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Reactivity Effects of Gadolinium 155 on a SNAP Reactor

AUTHOR

W. H. Heneveld
V. A. Swanson

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ABSTRACT

Results of experimental measurements of reactivity effects of various concentrations of gadolinium 155 on a SNAP Reactor are presented. Included are reactivity worth measurements with a water immersed core, temperature defect measurements, and transient test results in the SNAPTRAN machine.

PREPARED BY

W. H. Heneveld

DATE

12-1-69

DEPT/GRP NO.

736-610

V. A. Swanson

12-1-69

736-610

APPROVALS

DATE

Chas B. Hillig

12-10-69

H.C. Sturtevant

12-11-69

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H.C. Sturtevant

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INTRODUCTION

The reactivity effect of Gadolinium-155 in a SNAP reactor was investigated under the Aerospace Safety Program. One of the objectives of this program is the development of engineered safeguards that will assist in preventing inadvertant criticality upon water immersion of a SNAP reactor after launch. Gadolinium-155 has a large resonance in its cross section that preferentially poisons a water immersed SNAP reactor more than one in its normal operating configuration. This program was planned to measure the critical factors affecting the use of Gadolinium-155 in a SNAP reactor.

The program included measurements of the reactivity effect of gadolinium in water immersed as well as the operational core configuration and measurements of the effect of gadolinium on the temperature coefficient. Since the gadolinium resonance lies below the median fission energy of a SNAP reactor, as the reactor temperature and hence the neutron energy increase the effective cross section of the gadolinium decreases. This effect leads to a positive contribution to the reactor temperature coefficient and potential problems in the reactor control characteristics.

The data developed through this program, while obtained on a SNAP 10A reactor, will be used to establish the accuracy of analytical models that will be used in the design of other SNAP reactors. In addition to the interest in this material as a means of achieving water immersion subcriticality, it is also of interest as a long term burnable poison. The reactivity data will be used to infer cross section information which will be used to predict its burnup characteristics.

SUMMARY

This program is the result of the combined efforts of several groups and can be best described by dividing the report into several parts. The divisions will be made between the operational and the water immersed configurations and between the experimental and analytical efforts.

SNAPTRAN EXPERIMENTS

The SNAPTRAN-I Reactor, a SNAP 10A reactor specially adapted for high temperature and transient experiments, was used in the operational reactor phase of the program. This reactor is capable of operating at temperatures up to 1400°F and of step reactivity insertions of more than \$1.50, and hence was well suited to this application. The reactor is fueled with 37 uranium-zirconium hydride elements and is reflected with beryllium. The gadolinium-155 was mixed with a nickel powder to serve as a substrate, and rolled and formed into sleeves that were slipped over the individual fuel elements in the core.

The experimental program consisted of reactivity measurements at room temperature and elevated temperatures followed by a series of temperature limited power transients to determine the prompt temperature coefficient. These measurements were repeated (with the exception of one prompt coefficient) for each of three concentrations of gadolinium-155 in the core. The reactivity loss with gadolinium addition was found to be an almost linear relationship with no significant indication of a saturation effect. The expected change in temperature coefficient was found, extrapolating to a value of zero or slightly positive for the highest concentration of gadolinium ($\Sigma_{at} = 0.23$). Under the operating limits of the reactor this configuration was not used in the transient temperature coefficient measurements.

WATER IMMERSION TESTS

The SCA-4B critical assembly, which has been the basis of all previous studies of water immersed SNAP reactors, was used in this program. The same fuel, grid plates, and gadolinium sleeves as were used for Part I were used in these tests. Reactivity measurements were made as a function of gadolinium concentration in a bare, water immersed reactor, and in a beryllium reflected, water immersed reactor.

The method of determining the reactivity of an assembly that is potentially \$10 to \$11 supercritical is a critical aspect of these measurements. In these experiments boron filled aluminum tubes, referred to as "boron splines" were used to offset the excess reactivity. Their reactivity effect was determined by measuring the worth of one or a few splines at each characteristic location and summing these worths over the core. This method assumes no interaction between the splines, which has been found to be true in previous measurements. The reactivity effect of removing one or more of the gadolinium sleeves from each typical location and summing their worths was also determined. The two methods gave consistent results for the reactivity effect of the gadolinium. It was found that a $\sum_{at}$ of 0.217 was required to achieve a reactor that was just critical in water.

REACTIVITY EFFECTS OF GADOLINIUM¹⁵⁵
ON A SNAP REACTOR

Section 1 - Operational Environment

I. DESCRIPTION

A. FACILITY

The operational environment tests were performed in Test Cell #1 of the SNAP Environmental Test Facility (Bldg. 024) which is located in the Atomics International Nuclear Field Laboratory.

A detailed description of the SETF is presented in Ref. 1. The important feature of this facility which was utilized in this portion of the test program was the capability of purging the cell atmosphere with nitrogen from the existing LN₂ system and performing all thermal and transient tests with less than 2% oxygen in the cell. Except for installation of a control console, instrumentation, and heater wiring the facility was operated without modification.

B. SNAPTRAN ASSEMBLY

The SNAPTRAN reactor is basically a SNAP 10A/2 reactor with certain ancillary features to permit operation at high temperatures and provide for rapid insertion of reactivity. It was used successfully in an extensive transient testing program at NRTS (Ref. 2). The core consists of 37 uranium-zirconium hydride fuel elements, fully enriched in uranium-235, mounted on grid plates with a lattice spacing of 1.27". The lattice spacing was increased from the standard SNAP core spacing of 1.26" to accommodate the gadolinium sleeves. It is reflected by beryllium in the radial direction, with control provided by four beryllium drums which vary the neutron leakage from the core. This arrangement is shown in Fig. 1. Reactor characteristics are summarized in Table I.

