U.S. EPR Pre-Application Meeting: U.S. EPR Rod Ejection Accident Methodology Topical Report

AREVA NP Inc. and the NRC

October 25, 2007

Introduction

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Meeting Objectives

> Discuss the Rod Ejection Accident Methodology, the U.S. EPR application, and their coordination with the Design Certification application

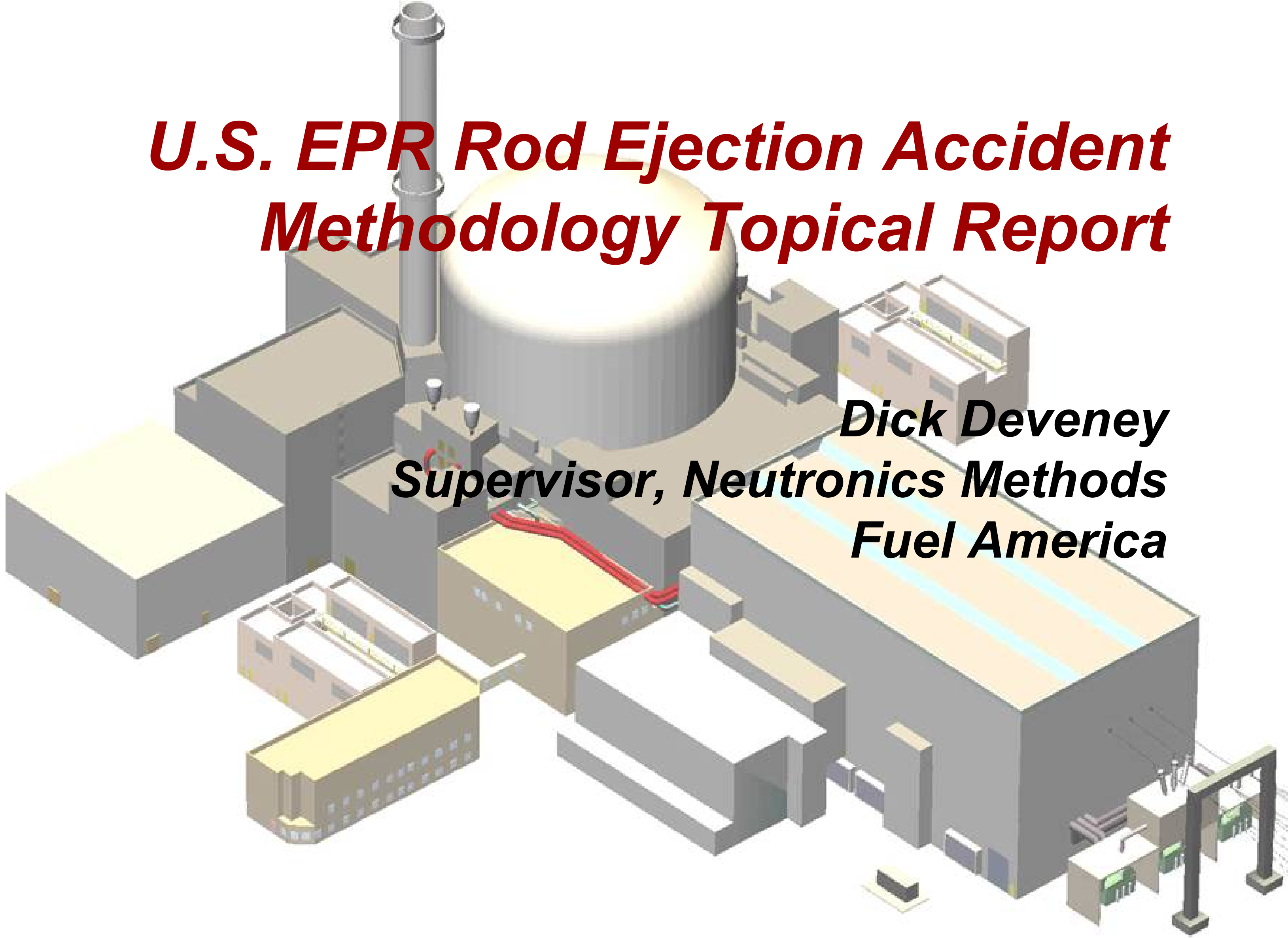
> Provide introduction to topical report contents and organization

> Obtain timely NRC feedback and interactions to support informed development of the Design Certification application

Presentation Overview

> Introduction	Sloan
> Overall Goals	Deveney
> Methodology Overview	Deveney
> Reactivity Initiated Accident (RIA) Requirements	Deveney
> Analysis Methods	Deveney
◆ Computer Codes for Rod Ejection Accident (REA) Methods	
◆ Boundary Conditions and Uncertainties	
> U.S. EPR Sample Problem Results	Witter
> Conclusions	Witter
> Summary and next steps	Sloan

U.S. EPR Rod Ejection Accident Methodology Topical Report



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Supervisor, Neutronics Methods
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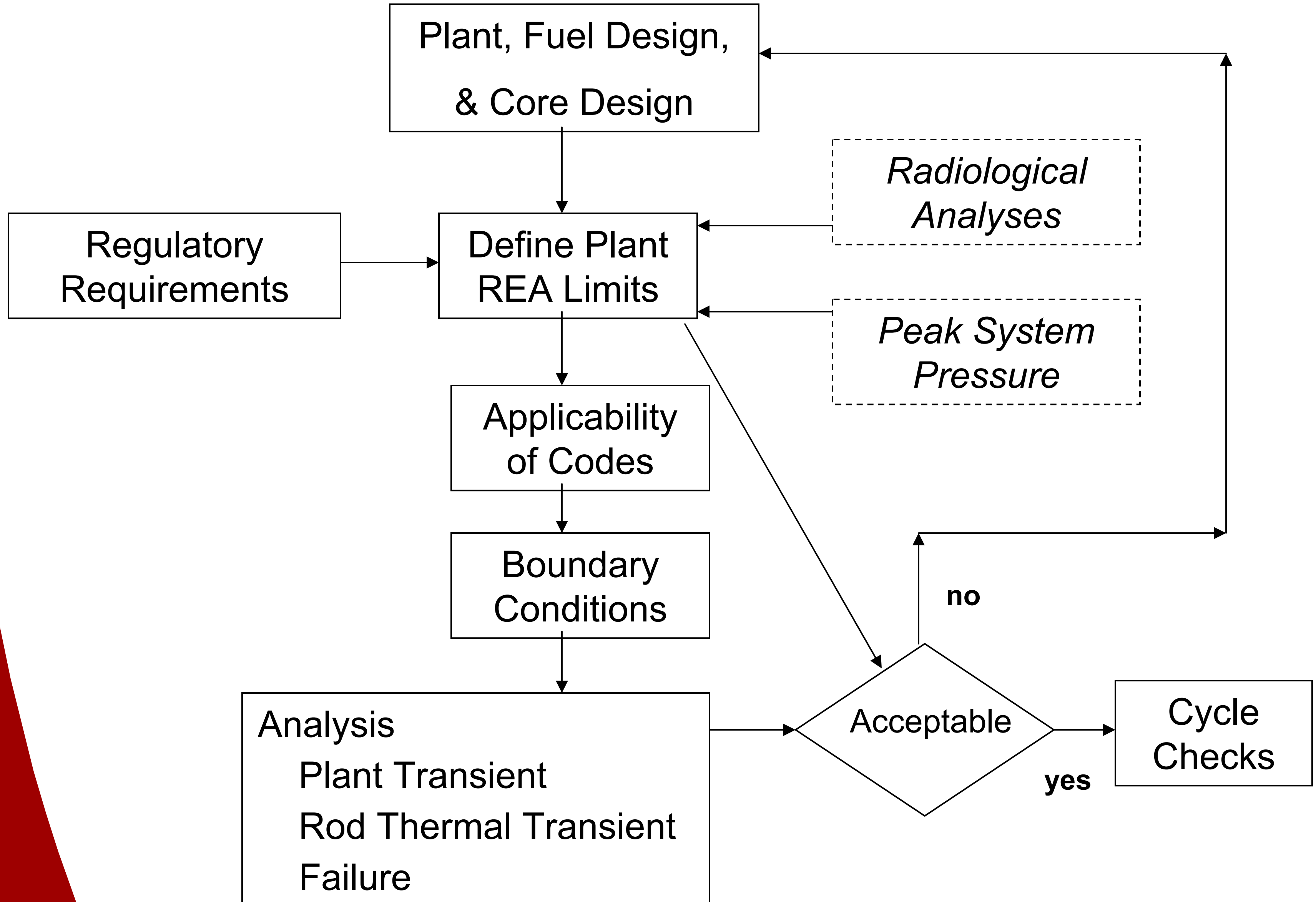
Overall Goals

- An approach that builds upon existing codes and methods
  - Parallel to existing methods except 3-D kinetics
  - Key parameters outlined by PIRT for PWR REA addressed
  - No PCMI coolability issues
- Method minimizes burnup dependencies
- Allows simple cycle specific confirmation

Methodology Overview



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Reactivity Initiated Accident (RIA) Requirements

