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IWS Analysis

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ABSTRACT

The effect of Gadolinium-155 on the prompt kinetic behavior of a zirconium hydride reactor has been deduced, using experimental data from the SNAPTRAN machine. The poison material makes the temperature coefficient more positive, and the Type IV sleeves were deduced to give a positive coefficient above 1100°F. A thorough discussion of the data and analysis is included herein.

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V. ANALYSIS OF TRANSIENT EXPERIMENTS

A. DATA REDUCTION SYSTEM

1. Processing Description

Data describing power, temperature, and control drum position during each transient were recorded on FM magnetic tape and then converted to a digital magnetic tape. This process was described in Part I, Section I-C. The tapes were subsequently processed by the STAC kinetics analysis program. The results were computer-plotted graphs of normalized power, mean temperature, and temperature coefficient of reactivity. The results for the various configurations were then compared to show the effect of Gadolinium-155 on the kinetics of the reactor.

2. The STAC Processing Code

The STAC code was designed to accomplish these objectives:

- (1) Provides a facility for managing, translating, plotting, and listing raw data tapes from the Analog-to-Digital Converter (ADC).
- (2) Combine and analyze the data to determine kinetic performance
- (3) Determine a temperature coefficient of reactivity.

The code consists of four independent sections which can be applied independently. Intermediate data are stored in re-usable interface data sets.

Section 0 provides a means of copying the 7-track raw data tapes produced by the ADC onto a 9-track master data tape. A listing can be made at the same time. Data channels having unreadable records are excluded from the new copy. An alternate routine allows a synthetic data tape to be constructed from punchcard input. This feature is valuable in checking the code. Noise and digitizing effects are simulated in the synthetic tape routine.

Section 1 converts each channel of data from the symbolic format used on the master data tape to the appropriate binary representation in engineering units, identifies the data from an input deck of ID cards, provides edits and plots as requested, and stores the converted data on a storage data set.

Words containing illegal characters are replaced with 0. If an illegal character occurs within the heading information section which identifies the data, the entire channel is rejected.

Section 2 scans the storage data set, storing neutron detector (power) data in the magnetic core memory. "Wild" points are replaced with data based on a polynomial fit to neighboring data. Then the data are converted to log space. Each channel of data has a "maximum valid indication" associated with it, above which the data are considered to be invalid. Each channel except the last has a factor, k_n , calculated for it which makes its log-overlap area match the overlap area of the channel above it:

$$\int_{T_{0.8,n}}^{T_{1.0,n}} \ln [k_n P_n(t)] dt = \int_{T_{0.8,n}}^{T_{1.0,n}} \ln [P_{n+1}(t)] dt$$

Where: P_n = power indication, n^{th} channel
 $T_{0.8,n}$ = Time when P_n reaches $0.8 \times P_n^{\text{max}}$
 $T_{1.0,n}$ = Time when P_n reaches $1.0 \times P_n^{\text{max}}$
 P_n^{max} = Maximum valid indication for channel n

These factors are calculated and applied to each channel in turn.

Then a composite is made using data from the first channel up to $T_{1.0,1}$; then data from the second channel from $T_{1.0,1}$ to $T_{1.0,2}$, etc., until a continuous composite power curve is made. The noise and small joining roughness are removed by a smoothing technique, in which a smooth curve,

continuous in its first derivative, is passed through the data (8). The logarithmic derivative of the data is obtained as a byproduct. The smooth curve is then converted back to linear space and integrated to give energy deposition.

Reactivity is calculated using the integral kinetics equations (8) and the pointwise logarithmic derivative obtained from the smoothing process. A reactivity value is also calculated for each channel of data by fitting a straight line to it in log space, and then using the slope of this line in the familiar "inhour equation." This is useful in obtaining very accurate values of inserted reactivity from the unsmoothed data.

The power, logarithmic derivative (inverse period), integrated power, and reactivity are written on an interface data set for later use. Edits and plots are given if requested.

