



BEIS Nuclear Innovation Programme Thermal Hydraulics Research & Development Phase 1

18 February 2019



Aim of Today

- ▶ Provide an overview of the work that has been done during the Nuclear Thermal Hydraulics R&D Phase 1 project.

Agenda

AM

- ▶ Overview of the Project
- ▶ Thermal Hydraulic Test Facility Specification
- ▶ Thermal Hydraulic Modelling Capability Specification

Lunch

PM

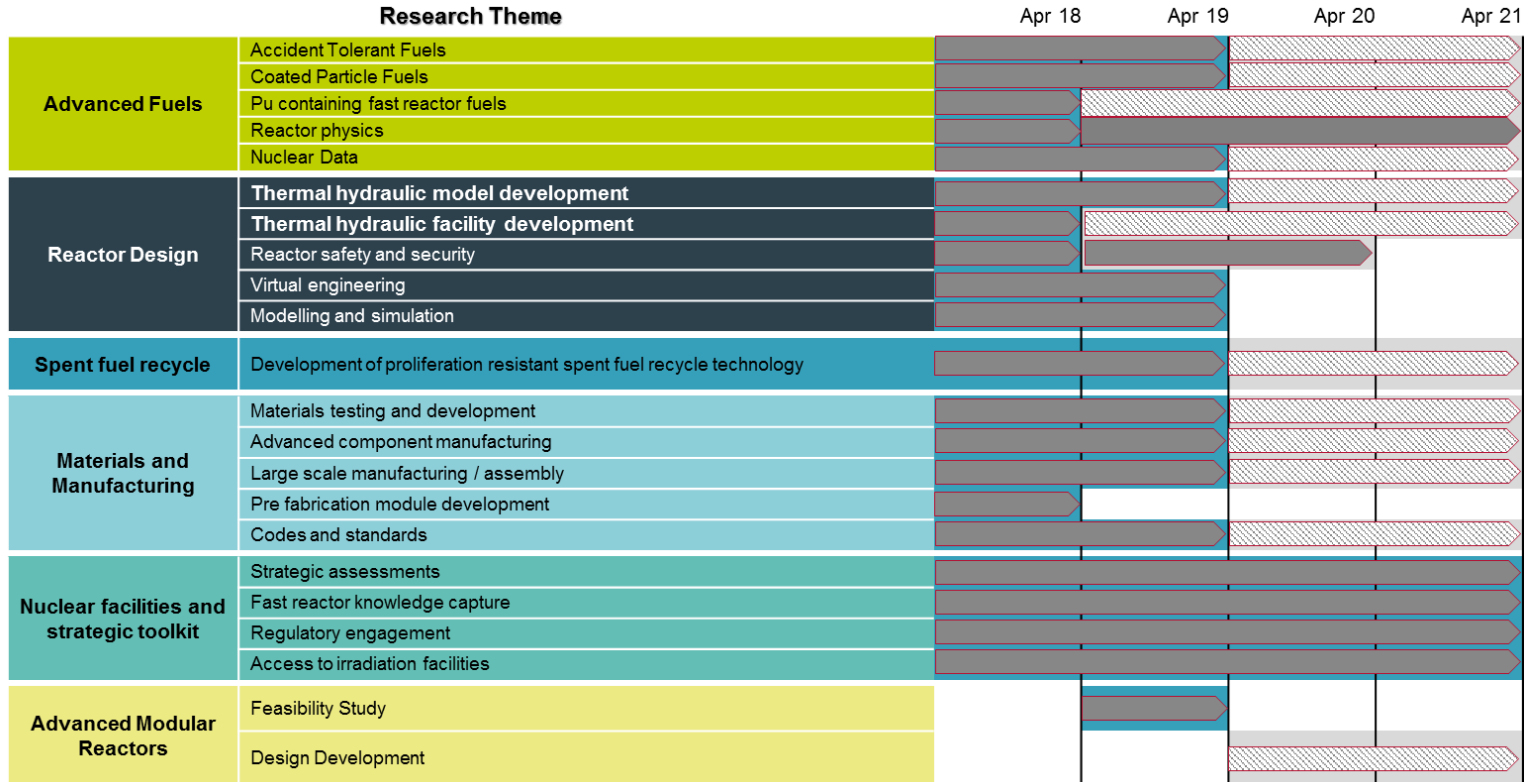
- ▶ Technical Presentations on the Initial Model Development



Project Overview – Carolyn Howlett



Introduction to BEIS Nuclear Innovation Programme



Aims

- ▶ by **2020** establish the UK as a partner engaged in collaborative design projects for new reactors (Generation IV and SMR), building on its existing and growing design expertise
- ▶ by **2030** maturing R&D results in deployment of new plant with significant UK design content and manufactured parts
- ▶ by **2050** R&D has facilitated UK industry to be a significant partner in the global deployment of Gen III+, Gen IV and SMR technologies

