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# U.S. EPR In-Core Power Measurement Core Protection Function Design Basis

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August 30, 2010

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# Meeting Purpose

- Present the U.S. EPR, DNBR safety function design approach using 3D direct in-core power measurements to provide improved core protection
  - Prevention of fuel damage via direct in-core power measurement
- Present how the U.S. EPR in-core power measurement and core DNBR protection system design complies with regulations and IEEE 603, 1998
  - Electrical isolation
  - Physical separation
  - Communications isolation and independence
  - Capability to mitigate Chapter 15 events in the presence of a single random failure
  - Place the reactor in a safe state when measurement system degradation occurs (Technical Specification basis shutdown, Automatic Reactor Trip)

# Topics

- Fundamental core parameters and their application in providing core protection functions
- Historical perspective, the evolution of core power measurements and core protection configurations used in the nuclear industry
- Key design features of the U.S EPR Core Protection System that make it unique, why it provides improved core protection
  - SPND sensor design and core locations
  - SPND sensor calibration
  - SPND sensor signal distribution, acquisition, and processing
  - I&C architecture design compliance with regulations and IEEE 603, 1998

# Path Forward

- **Provide the NRC staff with additional technical information to support a reasonable assurance determination of the adequacy of the system design regarding:**
  - ◇ Electrical isolation
  - ◇ Physical separation
  - ◇ Communications isolation and independence
  - ◇ System capability to mitigate certain Chapter 15 events in the presence of a single random failure

- **Meet with the NRC staff as needed to resolve technical issues**

# U.S. EPR Project Goal

- Obtain NRC approval of the U.S. EPR in-core protection function system design as presented on 8/30/2010

# U.S. EPR Protection System: Fundamentals of SPND-Based Protection System Functions for Remaining Within the Fuel Design Limits

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# Outline and Summary of Purpose

- Overview and definition of Specified Acceptable Fuel Design Limits (SAFDLs)
- Evolution of PWR monitoring and protecting against violating SAFDLs
- U.S. EPR application of self powered neutron detectors (SPNDs) for core monitoring and protection
- Summary: The core protection benefits of direct power distribution measurement and importance of using the full array of neutron flux information

Show the safety benefits afforded by the:

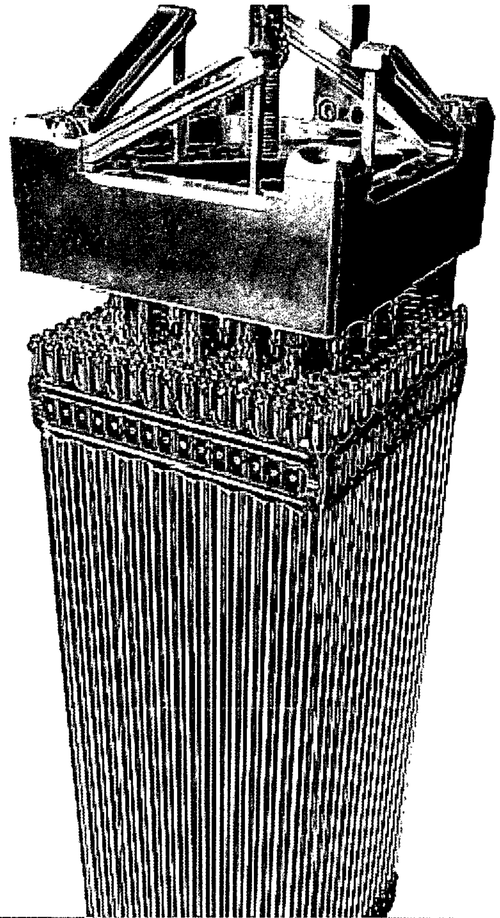
- Use of SPNDs to provide direct measurement of local power throughout the core
- Use of all 72 SPND measurements in each protection system division

# Outline

- **Overview and definition of Specified Acceptable Fuel Design Limits (SAFDLs)**
- Evolution of PWR monitoring and protecting against violating SAFDLs
- U.S. EPR application of self powered neutron detectors (SPNDs) for core monitoring and protection
- Summary: The core protection benefits of direct power distribution measurement and importance of using the full array of neutron flux information

# Fuel damage avoided by respecting specific limits

- **Fuel Centerline Melt (FCM)**
  - Overheating and melting leads to fuel redistribution
- **Departure from Nucleate Boiling (DNB)**
  - Heat transfer degradation leads to rapid overheating of fuel and cladding



**The safety approach establishes limits for reactor fuel and then specifies requirements for the protection system design to stay within these limits.**

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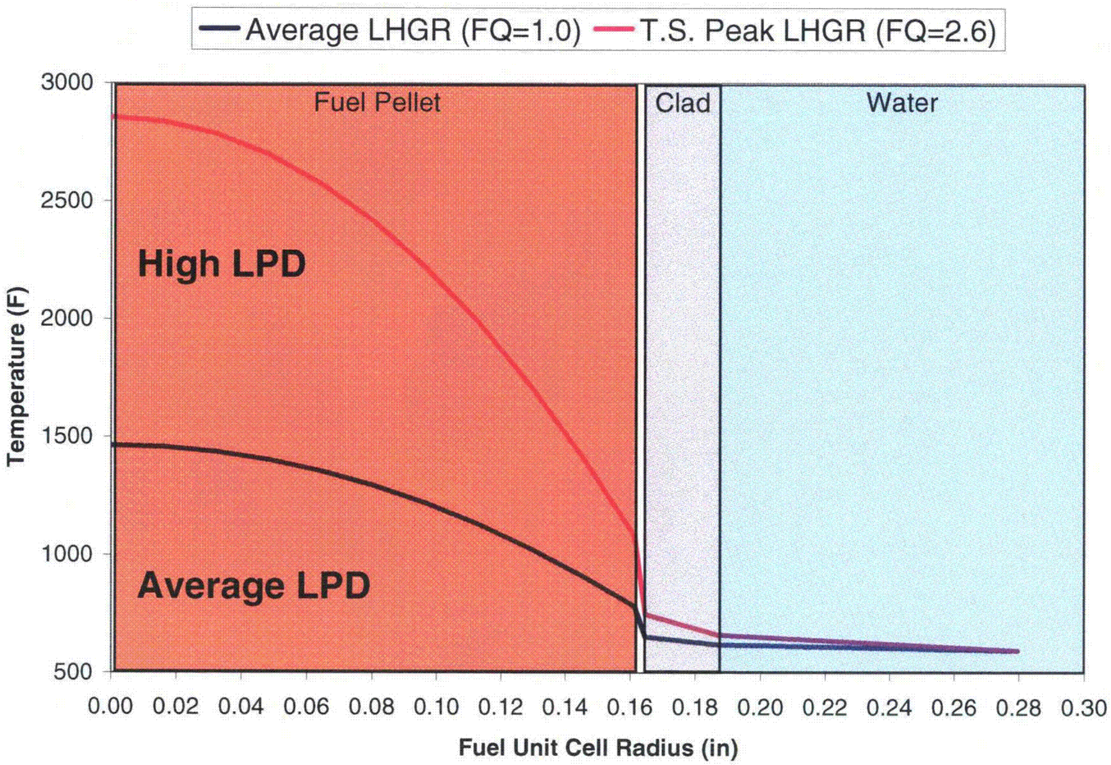
# Fuel Centerline Melt Protection Considerations




