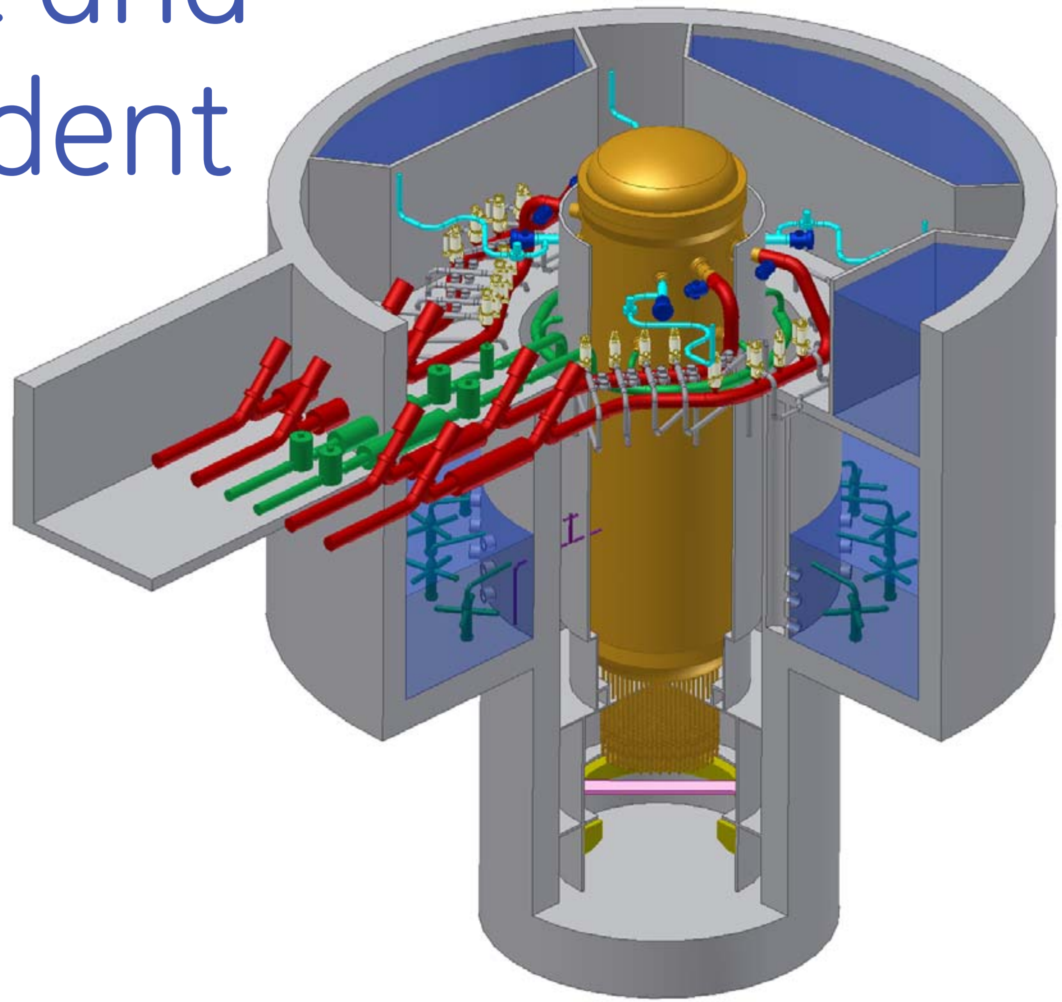
ESBWR Probabilistic Risk Assessment and Severe Accident Treatment



September 29, 2005

Rick Wachowiak

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Overview

Organization of the Documents

Objectives of the PRA

Level 1

Shutdown

External Events

Severe Accident Phenomena Treatment

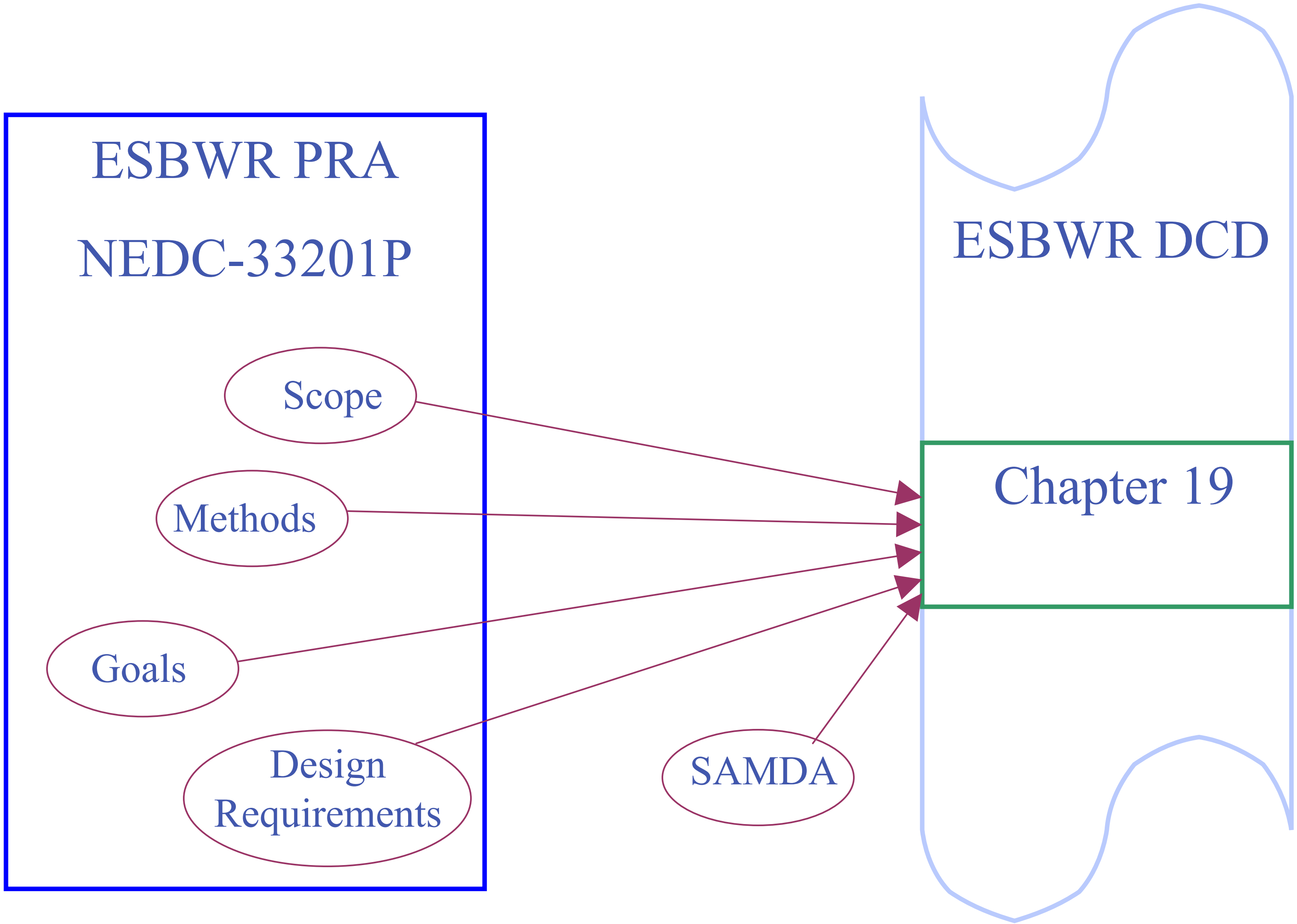
Level 2

Level 3

Regulatory Treatment of Non-Safety Systems

Review of Issues

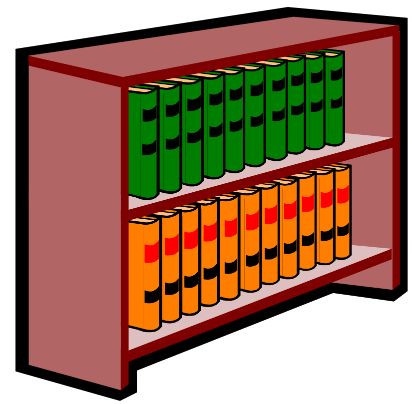
Document Relationships



Document Lifecycle

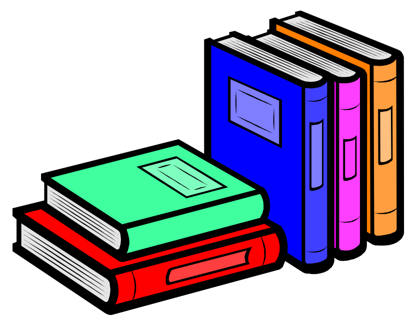
DCD

FSAR



Now → Future

NEDC-33201



Plant PRA

Use of Probabilistic Risk Assessment

Industry and NRC Use PRA to the Max Extent

Examples of Applications:

> Design change optimization
> Operational decisions
> Technical specifications

Certification Design is One Such Application

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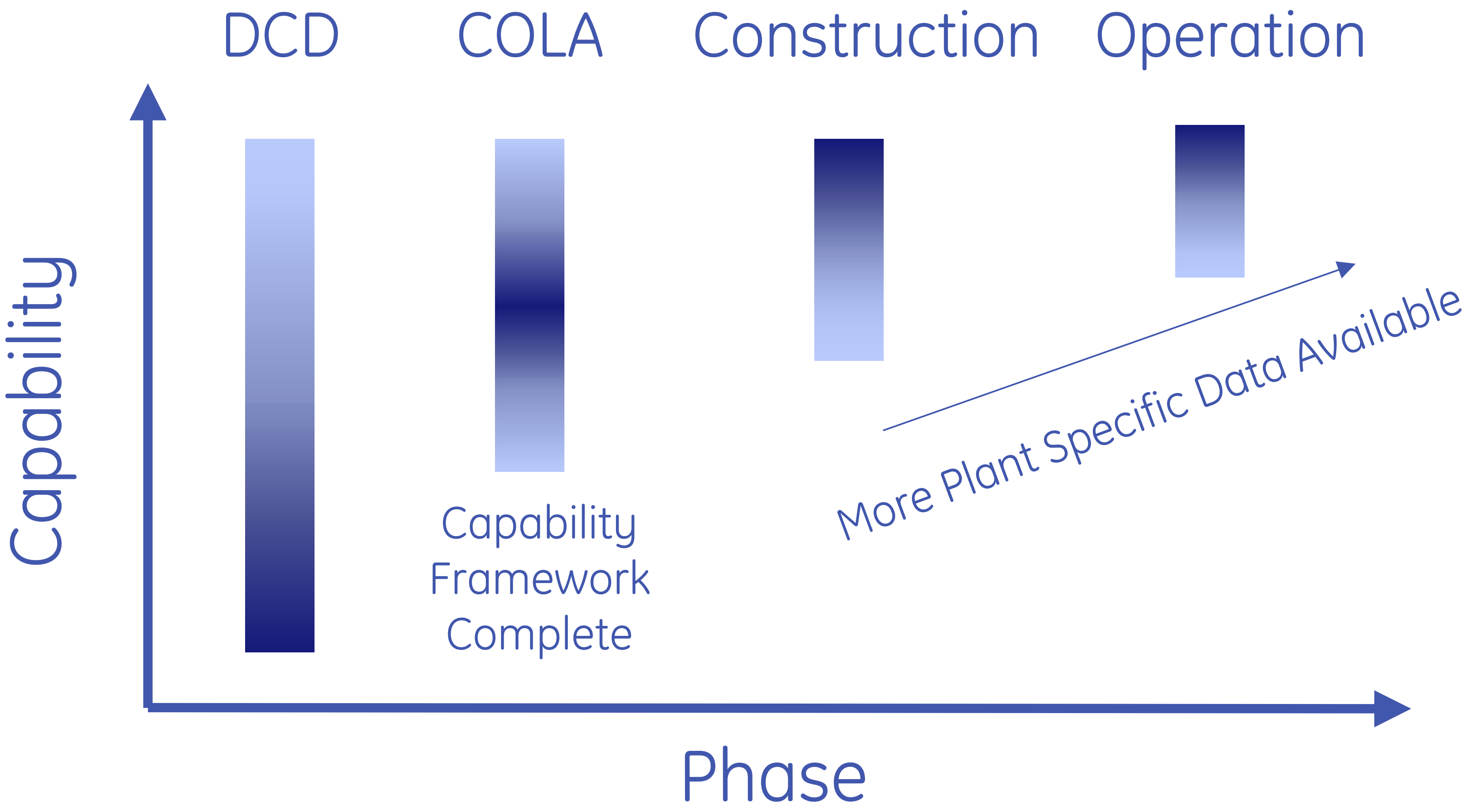
Vision of ESBWR PRA



DCD PRA Capability

Ensure Better Risk Performance than Existing Plants

Eliminate Severe Accident Vulnerabilities from the Design

Determine that ESBWR Meets Risk Goals

- CDF, LRF, Radiological Consequences

Determine Which Systems Require RTNSS

Determine Importance of Operator Actions

Attributes that Limit Capability

This is a Reality in DCD Phase

- Bounding initiating events
- Generic data
- Support system assumptions
- Design basis conservatisms
- Screening analyses

Future ESBWR PRA

Advance State of the Art

Fully Integrate all Models

Incorporate Information for As Built As Operated Plant in Later Phases

COL Applicant Will Fill in Details

> Site Data
> Design / Construction Details
> Procedures
> Component Data

Some expected uses:

- Maintenance Rule
- Risk Informed AOT
- Outage Management
- Operational Decisions

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PRA Scope

Internal Events, Power Operation
> Level 1, 2, and 3

Internal Events, Shutdown
> Level 1
> 99% SDCDF in mode 6, so no level 2 required

External Events (non-Seismic)
> Screening shows no impact on risk

Seismic
> Seismic margins analysis identified no outliers

Definitions

Core Damage

- PCT > 2200 °F (calculated by TRACG)
- Core Uncovered (estimated by hand calc, MAAP, other)

Containment Failure

- Uncontrolled Release
- Venting Release

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Initiators

Transients

- General
- Loss of Condenser
- Loss of Feedwater
- IORV
- Loss of Offsite Power

Special Initiators

Loss of Coolant Accidents

- Large Steam
- Medium / Small Steam
- Medium Liquid
- Small Liquid
- Break Below Core
- Break Outside Containment
- Vessel Rupture

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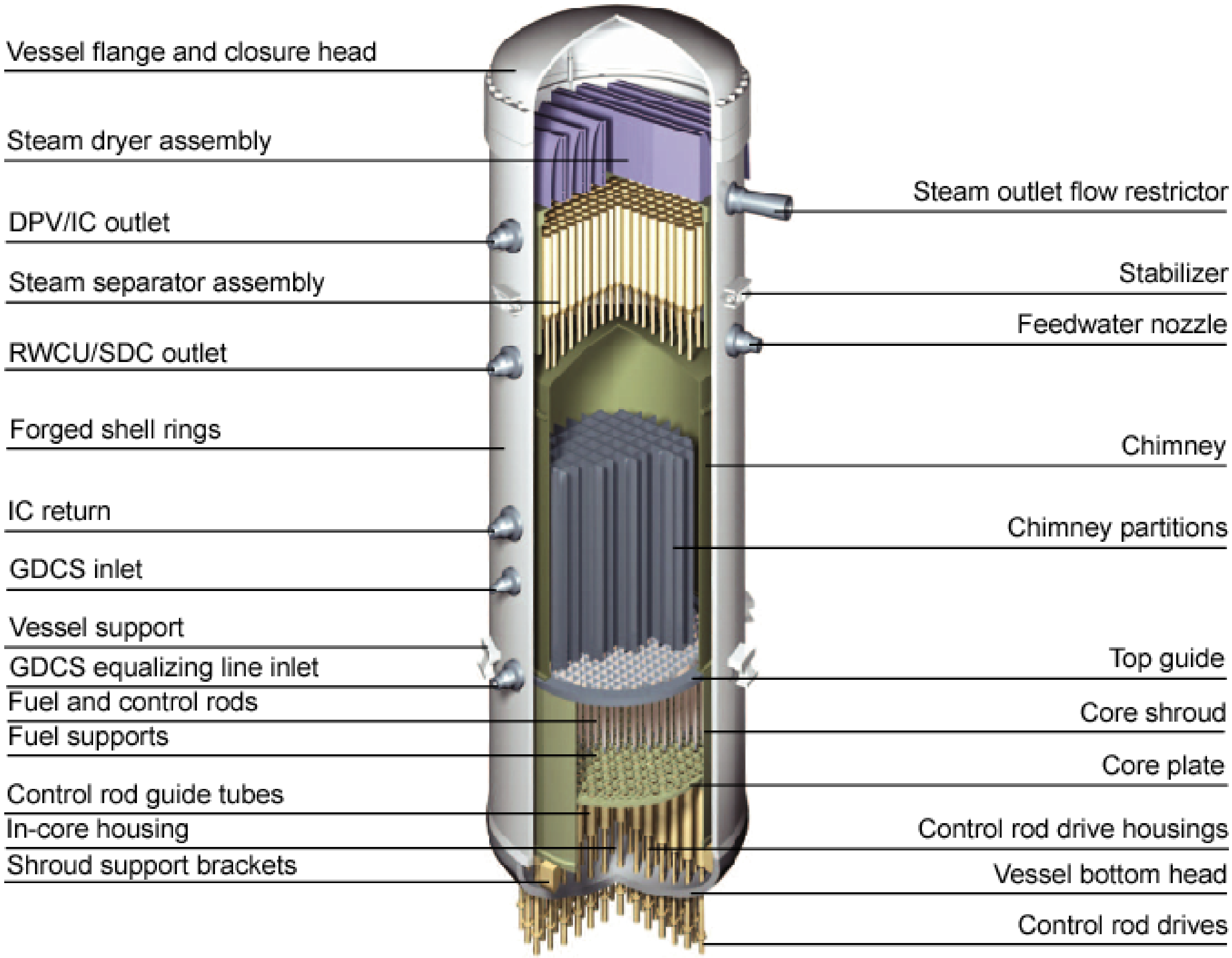
Initiator Values

Relied on NUREG 5750

Considered Bounding

Only Eliminated Contributions that are N/A


Vessel flange and closure head
Steam dryer assembly
DPV/IC outlet
Steam separator assembly
RWCU/SDC outlet
Forged shell rings
IC return
GDCS inlet
Vessel support
GDCS equalizing line inlet
Fuel and control rods
Fuel supports
Control rod guide tubes
In-core housing
Shroud support brackets
Steam outlet flow restrictor
Stabilizer
Feedwater nozzle
Chimney
Chimney partitions
Top guide
Core shroud
Core plate
Control rod drive housings
Vessel bottom head
Control rod drives

Summary of Lines Connected To RPV And Quantification Of Frequency Apportionment

ID	Line	Length (m)	No. Lines	No. Sections	Apportionment Method: By Length[1]	Apportionment Method: By No. Lines[2]	Apportionment Method: By No. Sections[3]	Final Frequency[4] (events/yr)	Notes
a	Main Steam (MSL)	92	4	44	6.22E-6	4.44E-6	4.13E-6	4.93E-6	Large Steam break
b	DPV/IC	70	4	64	4.73E-6	4.44E-6	6.01E-6	5.06E-6	Large Steam break
d	FW	95	8	74	6.42E-6	8.89E-6	6.95E-6	7.42E-6	Large Steam break
e	RWCU/SDC	39	2	31	2.64E-6	2.22E-6	2.91E-6	2.59E-6	Large Steam break
f	IC return lines	12	4	40	2.83E-6	5.45E-6	8.96E-6	5.75E-6	Medium Liquid break
g	GDCS	44	8	32	1.04E-5	1.09E-5	7.16E-6	9.49E-6	Medium Liquid break
g1	Equalizing lines	11	4	12	2.60E-6	5.45E-6	2.69E-6	3.58E-6	Medium Liquid break
h	RWCU/RPV Drainlines	20	4	20	4.72E-6	5.45E-6	4.48E-6	4.89E-6	Medium Liquid break
i	SLCS	40	2	30	9.45E-6	2.73E-6	6.72E-6	6.30E-6	Medium Liquid break
j	Instrument lines above L3	50	4	100	1.14E-4	1.14E-4	1.14E-4	1.14E-4	Small Steam break
j1	Instrument lines below TAF	75	6	150	1.71E-4	1.71E-4	1.71E-4	1.71E-4	Small Liquid break
j2	Instrument lines above TAF and under L3	50	4	100	1.14E-4	1.14E-4	1.14E-4	1.14E-4	Small Liquid break

Attribution of Line Frequencies To LOCA Categories

LOCA Category	Contributors[1, 2]	Frequency (events/yr)
Large steam LOCA (no FW line break)	a + b + e + (A)	3.33E-4
Large steam LOCA in FW line	d	7.42E-6
Medium liquid LOCA (no RWCU break)	f + g + g1 + i	2.51E-5
Medium liquid LOCA in RWCU	h	4.89E-6
Small steam LOCA	j + (B)	6.04E-4
Small liquid LOCA (no RWCU break)	j2	1.14E-4
Small liquid LOCA in RWCU	j1	1.71E-4
Main Steam Line Break (Outside Containment)	--	3.00E-3
Feedwater Line Break (Outside Containment)	--	3.40E-3
RWCU Line Break (Outside Containment)	--	3.40E-3
IC Line Break (Outside Containment)	--	5.06E-6

(A) = Spurious ADS 3.2×10^{-4}

(B) = One DPV Open 4.9×10^{-4}

Comparison of ESBWR PRA Internal Events Initiating Event Frequencies to Other Studies

Initiating Event	Frequency (per year)				
	ESBWR PRA	EPRI ALWR URD	NUREG/CR-3862	NUREG/CR-4832	NUREG/CR-4550
Transients					
Generic Transient	1.30	2.3E+1	6.4E+1	4.5E+1	2.5E+1
Transient with PCS Unavailable	3.74E-1	4.9E-1	6.8E-1	1.54E+1	5.0E-2
Loss of Feedwater	9.25E-2	3.7E-1	7.0E-2	6.0E-1	6.0E-2
IORV	4.60E-2	n/a	1.4E-1	1.4E-1	1.9E-1
Loss of Preferred Power (LOPP)	4.60E-2	3.5E-2	8.0E-2	9.6E-2	7.9E-2
LOCAs Inside Containment					
Large Steam LOCA (no FW line break)	3.33E-4	5.8E-4	n/a	1.0E-4	1.0E-4
Large Steam LOCA in FW line	7.42E-6				
Medium Liquid LOCA (no RWCU break)	2.51E-5	n/a	n/a	3.0E-4	3.0E-4
Medium Liquid LOCA in RWCU	4.89E-6				
Small Steam LOCA	6.04E-4	5.1E-3	n/a	3.0E-2	3.0E-3
Small Liquid LOCA (no RWCU break)	1.14E-4				
Small Liquid LOCA in RWCU	1.71E-4				
LOCAs Outside Containment					
Main Steam Line Break (Outside Containment)	3.30E-3	n/a	n/a	n/a	n/a
Feedwater Line Break (Outside Containment)	3.40E-3				
RWCU Line Break (Outside Containment)	3.40E-3				

Special Initiators Considered

Loss of Systems

> CRD
> RWCU
> SLCS
> Single Bus
> Etc.

