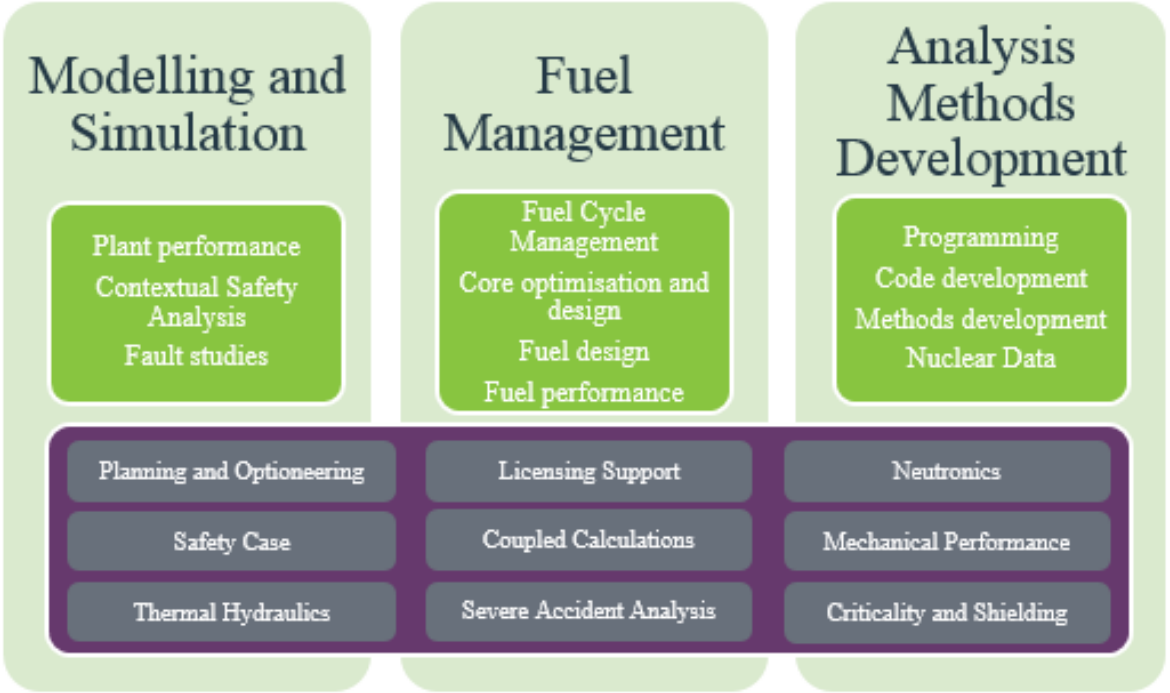
Use of UK core physics codes WIMS and PANTHER to model current and future BWR designs

John Lillington, Ben Lindley, Brendan Tollit, Peter Smith, Michael Dillistone

Introduction

- Question from BWR Hub Conference 2016 – can UK codes be applied to BWR core physics applications?
- Various modelling needs:
  - Support the operation of the UKABWR
  - Support research on future designs of BWR for application in the UK – e.g. the RBWR
  - Upskill the UK in BWR core analysis – BWR cores are complicated, and arguably one of the areas where BWR differs most significantly from PWR
- The UK core physics codes are the ANSWERS codes:
  - WIMS (Wood)
  - PANTHER (EDF Energy)
- Development of BWR core simulation capability by ANSWERS team at Wood
- We would like to thank **Horizon** for supporting ABWR developments and **Hitachi** for supporting RBWR developments.

