Latest developments using *Code_Saturne* at the EDF energy R&D UK Centre

Juan Uribe

EDF Energy, R&D UK Centre

Thanks to: Jacopo De Amicis, Charles Moulinec and Marcin Stryszowski

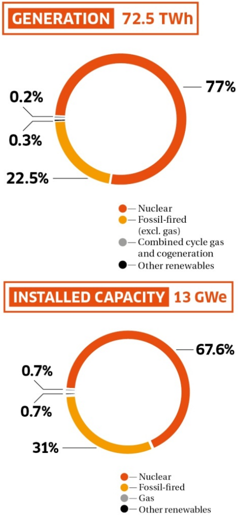
EDF Energy

Generation

- 8 nuclear power stations (14 AGRs, 1 PWR)
- 2 EPRs in project at Hinkley Point
- 2 coal and 1 gas powered stations
- 25 wind farms (including 1 off-shore)

Sales and Marketing

- 5.8 million customers
- Electricity: 52.8 TWh sold
- Gas: 25.7 TWh sold



EDF Energy R&D UK Centre

Mission:

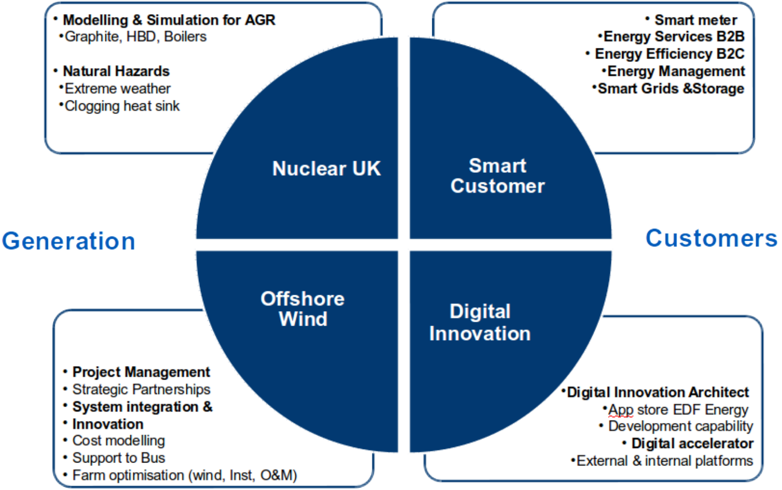
- Provide R&D Excellence from the UK to EDF Energy and EDF SA, to create value today and prepare the future.
- Maintain a portfolio of external revenue generating contracts (UKPN, Innovate UK, EU projects)
- Manage R&D relationship with UK institutions leveraging public funding.
- Manage university alliances with Generation and Campus, increase scientific recognition.
- Accelerate innovation in the UK being part of the EDF group open innovation network.

Key figures

2015

- 7.1M Turnover.
- 400k public funding.
- 66% Success rate for bids.
- 4 patents and 11 scientific publications.
- 49 Employees and 20 PhD students.
- 20% women.
- 15 Nationalities.
- 3 sites.

Activities at the R&D UK Centre



EDF Energy - April 2015

UK Nuclear Context

- Nuclear power will need to play an important role in support of a sustainable decarbonised electricity generation system in the UK.
- This outlines the need for both new nuclear build and life extension of the existing operating nuclear stations.
- Life extension will require R&D to address the technical, scientific and engineering challenges that it will present.
- R&D is key to attracting and maintaining the high level skills needed to support operations now and nuclear over the long term.

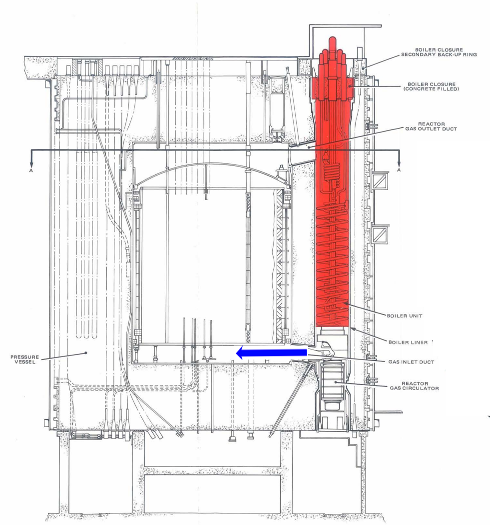
Themofluids group objectives

To assist EDF Energy on all related fluid dynamics problems in the operation of current AGRs by :

- Using tools from EDF R&D and adapting /develop them for the UK needs.
- Exploiting long standing expertise at the university of Manchester through the Modelling and Simulation Centre.
- Collaborating with other institutions in the UK (STFC, EPSRC, NNL, Sheffield ...) and leverage public funding.

People: 2 permanent, 1 VIE, 1 intern, 3 PhDs.