Spurious Actuations

Event Trees

See 11 x 17 Handouts

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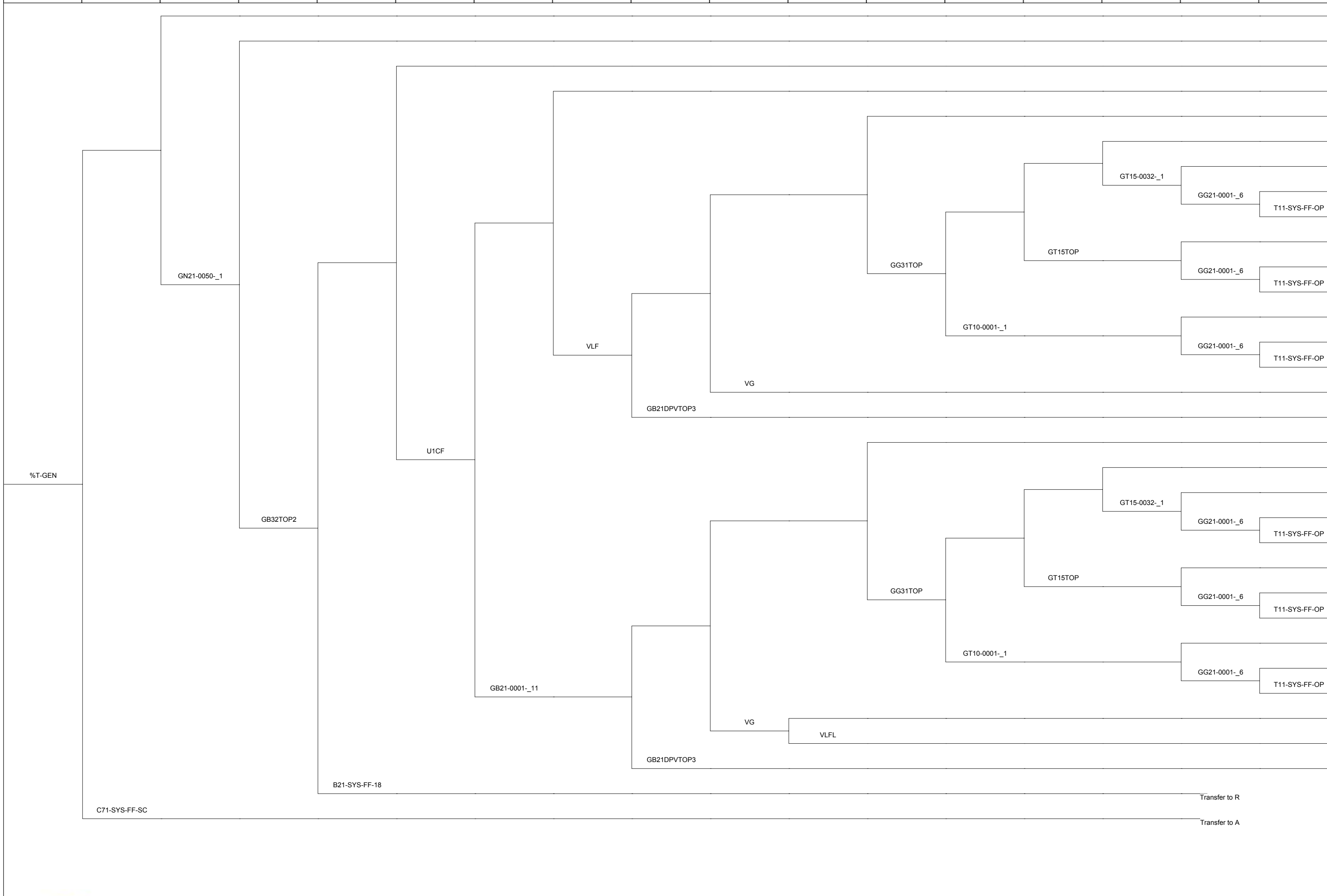
General Transient

T-GEN	C	TPCS	I	M	U1CF	XS2	VLF	ADS	VG	VLFL	WH	DL	WP	WT	WLL	WC	Class	Name
Generic Transient	(RPS or ARI) and CRM	BYPASS and 1/4 FDW	3/4 IC	1/18 SRV	1/2 CRD or 1/2 FDW	2 SRV	1/2 FAPCS or 1/1 FPS injection	4 DPVs	2/8 lines and (2/3 GDCS pools or 1/3 GDCS pools and 1/4	1/2 FAPCS or 1/1 FPS inyection after ADS	1/2 RWCU/SDC	All VB closed	4/6 PCCS	Long Term PCC pools inventory	1/2 FAPCS pool cooling after DESP	CIS vent		



Class	Name
OK	T-GEN001
OK	T-GEN002
OK	T-GEN003
OK	T-GEN004
OK	T-GEN005
OK	T-GEN006
OK	T-GEN007
CO	T-GEN008
CDII	T-GEN009
OK	T-GEN010
CO	T-GEN011
CDII	T-GEN012
OK	T-GEN013
CO	T-GEN014
CDII	T-GEN015
CDI	T-GEN016
CDIII	T-GEN017
OK	T-GEN018
OK	T-GEN019
OK	T-GEN020
CO	T-GEN021
CDII	T-GEN022
OK	T-GEN023
CO	T-GEN024
CDII	T-GEN025
OK	T-GEN026
CO	T-GEN027
CDII	T-GEN028
OK	T-GEN029
CDI	T-GEN030
CDIII	T-GEN031
RVR	T-GEN032
ATWS	T-GEN033

Loss of Preferred Power

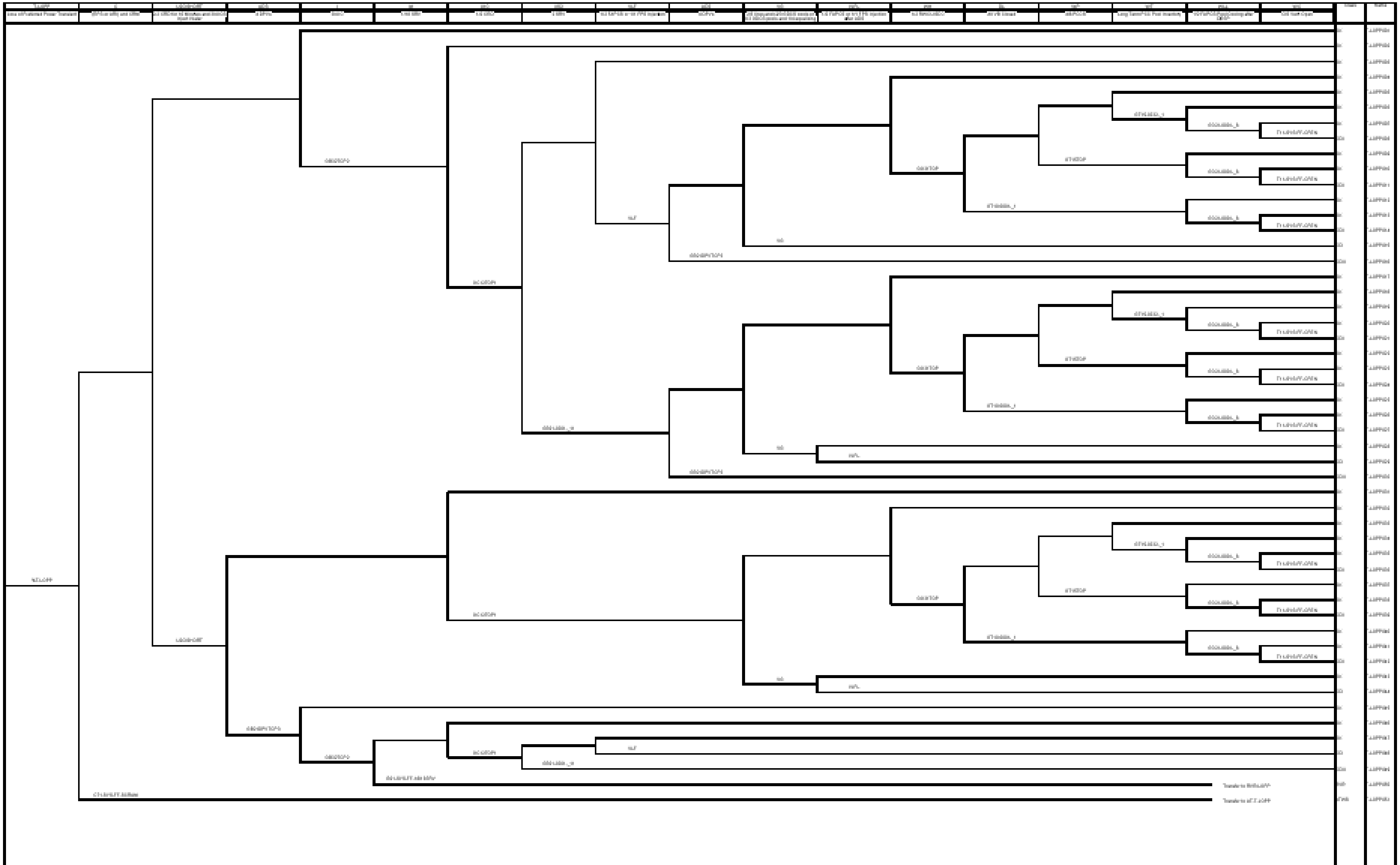
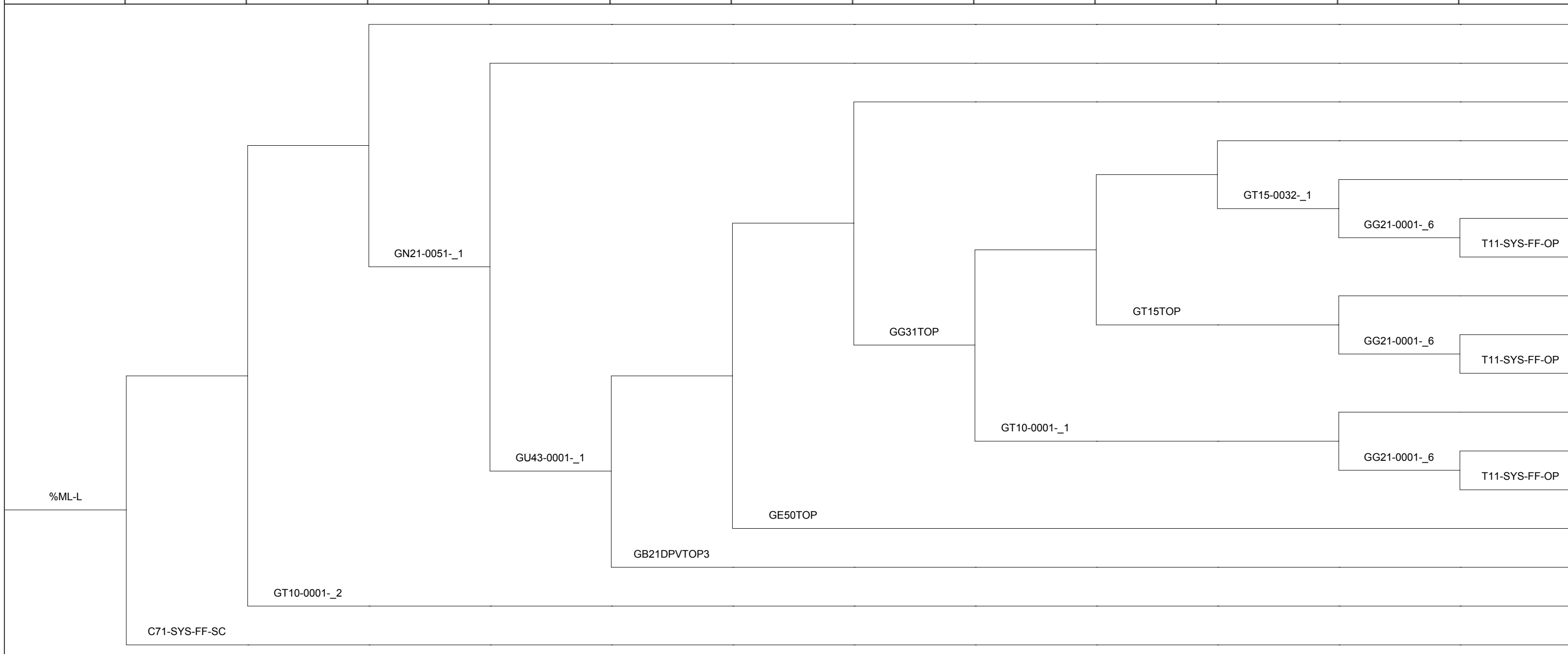


Figure 5. Loss of Preferred Power Transient | \Rick Wachowiak\ESBWR\Quant_Internal\ETs\T-LOPP.e | 9/28/2005 | Page 1

Medium Liquid LOCA
GDCS Line Break

ML-L	C	DS	UF	VF	ADS	VG2	WH	DL	WP	WT	WLL	WC
Medium LOCA not in RWCU	(RPS or ARI) and CRM	Steam suppression system	1/2 FDW	1/1 FPS injection	4 DPVs	2/8 lines, 2/3 GDCS pools and 1/4 equilizing lines	1/2 RWCU/SDC	All VB Closed	4/6 PCCS	Long Term PCC pools inventory	1/2 FAPCS pool cooling after DESP	CIS vent



Class	Name
OK	ML-L-001
OK	ML-L-002
OK	ML-L-003
OK	ML-L-004
OK	ML-L-005
CO	ML-L-006
CDII	ML-L-007
OK	ML-L-008
CO	ML-L-009
CDII	ML-L-010
OK	ML-L-011
CO	ML-L-012
CDII	ML-L-013
CDI	ML-L-014
CDIII	ML-L-015
CDII	ML-L-016
CDIV	ML-L-017

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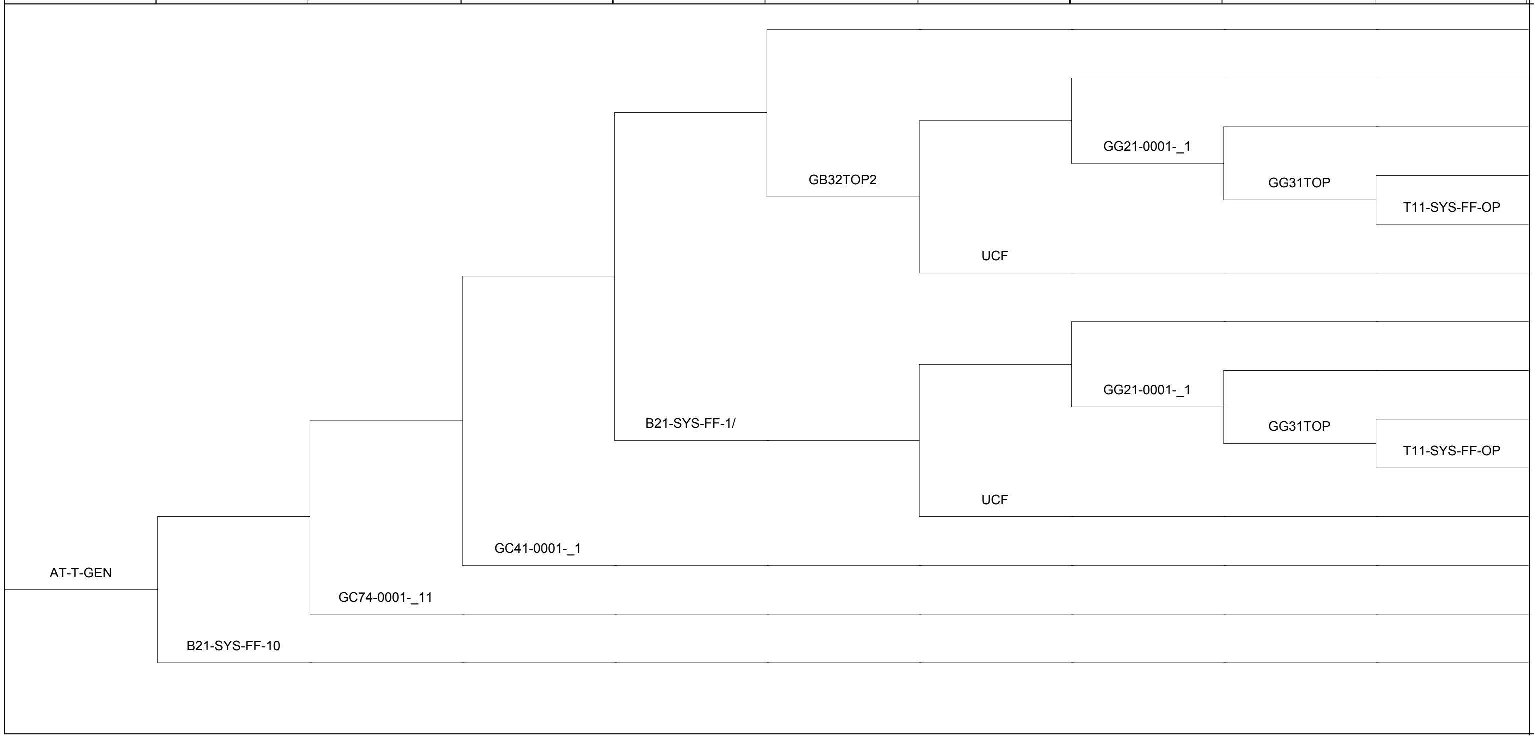
General Transient ATWS

