Small Modular Reactors Seminar

Arnhem, 20.04.2018

A smaller future for nuclear power

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Problem formulation

The commercialisation of small reactors may address current problems faced by the nuclear industry, such as:

- **Magnitude of investment for large reactor projects**
- **Teething troubles of novel reactor designs**
- **Consequences of severe accidents**

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Problem formulation

Recent reactor construction projects have revealed a number of issues that the nuclear industry should resolve, if it is to remain competitive:

- High investment risk: 5 - 10 billion USD per reactor unit
- Long lead times from order to production: 10 - 15 years
- Quality problems during construction
- Additional costs for lessons learnt from Fukushima
- Reduced costs for natural gas and intermittent renewables

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The SMR solution

The commercialisation of small reactors might address the problems:

- Considerably lower investment risk
- Shorter time from order to production
- Teething problems addressed once several units have been built
- Passive safety may be easier to implement in small units
- Source term from a severe accident is smaller
- Better economics may result from serial production of small units in automatised factory environment

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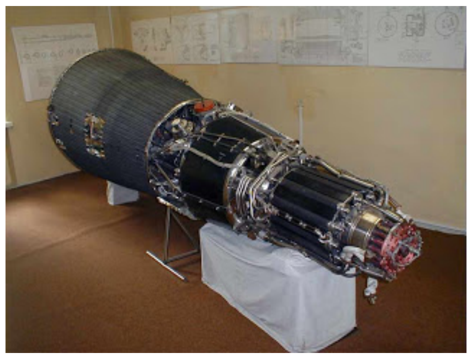
Historical background

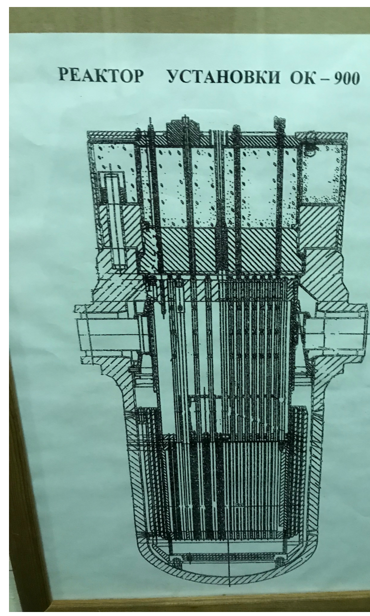


Many small power reactors were and are operated

- AM-1 (Obninsk, Russia)
- Shippingport (Pennsylvania, USA)
- Military reactors (Submarines, Arctic bases, Satellites)
- First generation water, sodium and gas-cooled reactors

- Military reactors (Submarines, Aircraft carriers)
- Russian atomic ice-breakers (36 - 54 MW propulsion)
- Bilibino power plant in Siberia (4 x 12 MWe)
- Indian PHWRs (100 - 220 MWe)

The atomic ice-breaker Lenin!



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What is new?

Small commercial reactors were shut-down as larger reactors came on-line.

- The cost of electricity from small LWRs and CO_2 cooled reactors was too high
- Sodium and helium cooled reactors had reliability problems (< 50 % availability)

What is causing the current interest in SMRs?

- Passive safety is becoming a new paradigm – easier to achieve in SMRs
- Investment risk is becoming an important issue – much less so for SMRs
- Long lead times and quality problems dissuade private investors – may be addressed by serial (automated) production of SMR units in factory environment
- Fuel cost is at an historical low – less of a penalty for SMRs that require fuel enrichment above 5 %

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SMRs under development

SMR concepts under development by commercial reactor vendors

- Integral PWRs
- Helium cooled reactors with TRISO coated particle fuels
- Sodium cooled reactors
- Lead-cooled reactors
- Molten salt reactors

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SMRs under construction: HTR-PM

He-cooled high temperature reactor, developed by Tsinghua University

- 210 MWe (2 x 250 MWth)
- Under construction in Shidaowan, Shandong province
- Pressure vessel dimensions: 5.7 x 25 m
- Coolant temperature: 250 - 750 °C
- Fuel form: TRISO coated particle pebble bed
- Fuel enrichment: 8.5 %
- Fuel residence time: 35 months
- Date for commissioning: end of 2018

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SMRs under construction: Akademik Lomonosov

Floating power plant, developed by OKBM Afrikantov

- 2 x 35 MWe KLT-40S reactors
- Based on proven atomic ice-breaker reactor (KLT-40) design
- Replaces Bilibino power plant
- Pressure vessel dimensions: 2.0 x 4.8 m
- Fuel active length: 1.2 m
- Fuel enrichment: < 20 %
- Fuel burn-up: 45 GWd/ton
- Date for commissioning: November 2019

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SMRs under construction: CAREM

CAREM: Integral PWR developed by CNEA in Argentina

- 25 MWe prototype under construction in Atucha
- Natural convection for full power heat removal (size < 150 MWe)
- Pressure vessel dimensions: 3.5 x 11 m
- Fuel active length: 1.4 m (hexagonal FAs)
- Fuel enrichment: 1.8 - 3.1 %
- 12 internal steam generators
- Commercial power plant: 4 x 120 MWe
- Intended use: power generation, research, desalination, cogeneration (8 MWe)

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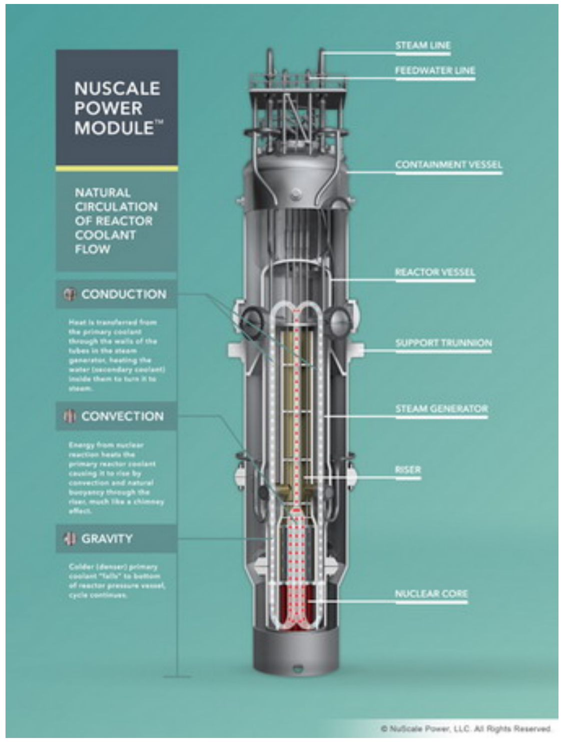
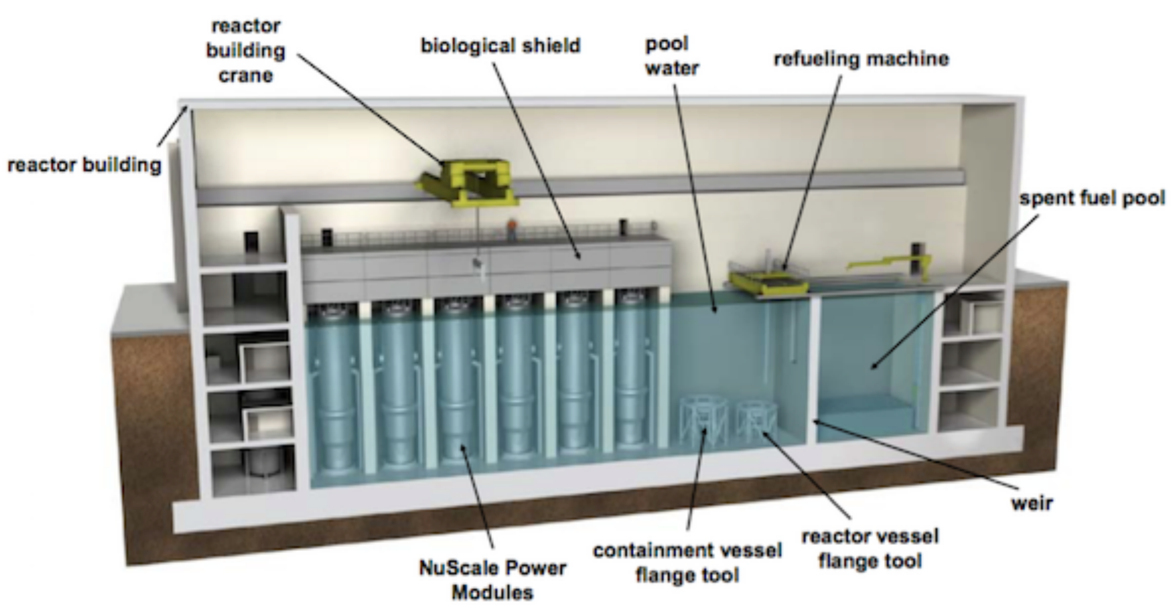
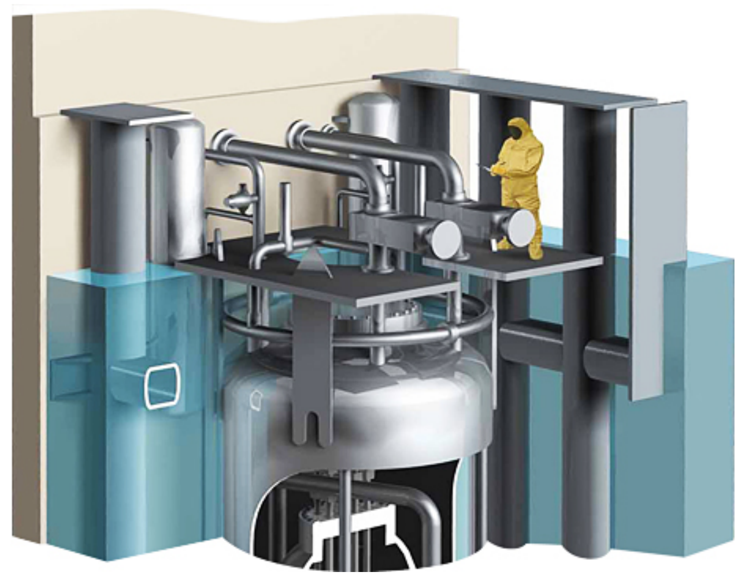
SMRs under licensing: NuScale



