Modelling the transient stability and dynamics of a pebble bed reactor using the FETCH code

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Demonstration reactor simulation by a combined neutronics and fluid dynamics code

Objectives

- Primary objective
  - investigate the stability of the reactor, in particular some of the temperature excursions in severe transients
- Secondary objectives
  - confirmation that radiative heat transfer is not important, in normal operation
  - check the reactivity as predicted by our model against the design burn up of an actual proposed reactor
  - an initial look at the possibility of changed operating parameters e.g. enrichment level

Simulation Data

- Material properties are taken from the general literature (TRISO fuel particles and graphite)
- Containment and reflector construction is minimally reproduced to provide the boundary conditions for neutron transport as simulated in the code which is used
- To simulate control rods, neutron absorption is incorporated in the reflector – initially to satisfy design conditions with fresh fuel – then modified in order to maintain power after burn up

Parameters – bed properties

- Moderator core radius 1.0 m
- (Fuel pebbles) Bed radius 1.85 m
- Bed Height 11.00 m
- Bed Properties Fuel Pebble Loading 452000 fuel spheres
- Initial Bed Temperature 482 degrees C

Parameters – Solid phase (pebbles)

- 0.92 mm diameter TRISO particles
- 9.6% ^{235}U initial enrichment
- Pebble Diameter 6.0 cm, including 5mm outer graphite layer
- Density 1774 $kg.m^{-3}$
- Thermal Conductivity 42 $W.m^{-1}.K^{-1}$
- Heat capacity 1400 $J.kg^{-1}.K^{-1}$

Parameters – gas phase (helium)

- Molecular weight 4.003 kg.kgmol^{-1}
- Gas Phase Density ideal gas law
- Thermal conductivity 0.216 W.m^{-1}.K^{-1}
- Heat capacity 5237.80 J.kg^{-1}.K^{-1}
- Dynamic Viscosity 0.27 mg.cm^{-1}.s^{-1}
- Initial Bed Pressure 9 Mpa
- Inlet Gas Temperature 482 degrees C
- Inlet Gas Velocity (downward) 4.4 m.s^{-1}

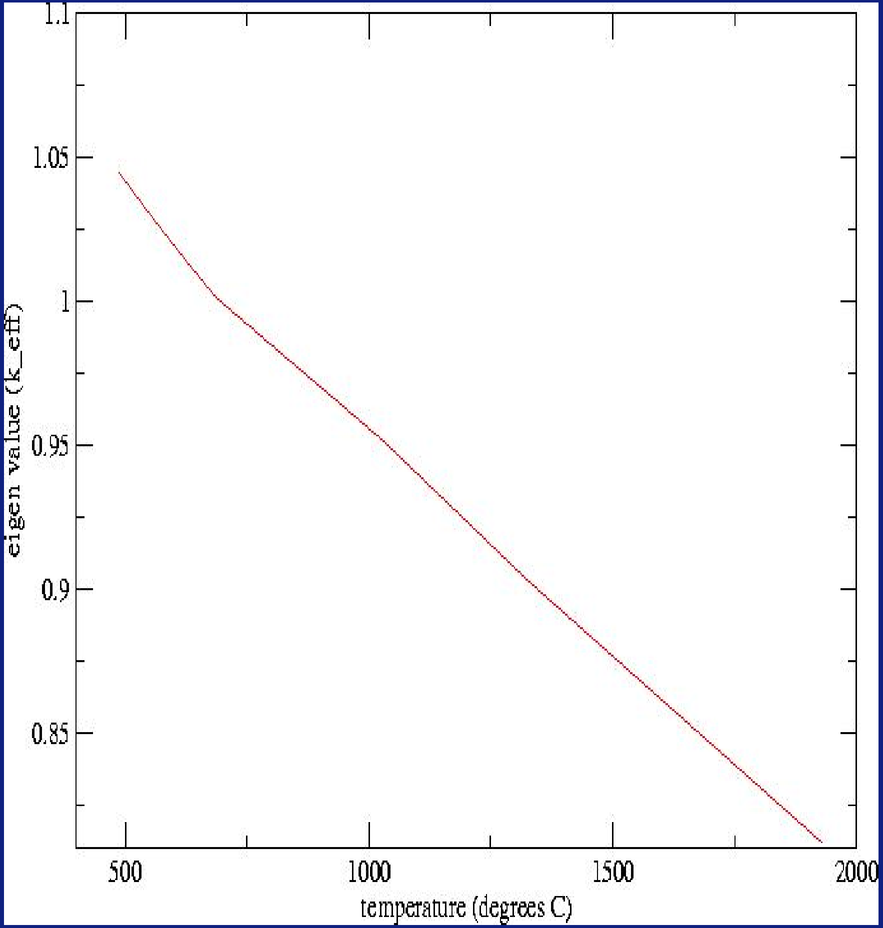
FETCH

- Development underpinned by the UK HSE/NNI
- Fully spatially coupled 2D/3D transient criticality/reactor physics code
- FEM single/multiphase fluids treatment (FLUIDITY) coupled to FEM radiation transport code (EVENT)
- Options for porous media (used in this work) and for fluidised granular material

Preliminary calculations

- Material neutron cross sections are generated using the lattice cell code WIMS8A
- FETCH code then calculates the neutron multiplication factor (k-eff) by solving the neutron transport equation in 2D R-Z geometry
- Time dependent calculations of transient and equilibrium fission rates and temperatures for the design reference case

Reference case - reactivity versus temperature

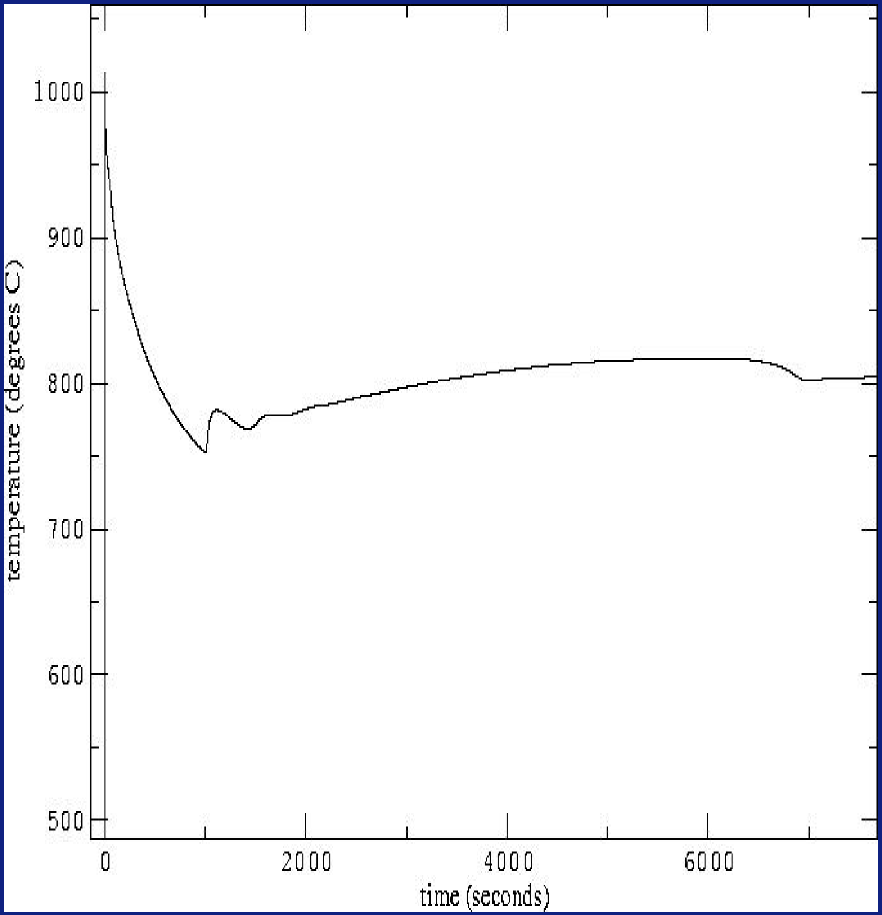


- Eigenvalues for fresh fuel
- Reactivity decreases with temperature
- Reference simulation of control rods
- Large surplus initial reactivity (about 6 dollars) at an initial fuel temperature of 482 degrees C

FETCH transient model

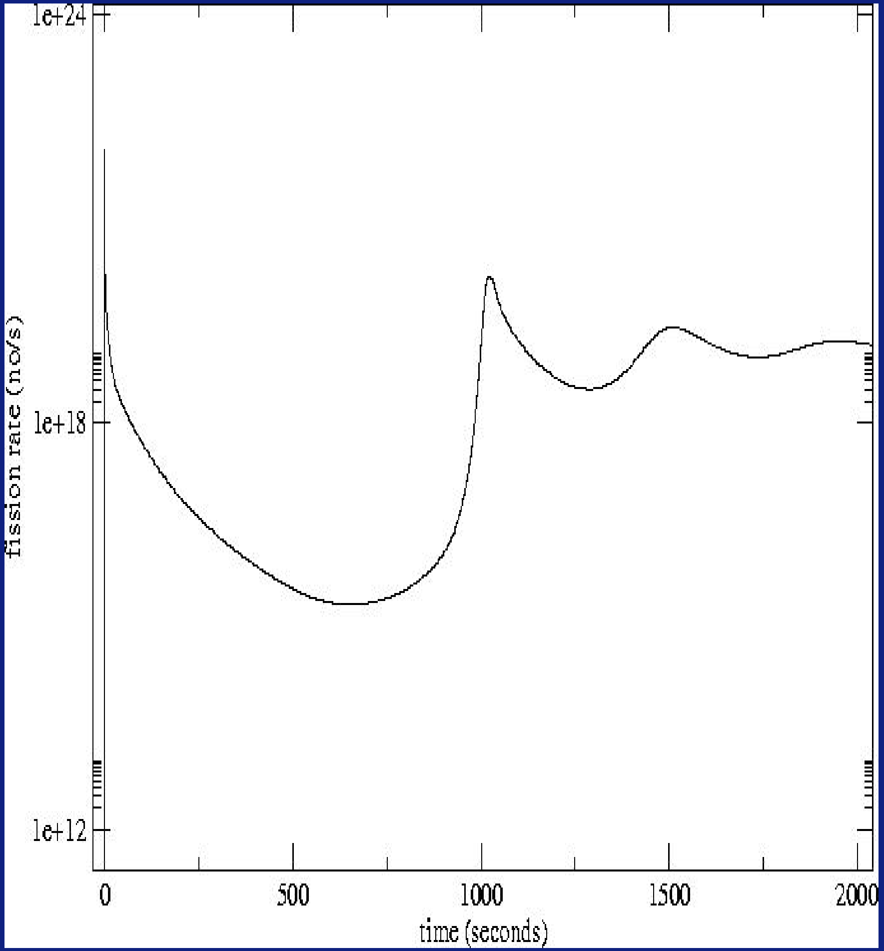
- Boltzmann neutron transport equation FEM solution
- Advection/diffusion in FEM
- Advection in mesh from fluids to neutronics
- Discretized Navier-Stokes
- Shows variation over elapsed time
  - Total power (fission rate)
  - Temperature
- Also produces snapshots
  - Power profile
  - Temperature profile