To provide for high temperature operation, the core and reflector are enclosed in an insulated box. The shafts of the control drums extend through this box to position the drive mechanisms in a low temperature environment. Four 12.5 kw electrical heaters are mounted on the inside walls of the box to heat the reactor. During all high

REACTOR LAYOUT

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Figure 1 - SNAP 10-A Reactor

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TABLE I

SNAPTRAX 2/10A REACTOR CHARACTERISTICS

Core Composition	
Fuel Elements	
Number	37
Lattice spacing (in.)	1.27
Fuel diameter (in.)	1.212
Cladding material	Hastelloy N
Cladding diameter, OD (in.)	1.25
Cladding thickness (in.)	0.015
Fuel alloy (wt % U in Zr)	10
Degree of hydriding, NH (10^{22} a/cc)	6.5
Active fuel length (in.)	12.25
Internal Reflectors	
Composition	Be
Cladding	None
External Reflectors	
Composition	Be
Cladding	None
Nominal thickness (in.)	1.875
Reflector Control Elements	
Number	4
Material	Be
Nominal thickness (in.)	1.875 min 3.629 max
Grid Plates	
Material	304 SS
Thickness (in.)	0.188
Core Vessel	
Material	316 SS
Internal diameter (in.)	8.875
Thickness (in.)	0.032
Maximum Uranium Loading (kg U^{235})	4.75
Mean Fission Energy (ev)	0.18

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SNAPZAM ASSEMBLY

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temperature operations an atmosphere of argon was maintained in the thermal box by means of a feed line and supply bottle located in the access area. This was necessary to minimize nitriding of the beryllium. A photograph of the SNAPTRAN machine is presented in Fig. 2.

Since the normal control drum drive speeds are not adequate to initiate prompt transients, an additional drive mechanism is provided to permit rapid insertion of one or two control drums. This motion, from 45° out to the full in position, is provided by a rack-and-pinion drive from a pneumatic cylinder. This drive mechanism is separate from the normal speed drive and is controlled by a separate portion of the reactor control system. Actual transient operations were initiated by a sequence timer which removed the tooth clutch clamps, fired two drums in, vented the gas pressure and scrambled all four drums to conclude the transient. Each of these operations was controlled by a preset timer to maintain flexibility of operation for the various transients. Typical drum step-in times of 220 msec (including relay closures) were measured with drum scram times of 250 msec.

C. DATA ACQUISITION

Steady State Nuclear Instrumentation

In measurements near delayed critical (from critical to approximately 30% supercritical) data on reactor power level and the rate of change of the power level was obtained from conventional boron lined ionization chamber and fission counter detectors. Five channels of nuclear safety instrumentation were used as listed in Table II.

TABLE II
Nuclear Safety Instrumentation

<u>Quantity</u>	<u>Detector</u>	<u>Function</u>
2	Fission Counter	Log Count Rate/period
1	Ion Chamber	Log N/period
2	Ion Chamber	Power Level

In addition to these channels, the reactor operator had one channel consisting of an ionization chamber and a range switching picoammeter which was used to monitor the flux level and to establish steady-state conditions.

Reactivity measurements were made by a separate channel in which an ion chamber signal was amplified by a picoammeter and converted to a variable frequency by a voltage to frequency converter. This frequency was counted on an electronic counter to provide a digital signal which was proportional to the reactor flux. A small digital computer (Computer Automation 816 with a 4k memory) was programmed to solve the inverse kinetics equation using the Code RHO (Ref. 3,4). This calculation was performed in real time so that a printout of the reactivity was obtained every 4 seconds. This equipment was used to perform control drum calibrations in the course of the program.

Reactor Transient Measurements

The reactor power level during the transient tests was measured by means of fast neutron scintillation detectors. These detectors are basically identical to those used previously in the SNAPTRAN Program (Ref. 5). The scintillator was a cylinder of NE-102 plastic, 2-3/4 in. diameter by 2 in. long. Two types of phototubes were used to detect the scintillations. For the more sensitive ranges (less than 100 kw reactor power) a 6324-A photomultiplier was used, while for the high-power levels an ITT type FW 114 photodiode was used. The photomultipliers were operated with 600 volts across the dynode string, and the photodiodes were operated with a 90-volt bias battery to collect the photoelectrons. The detectors were housed in a lead cave, 4-in. thick, covered with boral and located about 14 ft from the center of the reactor. The photomultiplier detectors had a sensitivity of about 2×10^{-9} amp/watt and the photodiodes had a sensitivity of 1.5×10^{-12} amp/watt.

The currents from these detectors were amplified by FET input solid-state amplifiers (Analog Devices 142B) to a standard level of 1 volt. The sensitivity of the different channels was adjusted by means of plug-in feedback resistors to achieve overlapping coverage of the power transient from about 1 kw full scale on the most sensitive range to 1000 Mw full scale on the least sensitive range. A total of 12 channels of power data were used in this system.

Temperature Measurements

Temperatures during the transients were measured by means of special thermocouple assemblies called energy probes. These consist of a very small piece of uranium-zirconium hydride fuel material (approx. .062 x .062 x .157 in.) to which 0.5 mil chromel and alumel leads are attached. The assembly is insulated with magnesium oxide and placed in a sheath. The leads are extended and the signal connected to a differential input amplifier (Analog Devices 142B). The outputs of up to 12 energy probes were used to obtain data on the power distribution in the reactor. Since the material in the energy probes is identical to the reactor fuel, the temperature rise in the probe on a fast transient corresponds to that of the adjacent fuel.

The amplified signals from the nuclear detectors and the energy probes along with drum position and timing signals were recorded as analog signals on magnetic tape. Two 14-channel instrumentation recorders (CEL Model 3300) were used in the FM mode at 60 ips with a 54 kHz center frequency. This provided a 10 kHz bandwidth which was quite adequate for the transients. The timing signal was a 100 kHz signal which was switched on concurrently with the "fire" signal from the transient timer. This signal was used as both a reference mark for synchronizing the channels and a time base in digitizing the data.

An eight-channel oscillograph recorder (Brush Mark 200) was used for on-line monitoring of the transients. All of the data on the magnetic tapes was played back for recording on the oscillograph so that it could be examined before proceeding with the test series.

