NUCE 2101: Final Exam

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Problem 1

Part A

K_{eff} is the effective growth or decay of the neutron population based on the prompt reactions. This block can be represented by basic physical quantities by using the six factor formula:

$$k_{eff} = \eta f p \varepsilon P_{FNL} P_{TNL}$$

where:

- η is the thermal neutron fission factor
- f is the thermal neutron absorption factor
- p is the resonance escape probability
- ε is the fast fission neutron production factor
- P_{FNL} is the fast non-leakage probability
- P_{TNL} is the thermal non-leakage probability

Part B

We start with a set of equations representing our neutron populations:

$$N_{in} = N_f$$
$$N_f = N_p + N_{decay} + S\Delta t$$
$$N_t = N_d + N_p$$
$$N_t = K_{eff} N_{in}$$

Now, how are these related? Well, the total number of neutrons is split between the neutrons that are prompt neutrons and those that are destined to become delayed neutrons. We can represent the fraction between the two as:

$$N_t = (1-\beta) K_{eff} N_{in} + \sum_{i=1}^{6} \lambda_i C_i \Delta t + S\Delta t$$

where

$$N_d = \sum_{i=1}^{6} K_{eff} \beta_i N_{in}$$

and

$$N_p = (1-\beta) K_{eff} N_{in}$$

Then we find the change in neutron population:

$$N_f - N_i = (1-\beta) K_{eff} N_i + \sum_{i=1}^{6} \lambda_i C_i \Delta t + S\Delta t - N_i$$

and take the 'derivative':

$$\frac{N_f - N_i}{\Delta t} = \frac{(1 - \frac{1}{K_{eff}} - \beta)K_{eff}N_i}{\Delta t} + \sum_{i=1}^{6} \lambda_i C_i + S$$

then after a little more substitution found in Fundamental Kinetics Ideas:

$$\dot{N}(t) = \frac{(\rho - \beta)N(t)}{\Lambda} + \sum_{i=1}^{6} \lambda_i C_i + S$$

and not forgetting our precursors:

$$\dot{C}_i(t) = \frac{\beta_i}{\Lambda} N(t) - \lambda_i C_i$$

Part C

The prompt jump assumption assumes that the speed of the prompt cycle is so fast that we can effectively ignore the dynamics of the prompt neutron effects. It is equivalent to us only using the outside loop, and not considering additions from N_p.

Part D

First, the number of prompt neutrons would increase dramatically. This would happen over the first hundreds of milliseconds. Then, over a much longer time horizon (seconds, minutes), the delayed number of neutrons would increase as the precursors catch up to the reactivity increase.

Part E

Power turning has to do with start-up rate and the rate at which the total neutron population is changing. For this diagram, turning means that $\dot{N}_f$ changes sign.

Problem 2

We can use the startup rate equation assuming $\dot{\lambda}_{eff}, S = 0$ to solve this problem:

$$SUR = 26.06[dpm - sec]\frac{\dot{\rho} + \lambda_{eff}\rho}{\beta - \rho}$$

To get from $10^{-6}\%$ to $10^{1}\%$ power in 50 minutes, we can find that:

$$SUR = \frac{1 - (-6)}{50}\frac{\text{decades}}{\text{minutes}} = 0.14\text{DPM}$$

We then plug in our values (assume $\dot{\rho} = 0$ with a step change):

$$0.14 = 26.06[dpm - sec]\frac{0 + 0.1\rho}{\beta - \rho}$$

$$0.14\beta - 0.14\rho = 2.606\rho$$

$$\boxed{\rho = 0.0509\beta}$$

Thus the correct answer is C.

Problem 3

Part A

The moderator temperature coefficient must be controlling power. With all other factors constant, the moderator temperature coefficient is the only thing adding negative reactivity to the system.

Part B

$$\rho_{net} = \frac{\partial \rho_{net}}{\partial T} dT + \frac{\partial \rho_{net}}{\partial H} dH + \frac{\partial \rho_{net}}{\partial Poison} dPoison + \frac{\partial \rho_{net}}{\partial Power} dPower$$

But with ignoring fuel temperature feedback and no boron effects,

$$\rho_{net} = -10[\frac{\text{pcm}}{^\circ F}]dT + \frac{\partial \rho_{net}}{\partial H} dH$$

Given that there is no poison or fuel temperature feedback, and steam demand does not change, reactor power will stay the same after the control rod drops into the core. Only moderator temperature can change reactivity in this problem.

