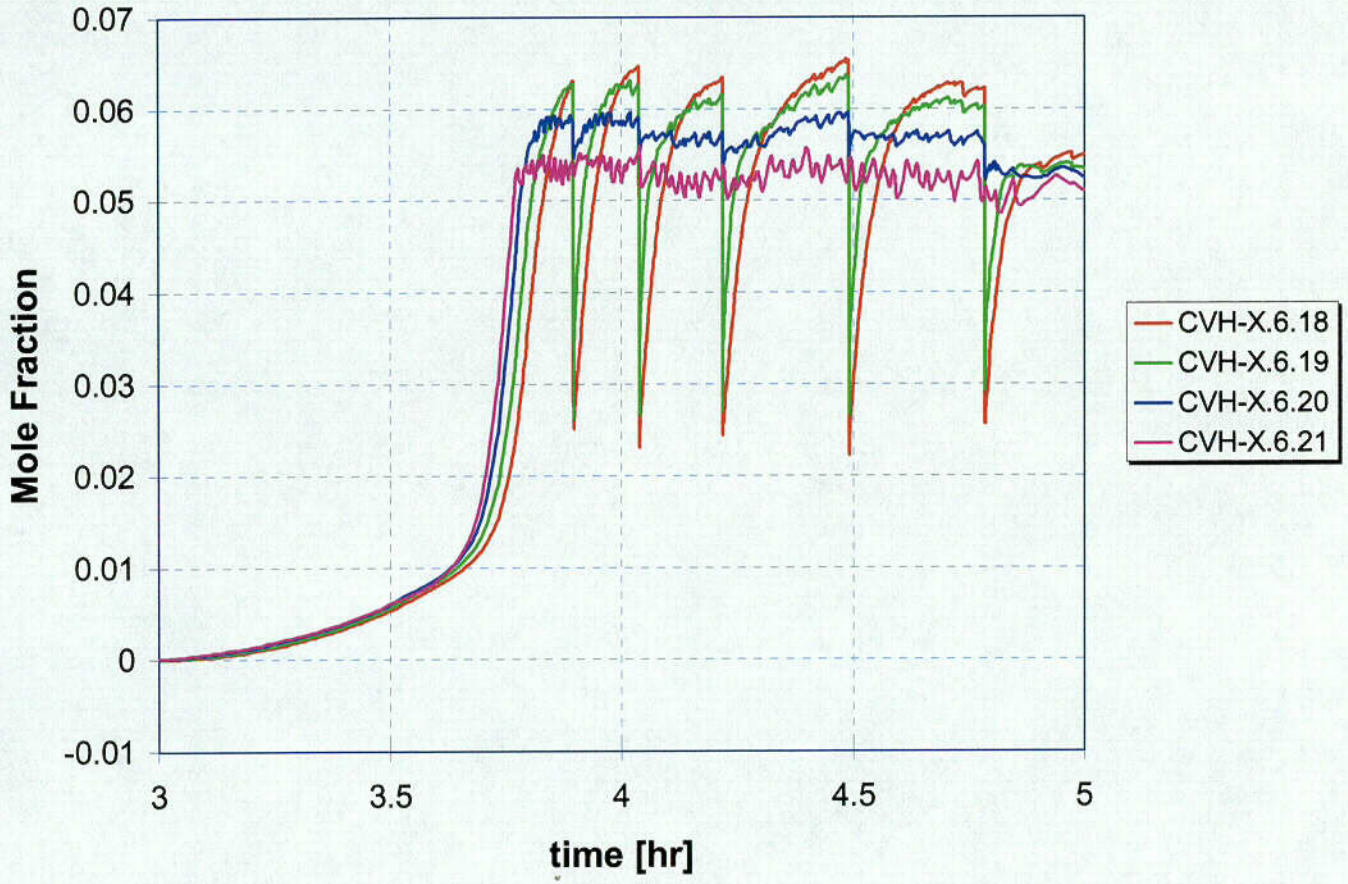
# Hydrogen Conc. in Ice Bed for Aux Power to Igniters (Reference $H_2$ Source Term, Run #21)