The analysis of the data from the experiment was performed using the STAC Code on an IBM 360-50 computer. Data from the transient were input to the code by means of digital magnetic tape. These tapes were prepared by a digitizing computer. The block diagram of this system is shown in Fig. 3. The timing signal from the analog tape is sent to the digitizing control unit which controls a gate on the signal channel carrying the FM data from the tape. The digitizing control permits selection of a delay time between the fire command and the start of the digitizing as well as the time interval between data points. The FM signal is converted into a pulse train of twice the repetition rate of the incoming frequency and passed through the gate of the digitizing control. Pulse trains of 108 to 151 kHz arrive at the frequency counter (General Radio Model 1191) which is operated in the period measurement mode. By counting its internal 10 MHz clock for 10,100, or 1000 input pulses, it is able to digitize the incoming frequency to an accuracy of better than 0.5%. Data points as closely spaced as 120 microseconds are used routinely. The accuracy and the data rate are inversely related such that better accuracy is achieved with lower digitizing rates.

Figure 3
Data Acquisition System

The digital data is input to a small computer (Computer Automation 816) which stores the data in its memory. This operation is repeated to obtain a total of 3,000 data points on a single channel. The data, together with header information which identifies the transient, the detector, the amplification, and the time base parameters is placed in a suitable format and reloaded on digital magnetic tape by the computer. This process is repeated for each of the data channels on the analog tape, producing a digital record of the transient that can be processed using the STAC code.

II. PROGRAM

A. FUEL LOADING

The SNAPTRAN core vessel was loaded initially with 37 lucite dummy elements. These elements were then replaced with fuel elements, without nickel sleeves, in a stepwise manner using the usual inverse multiplication technique until a critical configuration was achieved. The remaining lucite elements were replaced with fuel elements one at a time until all 37 elements were loaded. No beryllium shims were present on the reflector or drums. The SNAPTRAN fuel elements were then removed, the 1.27" (lattice spacing) grid plates replaced with the 1.26" grid plates, and the core reloaded with 36 elements. The last element was not loaded since the indications from the $1/M$ curve were that criticality might be achieved on the second drum. The core was again unloaded and reloaded with 37 SCA-4C fuel elements on the 1.26" grid plates. After determining the critical drum configuration, these elements were removed and the SNAPTRAN fuel elements with nickel sleeves were reloaded in the core vessel using the 1.27" grid plates. Subsequent loadings with gadolinium sleeves on the elements were completed in one step after calculation of the amount of drum and/or reflector shim required to provide the necessary excess reactivity.

B. DRUM CALIBRATIONS

Drums B and C were used for all excess reactivity measurements and transient reactivity insertions. Therefore, they were calibrated for each sleeve and/or shim configuration. Drums A and D acted as "safety" elements and were calibrated with the M1 sleeve configuration only. The calibration curves for drums A & D were substantially the same as those for drums B & C.

The calibration procedure consisted of positioning drum B all the way in, drum C full out, with drums A and D banked at the critical position. Drum C was then inserted to a position which would result in a 30-60 sec period. When sufficient data had been taken, drum B was moved out to establish a negative 30 sec period. This process was repeated until drum B was full out and C was inserted to the full in position. Both the positive and negative period data were fed to an on-line computer which continuously computed the reactivity changes taking place. (See section I-C for details). These reactivity increments were then compiled to produce an integral worth curve for each of the 2 drums.

C. FLUX DISTRIBUTION MEASUREMENTS

The relative radial and axial flux distributions were measured for the Type I sleeve configuration using $\frac{1}{4}$ " dia. x .005" thick gold foils. The foils were attached to $\frac{1}{4}$ " wide x .020" thick aluminum strips which were inserted in the interstices of the core. The axial

traverses were measured adjacent to the central element (interstice 5-10-14). The radial traverses were made by placing foils at the midplane of the core at several radial positions. The foils were counted on standard scintillation type β counters.

By suitable weighting and graphical integration, the average relative flux in the core was determined. The average absolute flux was obtained by comparing the activities of two Al - 18% U (93.11% U^{235}) foils irradiated in the SNAPTRAM core with two identical foils irradiated in a known thermal flux for the same length of time in the AE-6 reactor. The flux determined in this manner is an equivalent 2200 meter/sec thermal flux and is not the true flux in the core. However, the number of fissions per second occurring in the core can be calculated from this equivalent flux, the 2200 meter/sec macroscopic fission cross section of U^{235} , and the volume of the core. The power level at which the flux mapping was done can then be obtained from the conversion factor, 3.3×10^{10} fissions/watt-sec. This power determination was used to calibrate all the neutron detectors. The calibration factors were later refined by applying the results of the energy probe measurements made during the prompt transient tests.

D. CONFIGURATIONS

Gadolinium¹⁵⁵ in the form of Gd_2O_3 was incorporated in a nickel matrix and rolled into foils of 2 mil thickness. These foils were then cut, formed into sleeves, and spot welded so that they could be slipped over each fuel element. Sleeves were restrained from vertical movement in either direction by the upper and lower grid plates. The four types of sleeves fabricated for use in this program are given in Table III.

TABLE III
GADOLINIUM SLEEVES

<u>Type</u>	<u>Gadolinium Concentration, Σa^t</u>
I	Nickel only
II	$0.0730 \pm .0058$ (2 σ deviation)
III	$0.1499 \pm .0016$
IV	$0.2298 \pm .0209$

Six test configurations were constructed using these sleeves: four configurations each containing 37 sleeves of one gadolinium concentration, a mixed loading, and a central void configuration. The mixed loading consisted of Type IV sleeves on the inner 19 elements with Type I sleeves on the outer 18 elements. The central void configuration utilized Type I sleeves on 36 elements with the central element removed and a Type IV sleeve installed in that location.

During the central void configuration tests, measurements of the worths of aluminum and steel placed in the central void were conducted for the purpose of checking streaming calculations. Rods of aluminum and cold rolled steel, 12" long and $\frac{1}{2}$ ", $\frac{7}{8}$ ", and $1\frac{1}{2}$ " in diameter, were placed in the central position in the Type IV sleeve. The worth of each rod with respect to a void was then determined from the change in critical drum position.

