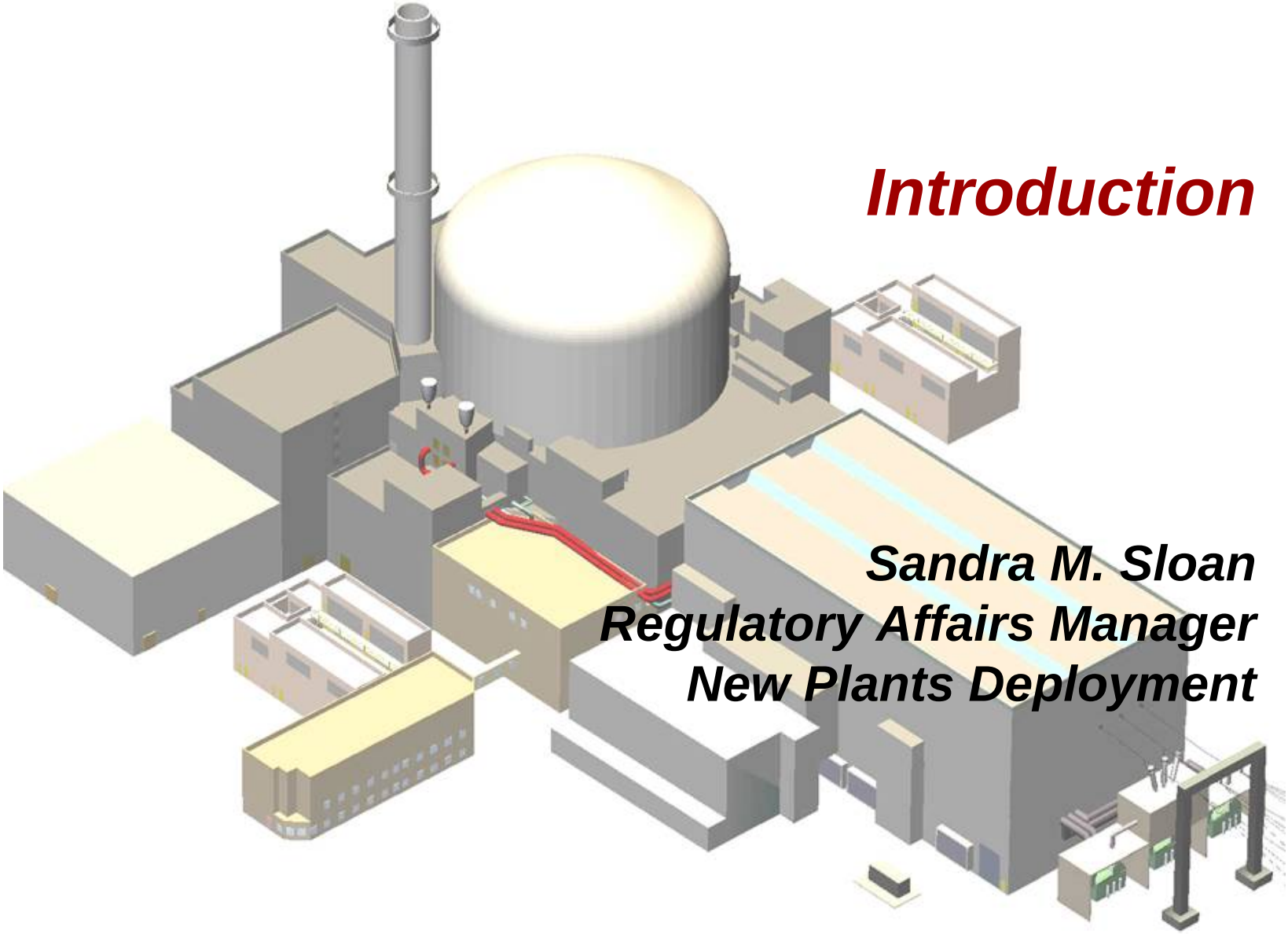
U.S. EPR Pre-Application Review Meeting

Critical Heat Flux Correlation for the U.S. EPR

AREVA NP and the NRC
November 14, 2006



Introduction

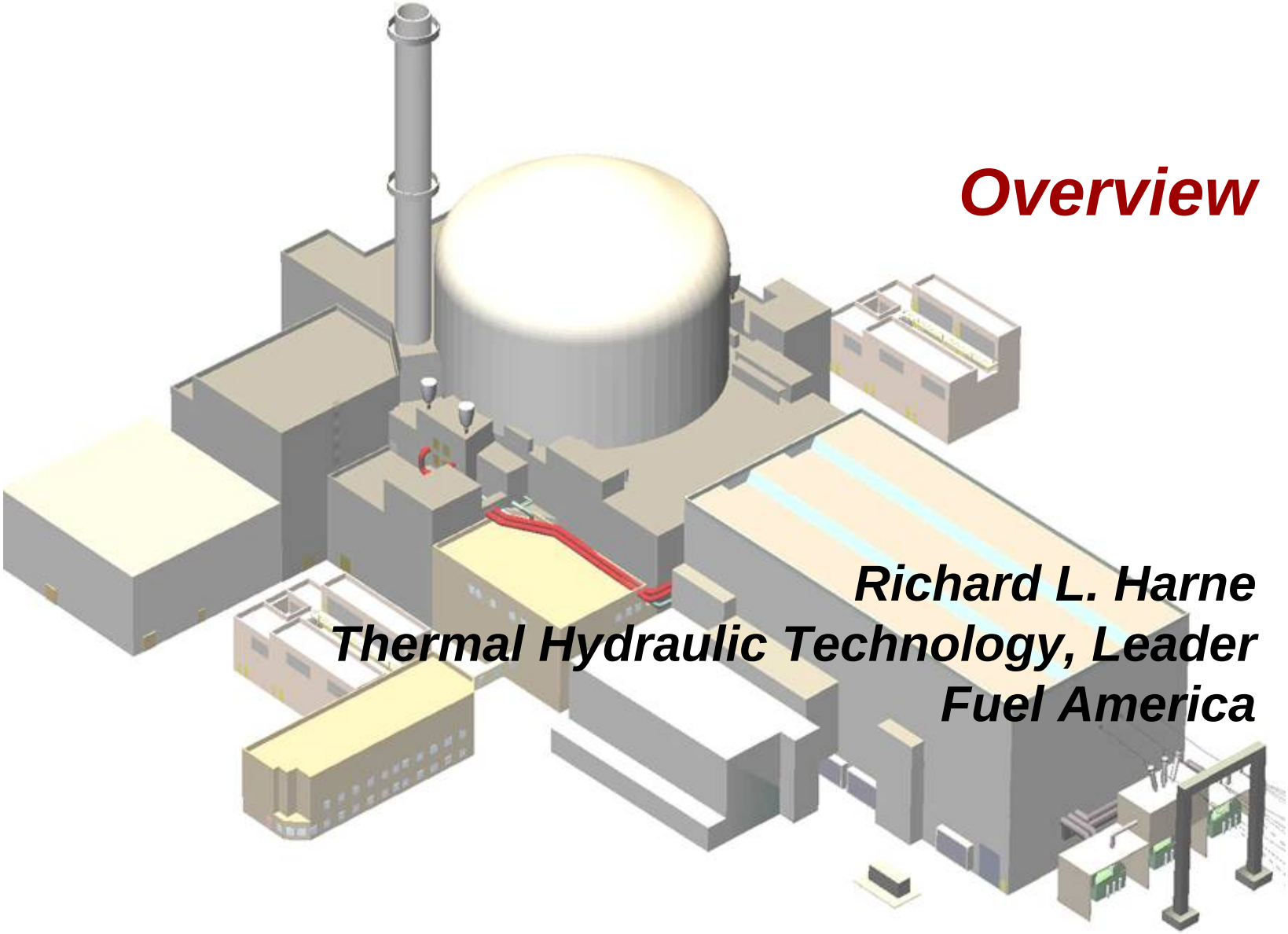
Sandra M. Sloan
Regulatory Affairs Manager
New Plants Deployment

Meeting Objectives

- **To describe the Critical Heat Flux Correlation developed for the U.S. EPR**
- **To discuss the CHF testing performed at the Karlstein test facilities**

Outline

- Overview and EPR fuel design (R.L. Harne)
- CHF correlation (D.A. Farnsworth)
- Testing for the U.S. EPR fuel design (Ch. Herer)
- Summary and next steps (S.M. Sloan)



Overview

Richard L. Harne
Thermal Hydraulic Technology, Leader