C05

# Hydrogen Conc. in Ice Bed for Aux Power to Igniters and Fans (Reference $H_2$ Source Term, Run #21)






C06

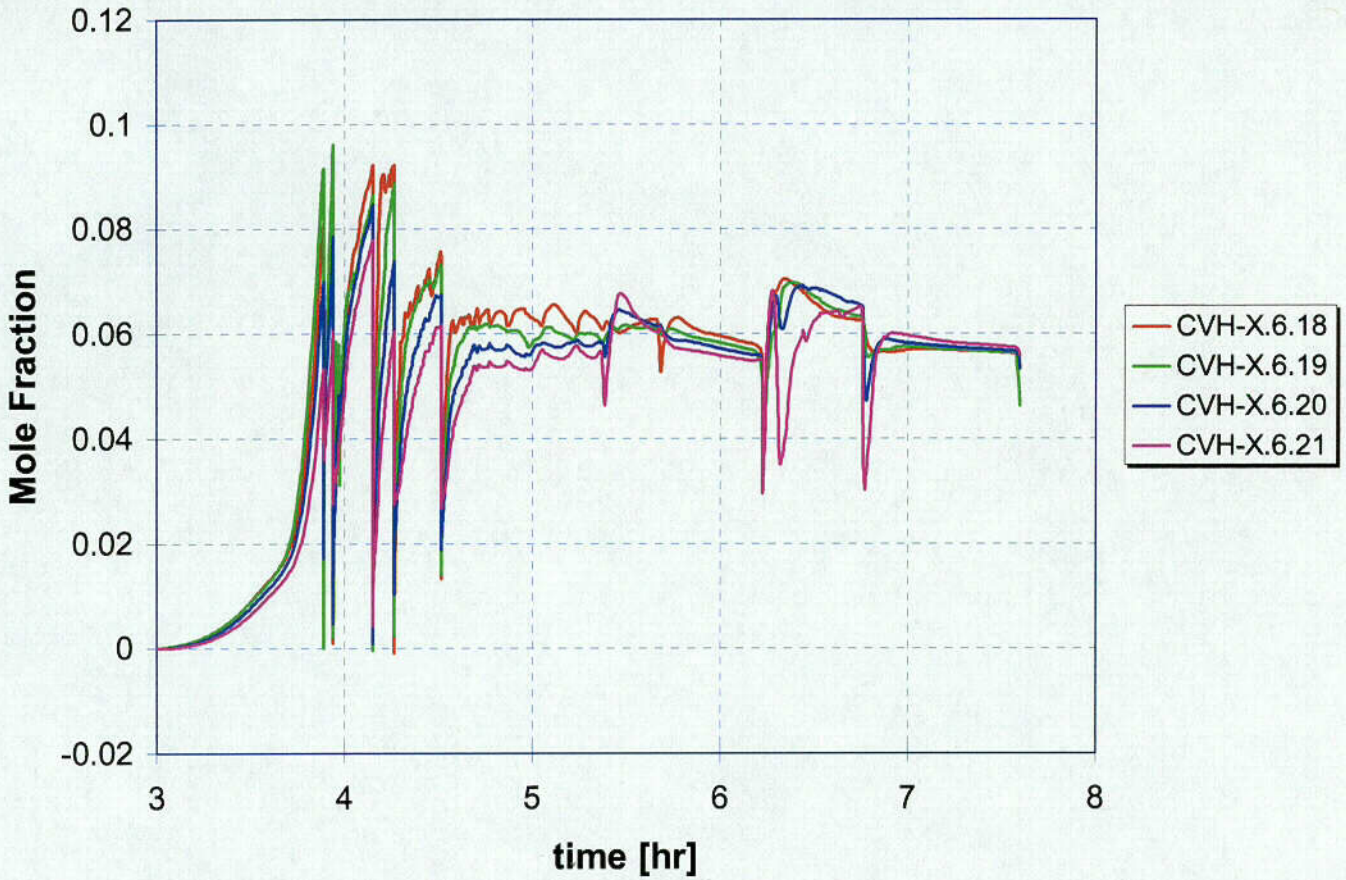
# Hydrogen Burned Locations for Reference $H_2$ Source Term

Table 5a. Hydrogen consumed in containment for period up to and including vessel breach (26-cell containment model), MELCOR run 21.*

| Location | Hydrogen consumed (kg) | |
|---|---|---|
| | Igniters only | Igniters and fans |
| Lower containment | 229 (58.2)** | 255.5 (61.4) |
| Ice condenser | 159 (40.4) | 105 (25.4) |
| Ice bed | 111.4 (28.3) | 25.9 (6.2) |
| Upper plenum | 18.2 (4.6) | 76.5 (18.4) |
| Lower plenum | 29.4 (7.5) | 2.7 (0.6) |
| Upper containment | 5.6 (1.4) | 55.4 (13.3) |
| Total | 393.6 | 416 |

* Total hydrogen released to containment up to and including vessel breach is ~ 570 kg.
** Percentage of burned

## Hydrogen Conc. in Ice Bed for Aux Power to Igniters (Low $H_2$ Source Term, Run #35)






C07

# Hydrogen Burn Behavior Sensitivity with Closed Refueling Drains

Table 6a. Hydrogen consumed in containment for period up to and including vessel breach (26-cell containment model) for MELCOR run 21, with no circulation through refueling drains.

