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ANS Winter Meeting 2016
Point Kinetics Modelling of Decay Heat and the Xenon Effect

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Las Vegas, 8th November 2016

EPSRC
Engineering and Physical Sciences Research Council

Introduction

- Simple point model of an Aqueous Homogeneous Reactor for medical isotope production

$$\frac{dP(t)}{dt} = \sum_{i=1}^{6} \lambda_i C_i(t) + \frac{\beta}{\Lambda}(\rho(t) - 1)P(t)$$

- Includes linear models for temperature feedback and void feedback due to radiolytic gas and steam and poisoning by Xe-135 and Sm-149

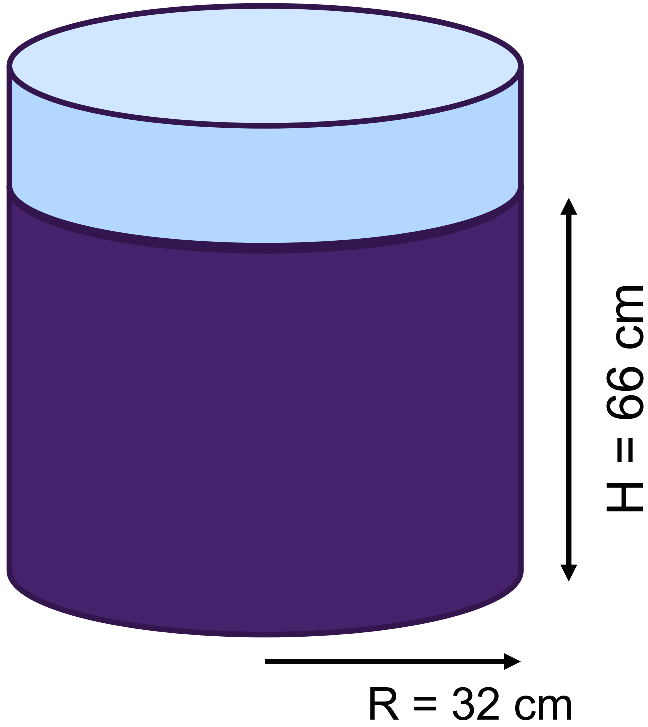
$$\rho(t) = \alpha_T\left(T_{FS}(t) - T_{FS,0}\right) + \gamma_V\left(V_G(t) - V_{G,0}\right) + \kappa_{XE}([Xe](t) - [Xe]_0) - \kappa_{SM}([Sm](t) - [Sm]_0)$$

- The constants κ_{SM} and κ_{XE} representing the reactivity impacts of Xe-135 and Sm-149 per unit concentration were estimated using MCNP
- An empirical equation based on the Way-Wigner formula is used to estimate the heat produced by radioactive decay as function of the power history

System Description

Characteristics

- Simple AHR consisting of an unreflected cylindrical vessel
- Vessel radius of 32 cm and fuel solution height of 66 cm
- Fuel solution is uranyl nitrate enriched to 20% U-235



Assumptions

- Single energy group
- 6 delayed neutron groups
- Xe-135 and Sm-149 remain in solution
- Fuel solution is well mixed

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Decay Heat

- Way-Wigner formula for radioactive decay heat

$$\frac{Q(T)}{P_0} = kT^{-1.2} \qquad T \geq 1s \qquad (1)$$

Q(t) is the decay heat

P_0 is the fission power before shutdown

k is a constant

T is the time since shutdown

- Adapting this equation for a variable power history

$$Q(t) = k \int_{-\infty}^{t_0} P_0 (t - t')^{-1.2} dt' + k \int_{t_0}^{t-1s} P(t')(t - t')^{-1.2} dt' \qquad (2)$$

t is the current time

t_0 is the simulation start time

- The integral is solved using a simple quadrature scheme and a term is added to account for decay products formed before simulation start

$$Q(t) = 5kP_0(t - t_0)^{-0.2} + k \sum_i P(t_i) \left((t - t_0) - i.\Delta t \right)^{-1.2} \Delta t \qquad (3)$$

