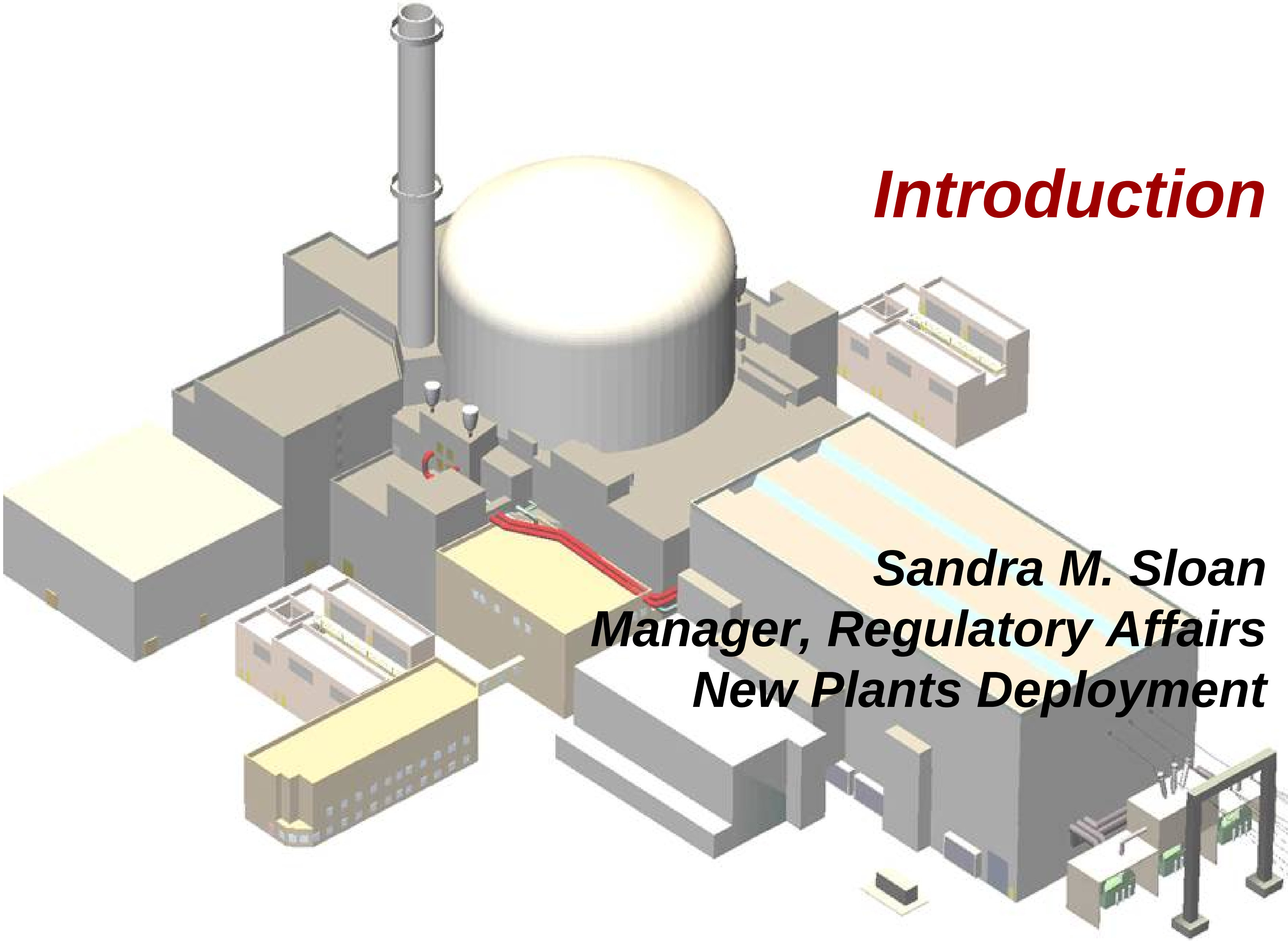
U.S. EPR Pre-Application Review Meeting: Codes and Methods Applicability Topical Report

AREVA NP Inc. and the NRC
August 1, 2006

Introduction



Sandra M. Sloan
Manager, Regulatory Affairs
New Plants Deployment

Meeting Objectives

> Provide overview of U.S. EPR design

> Describe topical report content and approach

> Describe relationship of this topical report to others

Outline

> **Introduction**	**Jerry Holm**
> **U.S. EPR design overview**	**Roger Stoudt**
> **Fuel analysis methods**	**Chris Lewis**
> **Safety analysis methods**	**Robert Salm**
> **Summary and next steps**	**Sandra Sloan**

U.S. EPR
Codes and Methods Applicability Report

Jerry Holm
Manager, Product Licensing
Corporate Regulatory Affairs

Introduction

> **November 2, 2005 meeting**
- **Pre-submittal meeting**

> **NRC approved codes and methods**
- **Minimize NRC review effort**

> **Future topical reports**
- **New or revised methods**

Report Content

> **Fuel analysis methods**
- **PRISM/CASMO**
- **COPERNIC**
- **LYNXT**
- **NEMO-K**

> **Safety analysis methods**
- **SBLOCA**
- **Non-LOCA**

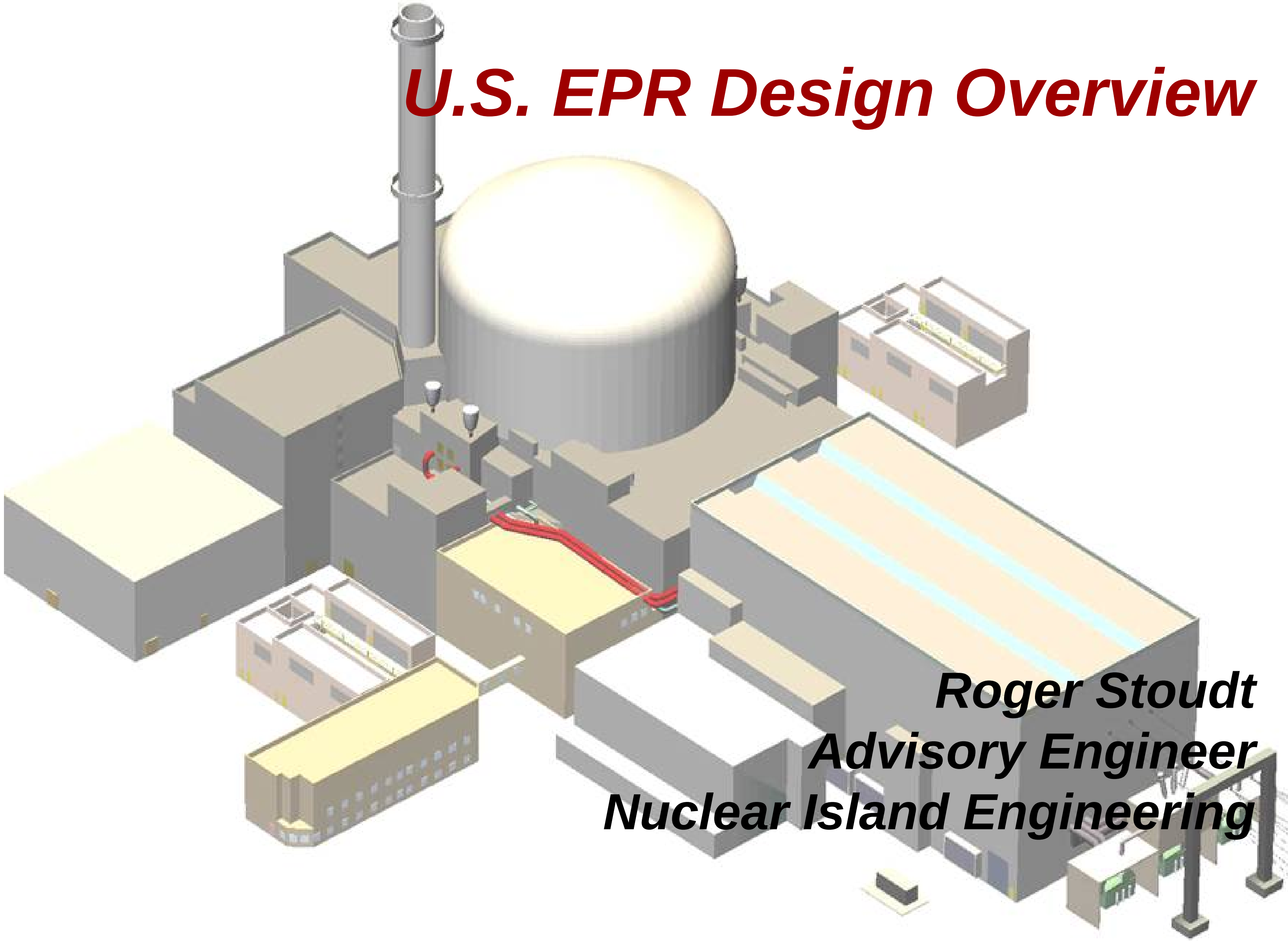
Bases for Methods Applicability Evaluation

