BEIS Nuclear Innovation Programme
Thermal Hydraulics Research & Development Phase 1 Overview

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Introduction

Aim

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

Outline

- Objectives and Scope
- Thermal Hydraulic test facility
- Thermal Hydraulic model development

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Thermal Hydraulics R&D Objectives

National Nuclear Thermal Hydraulics Facility ↔ Thermal Hydraulics Model Development

The objectives of the thermal hydraulics facility and model development are to:

- Increase UK participation and collaboration in international activities
- Increase uptake of modern digital engineering practices
- Improve UK predictive modelling capability and understanding
- Improve safety and understanding of through life performance
- Enhance the way that nuclear design programmes are delivered
- Develop a highly-skilled workforce to drive design improvements

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Thermal Hydraulics - Phase 1 Scope

- 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

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Thermal Hydraulics - Phase 1 Team

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

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- MANCHESTER 1824 The University of Manchester
- The University Of Sheffield.
- Science & Technology Facilities Council
- EDF ENERGY
- Westinghouse

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Critical Review (Facilities and Modelling)

- Critical Review of the State-of-the-Art in thermal hydraulic test facilities worldwide
  - SMR (water) and AMR (gas, liquid metal and molten salt) thermal hydraulic test facilities around the world were identified and reviewed
  - Several test facilities have been reviewed in more detail to understand their capability, research focus and measurement capabilities
  - There are no obvious gaps in international thermal hydraulics test requirements, and successful facilities have a strong research focus and have developed their own unique measurement techniques
- Critical Review of the State-of-the-Art in thermal hydraulic prediction capability
  - Critical review was led by Professor Laurence with support from a number of academics from the University of Manchester and University of Sheffield
  - There remain a large number of challenges in modelling nuclear thermal hydraulic phenomena
  - Computing power and Artificial Intelligence is increasing rapidly, and there is a growing potential and interest in using high fidelity tools for nuclear reactor design

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User Requirements Capture

- End 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

- This highlighted the need for:
  - The quantification and bounding of uncertainty in CFD to increase ‘trust’
  - The need for 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

Thermal Hydraulic Test Facility

Facility specification and Site assessment

- Test facility specification
  - This was developed from existing facilities and user requirements
  - This identifies the bounding parameters for the building i.e. height, size, power, etc.

- BEIS want the test facility to:
  - Be flexible
  - Bound all possible test rigs
  - Able to accommodate all 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

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Test Facility exploitation and Cross-cutting benefits

- Test facility exploitation
  - The exploitation plan explores some potential organisational structures and highlights the short and medium-term activities that should be undertaken

- The exploitation plan provides a vision for the facility:
  - 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

- Cross-cutting benefits
  - While the priority for the test facility will be the advancement of thermal hydraulics, there are opportunities for collaboration with the other research and development themes.
  - This is predominantly around supporting assurance and testing materials in prototypical loops.

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Facility option study

- Test facility option study
  - The research focus and initial test rig within the facility has been reviewed based on user requirements
  - This makes clear recommendations to maximise the value and appeal of the test facility:
    - Initial research focus - Natural circulation and heat transfer
    - Measurement and instrumentation - Novel measurement techniques required to generate high quality data of sufficient quality for CFD model validation, and differentiate UK facility
    - Cutting edge test rig - Large-scale natural circulation water-based test loop capable of reaching prototypical reactor conditions
    - Industry investment - It is important to maximise the industrial use of the UK facility, and its value and appeal to PWR, BWR, SMR and AMR developers by providing space, capability and flexibility
    - High temperature gas - Facility should have the ability to operate test rigs using high temperature gases e.g. helium (HTGR and GFR)
    - Liquid metal and molten salt - Small scale tests would develop the UK skills and expertise in the near term, and build the experience necessary for the UK facility to undertake larger liquid metal or molten salt tests in the longer term
- UKAEA is leading the design and build program for the test facility. A workshop was held in Bangor on 13 November 2018, which presented and discussed these recommendations with industry.