Reference case - temperature of the hottest pebble versus time – zero power to full power at restart



- Rises briefly to 1010 degrees C
- Moderate considering the surplus initial reactivity
- Initial fuel temperature and inlet gas temperature both 482 degrees C
- Equilibrium after about 7000 seconds

Reference case – fission rate versus time



- Second peak at about 1000 seconds
- Equilibrium after about 2000 seconds
- Equilibrium power about 400 MWt (fission rate about 1.25×10^{19})

Heat Transfer - Conduction/convection

- Conduction inside the pebbles (fuel particles to outside surface of graphite layer)
- Convection – boundary layer around a pebble – turbulent thermal diffusivity in the coolant - boundary layer around a second pebble
- Boundary layer – Gunn (modified) heat transfer coefficient
- Turbulent gas flow around pebbles

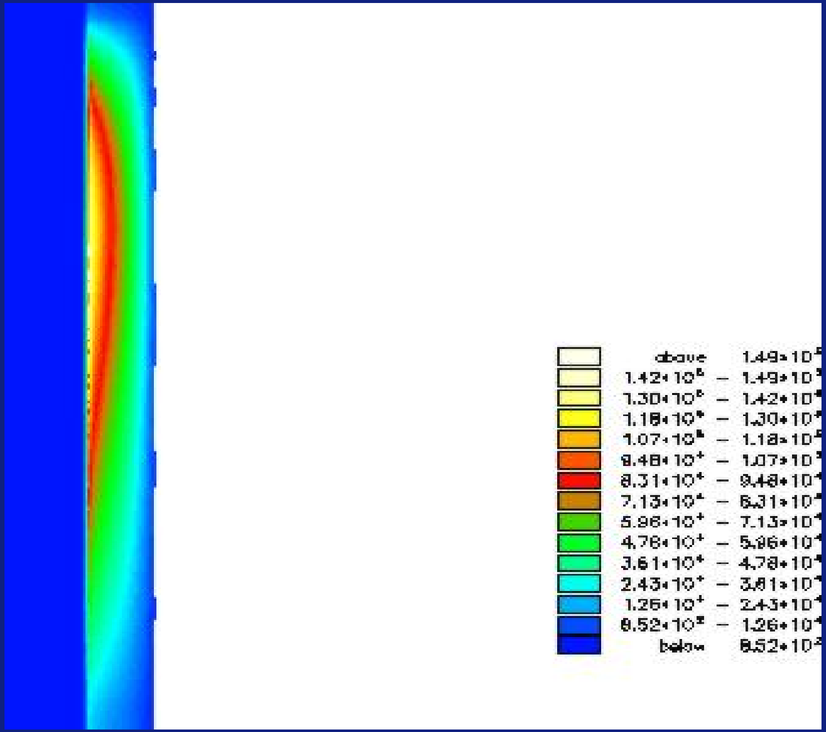
Radiative Heat Transfer

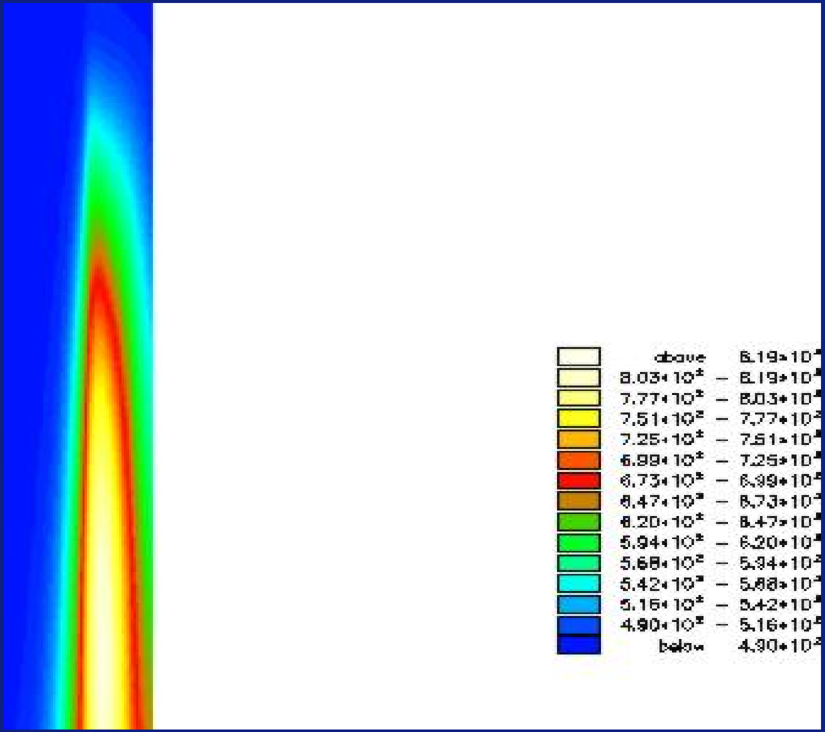
- Radiative heat transfer in a nonabsorbing medium (pebble to adjacent pebble or to wall from adjacent pebble, depending on view factor)
- Absorption and radiation in helium can be neglected

Heat Transfer - comparison

- Parallel convective heat transfer and radiative heat transfer
- Convective – effective coefficient (pebble surface to nearest solid surface) - boundary layers and turbulent diffusivity in series
- Radiative heat transfer – equivalent coefficient is a function of temperature
- In normal operation – comparable radiative coefficient would imply a temperature of >2500 K

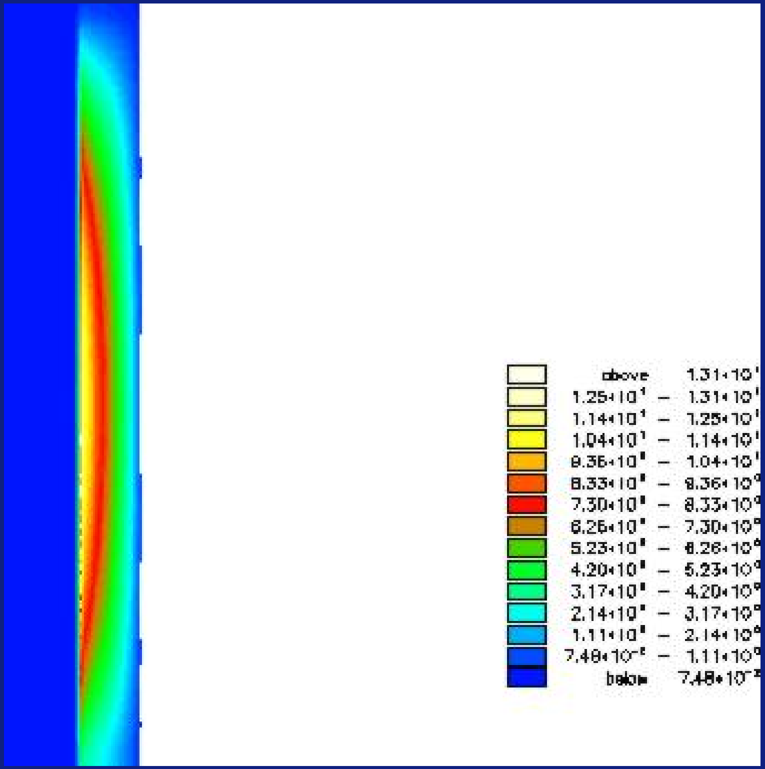
Reference power and temperature profiles at equilibrium

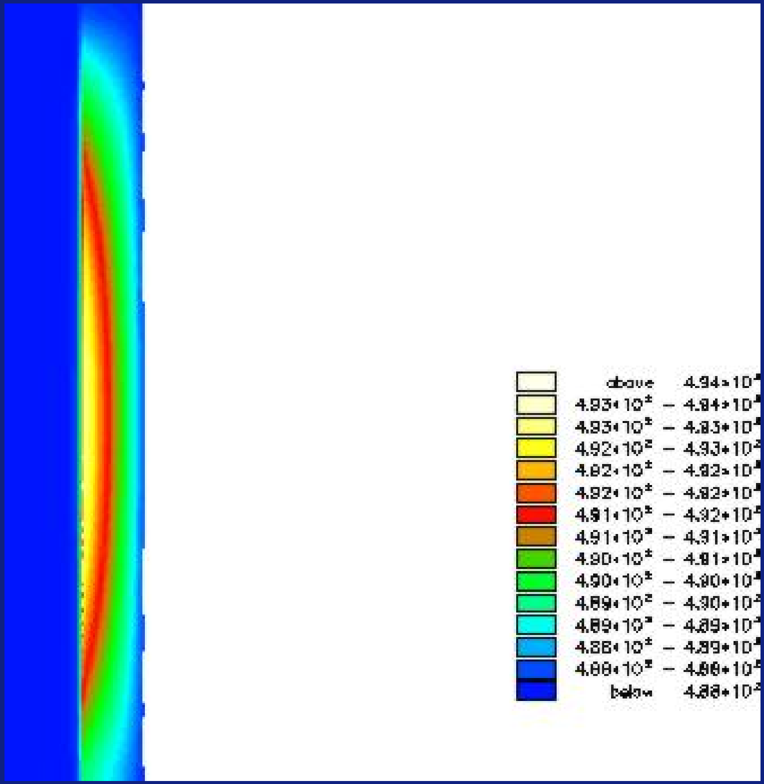




- Half section of reactor bed and inner reflector, centre line on the left
- Fission is concentrated towards the coolant inlet at the top
- Highest temperature is in the fissile material region towards the coolant outlet