- Comparison of physical characteristics of plants and fuel designs for which methods are currently approved and U.S. EPR
- Comparison of phenomena and conditions in currently approved plants and U.S. EPR
- Changes to methods will be documented and supported in the topical report
  - Minimal changes
  - None for most methods

Additional Topical Reports

- CHF correlation
- Large break LOCA methodology
- Fuel mechanical design for U.S. EPR
- Set-point methodology
- RIA methodology

U.S. EPR Design Overview



Roger Stoudt
Advisory Engineer
Nuclear Island Engineering

U.S. EPR Design Overview

> High level plant description

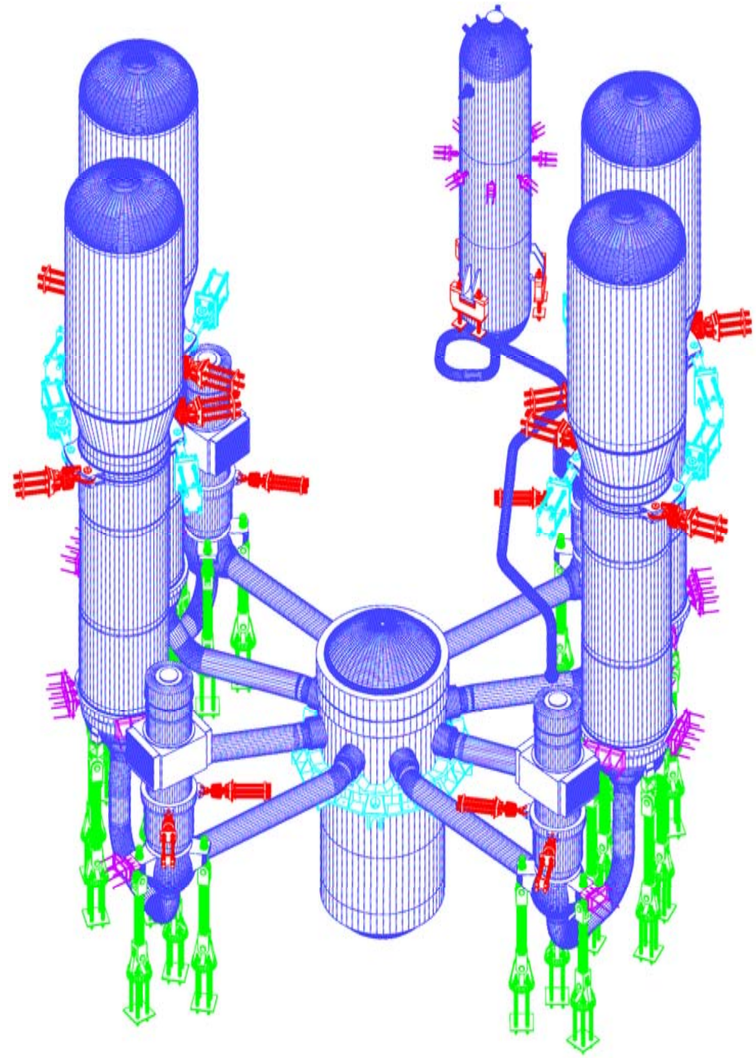
> U.S. EPR similar to current operating PWRs

> U.S. EPR design undergoing conversion to U.S. standards/requirements

Primary System Features

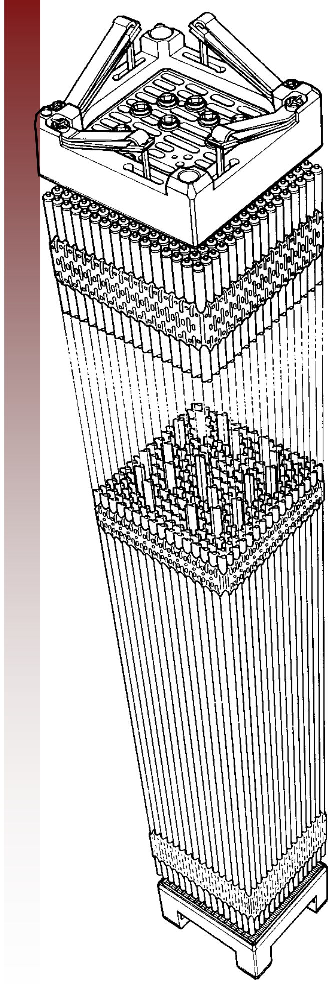
> **Conventional 4-loop design proven by decades of design, licensing and operating experience**

> **Main components enlarged as compared with existing designs to increase margin in transients and accidents**



Fuel Design Proven By Operation

- 17x17
- Typical pitch-to-diameter ratio
- M5® cladding
- Heated length similar to STP
- M5® HTP mixing grids
- Anti-debris lower end fitting
- Significant design margins



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U.S. EPR Fuel Assembly Comparison

	Current 17x17 HTP	U.S. EPR HTP
Lower Nozzle	FUELGUARD™	Same
Fuel Pin Array	17 x 17	Same
Fuel Pin Pitch (in)	0.496	Same
Fuel Rod OD (in)	0.376	0.374
Cladding ID (in)	0.328	0.329
Fuel Pellet OD (in)	0.3215	0.3225
Fuel Pellet TD (%)	95	96
Active Fuel Length (in)	144	165.354
Fuel Cladding	M5®	Same
Spacer Grid in Active Fuel	HTP	Same
Fuel Rods/Assembly	264	265
Guide Tubes/Assembly	24	Same
Instrument Tubes/Assembly	1	0
Guide Tube OD (in)	0.48	0.49