Fuel America

Overview

- The U.S. EPR CHF correlation has been developed specifically for application to the EPR fuel design
- The correlation is based on uniform and non-uniform CHF test data obtained from AREVA's KATHY test facility at Karlstein, Germany
- The correlation has been developed with specific conservatisms

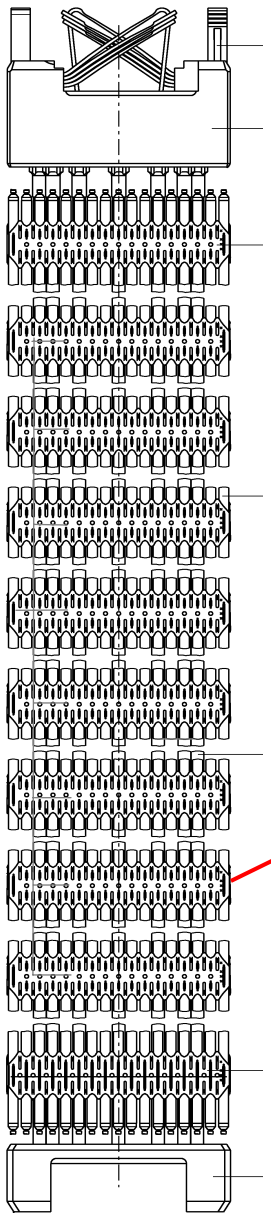
CHF Correlation for the U.S. EPR

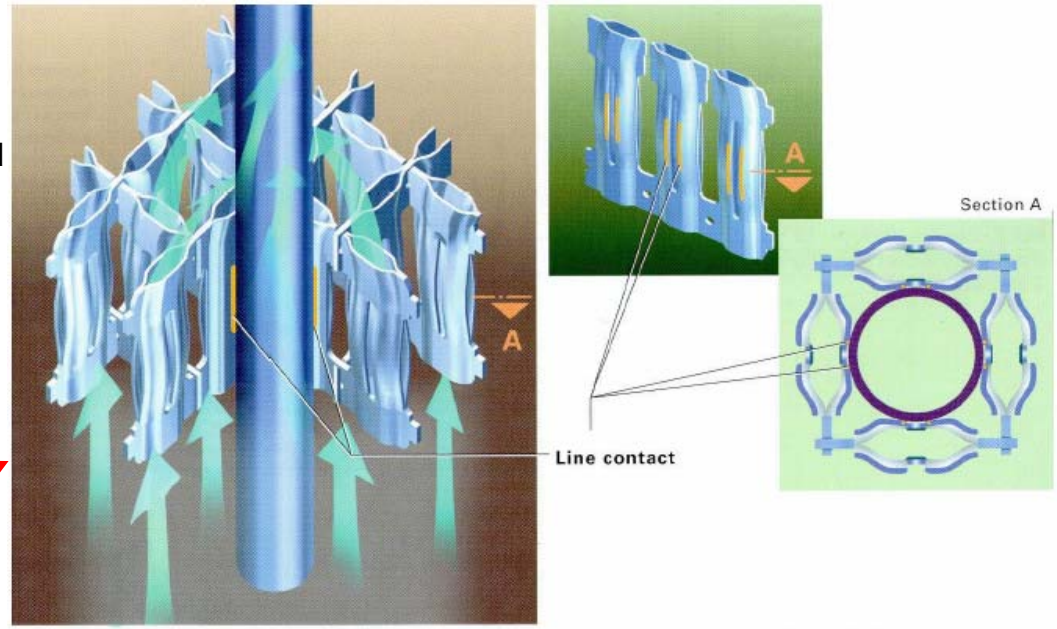
- > **EPR fuel design**
- > Test facility qualification
- > Test basis of the CHF correlation
- > Correlation development
- > Correlation validation
- > Characteristics of the correlation
- > Application of the correlation
- > Summary and conclusions