RIA Limit Requirements

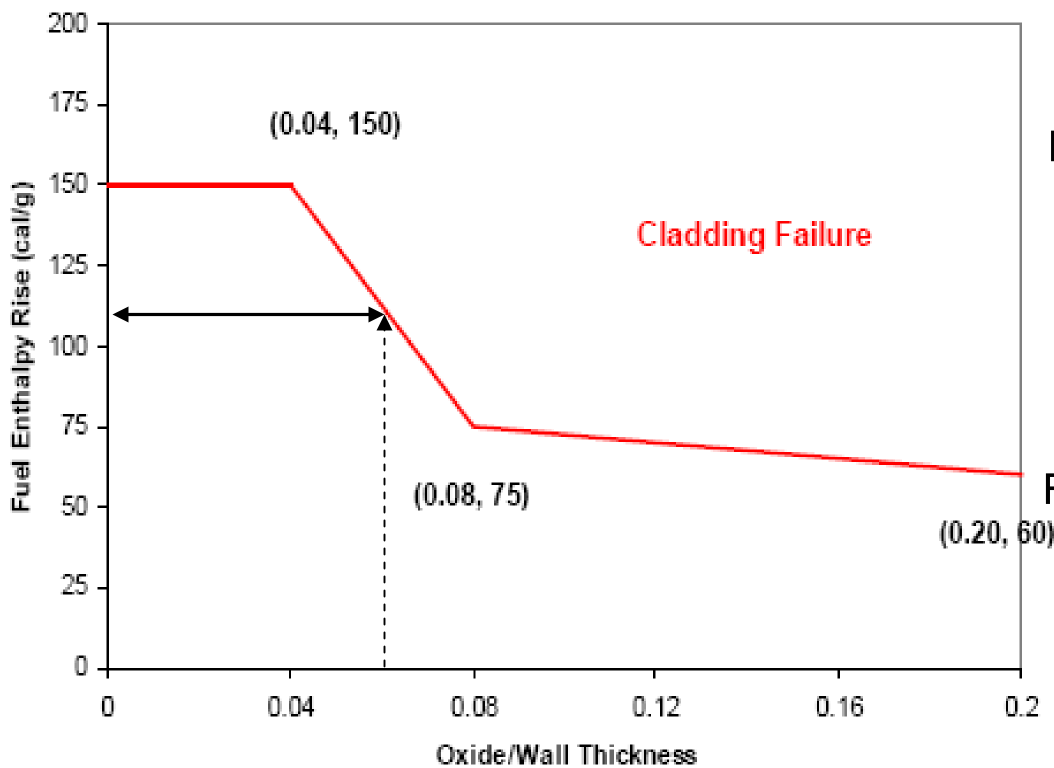
> **Summary of SRP Section 4.2 Appendix B**

- **Cladding failure**
  - **PCMI Δcal/g versus oxide thickness**
  - **Total Enthalpy limit of 170 cal/g for pins below system pressure and 150 cal/g for pins above system pressure for < 5% power**
  - **DNBR for > 5% power**
- **Coolability**
  - **230 cal/g limit**
  - **Preclude incipient melt conditions**
  - **Pressure boundary, reactor internals and fuel assembly structural integrity**
  - **No loss of coolable geometry due to fuel fragmentation and ballooning**
- **Radiological RIA impacts**
  - **Failed rods include enhanced transient fission gas release for energy depositions > 31.2 Δcal/g**
- **No deviations taken for U.S. EPR**

RIA Requirements
U.S. EPR PCMI Limits

U.S. EPR Limiting M5™ Fuel Rod from 0 to 62 GWD/MTU

FIGURE B-1: PWR PCMI Fuel Cladding Failure Criteria



Max Oxide/Wall =0.061

For limiting rod at 62 GWD/MTU

Results in PCMI limit of

110 cal/g

For rods from 0 to 62 GWD/MTU

RIA Requirements
REA Analysis Limits for the U.S. EPR

- Maximum Δcal/g $\leq$ 110 for PCMI
- Maximum total cal/g $\leq$ 150 for all powers
- Maximum fuel temperatures $\leq$ minimum rim melt temperature
  - Melt temperature at the maximum rim burnup for a rod average burnup of 62 GWD/MTU which is the lowest value for all burnups
  - Reduced by the appropriate uncertainty
- Maximum clad temperatures $\leq$ phase transition temperature
- Coolability concerns are avoided since conditions for fuel expulsion and ballooning are precluded
- Radiological consequences are based on equivalent DNBR failures.
  - The maximum number of allowed failures due to only DNBR is determined based on the radiological evaluation
  - The number of failures for REA are counted when MDNBR is exceeded
  - This number is increased for the enhanced transient fission gas release for energy depositions > 31.2 Δcal/g
  - Total must be less than the maximum number of DNBR only failures
- Limits are set to avoid burnup dependencies

Analysis Methods:
Computer Codes for REA Methods

Computer Codes for REA Methods Requirements

- NRC approved computer codes
- Codes/Methods capable of evaluating the parameters in "Phenomenon Identification and Ranking Tables (PIRTs) for Rod Ejection Accidents in Pressurized Water Reactors Containing High Burnup Fuel," NUREG/CR6742
- 3-D Kinetics with T-H and fuel temperature feedback
- Open channel T-H and fuel thermal model capable of calculating temperatures and DNBR related parameters
- Fuel performance code capable of providing fuel, gap, and cladding thermal properties as a function of temperature and burnup
- A plant system code capable of calculating system behavior versus time as well as a conservative estimate of trip actuation
- The data from the codes can be separately passed to each other or the codes could be directly coupled in the time solution domain

Computer Codes for REA
NRC Approved Codes

- NEMO-K - BAW-10221PA
  - Includes benchmarks for ejected rod simulations
  - This REA methods topical includes a subset of these comparisons and some additional comparisons
- LYNXT - BAW-10156A, Rev. 1
  - Includes ejected rod simulations
  - This REA methods topical includes REA comparisons with COPERNIC
- COPERNIC - BAW-10231PA, Rev. 1
  - Establishes fuel rod thermal properties with temperature and burnup
- S-RELAP5 - EMF-2310PA Revision 1
  - Used for the system input validation. It is approved for REA peak pressure evaluations

Computer Codes for REA
U.S. EPR REA Sample Problem Approach

- COPERNIC provides the fuel thermal properties for both NEMO-K and LYNXT simulations
- The REA occurs fast enough that the plant transient time dependence can be separated into a core model (NEMO-K) and system model (S-RELAP5)
- The NEMO-K power level and power distribution information is analyzed using LYNXT to obtain the temperatures and DNBR as a function of time
- S-RELAP5 is used to provide or validate the system inputs of inlet temperature, pressure, and flow boundary conditions to both NEMO-K and LYNXT

Computer Codes for REA
Added Features for REA and U.S. EPR

- NEMO-K Features
  - Flux rate trip
    - Excore signal model
    - Rate lagged processed signal
    - 2/4 trip logic and delays
    - Rod drop
  - Adjustment factors for uncertainties
  - Pellet weighted temperature for cross sections
- LYNXT Features
  - Increased the number of solution locations in the fuel pellet to more accurately model the peak rim fuel temperatures during an REA
  - Added temperature dependent lookup tables to provide the fuel, gap, and clad thermal properties from COPERNIC or other fuel performance codes
- The same temperature dependent gap conductance model is used in both NEMO-K and LYNXT
- S-RELAP5 model input changes
  - Point kinetics turned off
  - Power versus time input from neutronics simulation (NEMO-K)

Analysis Methods:
Boundary Conditions and Uncertainties

Boundary Conditions and Uncertainties Requirements

- This section addresses the requirements for the boundary conditions and uncertainties
- Parameters outlined in the referenced PIRT are also discussed
  - Plant transient analysis
  - Transient fuel rod analysis
    - The PCMI related parameters are not significant since they are effectively replaced by the cal/g limits
    - The thermal related parameters are retained
- Each of the parameters are discussed with respect to the need to bound, to apply uncertainty, or to demonstrate it to be of negligible consequence

Boundary Conditions and Uncertainties
U.S. EPR Sample Problem

> NEMO-K

> LYNXT

> Initial conditions

> Failure analysis

Boundary Conditions and Uncertainties U.S. EPR Sample Problem - NEMO-K

> The NEMO-K conditions are initialized with uncertainties applied to:
- Ejected rod worth
- Delayed neutron fraction
- Doppler temperature coefficient
- Moderator temperature coefficient

> Rationale is provided for the conditions of the remaining variables outlined by the PIRT for the plant transient simulations with NEMO-K.
- Rate of reactivity insertion
- Reactor trip reactivity
- Power peaking
- Heat capacity
- Fuel conductivity
- Gap conductance
- Coolant heat transfer
- Fractional heat deposited in fuel
- Pellet radial power profile

Boundary Conditions and Uncertainties U.S. EPR Sample Problem NEMO-K (cont'd)

- Other variables are also examined which may affect DNBR predictions
- Core design
  - An 18 month equilibrium core design is used as the base analysis
  - NEMO-K base results are compared to Cycle 1
    - When key parameters are the same, a very different core design yields similar results
    - Base analysis can be used to bound future cycles

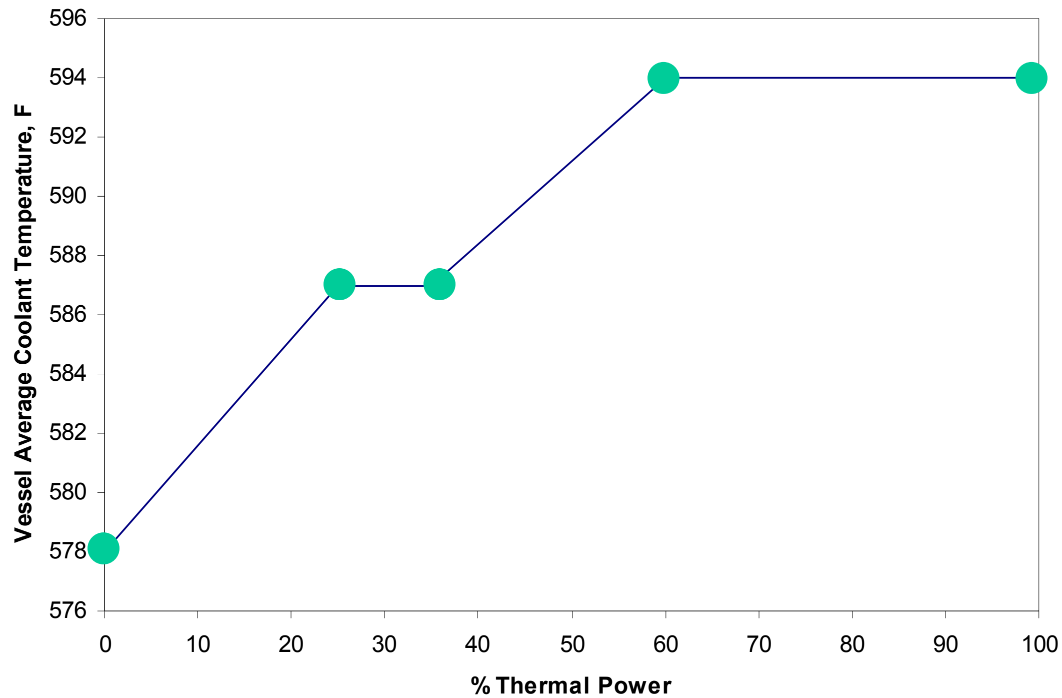
These conditions form the basis for the NEMO-K REA initial conditions and transients