As the amount of gadolinium in the core increased, additional beryllium reflection was required to provide the necessary excess reactivity for the transient and thermal tests. This was accomplished by adding $1/8$ " shim plates to the flat surfaces of the reflector block and to the flat surface of each drum. The following procedure was

then used for changing sleeve configurations:

1. The shim configuration was adjusted such that sufficient excess reactivity would be available to obtain a critical configuration with both the present and succeeding sleeve configurations.
2. Drums B and C were calibrated with each sleeve and shim configuration.
3. Excess reactivities of each configuration were obtained from critical drum positions.
4. Sleeve worths were then calculated from the difference in excess reactivities.

E. THERMAL TESTS

Isothermal temperature coefficient measurements were performed with each sleeve configuration. In each case, the following procedure was used. The reactor was brought to a source free power level of approximately 10 watts at room temperature and the critical drum configuration noted. The electrical heaters were then activated and the system temperature raised to 300°F. Heater power was reduced to achieve a uniform steady state system temperature at this point. This process was repeated at nominal system temperatures of 600°F, 900°F, and 1200°F. The reactor was maintained critical throughout the experiment and drum configurations noted periodically. Cr-Al thermocouples were placed throughout the assembly as indicated in Table IV. Temperatures were printed out on a data logger typewriter and multi-point recorder.

TABLE IV

THERMAL TEST THERMOCOUPLE SCHEDULE

<u>Location</u>	<u>No. of T/C's</u>
Reflector	8
Door Heaters	4
Core Interstices	28
Upper & Lower Grid Plates	4 each
Internal Beryllium	2
Control Drum Towers & Bases	1 each
Core Vessel-Reflector Interface	12
Argon Environment	4

F. TRANSIENT TESTS

Following the isothermal temperature coefficient measurements, a series of transient tests were conducted with each sleeve configuration. A typical test series consisted of a 60¢ transient from 75° F followed the next day by an 80¢ transient from ~ 100° F. The third day a series of cascaded \$1.20 transients were conducted as follows: A \$1.20 transient was performed at a system temperature of 75-100° F. Transient scram times were selected such that an average core temperature rise of at least 300° F was obtained. The heaters were then activated and the entire system brought to an isothermal temperature of 300° F. The next \$1.20 transient was then conducted at this temperature. This procedure was repeated at 600° F and 900° F for a total of four \$1.20 transients.

All transients were performed using both B and C drums in the coupled mode (simultaneous insertion) in the following manner:

- 1) B and C drums were set to a position such that subsequent insertion to 0° would insert the desired excess reactivity.
- 2) The reactor was brought to a source free critical level using drums A and D.
- 3) Drums B and C were withdrawn to 45° and the flux level allowed to drop several decades.
- 4) The console was switched to pulse operation, tooth clutch clamps were applied, and B and C drums charged.
- 5) Tape recorders were started.
- 6) The sequence timer was started.

The timer would then automatically release the clamps, fire B and C into 0°, vent, and scram all drums on the preset timing schedule.

III. RESULTS

A. FUEL LOADING

On the initial loading of SNAPTRAN elements, criticality was achieved on the 32nd element with an excess reactivity of approximately 53¢. With 37 elements loaded the excess was \$3.95 with the 1.27-in. lattice spacing grid plates. Reloading these fuel elements on the 1.26-in. grid plates produced an excess reactivity of \$3.80 with 36 elements. Since the 37th element would be worth approximately \$0.69 as determined from the average of the last five elements loaded, this indicates a total excess of \$4.49 for a fully loaded core. Thus, decreasing the lattice spacing from 1.27-in. to 1.26-in. is worth \$0.54. An excess reactivity of \$3.98 was measured for the SCA-4C elements on the 1.26-in. grid plates. This difference in reactivity was attributed to the difference in hydrogen content of the two fuel loadings.

Excess reactivities for the gadolinium sleeve configurations are presented with the shim configurations used for the thermal and transient test in Tables V-A and V-B, respectively.

B. FLUX DISTRIBUTIONS

The results of the gold foil flux distribution measurements are presented in Figures 4 and 5. No beryllium shims were installed on the reactor during these measurements. Data points were normalized to the maximum value for the axial measurements and to the central foil for the radial measurements.

C. DRUM CALIBRATIONS

A total of 34 drum calibrations were performed during the course of this program. All four drums were calibrated at ambient temperature in the M1 sleeve configuration. In addition, in this configuration,

drums B and C were calibrated at 280° F, 500° F, 800° F, and 1200° F average system temperatures. No change in the shape of the integral worth curve or variation in total worth was detected over this temperature region.

Drums B and C were also calibrated for each shim and sleeve configuration. The addition of beryllium to the reflector.

AXIAL FLUX DISTRIBUTION

Type I Sleeve Configuration SNAPTRON Assembly

Figure 4

Relative Foil Activity

KE 10 X 10 TO THE CENTIMETER 46 1510
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RADIAL FLUX DISTRIBUTION

Type I Sleeve Configuration SNAPTRAN Assembly

Figure 5

TABLE V A
THERMAL TEST CONFIGURATIONS

<u>Sleeve</u>	<u>Shim Thickness (inches)</u>		<u>Excess Reactivity (\$)</u>
	<u>Drum</u>	<u>Reflector</u>	
I	None	None	3.95
II	$\frac{1}{4}$	$\frac{1}{4}$ on 2 flats	2.05
III	1-7/8	$\frac{1}{4}$ on 2 flats	1.22
IV	1-7/8	$1\frac{1}{4}$ on 4 flats	1.43
Central Void	1-7/8	$\frac{1}{4}$ on 2 flats	3.15
Mixed Loading			

TABLE V B
TRANSIENT TEST CONFIGURATIONS

<u>Sleeve</u>	<u>Shim Thickness (inches)</u>		<u>Excess Reactivity (\$)</u>
	<u>Drum</u>	<u>Reflector</u>	
I	None	None	3.83
II	None	$1\frac{1}{4}$ on 4 flats	2.92
III	$\frac{1}{2}$	$1\frac{1}{4}$ on 4 flats	2.07
Central Void	None	$1\frac{1}{4}$ on 4 flats	2.50
Mixed Loading	$\frac{1}{2}$	$1\frac{1}{4}$ on 4 flats	2.93

block and drum noticeably altered the shape of the integral worth curve and the total worth of the drum. Three drum C calibration curves were selected for illustration and are presented in Fig.6. These curves represent the extreme variation from the no shim case.