$$(t - t_0) \geq 1s$$

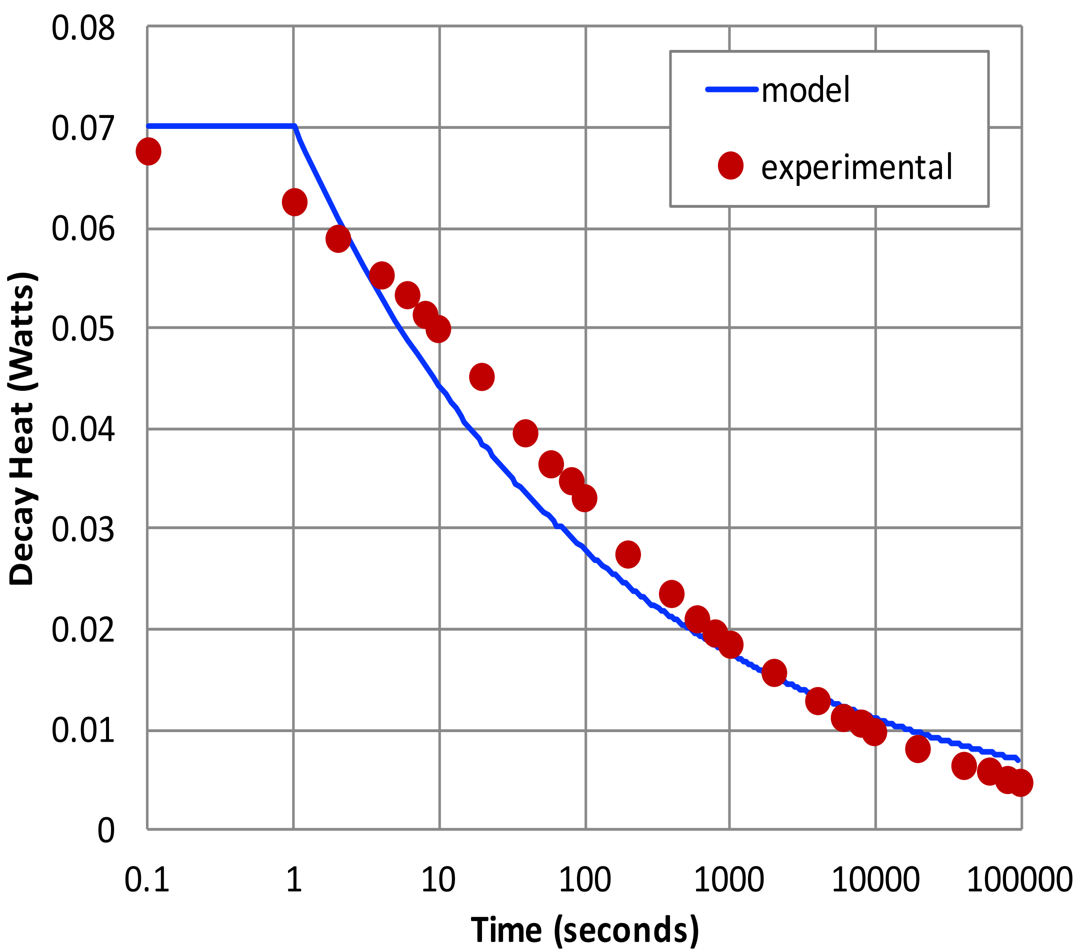
Decay Heat

- The constant k was evaluated by setting $Q(t = 1s)$ to 7% of the power before shutdown

- This gives a value

$$k = \left[\frac{0.014}{sec}\right]^{-0.2}$$

- The results of Eq (2) were compared to experimental data from a 1974 study [i] on uranium-fueled thermal reactors

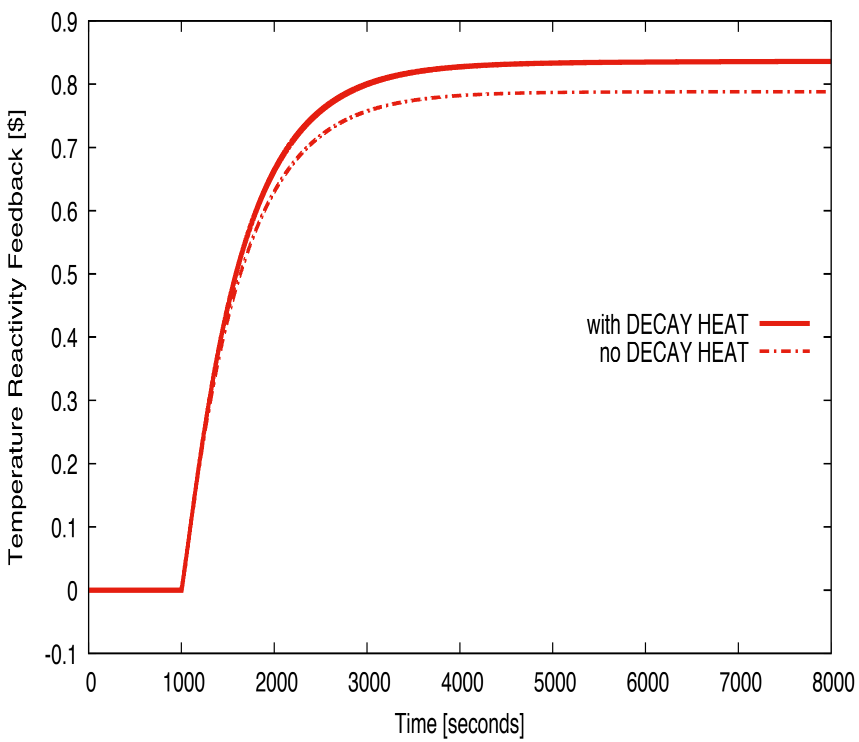


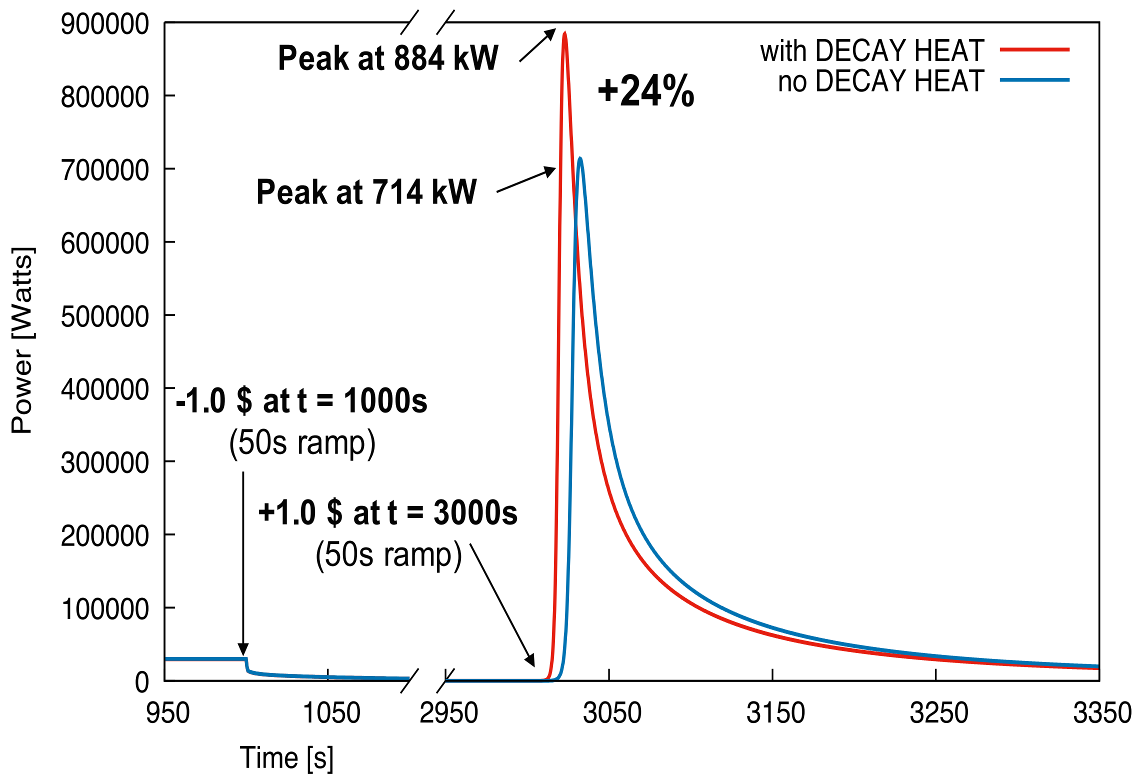
[i] Decay Energy Release Rates Following Shutdown of Uranium-Fueled Thermal Reactors, ANS-5.1/n18.6, American Nuclear Society, LaGrange Park, Ill., 1974, 298.