Boundary Conditions and Uncertainties U.S. EPR Sample Problem LYNXT

- The LYNXT results are run with uncertainties applied to:
  - Power peaking- measurement uncertainty, calculational allowance, fuel rod and assembly bow
  - Pellet and cladding dimensions – engineering hot channel factor locally applied in addition to power considerations
  - CHF and failure is assumed when the MDNBR reaches the design limit of the correlation
- Rationale is provided for the conditions of the remaining variables outlined by the PIRT for the LYNXT simulations
  - Cladding oxidation
  - Coolant conditions
  - Transient power
  - Heat resistances
  - Transient coolant heat transfer coefficient
  - Transient coolant conditions
- For each NEMO-K case, two LYNXT cases are run with fuel thermal parameters at minimum and maximum burnup expected at BOC and EOC to ensure that the range of heat transfer conditions are analyzed

Boundary Conditions and Uncertainties
U.S. EPR Sample Problem Initial Core Power Level

U.S. EPR average temperature versus power level



> **The percent power levels at 0, 25, 35, 60, 100 are analyzed as the initial conditions prior to rod ejection.**
  - **Endpoints of HZP and HFP will likely be limiting.**
  - **Since DNBR is one of the main failure criteria, the failures may be sensitive to the initial coolant temperature.**

Boundary Conditions and Uncertainties
U.S. EPR Sample Problem Initial Conditions

- To establish bounding values for the key parameters to avoid the need for a cycle specific analysis, several U.S. EPR cycles are surveyed
- Adverse xenon distribution obtained within LCO limits
- The limiting value for BOC and EOC conditions at HZP and HFP are obtained for
  - Ejected rod worth
  - Delayed neutron fraction
  - Doppler temperature coefficient
  - Moderator temperature coefficient
- To these values additional operation allowance and uncertainty are added
- NEMO-K simulations are run with these boundary conditions at the various power levels at BOC and EOC

Boundary Conditions and Uncertainties U.S. EPR Sample Problem Ejected Rod Worths

> **An example of this process is shown below:**

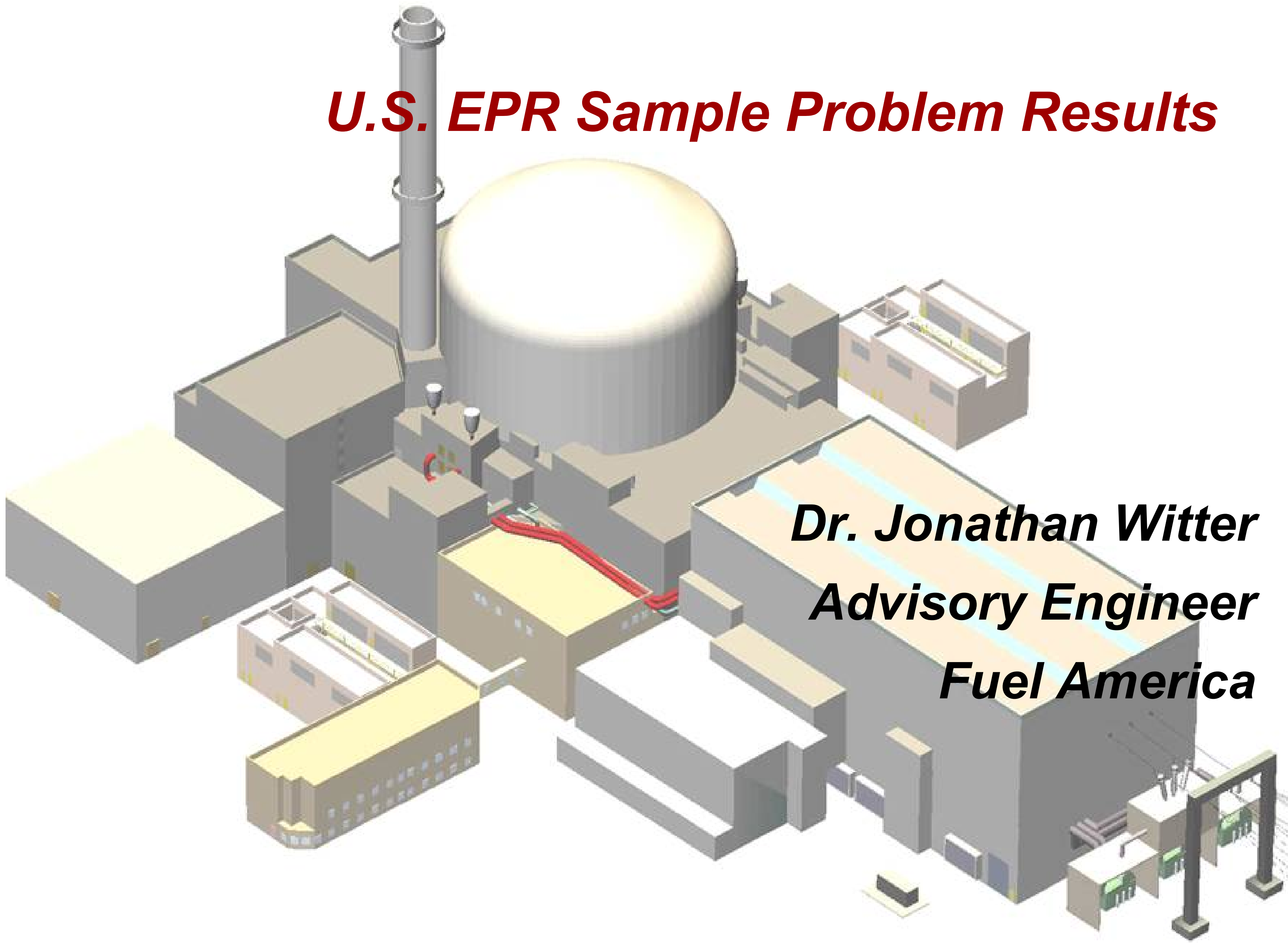
Case	Maximum Ejected Rod Worth in cycles 1, 2, 3 and Eq cycle (pcm)	Ejected Rod Worth in NEMO for the Example REA Analysis (pcm)
BOC, HZP	231	433
BOC, HFP	31	64
EOC, HZP	319	634
EOC, HFP	43	97

Boundary Conditions and Uncertainties
U.S. EPR Sample Problem Failure Conditions

- The minimum DNBR Safety Design Limit is used as a failure criterion
- Different assembly power distributions versus time from NEMO-K are run in LYNXT that have different changes in the peaking during the transient simulation
  - The higher the initial power the lower the change in the peak can be before failing
- The LYNXT power is scaled up or down by a constant value until the results will not exceed the criteria above
- Fuel rod powers higher than the scaled value on $F_{\Delta H}$ or F_Q will be assumed failed
- Fission Gas Release will be increased by the equation in SRP 4.2 Appendix B

$$TFGR = [(0.2286 \times \Delta H) - 7.1419]$$

U.S. EPR Sample Problem Results



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U.S. EPR Sample Problem Results

- Results for BOC HZP, BOC HFP, and EOC HZP are presented
  - NEMO-K results- Fraction of Power (FOP) and Peaking ($F_{\Delta H}$ and F_Q) versus time
  - System response for no flux rate trip conditions
  - LYNXT results- MDNBR, maximum fuel, average fuel and maximum clad temperatures versus time
- Summary results for all analyzed conditions

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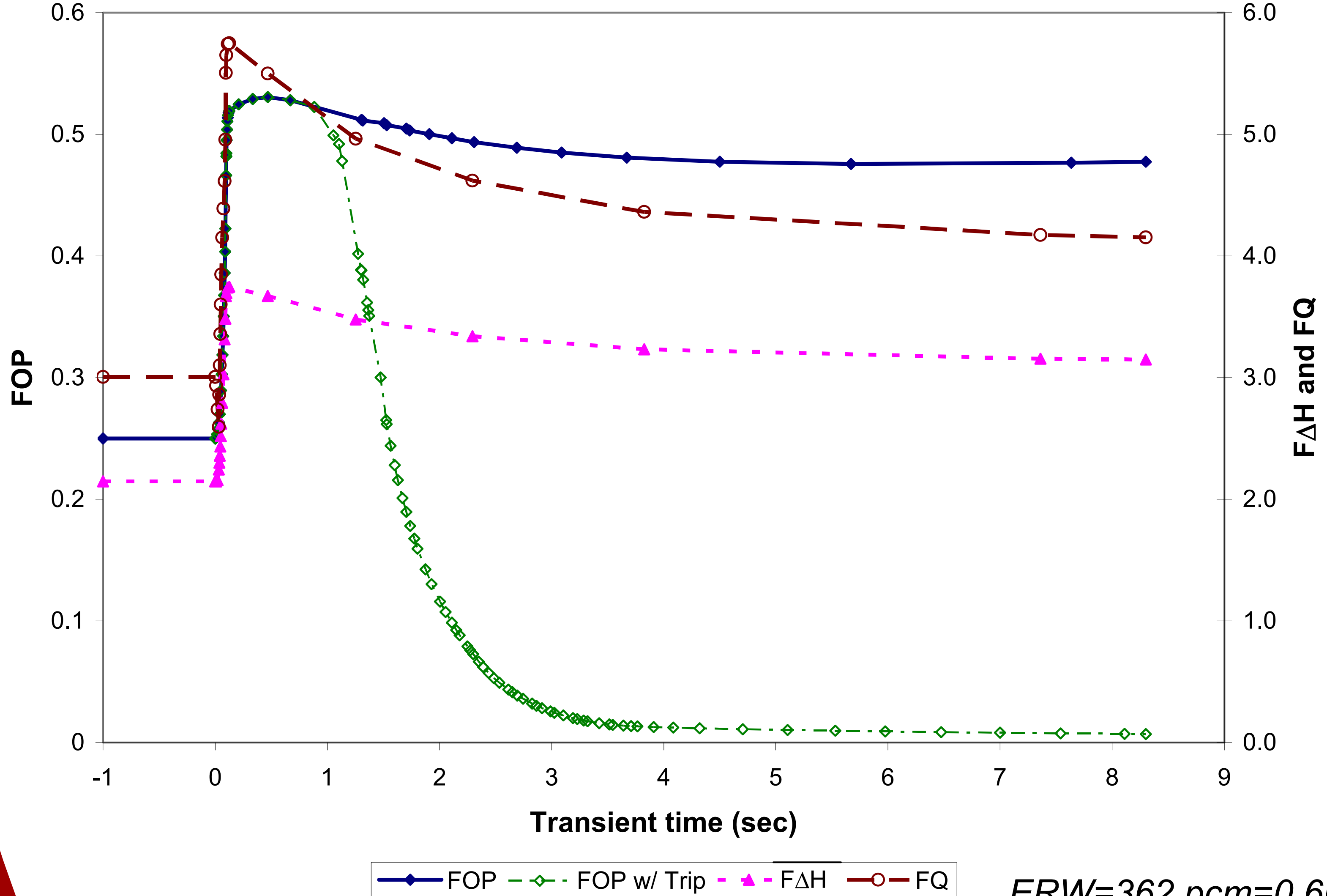
U.S. EPR Sample Problem Results
NEMO-K Results BOC HZP