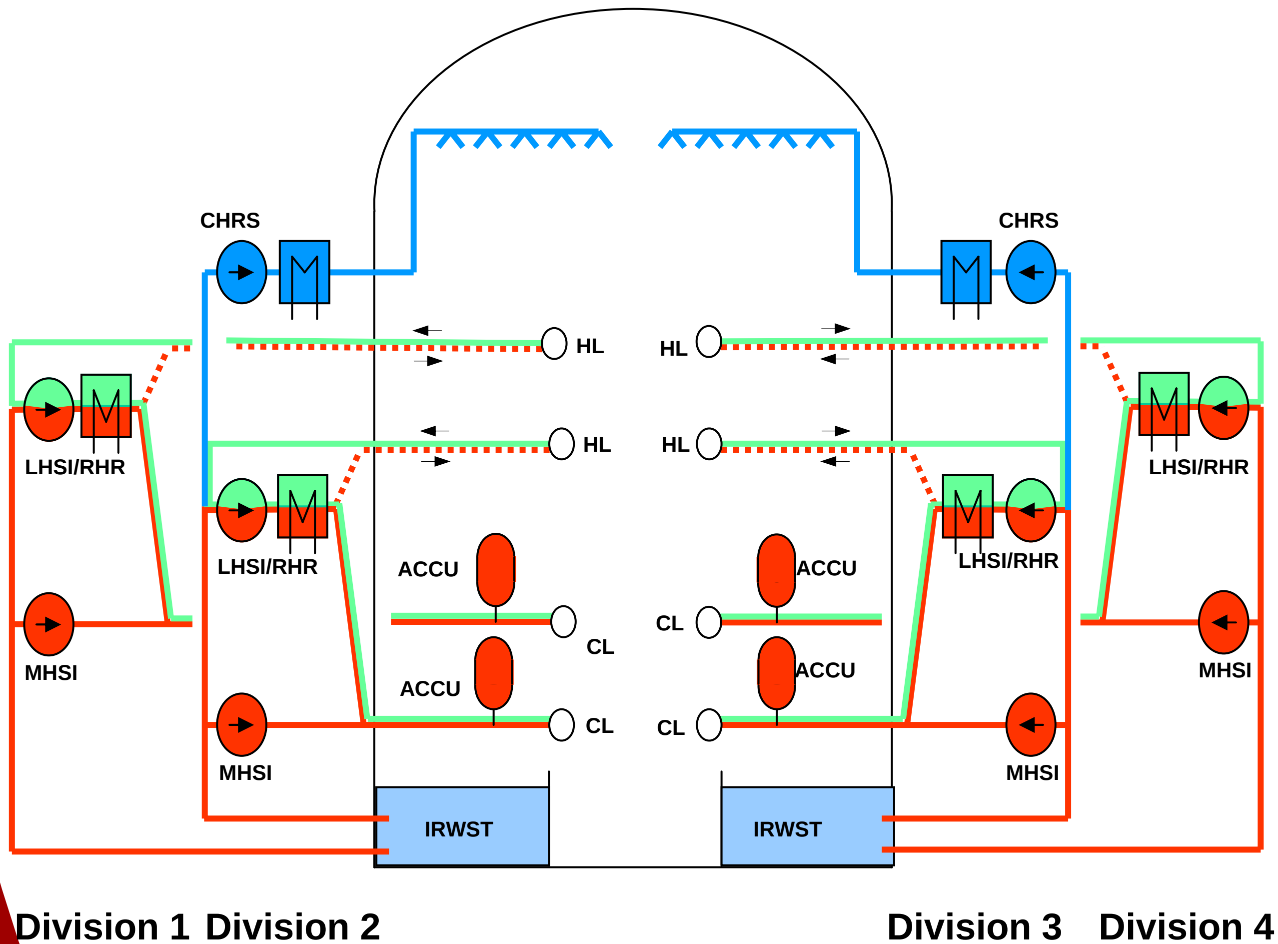
EPR

Reactor Coolant System: U.S. EPR vs. Current U.S. 4-Loop PWRs

> **RCS configuration**

- **Four separate loops – similar arrangement**
- **Pressurizer - similar arrangement**
- **Recirculating steam generators – with axial economizer**
- **Centrifugal reactor coolant pumps**
- **Four safety system trains - similar type, locations**
  - **Emergency feedwater**
  - **ECC accumulator**
  - **ECC pumped injection (medium and low head)**
- **Large dry containment with liner**

Primary System Safety Trains



- > Four-train, independent SIS
- > In-containment borated water storage pool
- > Combined RHRS/LHSI
- > Two-train extra borating system (not shown)
- > Containment spray for severe accident only

Reactor Coolant System: Parametrics

Parameter	U.S. EPR	Typical Current 4-Loop U.S. Design
Thermal power (MW)	~4,500	3,411
Hot leg temp (°F)	625	610
Cold leg temp (°F)	564	547
RCS flow per loop (gpm)	125,000	90,000
Primary system pressure (psia)	2,250	2,250
Total RCS volume (ft^3)	16,245	12,600
PZR volume (ft^3)	2,650	1,800
SG secondary inventory (lbm per SG)	182,000	106,000
Number of fuel assemblies	241	193
Average linear heat rate (kW/ft)	4.98	5.44
Peak linear heat rate (kW/ft)	12.95	13.06
Primary volume/power (ft^3/MW)	3.61	3.69
Secondary mass/power (lbm/MW/SG)	40.4	31.1
PZR steam-to-RCS liquid volume	0.070	0.061
LOCA Break Area/System Volume (1/ft)	3.17 (E-04)	3.27 (E-04)
Accumulator Volume/RCS Volume	0.35	0.30

U.S. EPR Design Features vs. Current U.S. 4-Loop PWR Designs

> Higher thermal power, lower LHR
> Larger primary and secondary volumes
> Longer active core, comparable to STP
> RCS volume/power essentially same
> Comparable cold leg mass flux (flows and flow areas increase with volume and power)