AT-T-GEN	MA	IA	SL	PA	I	UCF	WL	WHA	WC	Class	Name
ATWS after Generic Transient	9/18 SRV's	ADS Inhibition	2/2 SLCS	All SRV Close	3/4 IC	2/2 CRD or 1/2 FDW	1/2 FAPCS pool cooling	1/2 RWCU/SDC	CIS vent		



Class	Name
OK	AT-T-GEN001
OK	AT-T-GEN002
OK	AT-T-GEN003
CO	AT-T-GEN004
CDII	AT-T-GEN005
CDIII	AT-T-GEN006
OK	AT-T-GEN007
OK	AT-T-GEN008
CO	AT-T-GEN009
CDII	AT-T-GEN010
CDI	AT-T-GEN011
CDIV	AT-T-GEN012
CDIV	AT-T-GEN013
CDIV	AT-T-GEN014

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Systems Modeled

B21	Depressurization	yes
B32	Isolation Condenser	yes
C12	Control Rod Drive	yes
C21	Leak Detection and Isolation	no (incl in T10)
C31	Feedwater Control System	no (incl in N21)
C41	Standby Liquid Control	yes
C62	Instrument and Control	yes
C71	Reactor Protection System	point estimate
C74	Safety System Logic and Control	no (incl in C62)
E50	Gravity Driven Cooling System	yes
G21	Fuel & Aux Pool Cooling System	yes
G31	Reactor Water Cleanup	yes
N21	Feedwater and Condensate	yes
N37	Turbine Bypass	point estimate
N71	Circulating Water	no (incl in N21)
P21	Reactor Component Cooling Water	yes

P22	Turbine Component Cooling Water	no (incl in N21)
P41	Plant Service Water	yes
P51	Service Air System	no (incl in P52)
P52	Instrument Air	yes
P54	High Pressure Nitrogen	yes
R10	13.8 kV Power Distribution	yes
R11	69 kV Power Distribution	no (incl in R10)
R12	480 V Power Distribution	no (incl in R10)
R13	Uninteruptable AC Power	yes
R14	I&C Power Supply	no (incl in R10)
R16	250 V DC Power	yes
R21	Standby Emergency Power	no (incl in R11)
T10	Containment Isolation	yes
T11	Containment Overpressure Protection	point estimate
T15	Passive Containment Cooling	yes
T49	Flamability Control System	no
U43	Fire Protection System	no (incl in G21)

System Considerations

SCRAM Function

- Used point estimate
- ABWR model used
- GE will include this model in future rev of DCD

Containment Overpressure Protection

- Venting
- Dominated by operator action

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System Considerations (Service Water)

Service Water Systems

- Final configuration at COL
- Final model at COL
- Modeled conservatively in DCD using high level design requirements
  - Single failure proof, so 2 failures (one in each train) fails system
  - Failure of air will not fail system
  - Trains are separated

System Considerations (C&I)

These Systems Specified Late in DCD Process

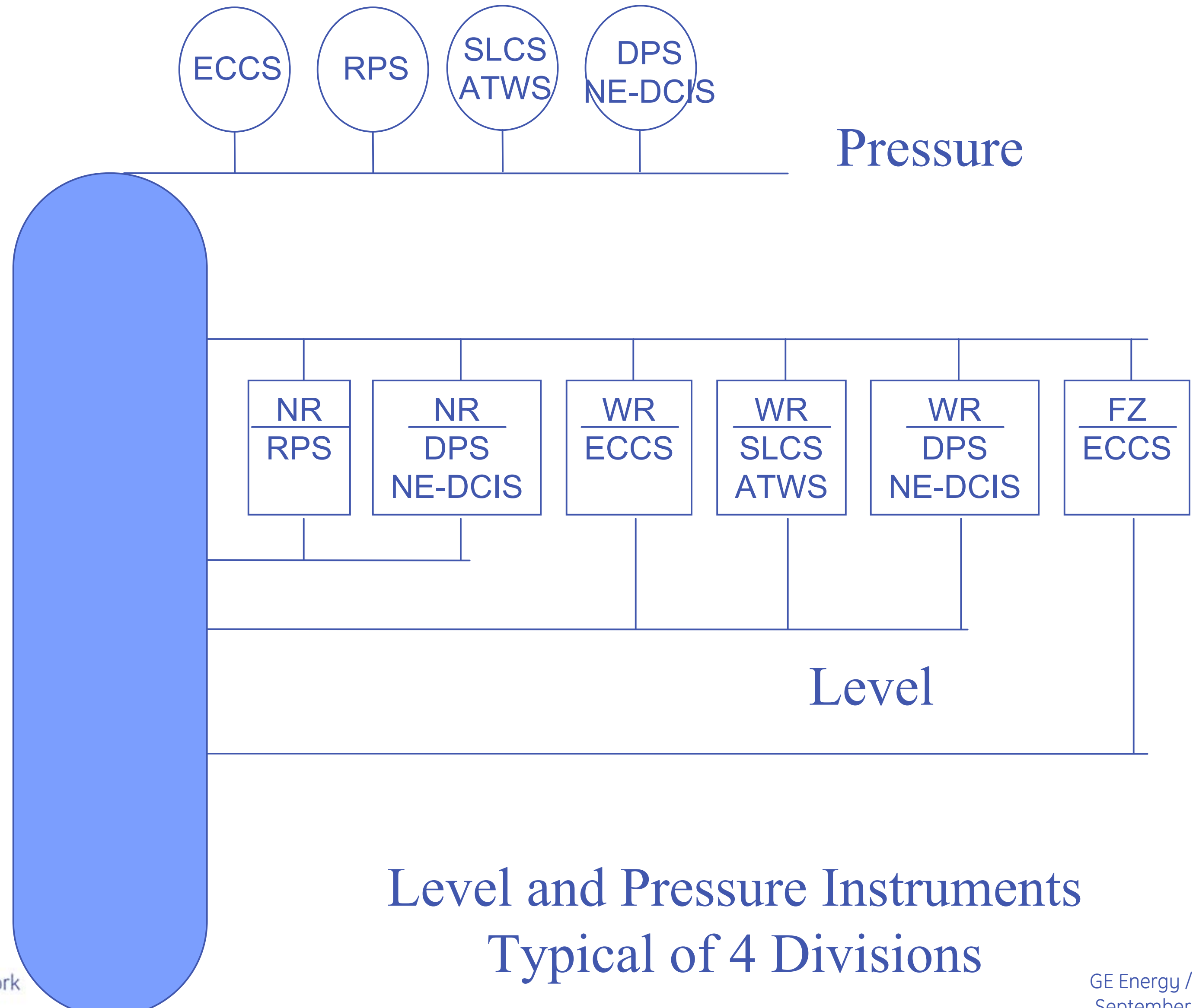
PRA Uses Simplified Representation

Captures All Failure Modes and Dependences

Includes Software Failure as Applicable

C&I Representation is Bounding

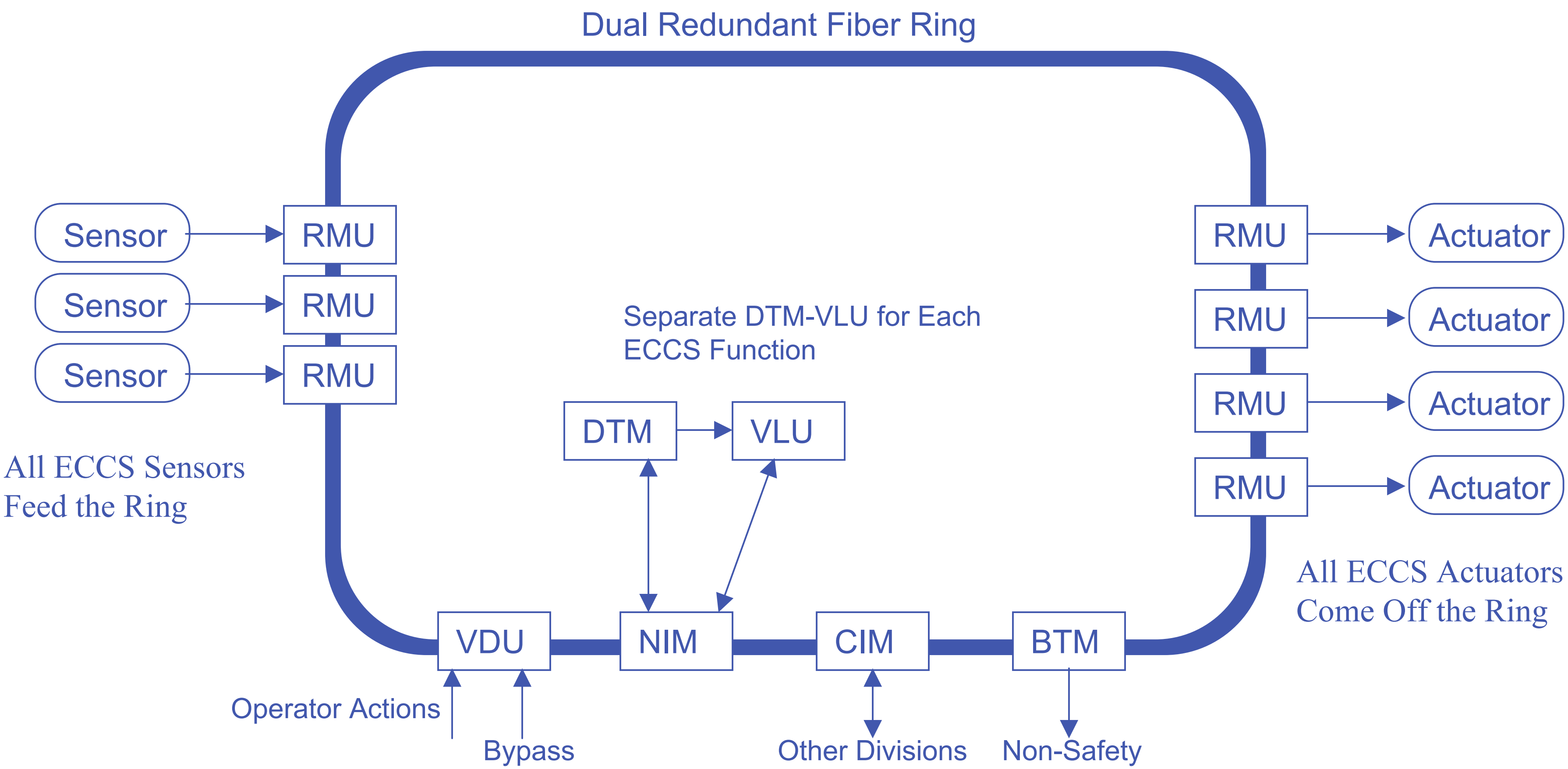
Sensor Breakdown



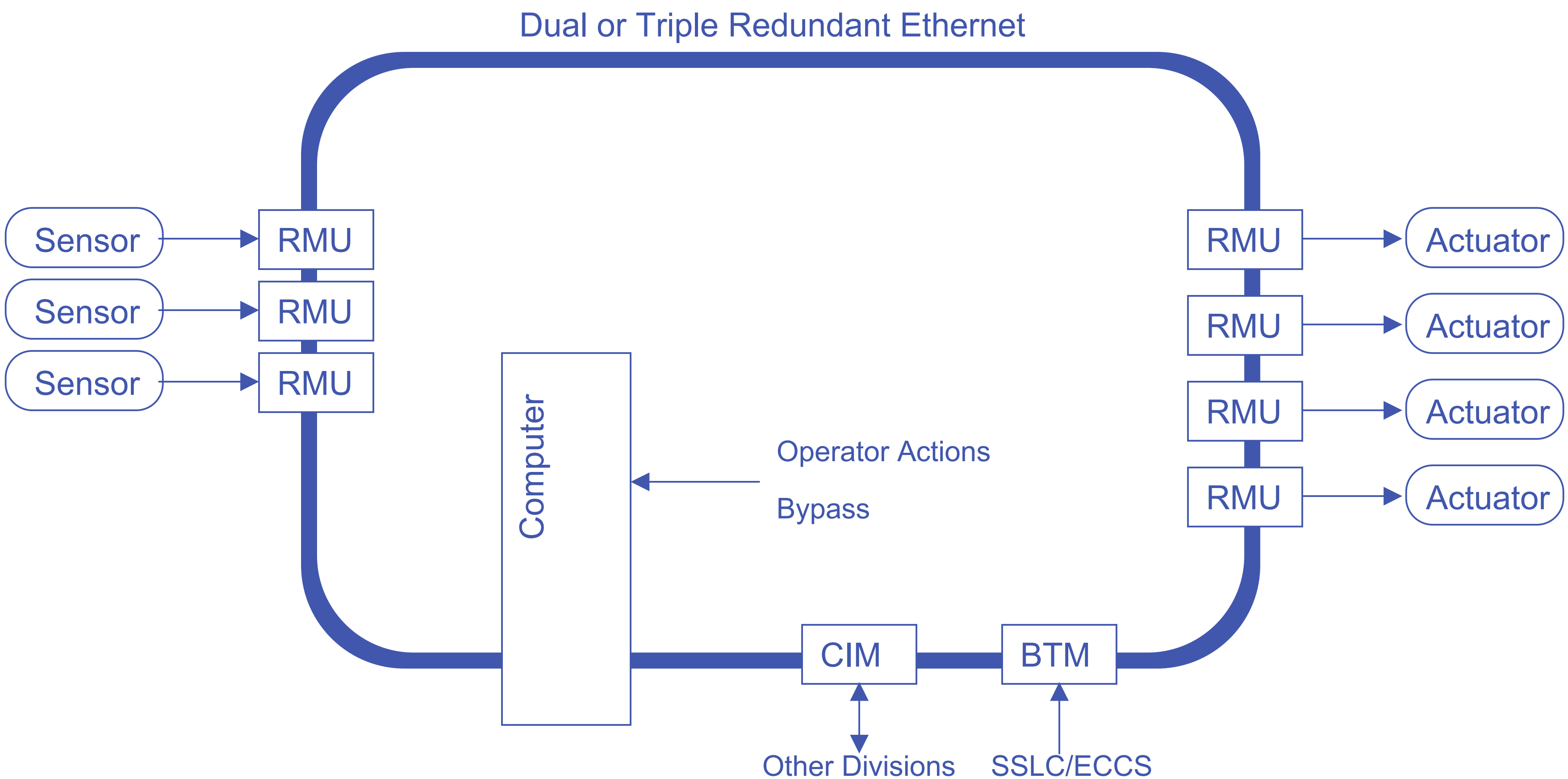
Level and Pressure Instruments
Typical of 4 Divisions

ECCS Information Routing Typical of 4 Divisions

Assume SSLC/RTIF-ATWS and DPS are organized in a similar manner with diverse components



NE Information Routing
Typical of RTNSS-A, RTNSS-B, and BOP



These modules don't really exist
The ethernet takes case of it

System Considerations (DPS)

DPS Specified Late in Design

Partly in Response to PRA Insights

Not Included in DCD Model

Instead, PIP Assumed to Provide DPS Function

Conservative Treatment

Cannot Quantify Importance of DPS

Simplified Drawings

Discrepancies With Tier 2

- Some Support Systems From Previous Revision
- Component Names Different

Support System Treatment is Bounding

Component Names Will be Changed

Basic Event Data

Generic Data Used

Generally from URD

Equipment in Harsh Environments Increased

- Example: GDCS Squib Valves

Failure Rates Increased for Components with Long Test Intervals

Human Actions

Pre-Accident

> e.g. Misposition of valves following maintenance

Post-Accident

> e.g. Backup of automatic actuation

Screening Values Used

Chapter 6 Deficiencies

"Preliminary" vs "Future" Designation

- Preliminary = Screening included in DCD
- Future = Detailed analysis to reduce values (COL)

Table 6-3b

- Provide basis for all timing used in screening values

Identify List of Actions that Require Procedures

- Include in DCD Chapter 19

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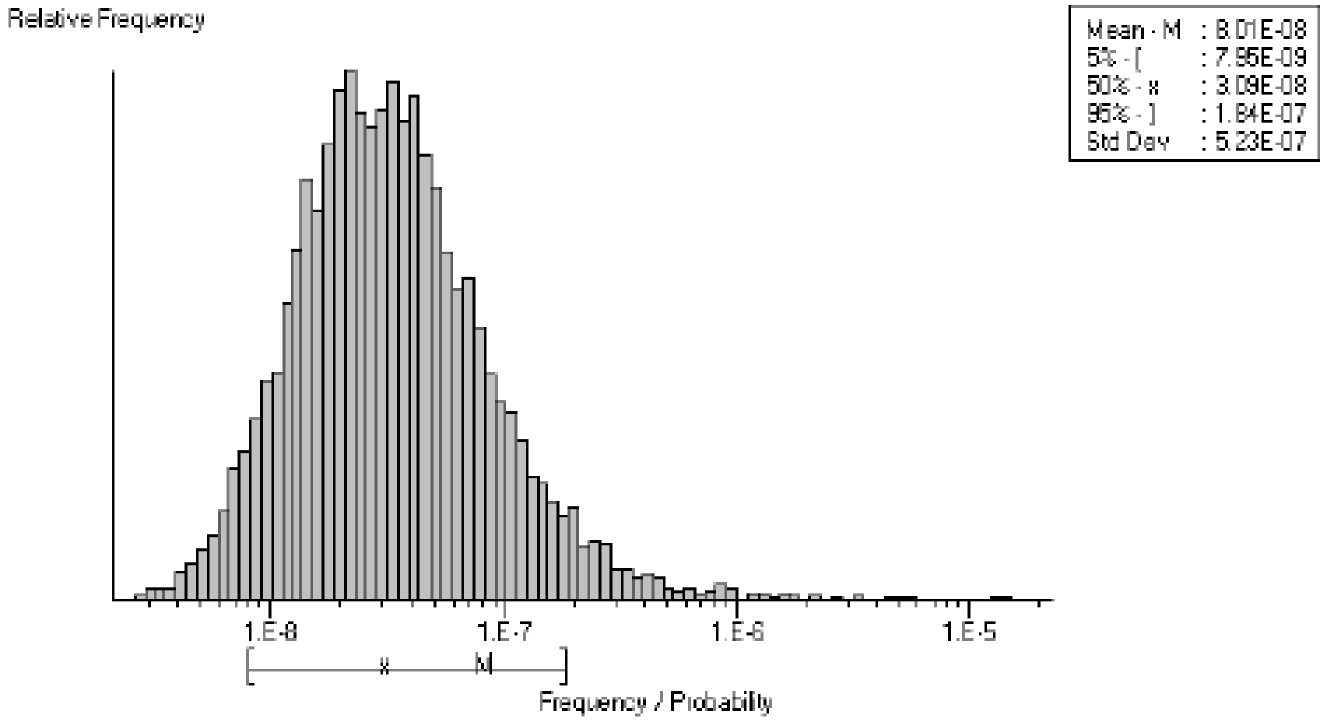
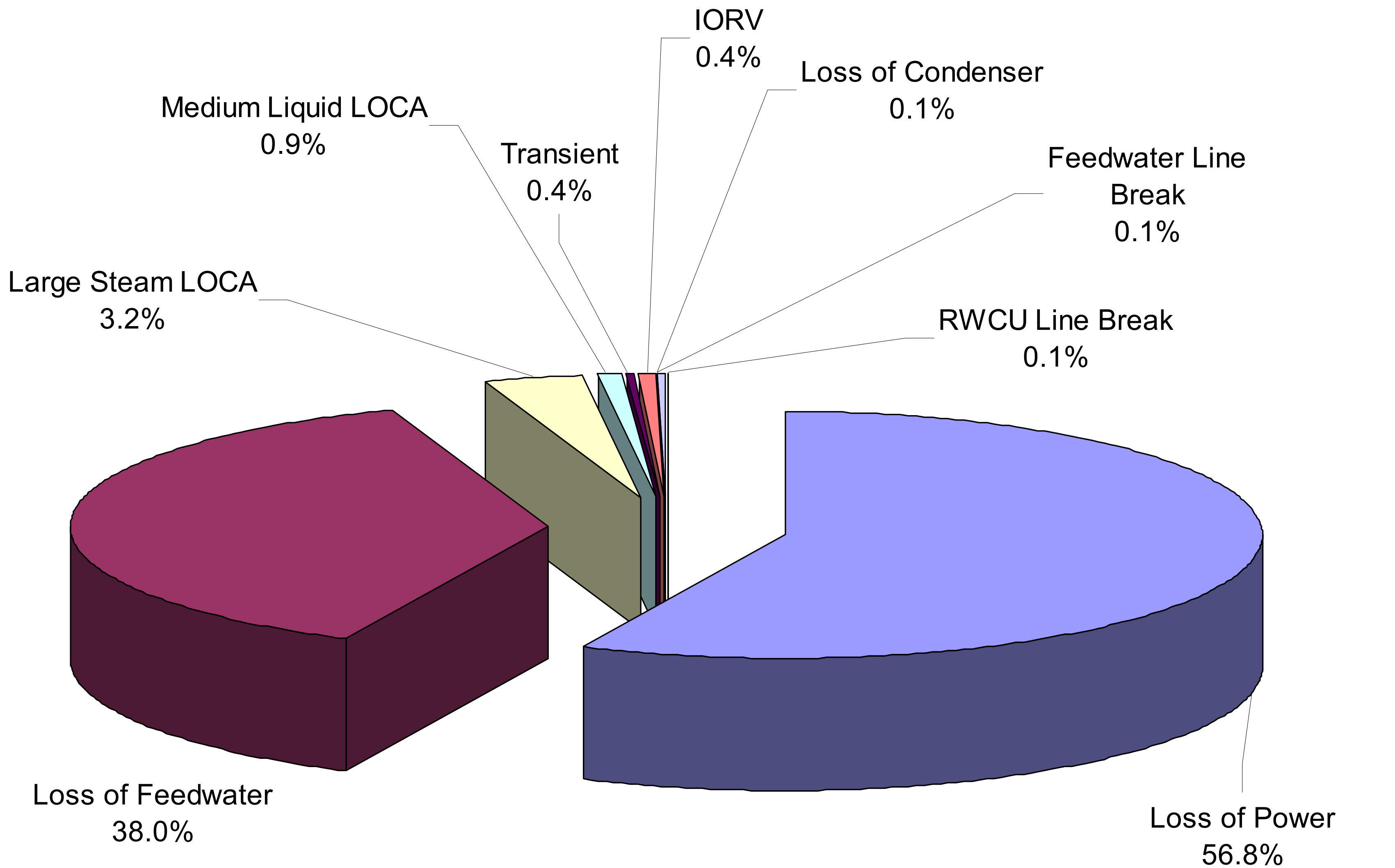
Level 1 Results

