Finite Element Modeling of the TREAT (as Built) Reactor and a Possible 20% Enriched Fuel TREAT Reactor

P. J. McDaniel, N. Fathi and C. de Oliveira

University of New Mexico

Abstract:

The possibility of building a 20% enriched core for the TREAT reactor is explored. The recommended C/U-235 ratio for a 20% core is approximately 4000 vs. 10,000 for the original TREAT. The thermal flux at the centerline will be lower by a factor of about 5 and the isothermal feedback coefficient will be about half of the isothermal feedback coefficient for the as built TREAT. This will affect the peak power reached during transients and the temperature rise of the core during those transients.

Introduction:

Recently there has been a move to convert all reactors with enriched uranium fuel to new fuel elements with enrichment less than 20% due to proliferation concerns. This has had a significant impact on the capabilities of a number of test reactors. The TREAT reactor, shutdown in 1999, is planned for a restart to test advanced fuels under the DOE Advanced Fuel Initiative. This reactor contains 5,185 grams of U-235 with an enrichment of 93.1% in the fuel form UO_2. This fuel is dispersed in a graphite/carbon matrix at a ratio of 1 part U-235 to 10,000 parts carbon (Iskendrian, 59). To say that this is a proliferation risk requires a lot of imagination. However, it seems useful to estimate the impact of conversion to a less that 20% enriched fuel form would be. So we undertook a study to model the original core of the TREAT reactor and estimate some of the important parameters that a 20% enriched core might have. A perspective view of the TREAT reactor is given in Figure 1.

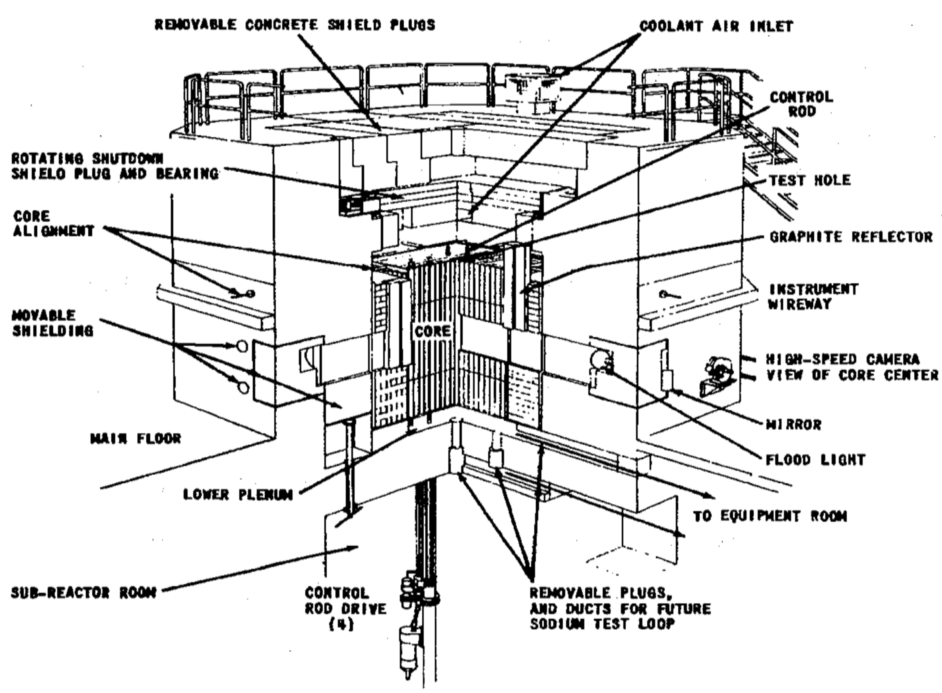


Figure 1: Perspective view of the TREAT Reactor

The TREAT reactor is a very flexible experimental tool allowing its fuel elements and reflectors to be rearranged in many ways. The central core and reflector area of the reactor consists of a fuel support plate that has a square matrix of 19x19 locations that can accept 4 in by 4 in fuel, control rod, or reflector elements. This is surrounded by a permanent graphite reflector and then a concrete biological shield. Every location external to the biological shield is accessible during steady state operation. The only restricted area is the control rod drive chamber below the core. A plan view of the reactor is presented in Figure 2 (Dickerman, 62).