Decay Heat

Reactivity Insertion Following Reactor Shutdown

- Following shutdown, fuel solution temperature falls, leading to an increase in system reactivity. This process is enhanced when decay heat is included.
- Take a system operating at **30kW** : after 1h of shutdown the effect of decay heat adds **~ 4 cents** of reactivity

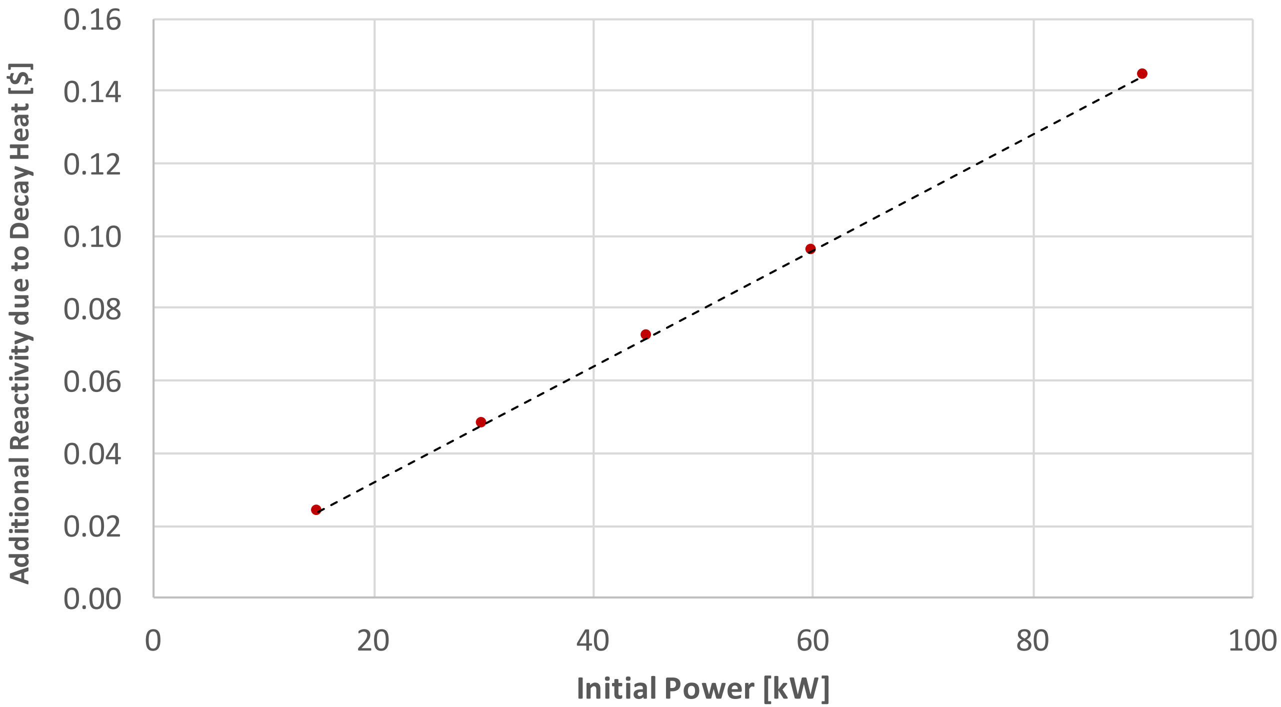




Decay Heat

Increased Reactivity due to Decay Heat

- The added reactivity at the moment of restart is proportional to the steady-state power of the reactor prior to shutdown
- Chart shows the maximum (at t = ∞) reactivity contribution of decay heat as a function of reactor power prior to shutdown



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Xenon Effect - Introduction

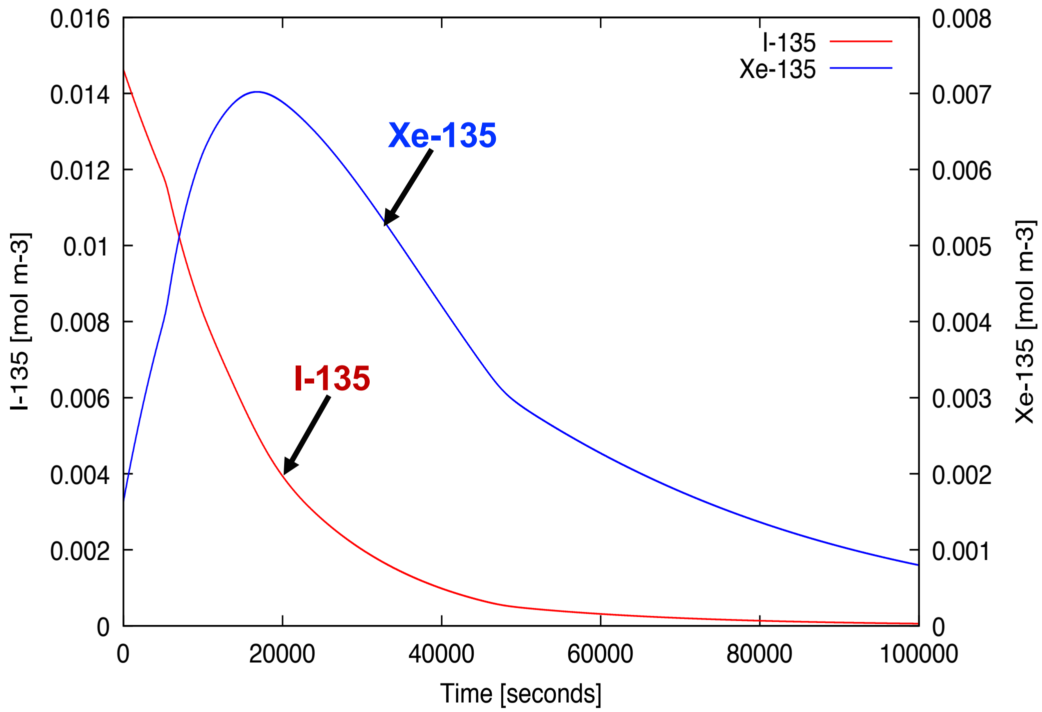
Xenon Effect in a PWR

- High neutron flux >> 10^{12} neutrons $cm^{-2}\ s^{-1}$
- Number density of Xe-135 is flux-independent while I-135 number density continues to increase with increasing flux

$$\frac{dXe(t)}{dt} = \frac{\gamma_{Xe}\Sigma_f\phi(t)}{N_A} + \lambda_I I(t) - \lambda_{Xe}Xe(t) - \sigma_{a,Xe}\phi(t)Xe(t)$$

$$\frac{dI(t)}{dt} = \frac{\Gamma_I\Sigma_f\phi(t)}{N_A} - \lambda_I I(t) - \sigma_{a,I}\phi(t)I(t)$$