EPR Fuel Design

Parameter	Dimensions
Pin pitch	0.496 inch
Heater rod diameter	0.374 inch
Guide tube diameter	0.490 inch
Grid spacer pitch	18.5 inches upper grid spans 20.0 inches lower grid spans
Heated length	14 feet

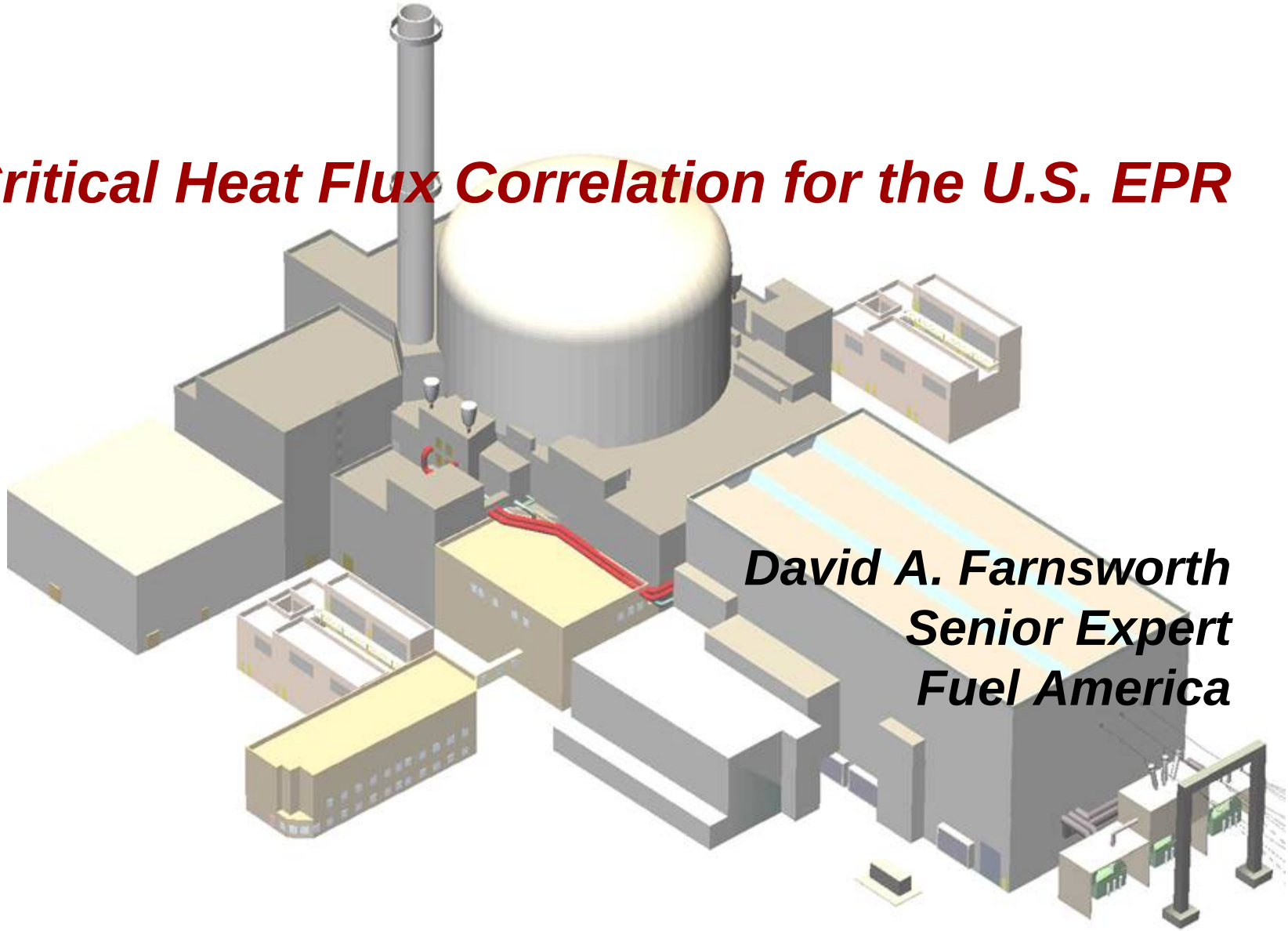
EPR Fuel Design





Based on proven HTP technology

Critical Heat Flux Correlation for the U.S. EPR



David A. Farnsworth
Senior Expert
Fuel America

CHF Correlation for the U.S. EPR

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- > **Test facility qualification**
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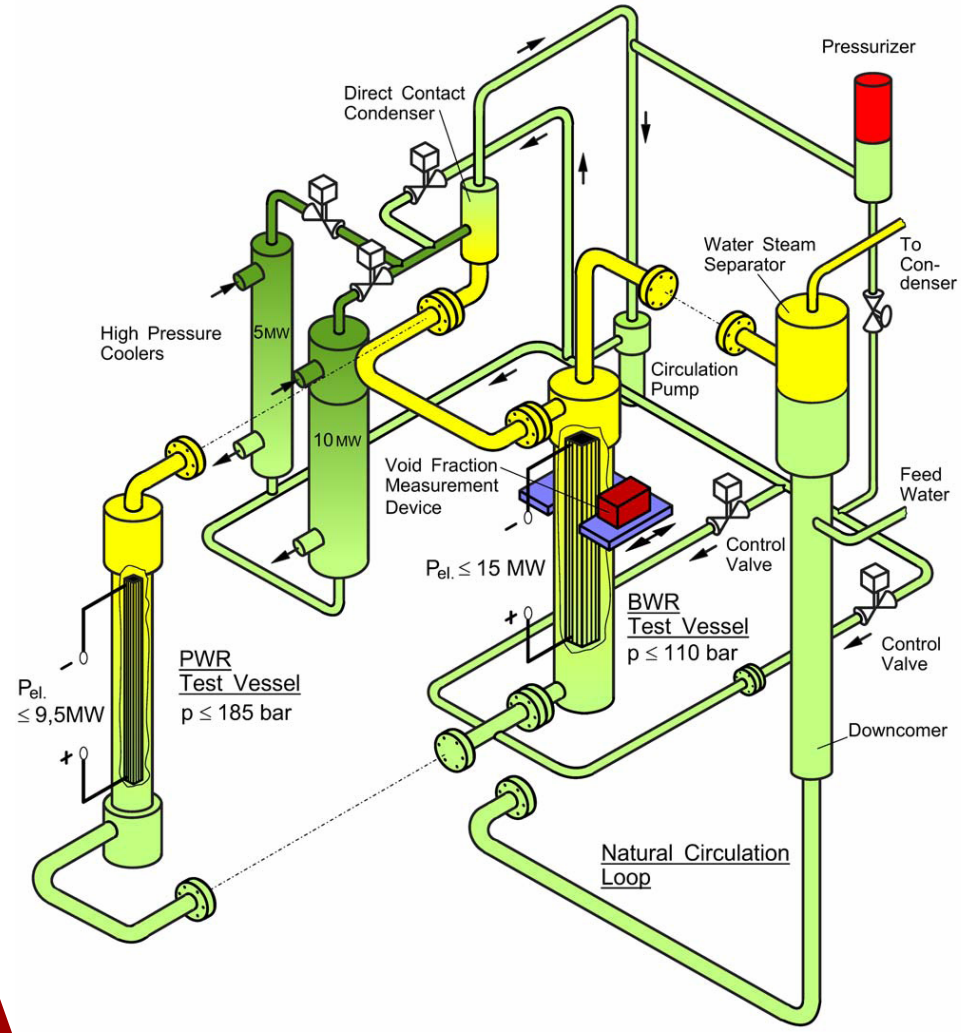
CHF Testing Performed Using AREVA's Karlstein Thermal Hydraulic Facility (KATHY)



- **Details of the operation of the facility will be covered later**
- **The U.S. EPR correlation will be the first AREVA PWR correlation for U.S. application based on KATHY testing**
- **Qualification information for the use of the KATHY data against the Columbia standard is discussed in this section**

CHF Facility Results Comparison

CHF Facility Results – Mass Velocity

CHF Facility Results - Pressure