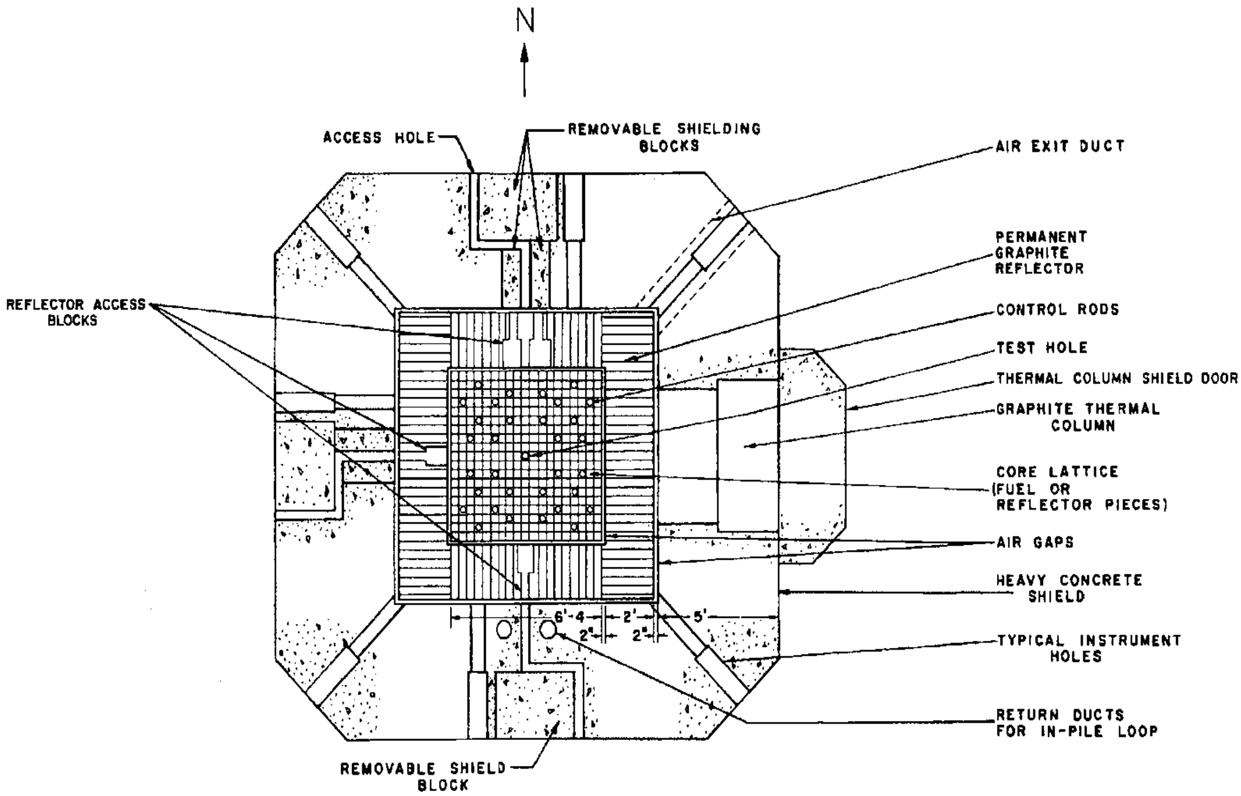


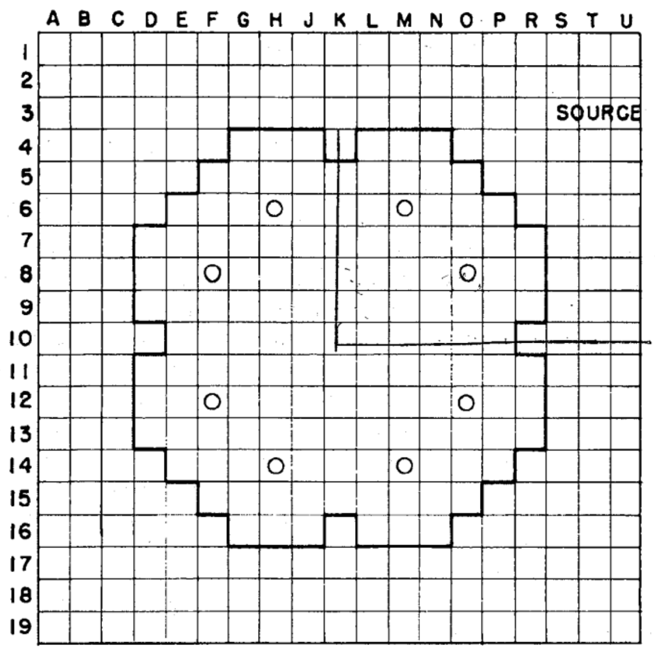
Figure 2: Plan View of TREAT

It is impossible to address all possible configurations of the TREAT reactor in one set of calculations. However, the impact of converting to 20% fuel can be most easily be addressed by analyzing the “small core” configuration, which was the minimum critical core configuration (Iskenderian, 59) . The loading diagram for the minimum critical core is described in Figure 3. With all control rods removed, it had a positive excess reactivity of ~60 inhours or a Δk_{excess} of 0.001566. All of our analysis is directed at this particular core arrangement as its performance is very well described in ANL-6173 (Kirn, 60).

Analytic Method:

Though the most popular method for neutronics calculations today is the Monte Carlo method, we chose to use a deterministic method for its ease in producing certain parameters of interest, particularly spectra and feedback coefficients. Since the core is so large and the uranium so dilute, TREAT has always been analyzed with diffusion theory codes. This probably won't be adequate for experiments with strong absorbers in the test section, but for a minimum critical core it should be more than adequate. Also since the fuel, control, and reflector elements are all homogeneous in the vertical dimension a 2-dimensional analysis should exemplify all of the important effects. This does require some estimate of the transverse buckling and that will be addressed below. The code we chose to use was FEMP2D, a two dimensional, P1, finite element code that was particularly adequate for the rectangular geometry of the TREAT core (McDaniel, 87). FEMP2D is called P1 because it does retain the full anisotropic downscatter cross sections in calculating inscatter sources.