| Location | Hydrogen consumed (kg) | |
|---|---|---|
| | Igniters only | Igniters and fans |
| Lower containment | 135 (35.4)** | 255.4 (60.9) |
| Ice condenser | 238 (62.5) | 104 (24.8) |
| Ice bed | 181.5 (13.5) | 20.5 (4.9) |
| Upper plenum | 13.5 (3.5) | 81.5 (19.4) |
| Lower plenum | 43 (11.3) | 2.0 (0.5) |
| Upper containment | 7.9 (2.1) | 60.0 (14.3) |
| Total | 380.9 | 419.4 |

* Total hydrogen released to containment up to and including vessel breach is ~ 570 kg.
** Percentage of burned

# Ice Melt Sensitivity to $H_2$ Source Term Uncertainty and Aux Power Options

Table 7. Ice melt percentage at time of vessel failure

| Source Term | Ice melt % | |
|---|---|---|
| | Igniters only | Igniters with fans |
| Run 21 | 46.7 | 64.2 |
| Run 32 | 37.5 | 51.2 |
| Run 35 | 46.1 | 64.9 |

# Direct Statistical Uncertainty for Burn Parameter Varations (Reference $H_2$ Source Term, Run #21)

Table 8. Deflagration parameter uncertainty range

| Parameter | Uncertainty Range, % | |
|---|---|---|
| | Low | High |
| Hydrogen conc limit for ignition with igniters | 5 (5)* | 7 |
| Max vapor conc for ignition | 45 (55) | 65 |
| Hydrogen conc limit for upward propagation | 3 (4.1) | 5 |
| Hydrogen conc limit for horizontal propagation | 5 (6) | 7 |
| Hydrogen conc limit for downward propagation | 7 (9) | 10 |

* (Default parameter)

Table 10. Maximum hydrogen concentration uncertainty interval (95%/95%) in Sequoyah containment for the STSBO_L accident event with igniters only

| Location | Concentration | |
|---|---|---|
| | 3.5 – 5 hrs (pump seals) | ~6.4 hrs (vessel failure) |
| Lower cont. (cell #9) | 14 – 16.6% | 3.2 – 4.6% |
| Ice bed (cell #19) | 9.5 – 14.7% | 3.5 – 7.9% |
| Upper cont. (cell #24) | 3 – 4.6% | 3.8 – 5.2% |

# Direct Statistical Sensitivity Study for Hydrogen Burn Parameters (Reference $H_2$ Source Term, Run #21)

Table 11. Spearman rank coefficients for the hydrogen burn parameter study at the 3.5 – 5 hour period (pump seals)

| Parameter | Rank coefficient | | |
|---|---|---|---|
| | Cell #9 | Cell #19 | Cell #24 |
| Hydrogen conc limit for ignition with igniters | 0.96 | 0.66 | 0.435 |
| Max vapor conc for ignition | -0.11 | -0.47 | -0.53 |
| Hydrogen conc limit for upward propagation | -0.14 | -0.07 | 0.19 |
| Hydrogen conc limit for horizontal propagation | 0.0068 | 0.03 | 0.35 |
| Hydrogen conc limit for downward propagation | 0.29 | 0.25 | 0.24 |

Table 12. Spearman rank coefficients for the hydrogen burn parameter study near the time of vessel failure ( ~ 6.4 hours)

| Parameter | Rank coefficient | | |
|---|---|---|---|
| | Cell #9 | Cell #19 | Cell #24 |
| Hydrogen conc limit for ignition with igniters | 0.29 | 0.57 | 0.41 |
| Max vapor conc for ignition | -0.20 | -0.012 | -0.1 |
| Hydrogen conc limit for upward propagation | 0.204 | -0.05 | 0.17 |
| Hydrogen conc limit for horizontal propagation | 0.12 | 0.14 | 0.26 |
| Hydrogen conc limit for downward propagation | 0.21 | 0.413 | 0.10 |

# Hydrogen Control Study for Sequoyah SBO Event Conclusions

- Hydrogen control required to mitigate severe threat to containment
- Either Aux. power to igniters or igniters and fans provides *adequate* control
- Aux power to igniters and fans produces more uniform burning throughout containment (with more burning at igniter locations)
- Aux power to igniters and fans causes a more rapid depletion of ice (e.g., ~ 37% increase in ice melt at vessel failure with power to fans)
- $H_2$ source term uncertainty is not a significant factor affecting hydrogen control (e.g., aux. power options)
- Circulation of upper containment air through refueling drains can significantly affect the degree of lower containment burning (elimination of circulation reduces lower compartment burns as a result of oxygen depletion and steam inerting); however, hydrogen control remains effective.
- Statistical uncertainty analysis for burn parameters indicated ice bed as the more sensitive region for hydrogen control uncertainty (ice bed hydrogen conc. for power to igniters only, uncertainty range 9.5 – 14.7% )