- The selected ejected rod worth for BOC HZP is not prompt critical
- The prompt jump doubles the power which is insignificant when starting at less than 5% power
- Results are bounded by the 25% initial power case with the flux rate trip disabled

U.S. EPR Sample Problem Results NEMO-K Results BOC 25% FOP



ERW=362 pcm=0.66$

U.S. EPR Sample Problem Results
Limiting Conditions No Trip

> To obtain the limiting conditions for the no trip simulations, the following steps are performed

- S-RELAP5 is run to estimate the pressure, temperature, and flow conditions that could occur
- NEMO-K is run at numerous conditions to define the highest power
- LYNXT is run with highest power and worst thermal conditions for DNBR

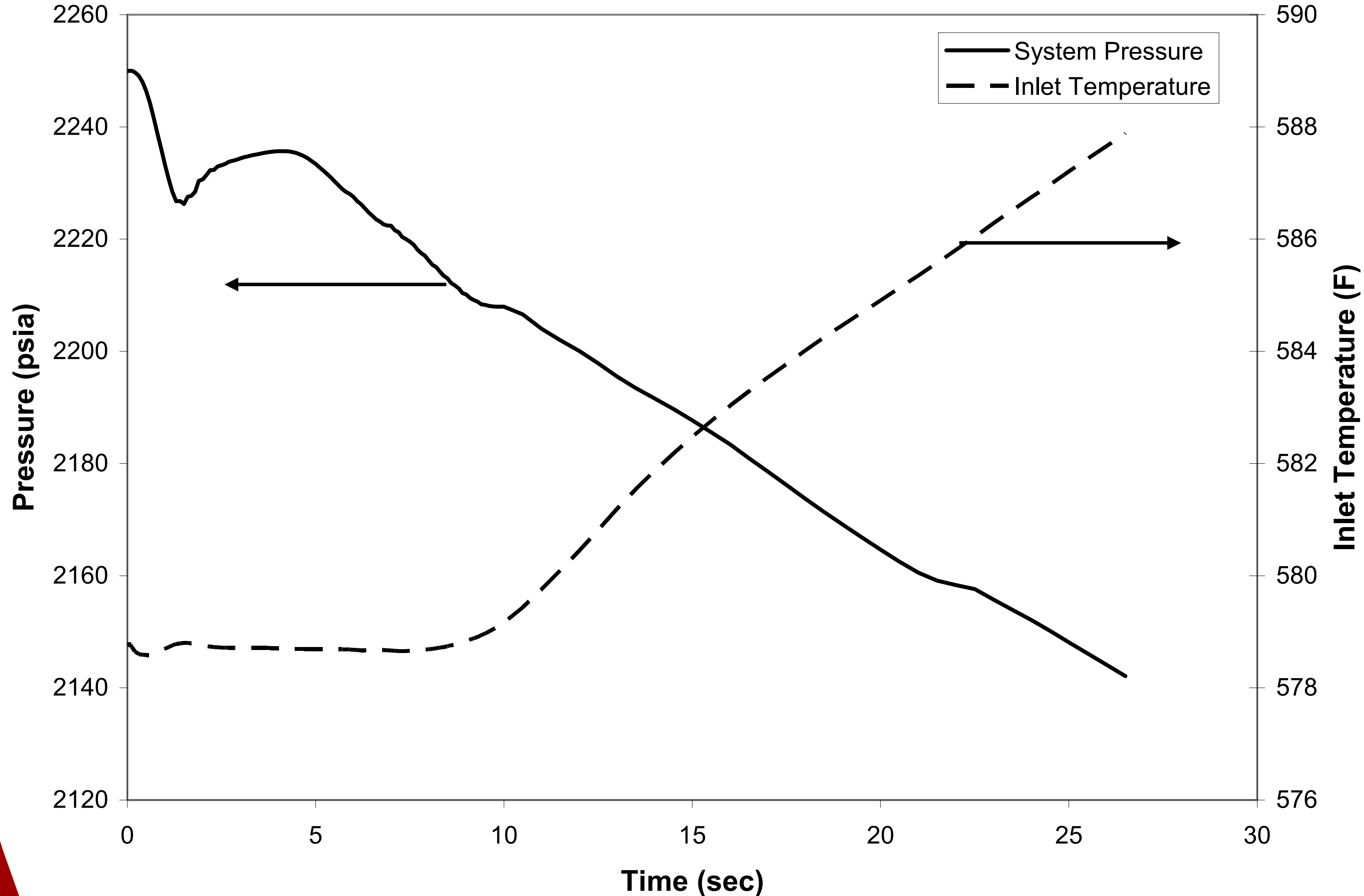
U.S. EPR Sample Problem Results

S-RELAP5 Boundary Conditions for No Flux Rate Trip Conditions

- Power versus time from NEMO-K
  - Near steady state power after ~5 seconds and held constant for remaining time of plant response simulation
- Assumed a leakage hole size of 2.95” in diameter based on control rod flange
  - Degrades thermal performance boundary conditions
- No credit for non-safety control systems
- Incore trips are ignored
  - Simulation terminated by plant system trip

U.S. EPR Sample Problem Results
S-RELAP5 Results for BOC 25% FOP

Trip occurred at 27 seconds on high secondary steam pressure



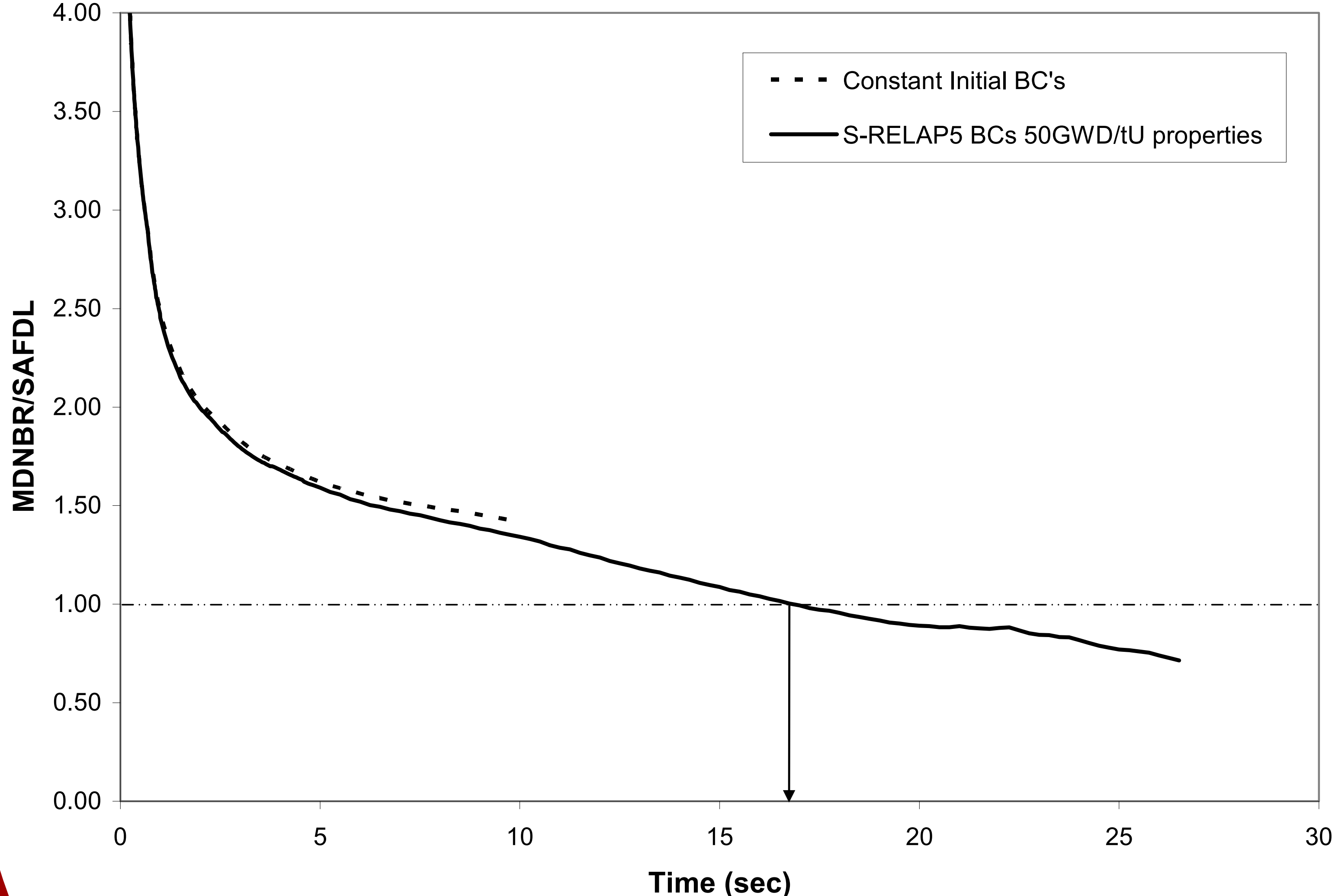
U.S. EPR Sample Problem Results- BOC 25%
NEMO-K Static Power Survey for No Flux Rate Trip

> **NEMO-K is run statically at the ranges of conditions defined by S-RELAP5**

- Pressure change 0 to -100 psi
- Inlet temperature change 0 to +10ºF
- Inlet mass flow 0 to -2.0%
- Individually and together