LOADING DIAGRAM OF TREAT



1. No. of Regular Fuel Elements 133

2. No. of Fuel Elements with Control Rod Holes 8
Reactor Supercritical by ~ 60 ih

Figure 3: TREAT Minimum Critical Core

The cross section data was derived from the SCALE6.1, 238 neutron group criticality cross section set based on ENDFVII.0 (Rearden, 11) . This cross section set was processed with the CENTRM/PMC module for a critical sphere reflected by graphite and collapsed to a 30 group set for most of the calculations. Basically the core of the critical sphere was chosen to give a k-eff of 1.0 for a composition representing the TREAT fuel elements. This gave a core radius of 61.3 cm. The 30 group set consisted of 20 fast groups and 10 thermal groups. The group boundaries are given in Table 1.

There were two considerations included in the analysis here that were not of the original core design for TREAT but were determined to affect core size after TREAT was built and operated. First the fuel elements were determined to have more boron in them than had been planned. The goal was to keep the boron to less than 1 part per million. As a result of the fabrication process the fuel elements had between 6.0 and 7.6 parts per million boron. For all of the calculations reported here, 7.0 parts per million boron were included. The second difference from planned was that all of the carbon was not converted to graphite. It was estimated that only 59% of the carbon had been converted to graphite. So all of the carbon was modeled as 59% graphite and 41% free carbon (Iskenderian, 60). This primarily affected the feedback coefficient. These same mixtures were used for the 20% enriched core though they will obviously depend on the production processes used should new fuel elements be required.