NuScale: Modular Integral PWR

- Up to 12 x 45 MWe power units in large water pool
- Natural convection for full power heat removal
- Pressure vessel dimensions: 2.9 x 17.4 m
- Fuel active length: 2.0 m
- Fuel enrichment: < 4.95 %





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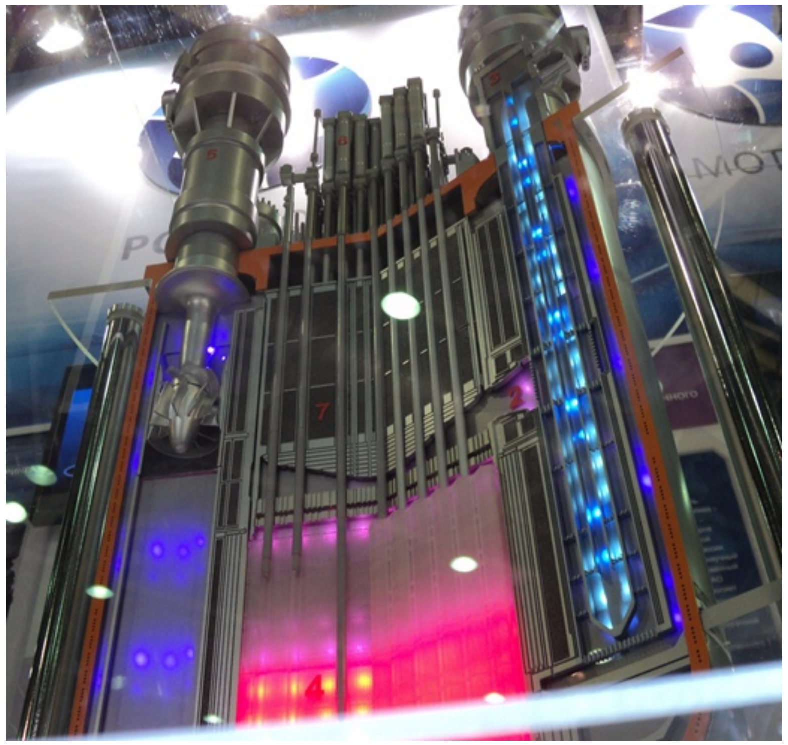
SMRs under licensing: SVBR-100



SVBR-100: lead-bismuth cooled fast reactor designed by AKME

- 100 MWe reactor for power production
- Based on Russian sub-marine reactor technology
- Vessel dimensions: 4.5 x 8.2 m
- Coolant temperature: 340 - 490 °C
- Fuel active length: 1 m
- Fuel enrichment: 16 % (later, U-Pu MOX, close fuel cycle)
- Fuel residence time: 7 - 8 years
- Breeding ratio: 0.84
- Site license for demonstration unit: Dimitrovgrad

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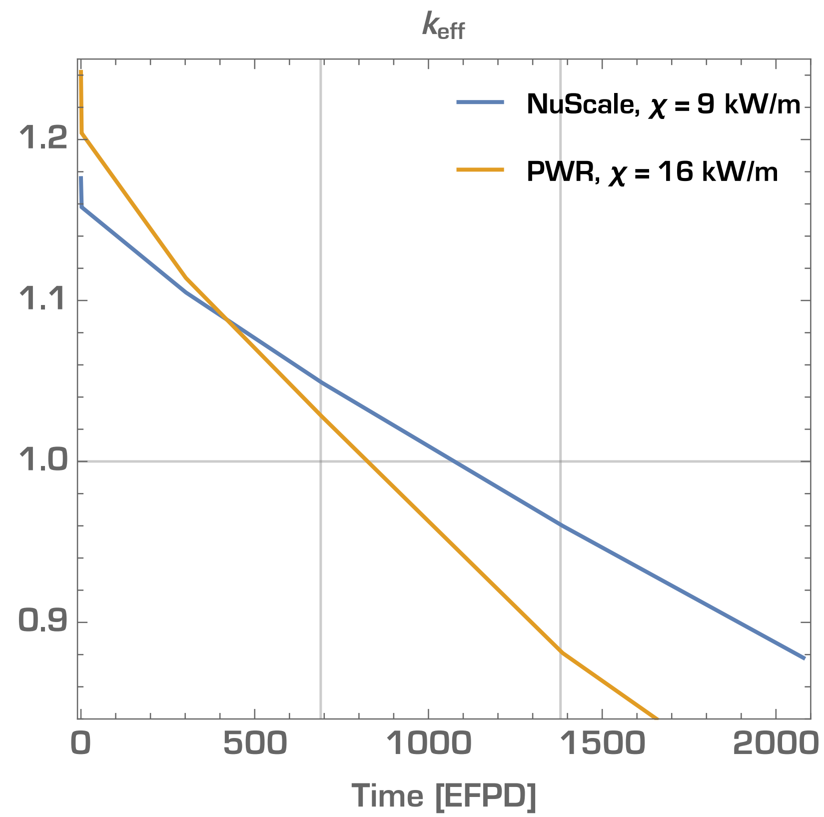
Fuel economy of integral PWRs

Fuel height is reduced to decrease pressure drop and increase natural convection

The number of fuel assemblies are reduced to achieve the desired power and improve transportability of the vessel

NuScale: 37 PWR assemblies with 1.83 m height

- Neutron leakage increases
- Reactivity decreases: lower burn-up
- Power density reduced to 9 kW/m
- Fuel cycle length increased to 24 months
- Total fuel residence time: 6 years
- Fuel average burn-up: 40 GWd/ton



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Lead-cooled reactors

Lead-cooled reactors would provide the following advantages:

- No exothermic reaction with structural materials nor water
- Very high boiling temperature: no loss of coolant
- Passive decay heat removal by natural convection in a highly compact design
- Retention of volatile fission products: source term limited to noble gases
- Gamma shield: minimises concrete inventory, simplifies core melt management

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Commercialisation of LFRs

The following reactor vendors are intending to commercialise LFRs:

- Rosatom (Russia)
- AKME (Russia)
- Westinghouse (US)
- China General Nuclear (biggest vendor in China)
- State Power Investment Corporation (Chinese vendor building AP1000)
- LeadCold Reactors (Sweden/Canada, KTH start-up company)
- Hydromine (UK/Italy start-up company)

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Fuel economy of lead-cooled reactors

Velocity of lead coolant limited to about 2 m/s

- Coolant flow area must be larger than for sodium cooled reactors
- In-core breeding ratio < 1 for UO_2 fuelled reactors without breeding blanket
- Fuel burn-up limited by reactivity loss (similar to LWRs)