Thermal Hydraulic Model Development

Thermal hydraulic model specification

- A 2-day workshop was held in April 2018 with over 30 members of UK thermal hydraulics community.
- This 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

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Thermal hydraulic model specification

- 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 Phase 2 budget!

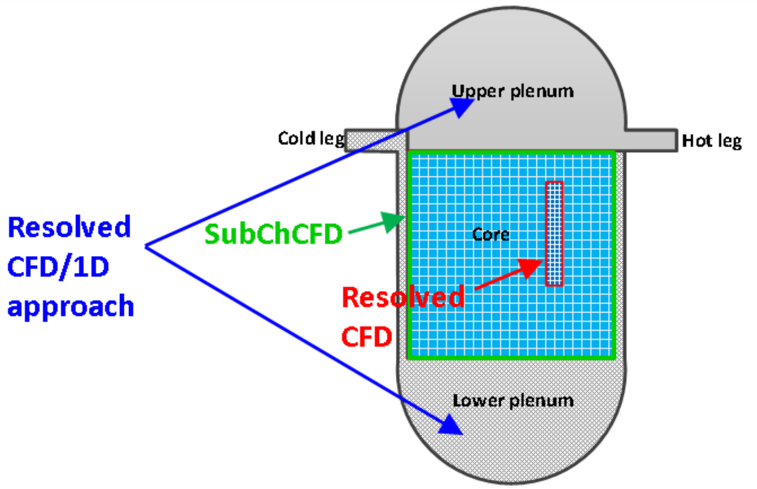
- Research ideas have been categorised into reactor and modelling technologies

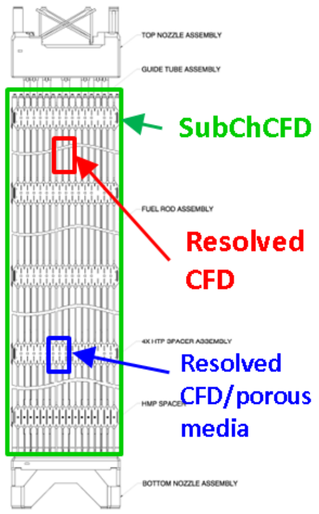
RP_1 - Gen III and SMR PWR New Build (PWR)
RP_2 - Gen III BWR New Build (BWR)
RP_3 - High Temperature Gas-cooled Reactors (HTGR)
RP_4 - Liquid Metal Fast Reactors (LMFR)
RP_5 - Molten Salt Reactors (MSR)

MP_1 - Improved value from UK modelling capabilities
MP_2 - Two-phase water modelling
MP_3 - Support to structural integrity assessment
MP_4 - Heat transfer and passive cooling
MP_5 - Support across all Gen IV technologies
MP_6 - Support to supercritical CO_2 power cycles

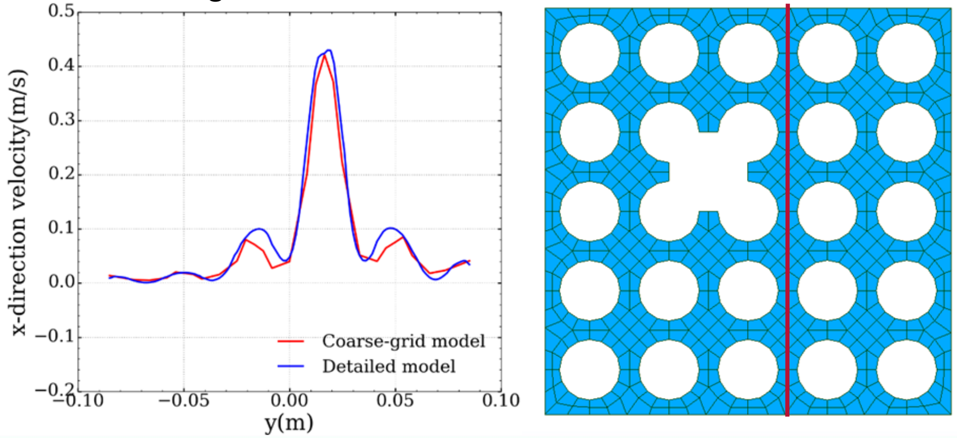
Initial model development - Smart component models