Group	Emax	Emin	Group	Emax	Emin	Group	Emax	Emin
1	2.00E+07	1.00E+07	11	1.15E+03	2.40E+02	21	3.00E+00	2.21E+00
2	1.00E+07	2.35E+06	12	2.40E+02	1.08E+02	22	2.21E+00	1.45E+00
3	2.35E+06	1.20E+06	13	1.08E+02	6.50E+01	23	1.45E+00	1.14E+00
4	1.20E+06	8.20E+05	14	6.50E+01	4.70E+01	24	1.14E+00	1.05E+00
5	8.20E+05	4.99E+05	15	4.70E+01	3.70E+01	25	1.05E+00	9.00E-01
6	4.99E+05	2.00E+05	16	3.70E+01	2.75E+01	26	9.00E-01	5.00E-01
7	2.00E+05	7.30E+04	17	2.75E+01	1.60E+01	27	5.00E-01	2.25E-01
8	7.30E+04	1.70E+04	18	1.60E+01	9.10E+00	28	2.25E-01	6.00E-02
9	1.70E+04	3.00E+03	19	9.10E+00	5.40E+00	29	6.00E-02	3.00E-03
10	3.00E+03	1.15E+03	20	5.40E+00	3.00E+00	30	3.00E-03	1.00E-05

Table 1: Energy Group Boundaries

Results:

The first item to estimate for the 20% core was the ratio of carbon to U-235 required to go critical with the small core geometry. The C/U-235 ratio was varied from 1500 to 7000 in the spherical model used to collapse the cross sections. The full 238 neutron group library was used for these calculations. The results are presented in Figure 4.

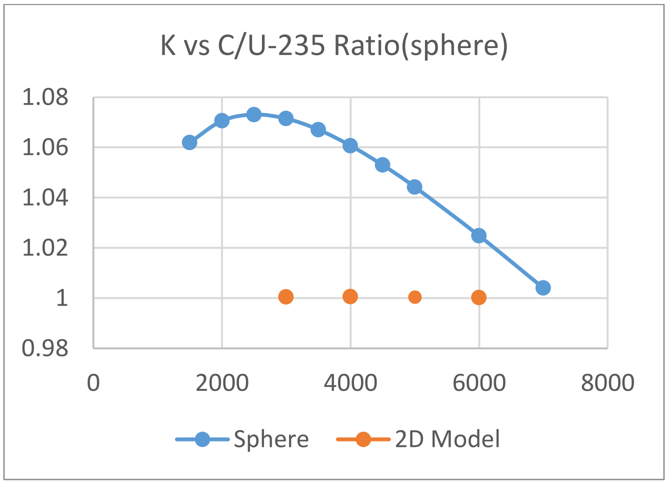


Figure 4: K-eff vs. C/U-235 ratio (Spherical Model)

The maximum k-eff in the spherical model occurred at a C/U-235 ratio of ~2500. Then the collapsed cross sections for a ratio of 3000, 4000, 5000, and 6000 were used to perform a 2D calculation of the core. The 2D calculation included the control element assemblies that had a lower loading of fuel and graphite so they did not achieve the K-eff of the sphere. The data for these calculations are plotted as the dots near the K-eff=1.0 line in the bottom of the Figure. This data is amplified in Figure 5.

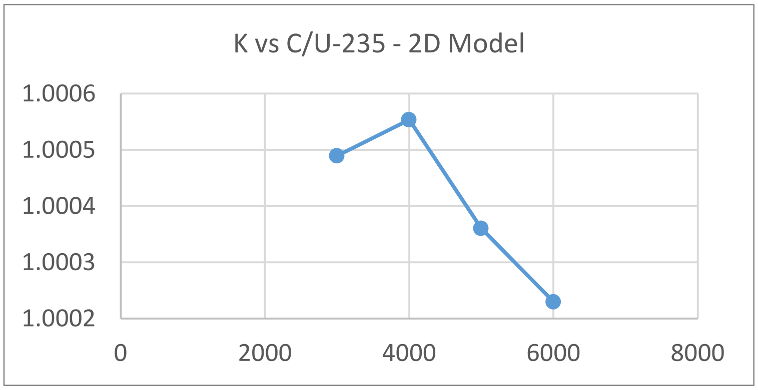


Figure 5: K-eff vs. C/U-235 ratio (2D Model)

The K-eff value peaks at a C/U-235 ratio of ~4000 so this was used in all subsequent calculations.