- **Temperature rise to the fuel center is proportional to the Linear Power Density (LPD)**
- **LPD is proportional to the fission rate/neutron flux**
- **The core power distribution (with associated peaking) will result in a range of fuel temperatures**
- **Fuel melt occurs ~4900 F**
  - **Fission product barrier is lost**

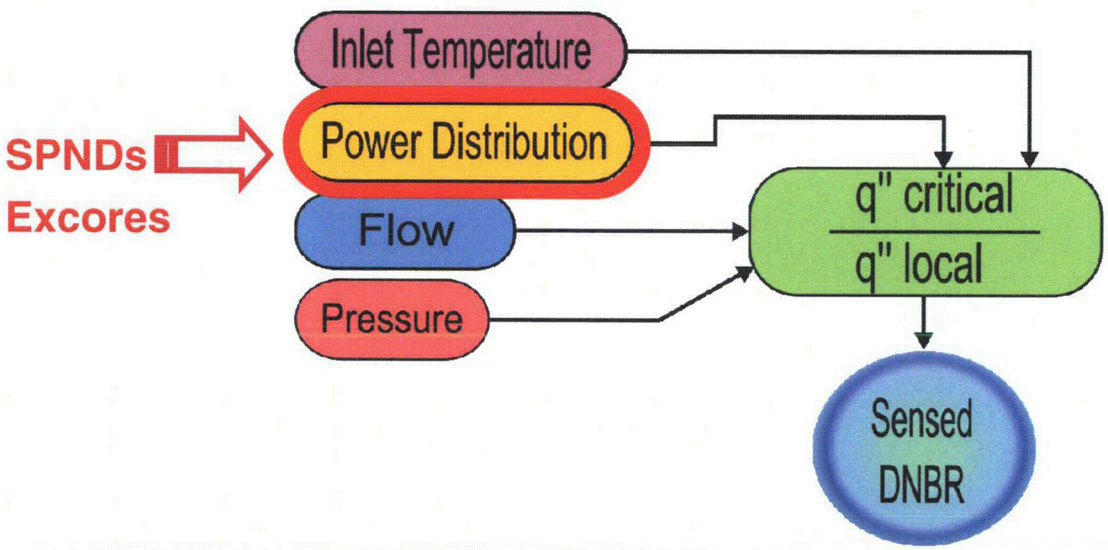
***LPD is also known as Linear Heat Generation Rate (LHGR)***

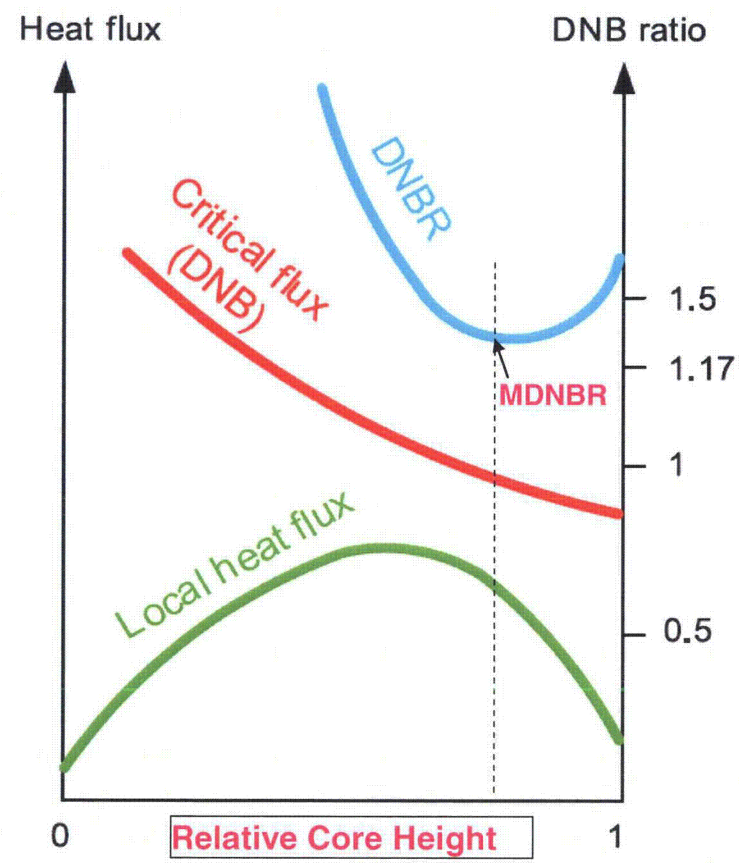
**Use of excore detectors infers the internal core power distribution and penalty factors are needed for the uncertainties**

**Use of incore SPNDs provides a more direct measurement of the core power distribution as it relates to LPD**

# Coolant Heat Transfer Mechanisms Leading to Critical Heat Flux/DNB

- **Departure from Nucleate Boiling (DNB)**
  - **The point at which the heat transfer from a fuel rod rapidly decreases due to the insulating effect of a steam blanket that forms on the rod surface as the temperature continues to increase.**