Calibration curves for drums B, A, and D are presented in Fig.7. These were taken during the M1 sleeve configuration with no shims on the reflector or drums. During the course of the thermal testing with the Type II sleeves, the drive shaft on drum B twisted about 8° . Thus full in is indicated as 8° instead of 0° . Since, for transient tests, only that portion of the drum from "step" to "full in" is of interest, the calibration curve is plotted as having zero worth at 8° .

D. WORTH MEASUREMENTS

The total worths of the various concentrations and combinations of gadolinium-nickel sleeves were measured in the SNAPTRAN Assembly. The results of these measurements are presented in Table VI A and are all relative to the nickel sleeve configuration.

TABLE VI A

SLEEVE WORTHS

<u>Sleeve Type</u>	<u>Worth Relative to Nickel (\$)</u>
II	-2.71
III	-5.04
IV	-7.29
Mixed Loading	-4.20
Central Void	-3.13 ⁽¹⁾

(1) From measurements reported in Ref. 7, void worth is - \$2.90. Therefore, the Type IV central sleeve is worth $\sim$ - \$0.23.

The worth of each of the aluminum and steel rods in the central position in the Type IV sleeve is presented in Table VI B. These worths are all with respect to a void.

DRUM C. INTEGRAL WORTH CURVES

Figure 6

DRUMS A, B, D INTEGRAL WORTH CURVES

Type I Sleeves, No Shims

Figure 7

TABLE VI B
ALUMINUM AND STEEL WORTHS

<u>Rod Diameter</u> <u>(inches)</u>	<u>Worth (¢)</u>	
	<u>Al</u>	<u>Steel</u>
$\frac{1}{2}$	+ 6.2	+ 9
$\frac{7}{8}$	+18.5	+17.5
$1\frac{1}{4}$	+43.5	+24

The reactivity effect as a function of $\Sigma_a t$ for gadolinium is presented in Fig. 8. Again, the worths shown are relative to $\Sigma_a t = 0$ (nickel only). The value of $\Sigma_{at} = .118$ for the mixed loading was obtained from an arithmetical average of the Σ_{at} for 19 Type IV and 18 Type I sleeves. No weighting factors were used.

REACTIVITY EFFECT OF GADOLINIUM SLEEVES

(Worth Relative to Ni Sleeves)

Figure 8

E. TEMPERATURE TESTS

Isothermal temperature coefficients were measured for each of the configurations shown in Table V A up to system temperatures of 1150°F. The reactivity loss at nominal system temperatures of 400°F, 600°F, 900°F, and 1150°F relative to ambient temperature operation is presented graphically in Fig. 9. The variation of temperature defect at 1200°F with gadolinium concentration is presented in Fig. 10.

The value of the temperature coefficient at various system temperatures is presented in Table VII for each configuration. This value was obtained by calculating the slope of the reactivity loss curve (Fig. 9) at each specified temperature.

F. TRANSIENT TESTS

A summary of the initial conditions for each of the transient tests conducted is shown in Table VIII. A detailed discussion of the results will be presented in another report.

ISOTHERMAL TEMPERATURE EFFECT ON REACTIVITY

Figure 9

TABLE VIIVARIATION OF TEMPERATURE COEFFICIENT
WITH TEMPERATURE

<u>Temperature, °F</u>	<u>Gadolinium Concentration (Σ_{at})</u>					
	<u>I</u> <u>Ni</u>	<u>Central</u> <u>Void</u>	<u>II</u> <u>0.073</u>	<u>Mixed</u> <u>0.118(1)</u>	<u>III</u> <u>0.15</u>	<u>IV</u> <u>0.23</u>
150	0.12¢/°F	0.12¢/°F	0.11¢/°F	0.10¢/°F	0.10¢/°F	0.04¢/°F
300	0.17	0.16	0.15	0.12	0.10	0.07
600	0.24	0.22	0.20	0.16	0.12	0.08
900	0.28	0.24	0.21	0.17	0.16	0.11
1200	0.29	0.25	0.22	0.21	0.17	0.14

(1) Arithmetical average

TABLE VIII
TRANSIENT TEST SUMMARY

Test No.	Date	Sleeve Configuration	Shim Configuration		Planned Reactivity Insertion	Initial Temperature	Comments
			Drum	Fixed			
1	10/29/68	Type I	None	None	60¢	80°F	Scrammed Before Peak
2	10/30/68	"	"	"	66¢	90	
3	10/31/68	"	"	"	80¢	100	
4	11/1/68	"	"	"	\$1.05	120	
5	11/4/68	Aborted - Failure in B drum charging system					
6	11/6/68	Type I	None	None	\$1.20	80	
7	11/7/68	"	"	"	\$1.30	100	
8	3/13/69	"	"	"	18¢		Drum Calibration Check
9	3/13/69	"	"	"	60¢	73	
10	3/14/69	"	"	"	80¢	93	Detector Amplifiers not Operating Properly
11	3/17/69	"	"	"	\$1.20	73	} Timing Signals Not Recorded on FM Tape
12	3/17/69	"	"	"	\$1.20	366	
13	3/17/69	"	"	"	\$1.20	609	
14	3/17/69	"	"	"	\$1.20	356	
15	3/20/69	"	"	"	\$1.20	82	High Background Noise on Tape Recording
16	3/20/69	"	"	"	\$1.20	350	
17	3/20/69	"	"	"	\$1.20	560	
18	3/20/69	"	"	"	\$1.20	860	
19	3/31/69	Type I + Void	"	1 1/4" on 4 flats	60¢	74	
20	3/31/69	"	"	"	80¢	210	
21	4/1/69	"	"	"	\$1.20	127	
22	4/1/69	"	"	"	\$1.20	320	
23	4/1/69	"	"	"	\$1.20	601	