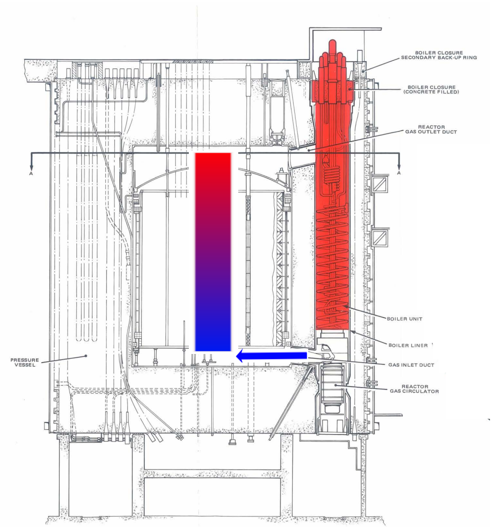
CFD in Advaced Gas-cooled Reactors



Gas path

1. Cold CO_2 enters the bottom of the core.

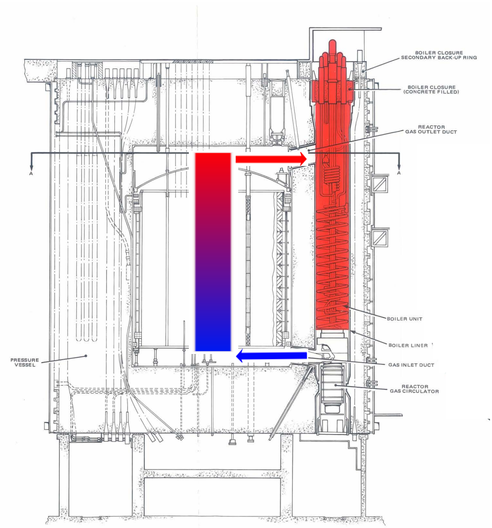
CFD in Advaced Gas-cooled Reactors



Gas path

1. Cold CO_2 enters the bottom of the core.
2. Traverses the core upwards extracting heat.

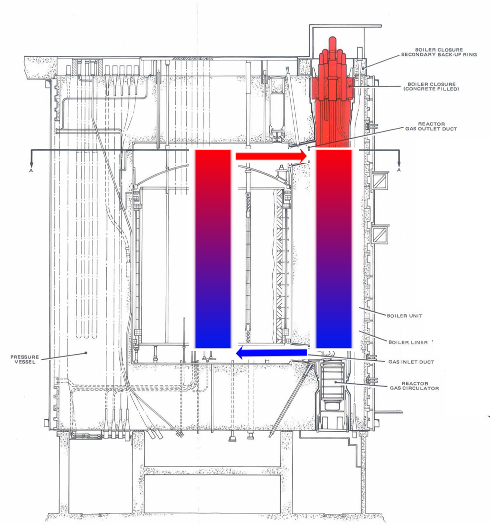
CFD in Advaced Gas-cooled Reactors



Gas path

1. Cold CO_2 enters the bottom of the core.
2. Traverses the core upwards extracting heat.
3. Crosses the hot box dome and enters the boiler.

CFD in Advaced Gas-cooled Reactors



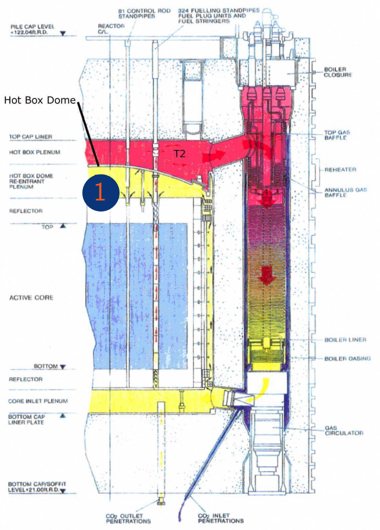
Gas path

1. Cold CO_2 enters the bottom of the core.
2. Traverses the core upwards extracting heat.
3. Crosses the hot box dome and enters the boiler.
4. Travels downwards transferring heat to the water, turning it into steam.

CFD at EDF Energy R&D UK

Projects:

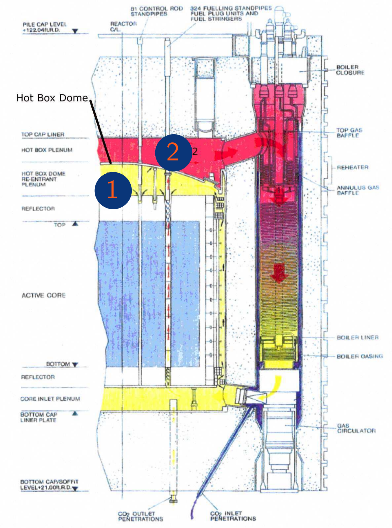
1. Hot Box Dome, lower plenum.



CFD at EDF Energy R&D UK

Projects:

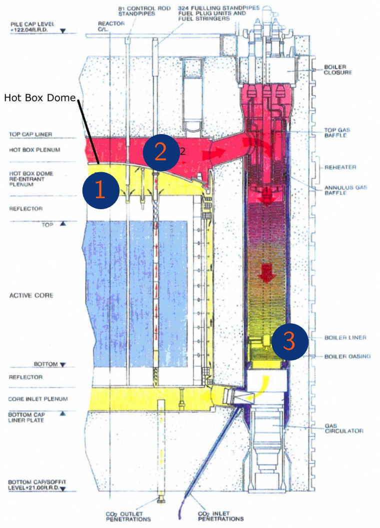
1. Hot Box Dome, lower plenum.
2. Hot Box Dome, upper plenum.



CFD at EDF Energy R&D UK

Projects:

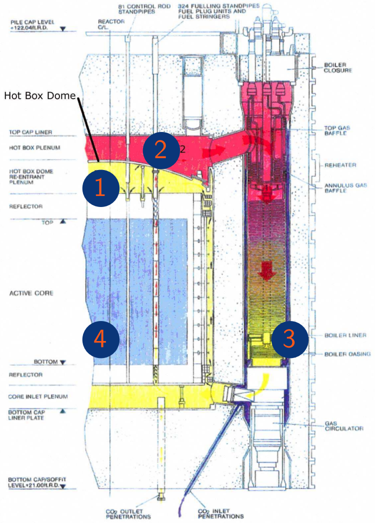
1. Hot Box Dome, lower plenum.
2. Hot Box Dome, upper plenum.
3. Pod Boilers.