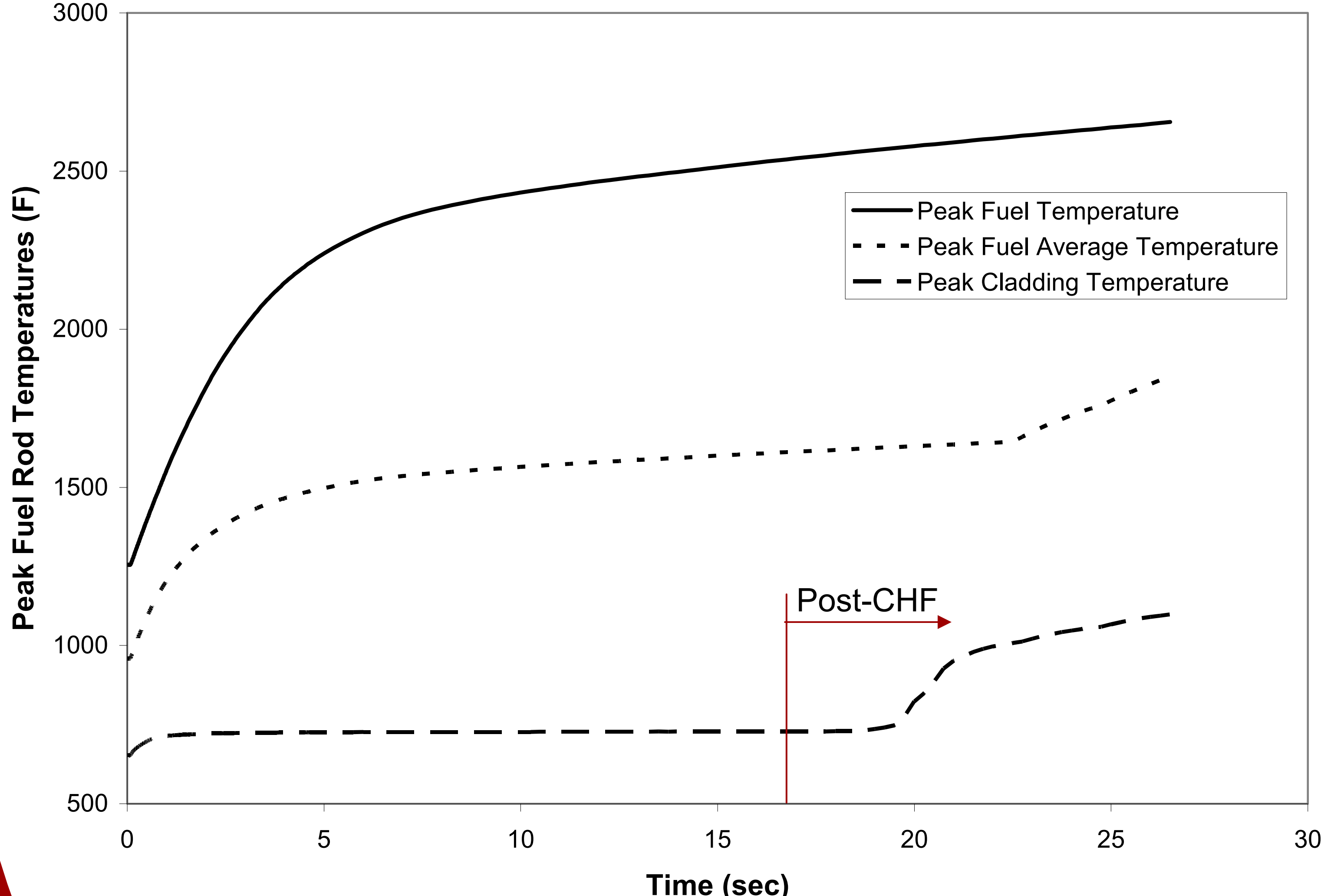
> Highest power calculated (no changes) 55%

U.S. EPR Sample Problem Results
LYNXT MDNBR Results for BOC 25% FOP



ERW=362 pcm=0.66$

U.S. EPR Sample Problem Results
LYNXT Temperature Results BOC 25% FOP



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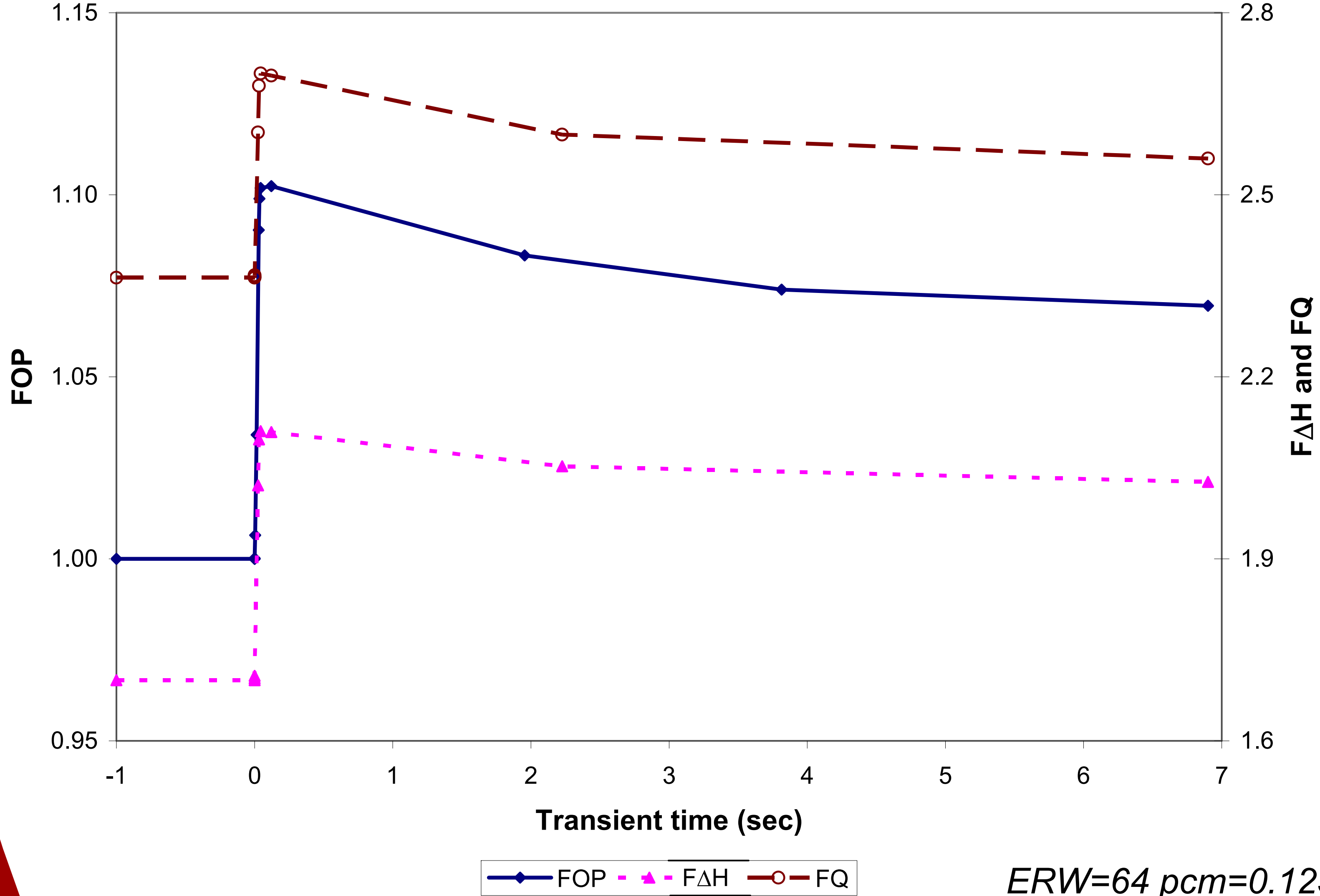
U.S. EPR Sample Problem Results
NEMO-K Results BOC HFP (Maximum Failures)



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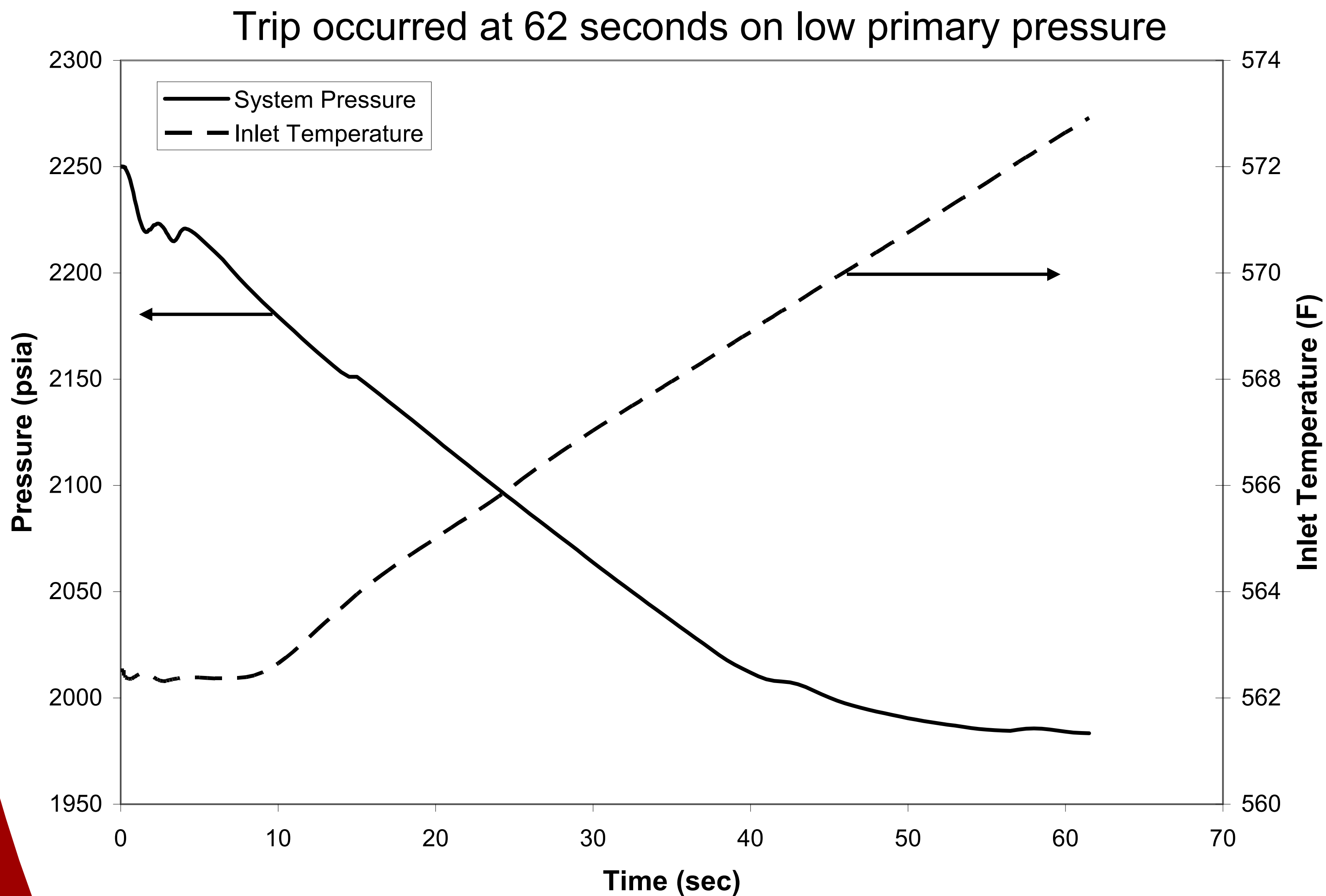
U.S. EPR Sample Problem Results
S-RELAP5 Results for HFP