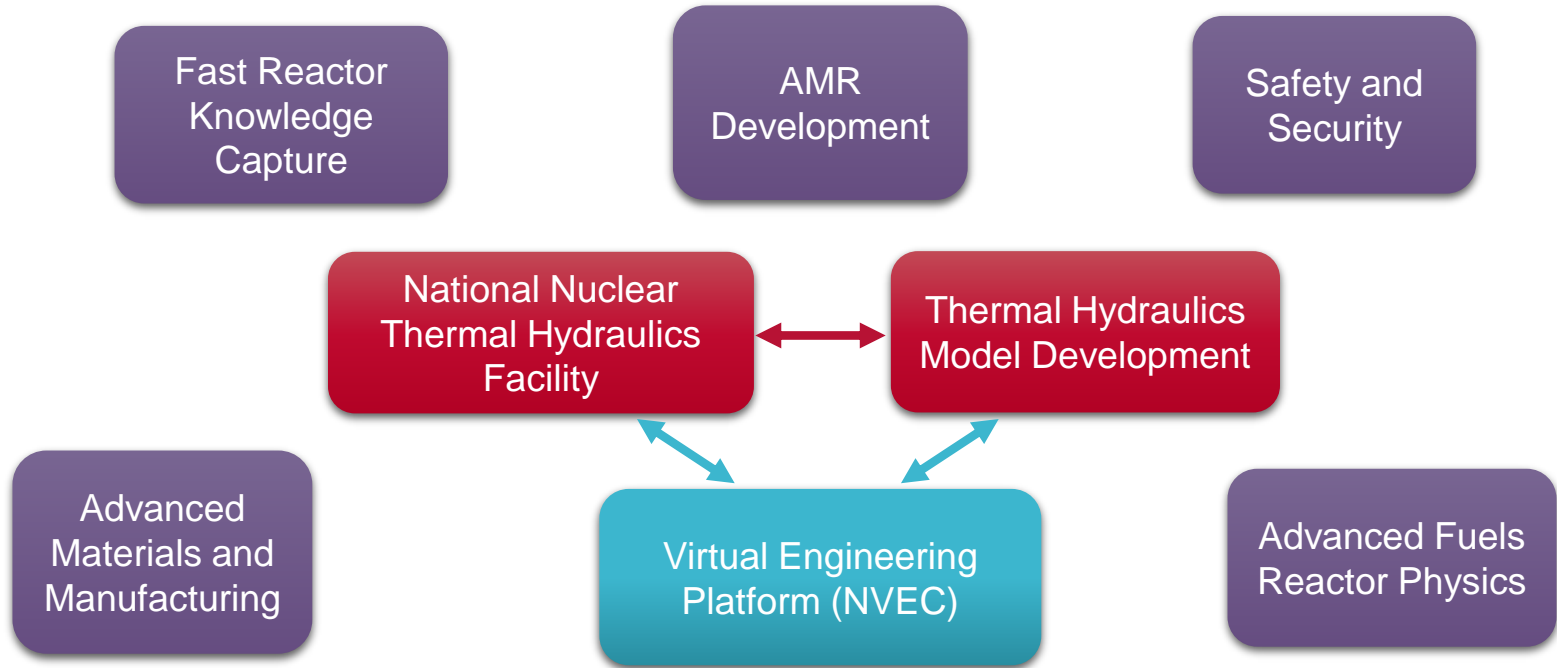
Benefits

- ▶ Enhanced designs, increased productivity and a step change in the way that nuclear design, development and construction programmes are delivered
- ▶ Increased and widespread uptake of modern digital engineering practices within the UK nuclear industry
- ▶ Improved understanding and safety of through life performance of reactor components
- ▶ A greater predictive modelling capability and understanding of passive safety arguments
- ▶ A highly-skilled workforce able to drive design improvements and underpin operations and regulation of future reactors
- ▶ Leverage to facilitate extended UK participation in associated international activities

How can development in Thermal Hydraulics meet these aims?

- ▶ Thermal hydraulics is fundamental to design, performance and safety of all NPP.
- ▶ The UK is already good at state-of-the-art thermo-fluid modelling across a range of industries.
 - ▶ Improvements in the capability to predict and control the temperatures of working fluids (and thereby the solid plant components) delivers improved design in terms of safety, efficiency and cost reduction.
 - ▶ The use of modern thermal hydraulic modelling methods leads to improved understanding and a faster design process.
 - ▶ The transfer of heat by 'natural circulation' is key to delivery of passive safety systems.
 - ▶ The UK already has competence and a good reputation in fluid modelling which can be used to leverage participation in international programmes.
 - ▶ By performing R&D in future reactor technologies you expand knowledge and awareness with UK industry.

Thermal Hydraulics with the NIP



Thermal Hydraulics - Phase 1 Team

- ▶ Led by Frazer-Nash, the team comprises 6 core members:



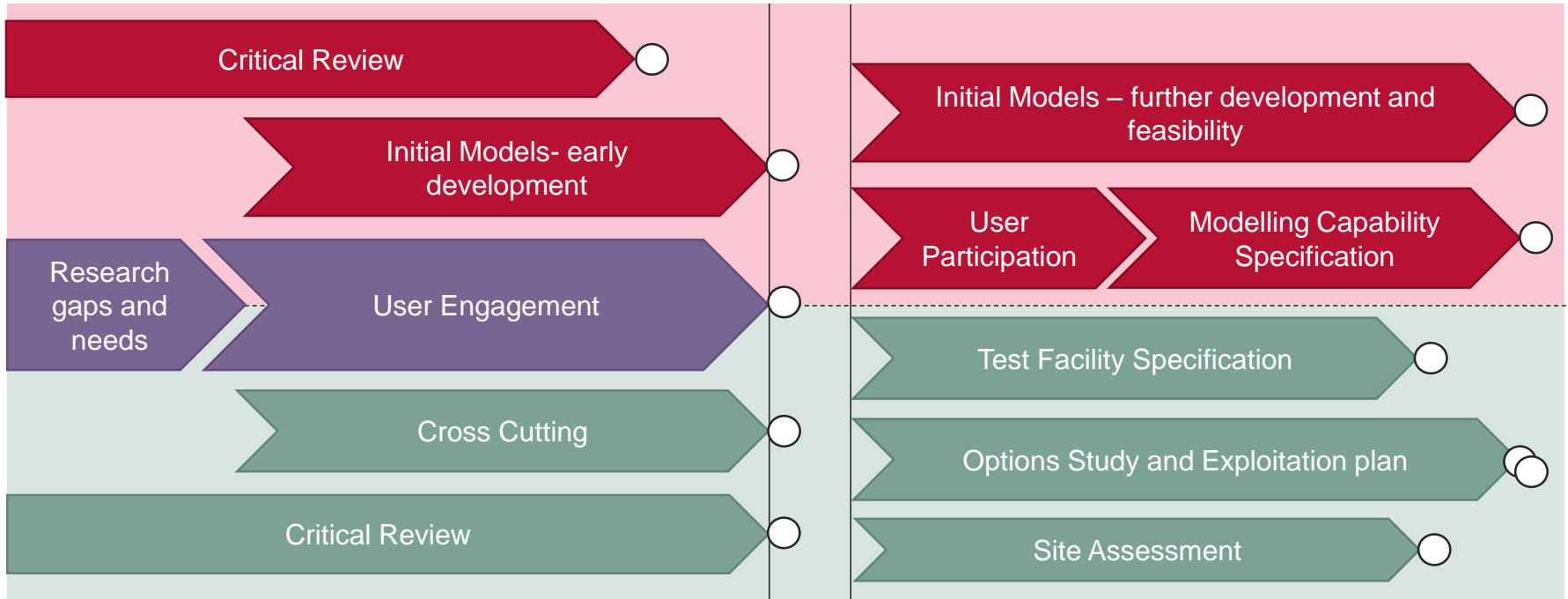
Everyone who contributed – Thank You!

University of Leeds	Rolls-Royce	Siemens PLM	CNL	Stern Labs
University of Cambridge	Moltex Energy	Holtec International	INL	KIT
Liverpool John Moores University	Hitachi Ltd	Hydromine	Virtual Engineering Centre	SIET
Imperial College London	NNL	NuScale Power	NNB GenCo	ENEA
Bangor University	UKAEA	Terrestrial Energy	Hitachi-GE	
ONR	U-Battery Team	DBD	Horizon	
ANSYS	Wood plc	NAMRC	Cammell Laird	

- ▶ **Thermal Hydraulic Test Facility**
 - ▶ A Critical Review of the State-of-the-Art in thermal hydraulic test facilities worldwide.
 - ▶ A Specification for a UK thermal hydraulics test facility.
 - ▶ Identification of opportunities to use the facility to benefit other 'NIRAB' programmes.

- ▶ **Thermal Hydraulic Model Development**
 - ▶ A Critical Review of the State-of-the-Art in thermal hydraulic prediction capability.
 - ▶ A Specification for an innovative thermal hydraulics modelling capability.
 - ▶ Initial Innovative Models.

