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The Influence of Poison Materials on the Prompt Temperature Coefficient of a SNAP Reactor - Theory vs Experiment

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ABSTRACT Recent transient experiments were performed to determine the effect of Gd-155, Sm-149 and Eu-151 prepoison materials on the prompt temperature coefficient of the SNAPTRAN-1 machine. Calculations were performed using AI's 28-group nuclear cross section library in a variant of the APC neutron transport code. These calculated coefficients are in rough agreement with the experiments between 200 and 500°F. Above 500°F the calculations indicate coefficients which are too positive for all the poisoned configurations.

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I. Introduction

The SNAPTRAN-1 transient testing machine was first used in a series of experiments conducted at NRTS to measure the prompt temperature coefficient over a wide range of dynamic and thermal conditions (1,2). A more recent set of experiments examines this same coefficient for a range of prepoison types and concentrations at various thermal conditions (3,4,5). This report completes the analysis of the recent set of experiments.

All of the new transients were conducted at reactor periods sufficiently long to eliminate the spatial neutronic effect as an important consideration. The periods were short enough, however, to avoid reflector and grid heating effects.

Since the energy deposition has the same spatial shape as power density, the temperature change distribution can be deduced from this using the heat capacity of the reactor. This distribution produces a "spatially-dependent-kinetics" effect which increases the reactivity feedback of the temperature change, relative to an isothermal change of equal magnitude.

The poisons investigated were dispersed in nickel sleeves which were fitted around each fuel element. The lattice spacing was increased slightly to allow space for the sleeves. The sleeve configurations available, and their measured cold worths were:

Type I:	Ni Sleeves	\$0.00 of prepoison
Type II:	Ni Sleeves	+ \$2.71 of Gd-155
Type III:	Ni Sleeves	+ \$5.04 of Gd-155
Type IV:	Ni Sleeves:	+ \$7.29 of Gd-155
Type Sm:	Ni Sleeves:	+ \$3.22 of Sm-149
Type Eu:	Ni Sleeves	+ \$2.42 of Eu-151

The Type IV sleeves were not used in the transient tests, except for mixed loadings of Type I and IV sleeves, since extrapolation of Types I, II and III data indicated that transients with Type IV sleeve would potentially be unsafe. Additional details concerning the experiments and data reduction can be found in the references.

The calculated coefficients are determined by analytically determining the multiplication factor of the assembly both before and after the transient deposition of energy. This reactivity change divided by the volume-averaged temperature change is considered to be the average coefficient over the range between initial and final average temperatures.

II. Calculational Methodology

The method used for the multiplication factor (k_{eff}) calculation is based on the APC and APCTC codes. First, the value of k_{eff} before the transient is calculated using APC. This is an R-Z consistent buckling transport, code based on ANISN (7,8,9), which iterates between R- and Z-direction calculations until a consistent set of fluxes, bucklings, and k 's are obtained. AI's 23-group SNAP cross section library is used, with 15 fast and 13 thermal velocity groups (10, 11,12).

The APCTC code calculates k_{eff} after the transient. The energy deposited during the transient is distributed spatially according to an input power profile, and spatial ~~temperatures~~, temperature-modified cross sections, and densities are calculated. The cross sections take into account both Doppler and thermal spectral effects. The density changes are used to modify both cross sections and Z-direction core dimensions.

The resulting eigenvalue problem, with cross sections varying spatially cannot be treated satisfactorily by consistent buckling. A straightforward variant of this method, consistent leakage, suffices, however. In this process, the codes do not convert the leakage into buckling, but iterate on leakage directly (DB^2). This is only slightly more complicated to program, and converges just as satisfactorily. The spatially varying cross sections used in each direction are obtained by averaging the variation in the other direction using flux-adjoint averaging. The averaging is repeated at each iteration. This process allows virtually exact consistency of leakage between R and Z problems. Consistency of eigenvalues was typically within 0.0002 $\Delta k/k$.

The temperature coefficient is, of course, the difference in reactivity caused by the temperature change divided by the magnitude of the change. Individual components such as expansion and Doppler effects can be examined by supplying appropriate data. This method is similar in principle to the method used successfully in analyzing the SNAPTRAN-1 and -2 experimental data.

III. Results

A. Transient Experiments

The configuration with unpoisoned sleeves was analyzed in detail. The temperature coefficient obtained using APC and APCTC is shown in Figure 1. Also shown is the fuel expansion component of the prompt coefficient. The previously obtained results ⁽¹⁾ using the TSN code for SNAPTRAN -1 and -2 are of particular interest, since those calculations used nearly the same reactor model with a much more cumbersome and expensive calculational process and the older, less accurate, 26-group cross section library. The figure shows excellent agreement between the current "best" calculation (labeled APCTC) and the earlier results, the new data being about 0.01 $\phi/\text{deg. F}$ more positive.