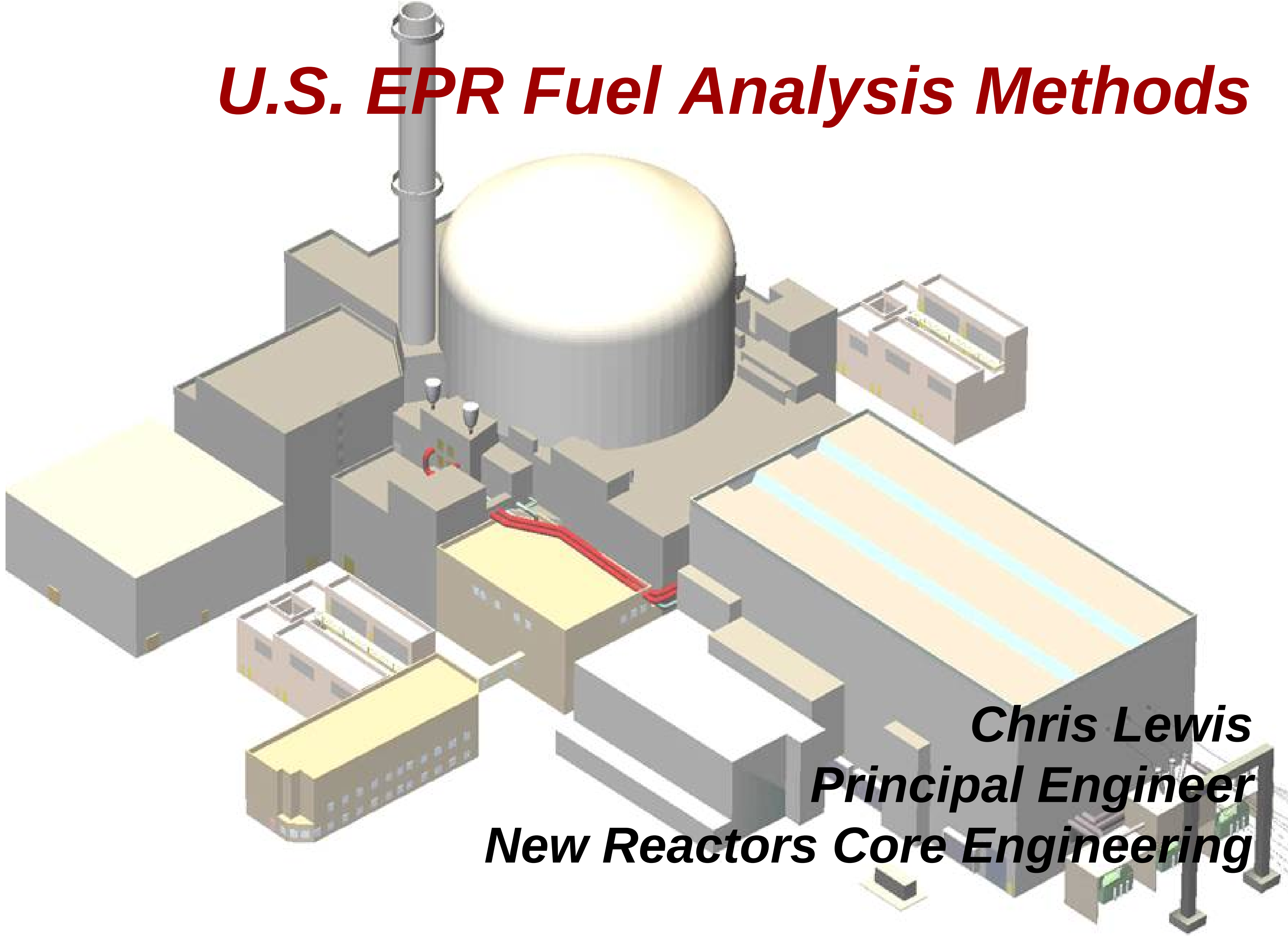
U.S. EPR Design Features vs. Current U.S. 4-Loop PWR Designs (cont.)

> **Medium head SI with safety grade SG cooldown**
  - **Improved SBLOCA performance**
  - **Improved SG tube rupture performance**

> **Elevations**
  - **Top of active core ~6 ft below cold leg (vs ~4 ft on current plants)**
  - **Loop seal elevation at top of active core**
  - **Improved LBLOCA reflooding and SBLOCA loop seal clearing**

> **Volumes**
  - **Pressurizer and SG volumes increased on a relative basis-- improves transient response**

U.S. EPR Fuel Analysis Methods



Chris Lewis
Principal Engineer
New Reactors Core Engineering

Objectives

> **Identify and validate methodologies for U.S. EPR analysis**

- **Neutronics**
- **Thermal-hydraulics**
- **Thermo-mechanical**

> **Present benchmarks and sample analyses for U.S. EPR**

Methodologies

> **Topical report identifies currently approved methodologies selected for use in U.S. EPR Fuel Analysis**

- **Neutronics - core design and neutronics input to safety**
  - **"Reactor Analysis System for PWRs," Volumes 1 and 2, EMF-96-029(P)(A), January 1997**
  - **"NEMO-K A Kinetics Solution in NEMO," BAW-10221P-A, October 1998**
- **Thermal Hydraulics – core hydraulics and DNB analysis**
  - **"LYNXT Core Thermal-Hydraulic Program," BAW-10156A, Revision 1, August 1993**
- **Thermo-mechanical – fuel/fuel rod response**
  - **"COPERNIC Fuel Rod Design Computer Code," BAW-10231PA-00, June 2002**

Methodologies (continued)

> **Additional Supporting Methodologies**

- **“Evaluation of Advanced Cladding and Structural Material (M5®) in PWR Reactor Fuel,” BAW-10227P-A, Revision 1, June 2003**
- **“Incorporation of M5® Properties in Framatome ANP Approved Methods,” BAW-10240P-A, Revision 0, May 2004**
- **“Fuel Rod Bowing in Babcock & Wilcox Fuel Designs,” BAW-10147P-A, Revision 1, May 1983**
- **Extended Burnup Evaluation,” BAW-10186P-A, Revision 2, June 2003**
- **“Fuel Rod Gas Pressure Criterion (FRGPC),” BAW-10183P-A, Revision 0, July 1995**
- **“Statistical Fuel Assembly Hold Down Methodology”, BAW-10243P-A, September 2005**

Neutronics: EMF-96-029(P)(A), "Reactor Analysis System for PWRs," Volumes 1 & 2

> **NRC approved general purpose physics code suite (MICBURN/CASMO-3/PRISM)**
- **Core design**
- **Incore monitoring systems**
- **Neutronics input to safety**

> **Broad range of applications**
- **14x14 to 17x17 fuel lattices**
- **Westinghouse 2-, 3-, and 4- loop plants, variety of CE plants**
- **Various axial fuel configurations**
- **Various burnable poisons (boron BP rods, IFBA, gadolinia)**

Neutronics: EMF-96-029(P)(A), "Reactor Analysis System for PWRs," Volumes 1 & 2 (continued)

- Minor methodology changes
  - 0.625 eV thermal energy cutoff
  - Heavy reflector cross sections
- U.S. EPR configuration similar to U.S. 4-loop core designs
  - 17x17 lattice (.374" rod O.D. and 24 guide tubes)
  - Gadolinia burnable poison
  - ~14 ft active fuel length
  - 241 assembly core
- Benchmarking/validation calculations demonstrate applicability for use on U.S. EPR configurations.
  - Uses new thermal energy cutoff of 0.625 eV
  - Includes plants with aeroball measurement system
  - Characterizes and evaluates heavy reflector modeling methodology

Neutronics: 0.625 eV Thermal Energy Cutoff

- Converges with German code methodology
- All validation calculations use new energy cutoff
- Impact on cold critical pin power measurement uncertainties < 0.1%
- One plant from original topical re-benchmarked with negligible change in results

Neutronics: Aeroball Measurement System (AMS)

- **AMS has been used in virtually all German reactors for decades**
- **Benchmarking includes two plants using AMS and POWERTRAX/S core monitoring**
  - **Siemens KONVOI 177 assembly core – 15x15 lattice**
  - **Siemens KONVOI 193 assembly core – 18x18 lattice**
- **10 cycles of measured data**
- **147 core power distribution maps**

Neutronics: Heavy Reflector Model

- > **Process similar to that for benchmarked plants**
- > **Physical problem simpler due to the elimination of large areas of moderator at the core boundary**
- > **PRISM vs. MCNP comparisons**

Neutronics: EMF-96-029(P)(A), "Reactor Analysis System for PWRs," Volumes 1 & 2

> **Basis for applicability**
- **Minimal changes to methodology**
- **Similarity of U.S. EPR fuel to current designs**
- **Satisfactory validation results**

Supports application of methodology ton U.S. EPR

Neutronics: BAW-10221P-A, "NEMO-K A Kinetics Solution in NEMO"

- NRC approved general purpose kinetics code
  - Transient core power distributions
  - Core reactivity during rapid transients
- Transient kinetics equations added to core simulator
- Current applications
  - 15x15 and 17x17 fuel lattices
  - Westinghouse 3- and 4-loop and B&W plants
  - Physics input to RIA and other fast transients

Neutronics: BAW-10221P-A, "NEMO-K A Kinetics Solution in NEMO"(Cont.)