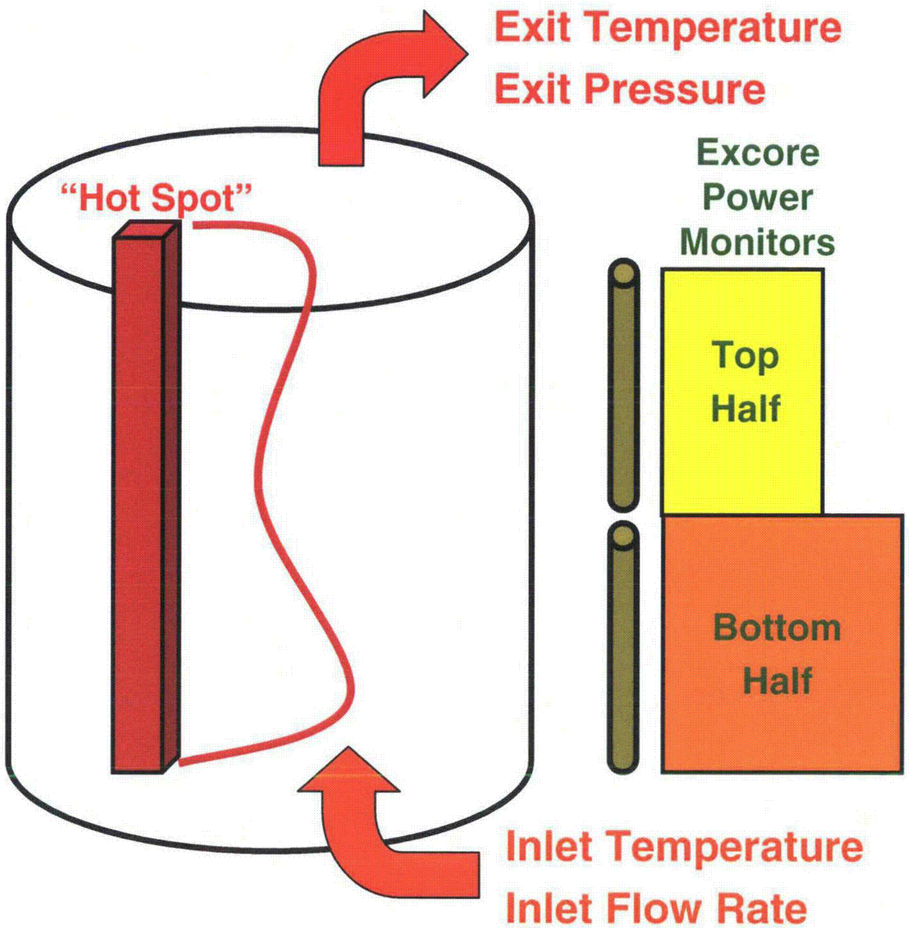




**Using the SPNDs to obtain a more direct measurement of core power distribution results in a more precise determination of the limiting DNBR locations in the core**

# Outline

- Overview and definition of Specified Acceptable Fuel Design Limits (SAFDLs)
- **Evolution of PWR monitoring and protecting against violating SAFDLs**
  - **Excore measurements used to infer internal incore conditions**
  - **Design evolution to better prediction of incore conditions using rod positions**
  - **Use of incore neutron detectors to directly monitor neutron flux for direct determination of incore LPD conditions**
  - **US EPR use of incore neutron detectors for core protection**
- U.S. EPR application of self powered neutron detectors (SPNDs) for Core Monitoring and Protection
- Summary: The core protection benefits of direct power distribution measurement and importance of using the full array of neutron flux information

# Historical Approach to Protection of SAFDLs

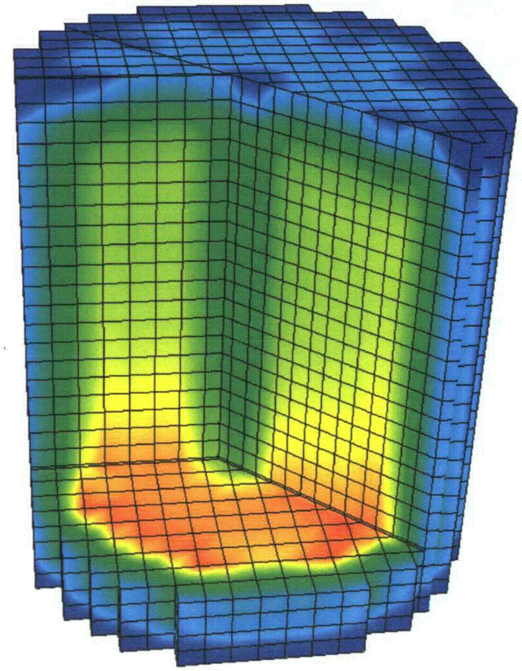



- Trips such as OP$\Delta$T & OT$\Delta$T globally protect LPD/DNBR
- LPD/LHGR (to protect against FCM) inferred from:
  - Core power ($\Delta$T)
  - Excore Axial Power Shape
  - Penalty/Allowance Factors
- DNBR inferred from:
  - Inlet Temperature
  - Inlet Flow Rate
  - Exit Pressure
  - Core Power ($\Delta$T)
  - Excore Axial Power Shape
  - Penalty/Allowance Factors

**Excore measurements are limited to a coarse representation of the core internal power shape and calculated correction factors are required to assure margin to the SAFDLs**

# Evolution to Measuring the Incore Power Shapes

- 1980's transitions Generation II reactors
- Core protection calculator by CE
  - Online calculation of LPD and DNBR
  - Leverages control rod position information to give improved resolution of the core internal power distribution and to respond to rod misalignment conditions
- Position of control rods influences the power distribution within the core
- Better resolution of the actual incore power shapes provides a real time calculation of maximum LPD and