It should be pointed out that because 2D calculations were used here the transverse buckling enters into the calculations. The transverse buckling was estimated by choosing the active core height plus 2 fast diffusion lengths (average of the fission energy groups 1-3) on both ends. This gave an effective transverse dimension of 157.5 cm. Using this transverse buckling, FEMP2D gave a k-eff for the as built small core of 1.00042 compared with the measured 1.001566. The transverse buckling dimension required to achieve the actual measured k-eff is 166.5 cm. This was used for the remaining calculations.

Once the critical core configuration had been determined, the spectrum at the center of the core was evaluated as that would be a first approximation to the flux that an experiment would see. The spectra at the center of the core for both the As Built TREAT (93% enriched) and a possible Upgrade TREAT (20% enriched) are plotted in Figure 6. The fast spectrum is dominated by the classic 1/E characteristic with no fission peak showing at all. The major difference between the two spectra is in the thermal range.

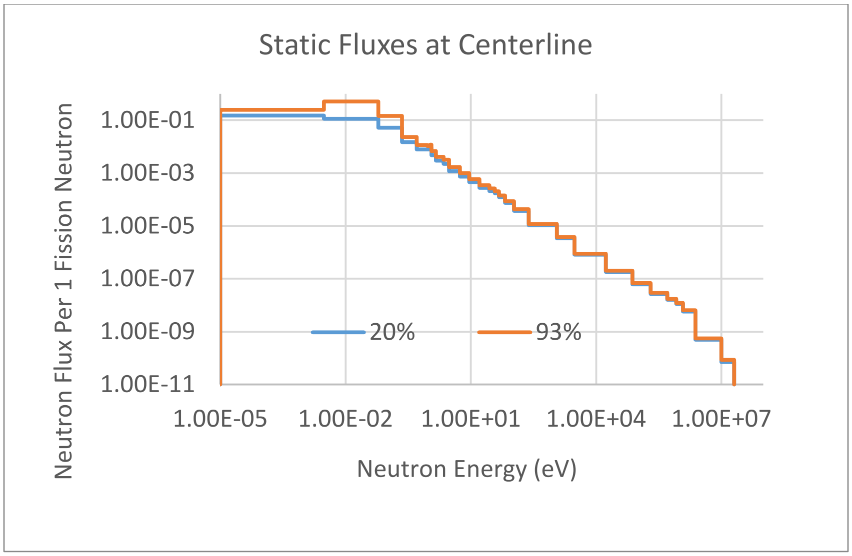


Figure 6: Centerline Flux Spectra for 93% enriched and 20% enriched TREAT Cores

The thermal range fluxes are expanded in Figure 7. It can be seen that the thermal flux in the range from 0.003 eV to 0.06 eV for the 20% enriched core will be significantly less than that for the As Built 93% enriched core. It is essentially a factor of 5 smaller.