WOOD Generic Modelling and Methods Development

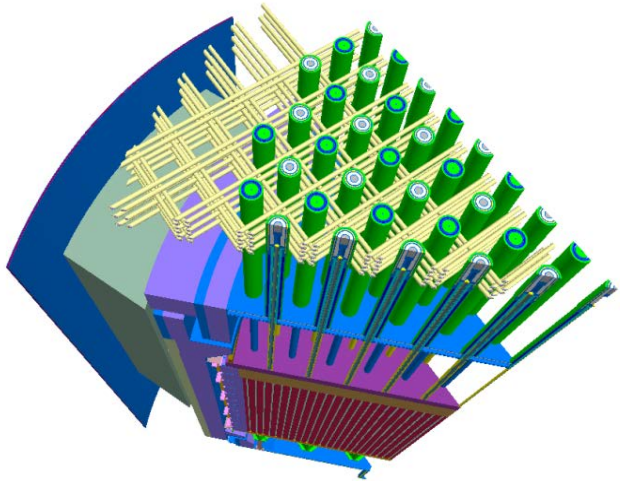


ANSWERS Overall Strategy

- Current generation
  - Further grow ANSWERS support to UK and international clients. Plant performance, safety and operation, fuel cycle, long term operation, EOL and decommissioning.
- New build
  - Promote ANSWERS software services to a widening range of UK and International vendors. Continue to extend the codes for flexible application across all major new reactor technologies.
- State-of-the-art Methodologies
  - Continue to develop the ANSWERS software to lead the way in radiation transport modelling capabilities.
- Resources
  - Undertake active recruitment campaign to maintain and grow high quality resources for the ANSWERS Team. Close engagement with leading ‘nuclear’ universities.

ANSWERS Physics Codes' Suite

- WIMS – A modular reactor physics software package for neutronics calculations. All thermal reactor types, including research reactors, can be analysed.
- PANTHER – A leading neutron diffusion and thermal hydraulics code for the analysis of any thermal reactor core.
- MONK – A powerful Monte Carlo tool for nuclear criticality safety and reactor physics analysis.
- MCBEND is a powerful Monte Carlo software tool for general radiation transport analysis for shielding and dosimetry analysis.



3D ray trace display of a reactor with upper concrete removed.

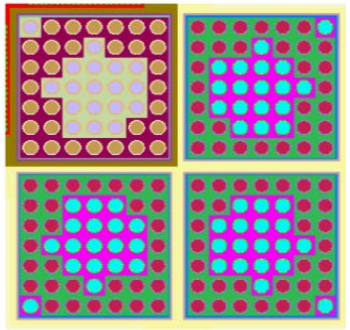
Visual Workshop ANSWERS Tool

Prepare and verify models.
Launch jobs for the Physics codes.
View Results
Interactive 3D displays.

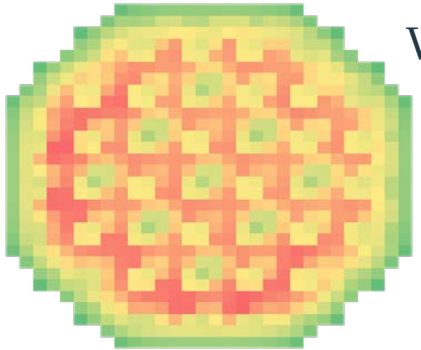
ANSWERS Codes' Validation for BWR Applications

- Computational (code-to-code) benchmark performed for ABWR statepoints with 10x10 fuel

- Example: Participation in UAM Benchmark (Uncertainty Quantification) – PWR and BWR



WIMS supercell model



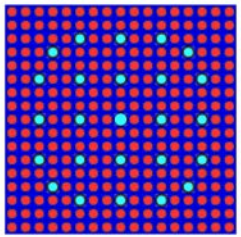
Powermap generated in PANTHER

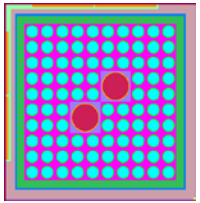
Core Physics Simulation

- PWR and BWR core analysis is almost universally performed using a 2-stage process:
  - 2D radiation transport calculation for each slice of each fuel assembly
    - Calculation performed at a range of conditions and burn-ups
    - A big interpolation table of macroscopic cross sections is generated
  - 3D core calculation
    - Thermal-hydraulic feedback
    - Interpolates on the macroscopic cross sections generated by the 2D calculation

Moving from PWR to BWR

- We have an operating PWR in the UK (Sizewell B)
- WIMS and PANTHER used as ‘frontline’ tools to support reactor operation
- To move from PWRs to BWRs consider the differences…