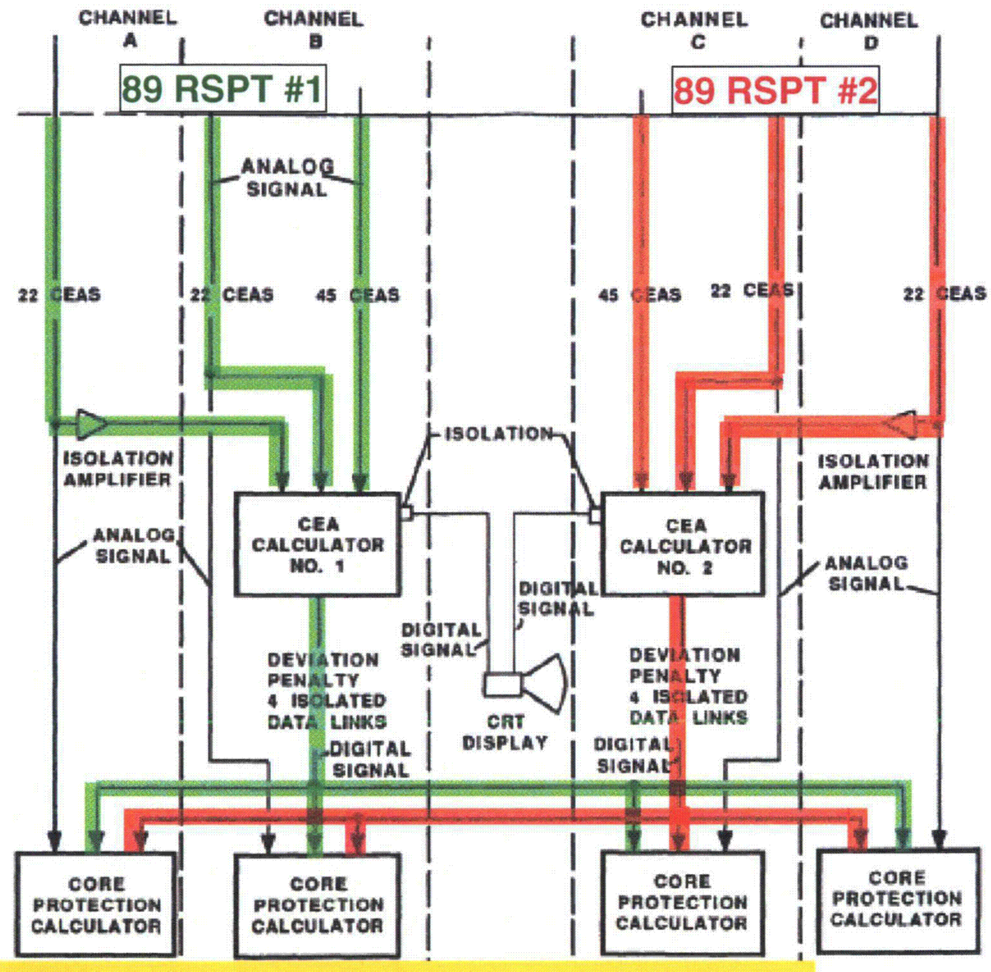
Example Full 3D Power Distribution

- *Excore detectors only measure flux from the lower power outer periphery of the core to get a global view of the core power shape*
- *Details of the interior higher power regions are missed by excores*

**Application of the control rod position information is based upon consideration of the information in aggregate shared across divisions**

# Combustion Engineering's CEA Calculator and Core Protection Calculator (CPC)

- **Introduction of common/shared core information in all protection channels**
  - Power measurement and global axial shape use excore neutron power detector measurements
  - Rod position measurements are shared to provide more accurate interpretation of the excore flux shape
  - Calculation of the penalty factors is performed in two protection system divisions (Control Element Assembly Calculators, CEACs)
  - Results of the penalty calculations are used in all four protection system channels
  - Reason to share data is to get the aggregate detailed 3D power shape as impacted by all rod positions
  - Low DNBR and High LPD margins




**The safety benefits provided by using more accurate information from within the core are most effective if all the information is used in aggregate**

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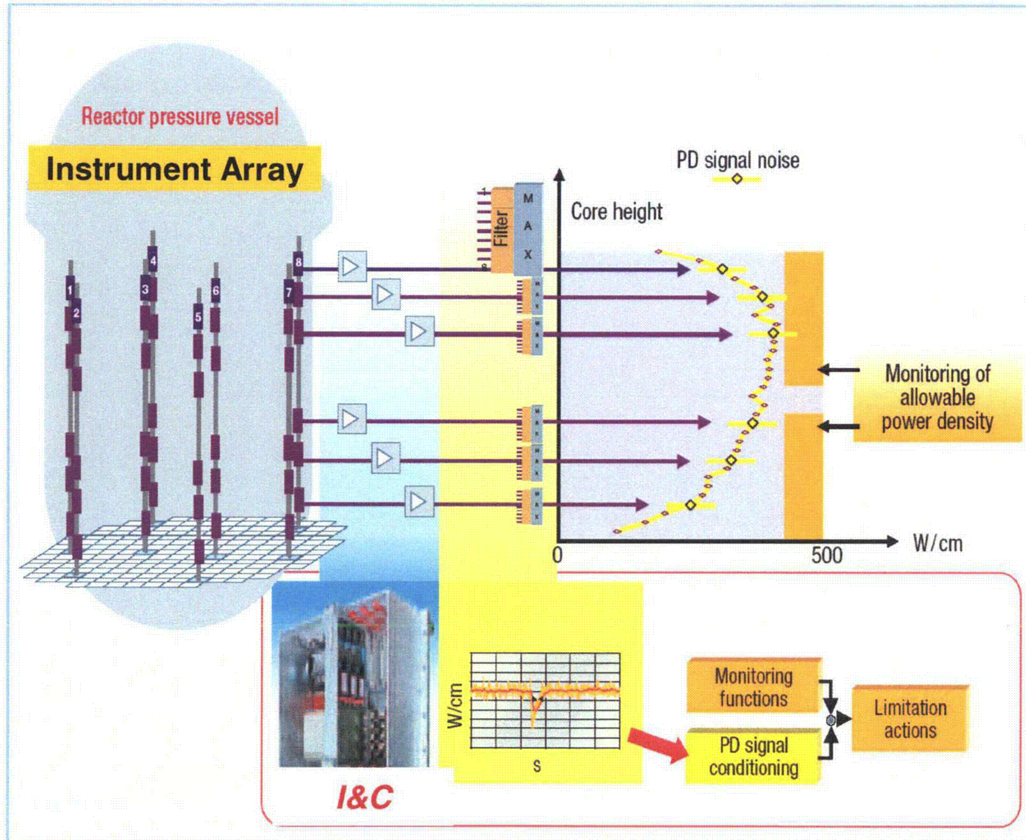
# Incore Self Powered Neutron Detectors (SPNDs) for Direct 3D Power Measurement