- U.S. EPR configuration similar to U.S. 4-loop core designs
  - 17x17 lattice (.374" rod O.D. and 24 guide tubes)
  - Gadolinia burnable poison
  - ~14 ft active fuel length
  - 241 assembly core
- Uses same cross section code (CASMO-3) as core simulator
- Benchmarked against industry standard problems
- No changes made to methodology

Supports direct application of methodology to U.S. EPR

Thermal-Hydraulics: BAW-10156A, "LYNXT Core Thermal-Hydraulic Program"

> **NRC approved general purpose thermal-hydraulic code**
  - Calculates core fluid conditions (pressure, temperature, flow distributions)
  - Calculates DNB under normal and accident conditions

> **Also used in:**
  - Setpoint verification
  - Control component cooling calculations

> **Current Applications**
  - 15x15 and 17x17 fuel lattices
  - Westinghouse 3- and 4-loop and B&W plants
  - Mixing vane and HTP spacer designs
  - Various top and bottom nozzle designs, including FuelGuard™

Thermal-Hydraulics: BAW-10156A, "LYNXT Core Thermal-Hydraulic Program" (Cont.)

- **EPR fuel hydraulically similar to current U.S. fuel designs**
  - **17x17 Lattice**
  - **HTP Spacer**
  - **FuelGuard™ Bottom Nozzle**
- **CHF correlation**
  - **EPR fuel design**
  - **Correlated using LYNXT**
- **No modeling changes were made to the code models**

Supports direct application of methodology to U.S. EPR

Thermo-Mechanical: BAW-10231PA, "COPERNIC Fuel Rod Design Computer Code"

- NRC approved general purpose thermal-mechanical code
  - UO_2 and Gd_2O_3-UO_2 fuel pellets
  - M5® rod material
  - Thermal and mechanical response during normal and accident conditions
- Approved for use in both best estimate and 95/95 bounding calculations of:
  - Rod internal pressure
  - Centerline fuel melt
  - Transient strain
  - Fatigue
  - Clad corrosion
- Provides input to non-LOCA transient analyses

Thermo-Mechanical: BAW-10231PA, "COPERNIC Fuel Rod Design Computer Code" (Cont.)

> **U.S. EPR fuel pellet/rod design fundamentally the same as used in current operating reactors:**
  - **< 5 w/o UO_2**
  - **2-8 w/o Gd_2O_3 as burnable poison**
  - **Fuel density = 96%**
  - **Rod burnup < 62 MWd/MTU**
  - **Rod OD = 0.374 inches**

> **Sample problems include subset of original topical problems**

> **No changes to the inherent code models for U.S. EPR application**

Supports direct application of methodology to U.S. EPR

Fuel Analyses Conclusions

- **Fuel design codes are generic in nature**
- **U.S. EPR similar in core/fuel design and conditions to current U.S. 4-loop PWRs**
- **Few or no modifications were made to the existing NRC approved methodologies**
- **Sample problems and benchmarking show similar behavior to current fuel**

The fuel analyses codes/methodologies are directly applicable to U.S. EPR analyses

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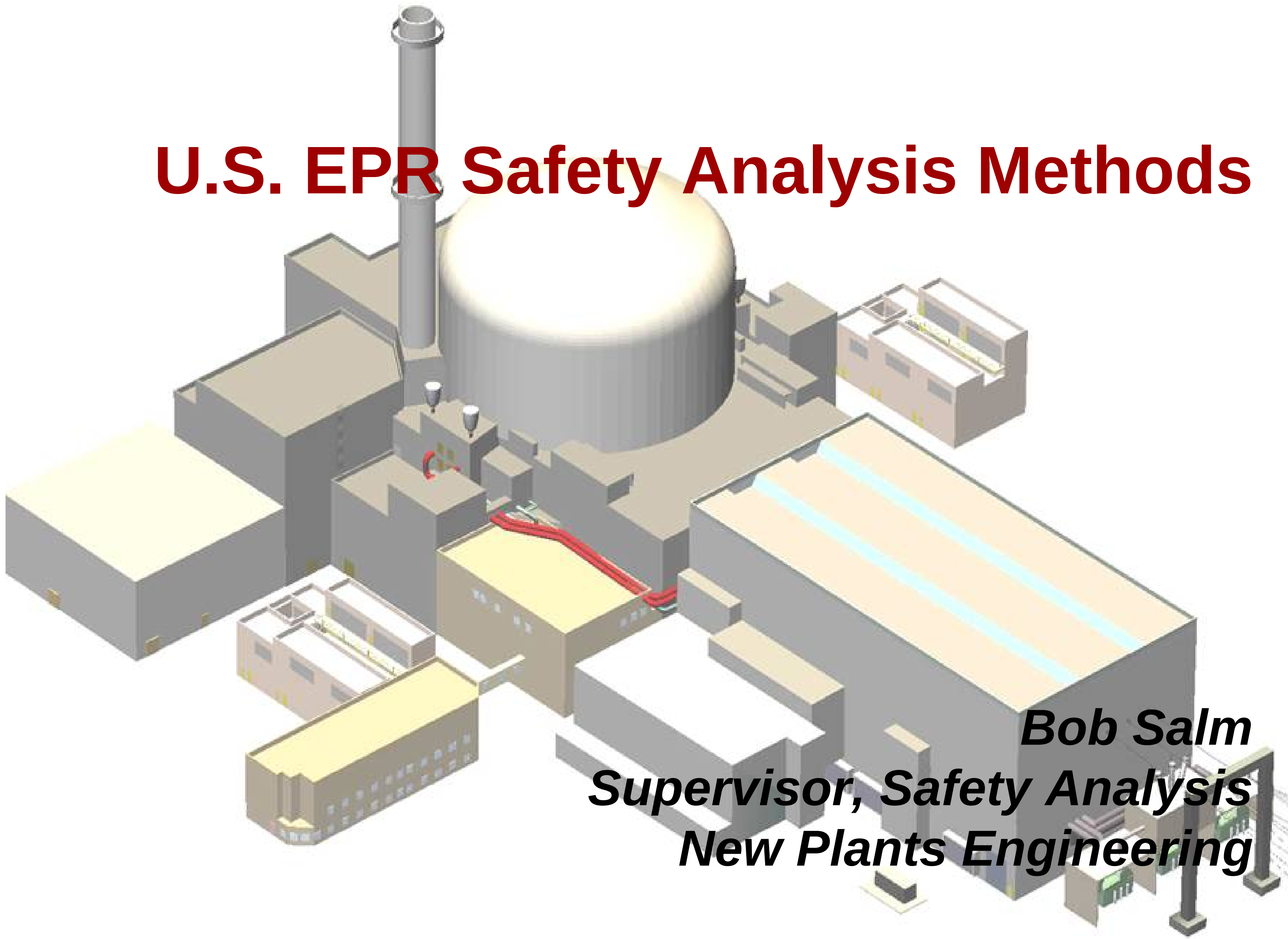
U.S. EPR Safety Analysis Methods



Bob Salm
Supervisor, Safety Analysis
New Plants Engineering

EPR

Objectives

- Identify and validate methodologies for U.S. EPR Chapter 15 safety analyses
  - Small break LOCA
  - Non-LOCA
- Present sample analyses for U.S. EPR

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Methodologies

> **Topical report identifies NRC approved methodologies selected for U.S. EPR analysis**