CFD at EDF Energy R&D UK

Projects:

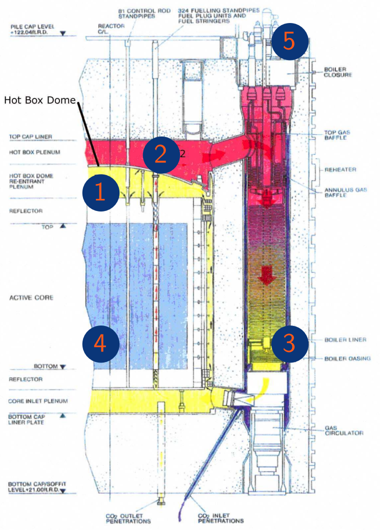
1. Hot Box Dome, lower plenum.
2. Hot Box Dome, upper plenum.
3. Pod Boilers.
4. Flow along nuclear fuel rods.



CFD at EDF Energy R&D UK

Projects:

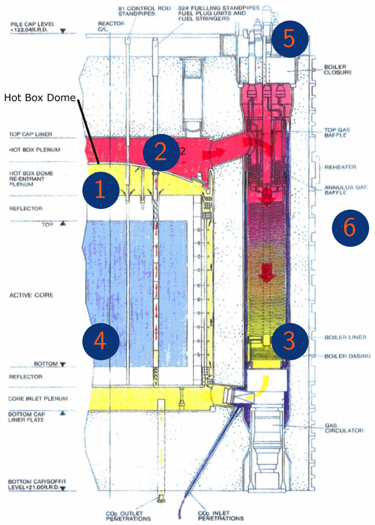
1. Hot Box Dome, lower plenum.
2. Hot Box Dome, upper plenum.
3. Pod Boilers.
4. Flow along nuclear fuel rods.
5. Steam penetrations.



CFD at EDF Energy R&D UK

Projects:

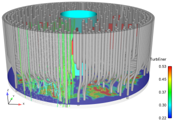
1. Hot Box Dome, lower plenum.
2. Hot Box Dome, upper plenum.
3. Pod Boilers.
4. Flow along nuclear fuel rods.
5. Steam penetrations.
6. Gas release.

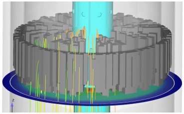


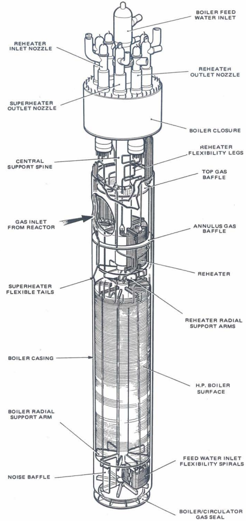
AGR pod boilers

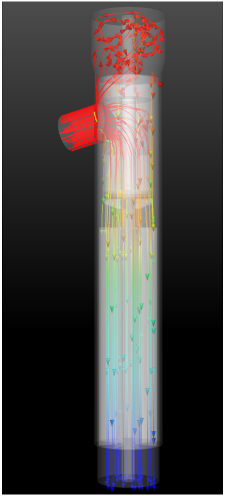
Critical component for Life Time Extension of AGRs

- 3D model of pod boiler.
- Use of porous theory to avoid excessive computational costs.
- Sub-models with detailed explicit geometry to compute source terms.
- Code coupling (NUMEL) for heat transfer with water tubes.
- Coupling with SYRTHES for solid temperature in critical components.





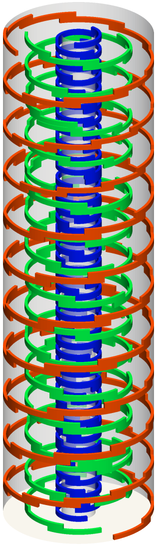




AGR pod boilers

New method for tube localisation for coupling with the water side.

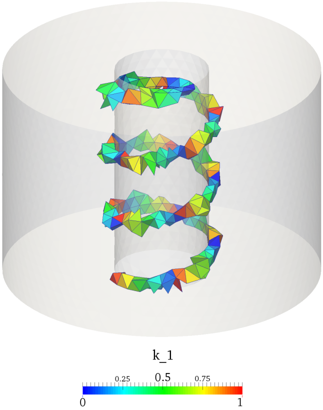
- Based on curve discretisation for each tube.



AGR pod boilers

New method for tube localisation for coupling with the water side.

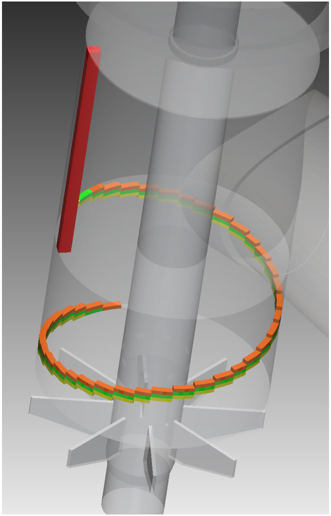
- Based on curve discretisation for each tube.
- Can be applied to any type of mesh.



AGR pod boilers

New method for tube localisation for coupling with the water side.

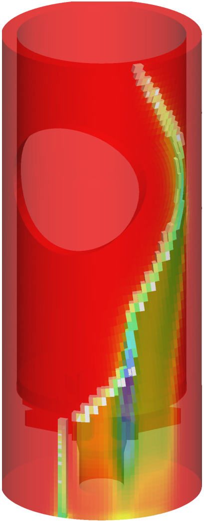
- Based on curve discretisation for each tube.
- Can be applied to any type of mesh.
- Can be refined in all directions.