- Detailed power shape replaces the coarse representation provided by excores
- >30 years of experience using SPNDs for core surveillance
- 72 independent sensors distributed throughout the core
- Postulated failures of SPNDs as a basis for setting more conservative reactor trip thresholds



# Outline

- Overview and definition of Specified Acceptable Fuel Design Limits (SAFDLs)
- Evolution of PWR monitoring and protecting against violating SAFDLs
- **U.S. EPR application of self powered neutron detectors (SPNDs) for core monitoring and protection**
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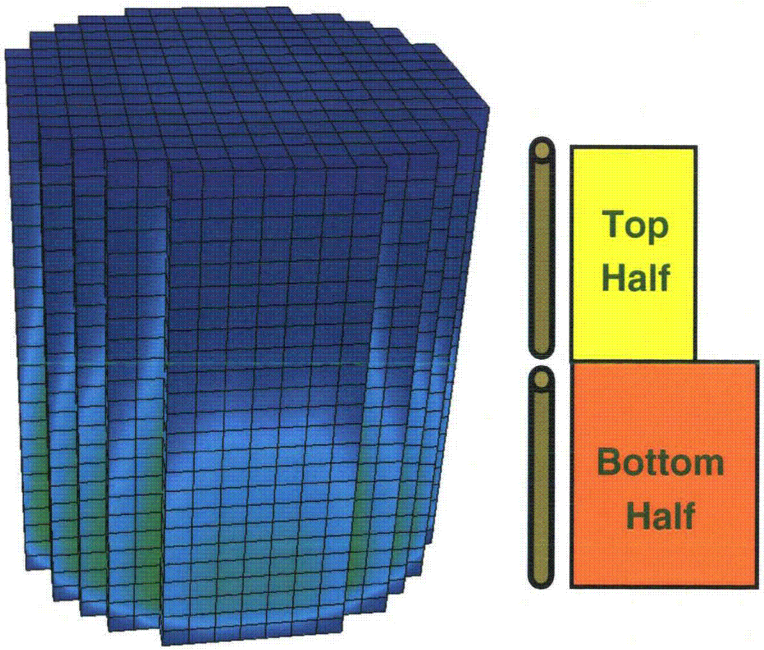
# US EPR Approach to Protection of SAFDLS

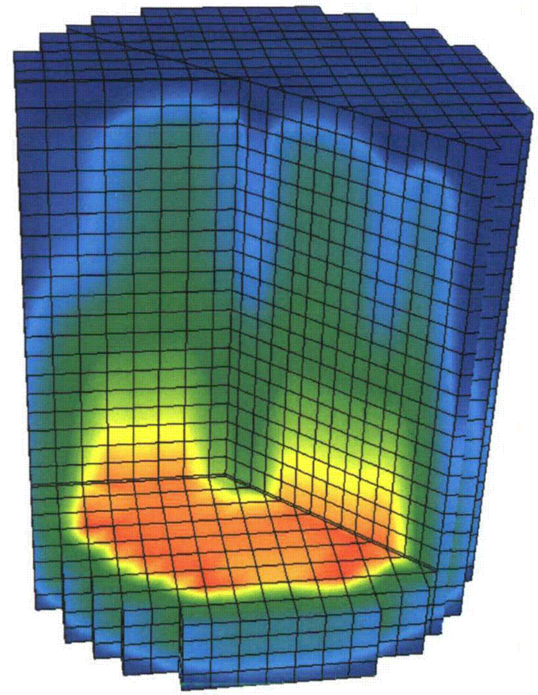
- **Low DNBR Trip**
  - faster response and provides a local measurement of the 3D core power distribution using incore measurements
- **High Linear Power Density Trip**
  - faster response and provides a local measurement of the local maximum LHGR using incore measurements
- **High Core Power Level Trip (HCPL)**
  - covers slower events and bounds LPD for symmetric events
- **Low Saturation Margin Trip**
  - bounds for HCPL calculation and for P-T conditions required to be covered by DNBR trips
- **High Flux Rate Trip**
  - bounds power levels for faster events and acts like a variable overpower trip
- **Low-Low RCS flow (one loop), Low RCS flow rate (2 loops) Trips**
  - bounds flow rates required to be covered by DNBR trips
- **Low Hot Leg and Pressurizer Pressure Trips**
  - provides floor to pressure for DNBR

**Primary protection of the SAFDLs is now provided by the incore based trips which more directly measure the local core power phenomena that could challenge them**

# Measuring, Instead of Inferring, the 3D Core Power Distribution

- **Excore power detectors**
  - Monitors periphery of core
  - Coarse axial power shape resolution
  - Use of control rod positions to provide inferred core internal power



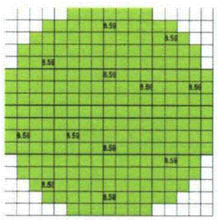



- **Incore detector system**
  - Monitors local power
  - Directly measure radial and axial power distribution effects

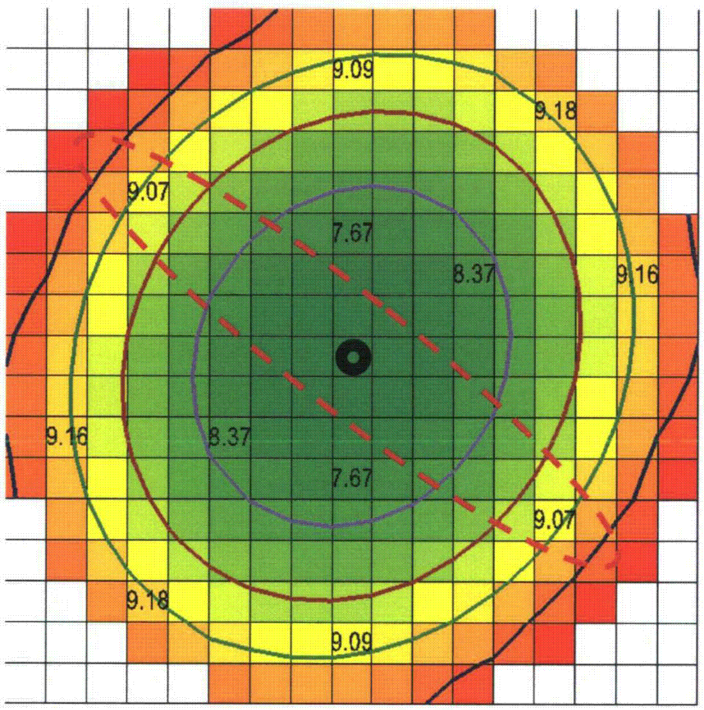
**For better resolution of LPD distribution, need full 3D array of 72 SPND readings**

