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Critical Reactor Laboratory

Temperature Coefficient of Reactivity

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ABSTRACT

The temperature coefficient of reactivity of the RPI Critical Facility was measured in the range from 58.3 to 108 degrees Fahrenheit. The coefficient is small and positive below approximately 95°F and small and negative above that. It is presumed that the temperature coefficient remains negative thereafter.

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PURPOSE:

A negative temperature coefficient is important to the safety of a reactor since it adds inherent stability with respect to temperature changes, such as might be induced in an excursion. The purpose of this experiment is the measurement of the temperature coefficient of reactivity of the RPI Critical Facility. ✓

THEORY:

The reactivity of a reactor is defined as $\rho = 1 - \frac{1}{k}$. The temperature coefficient of reactivity α_T, is the rate of change of reactivity with temperature. $\alpha_T = \frac{d\rho}{dT}$
Thus $\alpha_T = \frac{1}{k^2}\frac{dk}{dT}$
Since k is close to 1, α_T is approximately $\frac{1}{k}\frac{dk}{dT}$

The multiplication factor of a bare thermal reactor is $k = k_\infty P_T P_F = \eta_T f p \varepsilon P_T P_F$. $P_T = 1/(1 + L_T^2 B^2)$ and $P_F = \exp(-B^2 \tau_T)$ are the thermal and fast non-leakage probabilities.

Thus $\ln k = \ln k_\infty + \ln P_T + \ln P_F$.
Differentiating term by term gives:

$$\alpha_T = \frac{1}{k}\frac{dk}{dT} = \frac{1}{k_\infty}\frac{dk_\infty}{dT} + \frac{1}{P_T}\frac{dP_T}{dT} + \frac{1}{P_F}\frac{dP_F}{dT}$$

or

$$\alpha_T = \alpha_T(k_\infty) + \alpha_T(P_T) + \alpha_T(P_F)$$

Each of these temperature coefficients can be further differentiated so that

$$\alpha_T = \alpha_T(\eta_T) + \alpha_T(f) + \alpha_T(p) + \alpha_T(\varepsilon) - \frac{B^2 L_T^2}{1+B^2L_T^2}\left[\alpha_T(L_T^2) + \alpha_T(B^2)\right]$$
$$- B^2\tau_T\left[\alpha_T(\tau_T) + \alpha_T(B^2)\right]$$

For the bare thermal reactor, reactivity changes are explainable by using these coefficients. One can immediately guess that the temperature coefficients of p and ε will be unimportant due to the small concentration of U-238 in the fuel. ✓ This is the case and is also one of the causes of difficulty with the experiment. The resonance escape probability is one of the largest contributors to a negative temperature coefficient due to Doppler broadening of the resonances. In such small concentrations of U-238, $\alpha_T(p)$ becomes less important relative to the other coefficients which may be positive or negative. For this reason the temperature coefficient of this reactor is very small, and may be of either sign in the temperature range investigated.

a) Temperature coefficient of η_T

$\eta_T = \nu\, \sigma_f/\sigma_a$ Nu is essentially constant at thermal energies so the temperature dependence of eta is the variation of the ratio σ_f/σ_a with temperature. This is very small in the range in which we measured, as shown below.

$$\frac{\Delta \frac{\sigma_f}{\sigma_a}}{\Delta T} \cong \frac{\Delta \frac{g_f}{g_a}}{\Delta T} = \frac{\frac{.9581}{.9610} - \frac{.9759}{.9780}}{100°C - 20°C} \cong -10^{-5}/°C$$

b) Temperature effects on thermal utilization

Lamarsh shows that $\alpha_T(f) = -(1-f)[\alpha_T(\zeta) - \beta_M]$ where ζ is the thermal disadvantage factor and β_M is the coefficient of expansion of the moderator. $\alpha_T(\zeta)$ is always negative and β_{H_2O} is positive in the temperature range of interest so $\alpha_T(f)$ is always positive.

c) Temperature effects on the resonance escape probabiltiy

The temperature coefficient of p is always negative and is a function primarily of the resonance integral and the coefficient of expansion of the moderator. As the temperature increases, moderator is expelled from the unit cell, effectively increasing the fuel to moderator ratio. p decreases therefore as the relative resonance absorber concentration increases.