ELFR: 600 MWe

Item	Value
Fuel rods/SA	169
No of SA	433
Fuel height	1400 mm

SLFR:100 MWe

Item	Value
Fuel rods/SA	169
No of SA	151
Fuel height	700 mm

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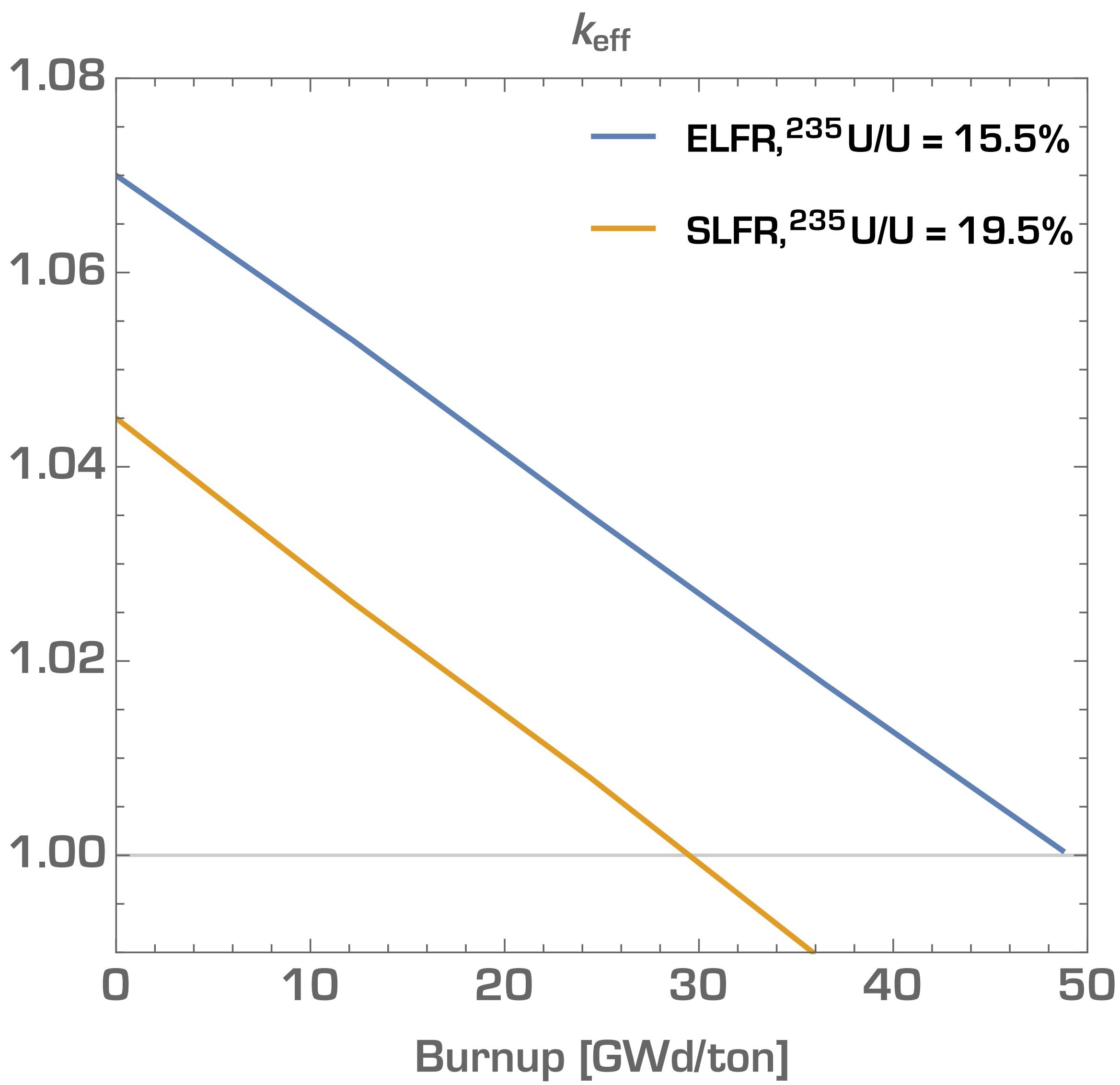
Reactivity loss and burn-up



ELFR enrichment (15.5%) adjusted to reach 50 GWd/t burn-up, in parity with PWR

SLFR: maximum permitted enrichment in commercial reactors: 19.5%

SLFR burn-up limited to 36 GWd/ton (compare with NuScale)

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Reactivity coefficients in fast reactors

In fast reactors, the power coefficients are of the order of 1 pcm/K (compare with the values for LWRs: 10 pcm/K!)

Axial and radial expansions of the core provide negative temperature feedbacks comparable with coolant and Doppler feedbacks

In case the coolant temperature coefficient is positive, it must be properly compensated for by the magnitude of the negative temperature coefficients

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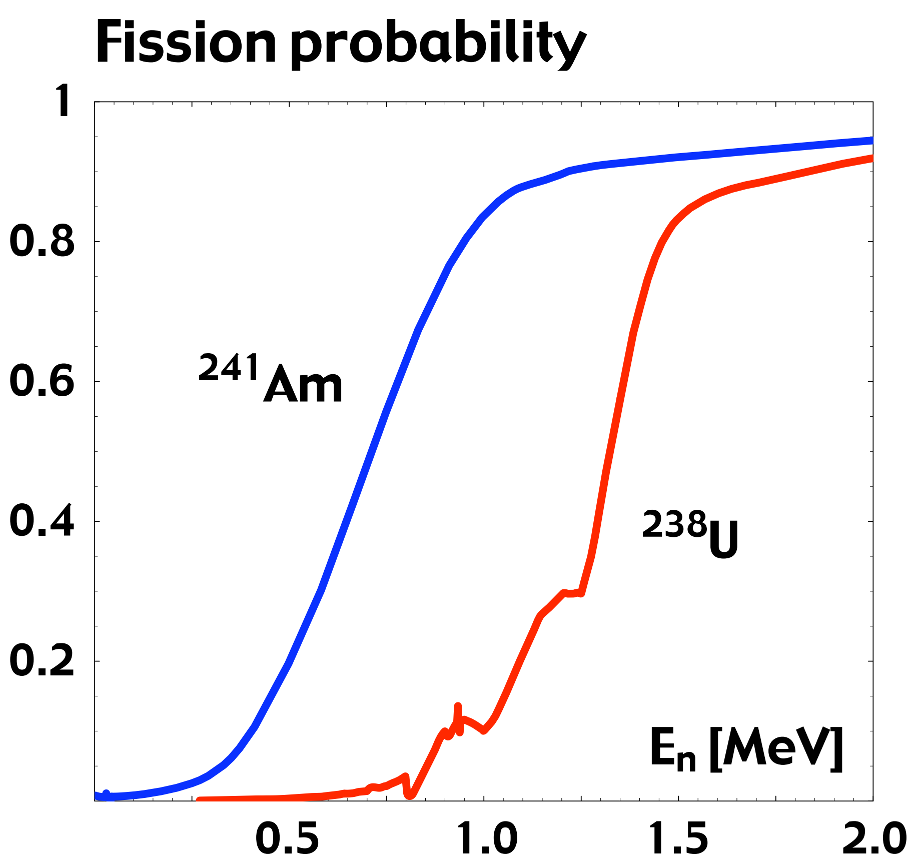
Coolant temperature feedback

When the coolant heats up, the coolant density decreases



- Moderation of fast neutrons by in-elastic and elastic scattering is less efficient
- Fission probability increases
- Neutron yield increases
- Reactivity increases

- Leakage of neutrons increases
- Reactivity decreases

The balance determines coolant temperature coefficient

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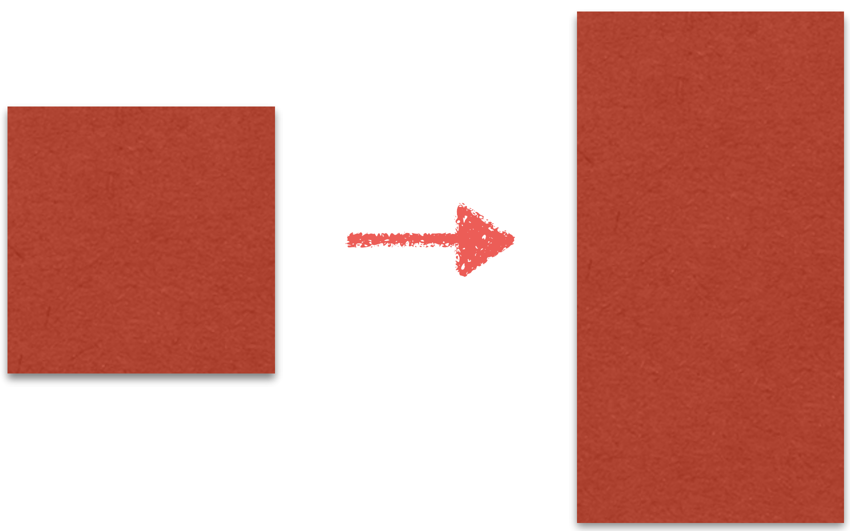
Axial expansion



When the fuel heats up, fuel pellets will expand in volume

- Axial expansion of pellets leads to an increase in core active height (By how much?)
- Radial expansion of pellets does not lead to an expansion in core radius (Why?)
- Axial expansion will increase the radial leakage of neutrons (Why?)
- Axial expansion feedback more important for cores with large H/D ratio (Why?)
- Feedback is delivered with speed of sound (How fast is that?)

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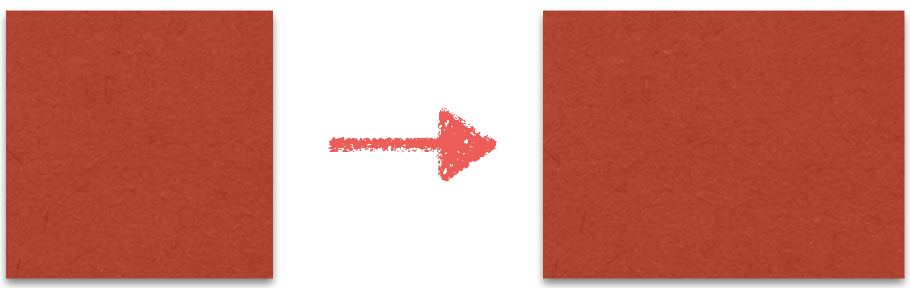
Radial expansion

When the grid plate heats up, the distance between fuel assemblies will increase



- By how much does the core radius increase?
- Radial expansion will increase the axial leakage of neutrons (Why ?)
- Radial expansion feedback is more important for cores with low H/D ratio (Why?)
- Feedback is delivered once the hot coolant temperature has been translated to the inlet of the core (How fast is that?)