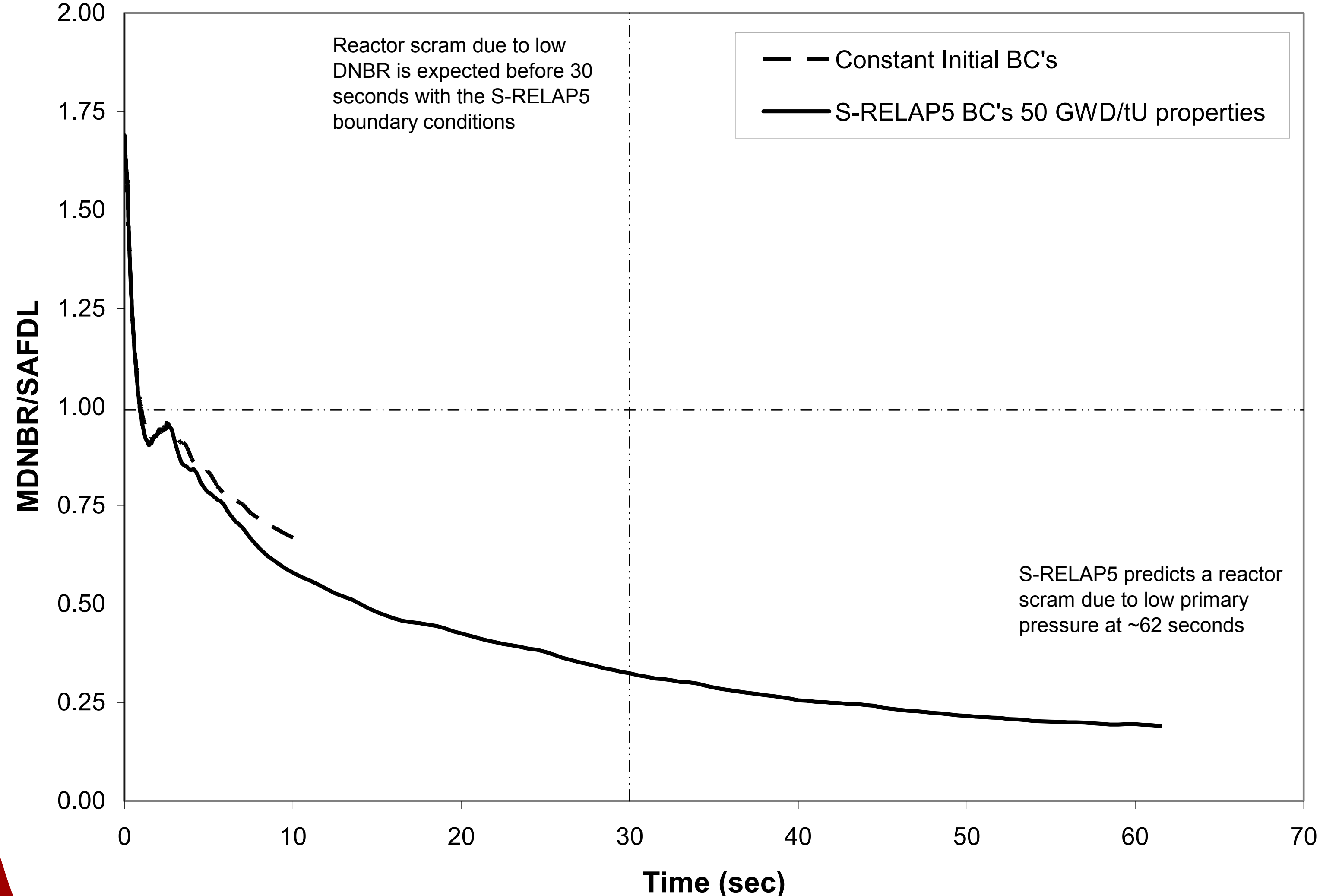


U.S. EPR Sample Problem Results
NEMO-K Static Power Survey for No Flux Rate Trip

Used to provide maximum power level predictions for HFP LYNXT T-H calculations

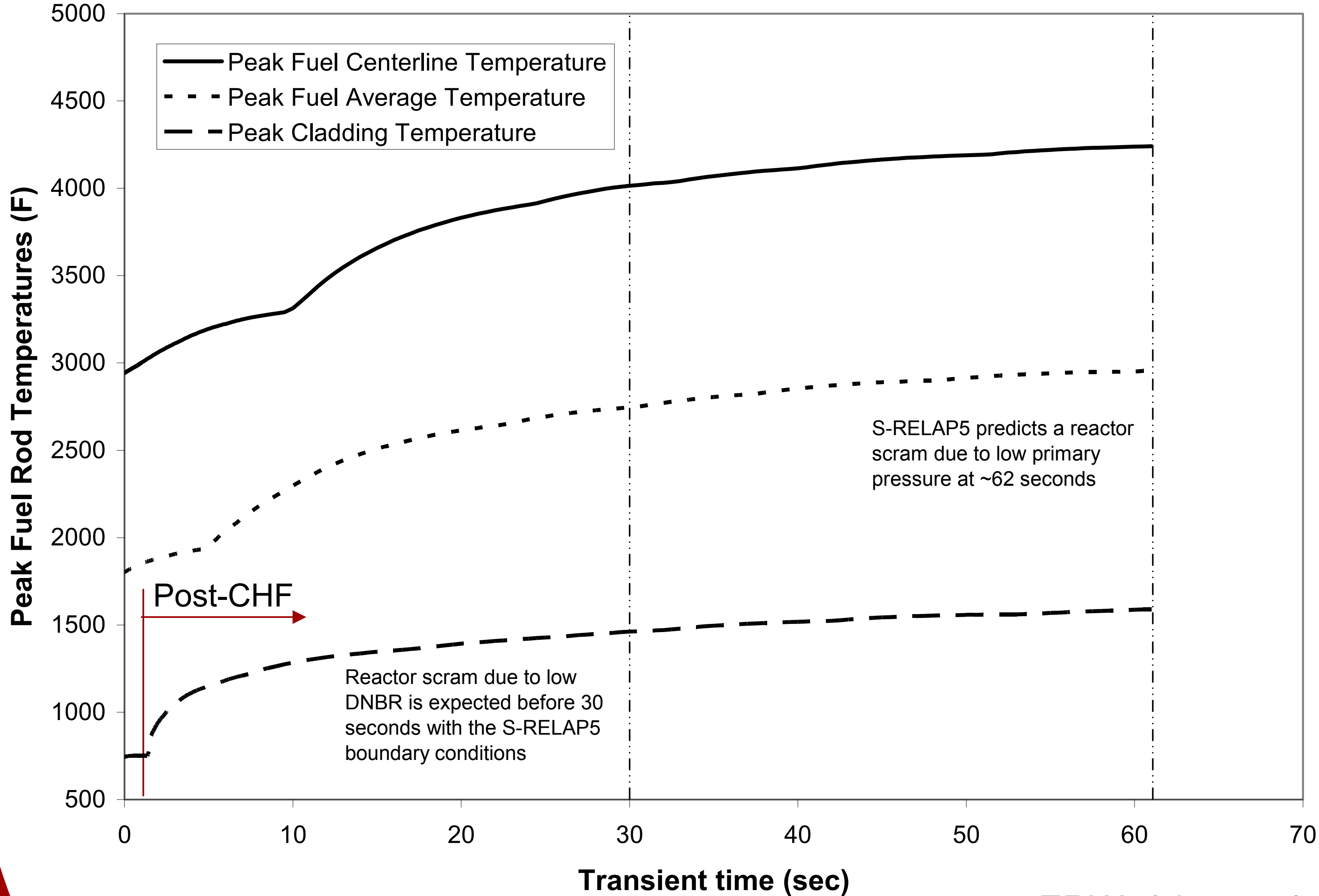
Core Condition	ΔPressure (psi)	ΔTinlet (ºF)	Flow, (%)	Resultant FOP
BOC HFP	0 to -250	0 to +10	0 to -2.5%	1.00 to1.08