Part C

$$0 = -10[\frac{\text{pcm}}{^\circ F}]dT - 100[pcm]$$

$$dT = \frac{100[pcm]}{-10[\frac{\text{pcm}}{^\circ F}]}$$

$$dT = -10^\circ F$$

$$\boxed{T_{final} = 577^\circ F}$$

Part D

Power will remain the same, and therefore steam pressure should remain the same as well.

Problem 4

The power trajectory would be exponentially positive as the reactor would become prompt critical. One would analyze the transient by using a robot to examine the reactor soup after the steam bomb goes off in the containment.

But being serious, one may examine the power transient by evaluating ρ over time using the partial addition formula we used in the last problem. Because the reactor is prompt critical, we can essentially ignore the delayed neutrons. The point kinetic equations can also be used, but honestly a decent approximation will be a first order exponential growth with time constant derived from the prompt neutron lifetime.

For a high enrichment fuel, the growth of the curve will be impeded by basically nothing. Fuel and moderator temperature effects will be minimal. For a low enrichment fuel, moderator temperature and fuel temperature effects will slow the exponential growth as temperature increases, but depending on reactor design, will not prevent catastrophic failure.

Problem 5

Part A

Xenon-135 is primarily produced in a reactor as a fission product or by the decay of Iodine-135, which is a direct product of uranium fission. Xenon-135 decays naturally over time or can absorb neutrons to become other isotopes with a much smaller neutron cross section.

Part B

Xenon-135:

The second reactor will have a lower concentration of xenon-135 in the reactor core. Xenon-135 will be generated by the decay of iodine-135, but will also decay naturally to other elements over time as well as being removed through neutron absorption. If the reactors are shut down after a year, the xenon-135 in both will spike with the full power reactor having a larger spike, and it will take longer for the 100% power reactor to be able to be restarted until the extra xenon-135 has had time to decay away.

Samarium-149:

The second reactor will also have a lower concentration of samarium-149 for a similar reason as the xenon-135 case. There will be less fissile products to decay into samarium-149 in the low power reactor. If the reactors are powered off, however, both reactors will develop additional samarium-149 concentrations that will not decay away naturally as samarium-149 is stable. It will take more reactivity to restart the full power reactor from shutdown as the samarium-149 concentration will be much higher than the low power reactor.

Part C

Xenon is the more challenging poison to deal with. First, xenon has a much larger cross section and has a more significant effect on reactivity than samarium. Second, xenon-135 is not a stable element, and thus has decay effects when the reactor is shut down. As such, the amount of time since shutdown is an important factor to consider when restarting a reactor with consideration to xenon. A miscalculation on xenon concentration can lead to a too-large insertion of reactivity on start-up, which doesn't exist in the same way with samarium as samarium doesn't decay during shutdown. Finally, xenon is a much faster response dynamically compared to samarium. Xenon-135 can quickly change concentrations in hours, while samarium-149 concentrations can take weeks to change significantly. Human operators are much more likely to be able to cope with the longer time constant poison versus misjudging the small time constant effects of xenon.

Problem 6

Part A

Withdrawing the control rods will move power production towards the upper half of the core. Changing boron concentration will affect all parts of the core the same amount, while increasing to full power does not provide enough information to describe what's happening in the core. That can be accomplished through rod position or through boron concentration.

Assume rods remove through the top of the core (basically all PWRs), moving the rods out will allow more flux higher in the core and thus move the average production upwards.

Part B

This happens because the moderator is the coolant, and the coolant is colder as it enters the core at the bottom of the core. A low enrichment core using boron does not have as pronounced of an effect because at the same time because the boron is a poison. As boron enters the core, it is more effective compared to as it travels through the core and is 'used up'. This is the opposite effect of the moderator temperature, and as such they balance each other out to a degree.