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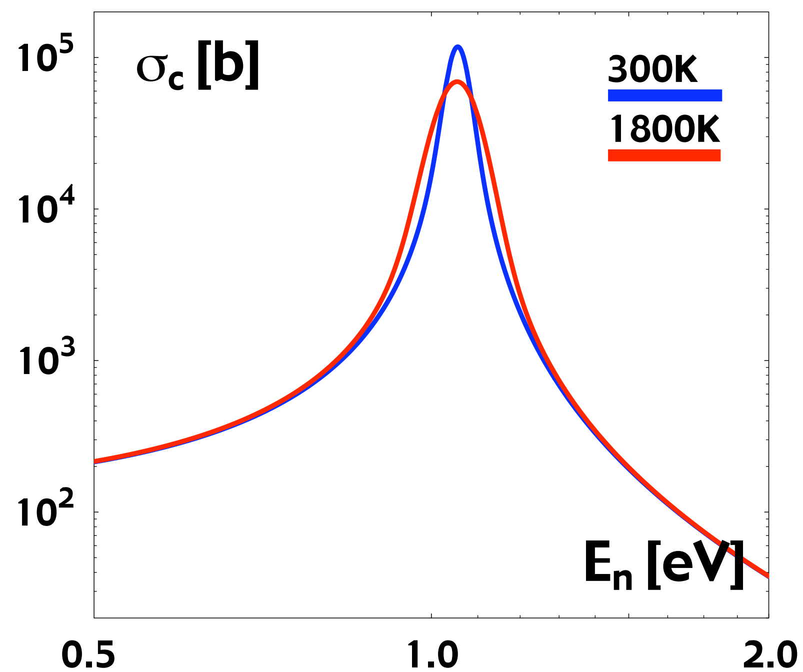
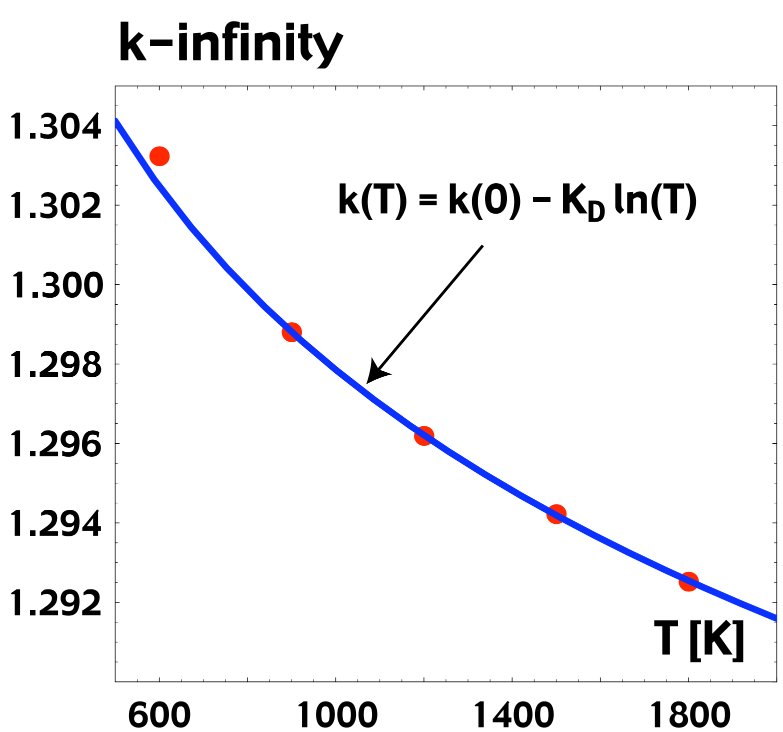
Doppler feedback (1)





When the fuel heats up, Doppler broadening of capture (and fission) resonances takes place

- Neutrons with energy higher than the position of the resonance are absorbed with higher probability
- Fewer neutrons reach the energy of the resonance peak position
- Net effect is an increase in neutron capture with temperature
- For oxide-fuelled fast reactors, the reactivity decreases logarithmically with temperature
- What is the temperature dependence in thermal reactors?

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Doppler feedback (2)

The Doppler coefficient α_D is the change of reactivity with temperature due to broadening of absorption cross section

$$\alpha_D \equiv \frac{d\rho}{dT} = \frac{1}{k^2}\frac{dk}{dT}$$

In a fast spectrum incorporating oxide fuel, reactivity decreases logarithmically with temperature

$$\rho(T) = \rho(0) - K_D \ln(T)$$

The constant of proportionality K_D is called "The Doppler constant"

$$K_D = T\frac{d\rho}{dT}$$

The Doppler coefficient is obtained by dividing the Doppler constant with T

$$\alpha_D = \frac{K_D}{T}$$

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Safety parameters depend on size!

ELFR: 600 MWe

Coefficient	Value
α_{Pb}	+ 0.23 pcm/K
K_D	- 960 pcm
α_{axial}	- 0.10 pcm/K
α_{radial}	- 0.32 pcm/K

SLFR:100 MWe

Coefficient	Value
α_{Pb}	- 0.02 pcm/K
K_D	- 660 pcm
α_{axial}	- 0.13 pcm/K
α_{radial}	- 0.47 pcm/K

Explain why!

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SEALER
SwEdish Advanced LEad-cooled Reactor

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SEALER
Technical aspects

- SEALER design
- Corrosion protection
- Transient performance
- R&D program

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SEALER
Design - general

- Small lead-cooled reactor
- 19.75 % enriched UO_2-fuel
- 3-10 MW electricity
- Core life: 10-30 years
- Reactor vessel: 2.7 x 6.0 m
- Transportable to/from site

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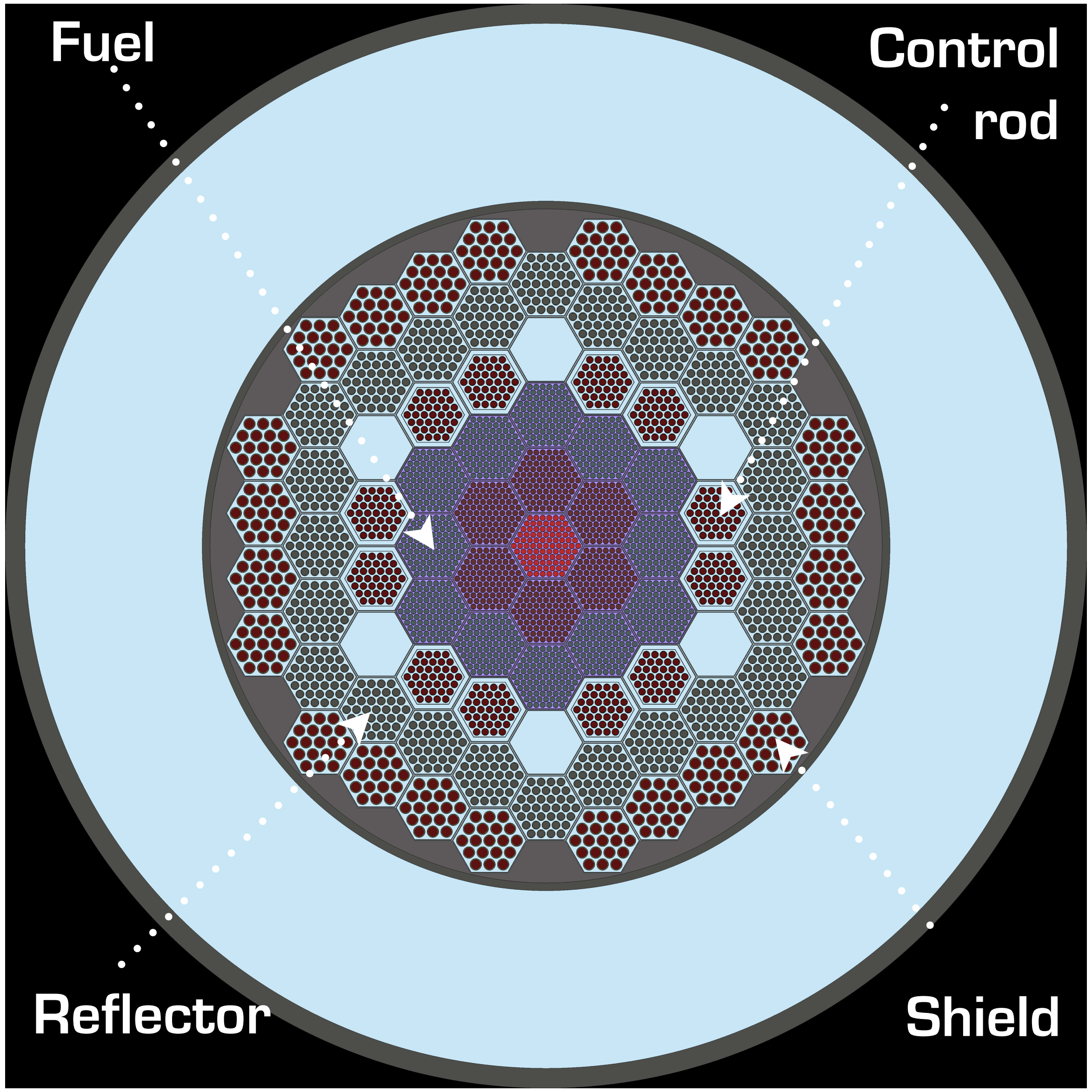
Design - core



- 19 fuel elements, 1729 fuel pins
- Core height: 110 cm
- Active core diameter ≈ 0.8 m
- 2415 kg of 19.75 % enriched UO_2 fuel
- 12 control rod elements (B_4C)
- 6 shut down rod elements $(W,Re)B_2$
- ZrO_2 reflector, $^{10}B_4C$ shield
- Core barrel diameter = 1.7 m

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Design - core

- All reactivity coefficients are negative, thanks to:
  - Uranium based fuel
  - High leakage core

Parameter	BOL	EOL
Effective neutron reproduction time	1.03 μs	1.33 μs
Effective delayed neutron fraction	752 pcm	704 pcm
Doppler constant	- 286 pcm	- 364 pcm
Fuel axial expansion reactivity coefficient	- 0.39 pcm/K	- 0.27 pcm/K
Diagrid radial expansion reactivity coefficient	- 0.39 pcm/K	- 0.39 pcm/K
Coolant reactivity coefficient (core)	- 0.29 pcm/K	- 0.19 pcm/K