U.S. EPR Sample Problem Results
LYNXT MDNBR Results for BOC HFP



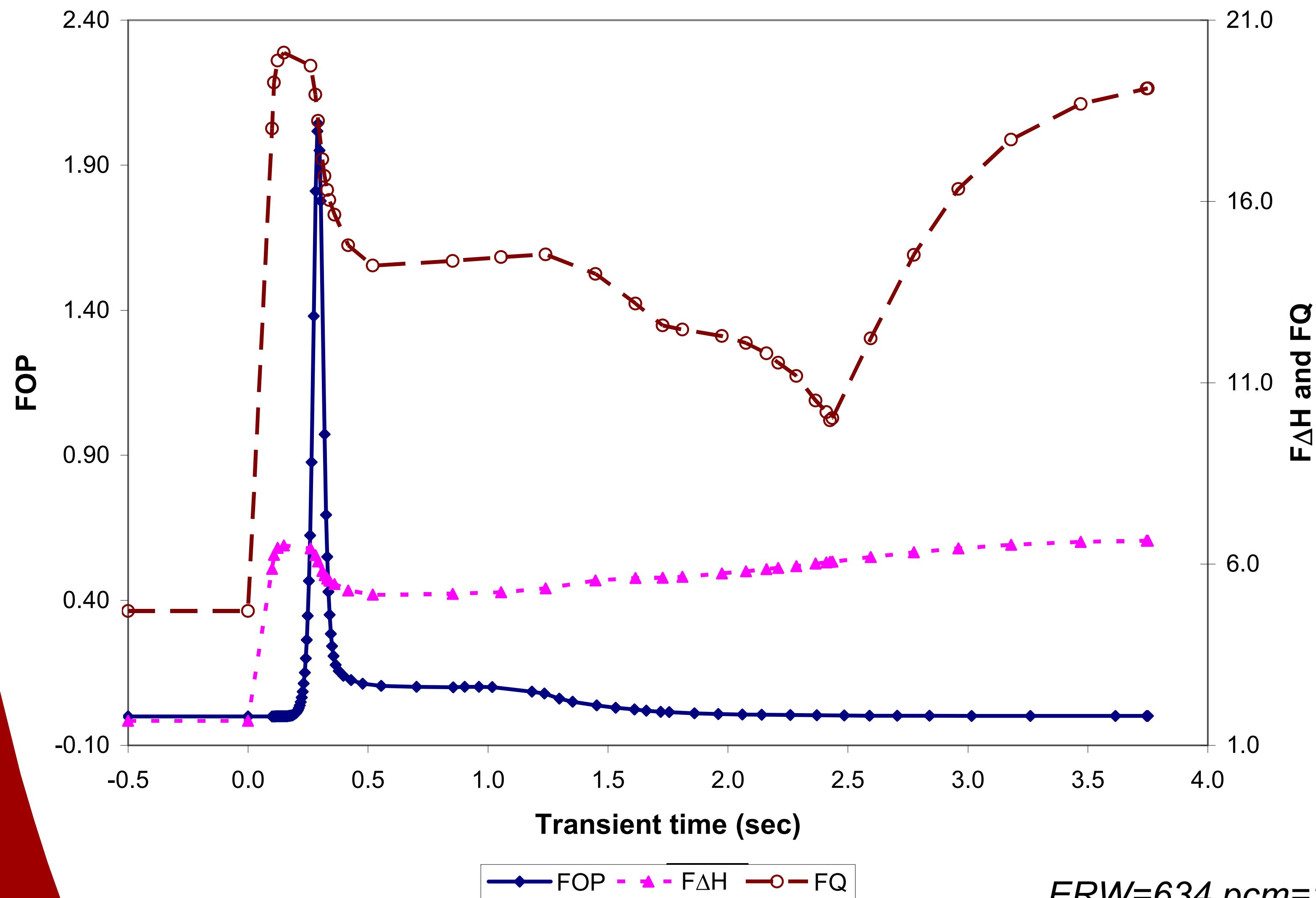
ERW=64 pcm=0.12$

U.S. EPR Sample Problem Results
LYNXT Temperature Results for BOC HFP



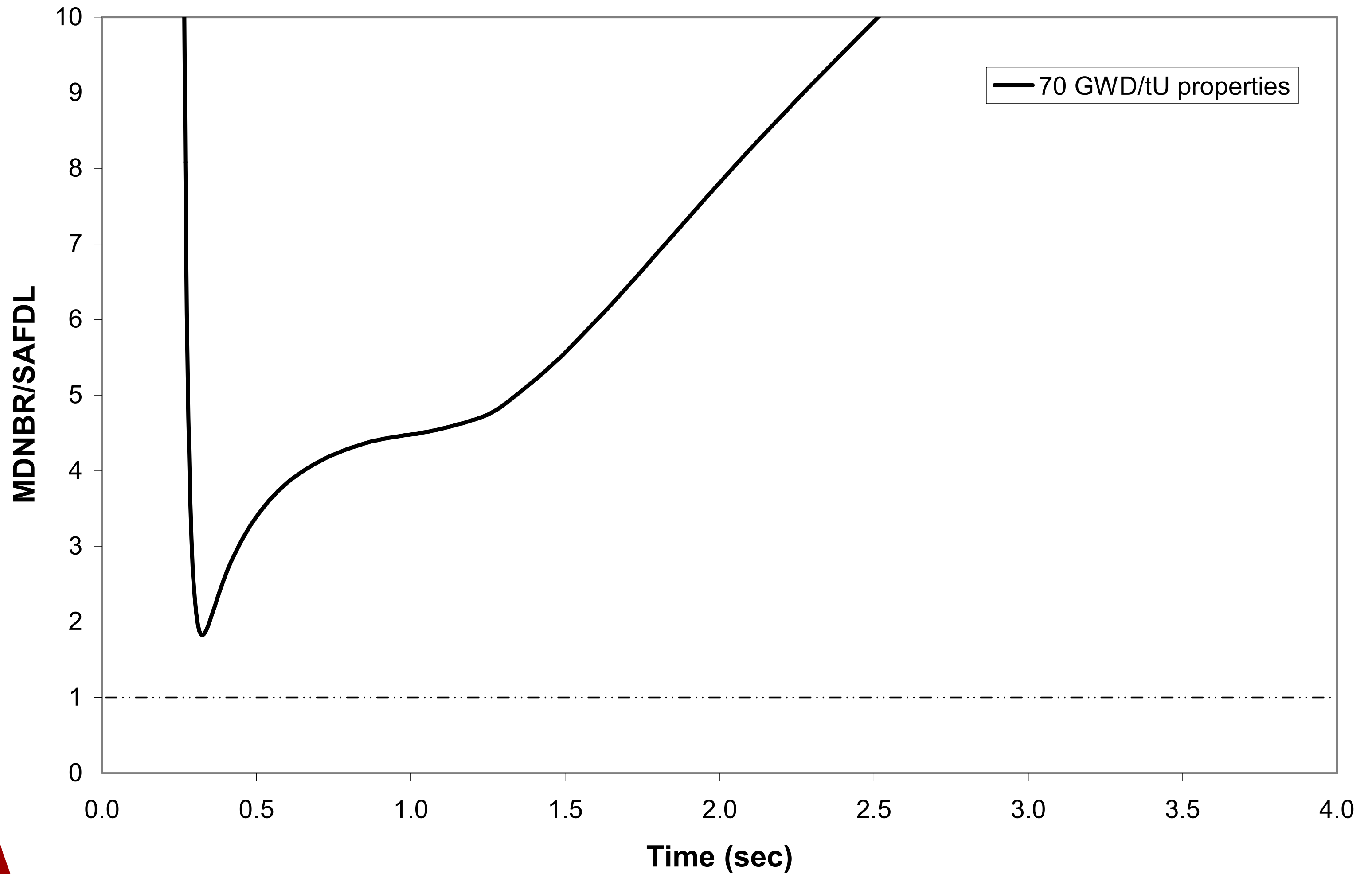
ERW=64 pcm=0.12$

U.S. EPR Sample Problem Results
NEMO-K Results EOC HZP (Maximum ∆cal/g)