Work on Phase 1 – Each ○ indicates an output



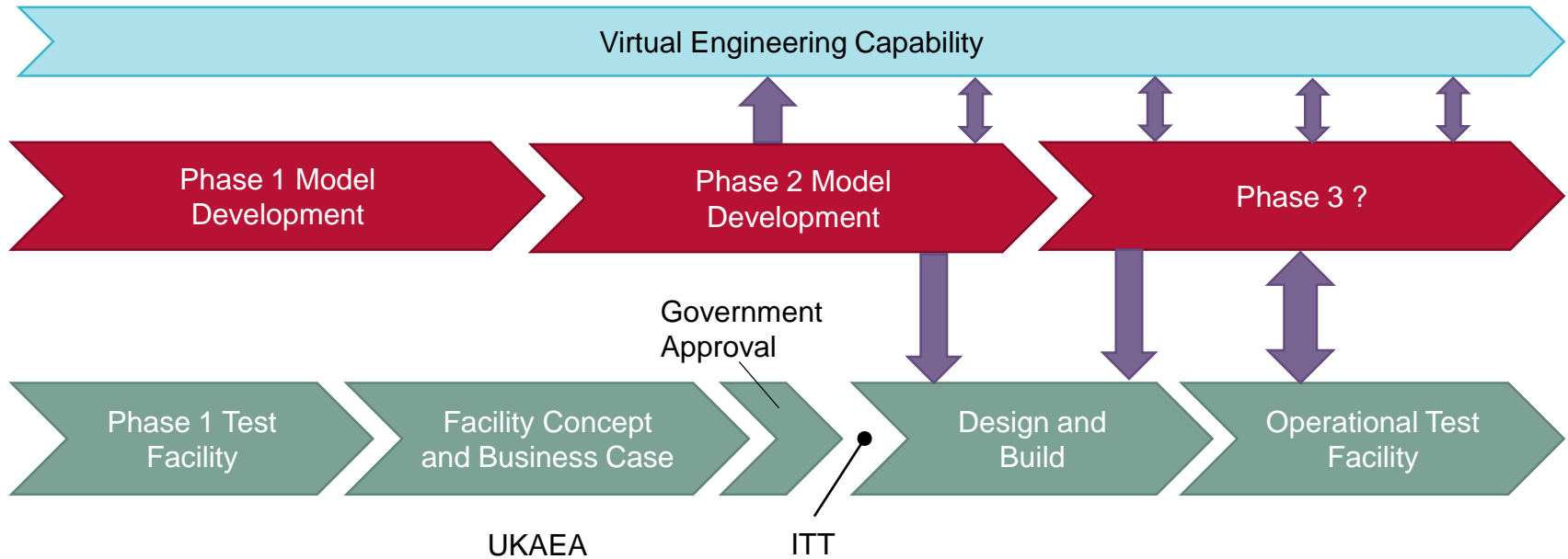
High Level Learning

- ▶ Nuclear Thermal Hydraulics is big and (in some places) fast moving.
- ▶ International collaboration is key and others are keen to collaborate.
- ▶ We are in a period of transition and opportunity in UK Civil Nuclear - it is important to keep an open mind and remain flexible.
- ▶ We should not look to the UK government for all the answers and decisions.
- ▶ The UK nuclear thermal hydraulics community may be small and fragmented but if we pull together we have a pretty good team.

High Level Achievements

- ▶ Improved and captured current understanding of the state-of-the-art.
- ▶ Greatly improved and captured understanding of the thermal hydraulic needs of SMR and AMR reactors.
- ▶ Specification documents that contain far more than it is feasible to progress in Phase 2.
- ▶ Innovative R&D which has benefited from continuous industry feedback.
- ▶ Consideration of aspects of a UK Test Facility beyond just the technical specification.
- ▶ Promoted UK expertise and interest in nuclear thermal hydraulics nationally and internationally.
- ▶ Bringing the UK nuclear thermal hydraulics community closer together, reinforcing academic and industrial relationships.
- ▶ 5 MEng projects and 12 PhDs have been influenced by and/or supported the work.
- ▶ Upskilling and building strong and lasting relationships within the core team and beyond.

Where is it going next?



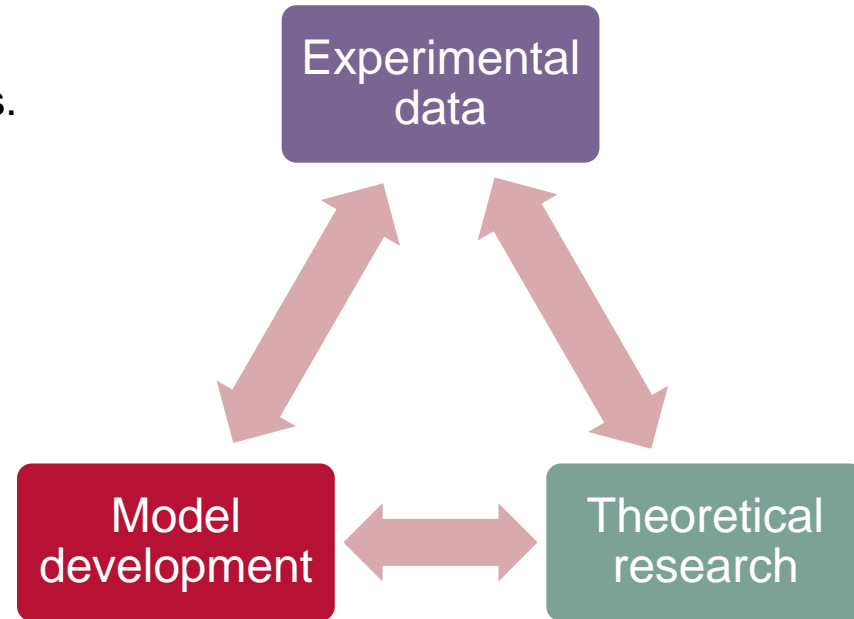


National Nuclear Thermal Hydraulic Facility (NNTHF) – Richard Underhill



The Need for a UK facility

- ▶ No large civil NTH test facilities have been designed or operated in the UK for over 30 years.
- ▶ UK facility will provide focus for NTH research.
- ▶ Essential for the UK to expand our worldwide engagement in thermal hydraulics.
- ▶ High quality experimental data is essential for model development and validation.
- ▶ Experimental tests are required to substantiate nuclear reactor designs and qualify components.



User Requirements for the Facility

- ▶ Potential Users
 - ▶ Gen III+, SMR and AMR developers.
 - ▶ Reactor operators and fuel vendors.
 - ▶ Researchers.

- ▶ Purpose and value of the Facility
 - ▶ Extend knowledge and understanding of NTH phenomena relevant to nuclear reactors.
 - ▶ Validate and/or develop the ability of a modelling code to predict a specific NTH phenomenon.