# Results of the Ability to Directly Measure Power Shape Impacts from Rod Movement

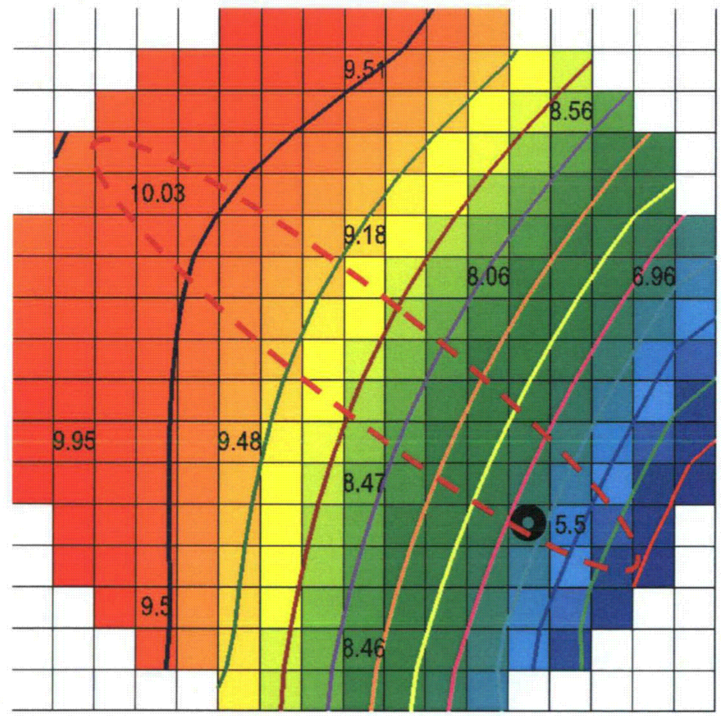
- The array of SPNDs can be used to respond to radial and axial shape redistributions regardless of event symmetry
- <u>Can better resolve movement of the incore hot spot</u>



Initial State, 8.6 kW/ft



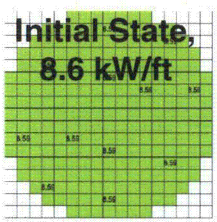

Rod J-09 Drop - Symmetric

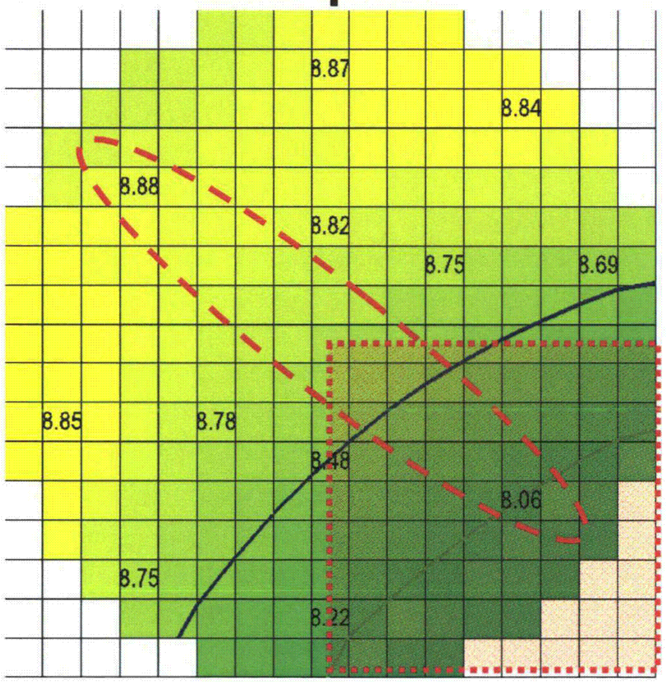



Rod N-07 Drop - Asymmetric

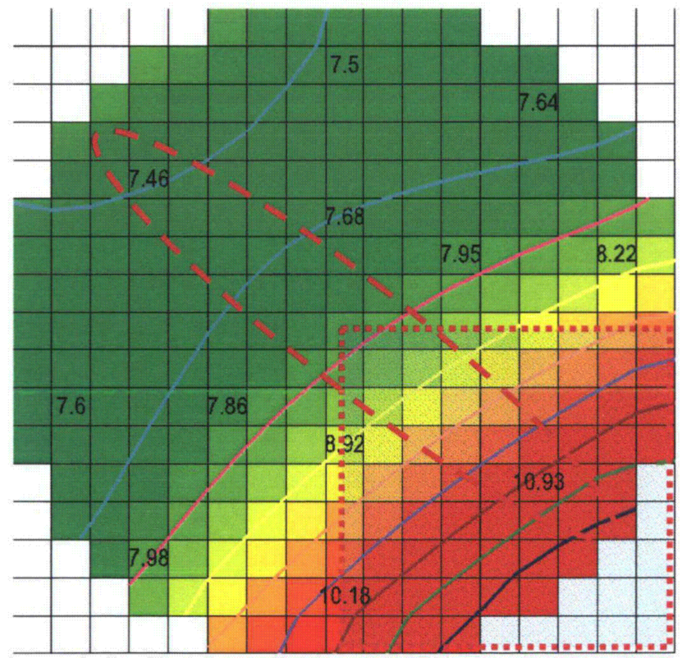
# Ability to Directly Measure Power Shape Thermal-Hydraulic or Xenon Transient Conditions

- Radial and axial power shifts due to influences from other than rod position changes can be detected by the incore SPNDs
- If LPD imbalance is significant enough, it will trigger use of a more conservative trip threshold for MDNBR Protection