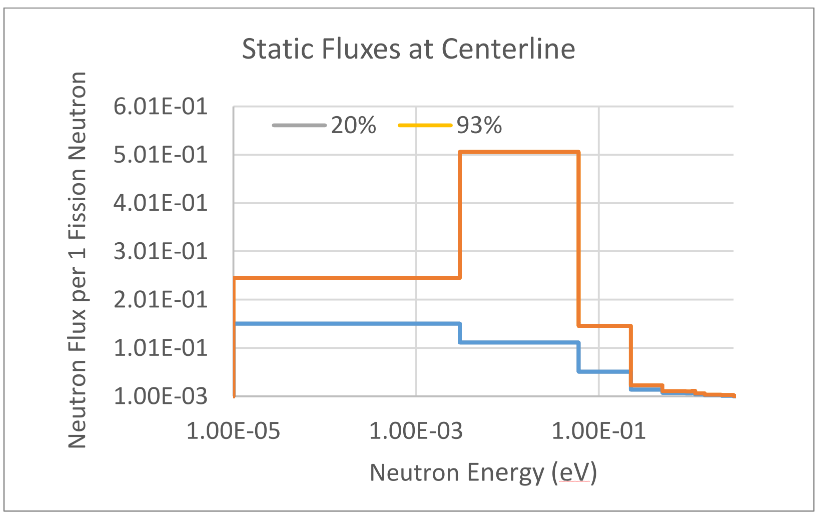


Figure 7: Comparison of Thermal Fluxes for 20% enriched core with 93% enriched core

This will affect the coupling of energy into experiments placed in the center of the core. The thermal flux can be enhanced for the 20% enriched core by including a flux trap around possible experiments, but no attempt was made to calculate this possibility.

The next quantity of most interest is the change in feedback coefficient for the 20% enriched core. The isothermal temperature feedback coefficient for the 93% core was calculated first. The results of this calculation are presented in Figure 8. The calculated isothermal feedback coefficient was dk/dT=-1.77E-4/^{o}C at 350^{o}C. Due to the design of TREAT and its air cooling system, it was possible to measure an actual isothermal feedback coefficient. This was accomplished by blowing hot air through the core and measuring the change in reactivity. The air flow changed the core temperature nearly the same amount throughout the core. This measurement gave a dk/dT=-1.8+/-0.2E-04/^{o}C (Kirn,60). A previous calculation by the design team had estimated the isothermal coefficient at dk/dT=-2.5E-04 which is also plotted in Figure 8 (Okrent,60). The feedback coefficient was calculated from 350^{o}C to 1100^{o}C, though the core will never get that hot. Typically the temperature feedback varies as $1/T^{1/2}$ and so a curve of that shape is plotted in Figure 8 also. It can be seen that the feedback due to the graphite scattering in the core is a little better than this estimate over the region of most transients in TREAT.

Of course the actual feedback coefficient in a core the size of TREAT is not an isothermal one. The experimental team measured the actual feedback coefficient in TREAT and the non-isothermal one came out to be approximately dk/dT=-1.3E-04/^{o}C or about 72% of the isothermal one (Kirn,60). Due to the feedback based on the scattering kernel in graphite, this value is pretty constant over most of the range of interest for transients in the 93% enriched core.