 - ▶ Develop/test instrumentation for measuring thermal hydraulic phenomena.
 - ▶ Develop physical data sets which can form tradeable Intellectual Property.
 - ▶ Investigate performance of manufacturing techniques, materials or components under reactor conditions.

 - ▶ Provide a mechanism for enhanced collaboration with NTH and other technical areas.
 - ▶ Enhance public awareness of nuclear technology and improve understanding of NTH.

- ▶ Databases have been developed by OECD NEA and IAEA of Thermal Hydraulic test facilities
 - ▶ The International Experimental Thermal HYdraulics Systems database <https://www.oecd-nea.org/tiethysweb>
 - ▶ NEA Research and Test Facilities DataBase <https://www.oecd-nea.org/rtfdb/public/search>
 - ▶ Liquid Metal-cooled Fast Neutron Systems Catalogue <https://nucleus.iaea.org/sites/lmfns/Pages/default.aspx>
- ▶ Large number of test facilities have been identified around the world for each reactor technology:
 - ▶ **87** water (PWR, BWR and SCWR) reactor SET facilities that address natural circulation, two-phase flow, flow-induced vibration and component flow phenomena;
 - ▶ **34** water (PWR and BWR) reactor containment facilities that address combustion, condensation, aerosol and non-condensable gas behaviour;
 - ▶ **24** gas (HTGR, VHTR and GFR).
 - ▶ **42** sodium (SFR).
 - ▶ **31** lead (LFR).
 - ▶ **16** molten salt (MSR).

(not a definitive, exhaustive list)

- ▶ A number of test **facilities** reviewed in more detail to understand their success.
- ▶ A selection of the state of the art:
 - ▶ **HZDR** (Germany) TOPFLOW test facility allows flow investigation in test sections with thin walls and glass windows for optical observation up to 5 MPa, as well as a test section loop with X-ray tomography and wire-mesh sensors to measure void fraction.
 - ▶ **PSI** (Switzerland) operates the large-scale PANDA facility, undertakes PIV and LIF measurements of natural convection/mixing, and detailed measurements of two-phase flow using cold-neutron imaging.
 - ▶ **Texas A&M University** (USA) specialises in PIV, LDV and LIF measurements to generate high fidelity data for validating CFD simulations for VHTR and PWR applications.
- ▶ No clear gap in the current experimental research requirements.
- ▶ Successful thermal hydraulic test facilities developed a strong, distinctive capability with focussed areas of research, measurement techniques or specific expertise.

User Requirements Capture

- ▶ **User Engagement**
- ▶ Industry and academia were contacted through questionnaires and workshops, including reactor developers, academic institutions, service providers and the UK regulatory body.
- ▶ A large number of user requirements were captured:
 - ▶ Split into experimental and modelling requirements.
 - ▶ Differences between technologies and the maturity of the requirements e.g. SMR and AMR.
- ▶ Quantification and bounding of uncertainty in CFD to increase ‘trust’.
- ▶ High quality validation data to support model development and reactor design activities.
- ▶ Improvements in the understanding and simulation of:
 - ▶ Natural convection.
 - ▶ Two-phase flow.
 - ▶ Single phase turbulent mixing.
 - ▶ Fluid flow driven component fatigue.

User Requirements Capture

- ▶ Breadth and depth of information varied greatly between reactor technologies and industry/academic/research perspective
- ▶ There were a number of common themes:
 - ▶ There is national and international interest in a new UK thermal hydraulics test facility.
 - ▶ The majority of responses came from users focused on water-cooled reactor technology.
 - ▶ There is shared interest in large-scale boiling water facilities with representative test articles, e.g. fuel assemblies and steam generators.
 - ▶ A test facility with state-of-the-art instrumentation is likely to have a large global appeal.
 - ▶ A UK facility could help up-skill personnel in the nuclear industry.
- ▶ UK facility should focus on Separate Effect Tests and Basic Tests.
- ▶ Designing a rig or a facility that is all-things-to-all-people is unrealistic.

Facility specification and Site assessment

- ▶ **Test facility specification**
 - ▶ Developed from existing facilities and user requirements.
 - ▶ Identifies the bounding parameters for the building i.e. height, size, power, etc.
- ▶ BEIS want the test facility to:
 - ▶ Be flexible.
 - ▶ Bound many future test rigs.
 - ▶ Accommodate advanced reactor technologies.
 - ▶ Be self-funding.
- ▶ **Menai Science Park (MSP) site assessment**
 - ▶ MSP has been assessed against facility specification.
 - ▶ Benefits and limitations have been identified.



Image courtesy of M-SParc

Facility Specification outputs

- ▶ Power – 16 MW
 - ▶ Accommodate large fuel bundle test.
- ▶ Height – 28 m should be acceptable
 - ▶ Accommodate 1:1 height scale tests.
- ▶ Test rig floor-space – 330 m² for large rig
 - ▶ Ideally space for 2 large rigs and 2 small rigs.
- ▶ Facility floor-space - 1,520 m²
 - ▶ Main control room, calibration laboratory, manufacturing workshop, storage and ancillary equipment.
- ▶ Rig weight
 - ▶ Concrete floor slab to support large test rig and coolant e.g. lead pool.
- ▶ Ventilation and fire suppression
 - ▶ Designed and appropriate for all possible coolants e.g. helium, sodium.
- ▶ Crane and lifting equipment
 - ▶ Designed to allow flexible location and assembly of rigs.
- ▶ Additional fluids
 - ▶ Gas storage for helium, argon, nitrogen and compressed air.

Test Facility Research Areas

- ▶ The UK test facility needs a research focus in order to be successful.
- ▶ Advanced and novel measurement techniques required - generate high quality data for model development, validation and improved physical understanding.
- ▶ Certification under reactor conditions of key reactor components e.g. pumps, valves, etc. can serve as an additional role for a facility.
- ▶ The model development and test requirements identified potential research areas:
 - ▶ Two-phase flow.
 - ▶ Natural circulation and heat transfer.
 - ▶ Support to structural integrity assessment.
 - ▶ High temperature gas.
 - ▶ Liquid metal.
 - ▶ Molten salt.