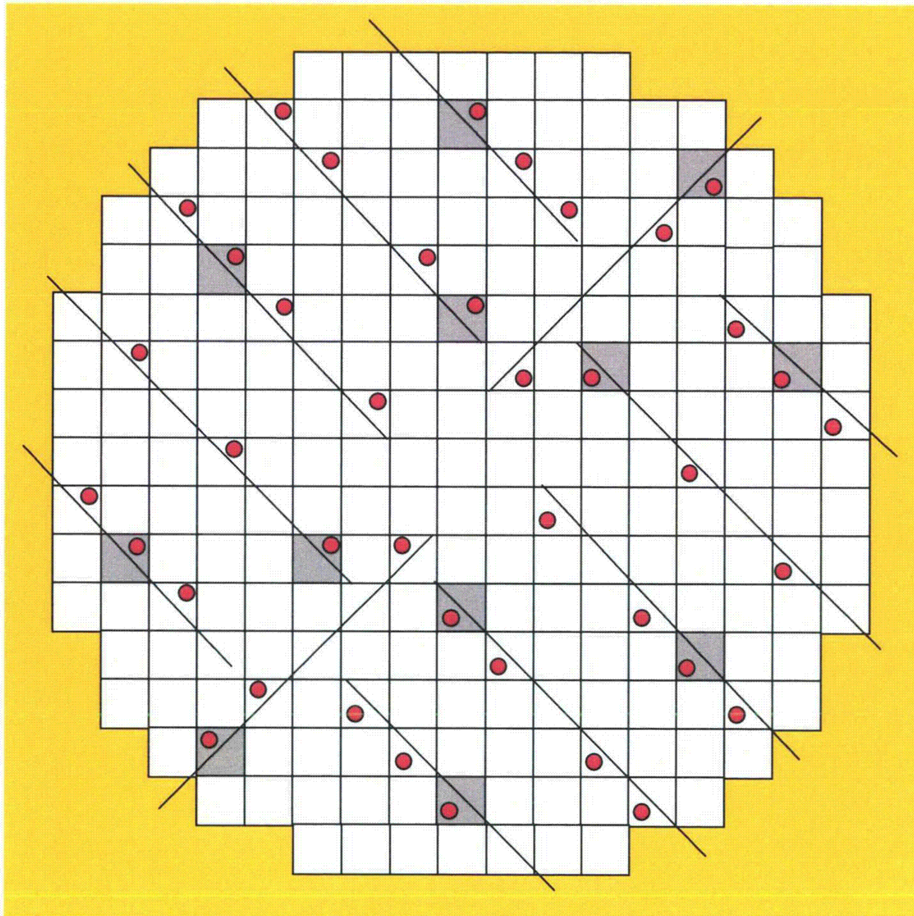




+10F Quadrant Over-heating




-90F Quadrant Over-cooling

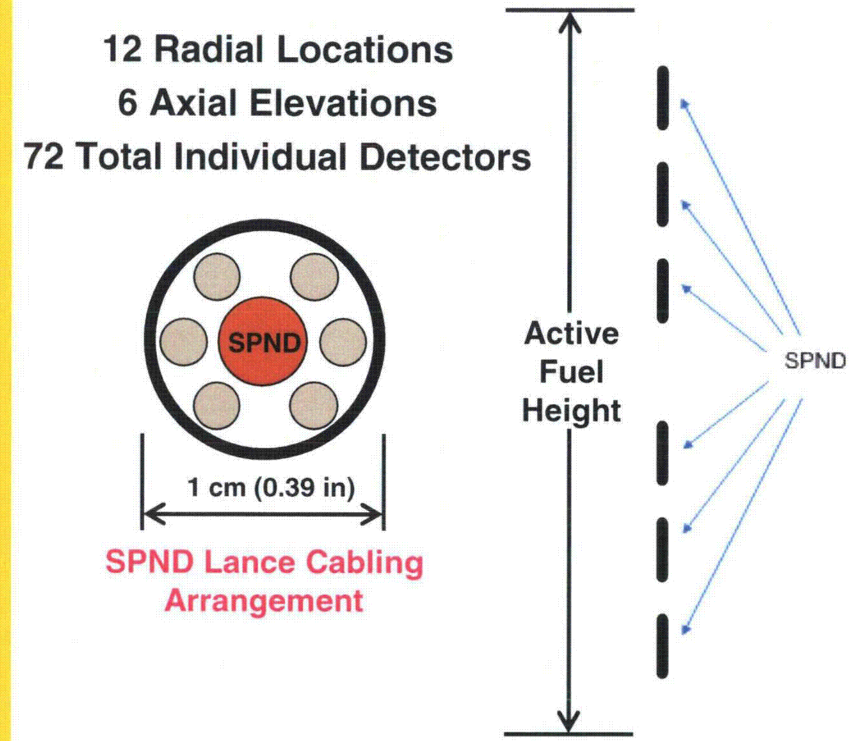
# Incore Neutron Detector Allocation



12 Radial Locations

6 Axial Elevations

72 Total Individual Detectors



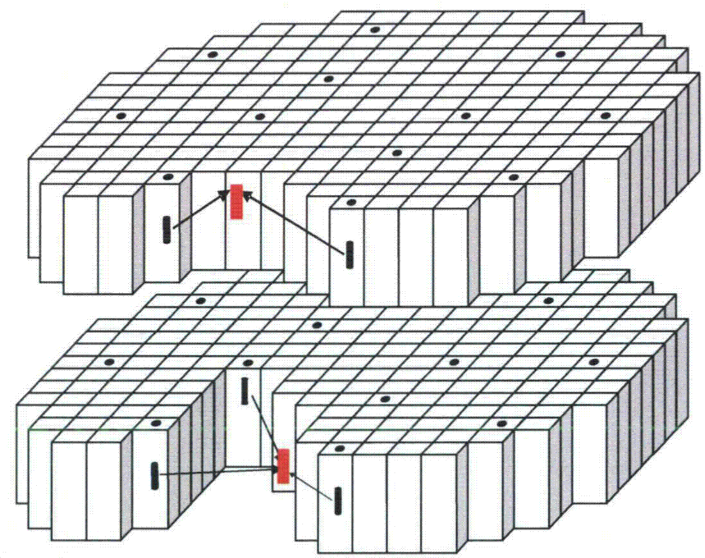

Aeroball Measurement System (AMS), with 40 locations of incore detailed measurements, used to calibrate the SPNDs to conditions for LPD and DNBR

Fuel Assemblies with SPND

Aeroball Measurement System Locations

# Principles of SPND Calibration for High Linear Power Density (LPD) Function

- At the time of calculation with the AMS flux measurement, the "hot spot" in each axial zone is determined
- All 12 SPNDs in an axial elevation are calibrated to read the maximum heating rate in that coverage zone
- Conservative approach since zones away from hot spot will respond as if they were the hot spot
  - Global power, rod influence, xenon transient, etc.
- All SPNDs are ranked and compared to the reactor trip threshold
  - Reactor Trip setpoint is conservatively lowered based on the number of failed SPNDs to cover the reduced accuracy in the resolution of the LPD measurement