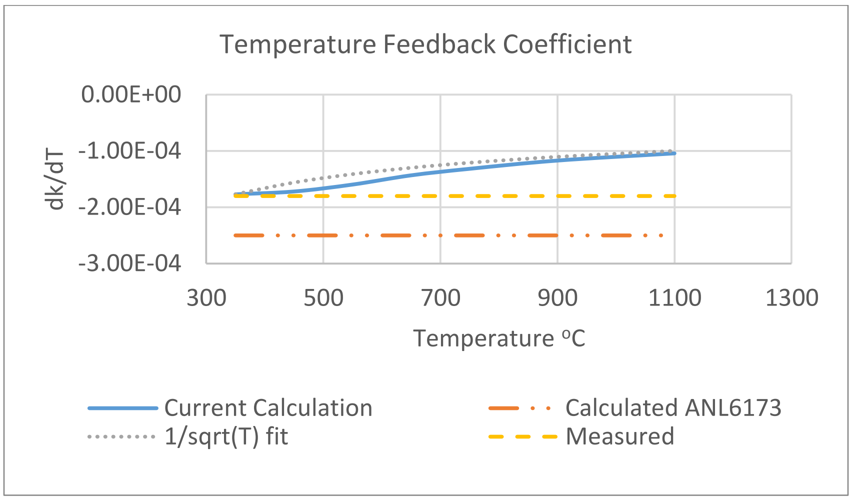


Figure 8: Isothermal Feedback Coefficient for TREAT As Built core

Given the modest success at calculating the isothermal feedback coefficient for the As Built TREAT, a calculation was made for the 20% core. For the 93% core, the dominant feedback mechanism is the hardening of the spectrum due to scattering in the graphite as the core heats up. For the 20% core with approximately 11 times the amount of U-238 in the core, there is also a Doppler feedback due to the widening of the resonances in U-238. A comparison of the isothermal feedback coefficients for the 93% and 20% enriched cores is presented in Figure 9. It appears that the isothermal feedback coefficient for the 20% enriched core will be about 56% of that for the 93% enriched core over the region of interest for transients in TREAT.

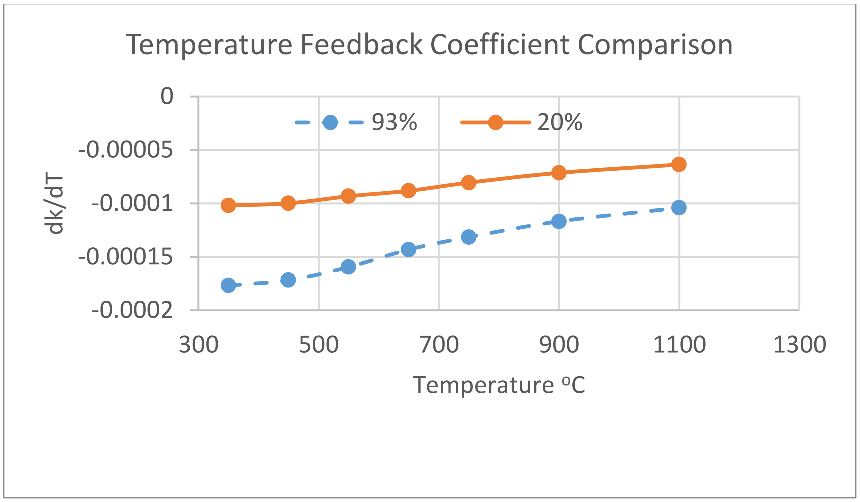


Figure 9: Comparison of isothermal feedback coefficients for the 93% and 20% enriched cores

Apparently the reason for this is that the thermal flux is significantly smaller in the 20% core.

An attempt was made to separate out the feedback effects between the hardening of the spectrum due to graphite scattering and the absorption in the U-238 resonances. To do this a calculation was run with the U-238 cross sections processed at the design number density. This gave the feedback coefficient reported in Figure 9. Then calculations were run with U-238 cross sections processed as infinitely dilute in graphite. There should be no Doppler contribution from U-238 in this case. The results of these two calculations are presented in Figure 10.

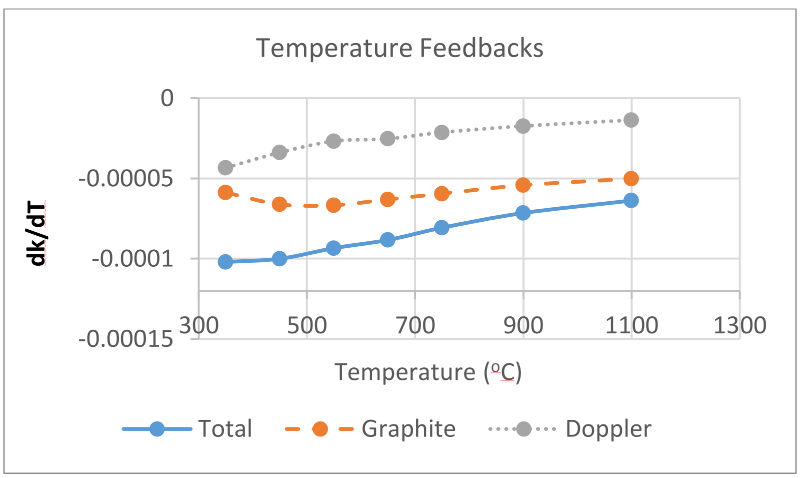


Figure 10: Components of the isothermal feedback coefficient in a 20% enriched core

It can be seen that the Doppler contribution is a significant fraction of the total feedback over the range of interest for TREAT transients. This would be important if the fuel in a 20% enriched core were to be agglomerated into fuel particles of some size (~several hundred microns). The Doppler feedback would be prompt and the graphite feedback would be delayed while the deposited heat leaked out of the fuel particles.