CHF Facility Results - Quality

CHF Facility Results - Summary

> **Qualification conclusions:**

- **There is no statistical difference in the means**
- **There is no bias with respect to the local conditions**

KATHY data are qualified for use in correlating CHF

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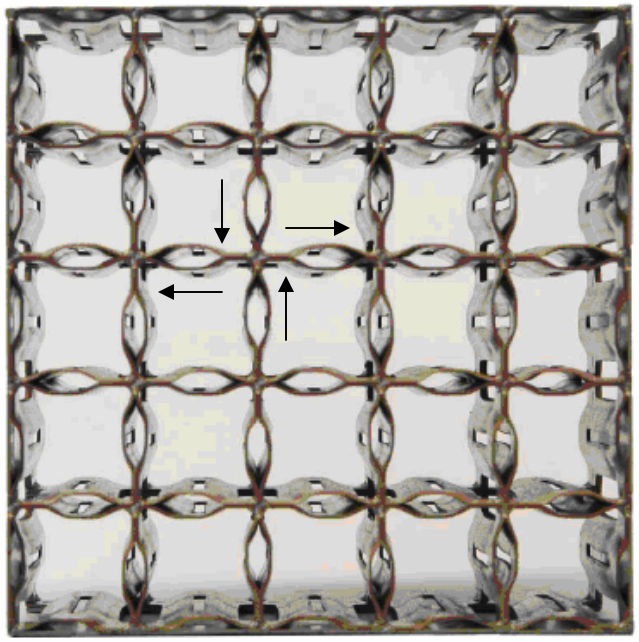
EPR Fuel Design Comparison to Tested Condition

Parameter	EPR Fuel Design	Test Geometry
Pin Pitch	0.496 inch	same
Heater rod diameter	0.374 inch	same
Guide tube diameter	0.490 inch	same
Grid spacer pitch	18.5 inch upper 20.0 inch lower	[ ]
Heated length	14 feet	[ ]

Selection of Axial Characteristics for Testing

EPR CHF Test Spacer Grid Design



Top View

The EPR fuel design utilizes the HTP spacer grid

EPR CHF Test Cross Sectional Geometries

CHF Test Basis

> **Nine total one-at-a-time parameter changes**

CHF Test Matrix

Eight Geometries	UC, GT	[ ]	[ ]	[ ]	[ ]

CHF Test Basis

> **Tested local condition ranges**

- Total data: **[ ]** points from eight geometries
- Pressure: **[ ]**
- Mass velocity: **[ ]**
- Quality (at CHF): **[ ]**
- CHF: **[ ]**