- Xenon number density after shutdown follows a familiar profile, increasing at first before eventually falling to zero



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Xenon Effect - Introduction

Xenon Effect in a PWR

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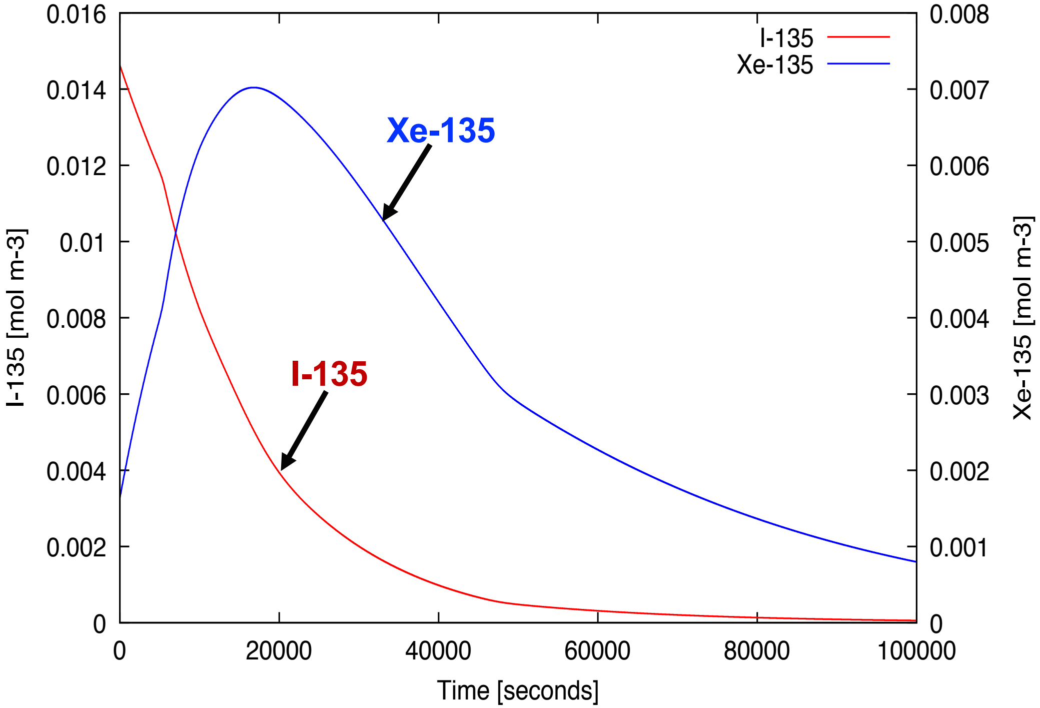

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Xenon Effect - Introduction

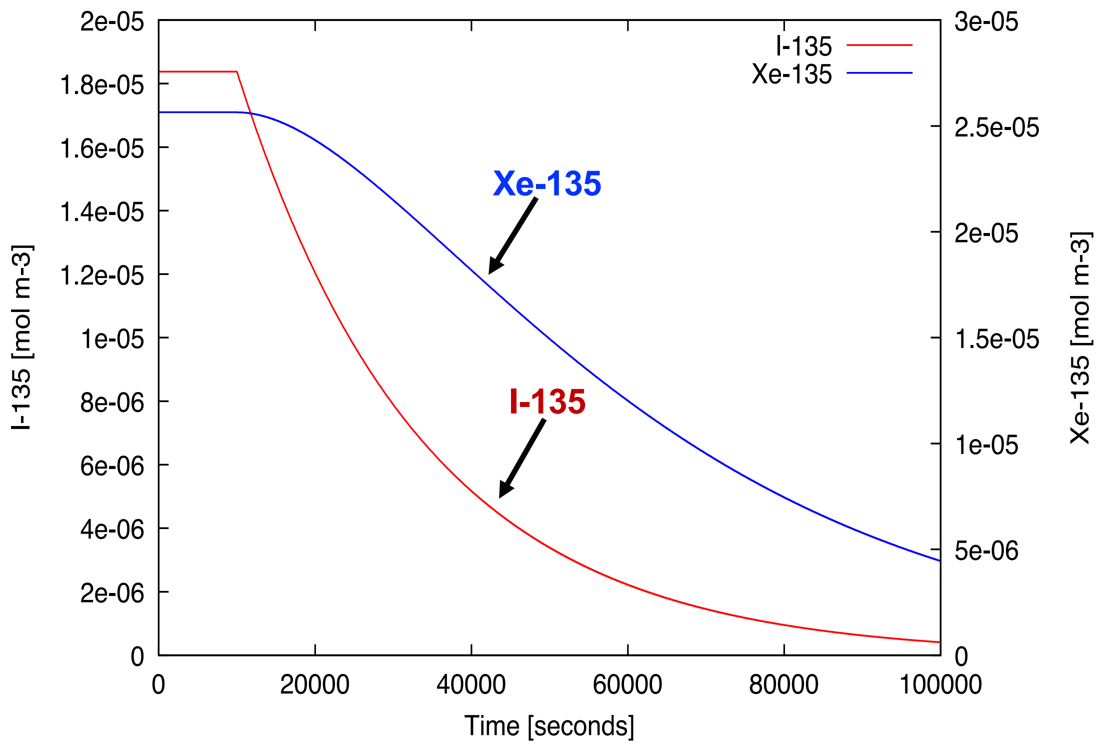
Xenon Effect in an AHR

- Comparatively low neutron flux < 10^{12} neutrons cm^{-2} s^{-1}

- Bateman equations are dominated by the decay terms resulting in similar number densities of I-135 and Xe-135