Test Facility Research Areas

▶ Two-Phase flow

- + Ongoing UK research and expertise in area
- + Broad range of active research worldwide
- + Active development of water reactor technologies and SMRs
- + Could attract more industry funding
- + Relevant to condensers and NPP containment, steam generators and steam turbines
- CHF and DNB tests require significant power
- Two-phase flow is only really applicable to water cooled reactors
- Little cross-over or applicability to advanced reactor technologies

▶ Natural circulation and heat transfer

- + Ongoing UK research and expertise in area
- + Relevant heat transfer experience from other industries, as well as LDA, PIF and LIF measurement techniques
- + Ongoing, but less active, research worldwide
- + Relevant to water and advanced reactor technologies
- + Important for passive safety arguments in new reactor designs
- Requires 1:1 height scale
- Novel measurement techniques or new materials required to get high quality data at reactor conditions

Test Facility Research Areas

▶ Support to Structural Integrity Assessment

- + Strong UK experience of fatigue simulation and FIV for other industries
- + Thermal mixing and fatigue applicable to other research programmes
- + Relevant to water and advanced reactor technologies
- + Support design substantiation and material testing
- Novel measurement techniques or new materials required to get high quality data at reactor conditions
- Often require prolonged endurance tests

▶ High Temperature Gas

- + Strong UK experience of gas e.g. AGRs
- + Supercritical CO₂ - could be used in the secondary loops of advanced reactor technologies
- + Relatively small cost associated with installing and testing using these fluids
- Fewer test and validation requirements identified, *(although this is true for all advanced reactor technologies)*
- Helium related research is only applicable to gas-cooled reactor technologies

Test Facility Research Areas

▶ Liquid Metal

- + Strong historical UK knowledge of sodium from the Dounreay Prototype Fast Reactor and experiments in Manchester in 1990s
- + Would strengthen the UK's position to collaborate internationally on SFR and LFR research programs
- + Actively progress SFR and LFR reactor technology design
- Fewer test and validation requirements identified,
- Limited current UK experience in designing and operating liquid metal test facilities

▶ Molten Salt

- + Would strengthen the UK's position to collaborate internationally on MSR research programs
- + Actively progress MSR reactor technology design
- Fewer test and validation requirements identified,
- Limited current UK experience in designing and operating molten salt test facilities

Test Facility Recommendations

- ▶ From the test facility review, user engagement, modelling research programme validation requirements, and our assessment and judgement.
- ▶ **Initial Research Focus** - Natural circulation and heat transfer
 - ▶ Relevant to all reactor technologies.
 - ▶ Offer the greatest value, opportunity and skills development to the UK.
- ▶ **Measurement and instrumentation** - Novel measurement techniques required
 - ▶ State-of-the-art measurement capability and specialist staff.
 - ▶ Push the boundaries of these techniques: generate high quality data for CFD model validation, as close to prototypical conditions as possible.

Test Facility Recommendations

- ▶ **Cutting edge test rig** - Large-scale natural circulation water-based test loop
 - ▶ Strong initial emphasis for the UK facility and support passive safety arguments.
 - ▶ Initially focus on one natural circulation issue, but it should be adaptable, modular and flexible to accommodate other natural circulation tests.
- ▶ **Industry investment** – Required to maximise the industrial use of the UK facility
 - ▶ Appeal to PWR, BWR, SMR and AMR developers by providing space, capability and flexibility.
 - ▶ Space for large industry led test programme - capability to run alongside the natural circulation research.
 - ▶ Run smaller, detailed (e.g. mixing and fatigue), alongside the larger test bays.
 - ▶ Certify key components under reactor conditions – additional funding to support the operation of the facility.

Test Facility Recommendations

- ▶ **High temperature gas** - Have the ability to operate test rigs using high temperature gases
 - ▶ Operate test rigs using helium and supercritical CO₂.
- ▶ **Liquid metal and molten salt** – Up-skill the UK in these reactor technologies
 - ▶ Small scale tests would develop the UK skills and expertise in the near term.
 - ▶ Build the experience necessary for the UK facility to undertake larger liquid metal (LFR or SFR) or molten salt tests in the longer term.
 - ▶ Accelerate by importing capability from elsewhere in the world.
 - ▶ Investment from an AMR developer.

- ▶ Our vision for the UK facility is:
 - ▶ World leading nuclear thermal hydraulic experimental capabilities.
 - ▶ Lead the validation of new thermal hydraulic models.
 - ▶ Active part in developing and inspiring the next generation of technical experts.
 - ▶ Bring together academic and industry partners.

- ▶ UKAEA is now leading the design and build program for the test facility.
 - ▶ Currently creating a business case for the design and build.
 - ▶ Starting point of these recommendations from Phase 1 and discussions with industry.

**As the UK nuclear thermal hydraulics community
how can we work together to support and influence the UK Facility?**



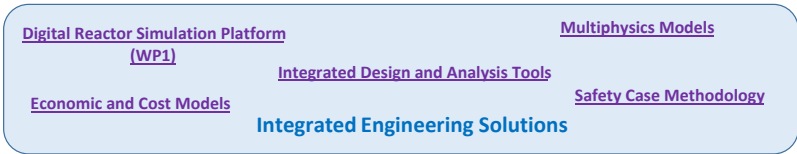
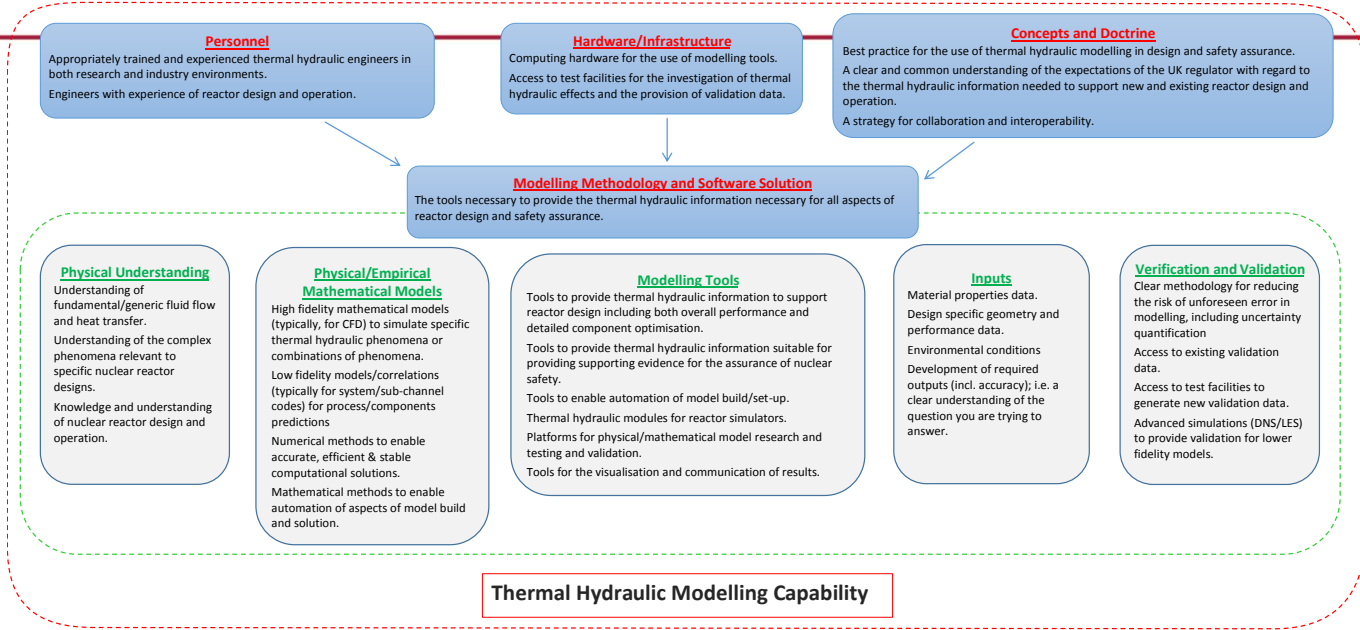
Thermal Hydraulic Modelling Specification – Graham Macpherson