CHF Correlation for the U.S. EPR

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CHF Correlation Development

- **Correlate in five independent variables**
  - Local condition variables: P, G and X
  - Geometric variables: Z_{CHF} and D_{GT}
- **Remove low flow data (G < 0.9 Mlb/hr-ft^2)**
- **Use [ ] as base correlation**
  - Allow [ ] only
  - Remove terms based on significance (T ratios)
- **Use existing BWU (Tong) F factor**
  - Six differing axial flux shapes (next slide)
- **[ ]**
  - [ ]
  - [ ]
- **Correlate using correlation and verification data bases**

Axial Flux Shape

U.S. EPR CHF Correlation Form

where:

F	: Standard BWU (Tong) F factor
$Q_{uniform}$	: Predicted uniform CHF, MBtu/hr-ft^2
Q_{CHF}	: Predicted CHF, MBtu/hr-ft^2
$\ln(P)$	: natural log of pressure, psia
G	: mass velocity, Mlb/hr-ft^2
X	: thermodynamic quality fraction at CHF
Z_{CHF}	: axial elevation of CHF, inches
D_{GT}	: guide tube outer diameter, inches

Correlation Coefficients and T Ratios

```
Rsqr = 0.9293D+00, Xmtp = 0.9999D+00, Cmtp = 0.1246D+00

     X1 = ln(P), natural log of Pressure, psia
     X2 = G, mass velocity, Mlb/hr-sq ft
     X3 = X, thermodynamic quality fraction at CHF
     X4 = Zchf, axial elevation of CHF, inches
     X5 = Dgt, guide tube diameter, inches
```

All coefficients are significant by T ratio

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CHF Correlation Validation

- **Group statistics**
  - **Correlation and verification data bases**
  - **Uncorrelated data base**
  - **Individual tests**
- **Individual statistics**
  - **Scatter plots**
  - **Linear regression bias checks**
- **Correlated independent variable ranges**
  - **Pressure: 284 to 2565 psia**
  - **Mass velocity: 0.945 to 3.164 Mlb/hr-ft^2**
  - **Quality at CHF: less than 36.9%**

CHF Correlation Performance by Group

CHF Correlation Performance by Test Section

Histogram of Measured-to-Predicted CHF Values

Measured-to-Predicted CHF - Pressure

Measured-to-Predicted CHF – Mass Velocity

Measured-to-Predicted CHF - Quality

Measured-to-Predicted CHF - Elevation of Burnout

Measured CHF - Predicted CHF

Variable Bias Investigation

No independent variable bias (< 1% Rsqr)

Good dependent variable correlation (> 93% Rsqr)

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CHF Correlation Trends and Application

> **Independent variable trend analysis**
- **Mass velocity**
- **Thermodynamic quality at CHF**
- **Pressure (at constant enthalpy)**
- **Elevation of burnout detection**

> **Application**
- **CHF data point**
- **Core simulation (14 foot cosine)**

CHF Correlation Trends – Mass Velocity

No discontinuities, evidence of inverse flow regime

CHF Correlation Trends - Quality

No discontinuities, quadratic strength regime dependent

CHF Correlation Trends - Pressure

No discontinuities, always increasing with pressure

Physical Property Relationship

CHF Correlation Trends - Elevation

Minor correlating factor, minor effects in all regimes

Typical CHF Test Point

Perfect prediction is when DNBR = 1.00

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CHF Correlation Application

> **Design limits (95/95)**

> **Conservatisms in the correlation**

CHF Correlation Application

CHF Correlation Application

Correlation limitations

- **1.30 design limit**
  - Provision for retained conservatism
- **Local condition ranges**
  - Pressure: 284 to 2565 psia
  - Mass velocity: 0.945 to 3.164 Mlb/hr-ft^2
  - Quality at CHF: less than 37%
- **Geometry range (EPR geometry)**
  - EPR HTP spacer grid
  - Fuel rod pitch: 0.496 inches
  - Fuel rod OD: 0.374 inches
  - Guide tube OD: 0.490 inches
  - Grid spacing: 18.5 – 20.0 inches
  - Heated length: 14 foot