The experimental result from the SNAPTRAN-1 and -2 series is also shown (dashed lines). This result was obtained by a bivariate correlation, in the variables temperature and period, of 54 transients conducted with an unpoisoned core. Although the test conditions varied widely, the data correlated with a standard deviation of $\pm 0.015\%$ /deg.F., as is shown on the Figure. Our new calculations agree with the experiment up to about 600 deg.F, but above this temperature, they fail to reproduce the measured change in coefficient. A cluster of 10 data points were obtained in the SNAPTRAN experiments in the range 800-1200 deg.F, so that portion of the experimental curve is statistically valid.

Another type of comparison is also shown. If the energy deposition is assumed to be uniformly distributed, a much simpler calculation, performed by the APC code can be used. The value of k_{eff} at several temperatures is obtained directly, and then $\Delta k_{eff}/\Delta T$ is evaluated for each interval between temperatures. Using this process, 5 evaluations of k_{eff} yield 4 data points, whereas 10 evaluations yield 5 points by the APCTC method. The APC curve shows a coefficient about 0.03%/deg.F more positive than the APCTC result. This means that neutron importance effects and nonlinearities increased the coefficient by ~25%. Previous studies with the TBAR code indicated a 22% effect due to neutron importance alone, using a simple power-squared-statistical weight function. Thus the new results appear to be reasonable.

The effect of reflector thickness was examined with the APC calculations. A change from 2.05" to 3.09" of Be made the coefficient about 0.012%/deg.F. more positive. This occurs because the increased reflector thickness reduces the thermal neutron leakage from the core and increases the flow of Be-moderated neutrons into the core.

Since fuel expansion increases with temperature, the fuel expansion component of the total prompt coefficient also increases with temperature, as shown in Figure 1.

The calculated data points are also shown (circled) on the Figure to illustrate the consistency of the calculated data. This indicates that convergence accuracy, which causes a more or less random error in a consistent buckling or leakage calculation, is not an important source of error in these calculations.

Figure 2 shows the measured coefficient data for the configurations analyzed. The data points for each type of sleeve are enclosed by a line which indicates the shape of the coefficient vs temperature curve which could be inferred from the data. In Figure 3, the unpoisoned and Gd poisoned data are compared to calculated results. The accuracy analysis (Sec.IV) indicates that agreement within 0.025 ϕ /deg. F. should be obtained, and the agreement in the range 200-500 deg. F. is approximately that. Above 500 deg. F. the calculated coefficient for the heavily poisoned cases is consistently more positive than the measured data. This is probably indicative of a deficiency in the thermal scattering kernel.

Figure 4 shows the same type of comparison with the Sm and Eu poisons. Again, agreement in the range 200-500 deg.F. is acceptable, with the poisoned coefficient calculation becoming too positive at high temperatures.

B. Isothermal Measurements

In addition to the transients, the recent SNAPTRAN experiments

included isothermal measurements of the worth of the various sleeves as a function of temperature (3)(4). The results of this are summarized in Figure 5. From the cold poison worths given in the references, and the effect of temperature on poison worth which can be inferred from Figure 5, hot poison worths may be obtained. These hot and cold worths were also determined analytically, using the APC code and the 28-group library, as discussed in Section II. A summary of the comparison of hot and cold poison worths is given in Table I.

Table I
Comparison of Calculated and Experimental Poison Worths

Type of Sleeve	Cold (70°F)			Hot (1292°F)		
	Measured Worth (\$)	Calculated Worth (\$)	Error (%)	Measured Worth (\$)	Calculated Worth (\$)	Error (%)
Eu-151	2.42	2.96	+22	2.69	3.43	+28
Sm-149	3.22	3.60	+12	2.57	3.11	+21
Gd-155 -II	2.71	3.17	+17	2.11	2.55	+21
Gd-155 - III	5.04	5.92	+17	3.71	4.96	+34
Gd-155 - IV	7.29	8.23	+13	5.42	7.06	+30

From Table I, it may be seen that the calculated poison worths are consistently higher than the measured worths. For the cold case, the error ranges from 12% to 22%. In every case, the error becomes worse as temperature increases. The calculation overpredicts the hot worths by 21% to 34%. The most probable cause of the inaccuracy is a thermal spectrum error, caused by

low hydrogen upscatter cross sections. This results in too soft a thermal spectrum at low temperatures. At high temperatures, the calculated spectrum becomes harder, but apparently the actual spectrum hardens still more, which leads to the increased error at high temperature.

Table II shows the effect of temperature on calculated and measured poison worth. Note that Gd-155 and Sm-149 decrease in worth with temperature, while Eu-151 increases with temperature. This results from the shape of the thermal cross section for these poisons. Also, the calculation overestimates the effect of temperature on poison worth for Gd-155 and Sm-149, but underestimates the effect of temperature on Eu-151 worth. This result is in disagreement with the prompt coefficient measurements, where the measured coefficient was significantly more negative than the calculated coefficient.