Reference power and temperature profiles at 0.25 seconds from start of transient



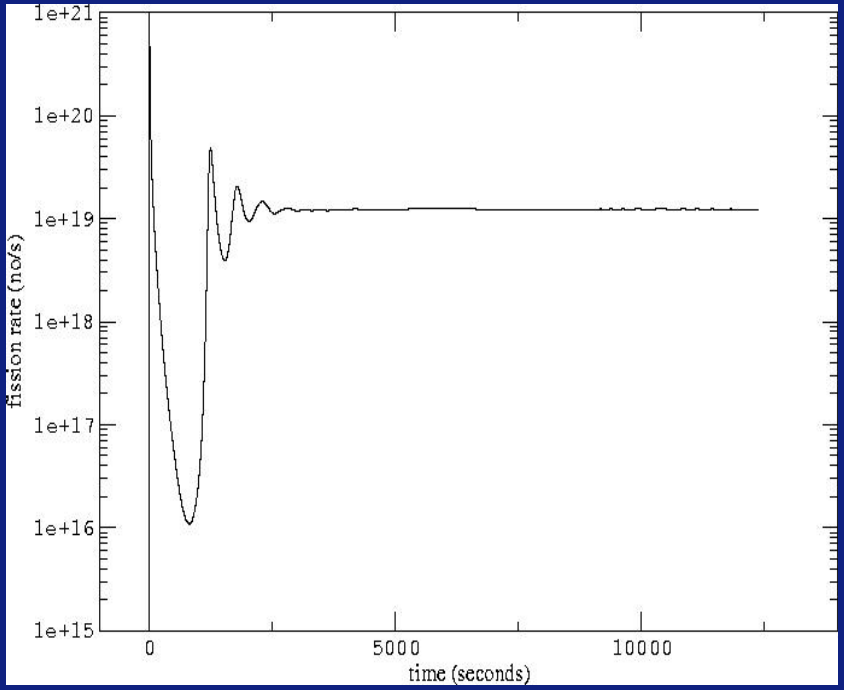


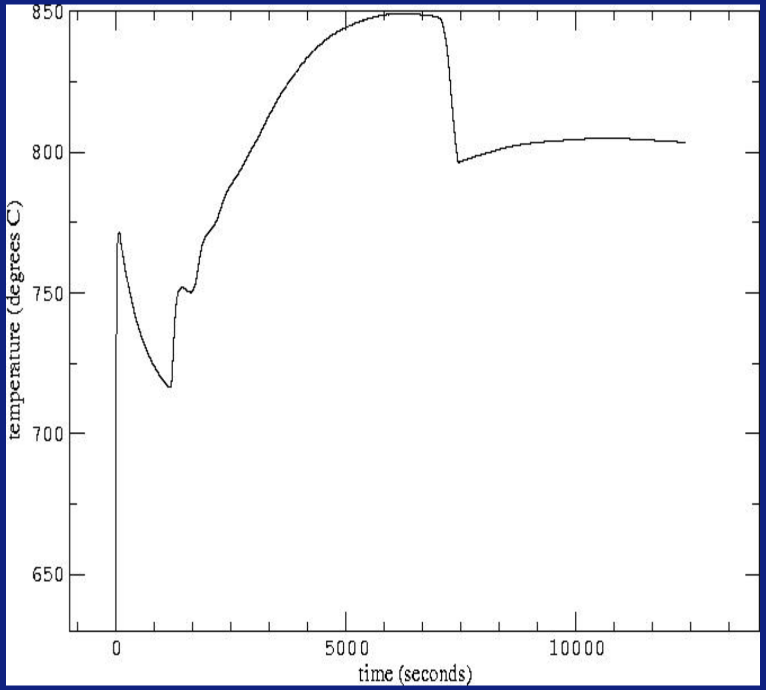
- Early in the transient the highest temperature and greatest fission rate regions still coincide
- The temperatures have hardly started to rise

Cases

- Transients - different initial starting temperatures
- Transient and equilibrium values
  - different initial surplus reactivities
  - different coolant flows
- Kinetic response to a varying coolant flow
- Behaviour with irradiated fuel
  - different burn up levels (with different initial enrichments)
  - different spontaneous fission assumptions

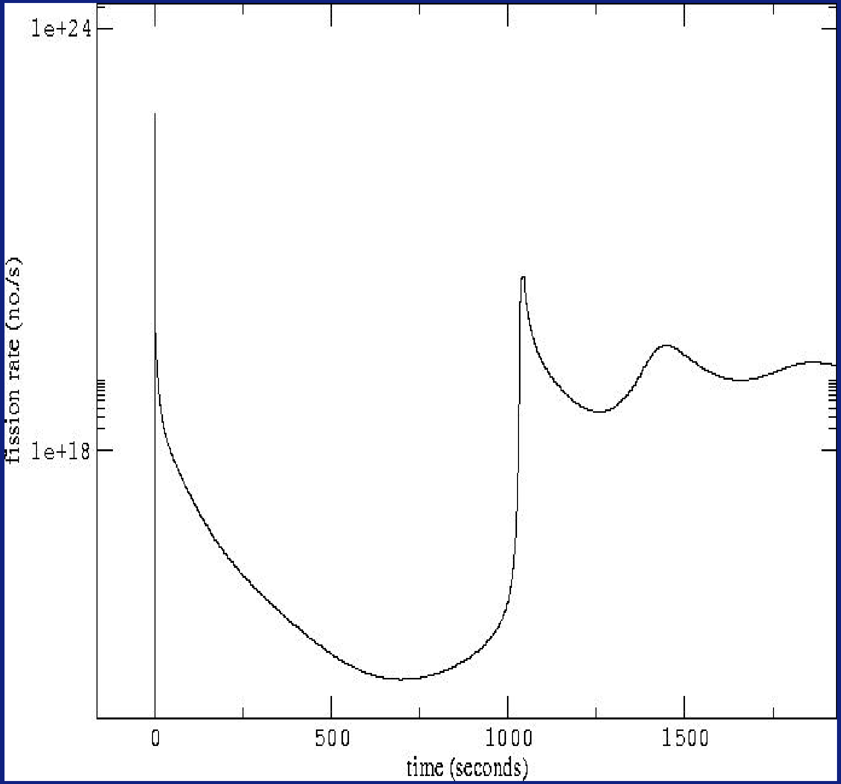
Hot restart - fission rate versus time and temperature versus time

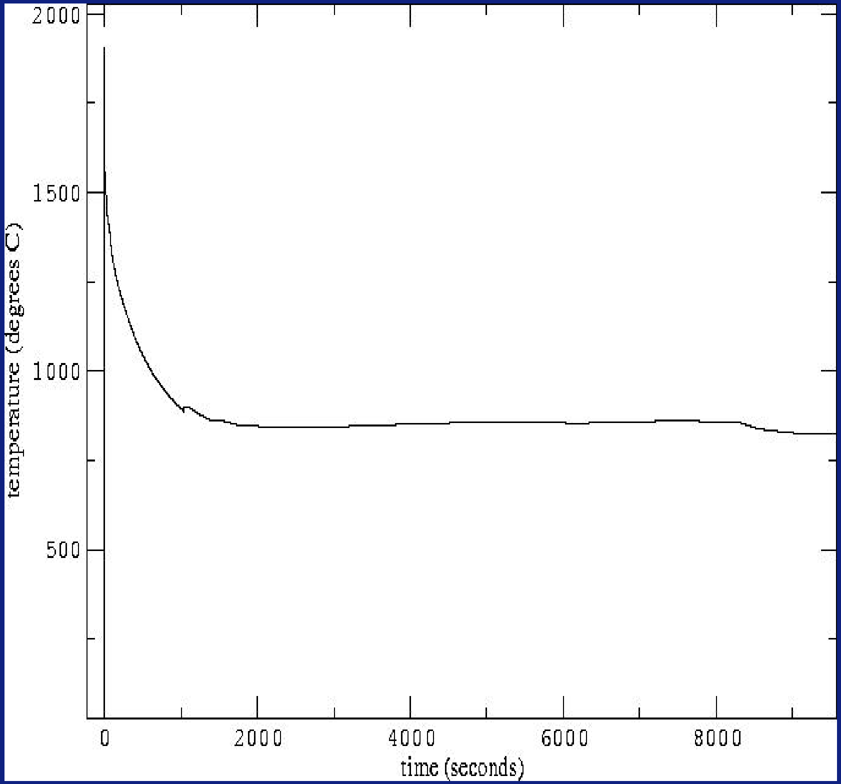




- Restart from a uniform reactor bed temperature equal to the mean equilibrium pebble temperature achieved in the reference case
- Transient fission rates are smaller
- Transient peak temperature is not only lower but also later

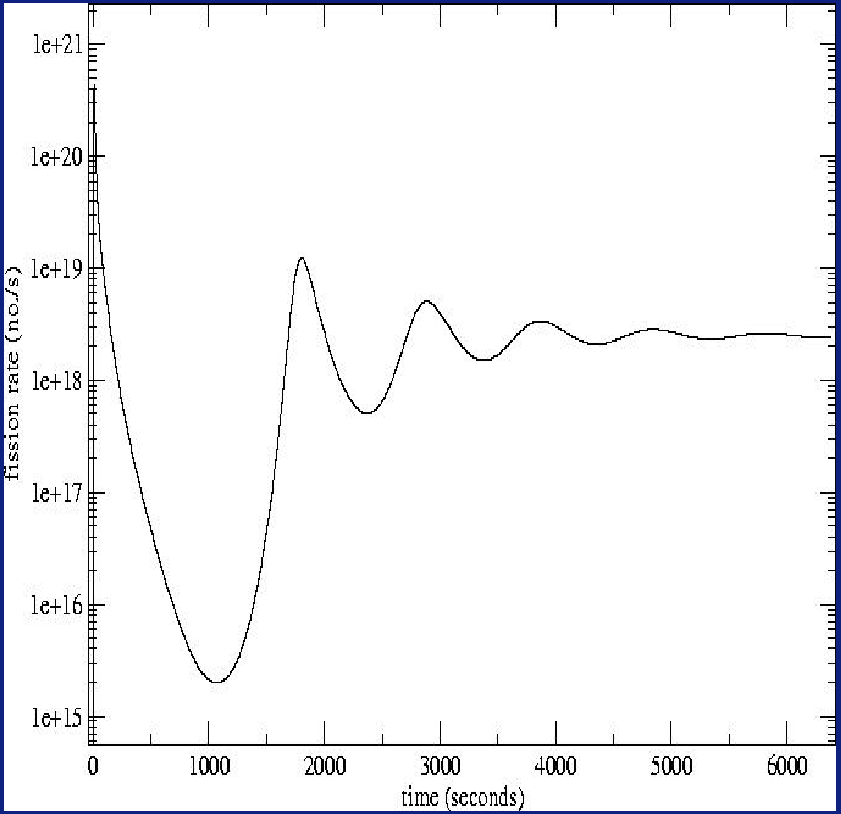
Cold restart - fission rate versus time and temperature versus time