The storage data set is scanned again, and temperature data from the energy probe are stored in memory. "Wild" points are replaced with data based on a polynomial fit to neighboring points, and then the initial temperature, T_0 , is determined by averaging the first few data points of all channels. Next the energy deposition in each energy probe is calculated using the integral of the heat capacity for the zirconium-uranium-hydride fuel material. The flux depression in each probe is accounted for at this point by dividing each energy deposition by the calculated ratio of power density in the probe to that in the fuel. Finally, a mean energy is calculated at each point by a least-squares fitting technique described in NAA-SR-11850 (8). In this technique, a precalculated power profile is fit to all the probe data, i.e., $\bar{E}_1$ is chosen such as to minimize:

$$R_1 = \sum_n \left[E_{n,1} - \bar{E}_1 \psi_{r,n} \psi_{z,n} \right]^2$$

where: R_i = fitting residual at i^{th} time point
 $\bar{E}_i$ = mean energy at i^{th} time point
 $E_{n,i}$ = n^{th} probe response at i^{th} time point
 $\psi_{r,n}$ = radial power profile at n^{th} position, normalized to 1.0 average
 $\psi_{z,n}$ = axial power profile at n^{th} position, normalized to 1.0 average

The resulting curve of $\bar{E}$ vs t is smoothed, and the mean temperature is calculated from the mean energy using the heat capacity integral. The smoothing method is the same as that used for power. These data are then stored in the interface data set. Edits and plots are given, if requested.

During the least-square fitting, a consistency check is performed. After $\bar{E}_i$ is calculated, the relationship of each channel of data to the mean is examined by calculating C_n such as to minimize:

$$R_n = \sum_i \left[\frac{E_{n,i}}{\psi_{r,n} \psi_{z,n}} - C_n \bar{E}_i \right]^2$$

and $S_n = \sqrt{R_n / (n-1)}$

where: R_n = fitting residual for n^{th} channel
 C_n = calibration factor for n^{th} channel
 S_n = standard deviation for n^{th} channel

The C_n 's ran typically between 0.9 and 1.1. A value of C_n not in the range 0.8 to 1.2 indicated a misplaced or defective probe, and was cause for rejection of the data. Values of S_n were usually 2%, or less, until a probe became defective.

Section 3 reads the interface data set into memory. Then a power calibration factor, P_{cal} , is calculated which minimizes

$$R_p = \sum_i \left[I_i - P_{\text{cal}} \bar{E}_i \right]^2$$

Where: R_p = fitting residual
 I_i = integrated power, i^{th} time point
 P_{cal} = power calibration factor

This factor is applied to both the power and integrated power data. The temperature which would result from the deposition of the calibrated integrated power is calculated from the heat capacity integral, and all of the results obtained up to that point are edited together.

The temperature coefficient is then evaluated by calculating $d\beta/dT$. The temperature from $\bar{E}_1$ is used first, and then the calculations are repeated using the temperature calculated from I_1/P_{cal} .

Three methods of evaluation are used. In the first, a numerical differentiation is performed by fitting a straight line to the ten nearest neighbors of each point. Then a single straight line is fit over the entire range of usable data. Finally, a straight line is fit to the data falling within the time interval over which the power is above half its peak value. Edits and plots are given.

Examples of the plots produced are shown in a later section.

B. ANALYSIS OF THE DATA

1. Neutronics Parameters

In order to apply the "backward kinetics" calculation, the kinetics parameters Λ (prompt neutron generation time), and β_{eff} (effective delayed neutron fraction) were required for each configuration. These were calculated as described in NAA-SR-11850 SNAPTRAN (8) except that AI's 28-group cross section library was used with the APC code. The 28-group library consists of fast and epithermal sections derived from Brookhaven's ENDF/B cross section source tape and from AI's ALENDF data, together with a specially prepared set of thermal cross sections. The APC code is a multigroup discrete-ordinates (P_{LSN}) neutron transport code based on ANISN. APC alternates between radial and axial cases until consistent eigenvalues and leakages are obtained.

This method was also used to calculate f , the ratio of the power density in an energy probe to the density in the surrounding fuel; and ψ_r and ψ_z , the radial and axial power density distributions.