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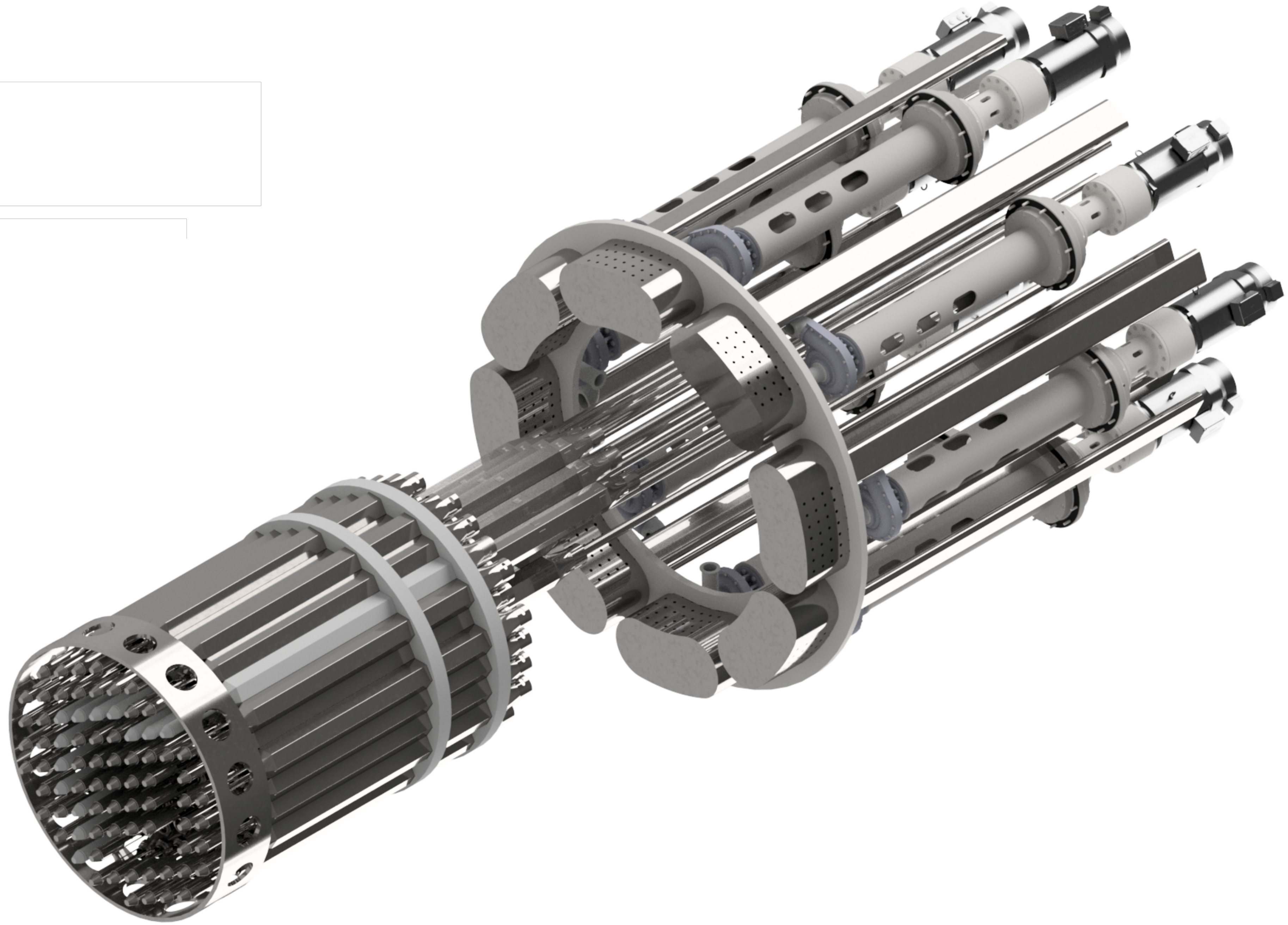
Design - primary system internals



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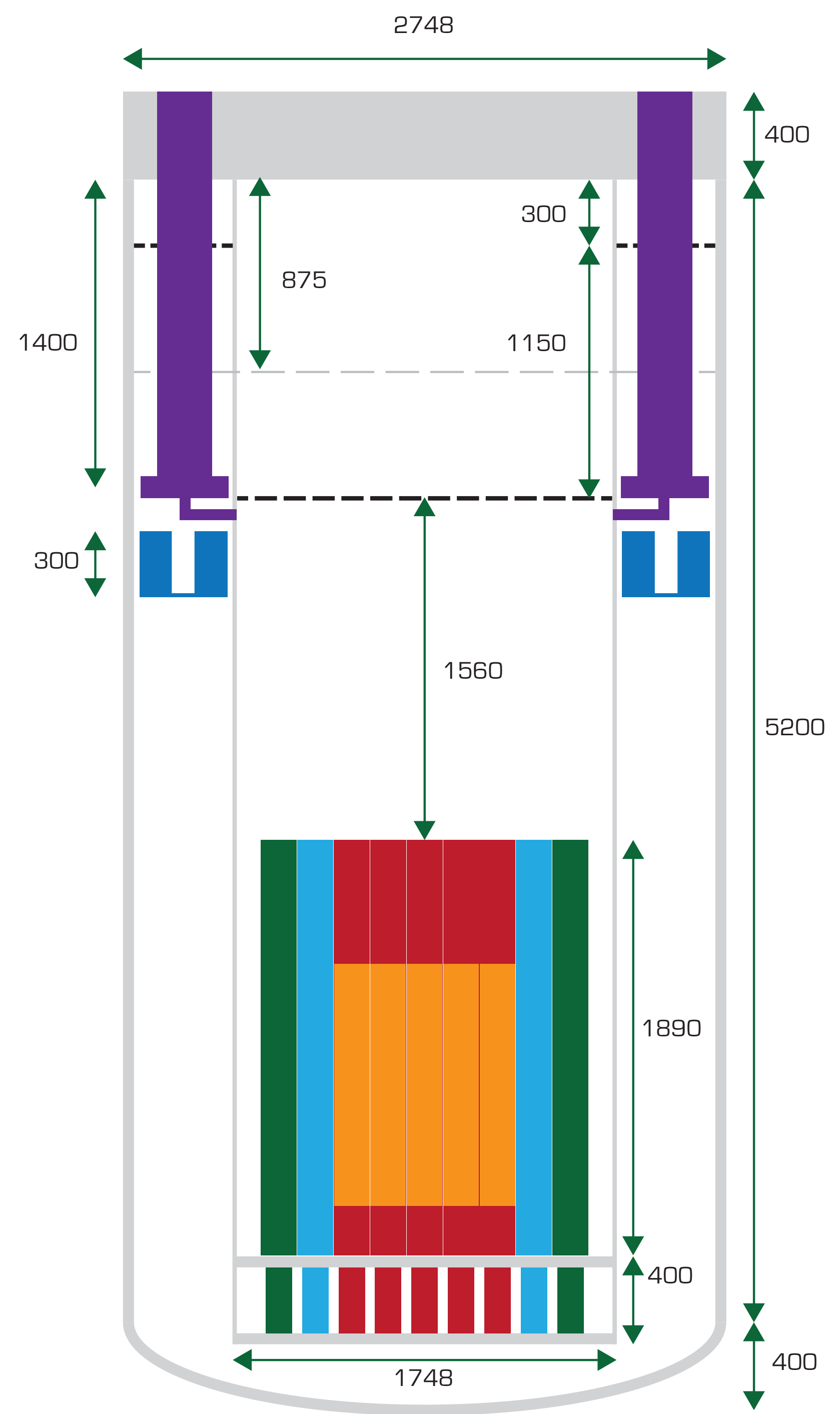
Design - primary system parameters



- 8 pumps operating @ 160 kg/s
- 8 steam generators @ 1 MWth
- Nominal lead flow rate: 1300 kg/s
- Max lead velocity in core: 1.6 m/s
- Max lead velocity relative to pump: 4.0 m/s
- Core inlet temperature: 390°C
- Core outlet temperature: 430°C
- Max cladding temperature: 450°C

