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FINAL REPORT ON THE
SNAP 10A PROTOTYPE
CRITICAL ASSEMBLY STUDIES
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FINAL REPORT ON THE
SNAP 10A PROTOTYPE
CRITICAL ASSEMBLY STUDIES

(Title Unclassified)

By

D. W. CLIFFORD

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ABSTRACT

A detailed experimental program conducted on the SCA-4C reactor assembly has yielded extensive design information for the SNAP 2/10A flight reactor. The experiments were primarily concerned with core reactivity and buckling measurements, and external reflector studies. The core measurements showed how control of hydrogen and beryllium in the fuel region could be used to control the excess reactivity of the system without excessive flux perturbations. The reflector thickness could be used as a fine adjustment of system reactivity. Data on shutdown margins and drum control were also provided. Additionally, other core parameters and various component and human mockups were studied in an effort to ascertain reactivity worths of core components and possible environmental effects on the system.

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I. INTRODUCTION

A. SCOPE

This report presents a brief description of the SNAP Critical Facility and the SCA-4C reactor, followed by a general description of the experimental techniques employed in the program. A brief summary of the results preceeds a later discussion of the experiments, their results, and the conclusions that may be drawn.

B. FUEL DESCRIPTION

The fuel furnished for the SCA-4C reactor consists of 37 standard fuel-moderator elements¹ and 12 special rods, which will be described in the discussion of the experiments. The individual rod compositions are given in the appendix to this report. The standard fuel-moderator is the γ -phase of Zr + 10 wt % of 93% enriched uranium alloy converted to the hydride. The core fuel-moderator volume is 520 in.³ and contains 5.1 kg of U²³⁵ and 464 g-moles of hydrogen. The standard elements are made up of cracked or rejected S2DR rods 10 in. in length, with an additional 2.25-in. piece to give a single element 12.25 in. long and 1.25 in. in diameter.

The fuel-moderator pieces are contained in Hastelloy N tubes of 11 mil wall thickness coated internally with Sm₂O₃, and the elements are sealed by welding an end cap at each end. The rods have a nominal N_H of 6.4×10^{22} H atoms/cc, and a nominal uranium content of 135 gm.

C. SYSTEM DESCRIPTION

The SCA-4C experimental program was conducted at the SNAP Critical Facility located at the Santa Susana Nuclear Field Laboratory of Atomics International. The facility provides remote control and observation of the reactor under test, while providing radiation protection for the test crew.^{2,3}

The frontpiece is a photograph of the SCA-4C machine, and a diagram of the core is shown in Figure 1. The reactor is a prototype of the SNAP 10A flight reactor and is designed to provide zero-power test capabilities for defining nuclear characteristics of the system² (estimates of power levels attained are of 1 watt or less). The cylindrical core vessel is 9 in. in diameter and is

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Figure 1. SCA-4C Core Diagram

designed to contain the 37 cylindrical fuel-moderator elements. From Figure 1 it can be seen that the fuel is arranged in a triangular array to form a hexagonal right cylinder measuring 8 in. across the flats and 9 in. across the corners. Six cusp-shaped lengths of beryllium fill the volume between the hexagonal fuel region and cylindrical shell. The fuel rods and beryllium inserts are supported and held laterally by grid plates at top and bottom.

The core is surrounded radially with a 2-1/4-in. beryllium reflector pivoted at the bottom to fall away from the core in halves (Figure 2). The halves, called safety elements, each contain two rotating control drums which provide fine control of reactivity by regulating the neutron leakage from the core (see Figure 17). The control drums are semicylindrical in shape, with a radius of curvature of 3.5 in. However, their maximum thickness is only 2-1/4 in., so they are not completely one half of a right circular cylinder. The safety elements and two of the drums are controlled remotely, whereas the other two drums are

called passive and are positioned by hand in the cell. In Figure 2, one safety is up with the drum rotated out, while the other safety is down with the drum in. The thickness of the reflector is variable in 1/8 in. steps from 1-7/8 in. to 2-1/4 in. Further discussion of the reflector follows in Section V.

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Figure 2. Beryllium Reflector Pivoted Away From Core

To assemble the reactor to criticality, the safety elements are first driven up individually by magnet-coupled linear-drive motors at a rate of 3°/min. Total movement is 15°. Figure 3 is a photograph of the drive mechanisms, showing the Slosyn motors, rack and pinion gear drive, magnet head, snubbers, and the safety arms extending through the table. After both safeties are up, the two active control drums may be adjusted, one at a time, to the desired critical configuration. Fission and ion chamber detectors provide flux monitoring through standard electronic instrumentation.

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Figure 3. SCA-4C Safety Element Drive Mechanism

D. REPRODUCIBILITY BETWEEN PHASES

The SCA-4C program was conducted in two separate phases, necessitated by scheduling of the critical facility. Phase I produced preliminary measurements of core reactivity and component mockup worths, the results of which led to an improved understanding and thus to various refinements in technique (so that the Phase II measurements are in many cases revisions of Phase I data). Phase II was more extensive and constituted the bulk of the experiments which provided final design criteria for the flight reactor.