The calculation started with an equivalent cylindrical fuel cell as illustrated in Figure I/V B1-1. Dimensions and compositions are given in Table I/V B1-1 and IV B1-2. Fluxes and power density were calculated using APC in the non-iterative radial mode. The probe-to-fuel power factor, f , was obtained from these data. Then cross sections were flux weighted to give spatially averaged cross sections. These were used as the core material in the R-Z APC calculation, using the model illustrated in Figure IV B1-2. The material compositions are described in Table I/V B1-3. The mixed type I & IV sleeves were simulated by filling the inner (Core I) zone with Type IV cell material, while the outer (Core II) zone was filled with Type I material.

The configuration with an empty Type IV sleeve in the center required a slightly different model shown in Figure I/V B1-3. The void streaming option of APC was used, the effective height adjusted to give an aluminum rod worth corresponding to the measurements reported earlier in this report. This height was then used with APC to provide the correct streaming leakage from the void enclosed by the center Type IV sleeve. Figure I/V B1-5 shows the resulting power depression at the center.

The values of Λ , β_{eff} , and f are tabulated in Table I/V B1-4 and I/V B1-5. The value of Λ for the unpoisoned case agrees precisely with the calculation reported in NAA-SR-11850, even though the latter value was based on different cross section data. The spatial power distribution, ψ_r , and ψ_z are shown in Figures I/V B1-4 through I/V B1-8.

Figure I/V B1-1
ACTUAL AND CYLINDRICAL CELL GEOMETRIES

ACTUAL
GEOMETRY

CYLINDRICAL
GEOMETRY

TABLE I/V B1-1
Cell Dimensions

<u>Zone</u>	<u>Contents</u>	<u>Outer Radius</u>
1	Fuel	1.5368 cm
2	Gap	1.5446 cm
3	Ceramic Barrier	1.5528 cm
4	Cladding	1.5908 cm
5	Sleeve	1.5968 cm
6	Coolant Channel and Probe	1.6936 cm

TABLE I/V B1-2

Cell Nuclide Densities

Units = Nuclei/ 10^{-24} cm^3

<u>Nuclide</u>	<u>Material</u>					
	<u>Fuel</u>	<u>Gap</u>	<u>Barrier</u>	<u>Cladding</u>	<u>Sleeve</u>	<u>Channel</u>
H	.06533	10 ⁻⁷				653.3 x 10 ⁻²⁴
Zr	.03522					352.2 x 10 ⁻²⁴
U-235	.002446					14.46 x 10 ⁻²⁴
U-235	.0001069					1.069 x 10 ⁻²⁴
O			.0435			
Na			.0078			
Al			.0165			
Sm-149			.00001988			
C				.000262		
CR				.0072		
FE				.00478		
NI				.0648	.0823	
MO				.00913		
Gd-155						See note below

Note: Gd-155 Densities

Sleeve Type

Density

I	0
II	.0002100
III	.0004093
IV	.0006463

R-Z CYLINDRICAL GEOMETRY

REFLECTOR OUTER RADIUS

NO SHIMS	16.551 CM
1 1/4" ON 4 FLATS	18.420 CM
1 1/4" ON 4 FLATS	
+ 1/2" ON 4 DRUMS	19.209 CM

TABLE I/V B1-3

Reactor Nuclide Densities

Units = Nuclei/ 10^{-24} cm³

<u>Nuclide</u>	<u>Materials</u>			
	<u>Reflectors</u>	<u>Vessel</u>	<u>Grids</u>	<u>Empty Sleeve</u>
Be	.12015			
O	.00088			
Cr		.01705	.0128	
Fe		.0562	.0345	
Ni		.01037	.0329	.0823
Mo		.00302	.0041	
Gd				.000575

- Notes:
1. Cross sections from homogenized cell calculations used in core zones.
  2. Empty sleeve in center used with Type I sleeves.