- **SBLOCA – "PWR Small Break LOCA Evaluation Model, S-RELAP5 Based," Revision 0, EMF-2328 (P)(A), January 2000**
- **Non-LOCA – "SRP Chapter 15 Non-LOCA Methodology for Pressurized Water Reactors," EMF-2310(P)(A) Revision 1, June 16, 2004**

EPR

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Applicability

- Topical report demonstrates NRC approved codes and methods are applicable to U.S. EPR
  - Describes events, analysis basis and acceptance criteria
  - Identifies important phenomena by event phase and plant component
  - Cites experimental benchmarks
  - Highlights U.S. EPR design features, configuration and functionality and how they are modeled
  - Shows phenomenological equivalence to current U.S. 4-loop PWRs
    - Similar plant behavior
    - Same range of conditions
    - No new phenomena

EPR

Small Break LOCA

> **Approved SBLOCA methodology is unchanged**

- **Break flow area ≤ 10% of the cold leg area (5" diameter or 0.5 ft^2)**
- **Deterministic approach using S-RELAP5**
- **Steady-state fuel conditions obtained from RODEX2-2A**
- **Satisfies 10 CFR 50.46 and Appendix K**

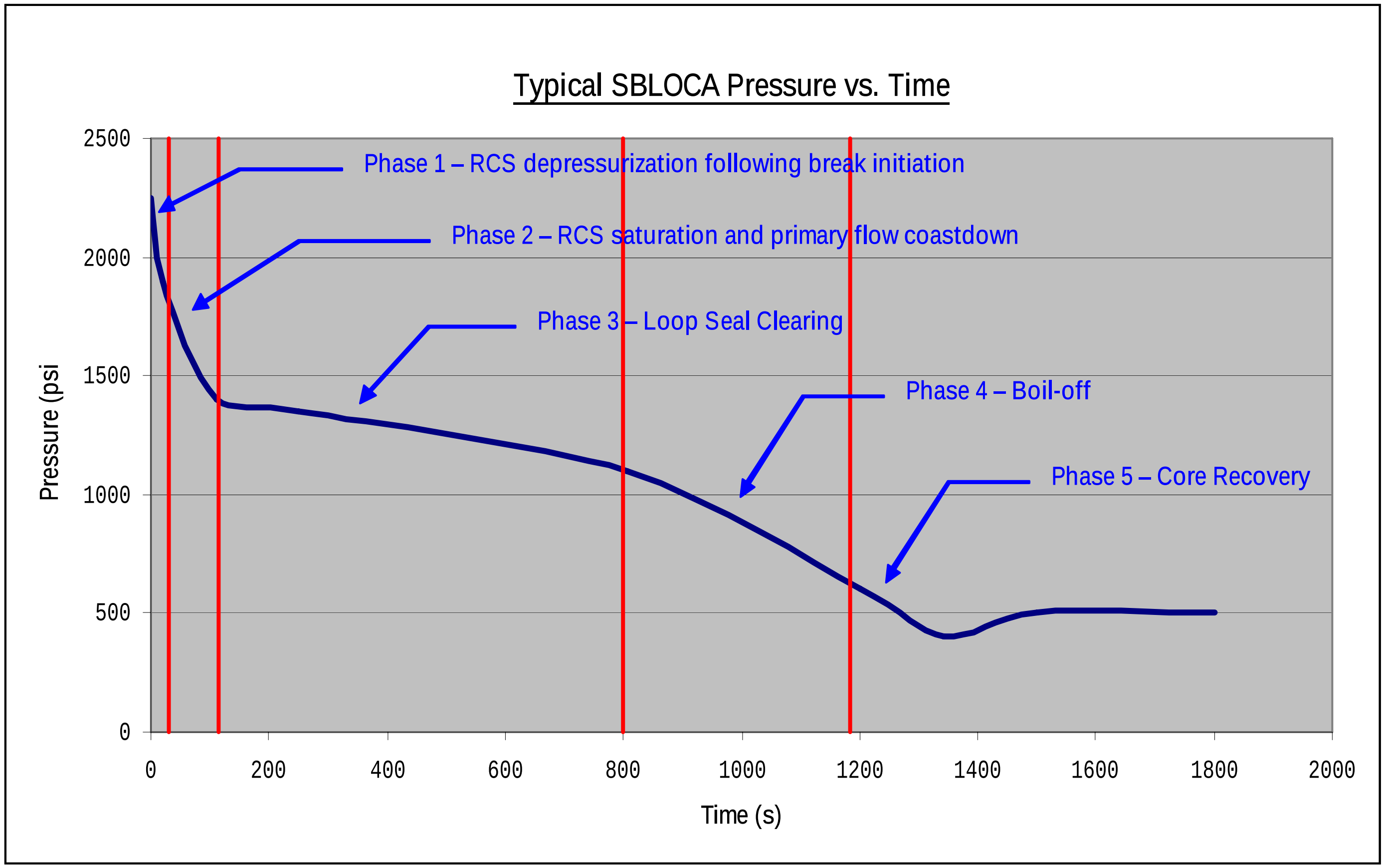
SBLOCA Methodology Justification

> **U.S. EPR justification approach, by event**

- **Describe transient, when necessary, by phase**
- **Identify important components/functionality**
- **Identify important phenomena**
- **Confirm phenomena same as for current 4-loop PWRs**

Similar design, same phenomena

Typical SBLOCA Transient Phases



SBLOCA Transient – Phase 1

- **RCS depressurization following break initiation in cold leg discharge piping**
  - **Characteristics**
    - **Rapid depressurization**
    - **Approach to saturation in hot legs**
  - **Events**
    - **Reactor trips on low RCS pressure**
    - **SG pressure rises to MSRT setpoint following turbine trip**
    - **LOOP assumed coincident with scram**
  - **Important components/phenomena**
    - **<u>Core</u> – fuel rod behavior (model prescribed by NUREG-0630)**
    - **<u>Break</u> – flowrate (Moody correlation per 10 CFR 50.46, Appendix K)**

SBLOCA Transient – Phase 2

> **RCS saturation and primary flow coastdown**

- **Characteristics**
  - **Transition to natural circulation as RC pumps coast down following LOOP**
  - **Saturation of RCS as depressurization continues**
- **Events**
  - **Safety injection is initiated on low-low RCS pressure signal**
  - **Programmed cooldown of SG initiated on SI signal**
- **Important components/phenomena**
  - **<u>Core</u> – Fuel rod behavior same as Phase 1; cladding temperature approaches saturation; counter-current flow at core exit (S-RELAP5 checks for CCFL)**
  - **<u>Steam Generator</u> – Heat transfer helps depressurize RCS**
  - **<u>Break</u> – Two-phase; includes MHSI**

SBLOCA Transient – Phase 3

> **Loop Seal Clearing**

- **Characteristics**
  - **Safety injection (MHSI) is insufficient to offset break flow**
  - **Steam collects in SG U-bends; natural circulation stops; condensation heat transfer is established**
  - **Core covered by mixture**
- **Important components/phenomena**
  - **<u>Core</u> – decay heat, heat transfer, phase separation and fuel behavior**
  - **<u>Steam Generator</u> – secondary side depressurizes with programmed cooldown**
    - **Condensation on SG primary side**
    - **Reflux boiling between core and hot leg sides of SGs**
  - **<u>Cold Leg/Pump/Downcomer</u>**
    - **Loop seal clears when RCS depletes sufficiently for steam to reach the break via cold leg piping and downcomer**
  - **<u>Break</u> – Quality approaches one after loop seal clearing**