- No increase in Xe-135 number density is observed following shutdown

- Number density of Xe-135 falls steadily resulting in a corresponding increase in system reactivity



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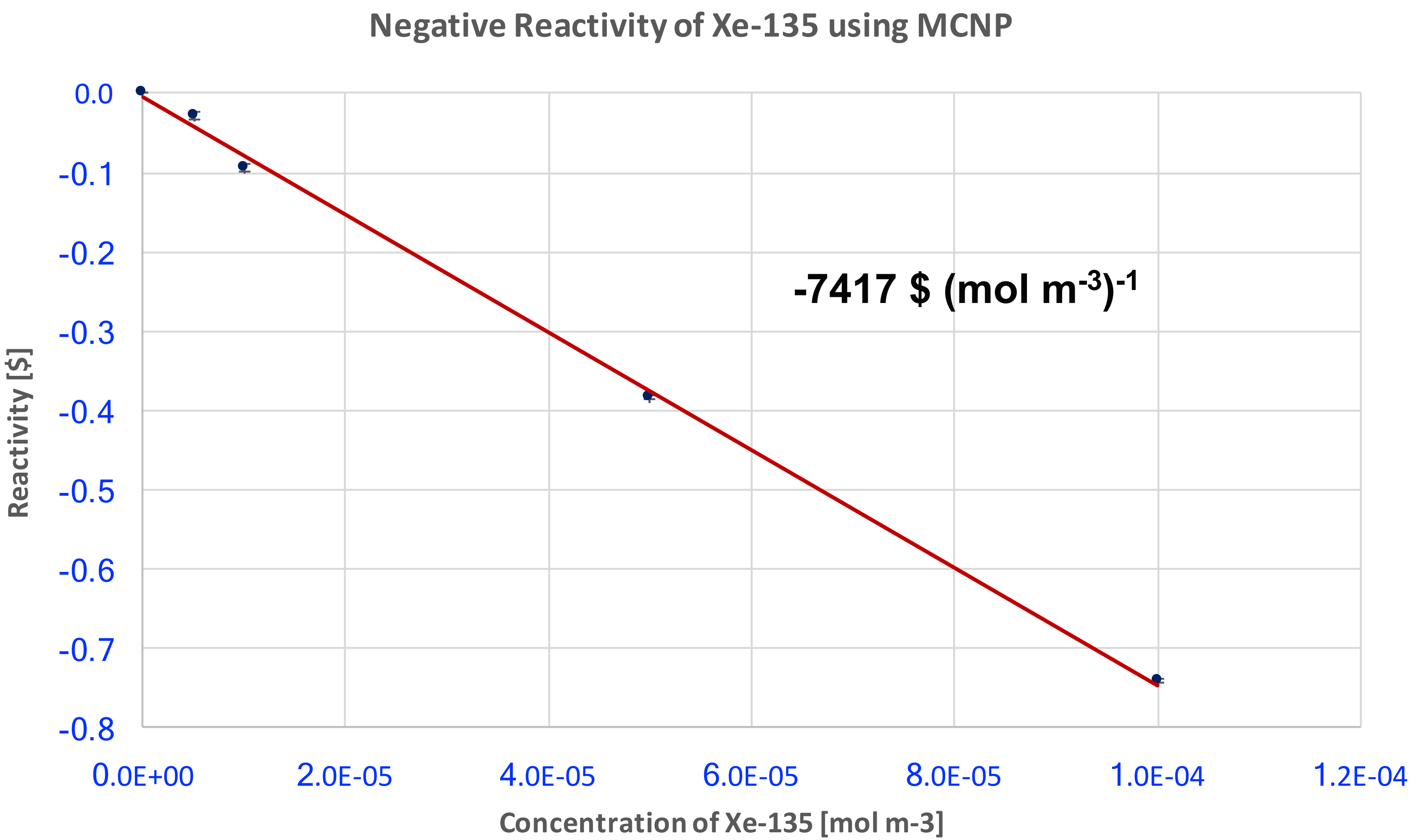
Quantifying the Negative Reactivity of Xe-135



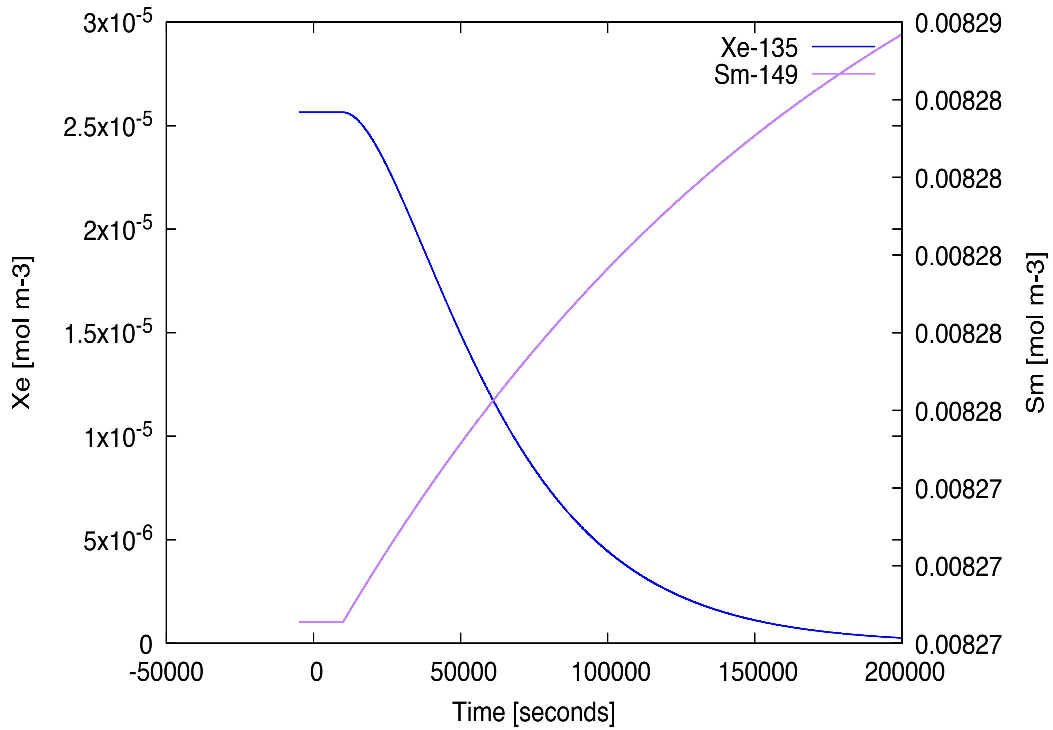
Xenon Effect

What about Samarium?