GEOMETRY FOR TYPE I SLEEVES WITH EMPTY TYPE IV SLEEVE IN THE CENTER

INFINITE CYLINDRICAL GEOMETRY

- NOTES:
1. TRANSVERSE BUCKLING FROM TYPE I SLEEVE ANALYSIS USED TO SIMULATE AXIAL LEAKAGE
  2. EFFECTIVE HEIGHT OF 34 CM USED IN VOID ZONES

TABLE I/V B1-4

BASIC KINETICS PARAMETERS

<u>Sleeves</u>	<u>Shims</u>	<u>Λ</u>	<u>β_{eff}</u>
Type I	None	$6.5 \pm 0.2 \mu \text{ sec}$	0.0079 ± 0.0003
Type I + Empty Type IV in Center Position	$1\frac{1}{4}"$ on 4 flats	$7.6 \pm 0.2 \mu \text{ sec}$	0.0077 ± 0.0003
Type II	$1\frac{1}{4}"$ on 4 flats	$7.2 \pm 0.2 \mu \text{ sec}$	0.0076 ± 0.0003
Types I and IV Mixed	$1\frac{1}{4}"$ on 4 flats + $\frac{1}{2}"$ on 4 drums	$8.0 \pm 0.2 \mu \text{ sec}$	0.0076 ± 0.0003
Type III	$1\frac{1}{4}"$ on 4 flats + $\frac{1}{2}"$ on 4 drums	$7.5 \pm 0.2 \mu \text{ sec}$	0.0077 ± 0.0003

TABLE I/V B1-5

Flux Depression Factors

<u>Sleeve</u>	<u>f</u>
Type I	.964
Type II	.906
Type III	.868
Type IV	.835

Note: Probes having nearest nearest-neighbors of different types use a weighted mean, i.e., for a probe located adjacent to 2 Type IV sleeves and 1 Type I sleeve:

$$f = 2/3 \times .835 + 1/2 \times .964 = .878$$

FIGURE I/X BI-4

POWER PROFILE FOR SNAPTRAN MACHINE - NO SHIMS
TYPE I SLEEVES

FIGURE I/X BI-5

POWER PROFILE FOR SNAPTRAN MACHINE
TYPE I SLEEVES WITH EMPTY TYPE IV
SLEEVE IN CENTER POSITION

FIGURE I/X BI-6

POWER PROFILE FOR SNAPTRAN MACHINE
TYPE II SLEEVES

FIGURE I/V BI-7

POWER PROFILE FOR SNAPTRAN MACHINE
MIXED TYPE I AND TYPE IV SLEEVES

FIGURE I/X BI-9

POWER PROFILE FOR SNAPTRAN MACHINE
TYPE III SLEEVES

2. Thermal Data

The heat capacity model was taken from an empirical fit to measured data from several sources, as reported in NAA-SR-11850. For transients initiated by a drum insertion of more than \$1, the following model was used:

$$C_P = C_D + C_E \left(\frac{\theta_E}{T} \right)^2 \frac{e^{\theta_E/T}}{(e^{\theta_E/T} - 1)^2} + C_L T$$

where:

- C_P = heat capacity, joules/deg R
- C_D = 6842 joules/deg R
- C_E = 12590 joules/deg R
- θ_E = 3463 deg R
- C_L = 2.5 joules/(deg R)²
- T = fuel temperature, deg R

For transients initiated by insertions of less than \$1, C_D was increased by 1110 joules/deg R to account for the heat capacity of the cladding.

It may be important to note that the power level resulting from this analysis refers to power absorbed in the fuel, not to total fission power. Fission in a SNAPTRAN reactor releases 203.9 Mev of energy, of which only 180.4 Mev is absorbed in the fuel during the transient. The remainder of the energy escapes with neutrons, photons, or neutrinos; or is released in the form of delayed beta or gamma decay after the transient.

3. Indirect Power Normalization

For transients initiated by reactivity insertions of less than \$1 the energy probes did not give reliable data (8). The small fuel sample lost energy by conduction to the thermocouple wires and to the sheath which enclosed it, so an indirect process was required for those cases.

The neutron detector calibrations were determined from transients conducted above \$1 in the usual fashion. These calibrations were used in the transients below \$1. The temperature was obtained by integrating the calibrated power data, and then applying the heat capacity model to deduce the temperature corresponding to that energy deposition.