d) Temperature effects on the fast fission factor

Thermal expansion of the fuel increases slightly the probability that fast neutrons escape from the fuel. An increase in temperature also tends to flatten the thermal flux in the fuel, changing the spatial distribution of the primary fissions which decreases the probability that primary fission neutrons escape the fuel. These two competing factors combine to make $\alpha_T(\varepsilon)$ small, and in this reactor, negligible.

e) Temperature effects on the non-leakage probabilties

The buckling B^2 decreases with increasing temperature since the reactor dimensions increase. This means that neutron leakage decreases giving a positive $\alpha_T(B^2)$. However, the reactor structure tends to expand very little so that $\alpha_T(B^2)$ is generally very small. Since $\alpha_T(L_T^2)$ and $\alpha_T(\tau_T)$ are both positive, the net temperature coefficients of the nonleakage probabilties are negative.

PROCEDURE:

A three rod bank was raised to approximately 20 inches and the reactor was brought citical on the remaining rod which was used thereafter to relate all reactivity changes. The two 18 kw heaters were turned on (the agitators had been on since the beginning to maintain an even temperature and to avoid perturbing the core as they were turned on). After the response of the reactor to temperature was noted (positive or negative period) negative or positive reactivity was added with the control rod to put the reactor on a small but opposite period. Due to the effect of the temperature coefficient, the reactivity added is eventually balanced as the reactor passes through critical. The temperature coefficient of reactivity between the two successive critical positions and temperatures is:

$$\frac{\Delta\rho}{\Delta T} = \left[\frac{(\text{¢}/in.)_f + (\text{¢}/in.)_i}{2}\right]\left[\frac{(inches)_i - (inches)_f}{T_f - T_i}\right]$$

This procedure is followed throughout the temperature range by relating successive critical positions and the corresponding temperatures. The coefficient applies at the midpoint of the initial and final temperatures.

DISCUSSION:

One of the experimental difficulties encountered involved the amount of reactivity to be inserted, which the temperature coefficient had to overcome. If too much recativity is inserted a very long time would be required to return to critical at the slow rate at which the bulk temperature of the water increased. On the other hand, too little reactivity would introduce possible large numerical errors since numbers which are almost equal must be subtracted. This allows large percentage errors to occur although the absolute error may be small. Based on trial and error, I think a one-half cent reactivity addition would be about the best compromise of these requirements.

The temperature coefficient of reactivity is one of the basic parameters affecting the stability of a reactor and is important both from a safety and from an operating standpoint. If the coefficient were positive, a power change would initiate reactivity additions causing the chain reaction to diverge. At best this would be a nuisance since the reactor would resist attempts to bring it to critical. At worst it would be a safety hazard which would allow the reactor to runaway. Although a large negative temperature coefficient presents no safety problem, the possibility of power overshoots during power changes occurs. In this case, the temperature increase causes such a large negative reactivity change that the reactor falls subcritical and the power level drops until the reactivity is zero. If the coefficient is negative and small, the reactor is stable.

An important distinction should be made between the temperature coefficient measured in this experiment, and the one actually responsible for safety. Due to the slow rate at which the temperature of the water changes, and the fact that the fuel is contained in thin plates, all temperature changes can be considered uniform. During a power change, the fuel temperature responds almost instantaneously. It is the prompt temperature coefficient of the fuel which is responsible for safety, since the moderator temperature changes more slowly.

At lower temperatures the temperature coefficient is positive, is zero between 90 - 100 degrees F, and is therafter negative. As stated, the temperature coefficient of f is always positive. Since the coefficients of η_T, ε, p, are negligible, $\alpha_T(K_\infty)$ is positive and must be compensated for by leakage. Although the temperature coefficients of the leakage are negative, they do not equal that of f at first, possibly because they involve a factor of B^2, which is a small number. As the temperature increases further leakage increases and dominates due to the fact that at lower moderator density the mean free path for scattering increases allowing more neutrons to escape. Although this reactor would continue to have an infinite reflector due to the large amount of water surrounding the core, reflectors of other reactors would become less effective if they had a fixed volume since some of the reflector would be expelled. At much higher temperatures the temperature coefficient would presumably remain negative. It is difficult to extrapolate the prompt temperature coefficient from the data, but it should also be negative since the most important factors affecting the fuel, eta andp, have negative coefficients. A power excursion would then