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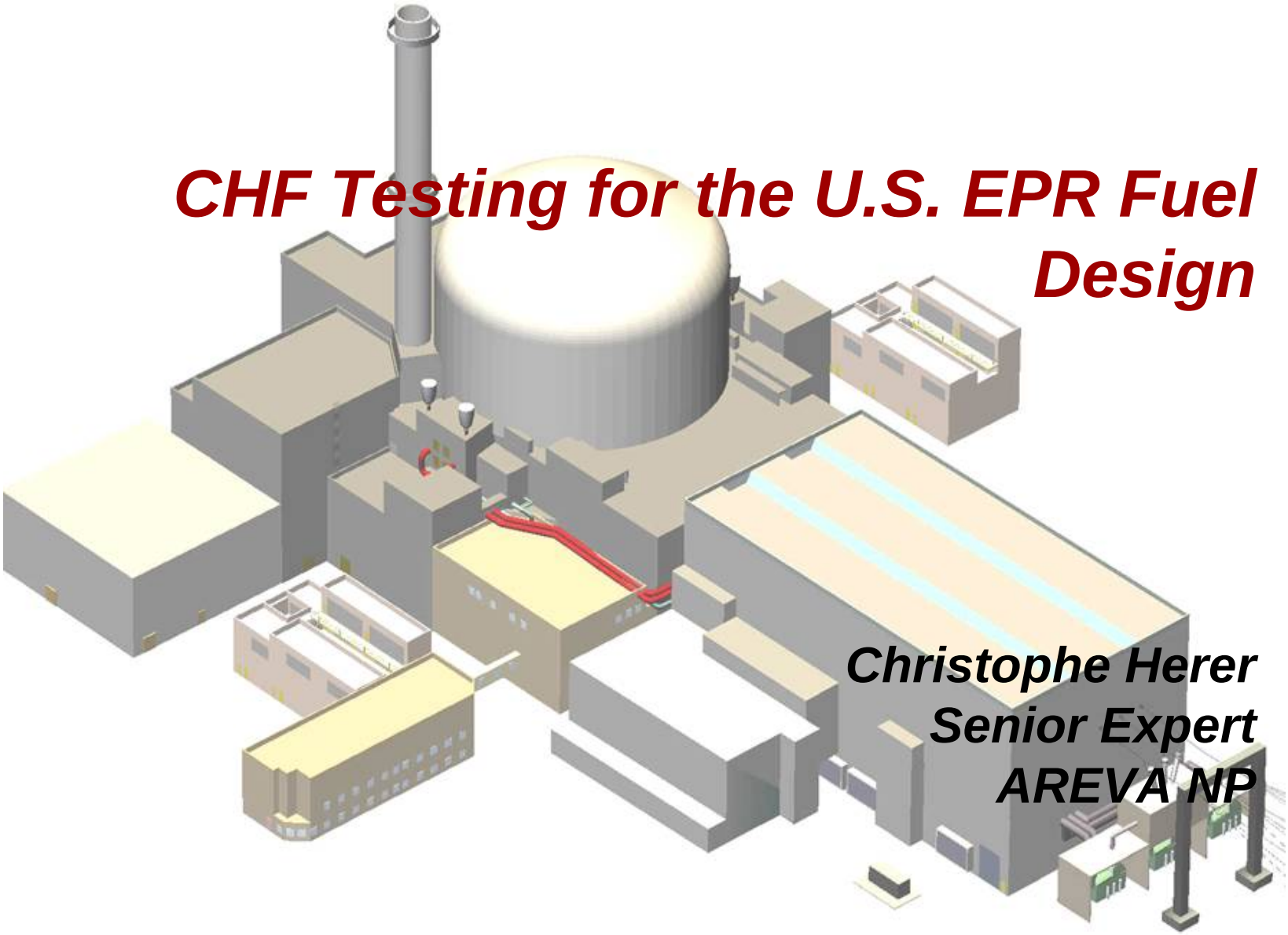
Summary and Conclusions

- The U.S. EPR CHF correlation has been developed specifically for application to the EPR fuel design
- The correlation has been developed using both uniform and non-uniform CHF test data obtained from the AREVA testing facility at Karlstein, Germany
- The correlation has been developed with specific conservatisms to support its use in analyses
- The correlation CHF design limit includes a conservative provision

CHF Testing for the U.S. EPR Fuel Design



Christophe Herer
Senior Expert
AREVA NP

Topics

> **Description of Experimental Support**
- **Description of KATHY test loop**
- **Description of test configurations**

> **Description of Testing at KATHY**
- **Bundle conditions matrix**
- **Test procedure**
- **On-line analysis**

Description of Experimental Support

KATHY Test Loop

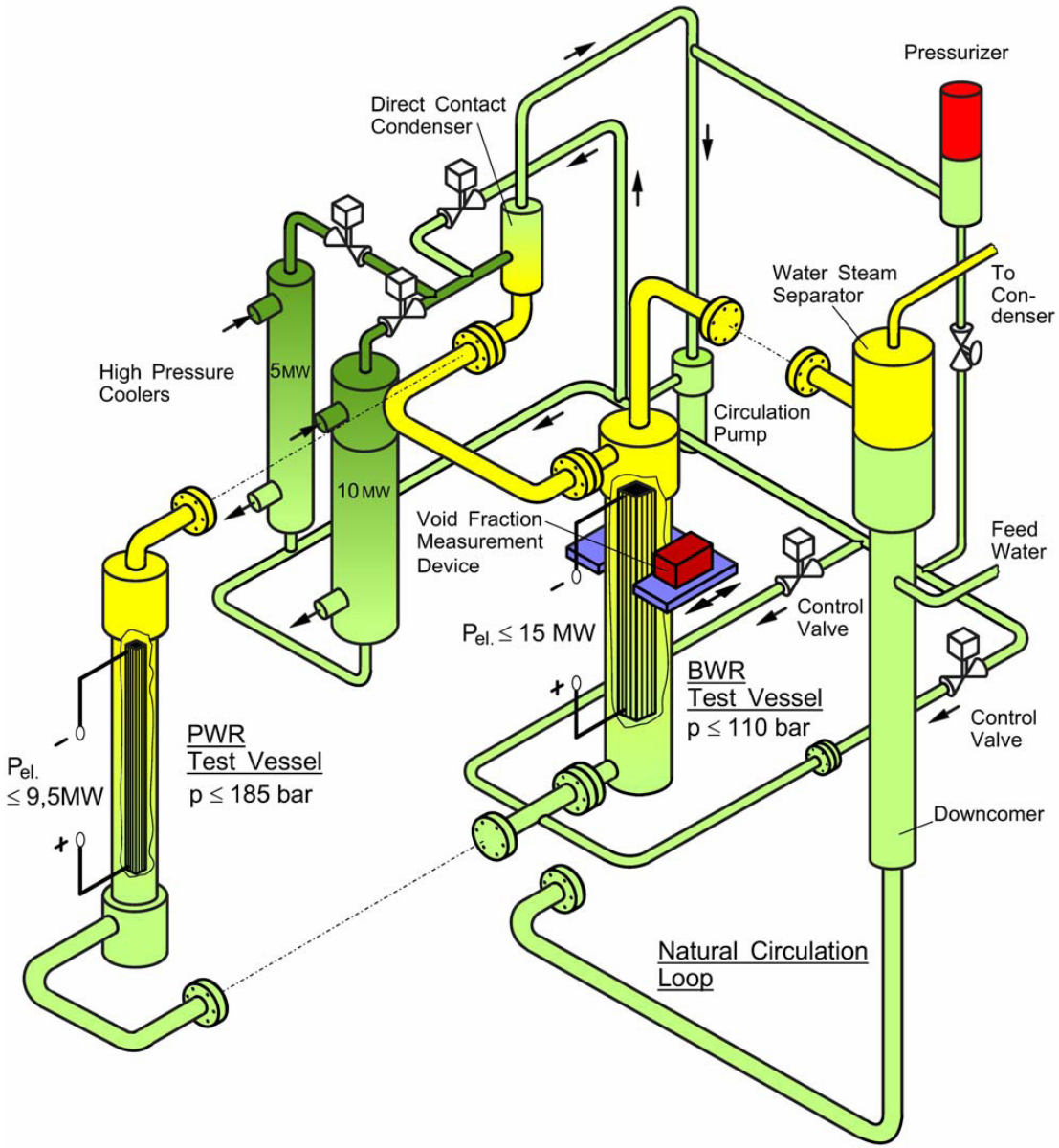
- Loop
  - Electrical heated pressurizer
  - Circulation pump
  - Downstream from the circulation pump the flow is divided into three partial flows
    - test vessel (test bundle)
    - two coolers
    - flow through the flywheel
- Direct contact condenser downstream from the test vessel
- Flywheel flow is used to keep the circulation pump constant
- The test bundle is connected to the 15 MW DC-power supply