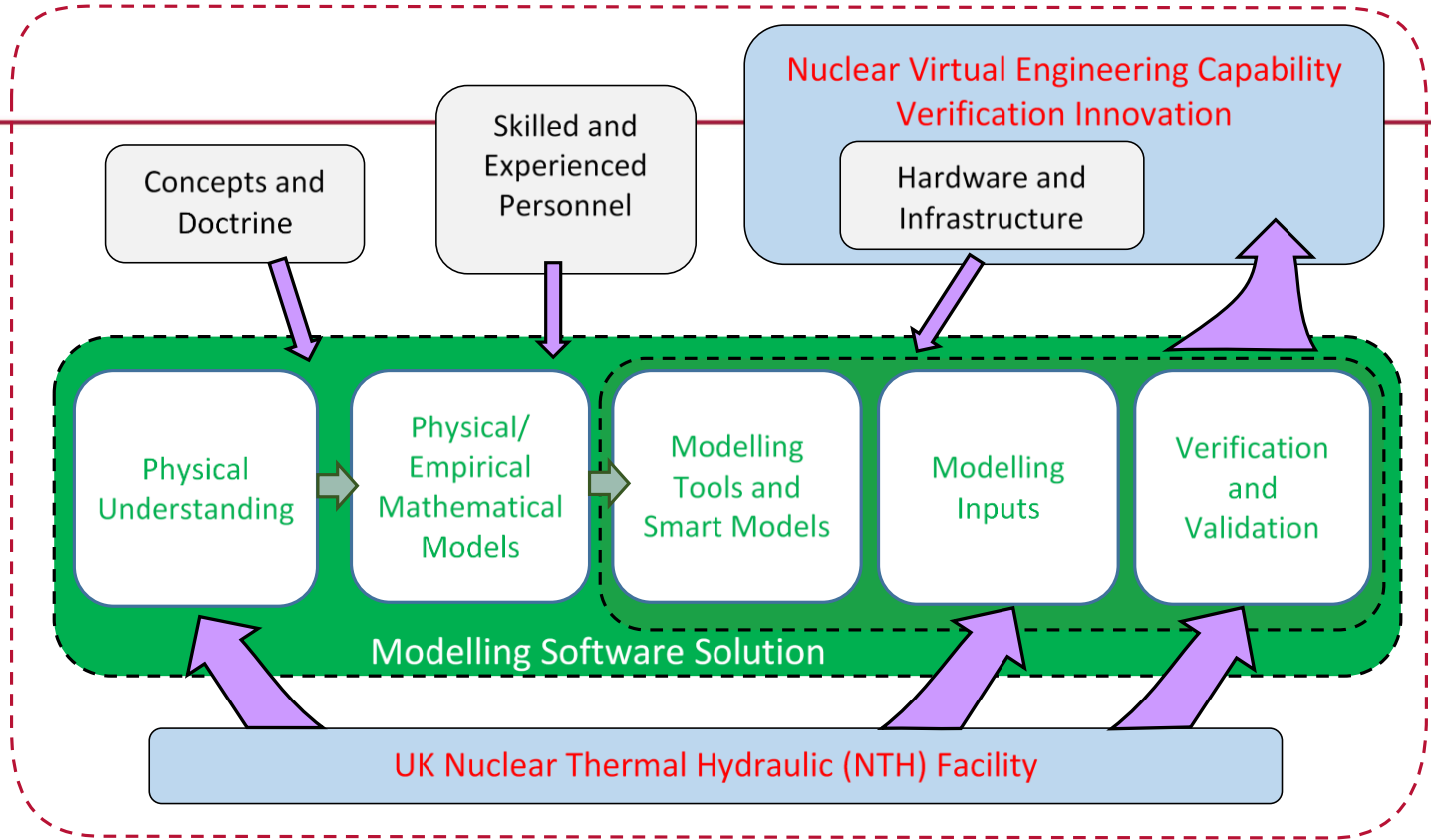


- ▶ What is a modelling capability?
 - ▶ More than just a tool - people and processes matter too.
- ▶ How did we assess what was out there and what to do?
 - ▶ Critical Review.
 - ▶ Requirements, engagement, synthesis.
- ▶ Why do we need one?
 - ▶ Design, optimisation, operation, upgrades, life-extension.
 - ▶ Safety assessment for licensing.
 - ▶ Cost and time-scale reduction.
- ▶ What did we find out?
 - ▶ There is a lot that can and needs to be done, and possible collaborators worldwide.
- ▶ What should we do next?

Design and Safety Case Development (D&S)

Providing a modelling capability to facilitate the thermal hydraulic aspects of reactor design, operation and safety assurance





Our Vision of UK Nuclear Thermal Hydraulics Modelling Capability

What tools are we talking about?

- ▶ **System Codes:** RELAP, TRACE, CATHARE, ATHLET, SAS, SAM ...
 - ▶ Whole plant models, often focussing on accident transients.
 - ▶ Includes core neutronics.
 - ▶ Accepted for safety justifications, correlations/closures historically derived by experiment.
- ▶ **Subchannel Codes:** COBRA, VIPRE, FLICA, PANTHER ...
 - ▶ Resolves within fuel bundle
 - ▶ Blurring of distinctions, coarse CFD for 3D regions, system codes able to resolve within channels.
 - ▶ Accepted for safety justifications, correlations/closures historically derived by experiment.
- ▶ **CFD Codes:** STAR-CCM+, Fluent, CFX, Code_Saturne, OpenFOAM, Nek5000 ...
 - ▶ All scales and costs have a role: RANS/URANS, LES (WMLES, DES etc) and DNS.
 - ▶ Not routinely used for safety justification, but **is used for design and optimisation**.
 - ▶ Can be used to inform correlations/closures.
- ▶ **Coupling** is generally essential – neutronics, structural, conjugate heat transfer, fuel performance...

How did we assess what was out there?

[Nuclear thermal hydraulics] is big. Really big.

You just won't believe how vastly, hugely, mind-bogglingly big it is.

- ▶ Few appreciated the scale and complexity of historical and current activity when the remit covers GEN III+, SMR, and GEN IV.
- ▶ The information available from IAEA and CSNI Technical Docs alone is vast.
- ▶ Superb new references are appearing:
 - ▶ *Thermal Hydraulics in Water-Cooled Nuclear Reactors*, D'Auria, F. 2017.
 - ▶ *A state-of-the-art report on scaling in system thermal hydraulics applications to nuclear reactor safety and design*, NEA/CSNI/R(2016)14, 2017.
- ▶ Gathered User Requirements and determined Use Cases for modelling from developers, operators, supply-chain, academia, national labs and regulators etc...
- ▶ Critical Review (Manchester, Sheffield, STFC)
- ▶ Held a 2 day workshop.
- ▶ Produced a Modelling Specification.