CDF = 3.2 x 10^{-8} per year



Breakdown By Initiating Event



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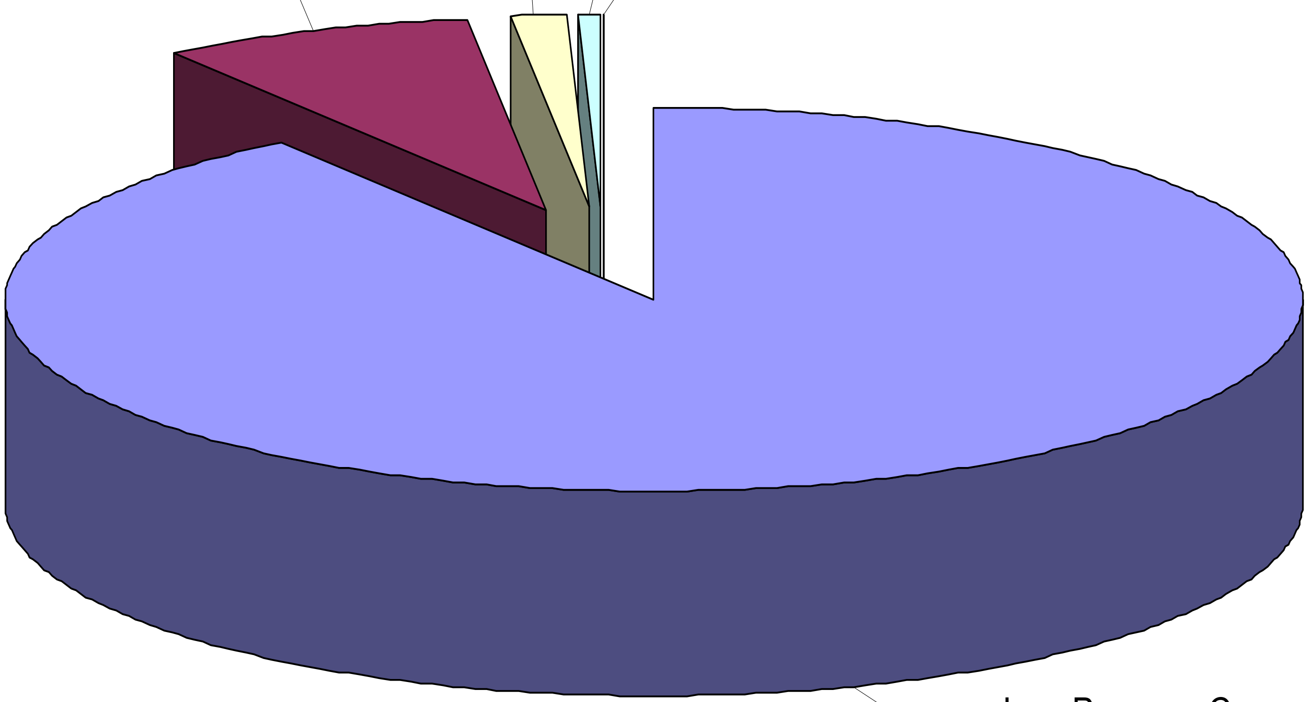
Breakdown By Accident Class



Sequence Descriptions

Contained in Table 7.2-4

Sequence	T-LOPP044			
Pct of Class I	57.08%			
Pct of CDF	51.50%			
Intitiator	Loss of Preferred Power			
Intiial water drop causes level to go below L1.5				
Failure to restore power within 15 minutes				
2 CRD Pumps fail to restore water before 15 minute timer expires				
Plant successfully depressurizes				
Depressurization causes ICS to be ineffective				
Injection systems fail				
Vessel fails at low pressure				
Low or no water in LDW				

This line not included in NEDC

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Cutsets

Only Top 10 Included in Report

Revision Will Provide More

> Top 99%
> Top 100
> What is preference?

Importance Analysis

Only Basic Events that Survived Truncation

Need Sensitivities for Others

Table 11-2 From Previous Quantification

> GE will update in next revision

Shutdown PRA

Manual Shutdown

Mode 5 (Hot Shutdown)

Mode 6 (Cold Shutdown) Un-Flooded

Mode 6 Flooded

Transition Between Modes Not Included

> Will need to add if we want to take advantage in Tech Specs

Initiators

> Loss of DHR

> Loss of Power

> LOCA

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Shutdown Results

CDF 4 x 10^{-9} per year

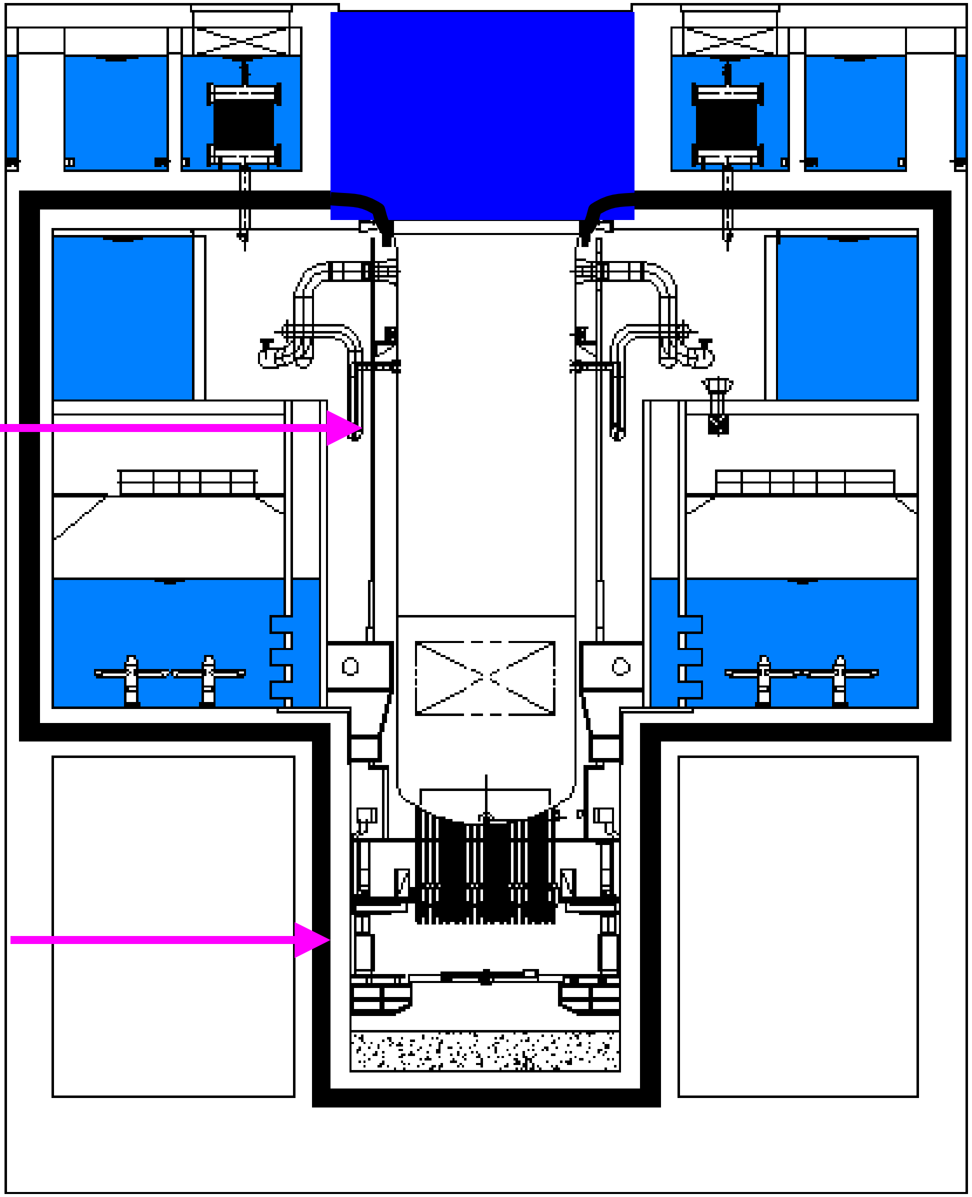
Dominated by LOCA Events (> 99%) With Containment Open

LDW Hatch Disables Passive Containment

90 – 360 Minutes to Close Hatch

Operator Action ~ 0.01

Containment Capacity During Shutdown LOCA



Approximate Water Level With Hatch Closed

Elevation of Hatch

Shutdown PRA Concerns

External Events Not Included

First Susceptible Cutset is $\sim 10^{-12}$

Barriers May Be Disabled During Shutdown

Fire, Flood, and Seismic Will be Included in Revision

Same Process for Power PRA

Determination of RTNSS Equipment

Flood Screening Analysis

Assumes Separated Divisions

Flood Zones Aggregated into Super-Zones

> Flood fails entire division

Uses NUREG-5750 Frequency

> 10% floods exceed floor drain capacity

Consideration for Propagation Included

RTNSS Check Will be Provided

Fire Screening Analysis

Assumes Separated Divisions

Fire Zones Aggregated into Super-Zones

> Fire fails entire division

FIVE Ignition Frequencies

Failed Fire Barriers Will Be Included

> European database of barrier failures

RTNSS Evaluation Will Be Included

Treatment of Severe Accidents

Severe Accidents in ESBWR......CDF ~ 10^{-8} per year

- That is, they are Remote & Speculative
- Could be treated as Residual Risk

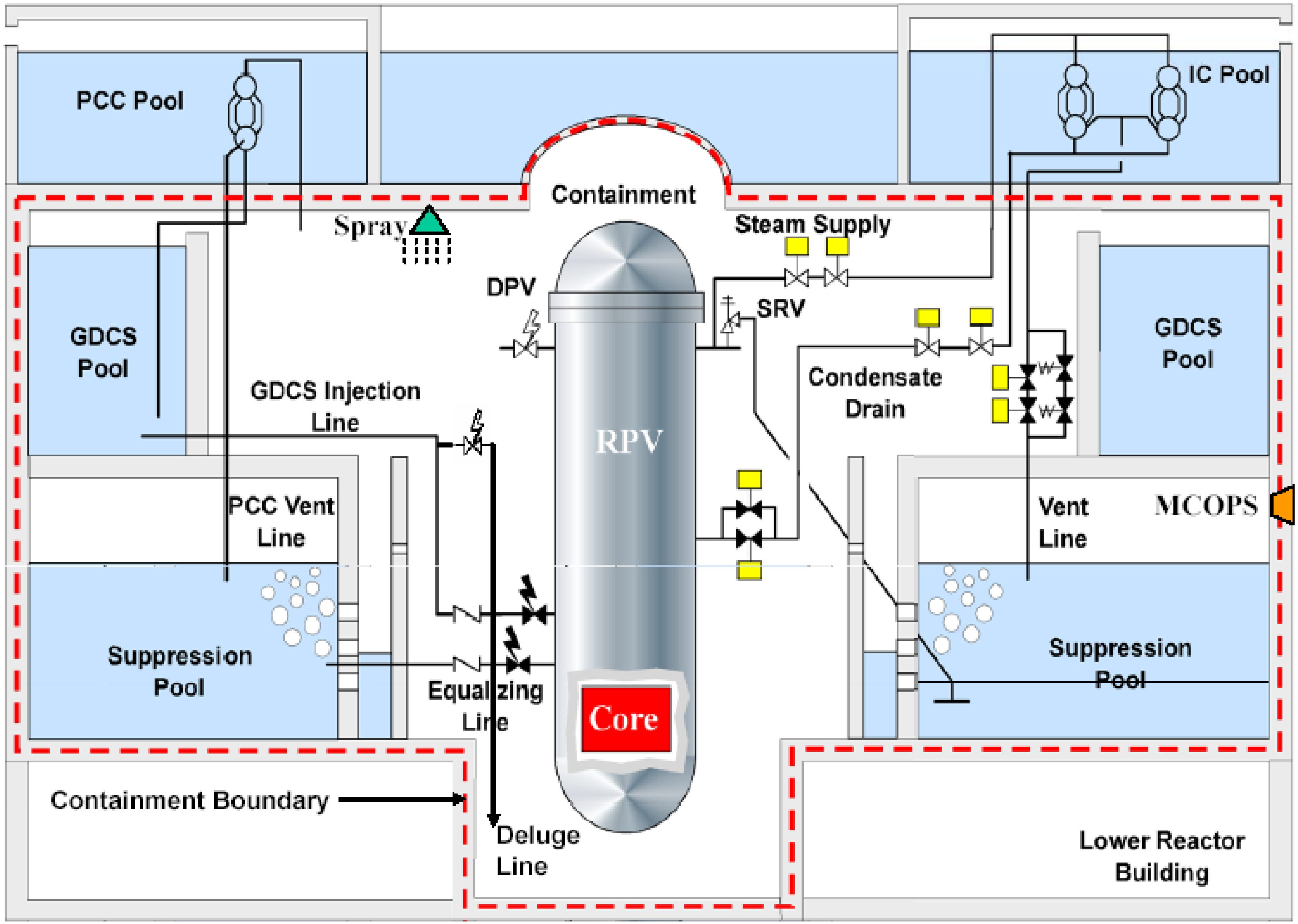
GE Designs for Defense-In-Depth

> Assess full compliment of severe accident threats
> Determine and Enhance ESBWR capabilities
> Verify by a full ROAAM treatment

Conclusion:

Containment Failure is Physically Unreasonable

ESBWR SA Containment Highlights



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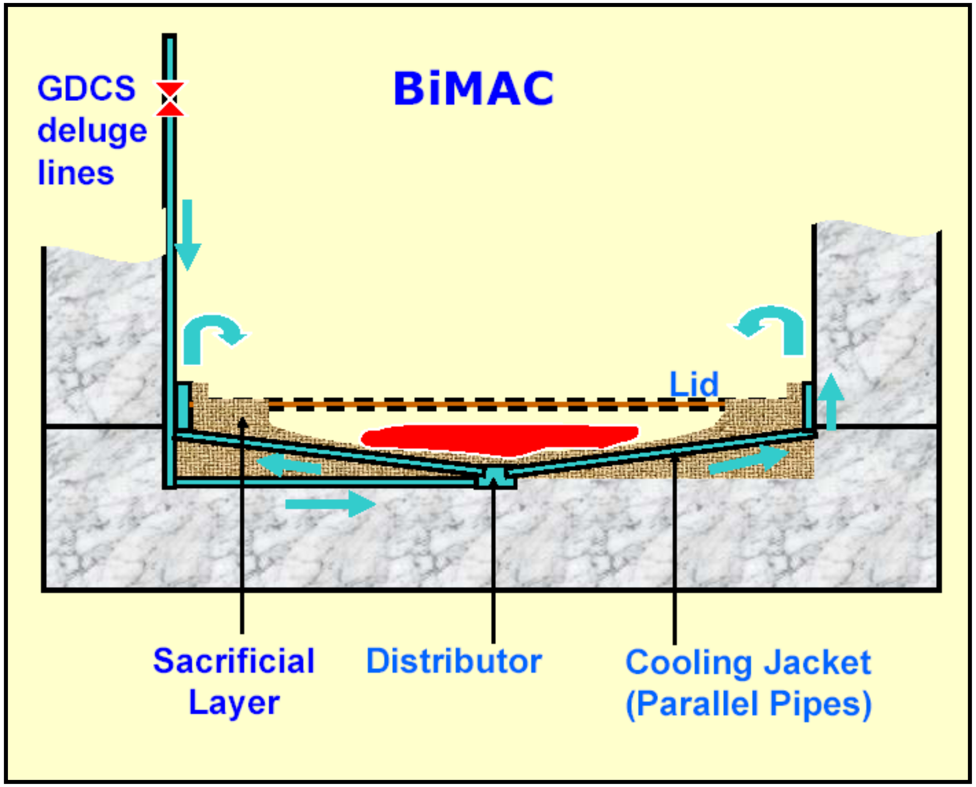
The Basemat internal Melt Arrest and Coolability (BiMAC) device