- During the hours following shutdown, the number density of Sm-149 increases towards a maximum value, introducing negative reactivity into the system

- The effect of Sm-149 is small compared to that of Xe-135 and offsets its effect very slightly

- Sm-149 has been included in the previous examples



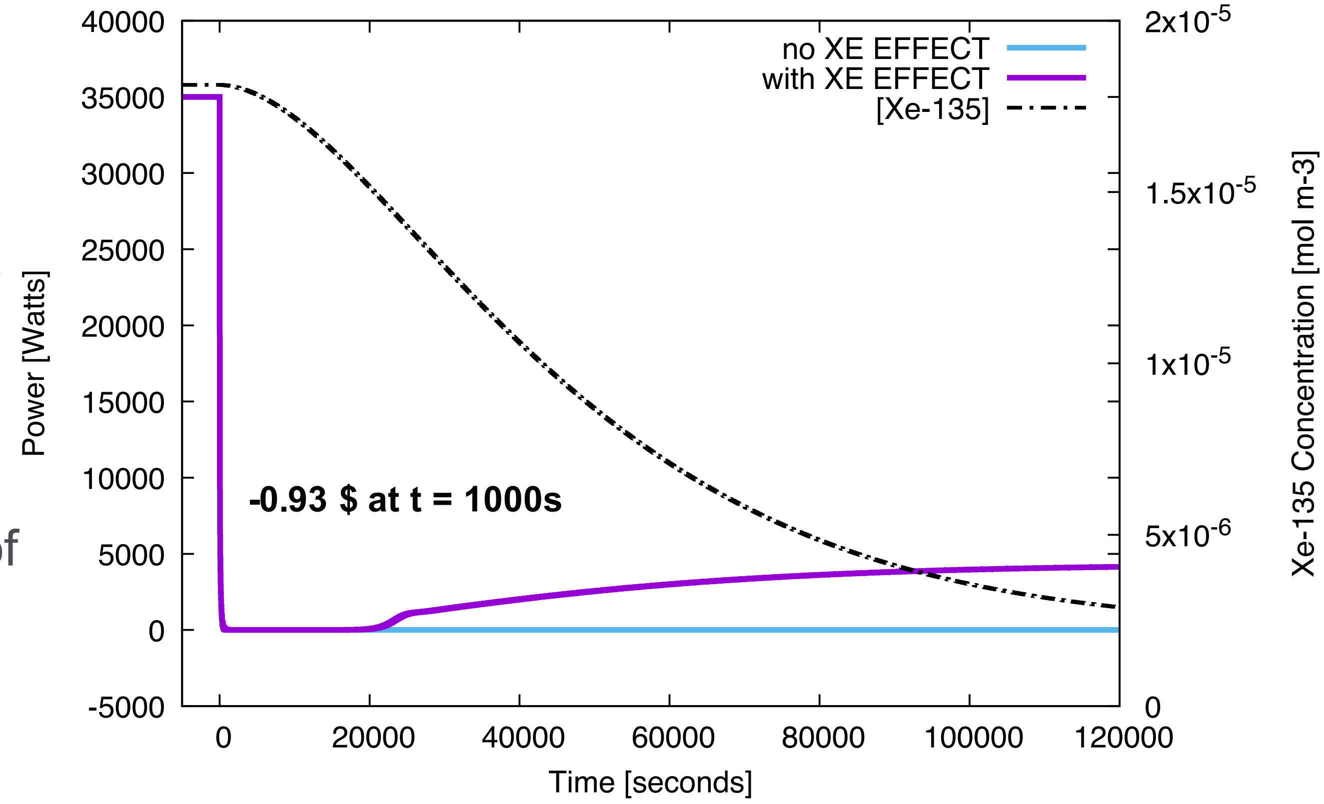
Xenon Effect – Spontaneous Restart in an AHR

Reactivity Insertion After Shutdown

- From an initial power of **35kW,** a reactivity insertion of **- 0.93$** was the minimum sufficient to produce a reactor shutdown

- A spontaneous restart due to the declining levels of Xe-135 is observed ~6 hours after shutdown

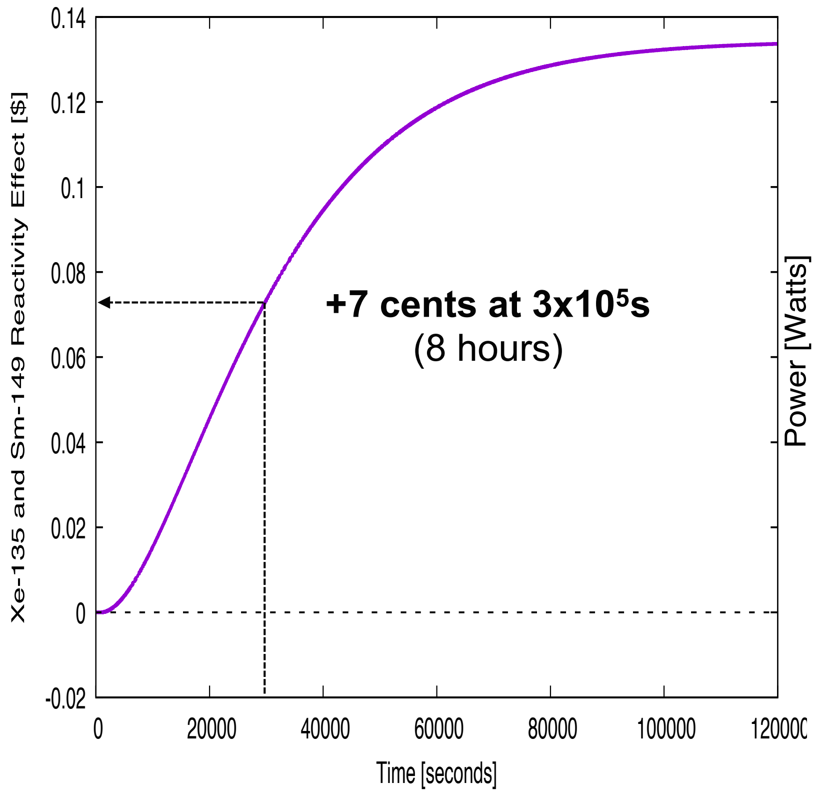
- Power continues to rise as the number density of Xe-135 falls