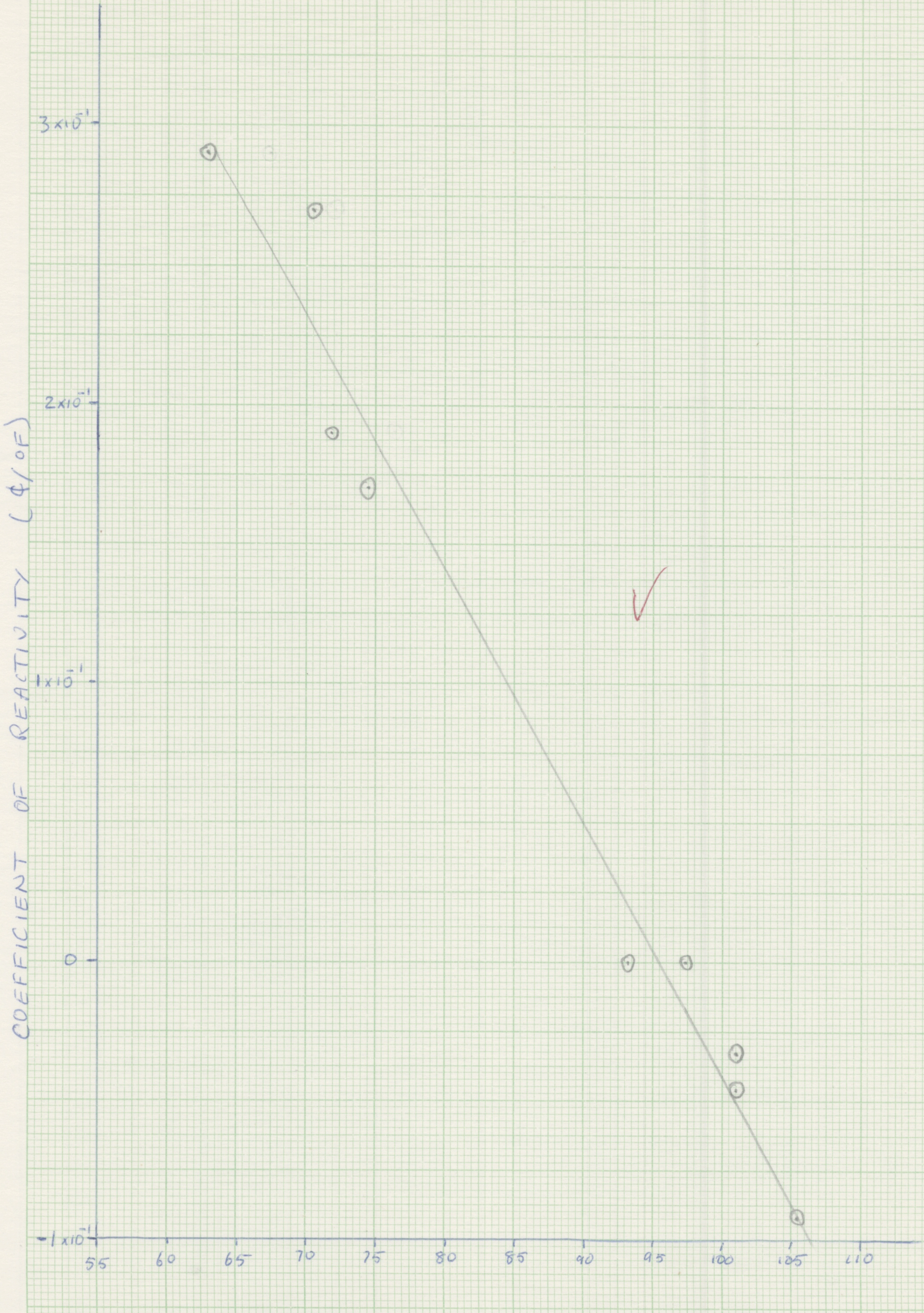
Initially, we are overmoderated

then be controlled by the temperature coefficient, eventually compensating for excess reactivity and inducing criticality, although at a possibly high power level. This of course assumes that no meltdown or other core disruptive accident occurs.