- Vision: To develop a modern CFD-based 'sub-channel' framework for Nuclear Power Plants
- Advantages: Significant reduction in computing cost with respect to conventional CFD; Ease of coupling with resolved CFD and/or porous media approach
- The development of the baseline model has been completed and validated against a number of 2D and 3D test cases.
- Benefits: This could be applied to any reactor technology, and could allow whole reactor to be modelled in CFD with ability to embed detailed CFD models in specific areas – Mesh size reduced by 150 times.
- Potential to bridge gap between empirical/data driven models to modern best practice and beyond





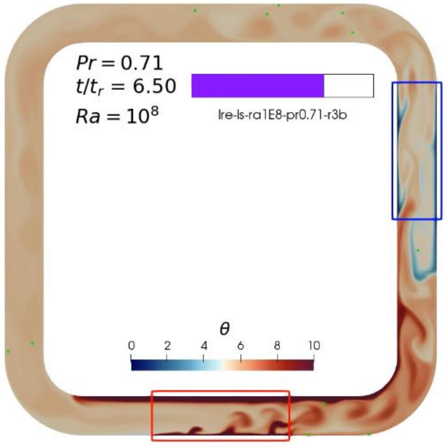
Fuel bundle with blockage
Coarse grid 0.14M cells, detailed 21M cells



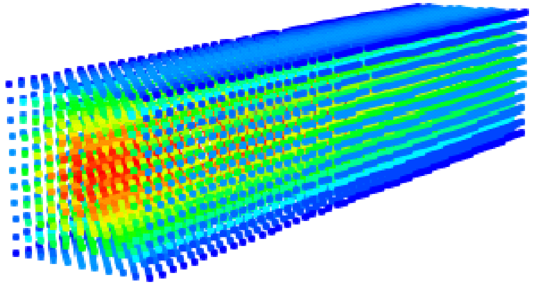
Initial model development - Single-phase flow

- Natural convection loop – Basic loops created and correlations for flow physics developed.
- CFD models have been developed to predict the complex, unsteady transient behaviour that occurs which depends on the initial system temperature.
- This addresses a key uncertainty in current methods for modelling natural circulation in NPP. This could be expanded to look at the impact of different reactor components, designs, fluids etc.

- Smoothed Particle Hydrodynamics (SPH) - The methodology has been demonstrated to be accurate (in 3D with bounded domains) using novel iterative shifting of SPH particles.
- This code will be used to analyse the PWR rod bundle case study to compare the results with the FV results.
- This a totally new innovative method of simulating nuclear thermal hydraulics, which could provide benefits in terms of accuracy and solution time.



Complex transient behaviour in a natural convection loop



Iterative shifting of SPH particles

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Initial model development - Two-phase flow

- Rod bundle boil off - Two-phase mixture front develops and travels down the bundle
- Exposed rod surfaces can experience dangerous increases in temperature (CHF)
- Initial 2D axisymmetric boiling model has been run
- In-house experiment - There is a lack of high resolution data in this area, so new experiment was setup and run at the University of Manchester
- Uses high speed cameras, wall temperature and void fraction (pressure) data for CFD validation
- Strong international interest and research in two-phase flow
- This will develop new models and experimental data to increase the UK involvement in this area