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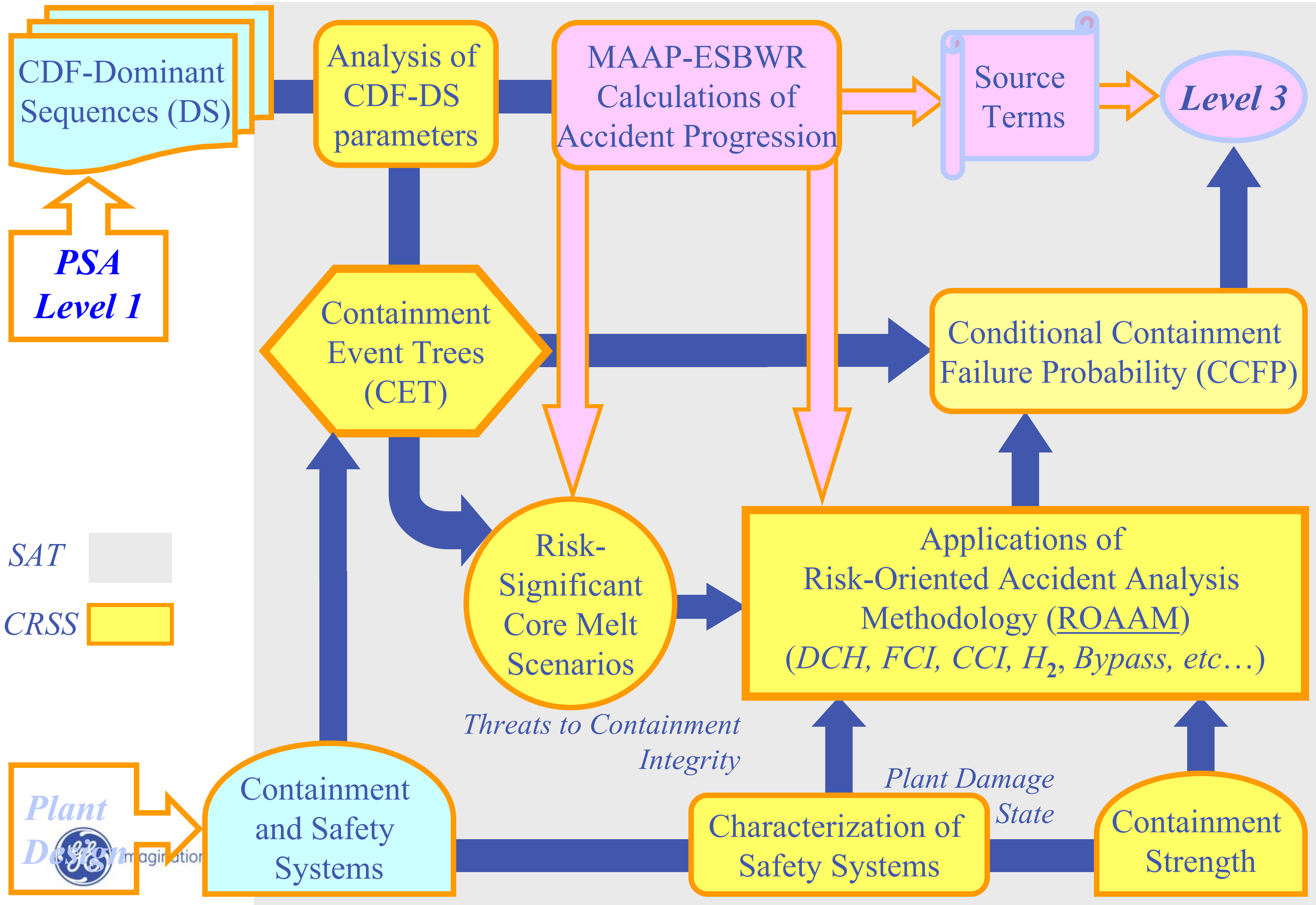
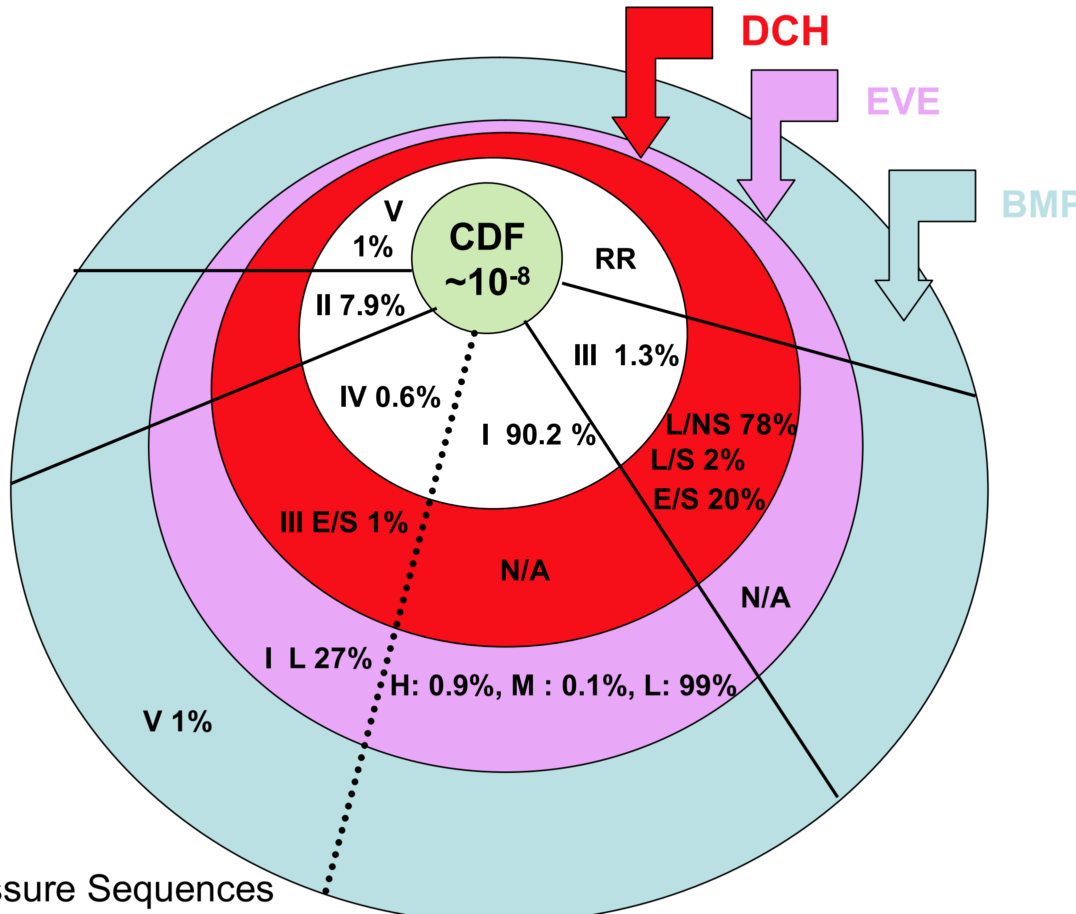
ESBWR Severe Accident Treatment – Work Structure



ESBWR SA Complexion



I Low Pressure Sequences
II Very Late Core Damage
III High Pressure Sequences
IV ATWS; 71% No RPV Failure
V Containment Bypass

L/NS Late Melt, Sprays Fail
L/S Late Melt, Sprays Available
E/S Early Melt, Sprays Available

SA Treats and Failure Modes

Direct Containment Heating (DCH)

- Energetic Failure of UDW
- Liner Failure of UDW/LDW

Ex-Vessel Explosions (EVE)

- Pedestal/Liner Failure
- BiMAC-Pipes Crushing,

Basemat Melt Penetration (BMP)

- BiMAC Thermal Failure (Burnout, Dryout)

Approach in this Presentation

Name all Possible Failure Modes

Identify Key Ingredients to each Claim Made

Establish that each Claim is well Based

Show Quantitative Evidence for Each

Of course in the time allowed this is an overview only. For full details see SAT report supplied in hard copy today. It will be made part of NEDC-33201 in the Oct submission.

Moreover we will address NRC Questions and Concerns from 9-15 Conference Call.

The Overarching Issue that Captures all NRC SAT Concerns in the 9-15 Conference is whether the ROAAM Approach Presented in Chapter 21 of the NEDC-33201 is Bounding

our answer will be imbedded in this presentation

Direct Containment Heating (DCH)

Energetic Failure of UDW.

The key bounding Ingredients are:

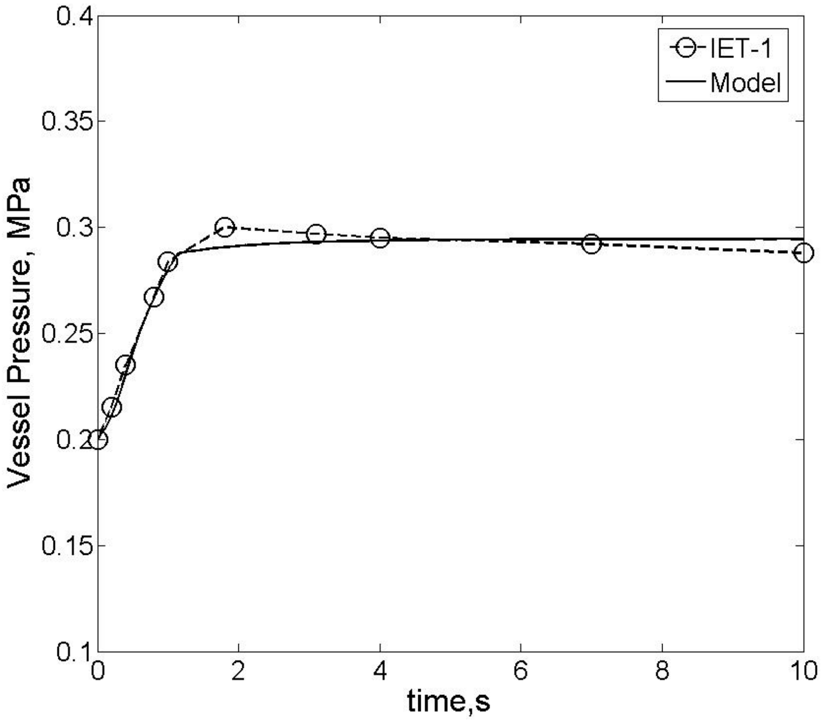
1. A conservative energy-release and transport model (CLCH) as used in PWR DCH issue resolution,
2. A creep rupture RPV breach area that is at the upper end of the uncertainty range used for the PWR case,
3. Understanding of the dynamics of pressurization in an open system such as the pressure suppression containment of the ESBWR—there are three regimes that we identified, bounded them all, and moreover found margins-to-failure in the space beyond are very great,
4. Using the lower bound of the DW fragility.

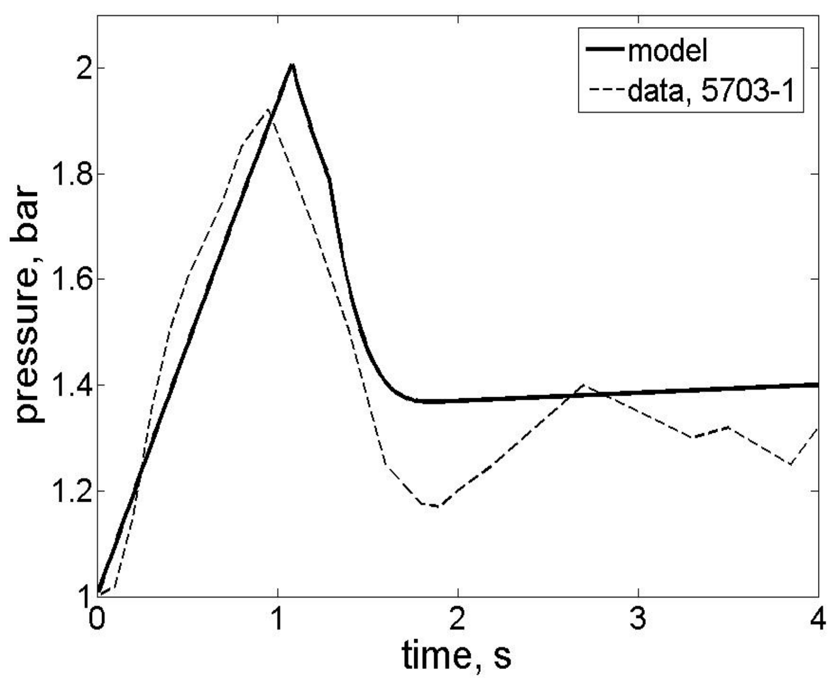
Failure is Physically Unreasonable

Direct Containment Heating (DCH)

Energetic Failure of UDW.

Validation Basis: IET DCH Tests... GE PSTF Vent Clearing





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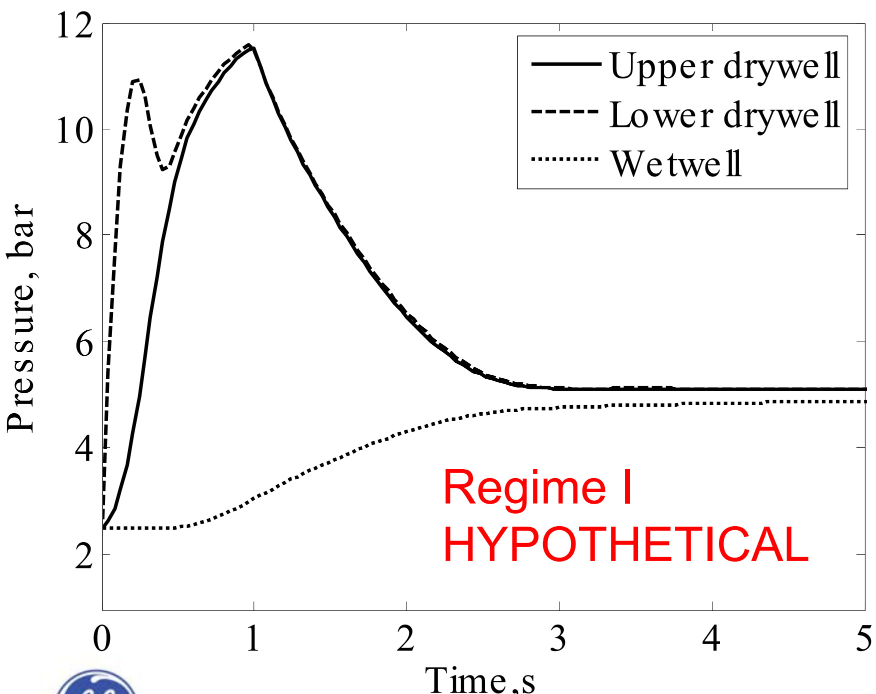
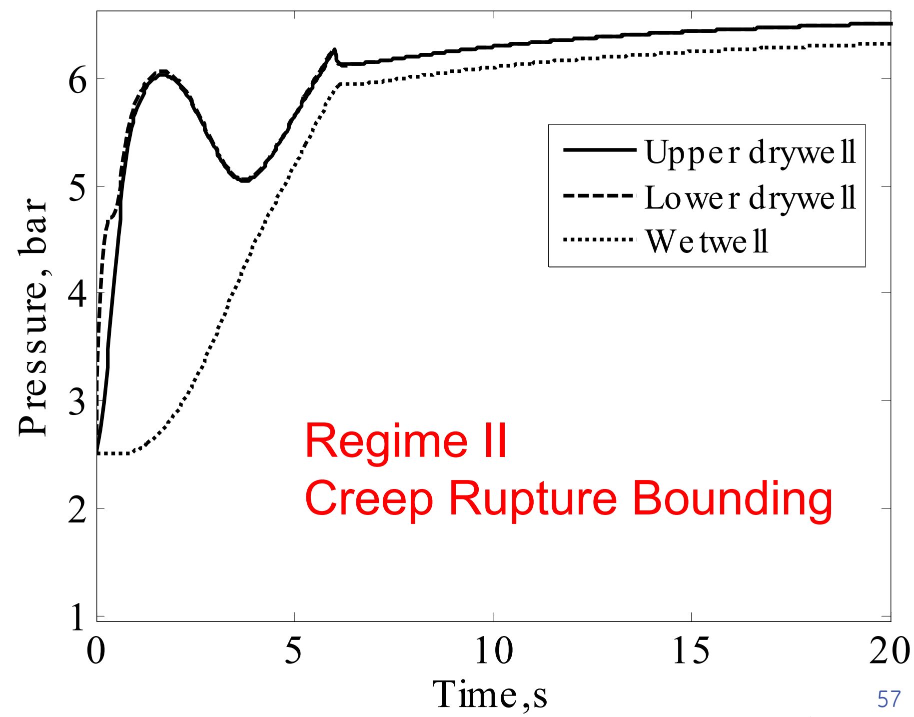
Quantification of Loads

Identified Three Dynamic Regimes

Used Complete Space (up to all fuel, Zr, and SS) to Bound Independently each Failure Mode





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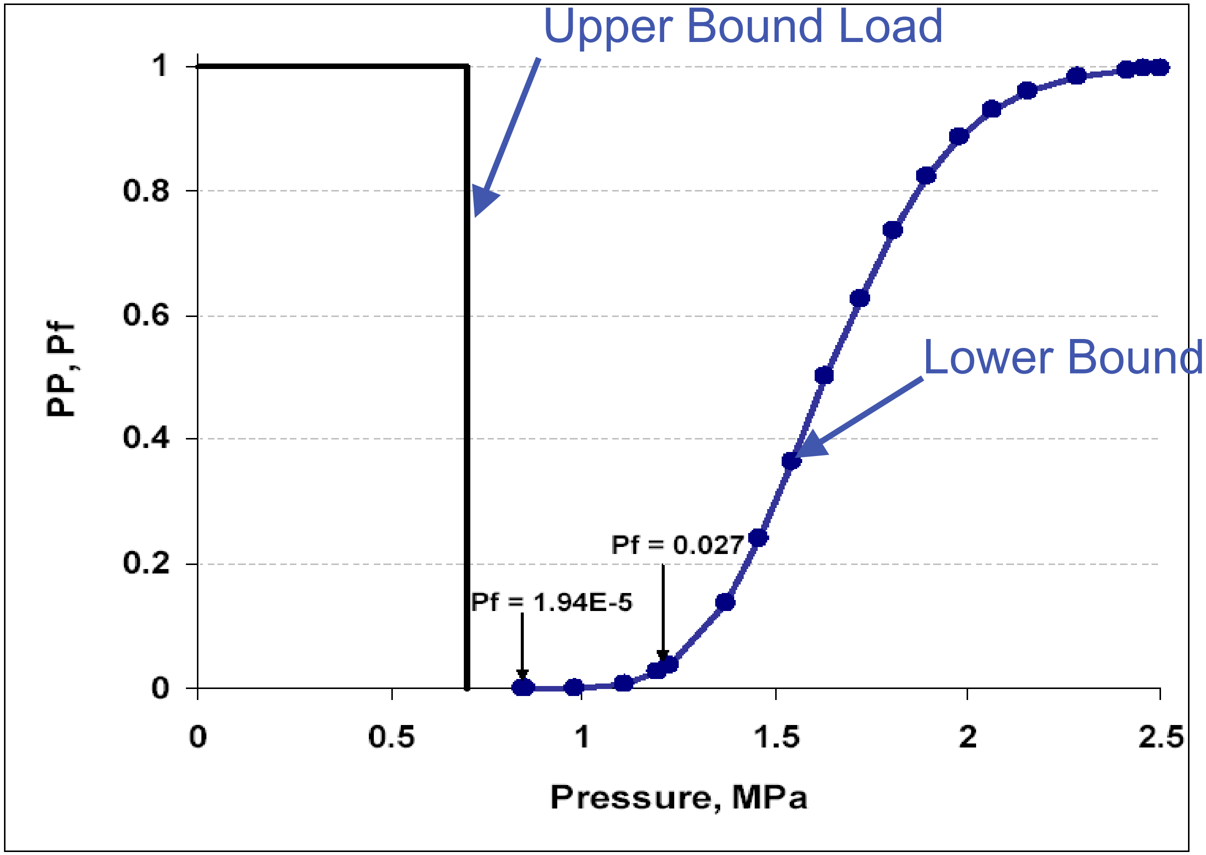
Minimum (bounding) Margins to Energetic DCH Failure



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Direct Containment Heating (DCH)

Liner Failure of UDW/LDW.

The key bounding Ingredients are:

1. A conservative energy-release and transport model (CLCH) as used in PWR DCH issue resolution,
2. Understanding the dynamics of atmospheric temperature rise and fall in the LDW/UDW, and exploring the whole parameter space of melt mass, breach area, etc.
3. Detailed, state of the art finite-element simulations that show the anchored, backed by concrete liner to be resilient for temperatures up to near melting,
4. Liner-concrete gap support struts, that separate the LDW gap space from that of the UDW, thus guarding against local melt-through due to melt splashing (which cannot be excluded).