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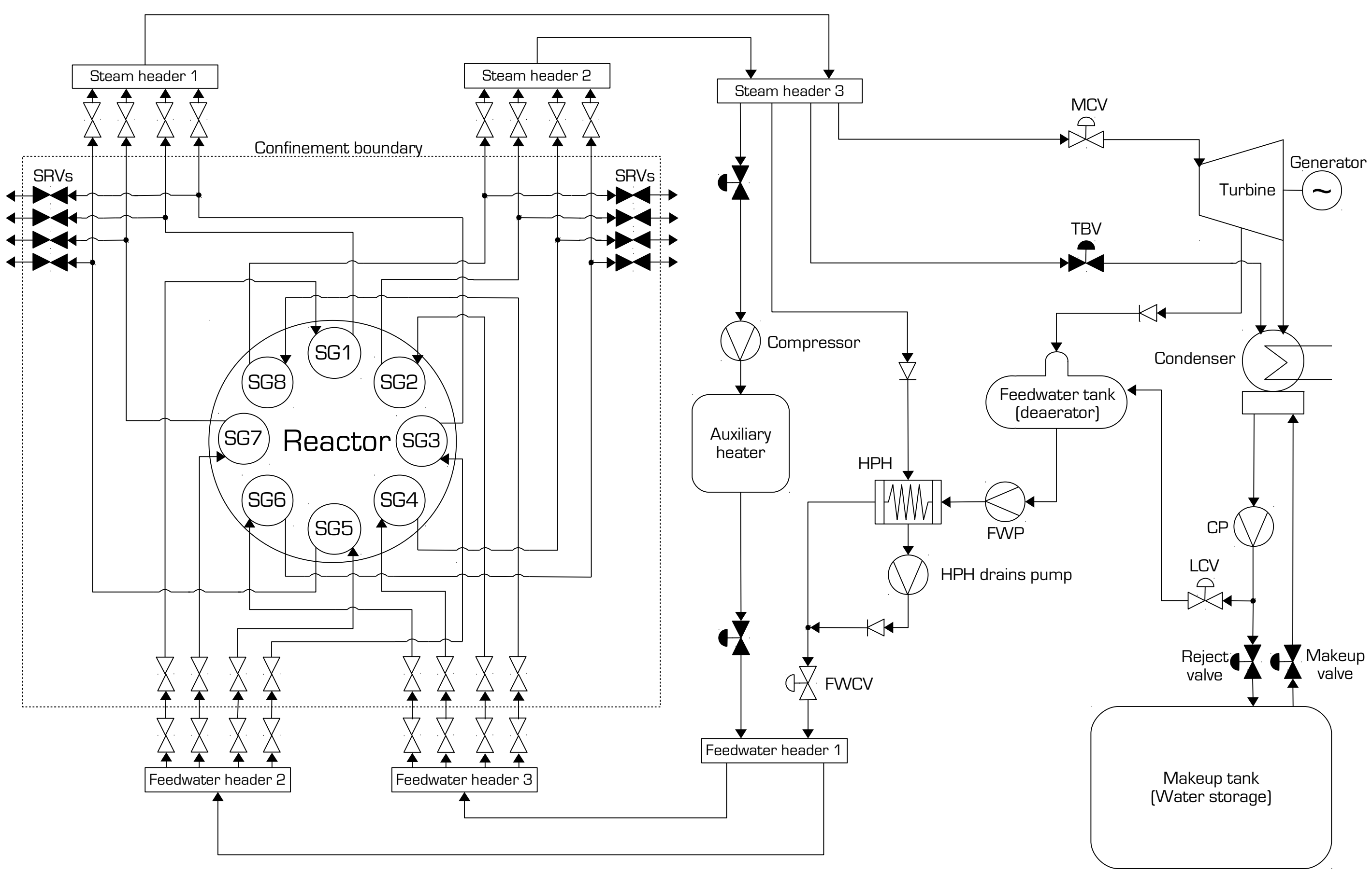
Design - BoP parameters



- Steam flow rate: 5.5 kg/s
- Live steam (1.8 kg/s @ 390°C) used for high pressure feed water pre-heating
- On-shelf turbine capacity: 7 MWe
- Turbine inlet pressure < 130 bar
- One turbine extraction (1.0 kg/s) for feed water tank heating to 180°C
- Conversion efficiency = 36%

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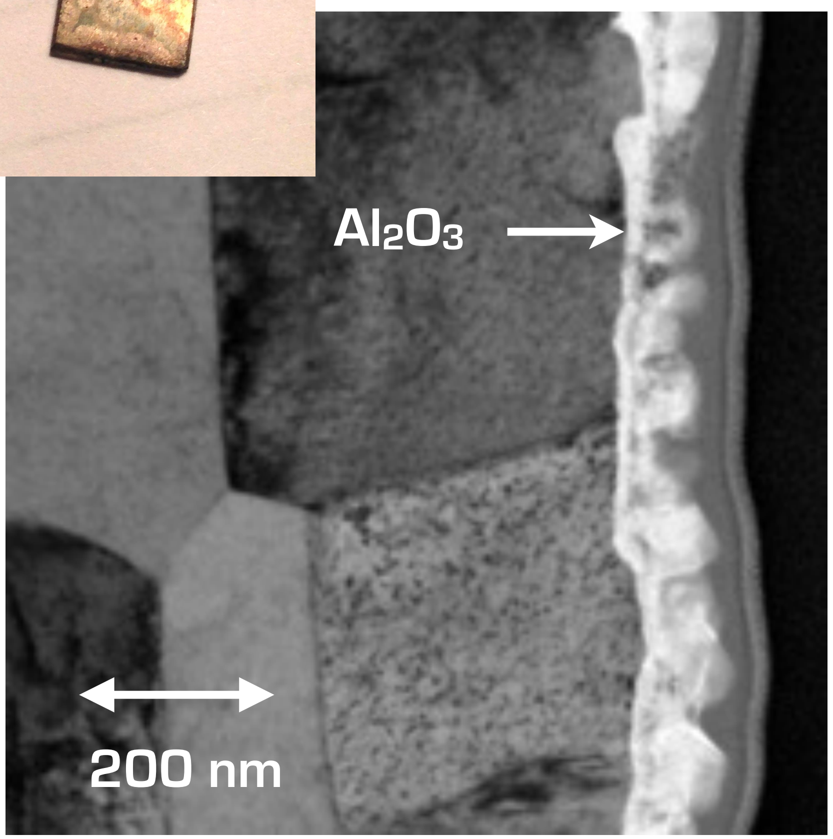
Corrosion protection



Alumina forming steels

- PhD thesis of J. Ejenstam
- Close collaboration with SANDVIK
- Fe-10Cr-4Al-RE is in perfect condition after 19 000 h of exposure to lead at 550 °C!
- 1 700 h corrosion test at 800°C successful
- Model Fe-10Cr-5Al alloy irradiated to 1.8 dpa by Oak Ridge. No hardening!
- 10 ton batch of Fe-10Cr-4Al-RE produced by SANDVIK.

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Corrosion protection

- Currently, only austenitic materials are qualified for use as pressure vessel (SS316) and fuel cladding tube (15-15Ti)
- Long term (30 year) corrosion performance at full power uncertain, even at SEALER operating temperatures (390-450°C).
- Corrosion products constitute potential issue for coolant management
- Primary vessel and core barrel to be protected by Fe-10Cr-4Al-RE weld overlay (1-2 mm thickness)
- Fuel cladding tubes to be protected by Fe-10Cr-6Al-RE surface alloy (weldability not required), produced with pulsed electron beam technique (GESA)
- Fuel assembly hex-cans to be manufactured from Fe-10Cr-4Al-RE

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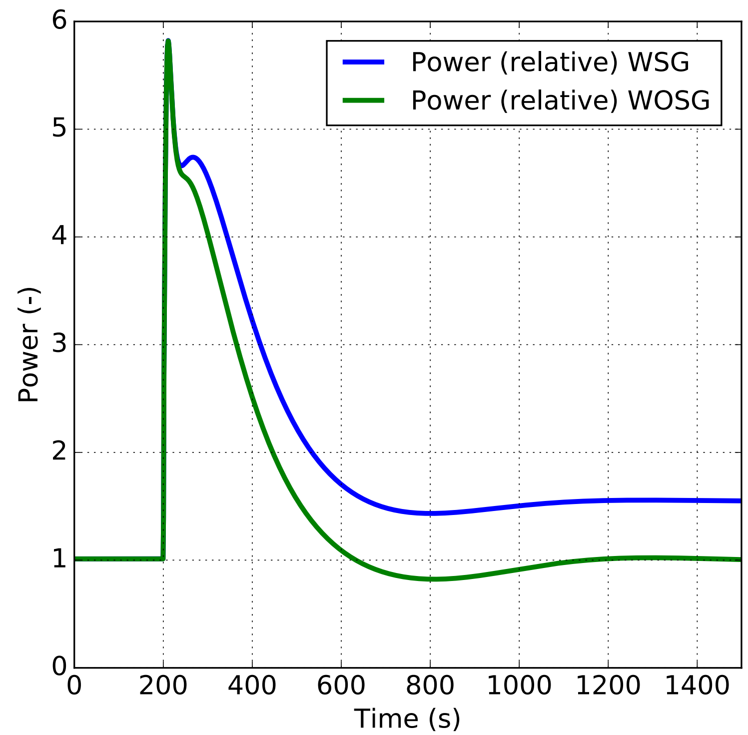
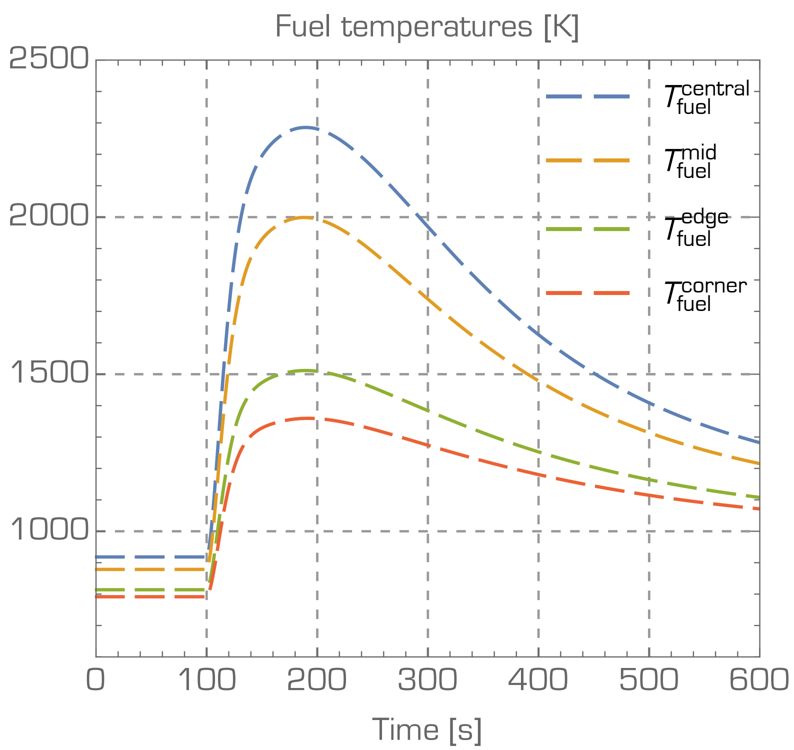
Transient performance - UTOP