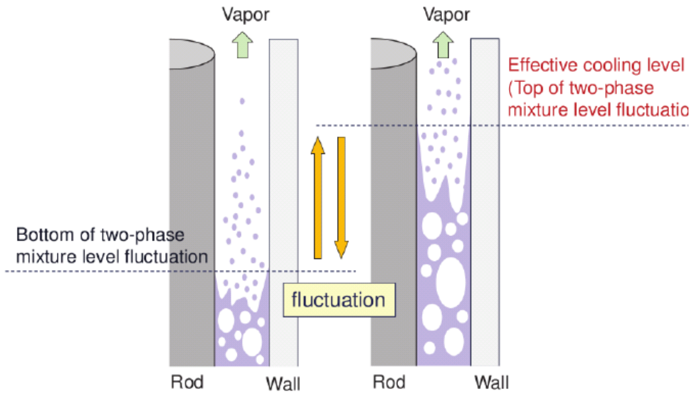
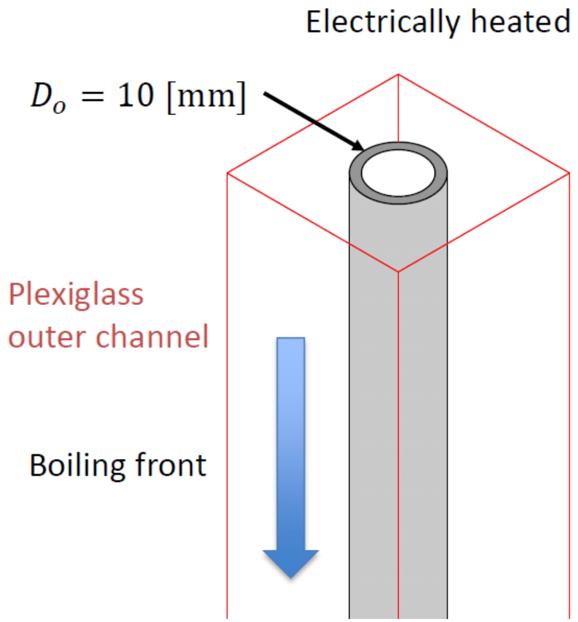
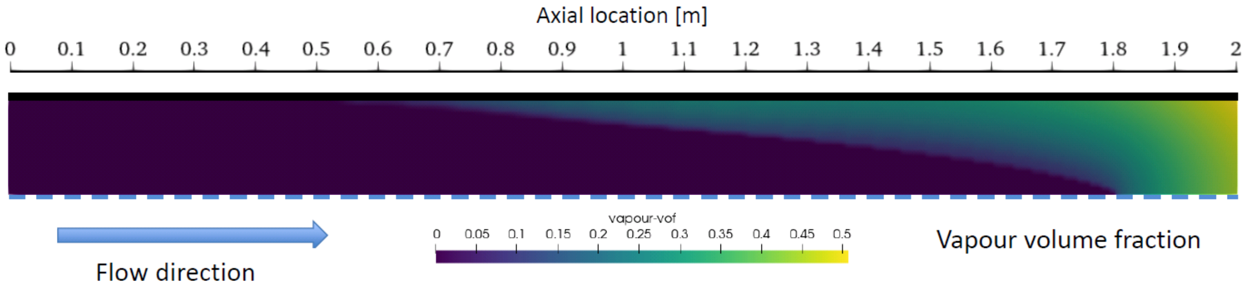


Image from (Arai et al., 2015)