Table II
Effect of Temperature Change on Poison Worth
Calculation vs Experiment

Type of Sleeve	% Change in Poison Worth Going from Cold to Hot	
	Measured	Calculated
Eu-151	+11%	+16%
Sm-149	-20%	-14%
Gd-155-II	-22%	-20%
Gd-155-III	-26%	-16%
Gd-155-IV	-26%	-14%

IV. Accuracy of Prompt Coefficient Calculations

The principal sources of error in matching the calculated coefficients to the measured data can be grouped as follows:

1. Experimental Error- Estimated to be approximately ± 0.015 ϕ /deg.F, from various sources discussed in Reference 3 and 5.
2. Variation in Poison Loading- The variance in both poison concentration and foil thickness are discussed in References 3 and 4. While the variance varies from foil type to foil type, a σ of about 5% (2 σ = 10%) is typical of the combination of these two errors.
3. Computational Model - The model used, a $P_{O}S_{4}$ R-Z consistent leakage calculation has given quite good results in criticality studies (e.g., Reference 11). The error in k_{eff} is typically no more than 1 or 2%. We might estimate modeling error to affect the coefficient by no more than 3%.
4. Convergence- There is an uncertainty due to the failure of axial and radial calculations to agree exactly, depending on the number of iterations. Agreement of 3×10^{-4} or better was typical. This could be expected to result in an error of about 1×10^{-4} in k_{eff} for the radial calculation. The convergence error within each leakage iteration caused comparatively insignificant error. For a typical ΔT of 300 deg. F., the convergence at each end of the temperature span would give an error of 0.007 ϕ /deg.F. in the coefficient. The consistency of the calculated data is in agreement with this estimate.

5. Cross Section Error- The cross section errors in $\sigma_a, \nu\sigma_f$ affect the absorption and fission rates directly, of course. Equally important, errors in the thermal scattering matrices tend to cause an incorrect variation of spectrum with temperature. These errors cannot presently be estimated quantitatively, but we can examine their origin to some advantage. Atomics International has had a competent, continual, and funded cross section development effort since about 1961. The AEC-sponsored Brookhaven Evaluated Nuclear Data File project has proceeded concurrently since about 1965. This store of data has been supplemented recently by the European KEDAK data files. Massive evaluation programs have contributed to their accuracy. The absorption, fission, and fast scattering data used in this study have been selected from the results of these studies.
- In sharp contrast, the thermal scattering matrices stem from a few weeks work done in 1965 in which some scattering data for zirconium-bound hydrogen generated by the SUMMIT II code was placed with scattering data for the heavier nuclides generated on rather arbitrary assumptions by the unpublished 100 GT code. Evaluation of these data has consisted of the single comparison with measured temperature coefficient results reported in Reference 1. Extensive scattering-law data have now been made available through the Brookhaven ENDF project, but we have no way to estimate how results using those data would compare with the results reported herein.

We might guess error due to our present section data to be about $\pm 0.015\phi/\text{deg.F.}$, although there is no firm basis in this.

Assuming a sum-of-squares error combinations, this gives us the following:

$$\text{Error} = \left[(0.023)^2 + (0.03 \alpha)^2 + 0.005 \Delta^2 \right]^{1/2} \phi/\text{deg. F.}$$

Where: α = | temperature coefficient

Δ = | effect of poison sleeves on α |

Using values of α and Δ from the data reported herein, we see that the experimental and cross section errors dominate, giving an estimated error in the comparison of $0.025\phi/\text{deg. F.}$

V. Conclusions

The APC-APCTC calculations produced results which were consistent and credible when compared to other calculations. The method is quite systematic and minimizes chance of human or machine error.

The comparisons with experiment, shown in Figures 3 and 4, show approximate agreement ($\pm 0.025\phi/\text{deg.F.}$) in the range 200-500 deg.F. Beyond that range, the calculation predicts erroneously low values of the coefficient for all the poisoned configurations.

The results indicate that our present coefficient calculations are satisfactory for rough evaluations of poison performance.

They do not give acceptable results in the upper limits of

temperature or poison loading, however. This difficulty is suspected to be due to inadequacy of the thermal scattering kernel.

Also, there is an inconsistency between the prompt and isothermal measurements for the Eu-151 poison loading. This is discussed in more detail in Reference 13.

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TEMPERATURE COEFFICIENT OF REACTIVITY UNPOISONED REACTOR WITH BE REFLECTOR

FIGURE 1

2.05" BE THICKNESS EXCEPT AS NOTED

TEMPERATURE COEFFICIENT OF REACTIVITY

FIGURE 2

EXPERIMENTAL DATA

- 1 - TYPE I Ni ONLY
- 2 - TYPE II Ni + Gd-155
- 3 - TYPE III Ni + Gd-155
- S - Ni + Sm-149
- E - Ni + Eu-151

TEMPERATURE COEFFICIENT OF REACTIVITY GD POISON - THEORY VS. EXPERIMENT

FIGURE 3

TEMPERATURE COEFFICIENT OF REACTIVITY SM & EU POISONS - THEORY VS. EXPERIMENT

FIGURE 4

EXPERIMENTALLY DETERMINED SNAPTRAN ISOTHERMAL TEMPERATURE DEFECT

FIGURE 5