- SAS (Argonne) and BELLA (LeadCold) codes were used for transient analyses
- Control rod withdrawal without scram was simulated with detailed model of steam generator (BELLA) and with multi-channel model of core (SAS)

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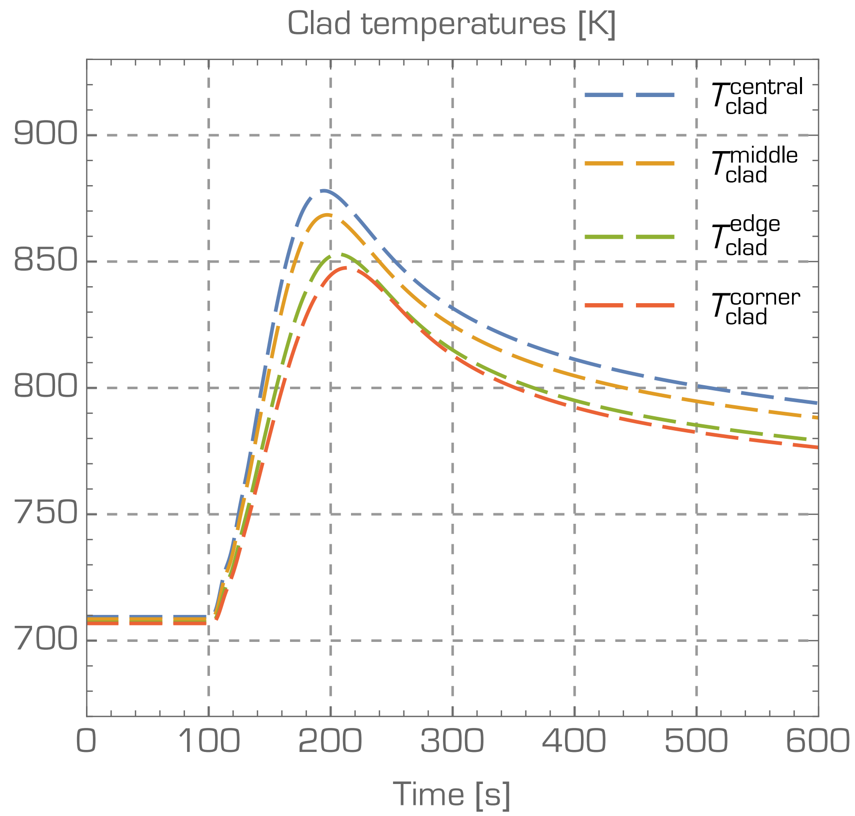
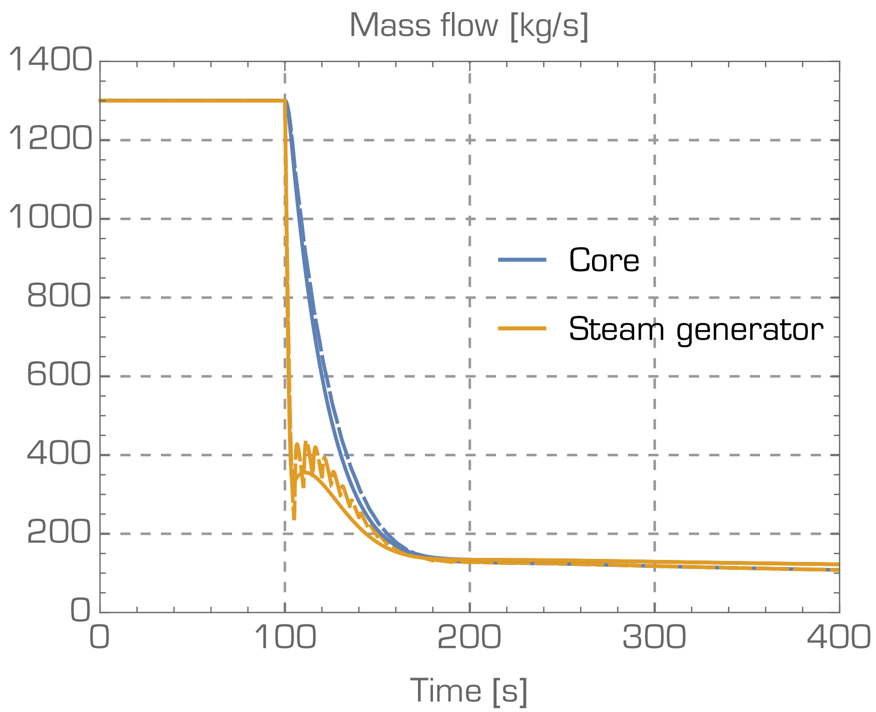
Transient performance - ULOF





- ULOF was modelled assuming cost-down off all pumps with half-life of ten seconds
- Flow reversal during transition to natural convection not observed
- Negative feedbacks lead to instant sub-criticality
- Maximum clad temperatures well below rapid creep limit
- SAS simulation features flow oscillations in steam generator that remain to be explained

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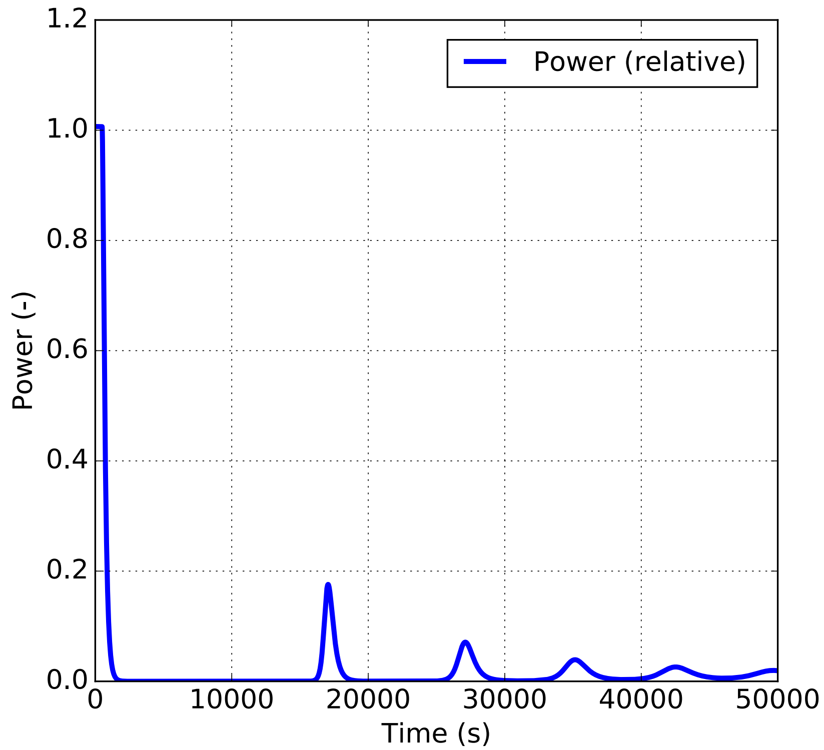
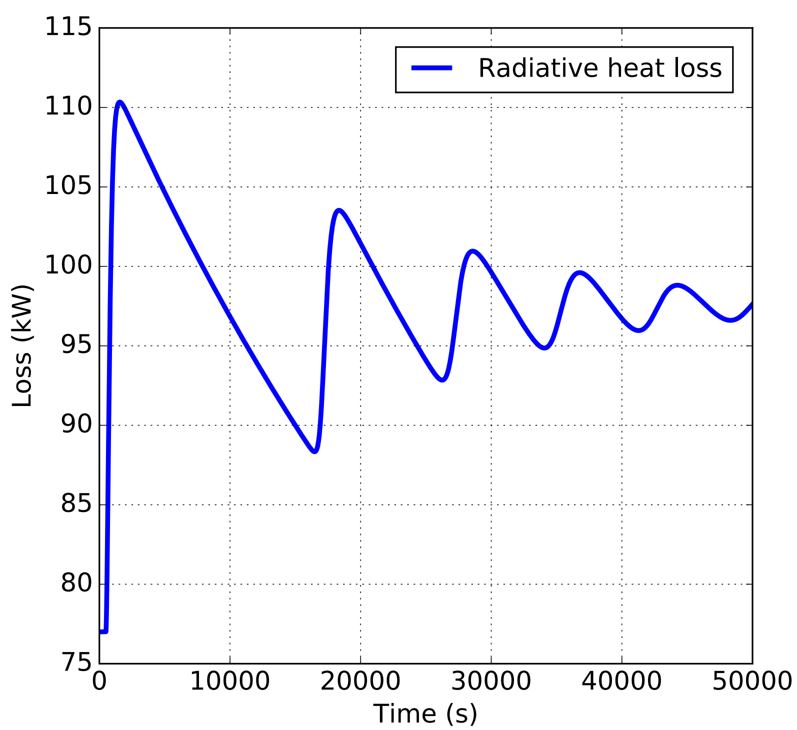
Transient performance - ULOHS