Large Release is Physically Unreasonable

Ex-Vessel Explosions (EVE)

Pedestal/Liner Failure, BiMAC-Pipes Crushing

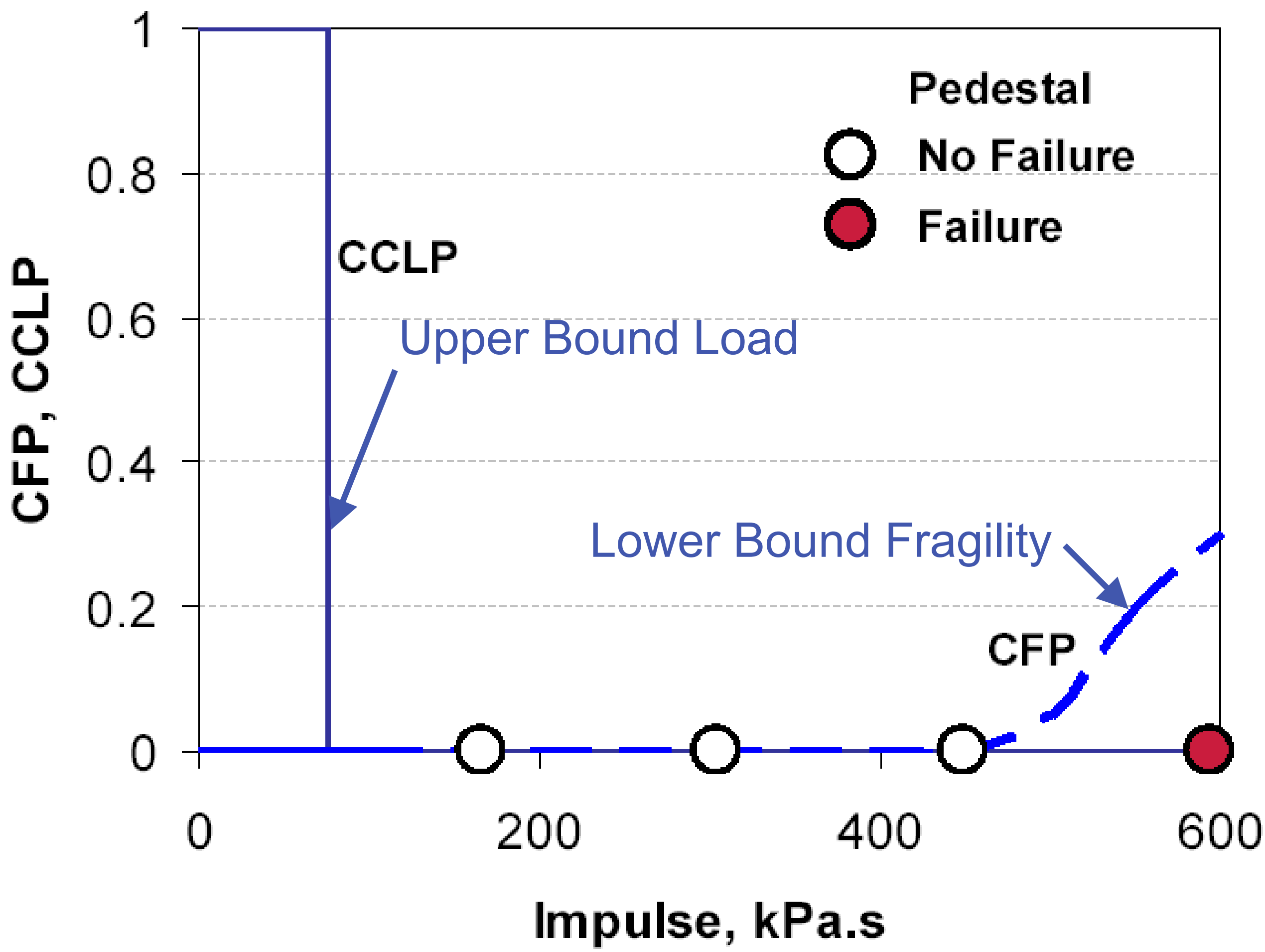
Energetic impulses that could potentially damage the reactor pedestal and BiMAC pipes cannot be conservatively excluded if there are deep, subcooled water pools on the LDW at the time of vessel breach.

Our approach relies in prohibiting the formation of such pools by design changes, and placing a high reliability requirement on the operation of the LDW deluge system

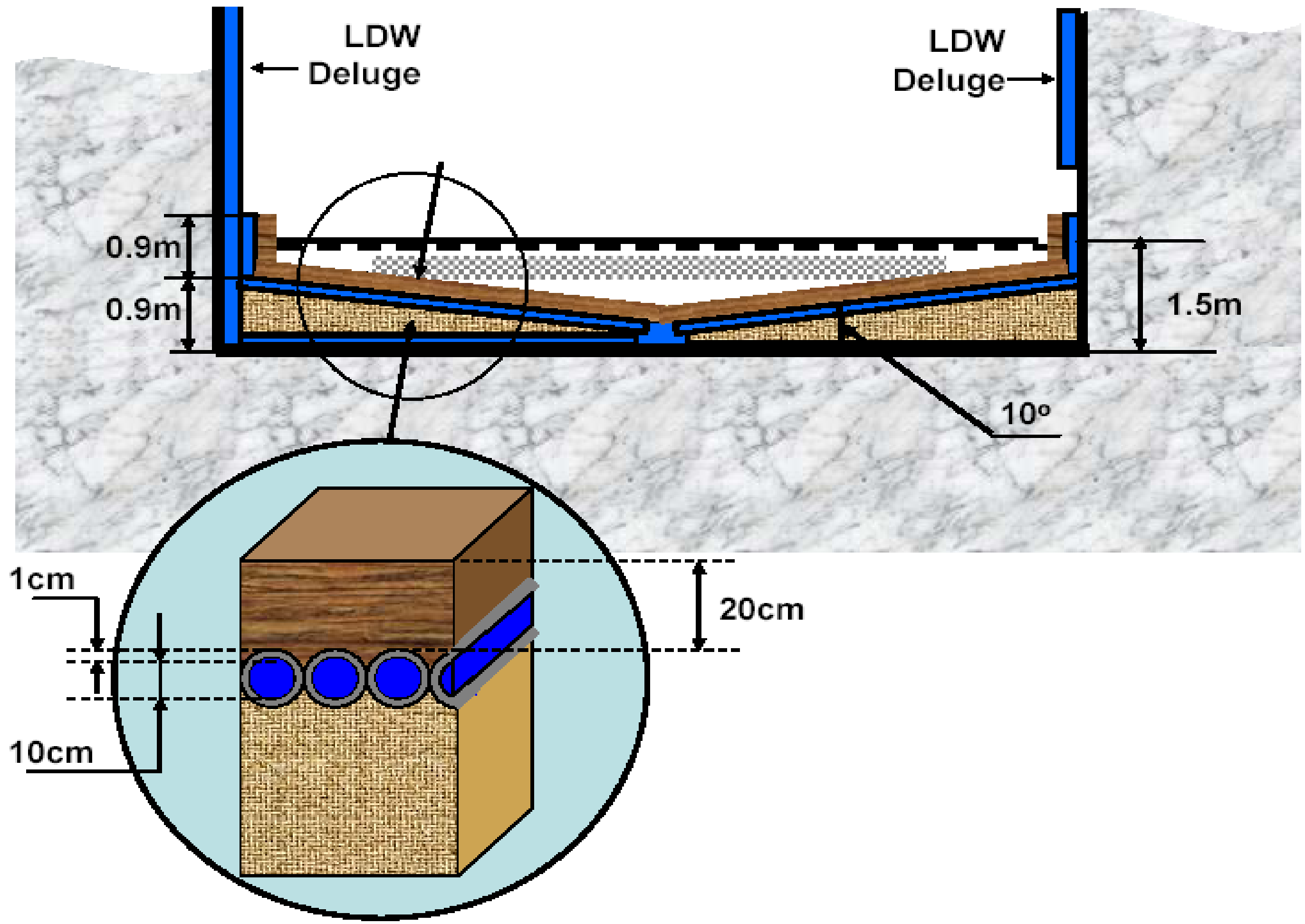
According to bounding estimates of impulses and fragilities (both pedestal and BiMAC) there are additional margins even for subcooled 1 to 2 meter pools.

Pedestal Failure Margins to EVE

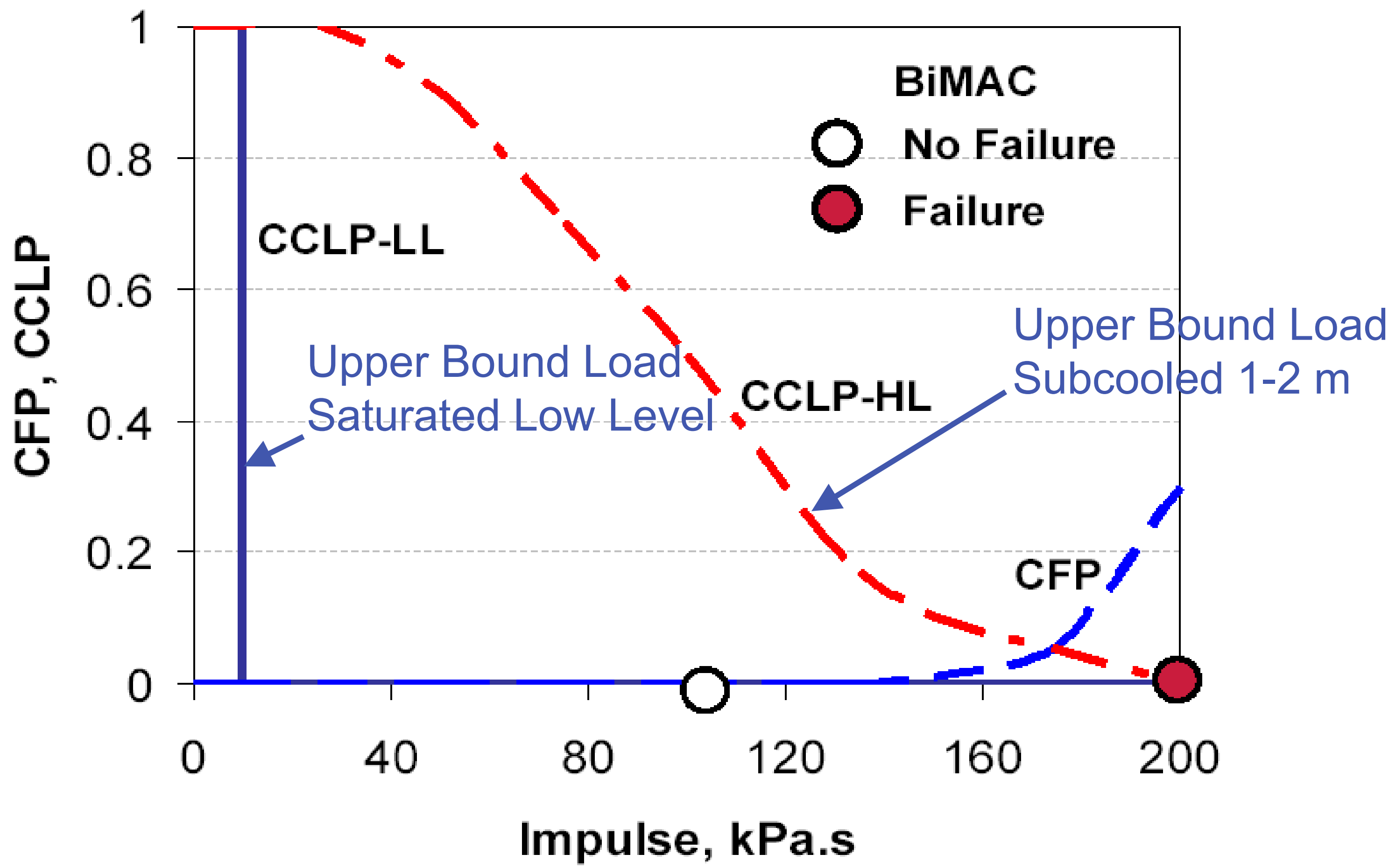
1 to 2 m Subcooled Pools



BiMAC Configuration



BiMAC Failure Margins Due to EVE 1-2 m subcooled pools



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Basemat Melt Penetration (BMP)

BiMAC Thermal Failure (Burnout, Dryout)

The key bounding Ingredients are:

Average thermal loads from full-core pools at bounding decay power levels,

Bounding local peaking of loads from verified CFD calculations,

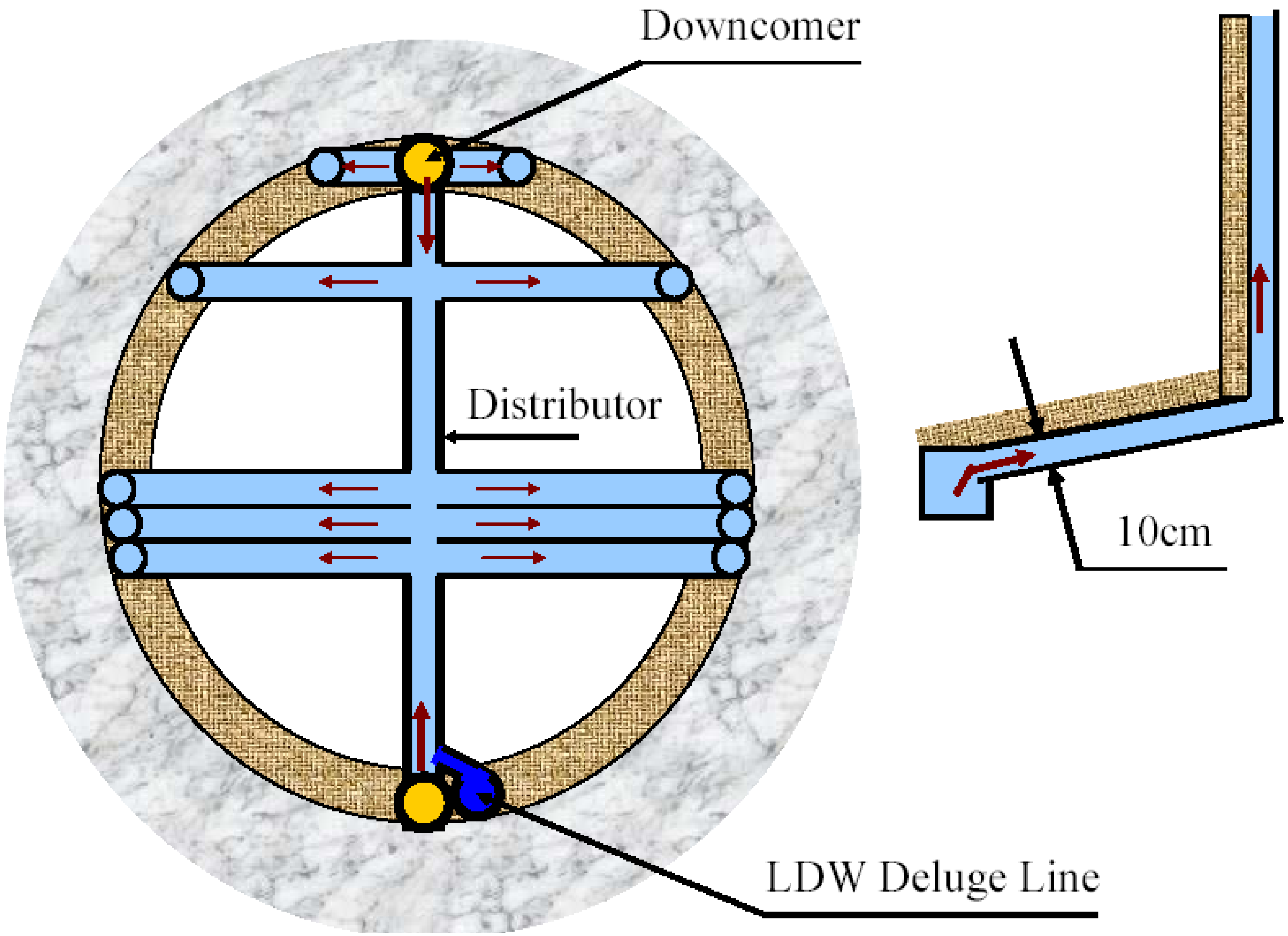
Lower bounds of CHF from ULPU in pool boiling (to be verified by full-scale experiments at the COL stage)

No flow-stability, or boil-off issues, found using a two-phase flow model verified with inclined-channel data from the SULTAN experiments

Full floor area coverage—the melt has no other place to go but inside the BiMAC.

Failure is Physically Unreasonable

BiMAC Flow Path



Average Thermal Loads and Peaking Factors

Table 3.4.3.1. BiMAC Capacity as a Function of Melt Pool Height, and Resulting Average Heat Fluxes. Total Decay Power taken at ~6 Hours into the Accident (36.4 MW)

Table 3.4.3.5. Summary of Power Split and Peaking Factor Results from the Direct Numerical Simulations (all fluxes in kW/m2).

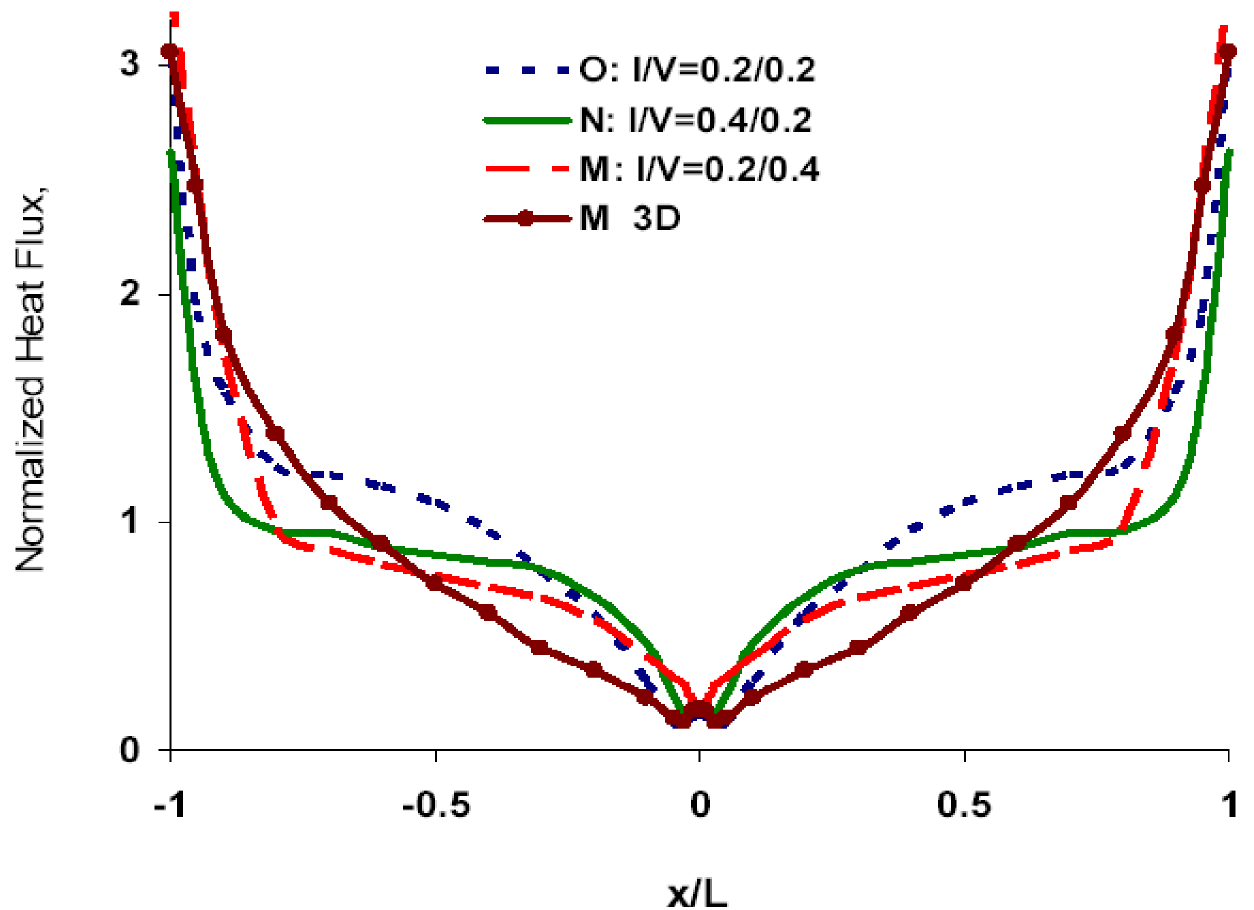
Table 3.4.3.1. BiMAC Capacity as a Function of Melt Pool Height, and Resulting Average Heat Fluxes. Total Decay Power taken at ~6 Hours into the Accident (36.4 MV

H_melt, m	**0.2**	**0.4**	**0.6**	**0.8**	**1.0**
V_melt[a], m^3	2.2	9.	20.5	35.8	53.8
Mass, tons	18	72.5	164	287	431
i_vertical[b]	51	47	41	29	1
V_sump, m^3	0.3	0.85	1.4	2	2.6
M_sacrificial layer, tons	7.6	15	21.7	27.3	30.7
Top Boundary, m^2	25	49	70.5	87.7	95.8
Bottom Boundary, m^2	25.4	49.7	71.5	88	97.3
Side Boundary, m^2	0	~0	0.8	2.1	5.1
	All melt assumed to be Fuel			All oxides + 20 tons of metal	All oxides + 160 tons of metal
Decay power, MW	1.5	8.6	21.5	36.4	36.4
Upward heat flux, kW/m^2	45	132	226	305	271
Downward heat flux, kW/m^2	15	43	74	100	89
Sideward heat flux, kW/m^2	-	-	300	320	350

Table 3.4.3.5. Summary of Power Split and Peaking Factor Results from the Direct Numerical Simulations (all fluxes in kW/m^2).