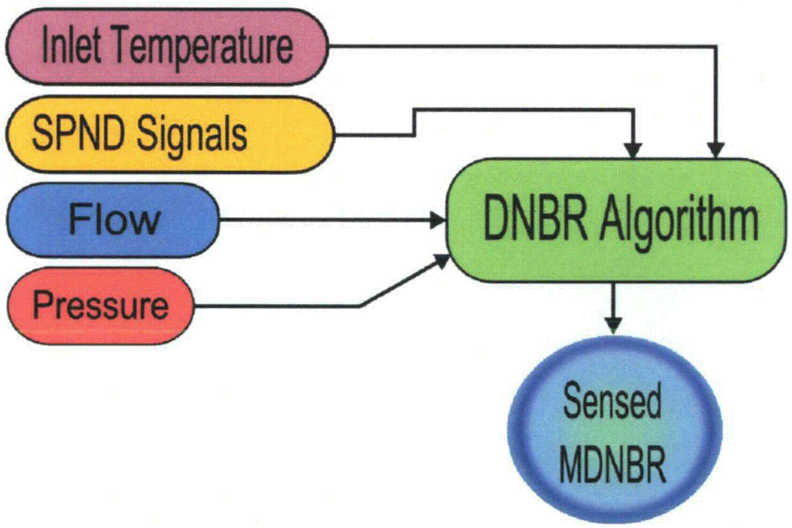


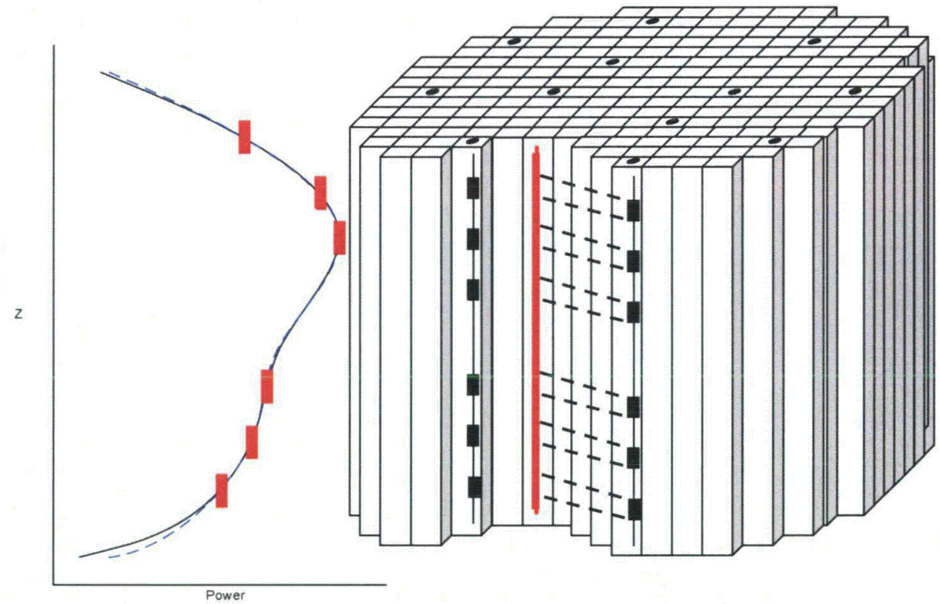
**Single point calibration is conservative and more tolerant to SPND failures and facilitates the resolution of power asymmetries**

# Principles of SPND Calibration for Low DNBR Function

## ▶ DNB Ratio Monitoring

- Each of the 12 SPND strings is calibrated to indicate the LPD axial distribution of the DNBR limiting "hot channel"
- Use the 6 elevations to reconstruct the power shape/enthalpy rise
- DNBR estimated using reconstructed power distribution and thermal hydraulic boundary conditions




**Single calibration gives conservative measure of non-limiting locations. Changes from the calibrated state are seen from the limiting location condition**

# Application of SPND Measurements

- Directly measure local power conditions in the core
  - 3D array of information is used in aggregate for LPD and DNBR
- Calibration of SPNDs uses the full array of 72 signals to protect the SAFDLs:
  - Calibrate to local "hot spots" for LPD and "hot channel" for DNBR
  - FCM protected by 6 axial slices of SPND measurements
  - DNBR protected by 12 radial strings of SPND measurements
  - Sharing of all signals enables the detection of core imbalances
- Incore reactor trips on High LPD and Low DNBR
  - Each division performs its own calculations
  - Trip threshold settings shifted according to the number of failed SPNDs
  - Detected imbalances will raise DNBR trip setting

# Outline

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- **Summary: The core protection benefits of direct power distribution measurement and importance of using the full array of neutron flux information**

# Summary

- U.S EPR utilizes an evolution of power measurement for core protection (FCM and DNBR SAFLDs)
  - ◇ Direct measurement of core 3D power distribution with array of SPNDs
- There is a precedent for the sharing of measured data across safety divisions to enhance the safety function
- U.S. EPR actions are based on direct local core power measurements - not inferred by indirect means
  - ◇ Direct measurement of a process variable is fundamental in an I&C system design for providing effective protective actions
- Use of the shared data is an integral consideration in the core design and the setpoint and transient analysis methods (ANP-10287P)
  - ◇ The function of the incore trip system is enhanced when all 72 SPND signals are available in each division

# List of Acronyms

- AMS - Aeroball Measurement System
- CEAC - Control Element Assembly Calculator
- CHF - Critical Heat Flux
- CPC - Core Protection Calculator
- FCM - Fuel Centerline Melt
- (M)DNB(R) - (Minimum) Departure from Nucleate Boiling (Ratio)
- LHGR - Linear Heat Generation Rate
- LPD - Linear Power Density
- OPDT - Over-Power, Delta-Temperature
- OTDT - Over-Temperature, Delta-Temperature
- SAFDL - Specified Acceptable Fuel Design Limit
- SPND - Self Powered Neutron Detector
- VLPT - Variable Low Pressure Trip
- VOPT - Variable Over-Power Trip