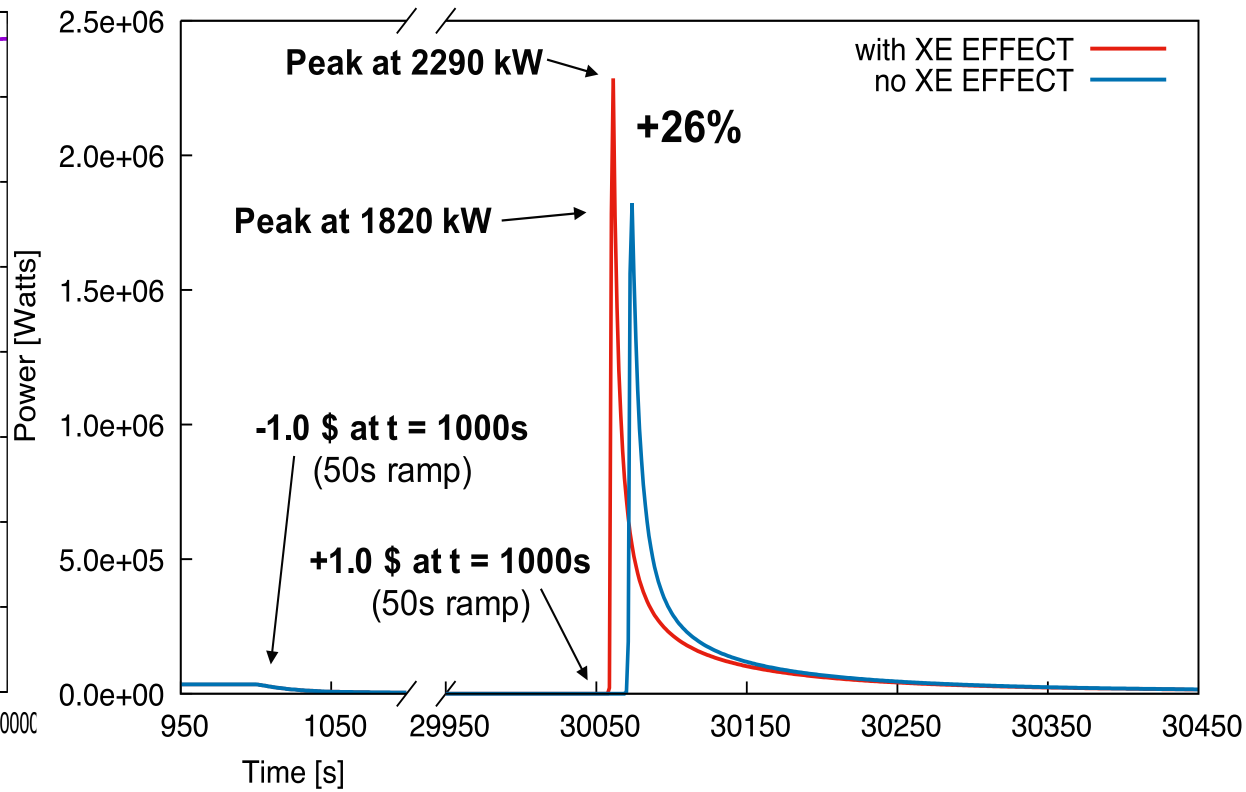


Xenon Effect – Shutdown Followed by Restart

Reactivity Insertion Following Reactor Shutdown

- Reactor is shutdown from an initial power of **35kW** by a reactivity insertion of **- 1.0$**