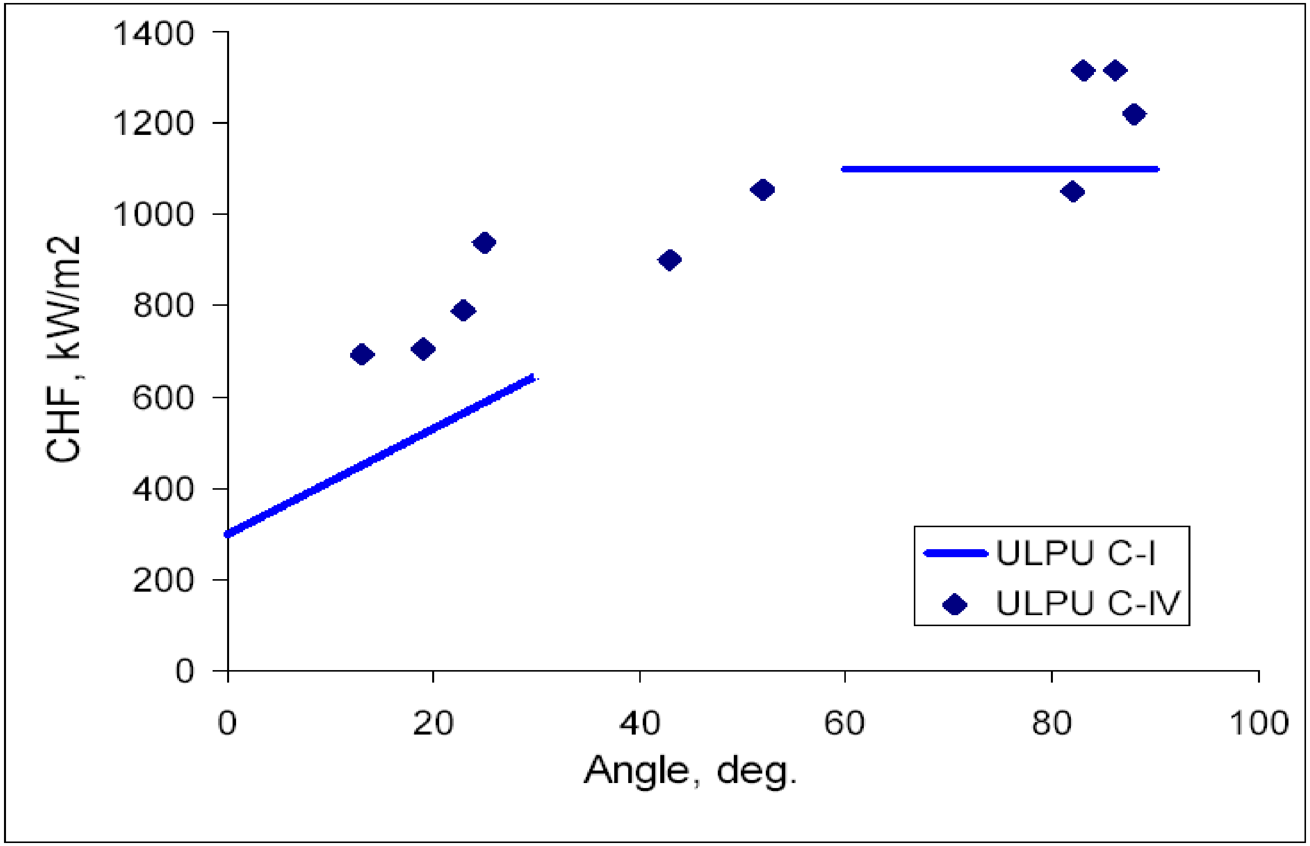
Case No.	q_{sp}	q_{dn}	q_s	q_{sp} / q_{dn}	q_{max} / q_{dn} or s
A	63	30	N/A	2.1	1.25
B	120	54	N/A	2.2	1.25
C	178	80	N/A	2.2	1.25
C-3D	238	68	N/A	3.5	1.2
M-3D	286	85	280	3.4	3.0 / 1.4
M	255	125	330	2.0	3.0 / 1.4
N	238	126	340	1.9	3.0 / 1.2
O	168	83	245	2.0	3.0 / 1.2

The Peaking at the Edge of Near-Edge Channels is the most Limiting



Coolability Limits for BiMAC

Applicability based on similarity of geometries and flow/heating regimes



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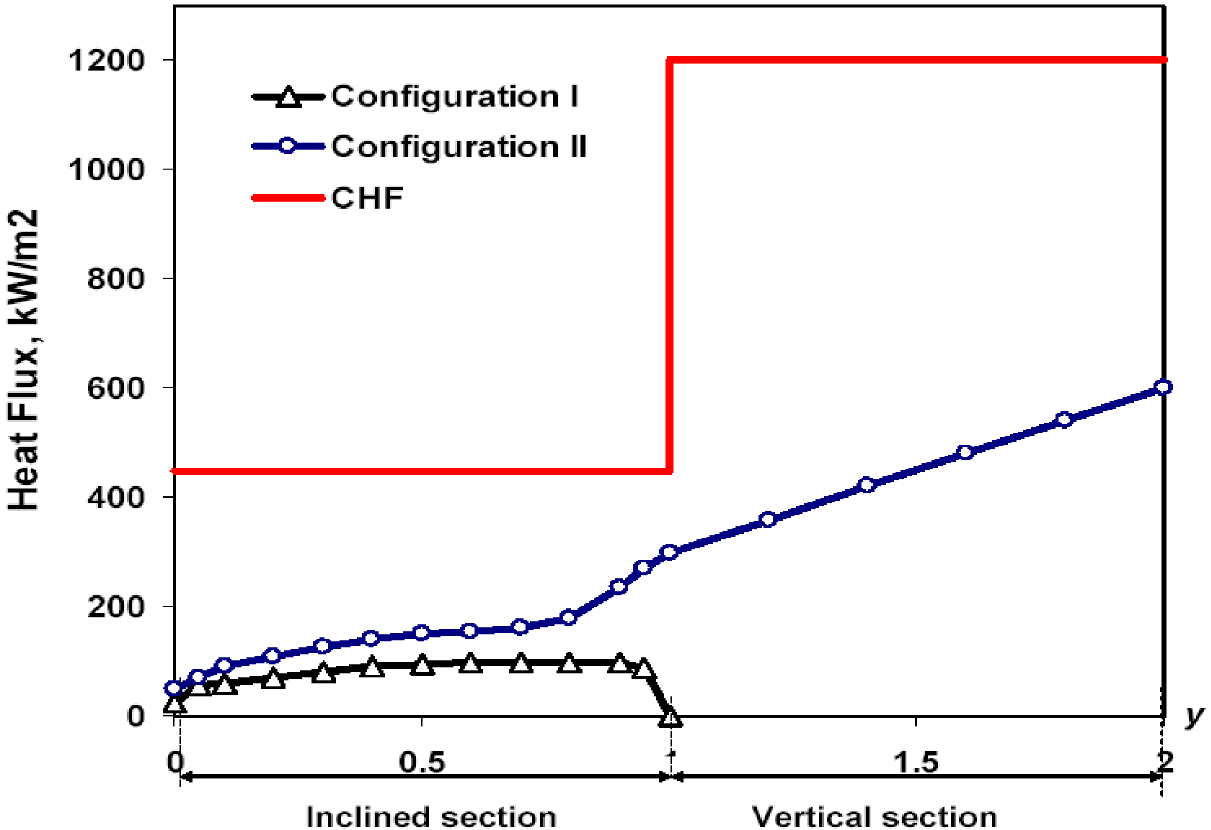
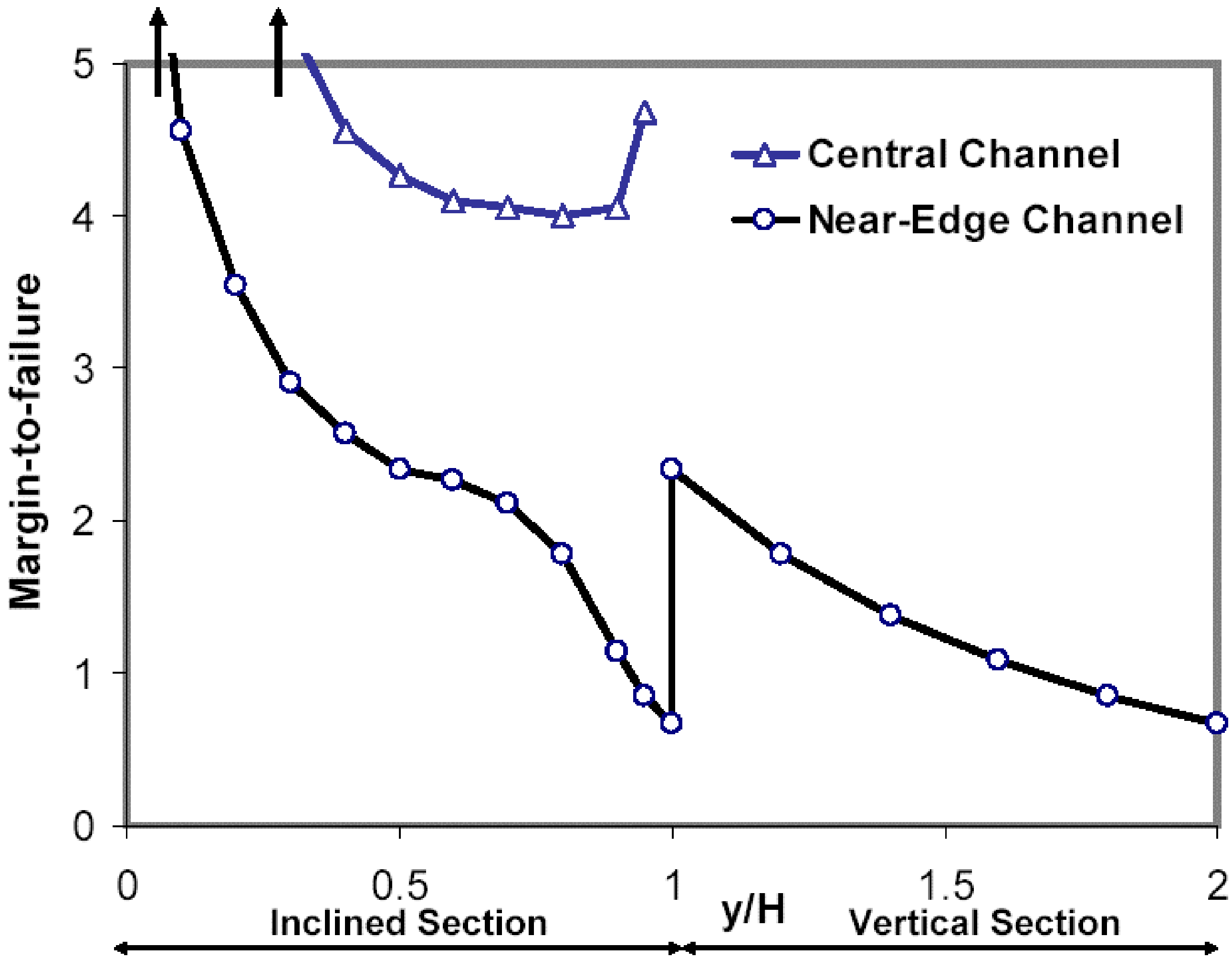
Thermal Loads against Coolability Limits in BiMAC Channels



Thermal Margins for BiMAC

Local Burnout



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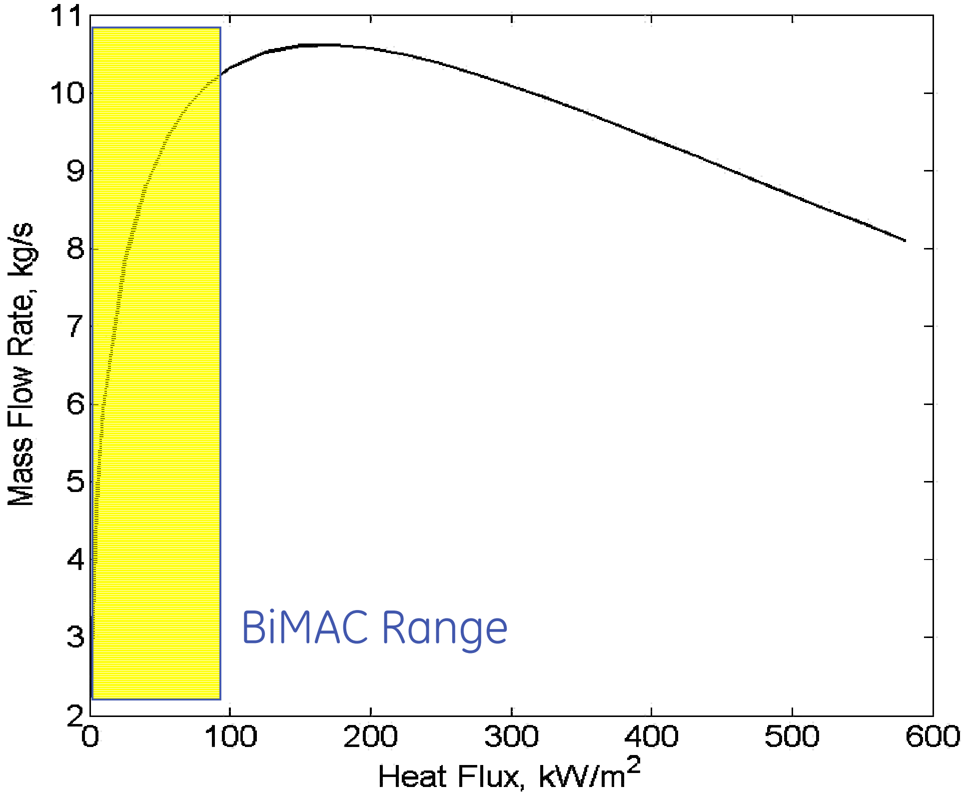
Natural Convection in BiMAC



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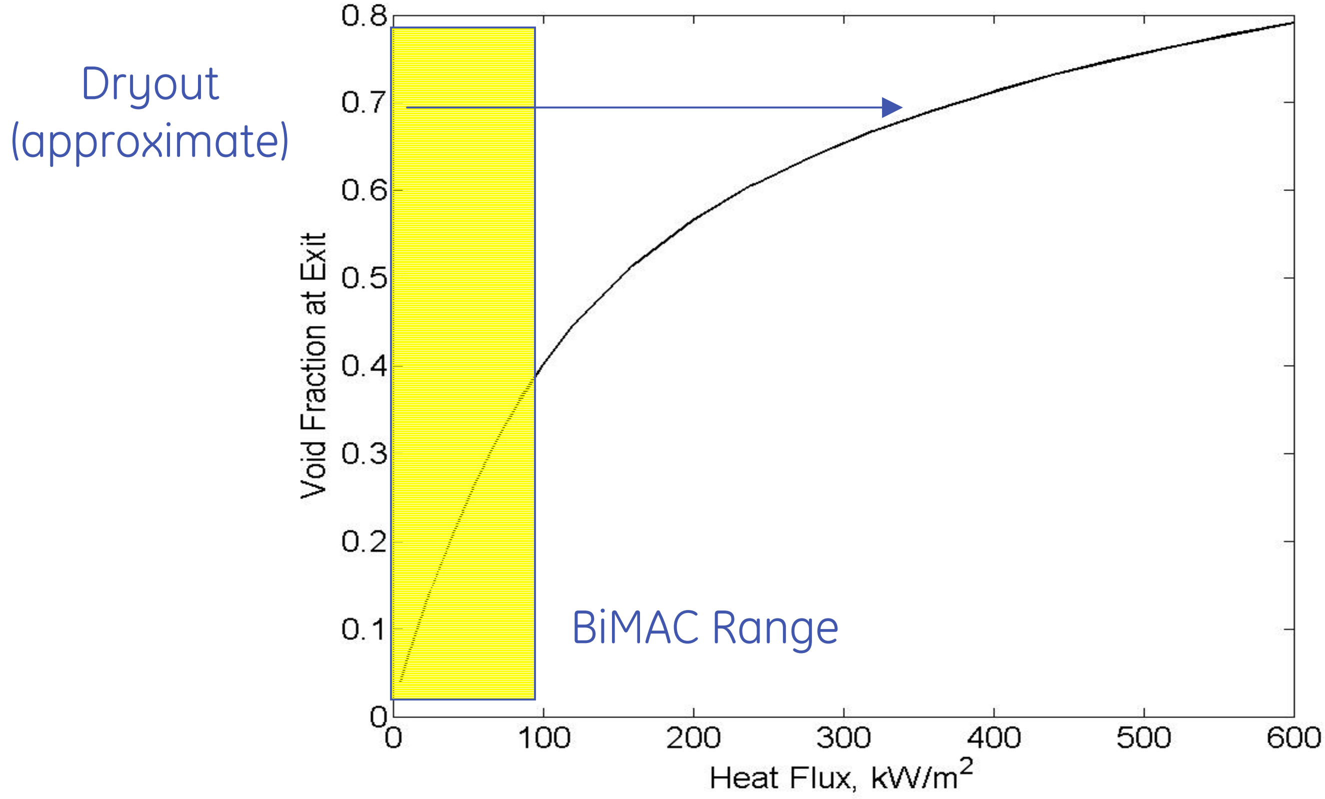
Wetting of BiMAC Horizontal Channels



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BiMAC Belongs In RTNSS Program

Qualification of function in the as-designed state

This is shown now in terms of principle and available experimental knowledge—it will verified by full-scale tests. These tests are of the engineering practice type so they belong to the COL stage of the review.

Verification of continuing ability to function as designed through-out the operating life.