AGR pod boilers

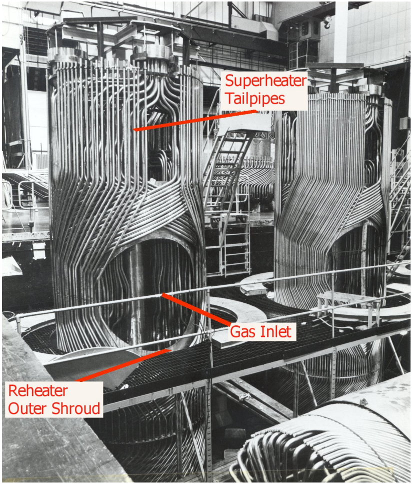
New method for tube localisation for coupling with the water side.

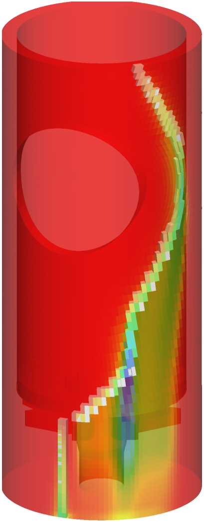
- Based on curve discretisation for each tube.
- Can be applied to any type of mesh.
- Can be refined in all directions.
- Enforces mass, energy and momentum conservation.



AGR pod boilers

New method for tube localisation for coupling with the water side.





AGR pod boilers

Because porous media theory is used, we need to include turbulence production due to the tubes into the model.
Model proposed by A. Nakayama and F. Kuwahara in 1999 for the standard k-ϵ model:

$$\frac{\partial \rho k}{\partial t} + \frac{\partial}{\partial x_j}(\rho u_j k) = \frac{\partial}{\partial x_i}\left[\left[\left(\mu + \frac{\mu_t}{\sigma_k}\right)\delta_{ij} + \frac{(k_{dis})_{ij}}{Le_k\,\phi_v c_p}\right]\frac{\partial k}{\partial x_j}\right] + 2\mu_t \phi_v S_{ij} S_{ij} - \rho\epsilon + \rho\epsilon_\infty$$

$$\frac{\partial \rho \epsilon}{\partial t} + \frac{\partial}{\partial x_j}(\rho u_j \epsilon) = \frac{\partial}{\partial x_i}\left[\left[\left(\mu + \frac{\mu_t}{\sigma_\epsilon}\right)\delta_{ij} + \frac{(k_{dis})_{ij}}{Le_\epsilon\,\phi_v c_p}\right]\frac{\partial \epsilon}{\partial x_j}\right] + C_{1\epsilon}\frac{\epsilon}{k} 2\mu_t S_{ij} S_{ij} - C_{2\epsilon}\rho\frac{\epsilon^2}{k} + C_{2\epsilon}\rho\frac{\epsilon_\infty^2}{k_\infty}$$

AGR pod boilers

Le_k and Le_ϵ are the Lewis numbers to rescale the thermal diffusivity to the k and ϵ diffusivities.

AGR pod boilers

Le_k and Le_ϵ are the Lewis numbers to rescale the thermal diffusivity to the k and ϵ diffusivities.

k_∞ and ϵ_∞ are the intrinsic averages of k and ϵ in case of fully developed, steady and macroscopically uniform flow (with zero mean shear stress).

AGR pod boilers

Le_k and Le_ϵ are the Lewis numbers to rescale the thermal diffusivity to the k and ϵ diffusivities.

k_∞ and ϵ_∞ are the intrinsic averages of k and ϵ in case of fully developed, steady and macroscopically uniform flow (with zero mean shear stress).

Nakayama and Kuwahara propose the following functional forms:

$$k_\infty = c_{k_\infty} |\mathbf{v}|^2; \qquad \epsilon_\infty = c_{\epsilon_\infty} |\mathbf{v}|^3.$$

AGR pod boilers

Le_k and Le_ϵ are the Lewis numbers to rescale the thermal diffusivity to the k and ϵ diffusivities.

k_∞ and ϵ_∞ are the intrinsic averages of k and ϵ in case of fully developed, steady and macroscopically uniform flow (with zero mean shear stress).

Nakayama and Kuwahara propose the following functional forms:

$$k_\infty = c_{k_\infty} |\mathbf{v}|^2; \qquad \epsilon_\infty = c_{\epsilon_\infty} |\mathbf{v}|^3.$$

with

$$c_{k_\infty} = 3.7 \frac{1-\phi}{\sqrt{\phi}}; \qquad c_{\epsilon_\infty} = 39 \frac{(1-\phi)^2}{\phi H}.$$

AGR pod boilers

Le_k and Le_ϵ are the Lewis numbers to rescale the thermal diffusivity to the k and ϵ diffusivities.

k_∞ and ϵ_∞ are the intrinsic averages of k and ϵ in case of fully developed, steady and macroscopically uniform flow (with zero mean shear stress).

Nakayama and Kuwahara propose the following functional forms:

$$k_\infty = c_{k_\infty} |\mathbf{v}|^2; \qquad \epsilon_\infty = c_{\epsilon_\infty} |\mathbf{v}|^3.$$

with

$$c_{k_\infty} = 3.7 \frac{1-\phi}{\sqrt{\phi}}; \qquad c_{\epsilon_\infty} = 39 \frac{(1-\phi)^2}{\phi H}.$$

The coefficients can also be evaluated with real geometry simulations.

Radiative heat transfer - Coupling with SYRTHES

The standard DOM implemented in *Code_Saturne* is not currently coupled with SYRTHES in the official distributions.

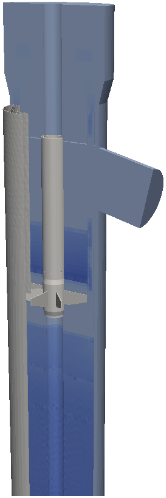
If the effect of radiation is to be taken into account in the solids, the radiative flux must be given to SYRTHES.