4. Data Selection for Differentiating

Not all of the data observed could be used in the temperature coefficient determination. The first and last few degrees of temperature rise occurred slowly, giving rise to numerical error in calculating $d\rho/dT$. Also, delayed gamma background response made the neutron detectors unreliable after the power had dropped far below the peak. The data chosen for the $d\rho/dT$ calculation began when the mean temperature had risen by 30°F, and ended when it came within 30° of the final temperature recorded, or after the power fell below 40% of the peak value, whichever came first.

5. Sample Analysis Results

The STAC Code produced a large volume of output, both tabular and graphical, for each transient. Figures I/V B5-1 through -12 are selected from the output of Transient 39. They are typical of all the transient results.

FIGURE I/V B5-1

FIGURE I/V B5-2

FIGURE I/V B5-3

TRANSIENT 39 + TAPE 008 + SECTION 1

700039
0007 0000

ENERGY PROBEEP2-1 0-4+0 1890F (1053F)

FIGURE I/V B5-4

TRANSIENT 39 * TAPE 008 * SECTION 1

700239
0012 am

FIGURE I/V B5-5

TRANSIENT 39 * TAPE 008 * SECTION 2

700-14-002
0015 0000

FIGURE I/V B5-6

FIGURE I/V B5-7

TRANSIENT 39 + TAPE 008 + SECTION 2

700239
0029 0000

FIGURE I/V B5-8

TRANSIENT 39 * TAPE 008 * SECTION 2

70039
0031 0000

FIGURE I/V B5-9

TRANSIENT 39 + TAPE 008 + SECTION 2

707371
0032 0000

FIGURE I/V B5-10

TRANSIENT 39 * TAPE 008 * SECTION 2

700-14-002
0000 0000

FIGURE I/V B6-11

TRANSIENT 39 * TAPE 008 * SECTION 2

700339
0055 0000

FIGURE I/V B5-12

TRANSIENT 39 * TAPE 008 * SECTION 2

700-39
0036 0000

The first four graphs show some of the data after translation to binary format and engineering units. The next two curves show the composite power and energy data, both before and after smoothing (points and line respectively). The 7th curve shows reactivity as a function of time, including the effects of drum bounce. The 8th shows how well temperature data from the two sources match after normalizing. The tendency of the data from integrated power to overshoot the energy probe data is typical, and is due to error in power measurement after the power falls a decade below its peak. The final four graphs show some of the temperature coefficient determinations. The results show satisfactory consistency.

C. TRANSIENT ANALYSIS RESULTS

1. Summary of Transients

A total of 31 transients covering five different reactor configurations were analyzed successfully. Table I/V C1-1 lists the transients, nominal reactivity and initial temperature reported by the experimenters, as well as the reactivity, power, and temperature data from the analysis. The mean temperature, defined as the middle of the analyzable temperature range, was used as an abscissa in the coefficient correlations. Temperature coefficients determined from both energy probe data and normalized integrated power data are shown. The former are preferable, but only the latter are available for transients conducted at reactivity less than \$1, i.e., below prompt critical. Also shown are the identities of the detectors used for peak power determination and the calibration factor applied. Factors in parentheses were deduced indirectly due to initial reactivity of less than \$1.

2. Correlations

The most important correlation of these data is probably the plot shown in Figure I/V C2-1. This shows the mean temperature coefficient for each transient plotted vs. mean temperature. Table I/V C2-1 gives the slopes and intercepts. The data from each reactor configuration have been plotted with a least-squares-fit line. These show a consistent variation of coefficient with temperature for a given configuration, a progressive reduction of the coefficient magnitude with increasing gadolinium content, and a tendency to slope toward a positive temperature effect at high loadings. The line for Type IV was located by extrapolating the linear fits to the preceeding data at 0°F and 1000°F, as shown in Figure I/V C2-2.