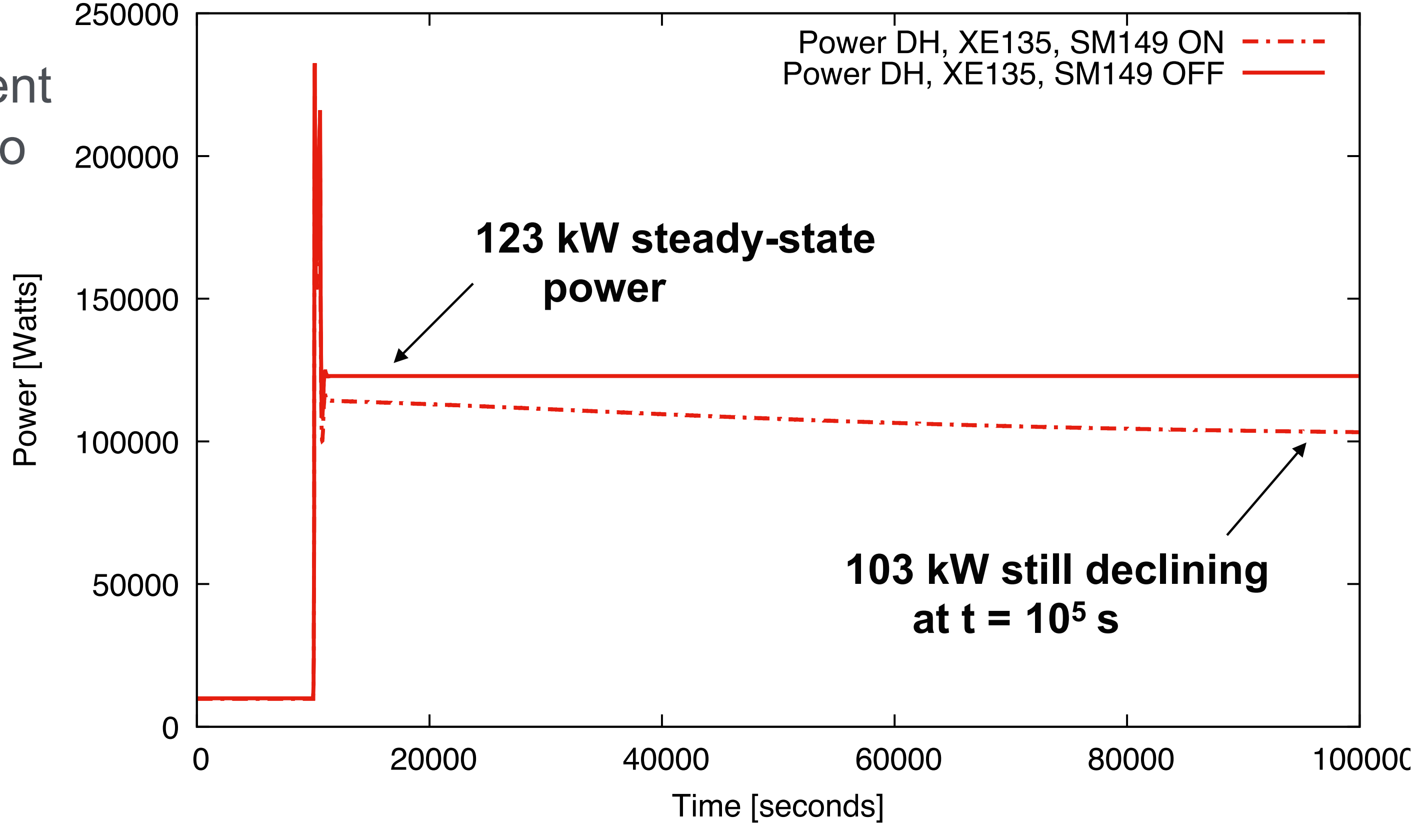




Combined Effect – Power Increase Transient

How about the combined effects of Xe-135, Sm-149 & decay heat?

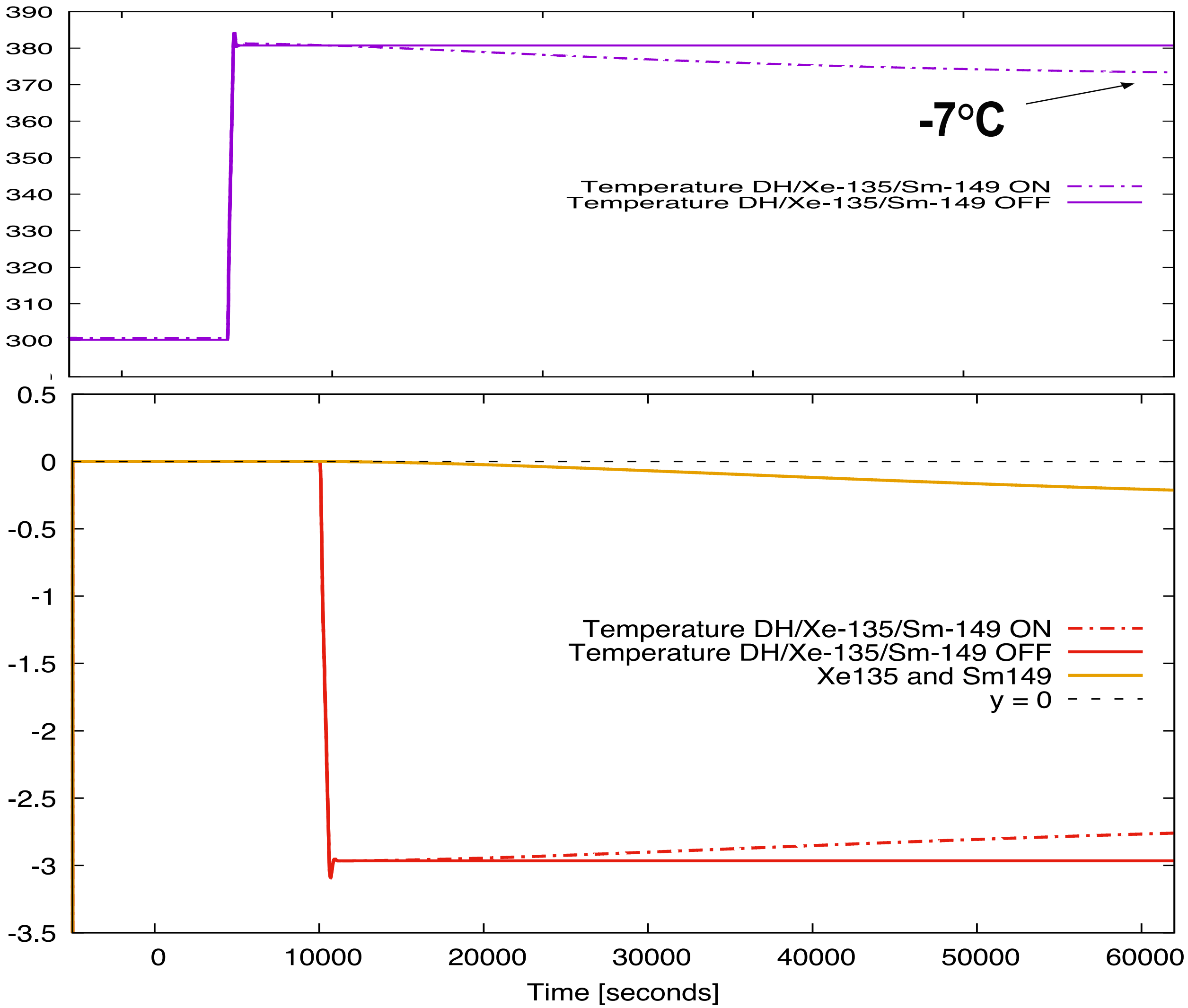
- AHR running with steady-state power of **10kW**
- Ramp reactivity insertion of **+3.0$ over 10 minutes**
- Power after transient diverges for the two models



Combined Effect – Power Increase Transient

Temperature [°C]

Reactivity [$]



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Conclusions

- A point kinetics model of an AHR for medical isotope production was formulated to include the effects of decay heat and Xe-135
- Both Decay Heat and Xe-135 were found to induce small changes in reactivity following a reactor shutdown with significant knock on impact on the dynamics of a reactor restart
- The effect of Sm-149 was also investigated but no significant effect was observed for the transients analysed
- Decay heat and Xe-135 were shown to have a significant impact on a point kinetics model used to predict the behaviour of an AHR during the period following a significant change in reactor power

Acknowledgements

The financial support of the UK Engineering and Physical Sciences Research Council (EPSRC) is gratefully acknowledged. I would also like to thank Emeritus Professor Mike Williams for his advice and guidance.