This requires a modification of:

- the boundary conditions of the DOM (the wall temperature must be consistent with the solid temperature);
- the boundary conditions in SYRTHES:

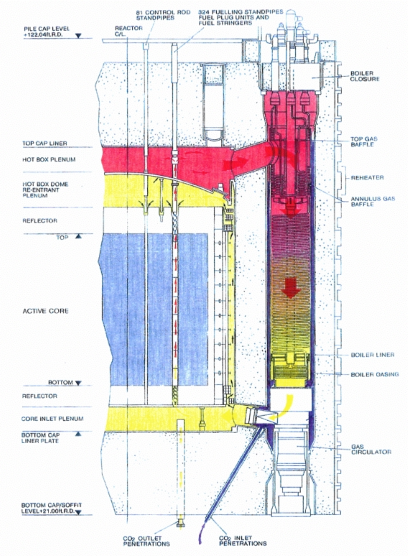
$$q_{tot}^{in} = h_f(T_f - T_w) + q_{rad};$$

- the communication between *Code_Saturne* and SYRTHES.



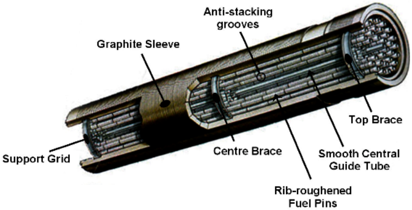
Gas mixing in AGRs fuel elements

- The AGRs have 320 fuel guide tubes.



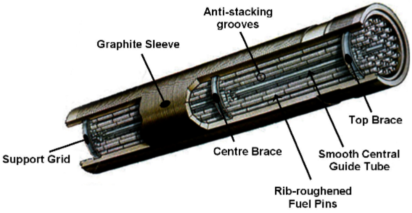
Gas mixing in AGRs fuel elements

- The AGRs have 320 fuel guide tubes.
- They contain fuel assemblies that are made of 8 fuel elements stacked vertically.



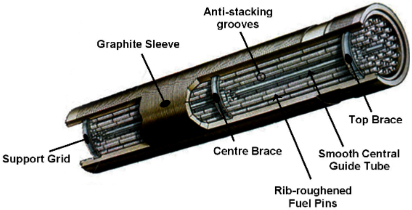
Gas mixing in AGRs fuel elements

- The AGRs have 320 fuel guide tubes.
- They contain fuel assemblies that are made of 8 fuel elements stacked vertically.
- Each fuel element ($\sim$1m long) has 36 pins that contain uranium pellets.



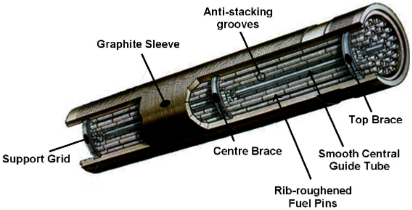
Gas mixing in AGRs fuel elements

- The AGRs have 320 fuel guide tubes.
- They contain fuel assemblies that are made of 8 fuel elements stacked vertically.
- Each fuel element ($\sim$1m long) has 36 pins that contain uranium pellets.
- Each pin has 12 helical ribs to increase heat transfer.



Gas mixing in AGRs fuel elements

- The AGRs have 320 fuel guide tubes.
- They contain fuel assemblies that are made of 8 fuel elements stacked vertically.
- Each fuel element (∼1m long) has 36 pins that contain uranium pellets.
- Each pin has 12 helical ribs to increase heat transfer.



The temperature at the end of the assembly is measured by a single thermocouple and therefore it is impossible to know from plant data how uniform the thermal field is.

Gas mixing in AGRs fuel elements

The problem:

- Because of the elements are stack vertically, there is the possibility that gas can enter via gaps in the sleeve contact points.

Gas mixing in AGRs fuel elements

The problem:

- Because of the elements are stack vertically, there is the possibility that gas can enter via gaps in the sleeve contact points.
- This gas is colder ($\sim$ T1) and therefore lowers the temperature of the gas inside the assembly.

Gas mixing in AGRs fuel elements

The problem:

- Because of the elements are stack vertically, there is the possibility that gas can enter via gaps in the sleeve contact points.
- This gas is colder ($\sim$ T1) and therefore lowers the temperature of the gas inside the assembly.
- We need to know how much mixing occurs before the end of the assembly to be certain that the thermocouple readings are representative.

Gas mixing in AGRs fuel elements

The problem:

- Because of the elements are stack vertically, there is the possibility that gas can enter via gaps in the sleeve contact points.
- This gas is colder ($\sim$ T1) and therefore lowers the temperature of the gas inside the assembly.
- We need to know how much mixing occurs before the end of the assembly to be certain that the thermocouple readings are representative.
- The power of the pins and the sleeve vary with height, therefore a periodic calculation is not possible.

Gas mixing in AGRs fuel elements

The problem:

- Because of the elements are stack vertically, there is the possibility that gas can enter via gaps in the sleeve contact points.
- This gas is colder ($\sim$ T1) and therefore lowers the temperature of the gas inside the assembly.
- We need to know how much mixing occurs before the end of the assembly to be certain that the thermocouple readings are representative.
- The power of the pins and the sleeve vary with height, therefore a periodic calculation is not possible.
- Very large scale problem, the fuel assembly is $\sim$ 8m tall and the ribs on the pin have a height of 0.5mm.

Gas mixing in AGRs fuel elements

AGR fuel elements.

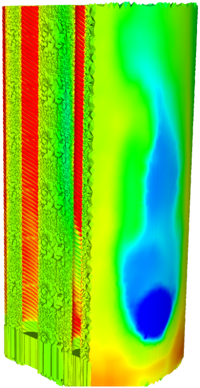
- Collaboration with STFC Daresbury.
- First ARCHER call for 20 million AU's ($\sim$1.3 million CPU hours, $\sim$ £25k).
- Effect of gas ingress at a given in mean temperature.
- Large domain, swirl generated needs to be taken into account.
- Mesh for 6.5m domain $>$1 billion cells.
- Largest production run to date using *Code_Saturne* on ARCHER and BlueJoule.