depends upon the ρ added whether or not it will be controlled

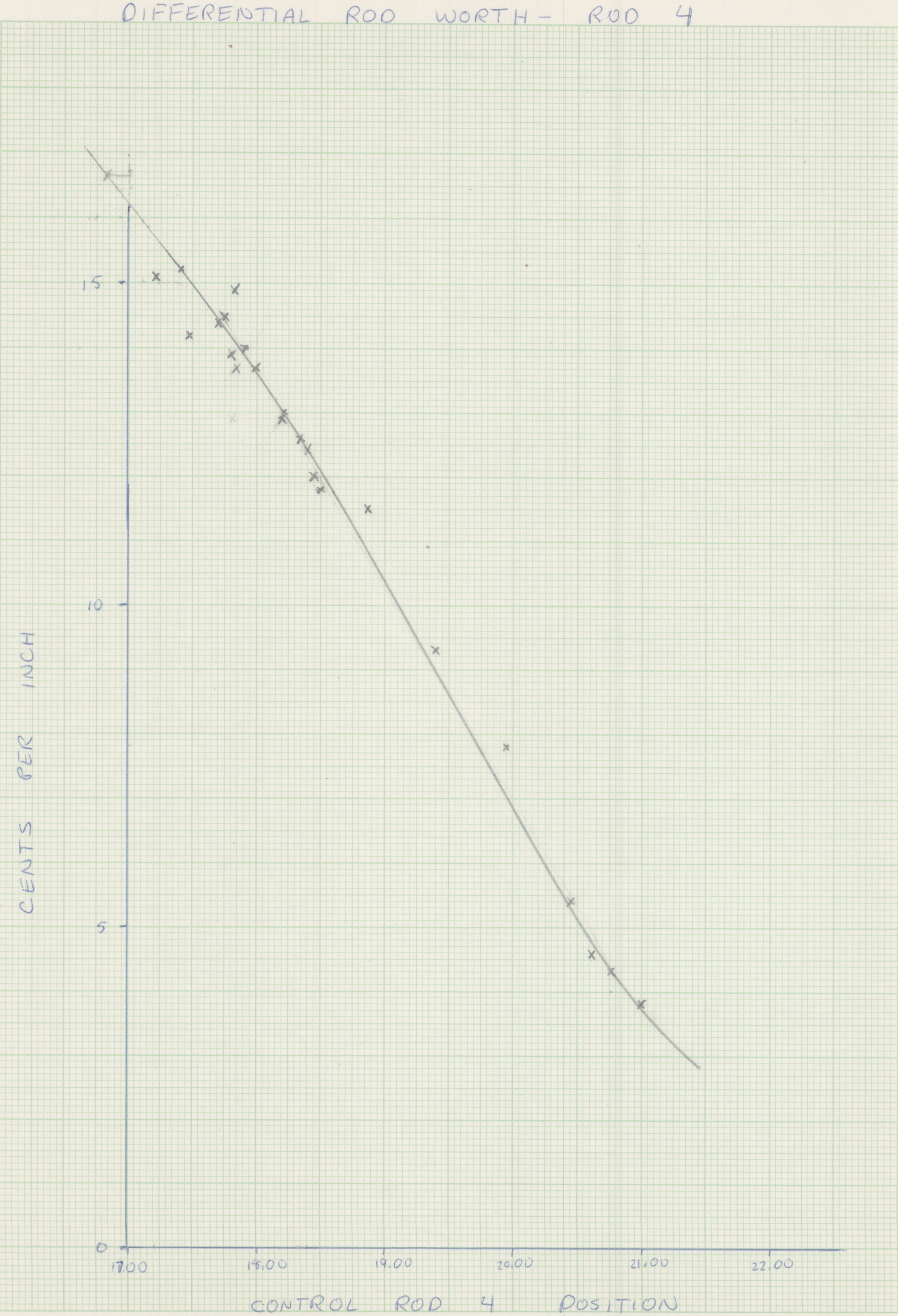
There is really no trade-off between safety and economecs as far as temperature coefficients are concerned. Although fuel loadings could be reduced slightly with a positive coefficient, and the core would be less reactive when clean and cold, the negative coefficient is needed at operating temperatures. In fact, when one considers the effort to reduce the possibility of core meltdown, one of the worst credible accidents, designing a negative coefficient seems one of the cheapest ways of decreasing that probability.

α_T(f) is one of the primary contributors to a positive temperature coefficient and for solid moderators this is through the thermal disadvantage factor $\zeta = \bar{\Phi}_M/\bar{\Phi}_F$. If ζ decreases with temperature, α_T(f) becomes more positive. As stated previously, this does occur since the flux tends to flatten as the diffusion length increases with temperature. If you assume that the moderating properties of liquid water acting only as a coolant do not change much, the contributions to the coefficient from leakage would depend only on the properties of the solid moderator. These might not change as rapidly with T as with a liquid moderator which has larger density changes. The net result could be a positive temperature coefficient.