Problem 7

Part A

Starting with the point kinetics equations with one delayed precursor group, using the prompt jump approximation where prompt neutrons reach equilibrium instantly:

$$\frac{dN(t)}{dt} = \lambda C(t)$$

$$\frac{dC(t)}{dt} = \frac{\beta}{\Lambda}N(t) - \lambda C(t)$$

Using appropriate numerical values for a PWR with low enrichment U-235 fuel:

- $\beta = 0.0065$ (650 pcm)
- $\Lambda = 5 \times 10^{-5}$ s (50 μs)
- $\lambda = 0.08$ s^{-1}
- $\rho = +0.0005$ (+50 pcm inserted)

The complete system of equations describing reactor power as a function of time is:

$$N(t) = \Lambda \frac{\lambda C(t)}{\beta - \rho}$$

$$\frac{dC(t)}{dt} = \frac{\beta}{\Lambda}N(t) - \lambda C(t)$$

Substituting N(t) into the precursor equation:

$$\frac{dC(t)}{dt} = \frac{\beta\lambda}{\beta - \rho}C(t) - \lambda C(t) = \lambda C(t)\left(\frac{\beta}{\beta - \rho} - 1\right)$$

Simplifying:

$$\frac{dC(t)}{dt} = \lambda C(t)\frac{\rho}{\beta - \rho}$$

With the given numerical values ($\beta = 0.0065$, $\rho = 0.0005$, $\lambda = 0.08$ s^{-1}, $\Lambda = 5 \times 10^{-5}$ s):

$$\frac{dC(t)}{dt} = 0.08 \times C(t) \times \frac{0.0005}{0.006} = 6.67 \times 10^{-3} C(t)$$

$$N(t) = 5 \times 10^{-5} \times \frac{0.08 \times C(t)}{0.006} = 6.67 \times 10^{-4} C(t)$$

Part B

The kinetics parameters chosen are justified as follows:

- $\beta = 0.0065$: This is the standard delayed neutron fraction for thermal fission of U-235.
- $\Lambda = 50\mu$s: This is the typical prompt neutron generation time for a pressurized water reactor.
- $\lambda = 0.08$ s^{-1}: This effective decay constant represents the lumping of six delayed neutron precursor groups into one equivalent group. This gives an effective half-life of $t_{1/2} = \ln(2)/\lambda \approx 8.7$ s, which is reasonable as a weighted average of the six precursor groups that range from $\sim$0.2 s to $\sim$80 s half-lives.

Part C

Power will stop increasing when $\frac{dN}{dt} = 0$, which occurs when temperature feedback effects add sufficient negative reactivity to cancel the +50 pcm reactivity insertion.

The reactor reaches a new equilibrium when:

$$\rho_{net} = \rho_{inserted} + \alpha_f \Delta T_f + \alpha_m \Delta T_m = 0$$

For $\rho_{inserted} = +50$ pcm, temperature feedback must provide -50 pcm.

Part D

At end of life (EOL) with +200 pcm reactivity insertion, several key parameters change:

- $\beta_{EOL} \approx 0.005$ (500 pcm): At EOL, approximately 40-50% of fissions come from Pu-239 and Pu-241 built up from neutron capture in U-238. Since Pu-239 has $\beta \approx 0.0021$ (much lower than U-235's 0.0065), the effective β is a weighted average that decreases to around 0.005.

The time constant for the transient becomes:

$$\tau_{EOL} = \frac{\beta - \rho}{\lambda \rho} = \frac{0.0045 - 0.002}{0.08 \times 0.002} = 15.6 \text{ s}$$

compared to BOL:

$$\tau_{BOL} = \frac{0.0065 - 0.0005}{0.08 \times 0.0005} = 150 \text{ s}$$

The EOL transient is much faster (10x shorter period) because $\beta - \rho$ is smaller relative to ρ.

The spent core actually experiences a more dramatic transient per unit reactivity insertion, but the stronger feedback from increased fuel temperature effects provides self-limiting behavior that prevents excessive power excursion. Plutonium-240 absorbs a lot of neutrons as 240Pu concentration builds up.

Problem 8

Part A

The one delayed-group model assumes all six precursor groups can be lumped into a single effective group with average parameters. This introduces errors:

- Each group has different decay constants (λ_i) ranging from 0.012 to 3.01 s^{-1}, corresponding to half-lives from 0.2 to 80 seconds
- The one-group model cannot capture the multi-timescale behavior - early time dynamics are dominated by fast-decaying groups, late time by slow groups
- Effective parameters (β_{eff}, λ_{eff}) are only approximate averages that work reasonably for long-term behavior but miss short-term details

This weakness matters most for short transients where individual group dynamics are important, less so for long-term steady-state calculations.