- BELLA was extended with model of radiative heat transfer from primary vessel
- Loss of heat sink simulation corroborates ≈ 100 kW of decay heat removal
- Concrete pit temperatures above service limit - RVACS system under design

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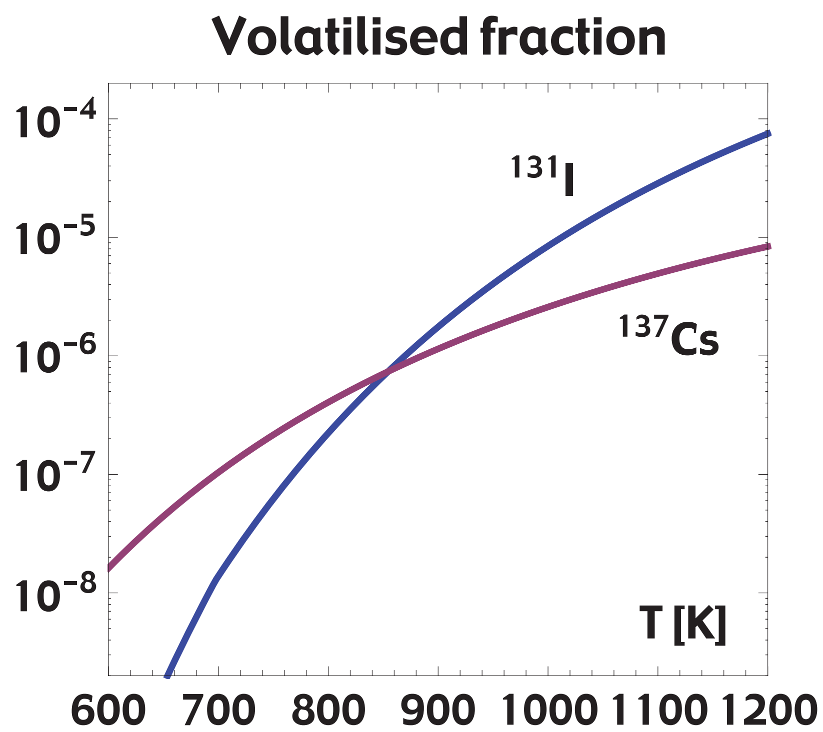
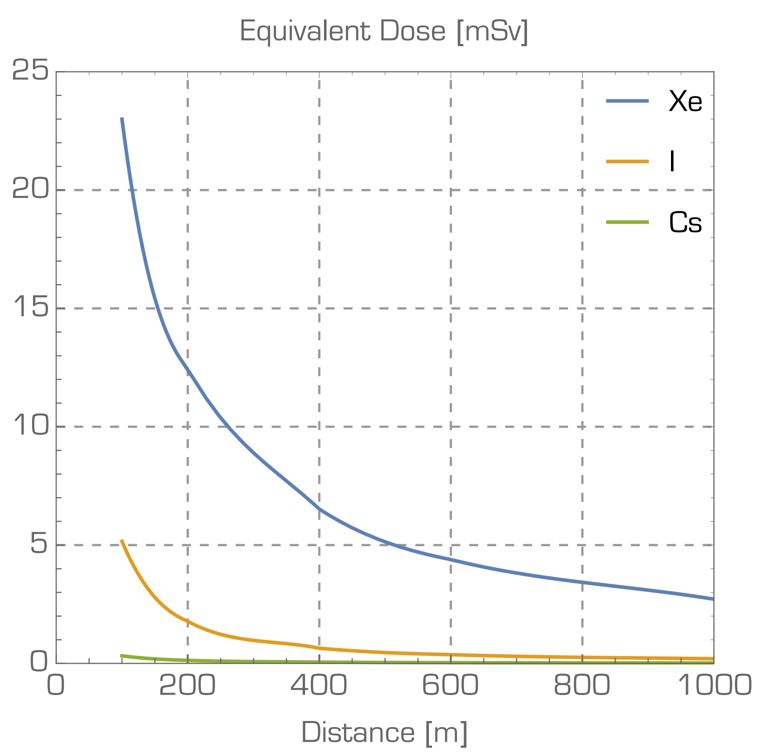
Radiological impact of severe accidents





- Radiologically important releases from a core melt: Xe, I, Sr, Te, Cs
- I, Sr, Te & Cs form stable compounds with lead when released from fuel
- Release factor at 1200 K < 100 ppm
- Mainly xenon contributes to dose
- Maximum dose (4 days exposure) at 150 m distance from release point less than CNSC criterion (20 mSv) for evacuation of public

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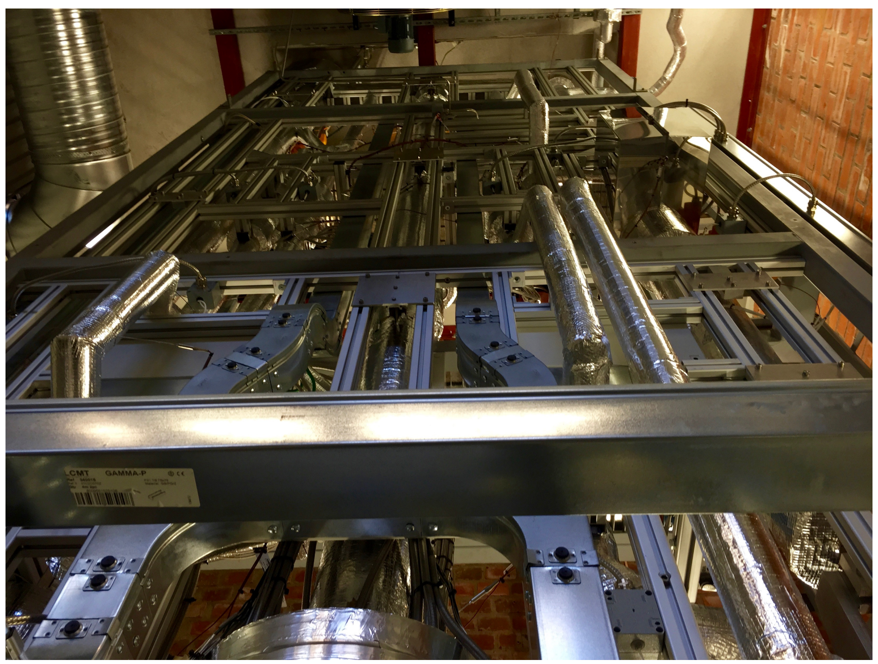
R&D - materials and components



- Stagnant and flowing corrosion tests of Fe-10Cr-4Al and alumina forming austenitic (AFA) steels
- Pump test facility for test of impeller endurance (target: > 2 years)
- Steam generator test facility
- 1:1 scale electrically heated mockup for integral system test
- Irradiation test of steels and absorber materials in materials test (fast) reactor

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SEALER
R&D - electrically heated mock-up

- One-to-one non-nuclear prototype of SEALER
- 8 MW power supply
- Validation of design & computer codes
- Life-time of pumps & steam generators
- Training facility for operators
- Potential location: Manitoba (lowest cost of electricity!)

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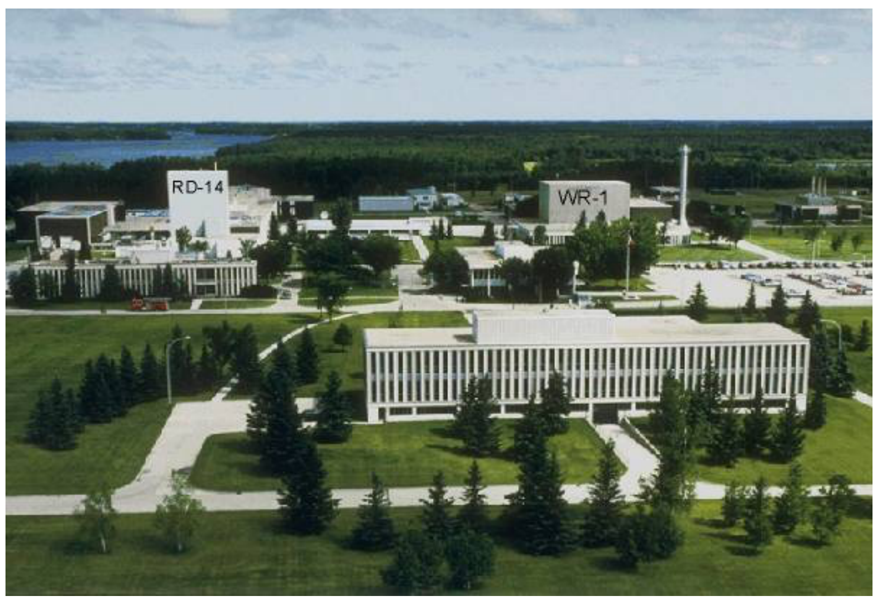
R&D - demo plant



- Customers request operation of demonstration plant
- May be built on a nuclear site in Canada
- Option to replace fuel elements
- Power uprating scheme: 1 MW_e → 3 MW_e → 10 MW_e
- Business model: power to site & advanced fuel qualification
- License to build: 2022 (if funded)
- Operational: 2026 (if funded)

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Thank you for your attention and...
...greetings from Janne!