Description of KATHY Loop

- Flow through the test bundle is adjusted by means of two lines
  - One line is designed for a mass flow of < 8 kg/s (17.6 lb/s)
  - One line is designed for a mass flow of > 8 kg/s
  - During the tests there is only one line opened depending on the required mass flow

- Two orifices and a turbine flow meter are installed to measure the flow
  - Pressure drop across the ISA 1932 orifice
    - Two Rosemount transducers type G1151-HP
    - Different measurement ranges
    - Density is calculated based on the measured temperature and pressure in the flow inlet pipes

Description of KATHY Loop



Description of KATHY Loop

> PWR test vessel

- Design pressure 185 bar (2680 psi)
- Design temperature 360 °C (680 °F)

> Pressurizer

- Volume 1 m^3
- Electrical power 300 kW
- Design pressure 185 bar
- Design temperature 360 °C

> Circulation pump

- Design pressure 210 bar (3050 psi)
- Design temperature 370 °C
- Pump head max. 11 bar (160 psi)
- Mass flow 40 l/s (634 gal/min)

Description of KATHY Loop

> **Electrical power supply**
  - **Maximum (gross) power 15 MWe / 10 MWe**
  - **Maximum Current**
    - **83 kA at 180 V DC (15 MWe)**
    - **40 kA at 240 V DC (10 MWe)**
    - **Supply mode: 4 Thyristor controlled rectifiers**

> **Control valve**
  - **Electro-hydraulic control valves with an opening and closing time of 1 second**

Description of KATHY Loop

- **Inlet temperature measurement**
  - **The inlet temperature is measured at the test vessel inlet by two independent temperature transducers**
- **Outlet temperature**
  - **The outlet temperature is measured by three independent temperature transducers**
- **Current**
  - **LEM transducers (Hall effect)**
  - **Four high precision and fast responding shunts**
- **Voltage**
  - **At least one heater rod is equipped with voltage taps across the heated length**
  - **As a backup, the voltage between the busbars is measured**

Description of KATHY Loop

- System pressure
  - The absolute system pressure is measured twice at the outlet of the test section (flow channel)

- Pressure taps can be adapted to measure the pressure loss across a section inside the test bundle (flow channel)
  - Rosemount G1151 and 3051S type transducers are used with a variety of measuring ranges

Description of KATHY Loop

> **Data acquisition system**

- **Signals of the loop instrumentation to digital converter are sampled and stored on hard disc**
- **256 analog input and 32 digital input channels available**
- **Sample rate per channel 20 Hz**
- **4 PCs monitor the test**
  - **One controls the acquisition and data flow**
  - **Three display and visualize selected channels, especially thermocouples (TCs) during CHF tests**
- **The data acquisition software is based on "LabView"**
- **The evaluation software (SI-generator) to transfer the measured values into physical values (pressure, temperature, mass flow, etc.) is written in "C"**

KATHY K23/25 Tests: 12 ft Cosine Axial Flux Shape

KATHY [12 ft Cosine Axial Power Shape Configuration]

KATHY [14 ft Uniform Axial Power Shape Configuration]

Topics

> Description of Experimental Support
- Description of KATHY test loop
- Description of test configurations

> **Description of Testing at KATHY**
- **Bundle conditions matrix**
- **Test procedure**
- **On-line analysis**

Bundle Conditions Matrix

Test Procedure

On-Line Analysis

> **Control of quality of CHF data point**

- **Analysis of the 'history' of the data**
  - **Stability of parameters (P, G, T)**
  - **Shape of wall thermocouple excursion**
  - **Verification of secondary detections**
  - **Independent verification of measured values**

On-Line Analysis

> **Independent verification of values**

On-Line Analysis

> **Statepoint stability is examined as CHF is approached**

On-Line Analysis

> **Close up of control plots**

On-Line Analysis

> Control of consistency of CHF data point

- Analysis using 'bundle' conditions
  - Linearity of CHF versus inlet temperature plot
  - Comparison with 'reference' test
- Analysis using local conditions
  - PC version of subchannel analysis code
  - Local conditions computed with a subchannel code
  - Comparison with other data and with 'reference test'
  - Use of any correlation (implemented in subchannel code)

On-Line Analysis

> **Example of figures (next slide)**

On-Line Analysis

On-Line Analysis

> **Example of values (next slide)**

- **Summary of data**
- **Comparison of measured power**
  - **Based on least square and least absolute value regressions**
- **Verification of linearity (R^2)**
- **Detection of abnormal values**
  - **In that case repetition of some data are discussed**
  - **Can also detect a problem in the test section**