3×10⁻¹
2×10⁻¹
1×10⁻¹
0
-1×10⁻¹
55
60
65
70
75
80
85
90
95
100
105
110
COEFFICIENT OF REACTIVITY (¢/°F)
TEMPERATURE (degrees F)

Bank Position (in)	Initial Temperature (°F)	Final Temp. (°F)	Initial Critical Position	Final Critical Position	$\frac{\Delta \rho}{\Delta T}$ ¢/°F
22.00	58.3	67.4	16.951	16.790	$+2.9 \times 10^{-1}$
22.00	67.4	76.4	16.790	16.687	$+1.9 \times 10^{-1}$
19.25	69.0	72.1	19.981	19.862	$+2.7 \times 10^{-1}$
19.25	72.1	77.0	19.862	19.753	$+1.7 \times 10^{-1}$
19.15	91.1	95.5	19.969	19.969	0
19.15	95.5	106.6	19.969	20.043	-4.6×10^{-2}
19.65	95.0	99.3	18.606	18.606	0
19.65	99.3	102.5	18.606	18.615	-3.3×10^{-2}
19.65	102.5	108.0	18.615	18.659	-9.3×10^{-2}

Temperature Coefficient Data



DIFFERENTIAL ROD WORTH - ROD 4
CENTS PER INCH
15
10
5
0
17.00
18.00
19.00
20.00
21.00
22.00
CONTROL ROD 4 POSITION

Critical Position	SuperCritical Position	Midpoint	Period	¢	¢/in
17.76	19.00	18.38	55	15.4	12.4
16.90	17.51	17.21	109	9.2	15.1
17.145	17.805	17.475	105	9.4	14.2
17.392	18.005	17.699	112	8.8	14.4
17.392	19.295	18.344	27	24	12.6
17.36	18.32	17.84	61.0	14.3	14.9
16.89	18.68	17.79	25.4	24.8	13.9
17.39	18.28	17.84	75	12.2	13.7
18.015	19.705	18.86	38.6	19.4	11.5
16.840	18.000	17.42	45	17.6	15.2
16.95	18.50	17.73	30	22.5	14.5
17.20	18.80	18.00	31.3	21.9	13.7
17.40	19.00	18.20	35	20.6	12.9
17.49	19.50	18.5	27.8	23.6	11.8
17.40	19.50	18.45	24.7	25.3	12.0
17.25	18.50	17.88	46.0	17.5	14.0
19.280	21.960	20.62	70	12.4	4.6
20.100	21.945	21.023	150	7.05	3.8
19.570	21.960	20.77	94	10.25	4.3
18.930	21.960	20.445	51	16.4	5.4
17.25	19.00	18.22	29.4	22.7	13.0
18.80	20.00	19.40	83.5	11.2	9.3
18.87	21.00	19.94	48.4	16.6	7.8

ROD 4. Calibration Data

CALCULATION:

Heating Rate of Water:

Neglecting structure, losses to atm

Total Heat Rate = 36 Kw = $\dot{m} c_p \Delta t = \rho V c_p \Delta t / \Delta\theta$

assume ρ, c_p independent of tempurature

$$\frac{\Delta t}{\Delta \theta} = \frac{36\ kw}{\rho V c_p}$$

@ 20°C, $\rho = 1000.52\ \frac{kg}{m^3}$ $\quad c_p = 4.1818 \times 10^3\ \frac{W \cdot s}{kg\,K}$

$$V = 2000 \text{ gallons} \times \frac{231\ in^3}{gal} \times \frac{1\ m^3}{6.102 \times 10^4\ in^3} = 7.57\ m^3$$

$$\frac{\Delta t}{\Delta \theta} = \frac{36 \times 10^3\ W}{10^3\ \frac{kg}{m^3} \times 7.57\ m^3 \times 4.18 \times 10^3\ \frac{W\text{-}s}{kg\,K}} = 1.14 \times 10^{-3}\ \frac{°K}{s}$$

$$= 6.82 \times 10^{-2}\ \frac{°K}{m} = 4.09\ \frac{°K}{hr} = 7.37\ \frac{°F}{hr}$$