Part B

For six delayed groups with prompt jump approximation:

Power is given by:

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

Precursor concentrations evolve as:

$$\frac{dC_i(t)}{dt} = \frac{\beta_i}{\Lambda} N(t) - \lambda_i C_i(t), \quad i = 1, \ldots, 6$$

In matrix form, define the state vector:

$$\mathbf{C}(t) = \begin{bmatrix} C_1(t) \\ C_2(t) \\ C_3(t) \\ C_4(t) \\ C_5(t) \\ C_6(t) \end{bmatrix}$$

The precursor equation becomes:

$$\frac{d\mathbf{C}}{dt} = \mathbf{A}\mathbf{C}(t)$$

where the matrix $\mathbf{A}$ is:

$$\mathbf{A} = \frac{1}{\beta - \rho} \begin{bmatrix} \beta_1\lambda_1 - \lambda_1(\beta-\rho) & \beta_1\lambda_2 & \beta_1\lambda_3 & \beta_1\lambda_4 & \beta_1\lambda_5 & \beta_1\lambda_6 \\ \beta_2\lambda_1 & \beta_2\lambda_2 - \lambda_2(\beta-\rho) & \beta_2\lambda_3 & \beta_2\lambda_4 & \beta_2\lambda_5 & \beta_2\lambda_6 \\ \beta_3\lambda_1 & \beta_3\lambda_2 & \beta_3\lambda_3 - \lambda_3(\beta-\rho) & \beta_3\lambda_4 & \beta_3\lambda_5 & \beta_3\lambda_6 \\ \beta_4\lambda_1 & \beta_4\lambda_2 & \beta_4\lambda_3 & \beta_4\lambda_4 - \lambda_4(\beta-\rho) & \beta_4\lambda_5 & \beta_4\lambda_6 \\ \beta_5\lambda_1 & \beta_5\lambda_2 & \beta_5\lambda_3 & \beta_5\lambda_4 & \beta_5\lambda_5 - \lambda_5(\beta-\rho) & \beta_5\lambda_6 \\ \beta_6\lambda_1 & \beta_6\lambda_2 & \beta_6\lambda_3 & \beta_6\lambda_4 & \beta_6\lambda_5 & \beta_6\lambda_6 - \lambda_6(\beta-\rho) \end{bmatrix}$$

Part C

The prompt jump approximation error is likely smaller than the one-group error.

The prompt jump assumes prompt neutrons equilibrate instantly (valid when $\Lambda \ll$ timescales of interest). For a 50 μs generation time and transients on the scale of seconds, this is excellent.

The one-group approximation loses the multi-timescale structure of the six groups, which significantly affects transient shape, especially in the first 10-20 seconds where fast groups dominate.

For this problem (low reactivity, second-scale transient), prompt jump introduces $< 1\%$ error while one-group can introduce 10-20% errors in peak timing and shape.

Problem 9

Part A

The boron concentration must be less than 1200ppm.

The plant startup within 10 hours of full power shutdown must have a higher xenon-135 concentration than a plant that has been shut down for 25 days. As a result, boron must be diluted to compensate for the xenon poisoning effect.

Part B

At first boron must be concentrated to reduce power. At this point, xenon will increase in the core as xenon burnup reduces. To compensate with this additional poison as power falls, boron must be diluted to maintain 50% power. Then, the xenon concentration will fall off as it decays (over days), so boron will need to be concentrated as the xenon negative reactivity diminishes and settles at 50% power. The boron concentration will be HIGHER at the end of the transient than at the start. An example of the xenon concentration can be found on page 11 of 'Xenon Transient Information Rev 2024-2'.

Samarium on the other hand will not have a significant effect as the amount of time spent on maintenance will be too short for significant samarium effects to build up.

Problem 10

Part A

To me, this looks like there was a major steam leak on the secondary side, temporarily increasing steam demand by a lot. I think this was on the secondary side because a primary side loss of coolant would be captured in the pressure data.

Part B

Subpart 1

I'm going to assume a step change in reactivity, such that $\dot{\rho} = 0$.

Because we're considering the first few milliseconds of the transient, we can ignore the contribution of precursors and delayed neutrons. This is an appropriate assumption because the fastest precursor is on the order of 300ms half-life. Much slower than our analysis.

$$\frac{dn(t)}{dt} = \frac{n(t)(\rho - \beta)}{\Lambda}$$

$$\frac{\dot{n}(t)}{n(t)} = \frac{(\rho - \beta)}{\Lambda}$$

$$\frac{781.88}{26.06} = \frac{(\rho - 0.000650)}{0.00026}$$

$$\rho = 0.008451$$

Subpart 2

I would assume rise rate decreases so rapidly because fuel temperature would go through the roof and Doppler broadening would add a lot of negative reactivity. There is not enough time for any other physics to happen other than those at the quantum level.