	PWR	BWR
Control rod insertion	From above	From below
Control rod location	Middle of fuel assembly	Corner of fuel assembly
Thermal-hydraulics	No boiling in core	Boiling in core
Reactivity control	Soluble boron	Control rods + flow rate *(leads to significantly greater control rod insertion at power than for PWR)*

Effects of Boiling

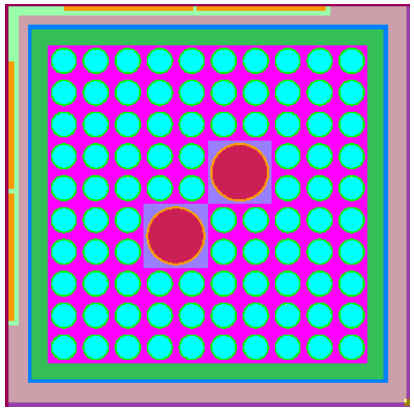
- Stronger feedback – tighter coupling between neutronics and thermal-hydraulics
- Strong spectral variation with fuel position (~Plutonium build-up different in different regions)
- Void fraction and therefore flow rate differs significantly between assemblies – necessary to solve momentum equations as well as mass, enthalpy

ABWR Lattice Physics Modelling Requirements

- We need to handle the following phenomena in WIMS:
  - Resonance shelf-shielding under range of different spectral conditions
    - ➔ WIMS resonance self-shielding treatment for thermal reactor applications has been confirmed to be applicable to the range of spectral conditions in an ABWR
    - ➔ Equivalence and subgroup theory with fine group treatment in the resonance energy range
  - Complicated geometry
    - Water rods
    - Boron carbide pellets in control blades

    ➔ WIMS method of characteristics transport solver can handle essentially arbitrary geometries
  - Automated input preparation of large number of lattices under different conditions. Perform burn-up calculations under different ***historical conditions:***
    - Different water densities
    - Rods in and rods out

    ➔ A prototype tool has been developed which uses an engineering description of the BWR assembly and automatically generates the lattice calculation sequence to be performed



ABWR Core Physics Modelling Requirements

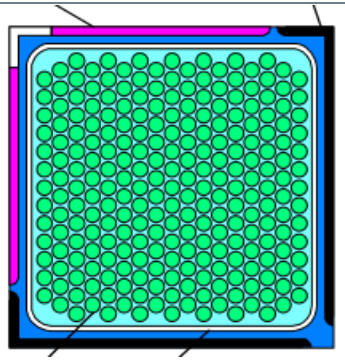
- PANTHER BWR models have been created which model the following BWR phenomena:
  - Control rod insertion from below
  - Interstitial placement of control rods
  - Interpolation of macroscopic cross-sections based on historic rod insertion and coolant density. In particular PANTHER has a capability to calculate element-dependent nuclide compositions based on local spectral variations (‘microscopic depletion’)
- Thermal-hydraulic considerations:
  - PANTHER can solve the momentum equation and calculate channel-dependent flow rate
  - PANTHER has appropriate thermal-hydraulic correlations for void fraction and heat transfer coefficient with bulk boiling in core

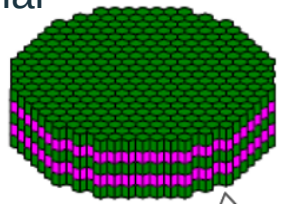
In the development of WIMS/PANTHER models for the ABWR, a series of physics tests have been performed to confirm individual aspects of functionality.