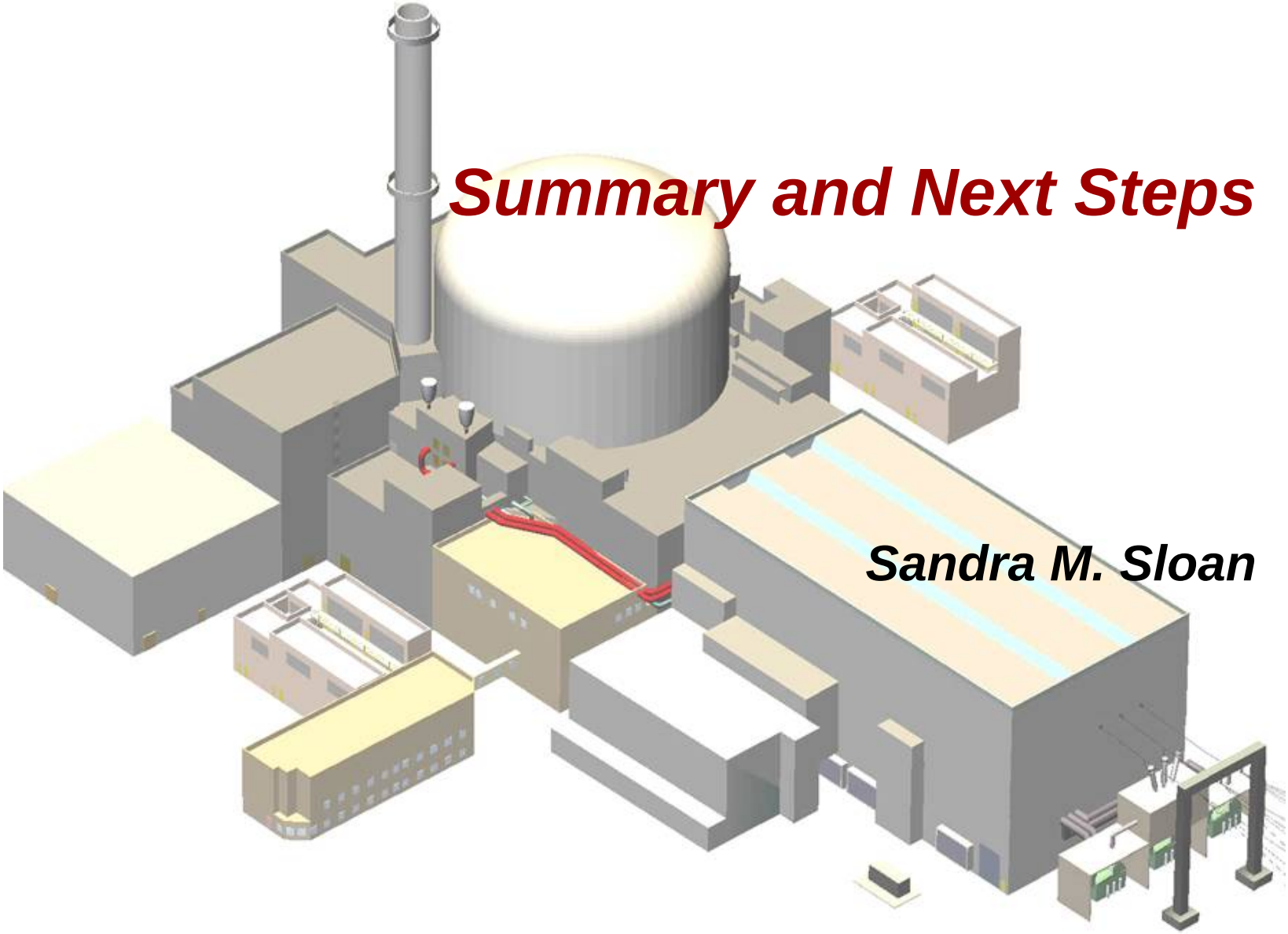
On-Line Analysis

Summary

> **High quality, reliable and consistent CHF data are available with the KATHY test facility**

- **KATHY facility is basically similar to Columbia University Heat Transfer Research Facility (CU/HTRF) with improved technology**
- **The high rate of data acquisition permits valuable checks using recorded history of parameters**
- **The use of on-line analysis based on bundle and local conditions allows detection of possible abnormalities**

Summary and Next Steps



Sandra M. Sloan

Summary

- The U.S. EPR CHF correlation has been developed specifically for application to the EPR fuel design
- The correlation has been developed using both uniform and non-uniform CHF test data obtained from the AREVA testing facility at Karlstein, Germany
- The correlation has been developed with specific conservatisms to support its use in analyses
- The topical report submittal will use a conservative correlation limit

Next Steps

> **Submittal of U.S. EPR CHF correlation topical report (December 2006)**

> **Next meetings:**

- **November 29 pre-submittal meeting: <u>Equipment Qualification Program Report</u>**
- **December 7 pre-submittal meeting: <u>Human Factors Topical Report</u>**

Acronyms

AFS	Axial Flux Shape
CHF	Critical Heat Flux
D_{GT}	Guide Tube Outer Diameter
DNBR	Departure from Nucleate Boiling Ratio
G	Mass Velocity
GT	Guide Tube
HMP	High Mechanical Performance
KATHY	Karlstein Thermal Hydraulic Facility
M/P	Measured to Predicted
OD	Outer Diameter
P	Pressure
Q_{CHF}	Predicted Critical Heat Flux
Q_{actual}	Actual Heat Flux
TC, T/C	Thermocouple
X	Quality
Z_{CHF}	Axial Elevation of CHF