(nore)

TABLE VIII (contd)

Test No.	Date	Sleeve Configuration	Shin Configuration		Planned Reactivity Insertion	Initial Temperature	Comments
			Drum	Fixed			
24	4/11/69	Type II	None	None	60¢	72°F	Detector Calibration Run. Scrammed Before Peak.
25	4/15/69	"	"	"	60¢	77	
26	4/15/69	"	"	"	60¢	230	
27	4/16/69	"	"	"	80¢	153	
28	4/17/69	"	"	"	\$1.20	118	
29	4/18/69	"	"	"	\$1.20	263	Scrammed Before Peak
30	4/18/69	"	"	"	\$1.20	617	
31	4/18/69	"	"	"	\$1.15	930	
32	4/21/69	"	"	"	\$1.20	78	Scrammed Before Peak
33	4/21/69	"	"	"	\$1.20	125	
34	4/29/69	I IV	$\frac{1}{2}$ "	$1\frac{1}{4}$ " on 4 flats	60¢	73	
35	4/29/69	"	"	"	60¢	370	
36	4/30/69	"	"	"	80¢	215	
37	5/1/69	"	"	"	\$1.20	138	
38	5/1/69	"	"	"	\$1.20	350	
39	5/1/69	"	"	"	\$1.20	620	
40	5/13/69	III	$\frac{1}{2}$ "	$1\frac{1}{4}$ " on 4 flats	60¢	72	
41	5/14/69	"	"	"	60¢	103	
42	5/14/69	"	"	"	60¢	270	Scrammed Before Peak
43	5/19/69	"	"	"	50¢	75	
44	5/19/69	"	"	"	50¢	350	
45	5/23/69	"	"	"	50¢	520	Scrammed to Limit Avg. Temp. Rise to 250°F
46	5/23/69	"	"	"	50¢	870	
47	6/3/69	I	None	None	50¢	70	
48	6/4/69	"	"	"	60¢	85	
49	6/5/69	"	"	"	80¢	95	Scrammed Before Peak
50	6/6/69	"	"	"	\$1.20	85	
51	6/6/69	"	"	"	\$1.20	350	
52	6/6/69	"	"	"	\$1.20	620	
53	6/6/69	"	"	"	\$1.20	860	

SECTION 2

WATER IMMERSION EXPERIMENTS

SECTION 2

WATER IMMERSION EXPERIMENTS

I. DESCRIPTION

A. FACILITY

Measurements of the reactivity effects of Gd^{155} on a water immersed SNAP core were performed in the SNAP Critical Facility (Bldg 012) which is located near the north boundary of the Atomics International Nuclear Field Laboratory. An artists view of the facility is shown in Figure 11. A detailed description is presented in Ref. 6.

B. SNAP CRITICAL ASSEMBLY-4B (SCA-4B)

The SCA-4B machine was used for all of the water immersion experiments. A photograph of this machine is shown in Figure 12. The assembly consists of an upper reflector tank and core vessel which are welded together and attached to the upper support structure and a base tank which is attached to a moveable frame. Raising the base tank to the operating level is accomplished by means of a magnet and motor-drive system. A dimensional drawing of these components is shown in Figure 13. This configuration also allows for attachment of a radial beryllium reflector when required.

C. OPERATION

The operation of the SCA-4B machine consists of the following steps:

- 1) Raising the base tank to the upper limit
- 2) Filling the base tank with water to a level just above the top of the fuel. Since the bottom of the core vessel is perforated, this also floods the core vessel.
- 3) Adding water to the top tank to achieve a critical configuration. Reactor control is accomplished by raising or lowering the water level in the top tank. With 3 inches of water in the top tank the reactor core is fully reflected.

Building 012 General Critical Building
Figure 11

1507-0580

SCA-4B CRITICAL ASSEMBLY MACHINE

5-21-63

CLASSIFIED

7611-1818A

Figure 12

TI-696-13-013
Page 45

NOTE: ALL DIMENSIONS IN INCHES.
BASE TANK IN UP POSITION

7-27-64

7611-Q558

SCA-4B Small Top Tank Configuration

Figure 13

All operations are performed remotely from the control console. Water levels are monitored by television observation of sight glasses mounted on each tank.

Adjustment of the core excess reactivity is provided by the use of boron carbide filled aluminum tubes (boron splines) which are inserted in the interstitial spaces in the core vessel as required. A measure of the excess reactivity is then obtained from the measurements of the water level in the top tank.

II. PROGRAM

A. CORE LOADING

Fuel elements with M sleeves were loaded onto the SNAPTRAN grid plates in the SCA-4B assembly in the manner described in Part I until a critical configuration was achieved. Then, with the addition of each element to the minimum critical configuration, boron splines were added to adjust the excess reactivity such that criticality was always achieved on the top tank water.

Upon completion of the experiments with this configuration, Type II sleeves were installed and all 37 elements reloaded in one step with the spline configuration of the preceding series. Consequently, the reactor was subcritical by the worth of the gadolinium. Criticality was then achieved by removing the poison splines in a stepwise manner using the inverse multiplication technique. This procedure was followed for each subsequent configuration.

B. CONFIGURATIONS

The configurations studied during the water immersion phase of the program are summarized in Table IX. Configurations 1 through 5 were fully

water reflected except for the 6 internal beryllium reflectors which were used throughout the program. (See Fig. 14). For configurations 6 and 7, an external beryllium reflector was installed around the core vessel. The reflector used was the basic SNAP 10A reflector block with control drums and accessory hardware removed. This entire assembly was fully immersed in water.