Science & Technology Facilities Council

Gas mixing in AGRs fuel elements

AGR fuel elements.

- Collaboration with STFC Daresbury.
- First ARCHER call for 20 million AU's ($\sim$1.3 million CPU hours, $\sim$ £25k).
- Effect of gas ingress at a given in mean temperature.
- Large domain, swirl generated needs to be taken into account.
- Mesh for 6.5m domain $>$1 billion cells.
- Largest production run to date using *Code_Saturne* on ARCHER and BlueJoule.



Science & Technology Facilities Council

Initial set-up

Mesh:

- Periodic unit: 5.4 million cells.
- Gap: 2.4 million cells.
- Total for 6.5 meters (gaps 2-8): 1.1 billion.
- Periodic unit full tetrahedral.
- Gap mesh created from extruding the surface of the periodic and filling the "holes". All prisms.
- Two cells in the boundary layer surface with a $5 < y^+ < 110$. Use of wall functions required.
- Coarse mesh, designed to get a max number of cells to match available resources.

Mesh generation

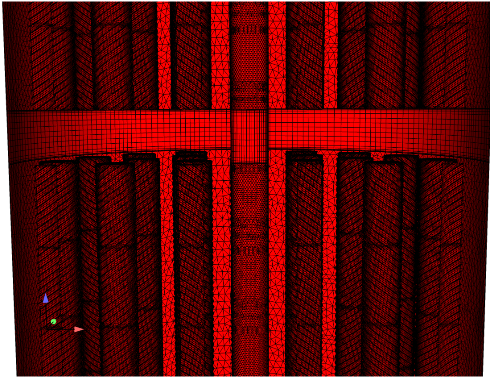
36 pins + 1 guide tube

Pin diameter $\sim$ 1.5cm

Sleeve diameter $\sim$ 19cm

Rib height $\sim$ 0.5mm

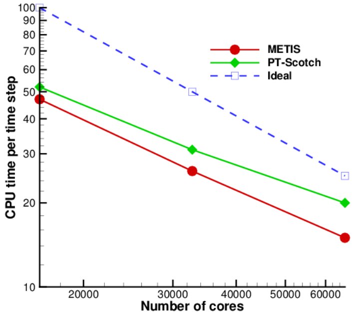
Number of elemental meshes to paste together $\sim$ 200.



Gas mixing in AGRs fuel element

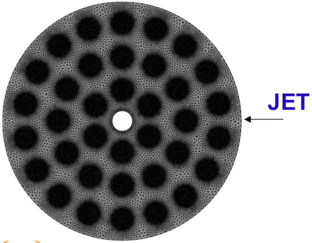
- Runs on STFC Blue Joule with 98304 MPI tasks.
- Run on ARCHER (Cray XC30) with 24576 MPI Tasks.

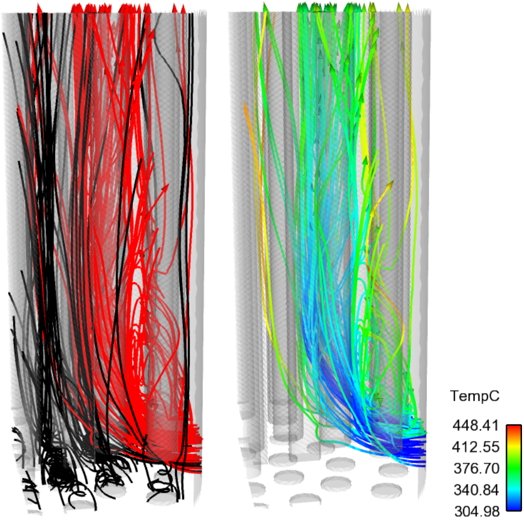
File name	Size	Time to read
mesh_input	131 GB	305 s
Restart files		
File names	Size	Time to read
Main (Input)	60 GB	132 s
Auxiliary (Input)	56 GB	242 s
Checkpoint files		
File name	Size	Time to write
Main (Input)	60 GB	2184 s
Auxiliary (Input)	56 GB	2471 s
Postprocessing	Size	Time to write
Several files	70 GB	470 s



Gas mixing in AGRs fuel elements

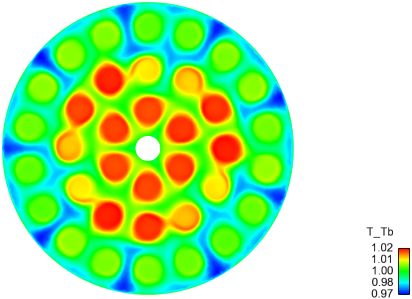
Gas is injected at the top of the second element (∼2 m). Injection in a rectangular zone at the sleeve surface in the middle of the gap. Its temperature is lower than the temperature in the fuel assembly. Constant mass flux imposed.