SBLOCA Transient – Phase 4

> **Boil-off**

- **Characteristics**
  - **Break flow exceeds MHSI capacity; vessel inventory decreases, potentially causing partial core uncovery**
  - **RCS depressurization continues due to SG cooldown and/or break flow; may reach accumulator discharge pressure**
- **Important components/phenomena**
  - **<u>Core</u> – same as Phase 3, except a portion may have only steam cooling; potential for clad swelling and rupture**
  - **<u>Steam Generator</u> – secondary side continues programmed cooldown; if primary pressure is above secondary, heat transfer via**
    - **Condensation on primary side**
    - **Reflux boiling between core and hot leg sides of SGs**
  - **<u>Break</u> – largely steam, includes MHSI and possibly accumulator water if discharging**

SBLOCA Transient – Phase 5

> **Core Recovery**
- **Characteristics**
  - **ECC flow (MHSI and potentially accumulator discharge) exceeds leak flow**
  - **Inner vessel region mixture level reaches its minimum and begins increasing**
- **Important components/phenomena**
  - **Core – same as Phase 4 except if partially uncovered, rewet and quench occur as vessel refills**
  - **Steam Generator – secondary side depressurizes with programmed cooldown; if primary pressure is above secondary,**
    - **Condensation on primary side**
    - **Reflux boiling between core and hot leg sides of SGs**
  - **Cold Leg/Pump/Downcomer – steam relief to break via cold legs and downcomer**
  - **Break – largely steam, includes MHSI and possibly accumulator water if discharging**

SBLOCA Phenomena Ranking and Validation

> **NRC approved SBLOCA methodology topical report EMF-2328 (P)(A)**

- **Identifies phenomena**
- **Ranks importance of phenomena to each phase**
- **Identifies benchmarks appropriate to phenomena and phase**

Methodology is applicable to the U.S. EPR

SBLOCA Sample Problems

> Covers the same cases reported in EMF-2328(P)(A), the SBLOCA methodology topical report

- Reports on analyses of a spectrum of break sizes (2.0, 2.5, 3.0, 3.5, 4.0 and 4.5-inch-diameter cold leg breaks)
- Presents details of limiting case (4.0-inch break)

> Behavior similar to that for current U.S. PWRs

> PCT results are favorable

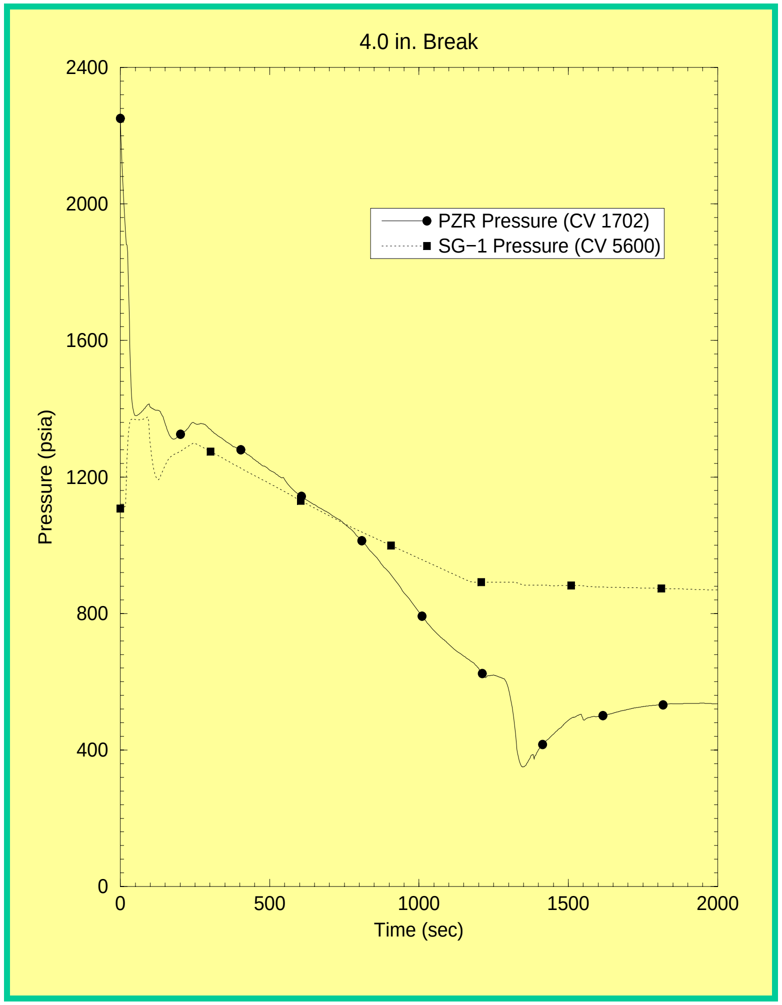
SBLOCA Sample Problem Results

Break Size	Break Area (ft^2)	PCT (°F)	Time of PCT (sec)
2 in	0.0218	No Heatup	N/A
2.5 in	0.0341	No Heatup	N/A
3.0 in	0.0491	No Heatup	N/A
3.5 in	0.0668	704.99	681.54
4.0 in	0.0873	1128.7	1056.1
4.5 in	0.1104	1011.3	893.15

SBLOCA Sample Problem Results (cont.)

4.0 Inch Cold Leg Break

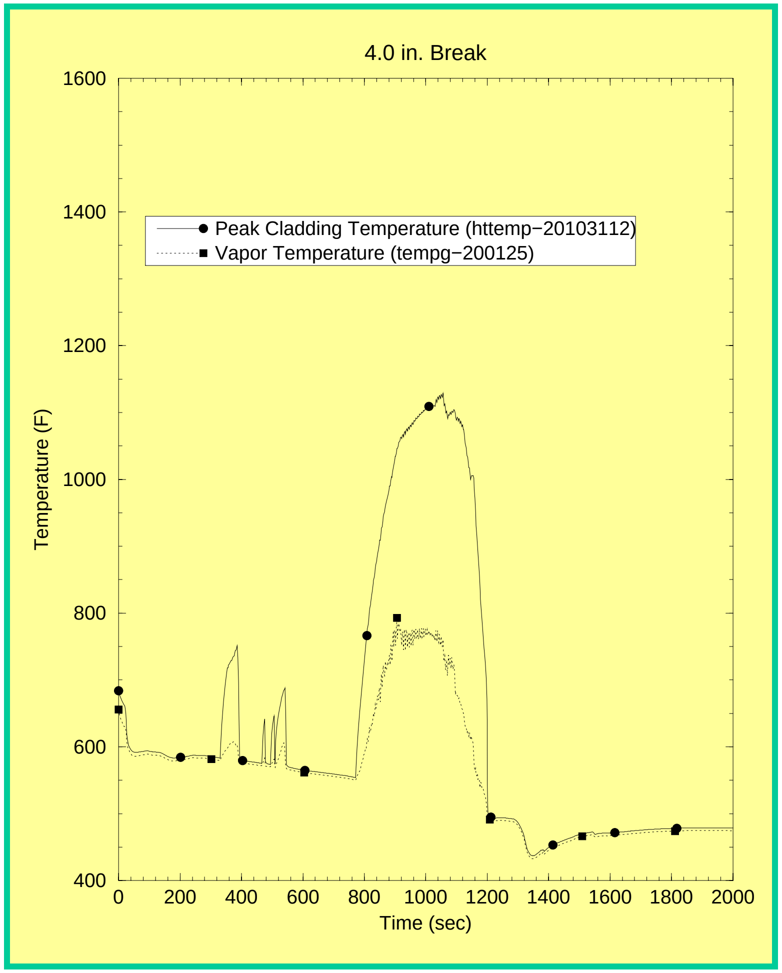
Primary and Secondary Side Pressures



SBLOCA Sample Problem Results (cont.)