Part C

At near steady state (around 800 seconds on the chart), the reactor power and temperature have stabilized after the initial transient. We can estimate the moderator temperature coefficient using the relationship between reactivity change and temperature change.

Given:

- Initial temperature: $T_i = 600°\text{F}$
- Final temperature: $T_f = 680°\text{F}$
- Temperature change: $\Delta T = 80°\text{F}$

At near steady state, the reactor is critical, so the net reactivity is zero. The reactivity balance is:

$$\rho_{net} = \rho_{inserted} + \alpha_m \Delta T = 0$$

From Part B.1, we found the inserted reactivity:

$$\rho_{inserted} = 0.008451 = 845.1 \text{ pcm}$$

Solving for the moderator temperature coefficient:

$$\alpha_m = -\frac{\rho_{inserted}}{\Delta T} = -\frac{845.1 \text{ pcm}}{80°\text{F}}$$

$$\boxed{\alpha_m \approx -10.6 \text{ pcm}/°\text{F}}$$

This value is reasonable for a PWR moderator temperature coefficient, typically ranging from -10 to -40 pcm/°F depending on core conditions and boron concentration.

Part D

Starting with the one delayed group prompt jump approximation:

$$n(t) = \frac{\lambda_{eff} C(t) \Lambda + S\Lambda}{\beta - \rho}$$

$$\dot{C}(t) = \frac{n(t)\beta}{\Lambda} - \lambda_{eff} C(t)$$

To find $\dot{n}(t)$, we take the implicit derivative of the first equation. Since both $C(t)$ and $\lambda_{eff}(t)$ can vary with time, we use the product rule:

$$\dot{n}(t) = \frac{\Lambda}{\beta - \rho} \frac{d}{dt}[\lambda_{eff} C(t)] - \frac{\Lambda(\lambda_{eff} C + S)}{(\beta - \rho)^2} \dot{\rho}$$

$$\dot{n}(t) = \frac{\Lambda}{\beta - \rho} \left[\dot{\lambda}_{eff} C(t) + \lambda_{eff} \dot{C}(t) \right] - \frac{\Lambda(\lambda_{eff} C + S)}{(\beta - \rho)^2} \dot{\rho}$$

Substitute $\dot{C}(t) = \frac{n(t)\beta}{\Lambda} - \lambda_{eff} C(t)$:

$$\dot{n}(t) = \frac{\Lambda}{\beta-\rho}\left[\dot{\lambda}_{eff}C(t) + \lambda_{eff}\left(\frac{n(t)\beta}{\Lambda} - \lambda_{eff}C(t)\right)\right] - \frac{n(t)(\beta-\rho)+S\Lambda}{(\beta-\rho)^2}\dot{\rho}$$

Simplify:

$$\dot{n}(t) = \frac{\Lambda\dot{\lambda}_{eff}C(t)}{\beta-\rho} + \frac{\beta n(t)}{\beta-\rho} - \frac{\Lambda\lambda_{eff}^2 C(t)}{\beta-\rho} - \frac{n(t)\dot{\rho}}{\beta-\rho} - \frac{S\Lambda\dot{\rho}}{(\beta-\rho)^2}$$

From the first equation: $\lambda_{eff}C(t)\Lambda = n(t)(\beta-\rho) - S\Lambda$, so:

$$\Lambda C(t) = \frac{n(t)(\beta-\rho) - S\Lambda}{\lambda_{eff}}$$

After substitution and algebraic manipulation, we get:

$$\frac{\dot{n}(t)}{n(t)} = \frac{\dot{\rho} + \frac{\dot{\lambda}_{eff}}{\lambda_{eff}}\left[(\beta-\rho) - \frac{S\Lambda}{n(t)}\right] + \lambda_{eff}\left(\rho + \frac{S\Lambda}{n(t)}\right)}{(\beta-\rho) + \frac{S\Lambda}{n(t)}}$$

Power turning occurs when $\dot{n}(t) = 0$:

$$\dot{\rho} + \frac{\dot{\lambda}_{eff}}{\lambda_{eff}}\left[(\beta-\rho) - \frac{S\Lambda}{n(t)}\right] + \lambda_{eff}\left(\rho + \frac{S\Lambda}{n(t)}\right) = 0$$

The key term $\frac{\dot{\lambda}_{eff}}{\lambda_{eff}}\left[(\beta-\rho) - \frac{S\Lambda}{n(t)}\right]$ arises from the implicit derivative of the product $\lambda_{eff}C(t)$. This accounts for the changing effective decay constant during the transient.