TABLE IX
WATER IMERSION CONFIGURATIONS

<u>Number</u>	<u>Sleeve Configuration</u>	<u>Gadolinium Concentration (Σ at)</u>
1	I	0 (Nickel only)
2	II	0.073
3	III	0.150
4	31 IV, 6 III	0.217 calculated average
5	Central Void with I, II, III, or IV sleeves	*
6	III with external Be reflector	0.150
7	Mixed Loading **	0.118

*The Central Void configuration consisted of 36 Type I sleeves with the central element removed and the designated sleeves installed in the central element location.

**The Mixed Loading consisted of Type IV sleeves on the inner 19 elements and Type I sleeves on the outer ring of 18 elements.

C. REACTIVITY MEASUREMENT TECHNIQUES

Immediately following the establishment of a new configuration, the worth of the water in the top tank was calibrated. This was accomplished by adding (or removing) boron splines to change the critical water level. Excess reactivity was then added by raising the water level a known amount and measuring the resulting period. In this fashion an

incremental water worth was measured over the useful range of from $1/8$ in. to $3\frac{1}{2}$ in. of water in the top tank and an integral worth curve constructed.

Spline and sleeve worths were then determined by removing a spline or sleeve and noting the change in critical water level. However, when sleeves were removed from the core they were not replaced with Ni sleeves so the worths obtained are with respect to the no sleeve condition. Total spline and sleeve worths were obtained by summing the individual values.

D. FLUX DISTRIBUTION MEASUREMENTS

Axial and radial flux distributions were measured for each configuration as described in Part I of this report.

E. WATER TEMPERATURE COEFFICIENT

In the course of a day's operation, the water pump would operate continuously for periods of up to 8 hours. During this time, the water temperature would rise to as high as 95°F as a result of the pumping action and would cool to $\sim 72^{\circ}\text{F}$ during the subsequent overnight shutdown period. It was then determined that increases in water temperature of this magnitude contributed a rather large positive reactivity effect to each spline and sleeve measurement. In order to correct the data that had been taken, the water temperature coefficient and rate-of-rise as a function of pumping time were measured. To extend the temperature range over which data could be obtained, electrical immersion heaters were placed in the water storage drums and water temperature raised to 110°F . The reactor was periodically brought to critical during the temperature rise and the excess reactivity from the reference water height measured. This test was conducted

with each of the four sleeve configurations (Nos. 1-4, Table IX). No water temperature measurements were conducted with the beryllium reflected configurations.

III. RESULTS

A. REACTIVITY MEASUREMENTS

The water immersion phase of the experiment was initiated with the fuel loading procedure. Fuel was loaded with Type I sleeves installed and a critical configuration achieved with 27 elements. Loading was continued to the full core using boron splines to offset the excess reactivity. The loading was completed with 37 fuel elements and 35 splines. This core, using SNAPTRAN fuel elements on a 1.27 inch lattice, was approximately 20¢ more reactive than the SCA-4B fuel on a 1.26 inch lattice for the same spline configuration.

The spline configuration was then rearranged to provide a more uniform distribution. The final configuration, 36 splines, is shown in the core loading diagram, Fig. 14. Spline and sleeve (fuel) locations were classified by radius as shown in Table X. Numbers given in the column headed "Typical Location" refer to the element numbers shown in Fig. 14. Spline configurations with gadolinium sleeves installed are presented in Figs. 15 through 18.

The reactivity effects of removing the splines one at a time are listed in Table XI for each sleeve configuration. The summation of these worths plus the excess reactivity controlled by the top tank water level was calculated as shown. As gadolinium was added to the core in increasing concentrations the number of boron splines required to maintain a critical configuration was correspondingly reduced. All of the splines were removed with a configuration of 31 Type IV sleeves and 6 Type III sleeves. By measuring the difference in worth between a Type IV and a Type III sleeve in each of the 6 locations containing the Type III sleeves it was calculated that a core fully loaded with Type IV sleeves would be 61¢ subcritical when immersed in water. Sleeve worth results are also presented in Table XI.

Figure 14

Spline Configuration, Type I Sleeves

Figure 15

Spline Configuration - Type II Sleeves

Figure 16

Soline Configuration - Type III Sleeves

Figure 17

Spline Configuration

Type III Sleeves with External Be Reflector

Figure 18

Spline Configuration

Mixed Loading with External Be Reflector

TABLE X

SPLINE AND SLEEVE CLASSIFICATION

Boron Splines

<u>Type</u>	<u>Typical Location</u>	<u>Radius</u>
1	18-11-10	.733 in.
2A	18-19-11	1.466
2B	18-19-26	1.940
3A	26-19-27	2.643
3B	27-20-19	2.933
3C	34-27-26	3.196
4A	27-20-Be	3.666
4B	27-34-Be	3.880

Gadolinium Sleeves

<u>Type</u>	<u>No. in Core</u>	<u>Typical Location</u>	<u>Radius of Center of Sleeve</u>
1	1	10	0
2	6	11	1.27
3A	6	19	2.18
3B	6	12	2.54
4A	12	20	3.35
4B	6	13	3.81

TABLE XI

WATER REFLECTED REACTIVITIES

Soline Worths

Position Type	<u>Type I Sleeves</u>		<u>Type II Sleeves</u>		<u>Type III Sleeves</u>	
	Number	Reactivity	Number	Reactivity	Number	Reactivity
1	3	49.6 $\neq$	2	44.9 $\neq$	1	40.5 $\neq$
2A	3	44.8	2	41.0	0	-
2B	6	40.3	3	35.8	3	32.8
3A	6	29.0	3	27.2	2	25.0
3B	3	28.5	0	-	0	-
3C	6	23.3	6	22.0	3	18.8
4A	3	20.4	3	18.4	0	-
4B	6	19.8	3	17.8	0	-
Total	36	1104.3 $\neq$	22	601.4 $\neq$	9	245.3 $\neq$
Top Tank Excess		40.0 $\neq$		21.0 $\neq$		5.0 $\neq$
Total Reactivity		1144.3 $\neq$		622.4 $\neq$		250.3 $\neq$

Sleeve Worths

<u>Type</u>	<u>Number</u>	<u>Type II</u>	<u>Type III</u>	<u>Type IV</u>
1	1	13.7 $\neq$	27.8 $\neq$	46.0 $\neq$
2	6	15.9	25.3	41.0
3A	6	9.1	20.3	28.5
3B	6	10.2	18.0	22.0
4A	12	8.8	21.8	30.5
4B	6	<u>13.1</u>	<u>22.4</u>	<u>31.5</u>
Total Worth		409.1 $\neq$	805.4 $\neq$	1070.4 $\neq$

The reactivity lost by the addition of gadolinium to the core was calculated from the spline and sleeve worth measurements and is plotted as a function of gadolinium concentration in Fig. 19.