This will require some periodic testing for the I&C features of the BiMAC system

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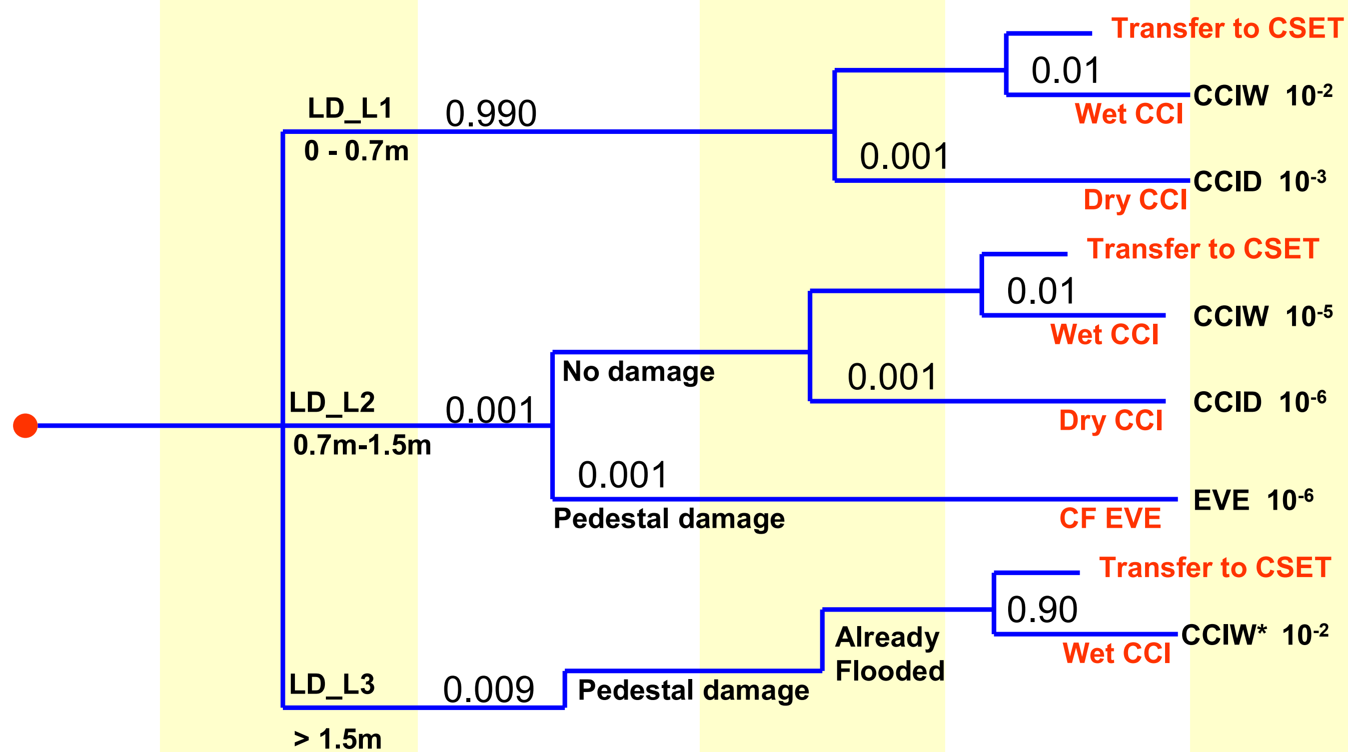
Conclusion:
The Low Pressure CPET

Class I: LP	LD_LVL	EVE_DAM	BI_SP	BI_FN	Rel. Cat.
RPV Failure at Low Pressure (< 1 MPa)	Water Level prior to RPV Failure	*Pedestal Intact*	GDCS Deluge Supply to BiMAC Successful	*Debris is Successfully Cooled*	



Shown are probabilities conditional on Class I
To get probabilities conditional on core melt multiply by ~1

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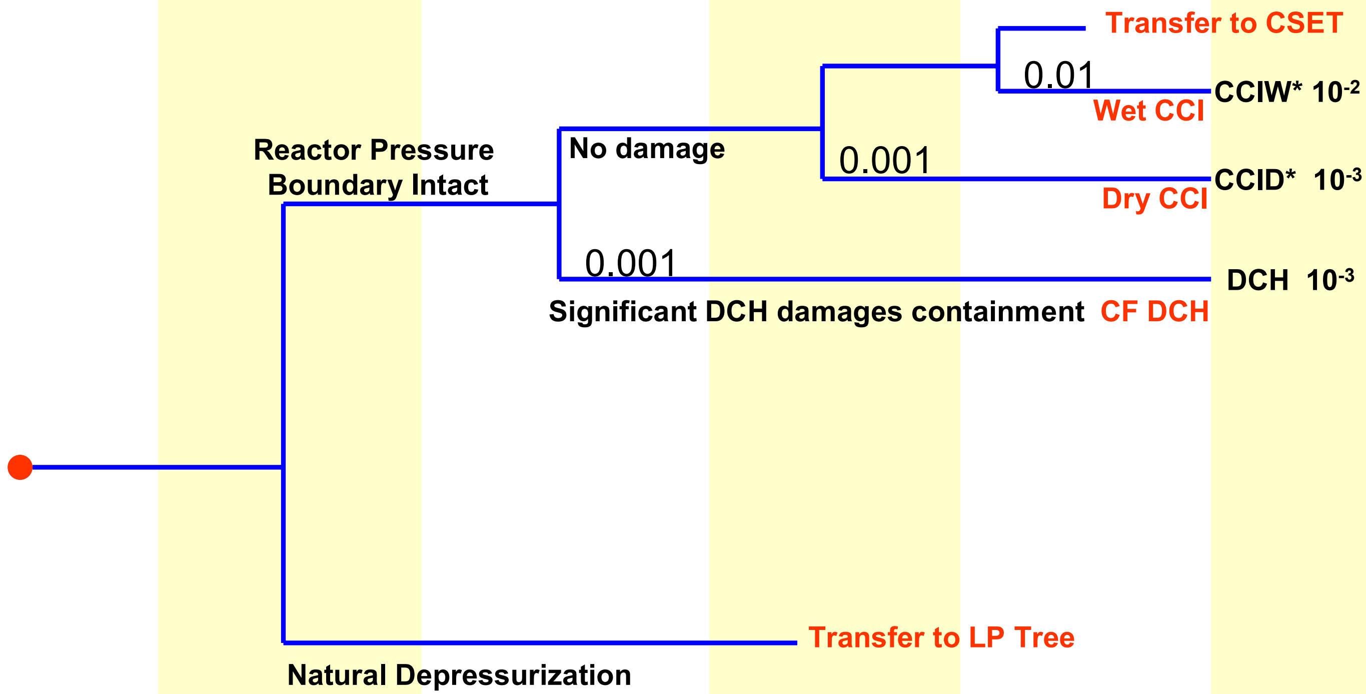
Conclusion:
The High Pressure CPET

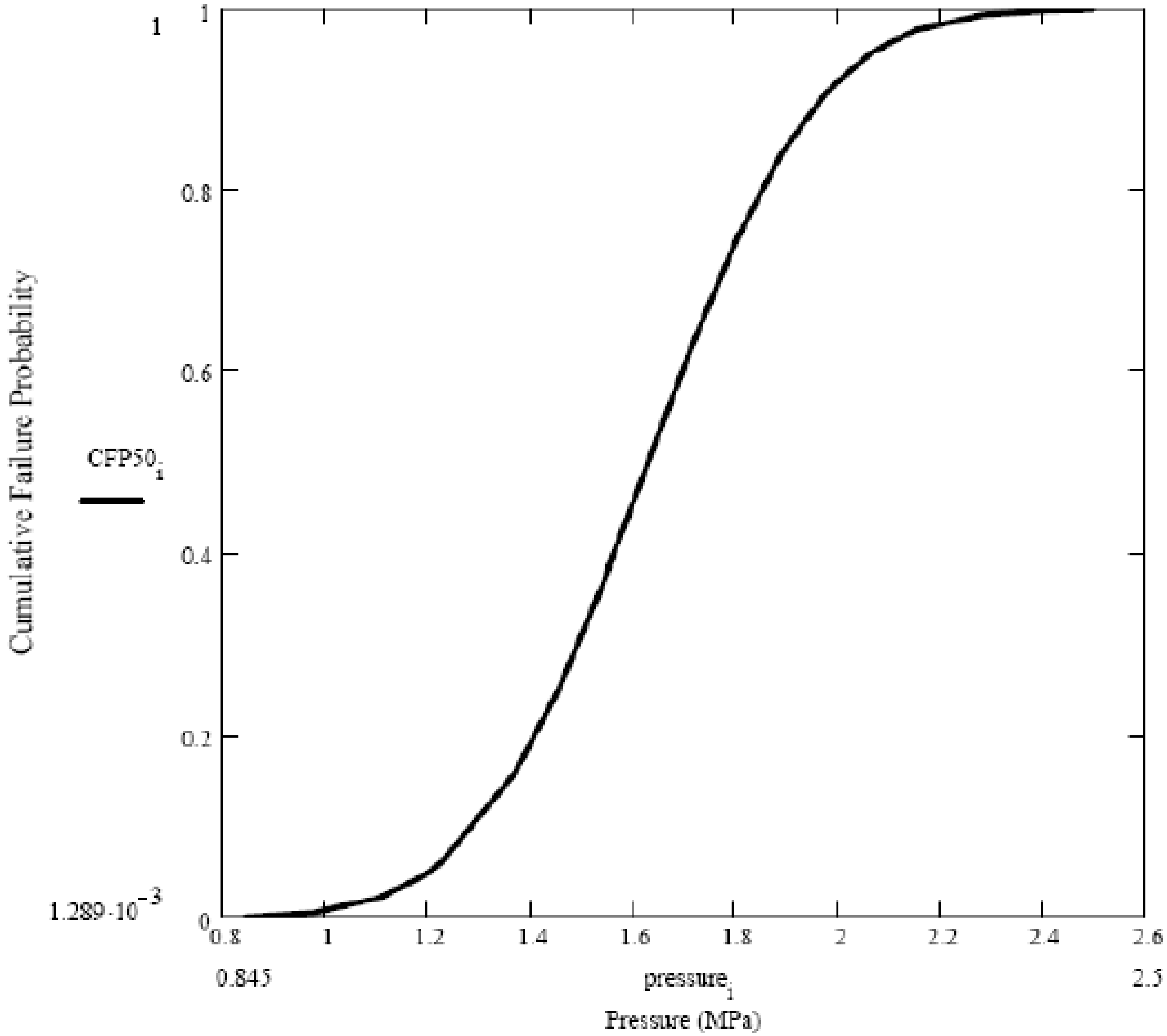
Class III: HP	RCB_I	DCH	BI_SP	BI_FN	Rel. Cat.
RPV Failure at High Pressure (> 1 MPa)	**Reactor Coolant Boundary Intact**	*Containment Intact Insignificant DCH*	**GDCS Deluge Supply to BiMAC Successful**	*Debris is Successfully Cooled*	



Shown are probabilities conditional on Class III
To get probabilities conditional on core melt multiply by ~10^{-2}

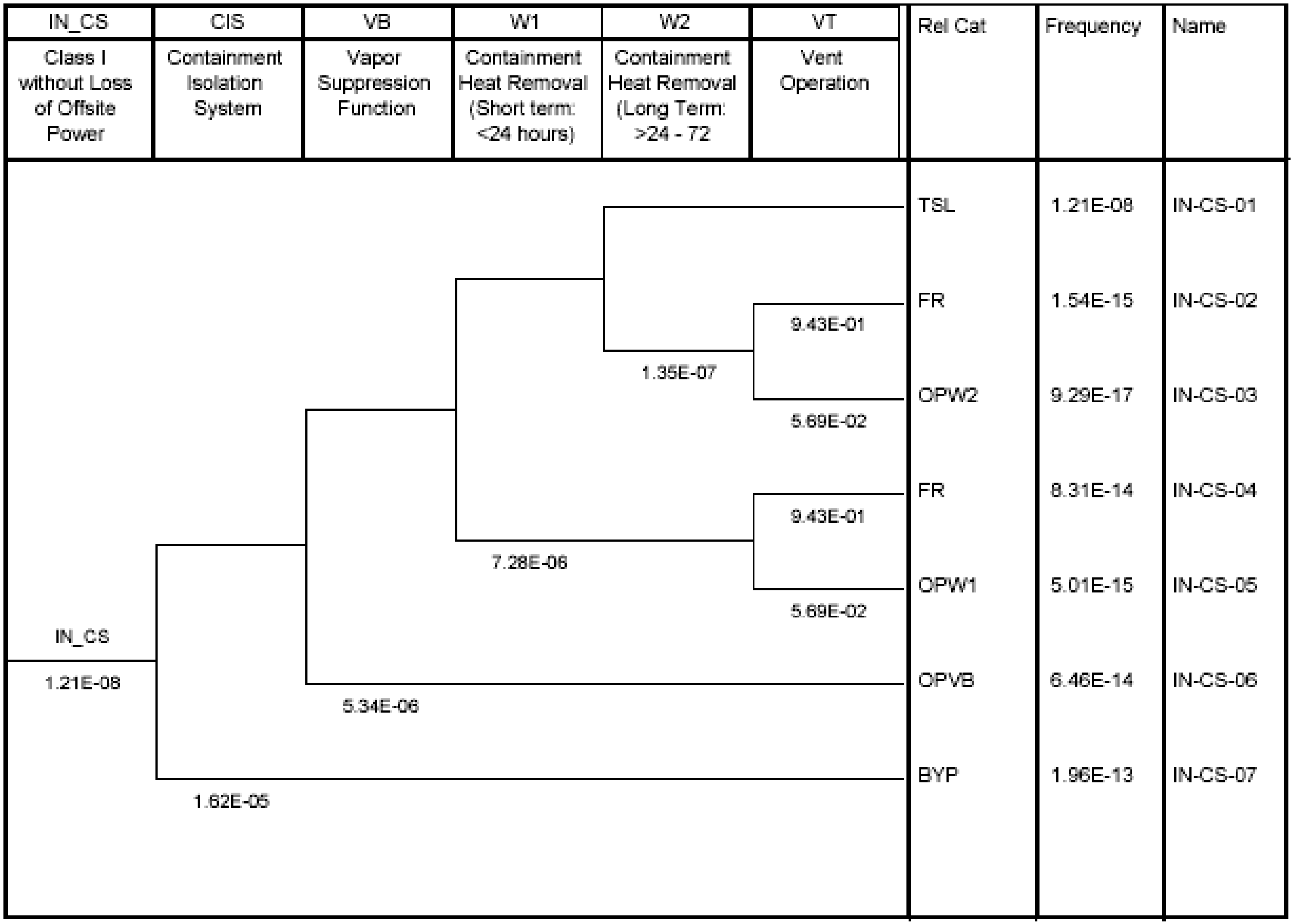
Threat	Failure Mode	Mitigative System
DCH	*Energetic DW Failure*	*Pressure Suppression Vents*
	UDW Liner Failure	*Reinforced Concrete Support*
	LDW Liner Failure	*Reinforced Concrete Support* *Gap Separation from UDW*
EVE	*Pedestal/Liner Failure*	*Dimensions and Reinforcement*
	BiMAC Failure	*Pipe Size and Thickness* *Pipes Embedded into Concrete*
BMP	*BiMAC Activation Failure*	*Sensing Instrumentation* *Valve Actuation*
	Local Burnout	*Natural Circulation*
	Water Depletion	*Natural Circulation*
	Local Melt-Through	*Refractory Layer*

Containment Fragility



Cumulative F. P. Pmed=1.632MPa,COV=.16

Containment System Event Tree



MACCS2 ESBWR Consequence Results by Source Term

Source Term	Release Category	Release Frequency (per yr)	Individual Risk (0-1 mile)	Weighted Individual Risk	Societal Risk (0-10 miles)	Weighted Societal Risk	Prob.of Dose > .2 SV (0-0.5 mile)	Weighted Prob of Exceedance
1	BOC	4.3E-12	8.47E-2	3.6E-13	1.09E-2	4.7E-14	1.00E+0	4.3E-12
2	CCID	3.2E-10	9.65E-2	3.1E-11	8.95E-3	2.9E-12	1.00E+0	3.2E-10
3	FR	2.4E-10	5.83E-2	1.4E-11	2.83E-3	6.8E-13	1.00E+0	2.4E-10
4	TSL	2.8E-8	0.00E+0	0.0E+0	6.12E-5	1.7E-12	4.97E-2	1.4E-9
5	VB	2.8E-13	4.53E-2	1.3E-14	2.08E-3	5.8E-16	1.00E+0	2.8E-13
6	OPW2	1.5E-11	8.06E-2	1.2E-12	5.66E-3	8.5E-14	1.00E+0	1.5E-11
7	BYP	4.6E-13	9.72E-2	4.5E-14	9.26E-3	4.3E-15	1.00E+0	4.6E-13
8	EVE	2.4E-10	9.86E-2	2.4E-11	9.91E-3	2.4E-12	1.00E+0	2.4E-10
Total	--	2.9E-8	--	7.0E-11	--	7.8E-12	--	2.2E-9

Level 3 Population Dose Curve

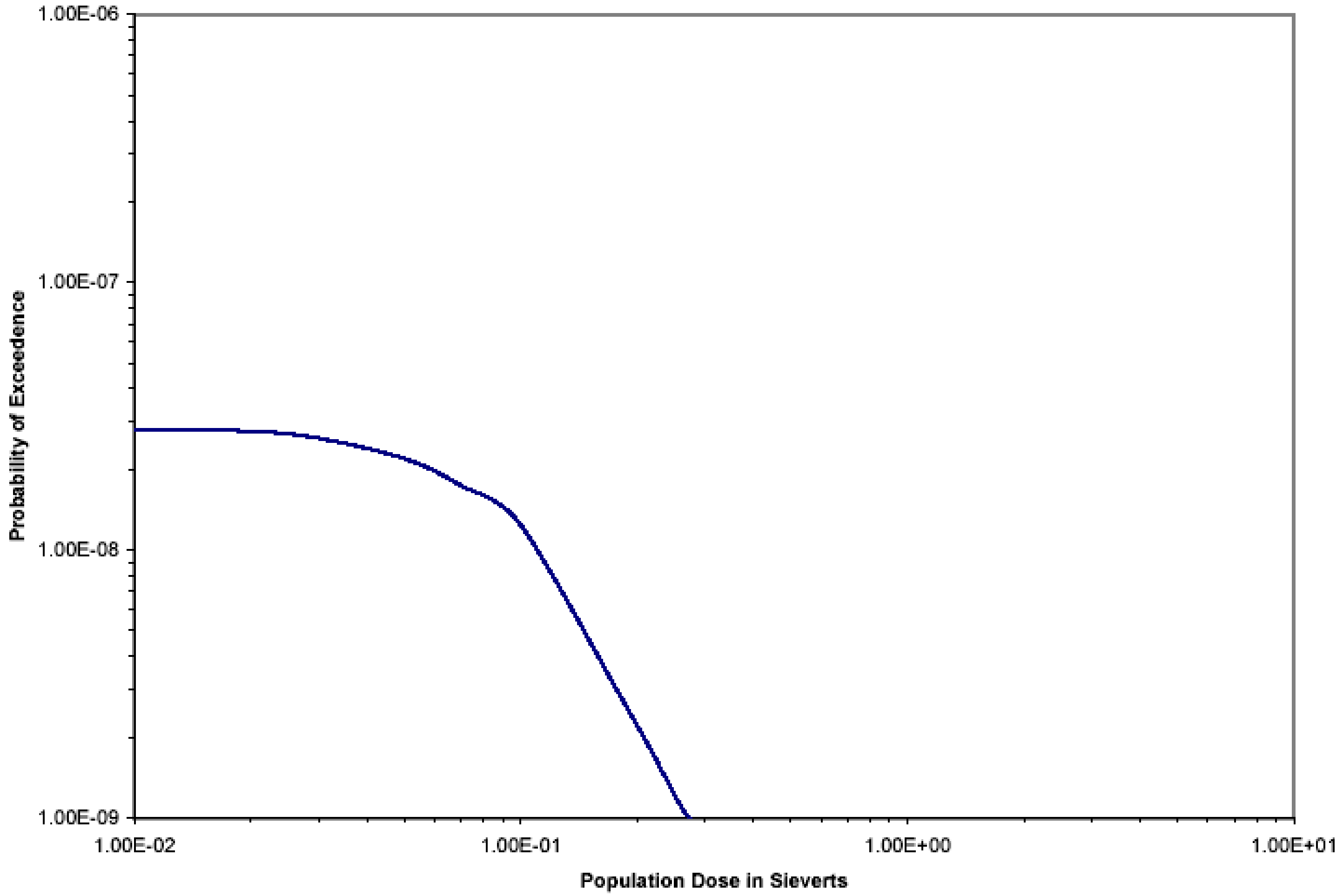


Figure 10-1. Whole Body Dose at 805 m (0.5 Mile) as Probability of Exceedence

The Bottom Line

Internal Events CDF	$3.2x10^{-8}$
Internal Events LRF	$1x10^{-9}$
CCFP	0.025
Probability of Exceeding 25 Rem at 1/2 Mile	$2x10^{-9}$
External Events Contribution	negligible
Shutdown CDF	$4x10^{-9}$

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Regulatory Treatment of Non-Safety Systems

Two Systems Identified

- Fire water refill of IC/PCC pools
- BiMAC

Sensitivity Analysis Provides Basis

- Calculated CDF using only safety-related and special treatment systems
- CDF = 4.0×10^{-5}
- LRF = 2.6×10^{-7}

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Other Sensitivities

Case	Core Damage Frequency (yr^{-1})	Large Release Frequency (yr^{-1})
Base	3.2×10^{-8}	8×10^{-10}
Safety + RTNSS	4.0×10^{-5}	2.6×10^{-7}
No Operator Credit	1.9×10^{-6}	4.0×10^{-7}
Squib Failure x 5	1.4×10^{-7}	2.4×10^{-9}
Squib Failure x 10	2.8×10^{-7}	4.2×10^{-9}
Truncation @ 10^{-14}	3.4×10^{-8}	9×10^{-10}

Conclusions

PRA Report Provides a Comprehensive Assessment of ESBWR Mitigation Capabilities

Incorporating Risk Insights During Design Drives Reliability

ESBWR Satisfies Risk Goals With Significant Margin