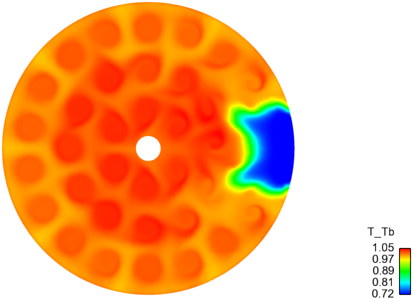


Gas mixing in AGRs fuel elements

Gap 2



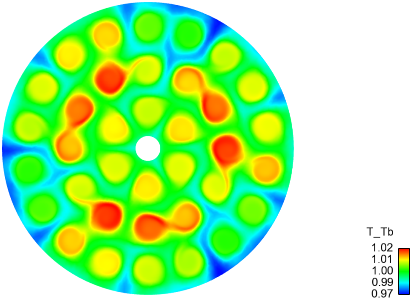
No Injection



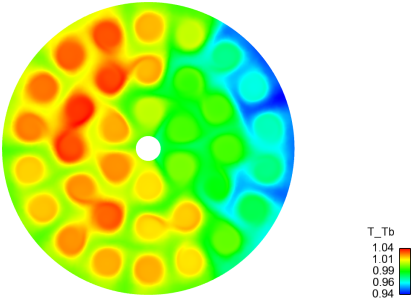
Injection

Gas mixing in AGRs fuel elements

Gap 3



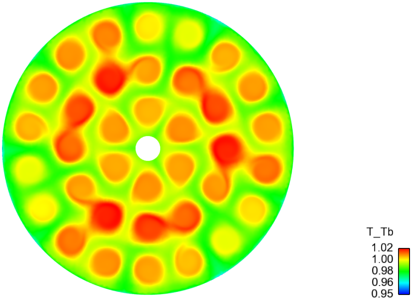
No Injection



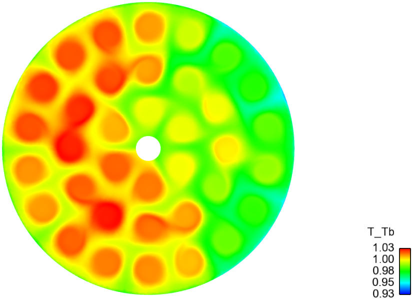
Injection

Gas mixing in AGRs fuel elements

Gap 4



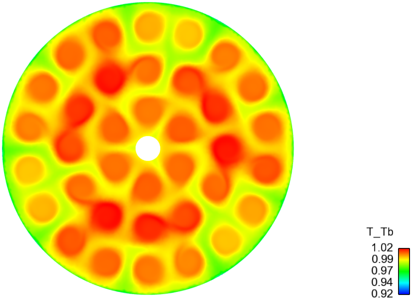
No Injection



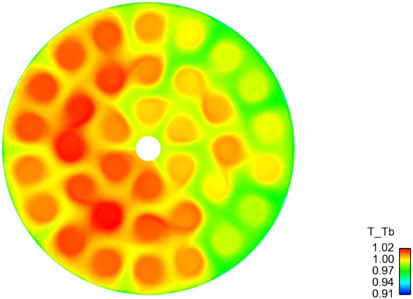
Injection

Gas mixing in AGRs fuel elements

Gap 5



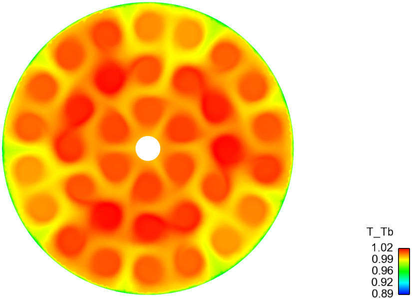
No Injection



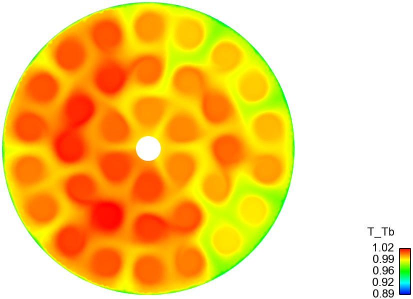
Injection

Gas mixing in AGRs fuel elements

Gap 6



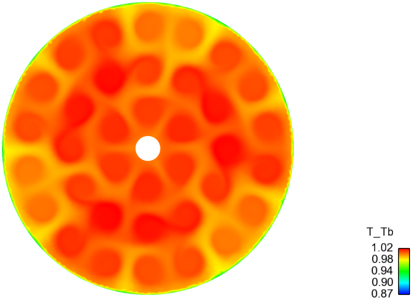
No Injection



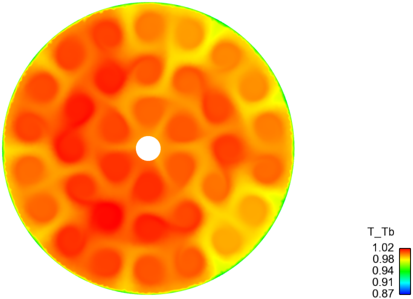
Injection

Gas mixing in AGRs fuel elements

Gap 7



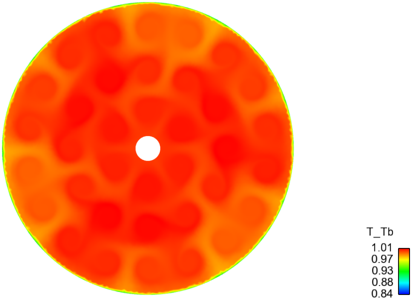
No Injection



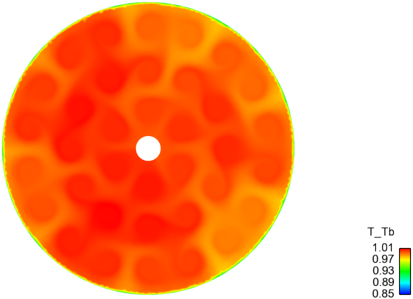
Injection

Gas mixing in AGRs fuel elements

Gap 8



No Injection



Injection

Gas mixing in AGRs fuel elements

Second phase

New EPSRC call in 2015 (18 months).

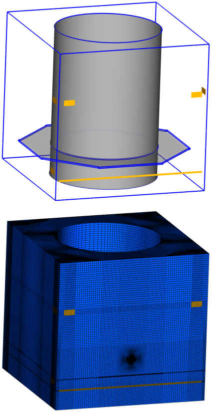
200 million AU's ($\sim$ 13 million cpu hours, $\sim$£260k) allocated to continue working.