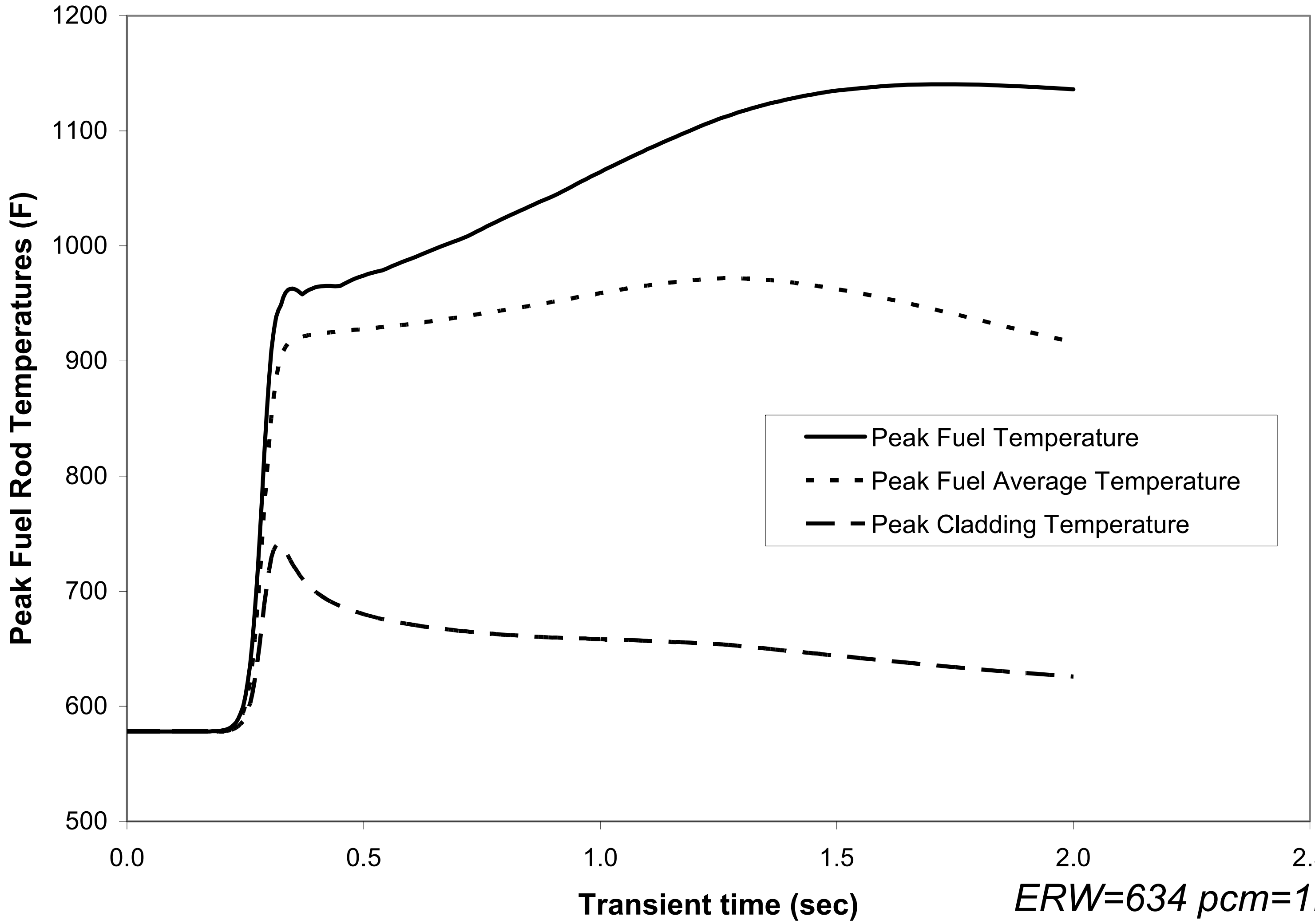
ERW=634 pcm=1.35$

U.S. EPR Sample Problem Results
LYNXT MDNBR Results for EOC HZP



ERW=634 pcm=1.35$

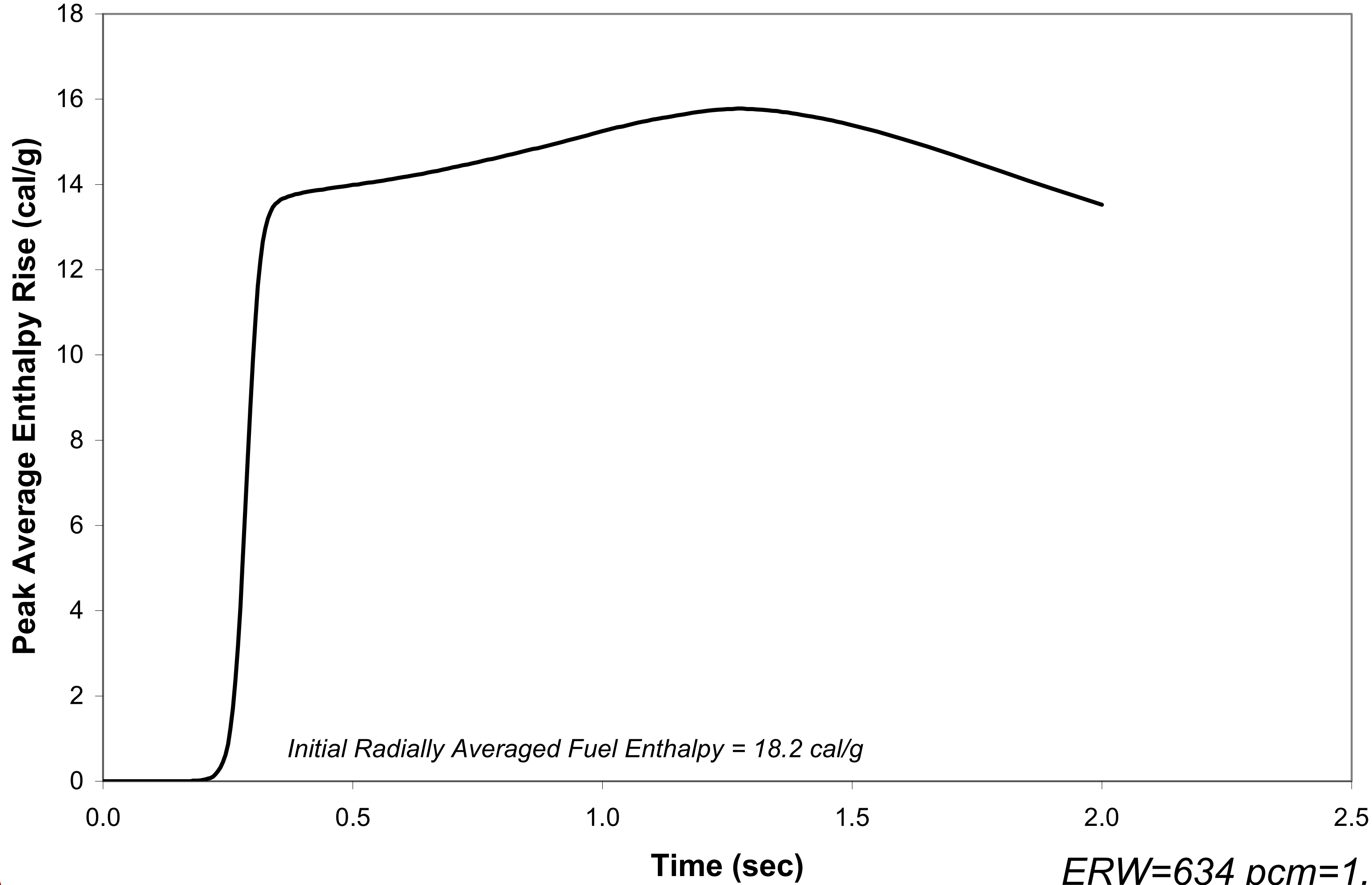
U.S. EPR Sample Problem Results
LYNXT Temperature Results for EOC HZP



ERW=634 pcm=1.35$

U.S. EPR Sample Problem Results

LYNXT Energy Deposition (Δcal/g) Results for EOC HZP



ERW=634 pcm=1.35$

This sample set shows the methodology applied

U.S. EPR Sample Problem Results
Failed Fuel Census

Core Condition	% Failed Rods in Census	
	Prompt < 5 sec	Static > 5 sec
BOC 25% (no trip)	0.0	1.8
BOC 60%	0.0*	0.0
BOC HFP (no trip)	0.3	7.2
EOC 60%	0.0*	0.0
EOC HFP (no trip)	0.0*	1.9

* Conservative peak pin analysis without cycle to cycle peaking allowance did not fail any pins.

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U.S. EPR Sample Problem Results
BOC Results

Parameter	Criterion	0	25	35	60	100
Maximum Neutron Power, FOP	-	0.32	0.55	0.69	0.98	1.10
Maximum cal/g	$\leq$ 150	-	70.4	50.4	63.9	109.4
Maximum Δcal/g, prompt	$\leq$ 110	-	10.0	10.9	11.8	7.2
Max. Fuel Temperature, ^{o}F	<rim melt	-	2655	1901	2529	4014
Maximum Cladding Temperature, ^{o}F	$\leq \varphi^{a}$	-	1098	727	951	1461
MDNBR/SAFDL Normalized	$\leq$ 1.0 for failure	-	0.71	1.86	0.96	0.33
Time of Trip (start of safety bank insertion), seconds	-	No Trip	No Trip[b]	0.850	0.825	No Trip
Equivalent nominal rods failed, %	$\leq$ 30	0	1.8	0	0	7.2

[a]Phase transition temperature for M5™
[b]Trip is disabled to bound consequences of powers lower than 25%.

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U.S. EPR Sample Problem Results
EOC Results

Parameter	Criterion	0	25	35	60	100
Maximum Neutron Power, FOP	-	2.04	1.75	1.75	1.58	1.17
Maximum cal/g	$\le$ 150	33.9	62.2	64.6	73.1	103.4
Maximum Δcal/g, prompt	$\le$ 110	13.8	10.2	9.0	6.0	7.9
Max. Fuel Temperature, °F	<rim melt	1140	2402	2534	2987	3856
Maximum Cladding Temperature, °F	$\le \varphi$[a]	741	777	774	1062	1337
MDNBR/SAFDL Normalized	$\le$ 1.0 For failure	1.82	1.36	1.33	0.97	0.46
Time of Trip (initiation of safety bank insertion)	-	1.000	0.850	0.850	0.825	No Trip
Equivalent nominal rods failed, %	$\le$ 30	0	0	0	0	1.9

[a] Phase transition temperature for M5™

U.S. EPR Sample Problem Results
Cycle to Cycle Checklist

> **3-D Kinetics not sensitive to cycle variations**
> **Static initial conditions can be used to characterize the applicability of the analysis of record**
> **Key parameters for HZP and HFP at BOC and EOC are compared to analysis of record**

U.S. EPR Sample Problem Results
Cycle to Cycle Checklist

Parameter	Acceptable values	Cycle Specific Criteria			
		BOC		EOC	
		HZP	HFP	HZP	HFP
Maximum Ejected Rod Worth, pcm	≤	433	64	634	97
β_{eff}	≥	0.0055	0.0055	0.0047	0.0047
MTC, pcm/°F	≤	2.16	0.01	-19.4	-28.47
DTC, pcm/°F	≤	-1.22	-0.96	-1.52	-1.28
Initial F_Q	≤	NA[a]	2.36	NA[a]	2.10
Static F_Q after ejection	≤	9.89	3.39	20.33	4.78
Maximum Design $F_{\Delta H}$	≤	NA[a]	1.70	NA[a]	1.70
Static $F_{\Delta H}$ after ejection	≤	5.34	2.37	6.51	2.63
Equivalent nominal rods failed, %	≤	0	30	0	30
Trip setpoints	Not Affected[b]				

[a] Not applicable since initial stored energy above the coolant temperature is zero.
[b] Any changes to the flux rate trip or low DNBR trip would have to be reviewed relative to their impact on this accident analysis.

U.S. EPR Sample Problem Results Conclusions

- Provides an REA methodology which meets regulatory requirements based on approved codes
- U.S. EPR sample problem demonstrates
  - Prompt energy deposition less than Δ110 cal/g
  - Total energy deposition less than 150 cal/g
  - No rim fuel melt or centerline fuel melt
  - No coolability issues
  - Failures for example cycle is less than 10% (30% radiological limit)
- Minimal burnup dependence allows simple cycle specific static checks to verify the analysis of record

Summary and Next Steps

Sandra M. Sloan

Summary

> Analysis performed using NRC-approved codes with enhancements

> Consistent with the requirements of 10 CFR 50, Appendix A & NUREG-0800

> Today's NRC feedback will inform development of the topical report and the Design Certification application

Next Steps

- Submittal of U.S. EPR Setpoints Analysis Methods Topical Report (by December 2007)
- Submittal of U.S. EPR Rod Ejection Accident Methodology Topical Report (by December 2007)
- Submittal of POWERTRAX/E Online Core Monitoring Software for the U.S. EPR Report (by December 2007)

Acronyms

BC	Boundary Conditions
BOC	Beginning of cycle
CHF	Critical heat flux
DC	Design certification
DCD	Design control document
DTC	Doppler temperature coefficient of reactivity
(M)DNB(R)	(Minimum) departure from nucleate boiling (ratio)
EOC	End of cycle
ERW	Ejected Rod Worth
FOP	Fraction of power
$F_{\Delta H}$	Maximum relative rod power, axially integrated enthalpy rise
F_Q	Peak relative pellet power
F_Z	Maximum relative axial power shape peaking factor
HZP	Hot zero power
HFP	Hot full power
LCO	Limiting conditions for operation
MTC	Moderator temperature coefficient of reactivity
pcm	percent milli-rho of reactivity (10^{-5} $\Delta\rho/\rho$)
PCMI	Pellet clad mechanical interaction
PIRT	Phenomena identification and ranking tables
PWR	Pressurized Water Reactor
RCSL	Reactor control surveillance limitation
REA	Rod ejection accident
RIA	Reactivity initiated accident
SAFDL	Safety analysis fuel design limit
SRP	Standard review plan
TFGR	Transient fission gas release
T-H	Thermal hydraulic