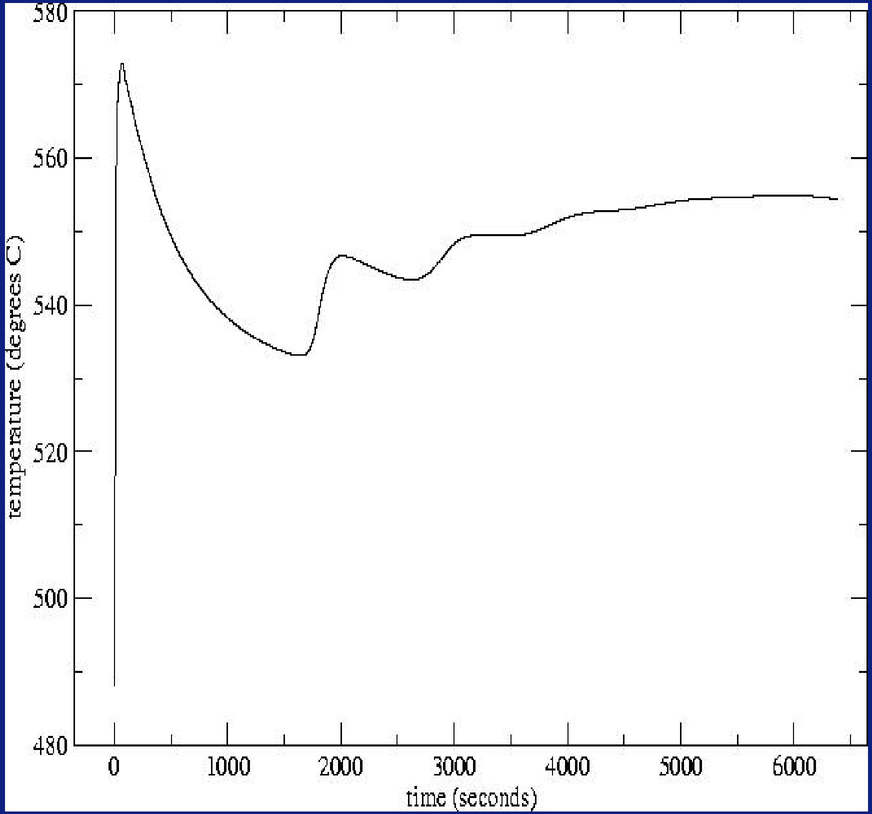




- More severe test than the reference case
- Fuel at 482 degrees C, coolant inlet 27 degrees C
- Excessive initial transient peak temperature approximately 1900 C

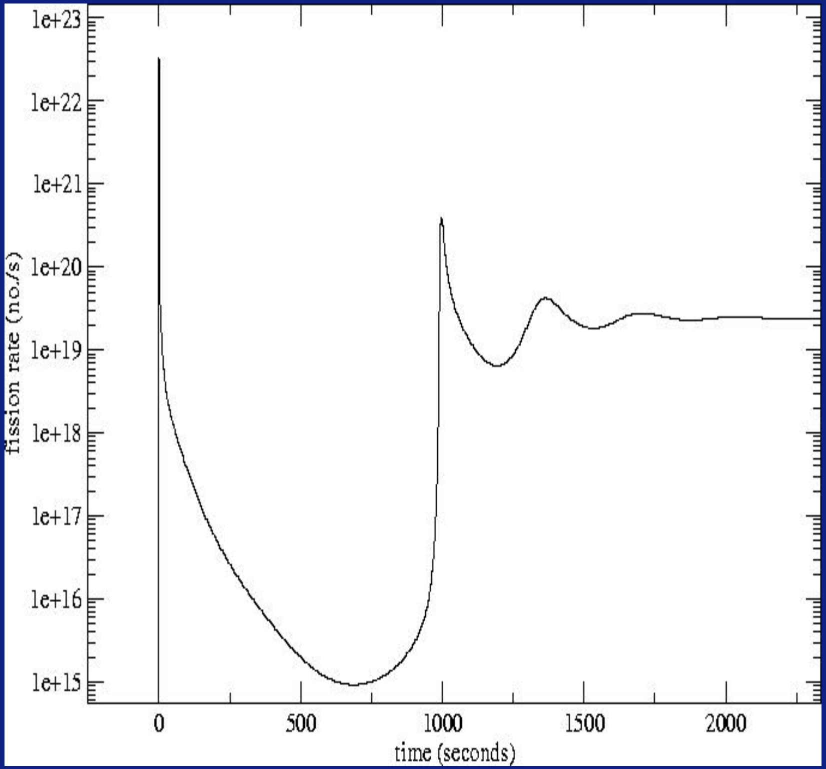
Decreased reactivity - fission rate versus time and temperature versus time

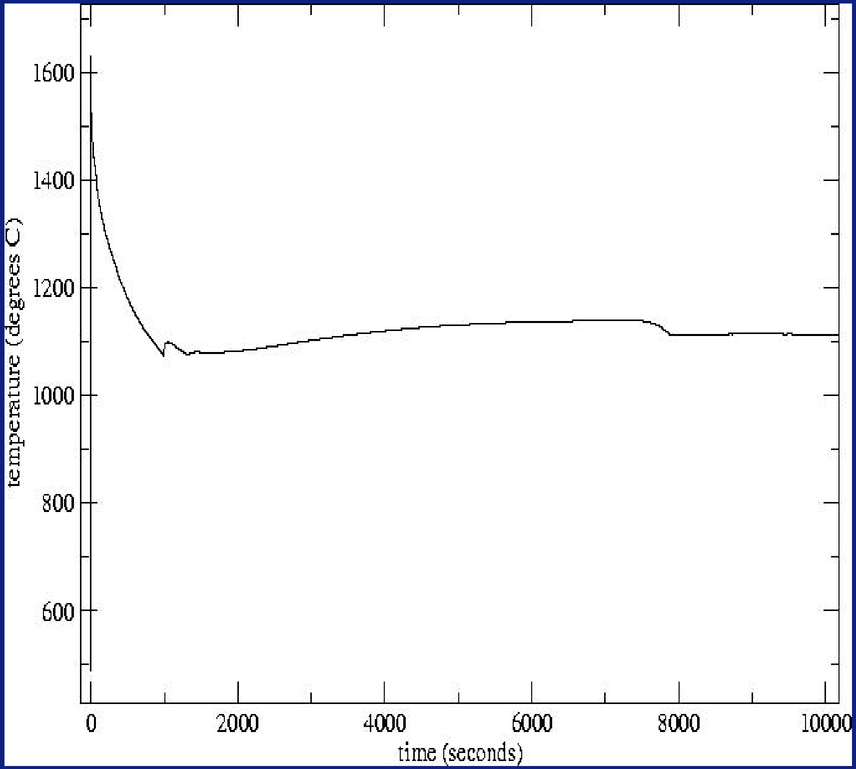




- Peak fission rate and temperature, equilibrium fission rate and temperature are all lower
- Equilibrium power about 80 MWt

Increased reactivity - fission rate versus time and temperature versus time





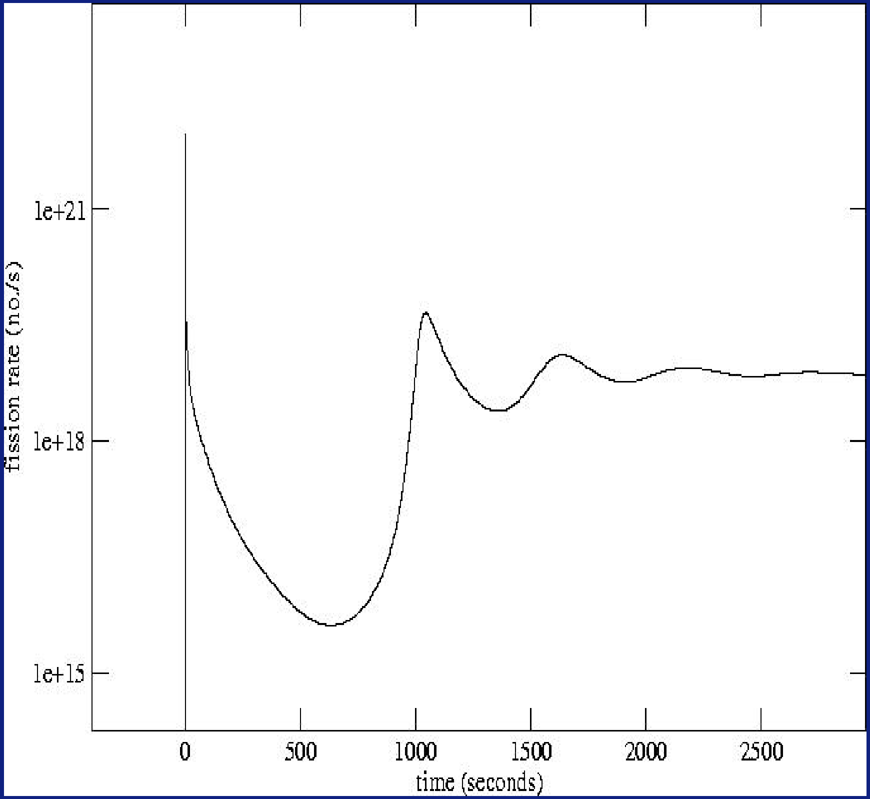
- Excessive peak temperature is above 1600 degrees C and the equilibrium temperature is above 1100 degrees C
- Equilibrium power 770 MWt