What did we find out? Critical Review

- ▶ Change in philosophy is possible: Best Estimate Plus Uncertainty (BEPU) vs. Conservative.
- ▶ Nuclear thermal hydraulics predictions potentially on the brink of radical change:
 - ▶ High resolution CFD and massively parallel coupled tools (US NEAMS, CASL/VERA).
 - ▶ Development and tuning of thermal hydraulics models by Machine Learning algorithms.
 - ▶ Data intensive simulations: methods like POD to reduce storage and analysis difficulties.
- ▶ Strong in engineering CFD and RANS models.
- ▶ PWR and AGR experience is valuable and relevant.
- ▶ Strong in HPC as well as in ML and AI.
- ▶ Less experience in some widely used system and subchannel analysis codes.
- ▶ AMRs provide the opportunity for the UK to develop expertise in alternative reactor designs.
- ▶ Collaborate rather than reinvent/compete. International activities are extensive, longstanding and the UK's research funding is limited by comparison.

What's happening around the world?

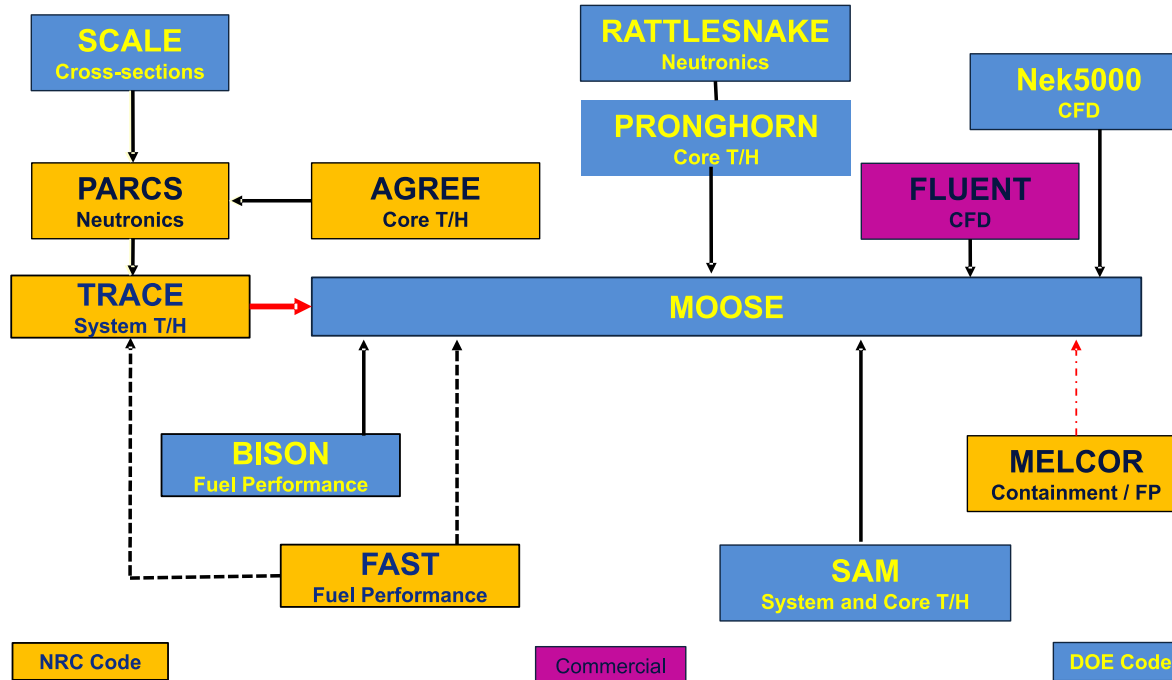
- ▶ IAEA's Coordinated Research Activities and Projects (CRAs and CRPs):
 - ▶ Modular High Temperature Gas-cooled Reactor Safety Design – UK is a participant.
 - ▶ Professor He (University of Sheffield) – UK representative on CRP related to SCWR.
 - ▶ Others related to passive safety in advanced reactors and CFD have no UK participation.
- ▶ European programmes:
 - ▶ Previous: NURISP, NURESAFE, THINS – ICL only from UK.
 - ▶ Current Horizon 2020: SESAME, MYRTE and SAMOFAR – not much formal UK participation.
- ▶ US programmes:
 - ▶ Consortium for Advanced Simulation of Light Water Reactors (CASL).
 - ▶ Virtual Environment for Reactor Applications (VERA).
 - ▶ Nuclear Energy Advanced Modelling and Simulation Program (NEAMS).

- ▶ US-UK Civil Nuclear Energy Research and Development (R&D) Action Plan (signed Sep 2018)
 - ▶ Radioisotopes for use in space technologies,
 - ▶ Nuclear reactor technologies,
 - ▶ Advanced fuels,
 - ▶ Fuel cycle technologies,
 - ▶ **Advanced modelling and simulation**, and
 - ▶ Enabling technologies.
- ▶ Modelling Best Practices Workshop (5 to 7 Feb, Daresbury), purpose:
 - ▶ *Technical exchange of activities and best practices in modelling and simulation.*
 - ▶ *Identify mutual gaps and needs in tools, methods, expertise, validation, integration.*
 - ▶ *Explore and identify collaboration opportunities between the researchers. This includes Identifying future mechanisms for collaboration e.g., research proposals, joint funding, staff exchanges, research papers.*
 - ▶ *Identify opportunities to establish a professional network between the US and the UK in modelling and simulation, with a specific emphasis on early and mid-career professionals.*

US-UK Workshop: Modelling and Simulation Best Practices and Research Collaboration Opportunities

- ▶ The US and UK are no-longer the leaders in civil reactor development.
 - ▶ Healthy basis of humility, self-awareness and realism, i.e. we're not kidding ourselves.
- ▶ Benchmarking, technical exchanges, collaboration are all welcome and encouraged.
- ▶ Coupling is everywhere, the future in the US is MOOSE.
- ▶ Uncertainty Quantification should be considered routine (tools like Dakota exist).
- ▶ ANL have Nek5000 and 1 million cores, but:
 - ▶ They are writing SAM – a system code (in MOOSE).
 - ▶ RANS still is the only option for long transients (minutes to hours).
 - ▶ DNS/LES influenced RANS models are of interest (passive heat transfer)
- ▶ Fuels are a main focus (accident tolerant, advanced reactors).
- ▶ DOE-NRC engagement on future reactor licencing – developing coupled tools (CRAB).