- Test mesh refinement.
- Test numerical schemes.
- Test turbulence models.

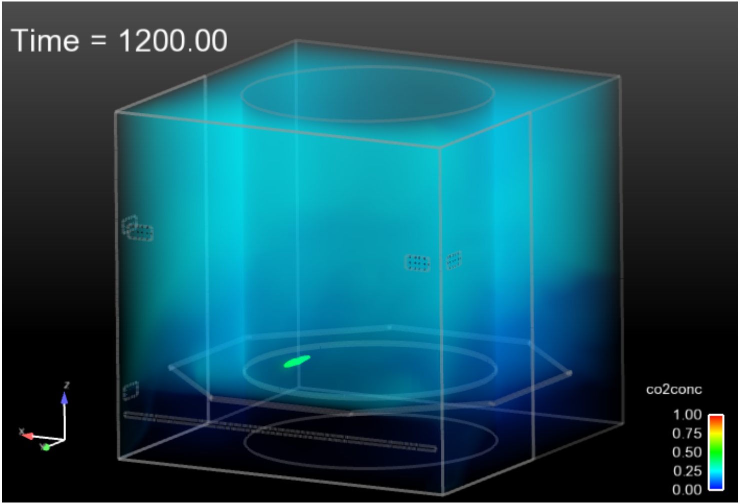
Gas release in reactor room

Fault studies group.

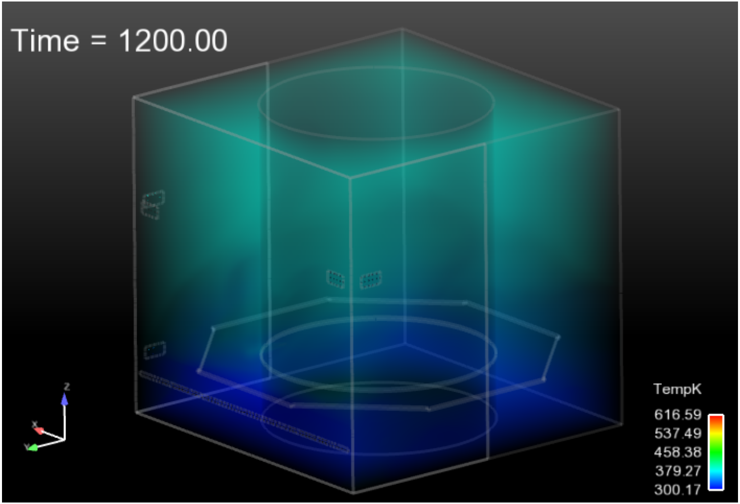
- Study the effect of sudden gas released from the reactor into the main room.
- Need to compute temperature of CO_2-air mixture as a function of time.
- Current approach using system code (MACE) developed at EDF Energy.
- Regulators have been suggesting comparing with more modern approaches (CFD).
- Current work using *Code_Saturne*.
- Small breach (0.076m in diameter) in a large room (50mx50mx48m).



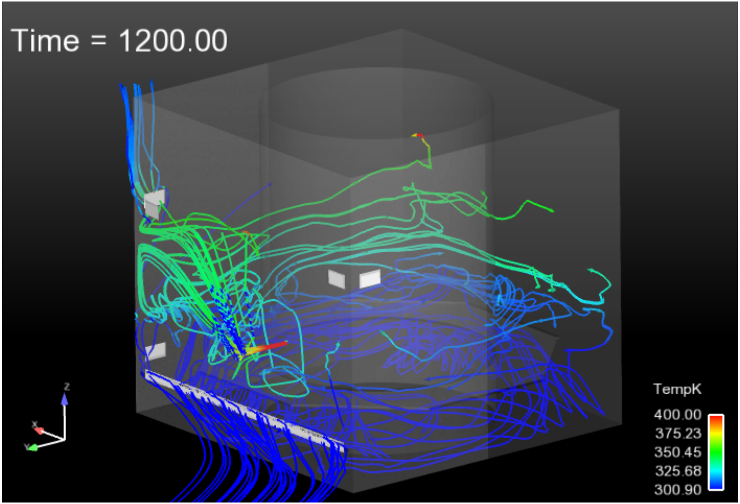
Gas release in reactor room



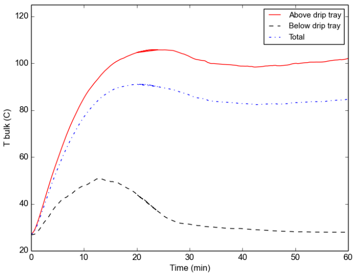
Gas release in reactor room

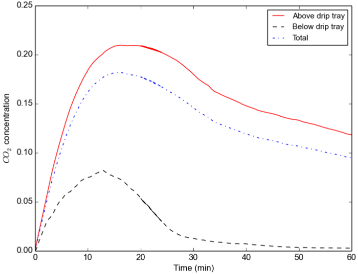


Gas release in reactor room



Gas release in reactor room





Bulk temperature vs. time

CO_2 concentration vs. time

Conclusions

- The EDF Energy R&D UK Centre is currently involved in different projects where the use of CFD is required to support operations in AGRs.
- The use of *Code_Saturne* is fundamental for these studies and the support from MFEE is vital for the success of the projects.
- The problems facing the future operation of AGR are varied and require use and development of different parts of the code.
- The use of CFD and High Performance Computing allow us to tackle larger problems supporting the safety cases for reducing over-constraint margins.
- The models developed in *Code_Saturne* will be transferred from the UK R&D Centre to the operational engineering unit (Barnwood) for routine studies.
- The strong links of the R&D Centre work with academic and industrial partners are an intrinsic part of the success of the projects to date.