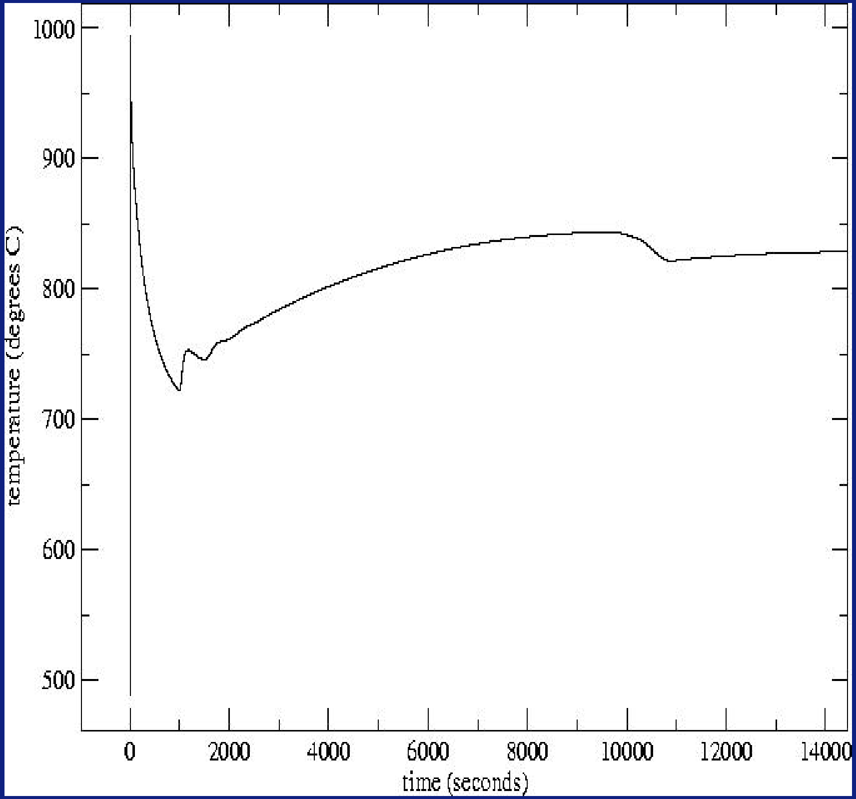
Transient analysis – variations in power removal

Variation of coolant flow

- Restart with lower flows
- Lower coolant flow – lower power – higher temperature – longer time constant
- Changes of coolant flow during operation
- Representative – sinusoidal variation - zero to 100% of design flow
- Mean output – compared with that from equivalent steady input

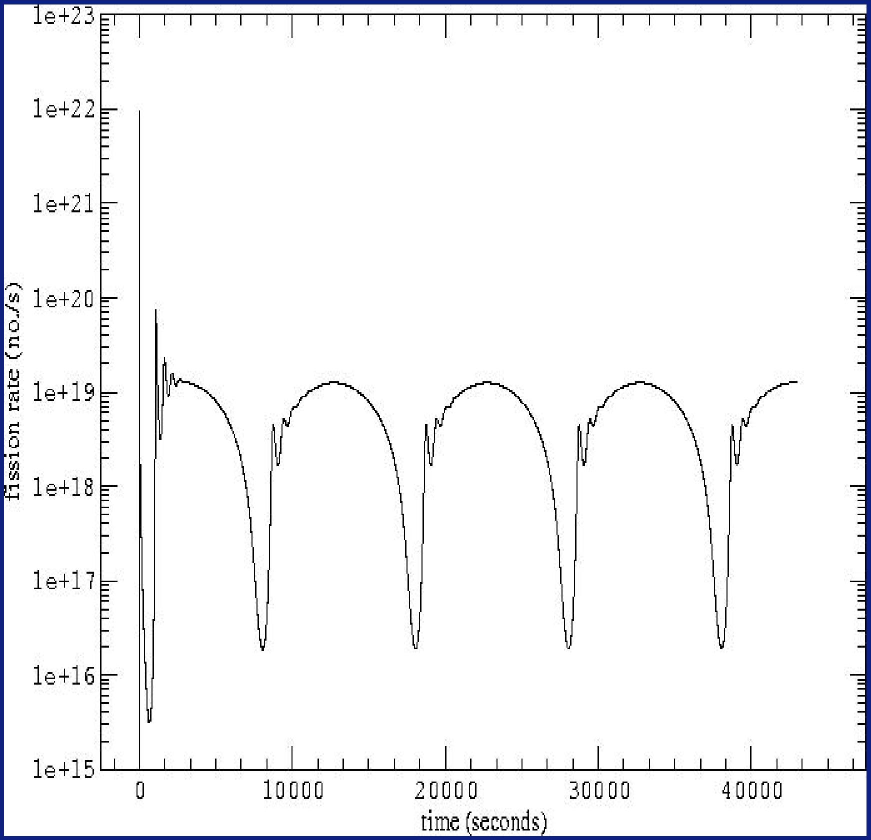
Lower coolant flow, 220 m/s inlet velocity - fission rate and temperature versus time

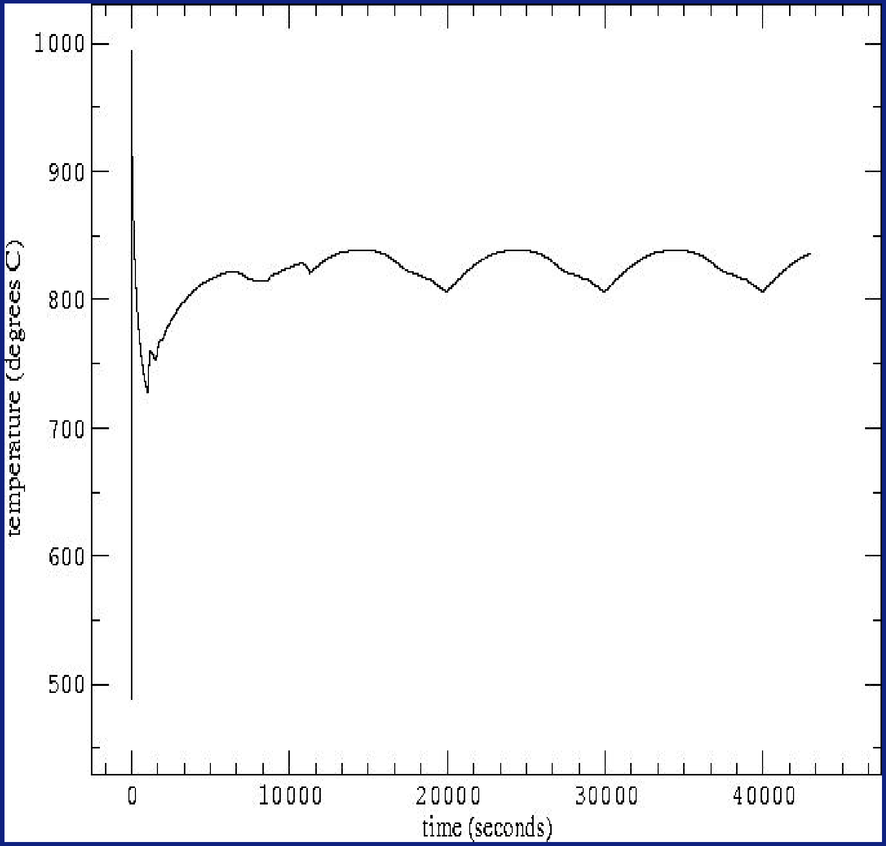




- 50% of design inlet velocity
- Lower power – higher temperature – longer time constant

Varying coolant flow, zero to 440 m/s – period 10000s - fission rate and temperature versus time





- fission and temperature follow the coolant flow variation, same frequency
- mean temperature, mean fission are the same as with a steady 220 m/s
- spatial distributions resemble the profiles in the reference case