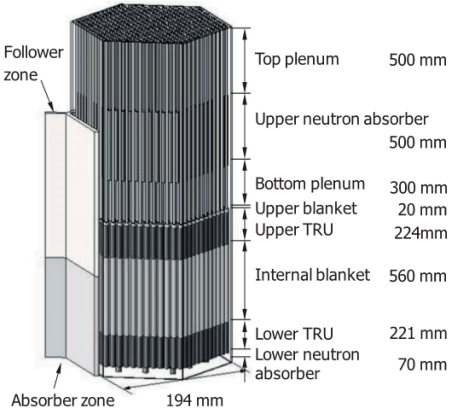
Validation against actual BWR plant data is a key future step

RBWR

- RBWR utilizes a tight lattice and a higher void fraction to facilitate a closed fuel cycle
- Hexagonal and ‘backfit’ designs under consideration
  - Hexagonal lattice allows tighter packing of fuel and fast neutron spectrum
  - Backfit design uses triangular lattice in square fuel assembly for improved compatibility with ABWR
- Use of regions with high TRU loading, plus internal blankets
- This introduces additional physics challenges:
  - High void fraction
  - Fast neutron spectrum
  - Exotic fuel composition (high transuranic loading, including minor actinides)
  - Leakage is key contributor to void coefficient
  - Bimodal power distribution







Source: Hino et al., “Core Design and Analysis of Axially Heterogeneous Boiling Water Reactor for Burning Transuranium Elements”, NSE, Vol. 187, Number 3 (2017) ; Hino. “Pu Utilization in BWR – BWR application for transmutation” ABWR Seminar, March, 2017

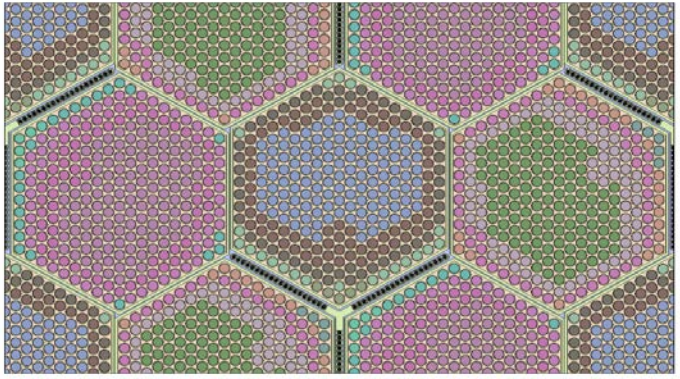
Lattice Physics: RBWR-specific challenges

- The RBWR has an unusual neutron spectrum – between that of a fast reactor and a thermal reactor
  - WIMS resonance shielding methodologies available for thermal and fast reactors
  - Studies currently ongoing into performance of the WIMS resonance shielding methodologies, with a view to deriving an appropriate treatment
- Non-standard lattice designs:
  - Backfit: triangular pitch in square channel box
  - Hexagonal: hexagonal lattice doesn't quite 'line up' so a larger unit cell is needed

  ➔ WIMS method of characteristics transport solver can handle these geometries
- 3D axial heterogeneity
  - Significant axial gradient in neutron flux spectrum between TRU and blanket regions

  ➔ WIMS has 3D transport solution capabilities (Method of characteristics, Monte Carlo)

  … but interface between 3D lattice calculation and 3D core calculation is non-trivial. Provided the 2-stage lattice+core calculation methodology is retained, this is arguably a question of implementation, albeit a very challenging one, rather than related to the capabilities of the codes themselves



Source: Hall and Downer, 2012. SERPENT Cross Section Generation for the RBWR. Serpent Users Group Meeting

RBWR Modelling Requirements – PANTHER

	Magnox	PWR	RBMK	VVER	RBWR
Large number of channels	✓				☺
Water		✓	✓	✓	☺
Bulk boiling			✓		☺
Hexagonal geometry				✓	☺
Multi-group neutron diffusion		✓ (used in PANTHER for some applications)			☺

The harder spectrum of the RBWR necessitates a *multigroup diffusion solution* instead of the typical 2-group solution. This challenges the use of nodal methods (typical for PWR and ABWR), especially in hexagonal geometry

Conclusions

- ***ABWR***
  - WIMS and PANTHER have capability to model ABWR
  - A calculation methodology has been developed to model the ABWR in WIMS/PANTHER
  - Validation against plant data is a key future step
- ***RBWR***
  - Very challenging physics and geometric configuration
  - Development of WIMS/PANTHER models of RBWR-TB2 and Backfit RBWR in progress