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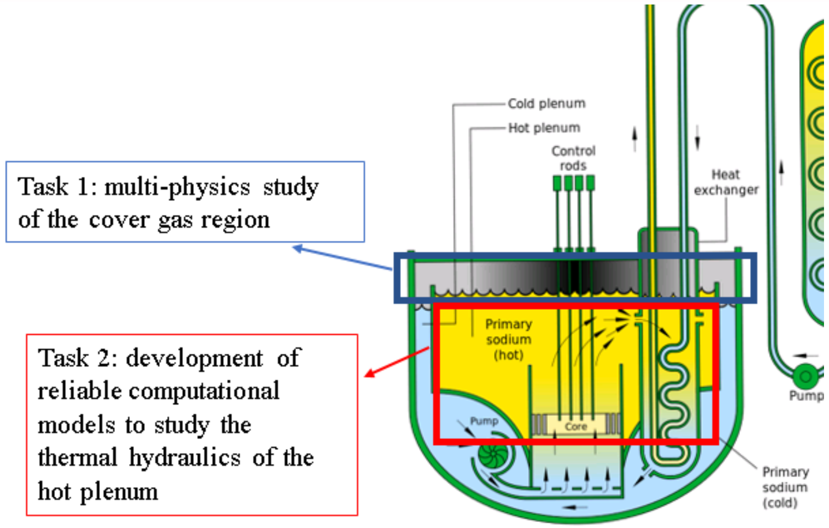
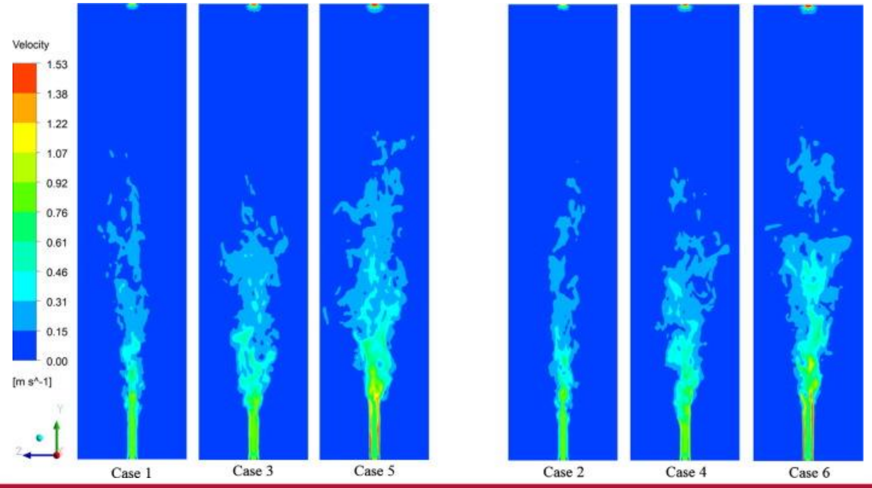
Initial model development - Different media

- Retrieval of experimental research carried out by University of Manchester during 1980-90s
- Cover Gas region - New models being developed to model aerosol dynamics and concentration in cover gas
- Validation against data from 2D axisymmetric and 3D Manchester experiments
- Advances in modelling of aerosols and radiative heat transfer in cover gas region could be of value to other reactor technologies
- Hot plenum region - Models being developed to simulate heat transfer and turbulence aided mixed convection in E-SCAPE test case
- This will improve UK understanding and knowledge of sodium fast reactor technology (liquid metal with low Prandtl number)
- This could provide leverage and experience to allow the UK to join international sodium reactor programmes





Thermal hydraulics R&D Phase 1 - Summary

- A specification for the National Nuclear Thermal Hydraulic Facility has been developed and is now being taken forward by UKAEA
- Research proposals have been developed based on user requirements and engagement with the UK thermal hydraulics community
- Innovative models have been developed that are relevant to both SMR and AMR reactor programs to increase UK understanding and improve UK capability
- A 1-day dissemination of the results of the Phase 1 research will take place in Sheffield on Monday 18 February 2019
  - Please contact me if you are interested in attending

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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

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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

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Project proposals of related modelling technologies

MP_3 - Support to structural integrity assessment

- P7_C - Improving the ability to predict structural vibration in reactor design
- P7_D - Predicting and assessing thermal fatigue

MP_4 - Heat transfer and passive cooling modelling

- P7_A - Improved prediction of flow and thermal development in fuel pin cooling passages
- P7_B - Improved accuracy of RANS models for turbulent heat convection
- P7_E - Improved prediction of the stalling of natural circulation flows
- P8_A - Investigate the impact of ‘real’ surfaces on NTH heat transfer modelling predictions
- P8_B - Improved wall models for accurate heat transfer

MP_5 - Support across all Gen IV technologies

- P6_A - Coupled tool selection
- P6_B - Tritium generation and migration in advanced reactor coolants

MP_6 - Support to supercritical CO_2 power cycles

- P5_D - Supercritical CO_2 power cycles
- P5_G - Predicting heat transfer to supercritical fluids