Finally in order to perform transient analysis, we calculated the neutron lifetime in the TREAT reactor. The reported lifetime for the small core TREAT was listed at between 700 μsec and 1000 μsec in ANL 6173. Our calculation gave 246 μsec for the As Built TREAT and 185 μsec for the 20% enriched TREAT. This is a major discrepancy that we have not been able to resolve. The process we have used is to calculate k-effective for a reactor supercritical by a little over 1$ worth of reactivity and then calculate the time constant alpha that this would produce in a transient. An eigenvalue search for alpha is made by requiring k to be equal to 1.0. We have

$$\alpha = \frac{k-1}{l} \qquad l = \frac{k-1}{\alpha}$$

This analysis has worked quite well for several fast reactors that we have analyzed, so the discrepancy was a bit of a surprise.

Since one of the goals was to model transients in a 20% enriched core, we attempted to replicate 4 of the transients reported in ANL-6173. These transients involved the rapid insertion Δk's of 0.95%, 1.15%, 1.55% and 1.9%, or reactivity insertions of 1.319$, 1.597$, 2.153$, and 2.639$. We modeled the transients by matching the initial periods for each as reported and attempted to calculate the peak power observed and the peak centerline temperature observed. We used the reported temperature feedback coefficient of dk/dT=-1.3E-04/^{o}C peak. Our point kinetics model gives close but not exact answers compared to the measured data for the peak power. It underestimates the peak temperature rise by 30 to 60^{o}C. The results are presented in Table 2. Also presented are the results for a similar set of transients for the proposed 20% core. To obtain these transients our isothermal feedback coefficients were reduced by 72% so they could be based on the peak temperature rise. We used the neutron lifetimes that met the data for the initial periods of the transients for the As Built TREAT (700-1000 msec), but reduced them by the ratio 187/246 that we calculated for the lifetime in the 20% enriched reactor. We also added 56.2 kg (2710.2 vs. 2654) to the core mass without changing the reported specific heat to model the added U-238. The results of these calculations are presented in Table 2 also

			Peak Power (MW)		
Δk	ρ($)	Tau	Measured	PK Mod	Restart(PK)
0.0095	1.319	0.31	54	62.8	140.3
0.0115	1.597	0.19	140	134	319
0.0155	2.153	0.105	380	399	1007.3
0.019	2.639	0.075	860	781	2025.1

			Temperature Rise (K)		
Δk	ρ($)	Tau	Measured	PK Mod	Restart(PK)
0.0095	1.319	0.31	119	91.7	159
0.0115	1.597	0.19	145	110	191
0.0155	2.153	0.105	176	145	254
0.019	2.639	0.075	237	176	310

Table 2: Peak powers and maximum temperature rise for transients reported in ANL-6173

It can be seen that the point kinetics model estimates an approximate doubling of the peak core power and a ~50% peak temperature increase for the 20% enriched core versus the 93% enriched core. This is not unexpected given the smaller temperature feedback coefficient and shorter lifetime for the 20% enriched core.

Conclusions:

It appears a 20% enriched core would be possible for a TREAT core. The C/U-235 ratio would need to be about 4000. However it would have some disadvantages. The peak flux on the centerline in the thermal range would be down about a factor of 5 if no adjustments are made. The isothermal feedback coefficient would be about 56% of that for the 93% enriched TREAT. The peak flux experienced in a super prompt critical transient would be about twice that obtained in the 93% enriched TREAT. And finally the temperature rise in the core would be about 50% greater than that for the 93% enriched TREAT.

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