TABLE I/V C1-1
SUMMARY OF TRANSIENT RESULTS

TRAN NO.	SLEEVE TYPE	NOMINAL REAC-\$	NOMINAL T(0)-DEG.F	OBSERVED REAC-\$	OBSERVED T(0)-DEG.F	PEAK PWR CHANNEL	POWER CALIB.	PEAK POWER	MEAN TEMP. DEG.F	TEMPERATURE COEFF. FROM	
										ENERGY PROBE C/DEGF	CALIB. POWER C/DEGF
004	I-NI	1.05	120.	1.05	105.	PD-1	.215	13.8MW	155.	-0.118	-0.125
006	"	1.20	80.	1.18	71.	PD-2	.225	168.MW	212.	-0.113	-0.113
007	"	1.30	100.	1.30	91.	PD-2	.207	386.MW	292.	-0.126	-0.120
021	I-NI (CT.VD)	1.20	127.	1.20	118.	PD-4	.379	160.MW	264.	-0.128	-0.128
022	"	1.20	320.	1.21	306.	PD-4	.386	177.MW	439.	-0.152	-0.153
023	"	1.20	601.	1.21	579.	PD-4	.377	206.MW	700.	-0.172	-0.168
026	II-NI+GD	0.60	230.	0.61	-	PD-6	(1.02)	506.KW	487.	-	-0.083
027	"	0.30	153.	0.79	-	PD-6	(1.02)	1.07MW	363.	-	-0.090
028	II-NI+GD	1.20	118.	1.22	82.	PD-5	.905	209.MW	263.	-0.108	-0.108
030	"	1.20	617.	1.19	630.	PD-5	.872	266.MW	780.	-0.111	-0.111
031	"	1.15	930.	1.15	908.	PD-5	.931	158.MW	1029.	-0.115	-0.115
033	"	1.20	125.	1.21	105.	PD-5	.813	259.MW	310.	-0.096	-0.092
034	I+IV NI+GD	0.50	73.	0.58	-	PD-4	(.920)	462.KW	331.	-	-0.069
035	"	0.60	370.	0.60	-	PD-4	(.920)	615.KW	599.	-	-0.069
036	"	0.30	215.	-	-	PD-6	(1.02)	1.24MW	524.	-	-0.078
037	I+IV NI+GD	1.20	138.	1.20	128.	PD-5	.868	196.MW	322.	-0.092	-0.095
038	"	1.20	350.	1.21	347.	PD-5	.826	284.MW	558.	-0.088	-0.089
039	"	1.20	620.	1.20	609.	PD-5	.814	324.MW	822.	-0.083	-0.083
041	III NI+GD	0.60	103.	0.60	-	PD-4	(.920)	548.KW	406.	-	-0.060
042	"	0.60	270.	0.59	-	PD-4	(.920)	-	394.	-	-0.063
043	"	0.50	75.	0.49	-	PD-4	(.920)	301.KW	351.	-	-0.054
044	"	0.50	350.	0.50	-	PD-4	(.920)	454.KW	569.	-	-0.053
045	"	0.50	520.	0.51	-	PD-4	(.920)	-	648.	-	-0.054
046	"	0.50	870.	0.51	-	PD-4	(.920)	-	1038.	-	-0.056
047	I-NI	0.50	70.	0.48	-	PD-4	(1.22)	150.KW	223.	-	-0.117
048	"	0.60	85.	0.58	-	PD-4	(1.22)	249.KW	247.	-	-0.121
049	"	0.80	95.	0.77	-	PD-6	(1.41)	583.KW	194.	-	-0.119
050	I-NI	1.20	85.	1.19	104.	PD-5	1.22	192.MW	250.	-0.110	-0.109
051	"	1.20	350.	1.21	388.	PD-5	1.23	219.MW	521.	-0.135	-0.134
052	"	1.20	620.	1.21	647.	PD-5	1.19	249.MW	769.	-0.149	-0.149
053	"	1.20	860.	1.19	907.	PD-5	1.27	218.MW	1014.	-0.152	-0.156

NOTE: CT.VD. refers to the configuration having a Type IV sleeve replacing the center element.