Transient analysis – kinetic response

Long periods – 10000s or 1000s

- Mean fission rate and temperature comparable with steady equivalent

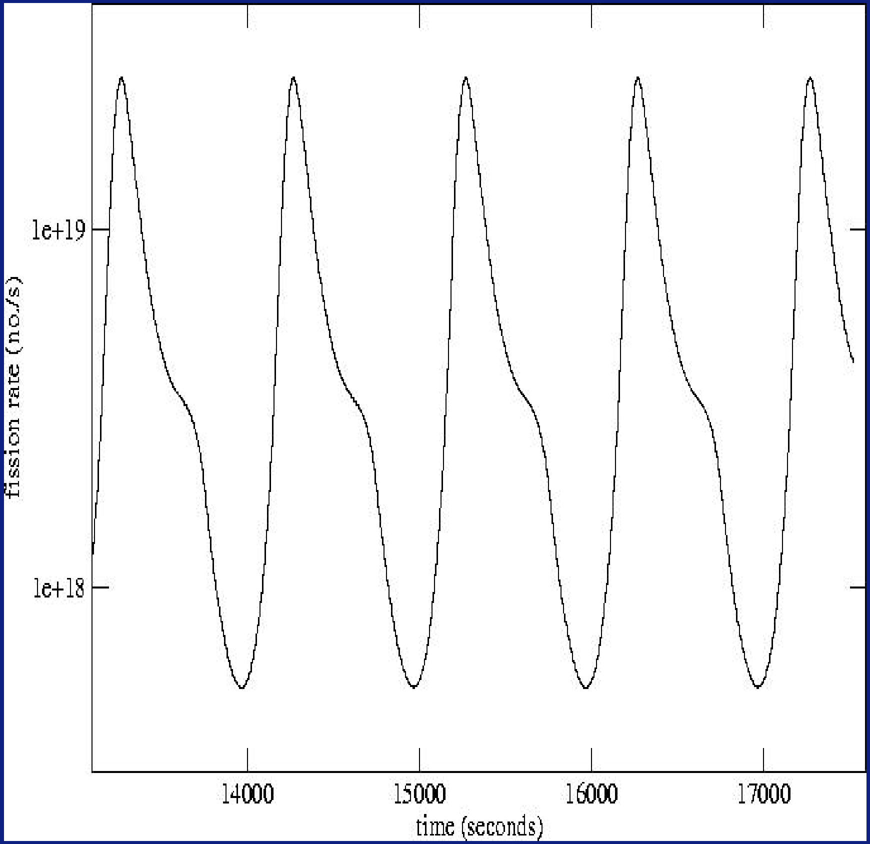
Power spectrum – 1000s period

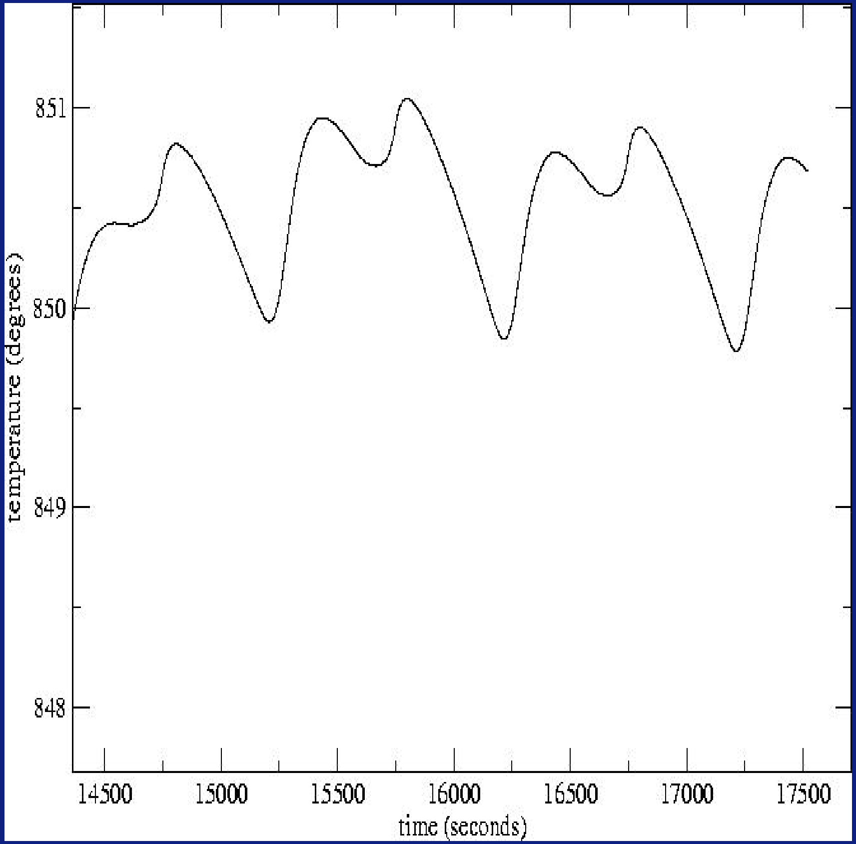
- Frequencies – multiples of $10^{-3}s^{-1}$

Short periods - 10s or 100s have also been investigated with the following results

- Mean fission rate reduced by about 50%
- Fission and temperature regions coincide (as in the beginning of restart transient)

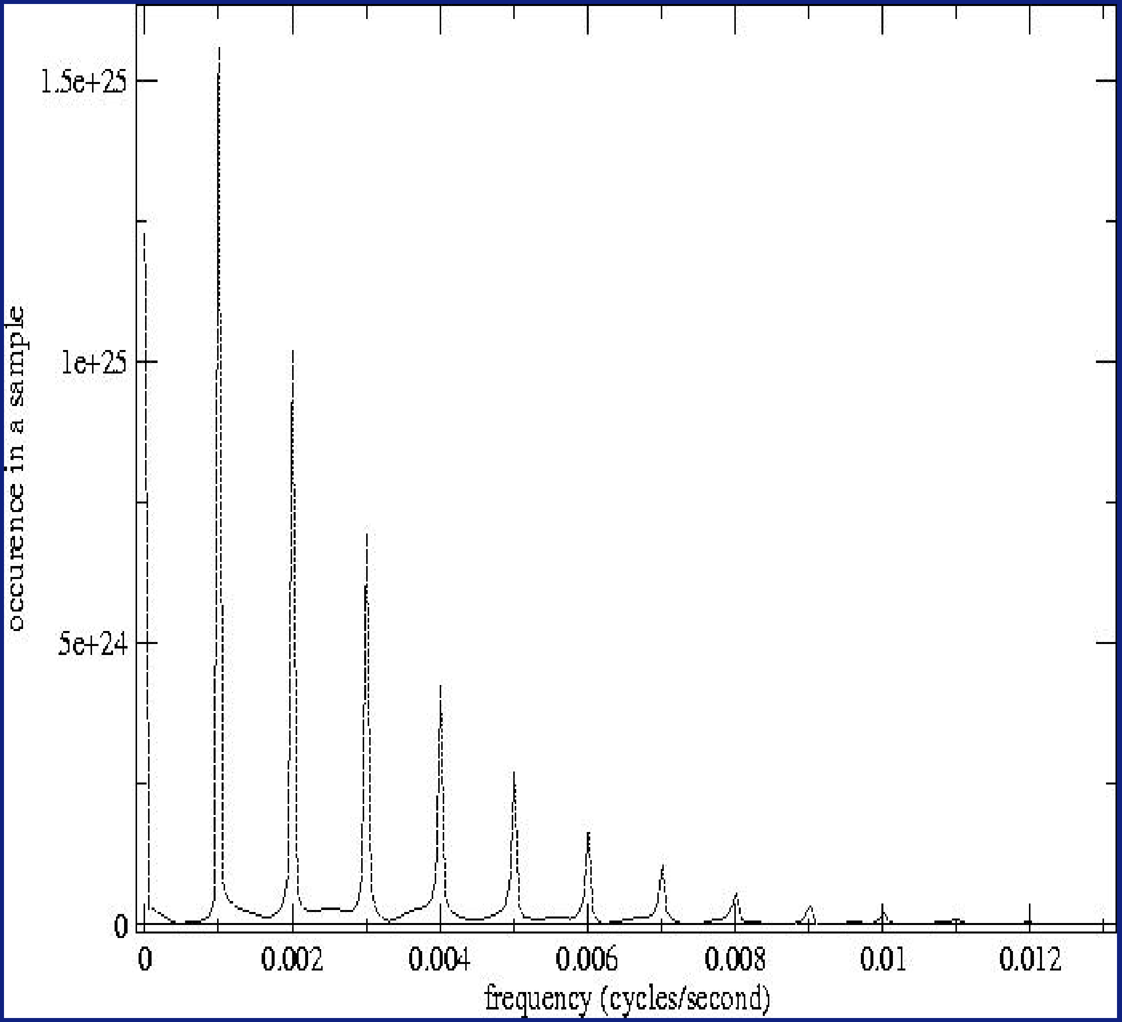
Varying coolant flow, zero to 440 m/s – period 1000s - fission rate and temperature versus time





- Fission and temperature – additional response frequencies (following slide)
- Mean temperature, mean fission reduced slightly compared with a steady 220 m/s

Varying coolant flow, zero to 440 m/s – period 1000s - fission rate – frequency response

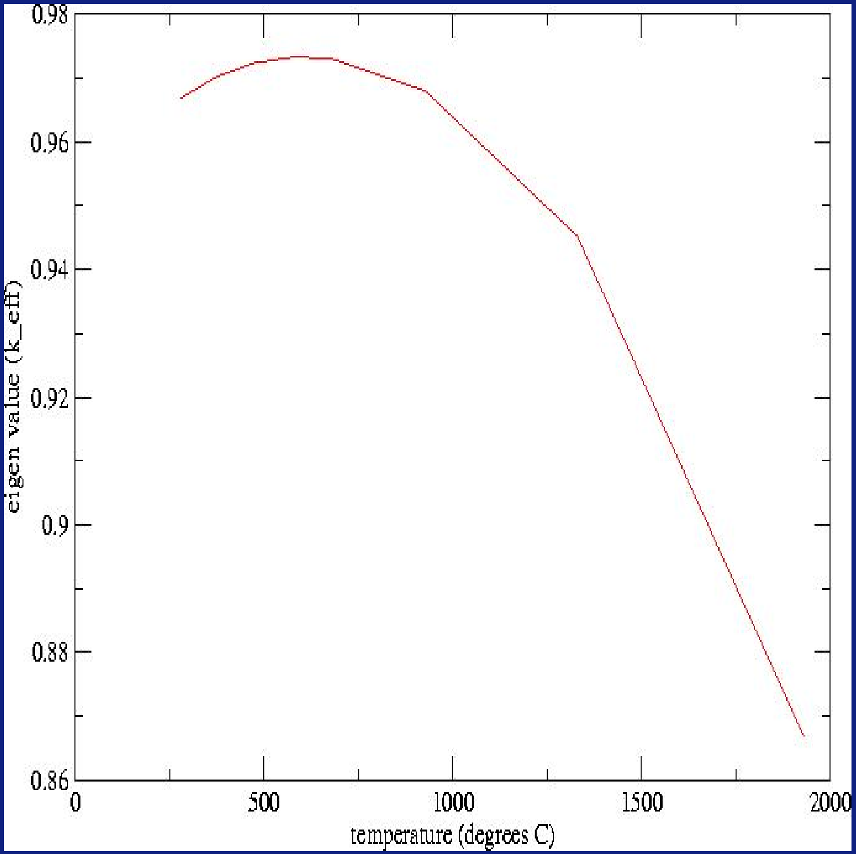


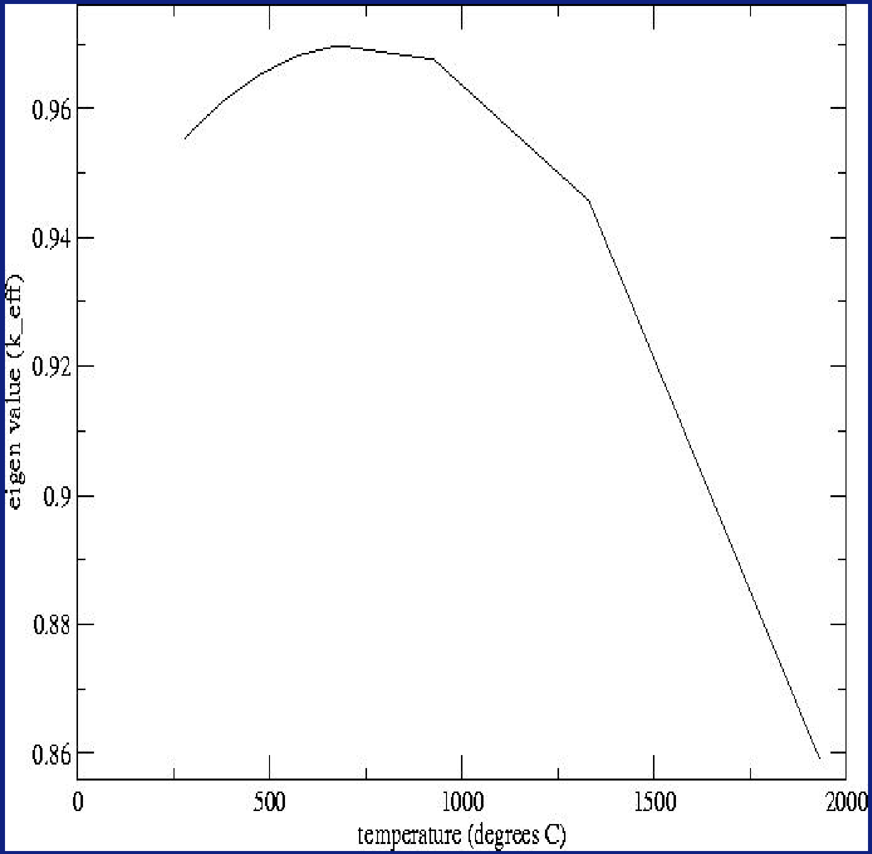
- Spectrum of frequencies obtained by Fourier transform of the fission rate variation over several cycles, after the initial transient
- Dominant frequency is the imposed 0.001 cycles/s. The response also contains integer multiples of this frequency.