4.0 Inch Cold Leg Break

Vapor and Clad Temperatures for Hot Node



Non-LOCA

> Comprises Non-LOCA events from NUREG-0800, Chapter 15

> Deterministic approach using S-RELAP5

> Methodology change to obtain initial fuel conditions from COPERNIC code rather than RODEX2A

> Provides system fluid boundary conditions input to external DNBR, fuel centerline melt and radiological calculations

Non-LOCA Methodology Justification

> **Assessment approach the same as SBLOCA**

- **Event description**
- **Identification of important components/functionality**
- **Identification of important phenomena**
- **Justification that phenomena same as for current 4-loop PWRs**
- **Justification that NRC approved analysis methodology is applicable**

Similar design, same phenomena

Non-LOCA Sample Problems

- Topical report presents same scenarios reported in EMF-2310 (P)(A)
  - Non-LOCA
    - Post-scram main steam line break
    - Loss of external load / turbine trip
    - Loss of normal feedwater
    - Loss of coolant flow
    - Uncontrolled bank withdrawal at power
    - Steam generator tube rupture
- Behavior similar to those for current U.S. plants reported in referenced topical reports

Results demonstrate applicability of approved methodologies to U.S. EPR

Safety Analysis Conclusions

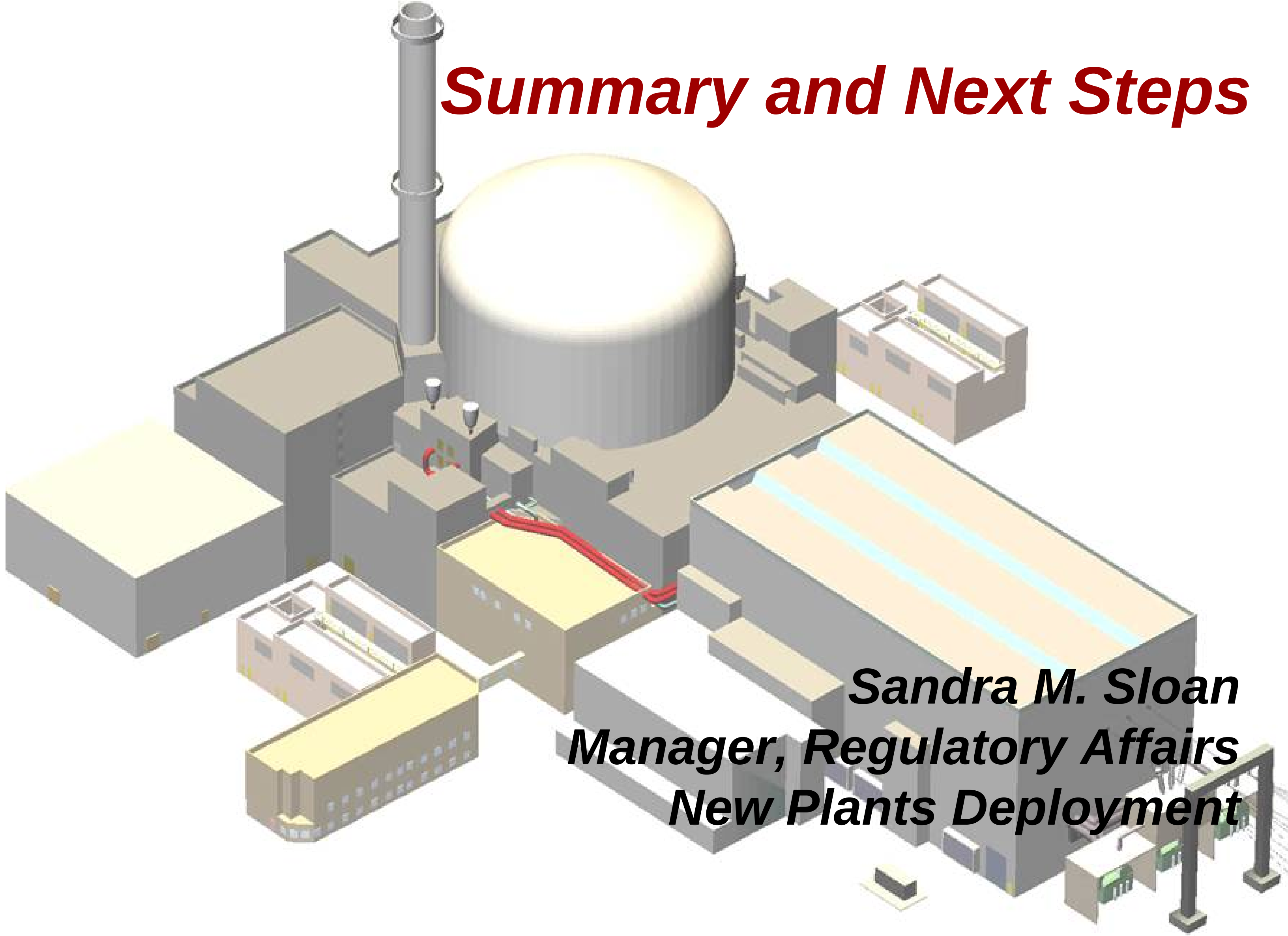
> U.S. EPR is similar in design and functionality to current U.S. 4-loop plants

> Phenomena associated with U.S. EPR Chapter 15 events are same as for current U.S. 4-loop plants

> Sample problem results for the U.S. EPR show similar behavior to current U.S. 4-loop plants

> Approved safety analysis codes and methods are applicable to U.S. EPR

Summary and Next Steps



Sandra M. Sloan
Manager, Regulatory Affairs
New Plants Deployment

Summary

> **Thorough evaluation of fuel analysis and safety analysis methods performed**
- **Differences in physical characteristics evaluated**
- **Phenomena and conditions compared to currently-approved applications**
- **Most methods are directly applicable to U.S. EPR**
- **Minimal changes are described and justified**

Topical report will demonstrate applicability of codes and methods to U.S. EPR

Next Steps

> **Codes and Methods Applicability Topical Report**
- **Submittal in mid-August 2006**
- **Request safety evaluation report approving use of methods for U.S. EPR, by August 2007**
- **Post submittal meeting proposed in October 2006**

> **Next U.S. EPR pre-application meeting**
- **August 30: I&C**

Acronyms

- BP – burnable poison
- CCFL – counter current flow limit
- CHF – critical heat flux
- DNB – departure nucleate boiling
- EPR – evolutionary power reactor
- ID – inner diameter
- IFBA – integral fuel burnable absorber
- LBLOCA – large break loss of coolant accident
- LHR – linear heat rate
- LOOP – loss of offsite power
- MHSI – medium head safety injection
- MSRT – main steam relief train

Acronyms (continued)

- OD – outer diameter
- PCT – peak cladding temperature
- PWR – pressurized water reactor
- PZR – pressurizer
- RC – reactor coolant
- RCS – reactor coolant system
- RIA – reactivity insertion accident
- SBLOCA – small break loss of coolant accident
- SI – safety injection
- SG – steam generator
- STP – South Texas Project
- TD – theoretical density