FIGURE I/V CE-1
TEMPERATURE COEFFICIENT OF REACTIVITY FROM THE IWS EXPERIMENTS

Table I/V C2-1

Temperature Coefficient Results

<u>Configuration</u>	<u>Temperature Intercept</u>	<u>Coefficient Slope</u>
Type I Sleeves	-0.107 $\mu/\text{deg F}$	$-4.8 \times 10^{-5} \mu/(\text{deg F})^2$
" " " with Type IV		
Sleeve + Void in Center	-0.104	-9.9×10^{-5}
Type II Sleeves	-0.087	-2.5×10^{-5}
Mixed Type I & Type IV Sleeves	-0.080	-2.4×10^{-7}
Type III Sleeves	-0.062	$+8.7 \times 10^{-6}$

FIGURE I/V CE-2

Temperature Coefficient vs. Gd Loading

D. EVALUATION OF RESULTS

1. Relationship to Other Data

First, it should be recognized that the results reported in this section do not, and should not, agree with data reported elsewhere in this report. These data are transient prompt temperature coefficient of reactivity data. This type of data is typically more positive than static isothermal data by roughly 0.1 ¢/deg. F since it does not involve grid plate or reflector temperature effects. It should be larger in magnitude by a factor of about 1.2 than prompt isothermal data deduced from static measurements, due to the peaking effect. In prompt transients, the energy is deposited preferentially in the center of the core. Since the deposition is more effective than average in the center, the result is a larger coefficient.

In actual practice, attempts to extract prompt data from isothermal static data involve considerable inaccuracy. The corrections for grid and reflector temperature effects tend to be large, temperature variant, and difficult to measure or calculate independently.

The comparison with SNAPTRAN I is quite valid, however. The comparison of data is shown in Table I/V D1-1. This comparison uses data taken without gadolinium and ignores the slight effect of the nickel sleeves in this experiment. The agreement appears to be quite satisfactory in all respects.

2. Experimental Errors

The problem of instrument calibration is an important error source. The energy probe calibration depends upon the temperature of the probe relative to that in the reactor as a whole. The voltage is easy to measure and is accurately known. The power density in the energy probe, however, is affected by flux depression resulting when poison shims surround the fuel elements and from flux distortion resulting from neutron leakage near the control drums.

The energy absorption rate is not quite proportional to power density, either. About 12.4 Mev of the 180.4 Mev per fission absorbed promptly in the fuel is due to neutron and photon interactions. These particles travel over mean path lengths large in comparison to the probe

Table I/V D1-1

Comparison of Kinetics Results for the Unpoisoned SNAPTRAN Reactor

	<u>SNAPTRAN I</u>	<u>THIS STUDY</u>
Measured Temp. Coeff. at 0 deg. F	-0.121 ϵ /deg. F	-0.107 ϵ /deg. F $\pm 14\%$
Calculated Temp. Coeff. at 0 deg. F	-0.134 ϵ /deg. F	-
Measured Λ (using calculated β_{eff})	6.6 ± 0.2 μ sec	-
Calculated Λ	6.5 μ sec	6.5 ± 0.2
Calculated β_{eff}	0.00794	0.0079 ± 0.0003
Measured Variation of T.C. with Temperature	-6.2 $\times 10^{-5}$ ϵ /(deg. F) ²	-4.8 $\times 10^{-5}$ ϵ /(deg. F) ²
Calculated Variation of T.C. with Temperature	-8.75 $\times 10^{-5}$ ϵ /deg. F) ²	-

size. Thus, the absorption from these effects is more representative of the reactor as a whole than it is of the lower power density. The rest of the prompt absorption is due to fission fragment recoils, which travel only about 0.001 cm in fuel or probe material. The transport of these particles is not an important problem.

The probes also tend to degrade from use at high temperatures. Hydrogen loss lowers their heat capacity, and prolonged exposure to a hot reducing environment tends to degrade the junction quality. Junction resistance checks and intercomparison between various probes were used to control these effects. Some probes failed and were replaced during the course of the experiments, and the new probes did not give noticeably different performance when compared to the unreplaced probes. Intercomparison between probes gave agreement usually within $\pm 10\%$.

Neutron detectors were affected by nonlinearity, gamma sensitivity, and calibration uncertainty. Really bad nonlinearity was detectable by comparison with other detectors. Gamma sensitivity was a problem only after the power peak, and this was eliminated by rejecting data occurring after the power fell below half its peak value.

Neutron detector calibration was not a problem for transients run above prompt critical, since the energy probe response was used. For the delayed-critical transients, the energy probes lost heat too rapidly by conduction to their non-fuel components to be useable. The indirect calibration discussed earlier involved additional error sources in calculating the ratios of detector responses. There may also have been some error due to the effects of detector nonlinearity on the indirect calibration, but it was not possible to observe it independently.