Irradiated fuel

- The reactivity as predicted by our model is checked against the design burn up of an actual proposed reactor
- 95000 MWd/t (the discharge burn up with design initial enrichment)
- Alternative 5% initial enrichment - 47500 MWd/t
- Reactivity – variation with temperature
  - Increases at first at lower temperatures and then decreases again
  - Nevertheless there are no excessive temperatures
- Neutron absorption by fission products compensated by simulation of mostly withdrawn control rods
- Results in - stable reactor – smooth transients

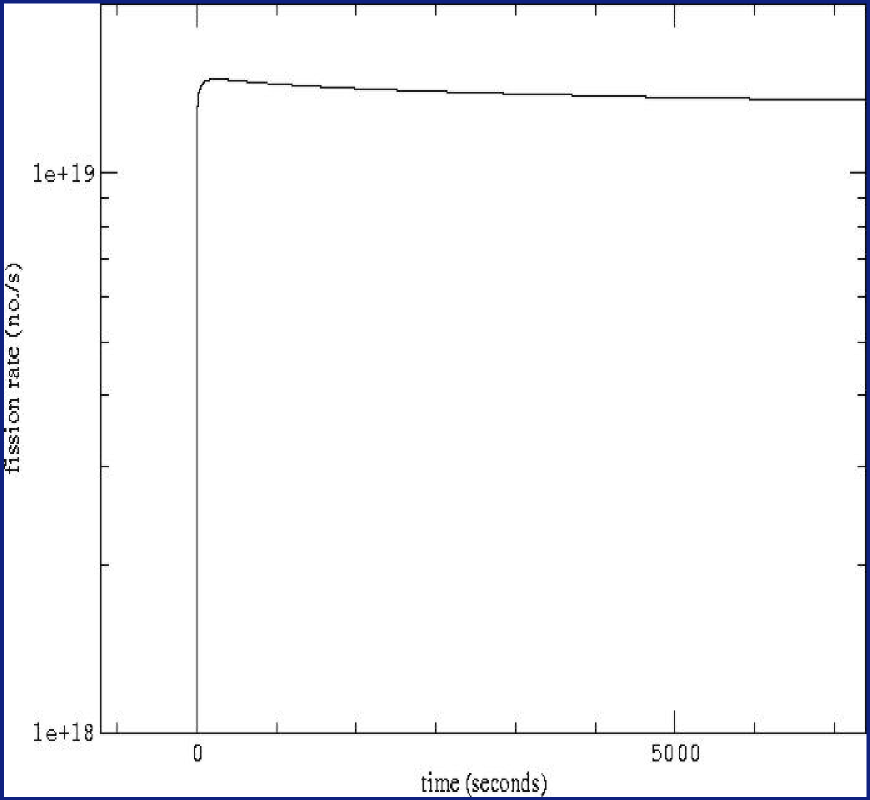
Eigenvalue versus temperature with irradiated fuel
- 95000 MWd/t burn up (9.6% initial enrichment)
- 47500 MWd/t burn up (5.0% initial enrichment)

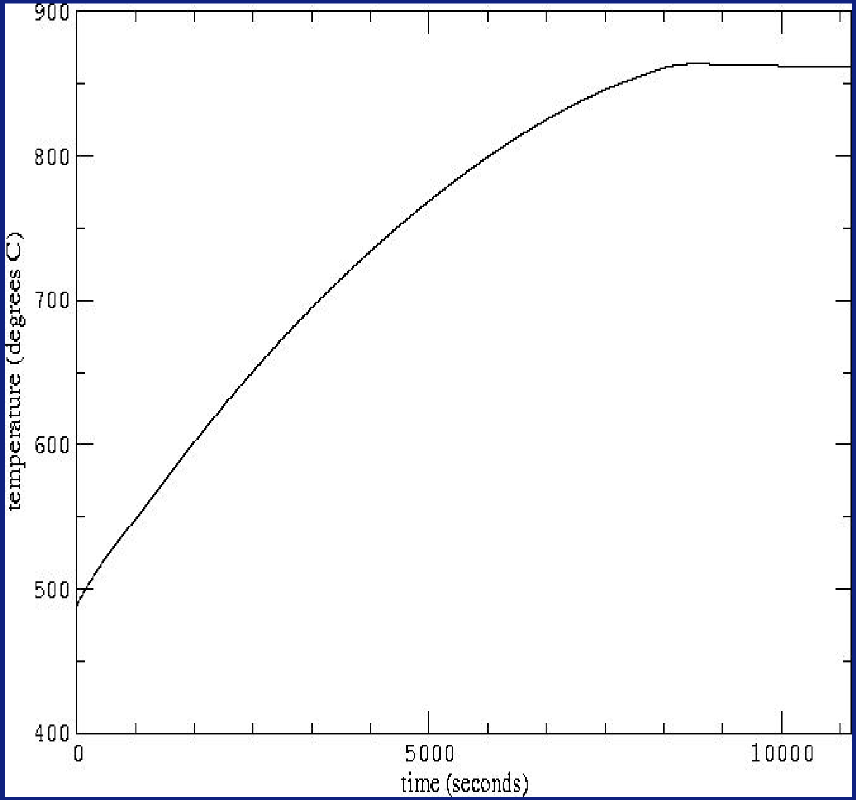




- criticality increases at first at lower temperatures and then decreases
- spontaneous fission is omitted in this static calculation - misleading apparently low eigenvalues

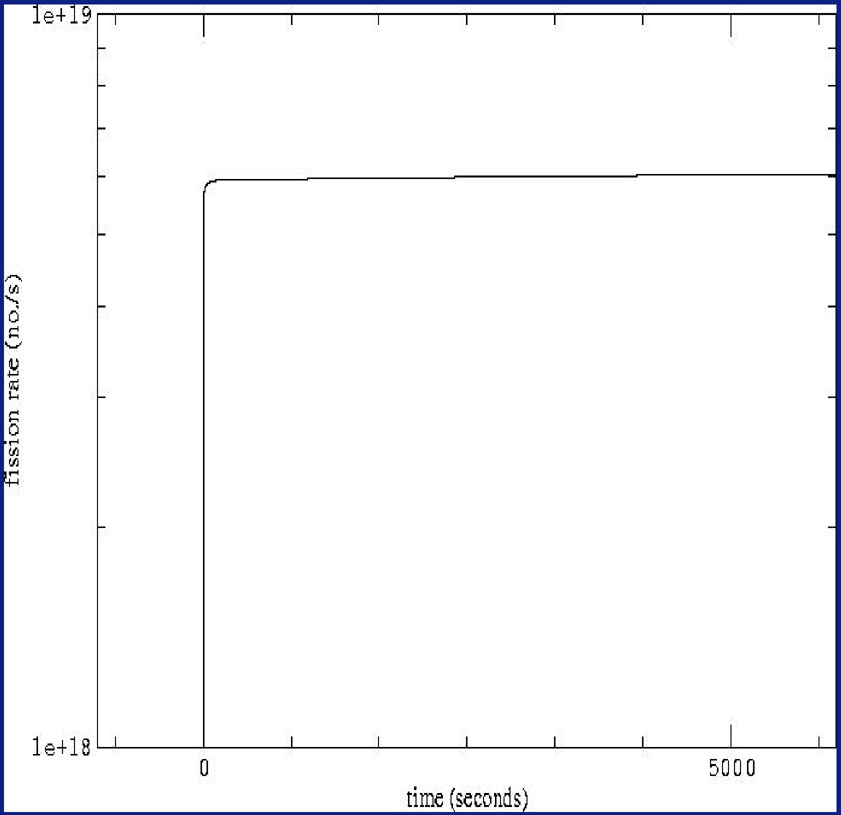
Irradiated fuel – 95000 MWd/t burn up (9.6% ^{235}U initial enrichment) - fission rate and temperature versus time

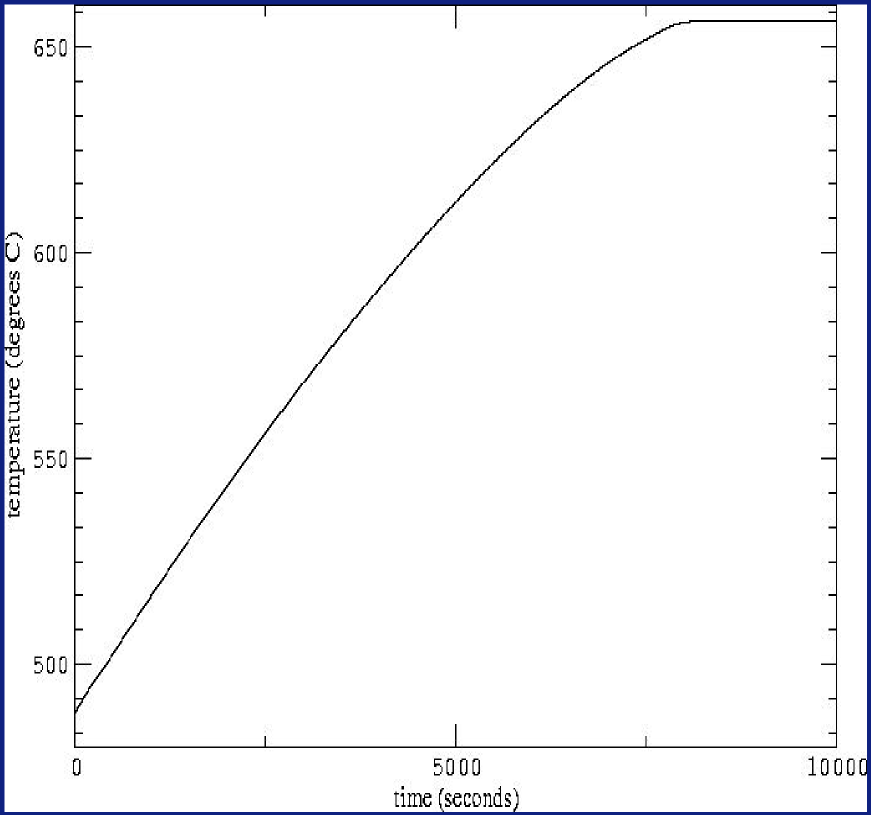




- Neutron absorption by fission products
- Transients are much smoother than with fresh fuel
- About 400 MWt at equilibrium