Comprehensive Reactor Analysis Bundle (CRAB)



Thermal hydraulic model specification – workshop

- ▶ 2-day workshop held in April 2018: >30 members of UK and international TH community.
- ▶ Driven by the URs: some areas of commonality, others coolant and reactor specific.
- ▶ Different level of maturity of technologies, difference in maturity of requirements.
- ▶ Focussed on 8 core areas for model development:
 - ▶ **Multi-fidelity** – The use of modelling methods across the full range of fidelities and scales.
 - ▶ **Best Practice and Uncertainty Evaluation** – Improving the confidence in and quality of model predictions.
 - ▶ **Boiling and condensation** – The application of and improvement to mechanistic modelling predictions.
 - ▶ **Large-scale multi-phase flows** – The prediction of the effects of complex, transient, multi-phase flows.
 - ▶ **Advanced fluids** – The additional challenges of molten metals, molten salts and supercritical water.
 - ▶ **Multi-physics** – The coupling of thermal hydraulics modelling with neutronics and chemistry.
 - ▶ **Turbulent flow** – The prediction of pressure drops, mixing and buoyancy driven circulation.
 - ▶ **Turbulent heat transfer** – The prediction of heat transfer and buoyancy influenced convection.

Thermal hydraulic model specification – outputs

- ▶ **Thermal hydraulic model specification.**
- ▶ 34 research and development proposals identified with details of the proposed research.
- ▶ Provides selection of research ideas for planning and specification of Phase 2 and beyond.
- ▶ Too many research ideas to fund in £2.5m Phase 2 budget.

- ▶ Discussed with US NEAMS TH lead – considered to be a pretty good list.
- ▶ Research ideas categorised into reactor and modelling technologies:
 - ▶ Gen III and SMR PWR New Build
 - ▶ Gen III BWR New Build
 - ▶ High Temperature Gas-cooled Reactors
 - ▶ Liquid Metal Fast Reactors
 - ▶ Molten Salt Reactors
 - ▶ Improved value from UK modelling capabilities
 - ▶ Two-phase water modelling
 - ▶ Support to structural integrity assessment
 - ▶ Heat transfer and passive cooling
 - ▶ Support across all Gen IV technologies
 - ▶ Support to supercritical CO₂ power cycles

Thermal hydraulic model specification – outputs

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- ▶ Provides selection of research ideas for planning and specification of Phase 2 and beyond.
- ▶ Too many research ideas to fund in £2.5m Phase 2 budget.

- ▶ UK government strategy does not present any **objective criteria** on which to further down-select or prioritise the research.
- ▶ In the absence of a reactor build programme prioritisation become **subjective and contentious.**

- ▶ We have enjoyed contributions from many with **long and illustrious careers** in this area.
- ▶ There is a **plurality of strongly held views** on what the future will or should be.
- ▶ It would be unwise to dismiss this lack of consensus – it indicates there being no single ‘right’ way, **several points of view are likely to have merit.**

Thermal hydraulic model specification – risks and decisions

It will not be possible to satisfy everyone, and there is more than one route to success, therefore:

- ▶ There is a significant risk that the breadth will cause the Phase 2 budget to be **spread thinly** and therefore **fail to make an impact anywhere**.
- ▶ There is a risk that the efforts of this project will not align well with the other areas of government funded research and the programme as a whole will fail to **deliver a cohesive outcome**.
- ▶ With no shortage of innovative ideas, the project requires a **rationale for focussing its efforts**.


We identified three areas where policy input would provide clarity, which has been achieved:

1. In BEIS NIP activities the focus is on AMRs and SMRs, not Gen III LWR reactors.
2. BEIS want their funding to improve the skills of industry to enable commercial developments and services, with the demand/definition originating from reactor developers.
3. The US-UK Action Plan steers where we place our collaboration focus.

What should we do next?

- ▶ 2 of the 34 proposals were overarching, community-wide projects:
 1. *Increased Participation in Benchmarking*
 - ▶ Frazer-Nash invited to the next CSNI/WGAMA CFD Task Group meeting.
 - ▶ 6th CFD benchmark selected: Fluid-Structure Interaction test case, starting in 2019.
 - ▶ Will participate as a UK representative and deliver results for this benchmark test case.
 - ▶ Agreed collaboration with ANL to work together (Nek5000).
 2. *Maximising UK Nuclear Thermal Hydraulics Collaboration and Collective Learning*
 - ▶ BEIS TH Phase 2 Modelling ITT – Technical Volumes, Focussed R&D, Case Studies and a lot of engagement and collaboration.
 - ▶ Reflects much of the spirit and detail of what we recommended.

- ▶ We have, as a UK community a lot of modelling knowledge and skills to offer.
- ▶ There are a lot of tools and programmes out there, let's not reinvent the wheel.

A background image showing a person's hand in a blue suit sleeve, holding a glowing, interconnected network of white nodes and lines. The network is set against a dark blue background with a subtle grid pattern.

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Project proposals to support specific reactor technologies

RP_1 - Support to Gen III and SMR PWR New Build

- ▶ P4_A - Clad ballooning following LOCA
- ▶ P6_D - State of the art CRUD deposition models and the effects on heat transfer mechanisms
- ▶ P7_F - Improved prediction of passive cooling in NPP containment volumes

RP_2 - Support to Gen III BWR New Build

- ▶ P2_C - Developing sensitivity and uncertainty methods for BWR dynamics
- ▶ P6_C - Coupled 3D neutronics and CFD thermal hydraulics applied to BWR fuel channels

RP_3 - Support to High Temperature Gas Cooled Reactors

- ▶ P6_E - Modelling of air ingress accidents in HTGRs

Project proposals to support specific reactor technologies

RP_4 - Support to Liquid Metal Fast Reactors

- ▶ P5_A - Dissolved gas transport in molten metals and molten salts
- ▶ P5_E - Liquid metal heat transfer modelling
- ▶ P5_F - Modelling of cover gas dynamics

RP_5 - Support to Molten Salt Reactors

- ▶ P5_A - Dissolved gas transport in molten metals and molten salts
- ▶ P5_B - Molecular dynamics capabilities for thermophysical, thermogravimetric phase equilibrium prediction over lifecycle
- ▶ P5_C - Heat transfer correlations for mixed convection and transitional flows in MSRs

Project proposals of related modelling technologies

MP_1 - Improved value from UK modelling capabilities

- ▶ P1_A - Development of innovative coarse grid models for reactor design
- ▶ P1_B - High fidelity modelling to improve the accuracy of low fidelity methods
- ▶ P1_C - Reducing the cost of CFD - Efficient and effective meshing
- ▶ P2_A - Increased participation in benchmarking
- ▶ P2_B - Maximising UK collaboration and collective learning

MP_2 - Two-phase water modelling

- ▶ P2_D - UK LWR predictive modelling validation centre
- ▶ P3_A - Improving the prediction of heat transfer by fundamental multi-scale modelling of bubble growth process
- ▶ P3_B - Improved two-phase flow regime transition modelling
- ▶ P3_C - Film dry-out modelling in CFD
- ▶ P3_D - Improved component scale boiling model
- ▶ P3_E - Prediction of DNB using CFD
- ▶ P4_B - CFD modelling of macroscopic convective boiling flows in NPP