The experiment itself allowed certain complications. In the prompt critical transients, a drum bounce of about ± 0.02 maximum amplitude prevented establishment of a true asymptotic period prior to thermal feedback, and probably affected the linearity of the reactivity-vs.-temperature curves. Axial conduction, especially to the grid plate, was not a problem. Calculations have shown that SNAP experiments conducted at reactivity over 0.40 are not affected by this error. Thermocouples on the grid plates confirmed this. Heat loss to the cladding is not negligible, however. As

stated earlier, the heat capacity was increased by about 6% to account for this effect. The time constant for this conduction is roughly 1 sec, although it varies with temperature. Since an \$.80 reactivity insertion gives a period of 1 sec, and the temperature rise proceeds at that rate initially, we estimate a potential error of about 3% due to this effect on transients below prompt critical.

3. Data Acquisition and Analysis Problems

The results were very sensitive to time shifts in the recording-digitizing process, and precise synchronization was required. Errors in this class were detectable by comparison between detectors, and were well controlled. Detector and recording noise was a problem only when useable neutron detectors were too widely spaced in sensitivity.

The software on both the digitizing and analysis computers gave little trouble. Several selections of the smoothing interval were used on a set of 4 transients, with negligible effect on the results. Numerous hardware errors occurred in the area of tape writing or reading errors. These resulted in replacement or rejection of the erroneous data, however.

The accuracy of all the analysis depended on the calculation of the spatial power profiles (ψ_r and ψ_z), flux depression factors (f), prompt neutron generation time (Λ), and the effective delayed neutron fraction (β_{eff}). The uncertainties in Λ and β_{eff} due to error in the calculation itself were 3% and 4%, respectively. It was not possible to evaluate the uncertainty due to cross section error. In the SNAPTRAN experiments β/Λ calculated in the same way as herein agreed with β/Λ from the experiments within 2%, and Table I/V D1-1 shows that that value also agrees with the calculation performed for this experiment. The number of transients performed in this series was not sufficient to conclude a new value of Λ . It was not possible to estimate the error in f , except to note that $0.8 < f < 1.0$. Thus, if the amount of depression were in error by 20%, the error in f would be $0 < \text{error} < 4\%$.

The results also depended on the accuracy of the drum calibration, of course. In the SNAPTRAN experiments, the uncertainty in the 45° to 0° worth of a single drum was estimated as about 1.5%. Then, for an insertion

of \$1.20, the reactivity above \$1 would be in error by about 8%. This experiment probably had similar accuracy. The use of more reactivity would have reduced this relative error, but would have made the fuel too radioactive for safe sleeve changing.

4. Overall Accuracy Estimates

The standard deviation of the final correlation in SNAPTRAN I was ± 0.015 ¢/°F . Due to the large number of transients correlated, the error in the correlation itself may have been less, of course. In this study, only a few experiments were done per configuration. From Figure I/V C2-1, we might estimate the linear fit of the Type I data to be in error at 0°F by ± 0.01 ¢/°F (9%) due to random error and delayed-critical normalization problems. Combining this error with the estimated drum calibration, Δ , β_{eff} , and f errors by the sum-of-squares method gives an overall uncertainty of 11% in temperature coefficient. The agreement shown in Table I/V D1-1 is of this same order. The fits for the other configurations are probably of comparable absolute accuracy, i.e., ± 0.015 ¢/°F .

It might also be noted that the reflector configuration can affect the temperature coefficient. The slight difference between the Type I results and the original SNAPTRAN data, as well as the difference between the Type I and the Type I + center void results may be partly due to the change in reflector effect. Past studies have shown that a thicker reflector enhances the coefficient, as this example would indicate. Consequently, it must be kept in mind that one is measuring the effect of both poison addition and reflector configuration change.

REFERENCES

- 8) J. F. Jackson, W. A. Rhoades and L. I. Moss, "Analysis of SNAPTRAN-1 and -2 Reactor Kinetics Experiments," NAA-SR-11850 (June 26, 1967).