Irradiated fuel – 47500 MWd/t burn up (5.0% initial enrichment) - fission rate and temperature versus time





- Neutron absorption by fission products
- Transients are much smoother than with fresh fuel
- About 200 MWt at equilibrium

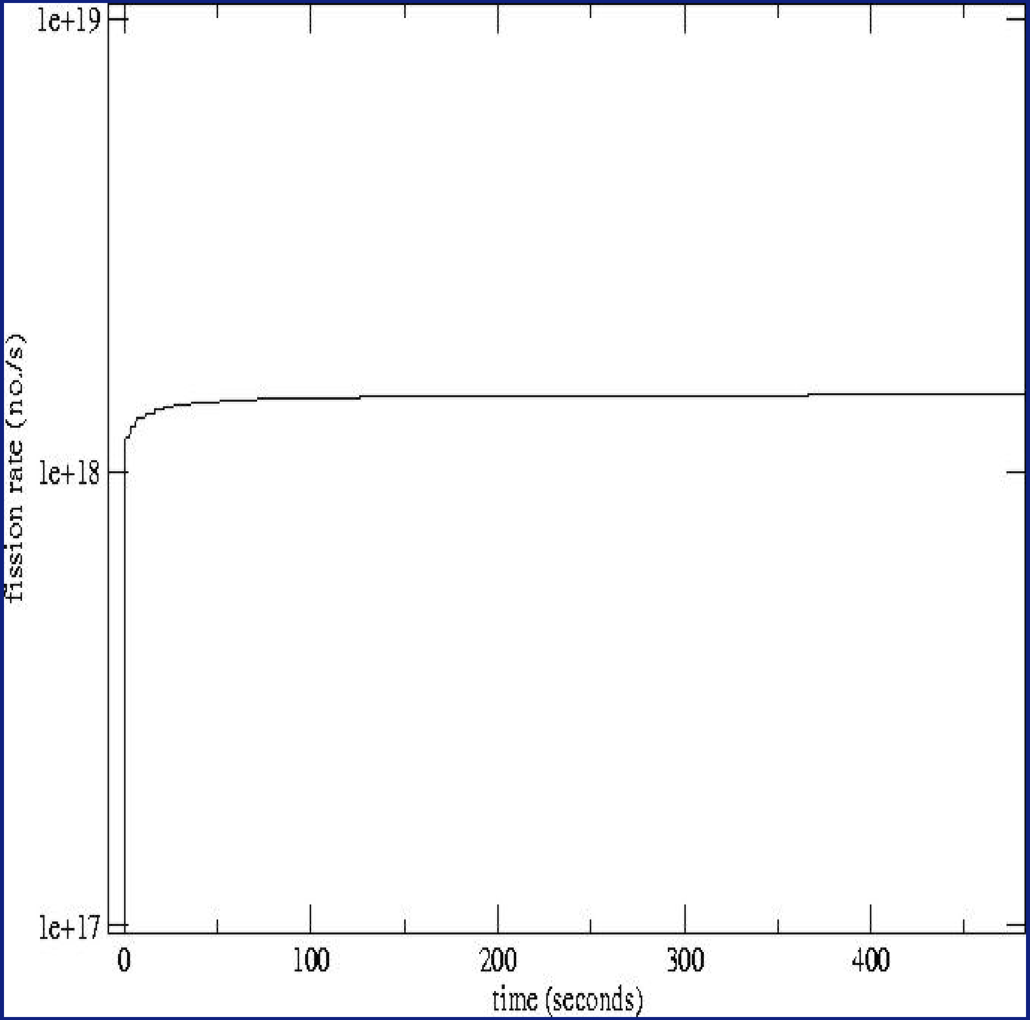
Spontaneous fission

- Spontaneous fission (simulated by spatially-uniform steady-state source)

- Spontaneous fission of ^{238}U in fresh fuel

- Spontaneous fission of curium in irradiated fuel
  - Actinide concentrations calculated by WBRNUP module in WIMS8A
  - Amplified effect on total fission rate

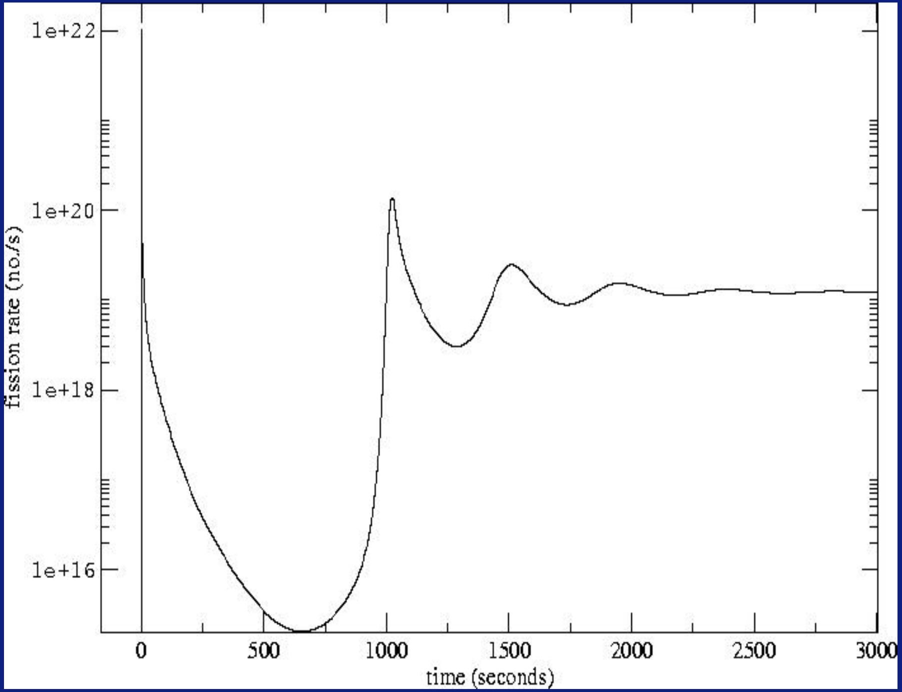
Induced fission rate at 95000 MWd/t (sensitivity to estimate of spontaneous fission)

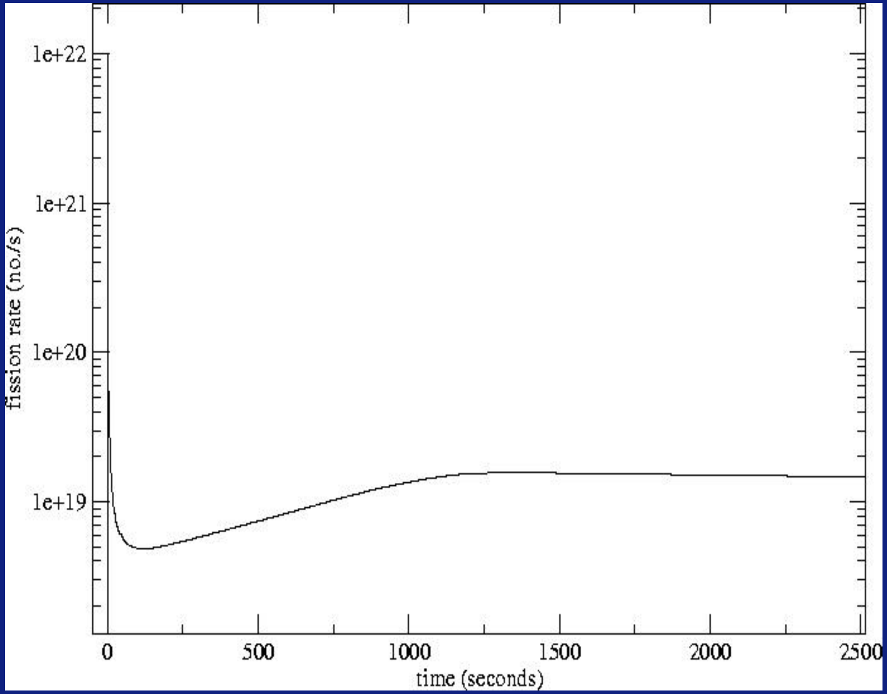


- Estimated neutrons from spontaneous fission in previous slide with this burn up -10^{10}n/s
- Power was 400 MWt (induced fission rate 1.25×10^{19} s^{-1})

- Assumed spontaneous fission in this case is reduced - 10^9n/s
- Induced fission rate reduces to 1.5x1018 s^{-1} (50 MWt)

Induced fission rates from fresh fuel (sensitivity to added steady neutron source)





- Graph on left – induced fission rate with1.5×10^3 neutrons/s from ^{238}U spontaneous fission in reference case
- Graph on right – added 4×10^8 neutrons/s steady source
- Transient behaviour becomes more stable
- Little amplification - Induced fission rate increases by less than 20%

Conclusions and discussion

- Radiative heat transfer makes a negligible contribution
- The reactor is stable
- At normal power level settings, a severe restart transient need not lead to excessive temperatures.
- The establishment of equilibrium temperatures and fission rates is a comparatively slow process, with time constants 100 to 1000 seconds

Conclusions and discussion

- Optimum mean power is maintained during a transient only when the time constant is long, for example 10000 seconds
- Long burn up is feasible, possibly 95000 MWd/t throughout the fuel in the reactor
- Lower initial enrichment may be feasible
- The simulation of a superimposed steady source (for example from spontaneous fission of products of irradiation) has a surprising effect

Discussion - options for future consideration

- Simulation of heat transfer within a pebble
- Improved simulation of turbulent coolant flow around a pebble
- Verification of spontaneous fission in irradiated fuel and its effect on induced fission