Part E

Values estimated from graphs at t = 17.2s (power peak):

- $\Delta T_{ave} \approx 611 - 600 = 11°\text{F}$
- $\frac{d(\Delta T_{ave})}{dt} \approx \frac{620-600}{25-5} = 1.0°\text{F/s}$
- $\lambda_{eff} \approx 0.13\ \text{s}^{-1}$
- $\dot{\lambda}_{eff} \approx 0.081\ \text{s}^{-2}$
- From Part B.1: $\rho_0 = 0.008451$ (845.1 pcm)
- From Part C: $\alpha_m \approx -10.6$ pcm/°F
- $\beta = 0.0065$ (650 pcm)

At power turning ($\dot{n}(t) = 0$):

$$\dot{\rho} + \frac{\dot{\lambda}_{eff}}{\lambda_{eff}}\left[(\beta-\rho) - \frac{S\Lambda}{n(t)}\right] + \lambda_{eff}\left(\rho + \frac{S\Lambda}{n(t)}\right) = 0$$

Assuming negligible source term $S \approx 0$ at high power:

$$\dot{\rho} + \frac{\dot{\lambda}_{eff}}{\lambda_{eff}}(\beta-\rho) + \lambda_{eff}\rho = 0$$

The reactivity includes both moderator and fuel temperature feedback:

$$\rho(t) = \rho_0 + \alpha_m \Delta T_{ave} + \alpha_f \Delta T_{ave}$$

$$\dot{\rho} = (\alpha_m + \alpha_f) \frac{d(\Delta T_{ave})}{dt}$$

Substituting into the power turning equation:

$$(\alpha_m + \alpha_f) \frac{d(\Delta T_{ave})}{dt} + \frac{\dot{\lambda}_{eff}}{\lambda_{eff}} \left[\beta - \left(\rho_0 + \alpha_m \Delta T_{ave} + \alpha_f \Delta T_{ave}\right)\right] + \lambda_{eff} \left(\rho_0 + \alpha_m \Delta T_{ave} + \alpha_f \Delta T_{ave}\right) = 0$$

Solving numerically for α_f using the given values:

$$\begin{aligned} \alpha_m &= -10.6 \times 10^{-5} \text{ per } ^\circ\text{F} \\ \rho &= 0.008451 + (-10.6 \times 10^{-5})(11) + \alpha_f(11) \\ \dot{\rho} &= (-10.6 \times 10^{-5} + \alpha_f)(1.0) \end{aligned}$$

Using SymPy to solve:

$$\boxed{\alpha_f \approx 7.96 \text{ pcm}/^\circ\text{F}}$$

Note: This positive value is non-physical, as fuel temperature coefficients should always be negative due to Doppler broadening. This suggests the model assumptions may not be valid for this extreme transient.

Physical interpretation: The only physically reasonable explanation for the continued increase in average coolant temperature even as power is turning is that the fuel temperature is much hotter than the moderator temperature and continues dumping heat into the coolant via conduction. This large temperature gradient between fuel and moderator violates our assumption that both can be approximated by ΔT_{ave}. The fuel has likely reached extreme temperatures above normal operating conditions while the moderator lags significantly behind. In a real scenario, fuel damage or melting would likely have occurred.

Part F

Recommendation: Do NOT restart this plant without extensive inspection and fuel integrity assessment.

The analysis reveals several concerning indicators:

Evidence of severe fuel damage:

- The non-physical positive fuel temperature coefficient from Part E indicates the normal reactor physics models have broken down
- The continued increase in average coolant temperature even as power was turning suggests fuel temperature was far exceeding moderator temperature
- The extreme reactivity insertion (845 pcm) combined with the rapid power excursion likely caused fuel temperatures to reach damage thresholds

- Power rose extremely rapidly in the first few seconds, indicating prompt-critical-like behavior that would cause severe thermal stress

The fuel almost certainly experienced temperatures well beyond design limits. Cladding integrity is highly suspect. Restart should be prohibited until a comprehensive inspection confirms the core is safe to operate, and additional care should be paid to the chemistry of the coolant to look for zirconium or zirconium-irradiated products.