B. CENTRAL VOID CONFIGURATION

Table XII presents the central fuel element worth and the worths of the various sleeves installed in the central location with the fuel element removed. Sleeve worths are all with respect to the nickel sleeve.

TABLE XII
CENTRAL VOID AND SLEEVE WORTHS

<u>Item</u>	<u>Worth (¢)</u>
Central element	+152
Type II sleeve	- 47
Type III sleeve	- 83
Type IV sleeve	-112

C. BERYLLIUM REFLECTED CONFIGURATION

Critical configurations were achieved with Type III sleeve and mixed sleeve (IV & I) loadings with the external beryllium reflector block installed around the core vessel. Spline worths and excess reactivity measurements are presented in Table XIII. Since no water temperature coefficient measurements were conducted with these configurations, the data reported in Table XIII are uncorrected for water temperature variations. A review of the corrections applied to the data from the unreflected configurations indicates a probable error of about 50¢ in the total reactivities reported in Table XIII.

Comparing the total worth of the splines in the Type III, water reflected configuration, \$2.45, with the same spline worth in the beryllium reflected configuration, \$8.65, indicates that to a first approximation the reflector is worth about \$6.20 with respect to water when fully immersed.

D. TOP TANK CALIBRATION

An integral worth curve for the water in the SCA--B top tank was determined for each configuration. Very little change in the shape of the curve or the total worth of the water in the top tank was noted. A typical integral worth curve is presented in Fig. 20.

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Figure 19

Reactivity Effect of Gadolinium

Figure 20

Top Tank Integral Worth
(SCA-4B Assembly)

Integral Worth - ϕ

Water Height - Inches

TABLE XIII
BERYLLIUM REFLECTED REACTIVITIES

<u>Spline Worth</u>				
<u>Position</u> <u>Type</u>	<u>Type III Sleeves</u>		<u>Mixed Loading (IV+I)</u>	
	<u>Number</u>	<u>Reactivity</u> <u>(ϕ)</u>	<u>Number</u>	<u>Reactivity</u> <u>(ϕ)</u>
1	3	44.6	6	30.9
2A	3	39.2	6	32.9
2B	6	35.95	8	32.7
3A	3	28.0	3	28.7
3B	3	25.8	4	26.7
3C	6	25.5	6	25.2
4B	6	19.8	6	29.6
Total	30	900 $\dagger$	39	1166 $\dagger$
Top Tank Excess		13		20
Total Reactivity		913 $\dagger$		1186 $\dagger$

<u>Sleeve Worth</u>				
<u>Position</u> <u>Type</u>	<u>Type III Sleeves</u>		<u>Mixed Loading (IV+I)</u>	
	<u>Number</u>	<u>Reactivity</u> <u>(ϕ)</u>	<u>Number</u>	<u>Reactivity</u> <u>(ϕ)</u>
1	1	27.5	1	20.5
2	6	25.9	6	21.8
3A	6	18.0	6	23.2
3B	6	16.1	6	26.8
4A	12	25.0	0	
4B	6	29.6	0	
Total Worth	37	865 $\dagger$	19	451 $\dagger$

E. FLUX DISTRIBUTIONS

Relative axial flux distributions obtained from the gold foil activation data are presented in Figure 21 for those sleeves configurations with no external beryllium reflector installed. The Type IV sleeve configuration consisted of 31 Type IV and 6 Type III sleeves as discussed earlier in this report. Figure 22 shows axial flux distributions for two sleeve configurations with the external beryllium reflector installed.

All axial distributions have been normalized to the maximum value in each case. No significant effects on the axial flux distribution were observed as a result of changing sleeves or adding the external reflector.

Radial flux distributions are presented in Figure 23 for those sleeve configurations without the external beryllium reflector. Again, the Type IV configuration contained 6 Type III sleeves. Figure 24 presents the radial distributions obtained with the external beryllium reflector installed. All radial flux data were normalized to the central foil in each case. A significant change in radial flux distribution occurred in the Mixed Loading configuration with the external reflector installed. Flux peaking in the outer ring of elements is quite evident.

F. WATER TEMPERATURE COEFFICIENT

From the excess reactivity measurements obtained during the water heating tests, a water temperature coefficient was calculated for the operational range of temperatures; i.e., 70⁰ F to 100⁰ F. These results are presented in Table XIV.

Figure 21

Figure 22
Axial Flux Distributions

(External Be Reflector Installed)

○ - Type III
X - Mixed Loading

Figure 23

Relative Foil Activity

Radial Flux Distributions
(No External Be Reflector)

O - N1

X - Type II

□ - Type III

◇ - Type IV

Radial Distance - Inches

Figure 24

Radial Flux Distributions
(External De Reflector Installed)

TABLE XIV

SCA-4B WATER TEMPERATURE COEFFICIENT

<u>Sleeve Type</u>	<u>Temperature Coefficient ($\phi/^{\circ}\text{F}$)</u>
I	+0.39
II	+0.53
III	+0.53
IV	+0.57

Spline and sleeve worth data were corrected using these values and the rate-of-rise heating curve. Due to its long time constant the fuel temperature changed very little during the short time (~ 5 min/run) that the core was immersed in water. The abrupt change in coefficient between the nickel and gadolinium sleeve configurations is significant, but a quantitative explanation is, as yet, unavailable.

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