II. PROCEDURES, ERRORS, AND SUMMARY OF RESULTS

A. PROCEDURES

Before any nuclear experiment may be undertaken, a detailed test procedure must be submitted and approved. This procedure outlines the techniques and sequence of operation, as well as accounting for all possible hazards. The experimental techniques employed at the SNAP Critical Facility are fairly standard and well-accepted practices. Reactivity is commonly found by first calibrating a control drum and then by using the drum to measure other reactivity changes. The drums are calibrated by the period-bump method wherein one drum is rotated in from the steady-state critical configuration so that a convenient stable period results. This period is accurately measured and then the opposing drum is rotated out until the steady-state condition is again reached. The increment each drum is moved is then assigned a reactivity value as obtained from the measured period in conjunction with the inhour equation. In this manner, the total worths of the active drums are found each time the core or reflector configuration is changed appreciably. The inhour tabulation used was obtained from the six delayed group inhour equation using values of β_i and λ_i for uranium²³⁵ given in ANL 5800, "Reactor Physics Constants."

When measuring other reactivity changes, steady-state critical configurations are determined before and after the change is made. The difference in drum positions in the two cases yields the worth of the change from the calibration curves of reactivity vs drum position. Other techniques employed are pulsed neutron decay and inverse multiplication, but these methods are not relied upon for accurate measurements. Relative flux mappings are obtained by irradiation of U²³⁵ foils positioned throughout the core during operation (discussed in Section IV).

B. ERROR DISCUSSION

With an awareness of the procedures used in this series of experiments, a general discussion of their accuracy and the errors involved may follow. As described in the preceeding paragraph, the majority of measurements are obtained either directly or indirectly from a drum calibration obtained from a plot of reactivity worth vs drum position. The accuracy of this curve is then the determining factor in the accuracy of a measurement made by this method.

In analyzing the operation of calibrating a drum, the first consideration is determining the position of the drum. During the SCA-4C program all control element positions were determined by affixing precision potentiometers at the rotational axis of the element. A regulated d-c power supply furnished a voltage which was applied across each pot. The voltage drop across the variable portion of each pot was then measured and presented in digital form in the control room by a digital voltmeter. The drum positions were read in volts with 0 to 10 volts corresponding to drum rotations from 0 to 135°. In combining the errors contributed by (a) nonlinearities in the potentiometer; (b) variations in power supply output; and (c) sensitivity, measuring, and digitizing of the DVM, an error of ± 0.025 volts results, or an uncertainty in drum position of about ± 20 min of rotation (or $1/3^\circ$). This error would be observed over an extended period of time (several days). Over a short period of time (a few hours), the positions indicated should be much more consistent. The fluctuations in voltage supply may be neglected, and the uncertainty drops to about 6 min or 0.1° . This error corresponds to an uncertainty of about 0.5¢ at the maximum slope on the drum curves.

Other errors involved in obtaining a drum calibration curve arise from period measurements and the determination of the steady-state critical configurations. The periods are measured by repeatedly recording the output of an ion chamber over a given interval of time as the flux rises. This recording is done through an electronic system and results in outputs accurate within less than 0.5%. This error is insignificant, since the manual plotting and curve fitting result in an uncertainty of 1.5% in the magnitude of the period. If an accurate tabulation of the inhour equation is assumed, the reactivity of the drum interval can then be determined with an accuracy of 1%. This would amount to an uncertainty of 0.2¢ if a 30-sec period were measured.

The consistency of the difference between the critical positions of the two active drums when interchanged indicates that the steady-state is being repeated at each run with an accuracy of 6 min or 0.1° . If all of these errors are then combined, it is found that each period and steady-state operation involves an error of less than 1¢. As approximately 10 of these operations are combined to calibrate a drum, a total worth is obtained involving an uncertainty of ± 10 ¢ or about 5% of the total worth. Hopefully, the error is somewhat less, but this cannot be guaranteed.

In comparing critical configurations before and after a small reactivity change, the slope of the calibration curve is effectively invariant in the linear region, and the position uncertainty determines the accuracy of the measurement. Differences of the order of 10¢ could be determined within $\pm 1.0\text{¢}$. In the more general case, the error can be assumed to be of the magnitude of 1¢ (for uncertainty in two drum positions) plus 5% of the reactivity difference measured. If, in this report, experiments are discussed wherein the results might be expected to deviate differently than described here, it will be so noted at that time.

C. SUMMARY OF RESULTS

The reactor was initially brought to critical with 32 fuel rods in the core (five Lucite "dummy" rods filled the other positions) with the minimum (1-7/8 in.) reflector. Loading continued to full core (37 fuel rods) and drum calibrations were performed. A control drum was found to be worth about \$2.25, and the total excess reactivity was determined to be about \$4.80. In an effort to lower the excess to conform to flight system requirements, a number of low-hydrogen fuel rods were substituted into the core. It was found that seven low- N_H fuel elements lowered the excess by \$1.48, while 10 low- N_H rods caused a \$1.98 decrease in reactivity.

As an alternate means of lowering the total excess, two beryllium rods were substituted for fuel rods in the core. It was found that the two beryllium rods reduced the reactivity anywhere from \$1.25 to \$3.00, depending on position, with a substantial weight reduction. Flux mappings made with the beryllium and low- N_H rods in the core showed no excessive flux perturbations. Neither the low- N_H rods, the beryllium rods, nor even a poison rod in the center position has any measurable effect on drum worth.

Several experiments were designed to study other nuclear characteristics of the core. Fuel claddings containing various amounts of samarium poison were compared at various radial fuel positions. In the center position, the samarium coatings were worth about 0.95¢/mg-in., while peripheral worths were about 1/4 that.

Detailed reflector studies were conducted to determine the effects of cross-shimming active and passive surfaces. The results showed that the reactivity could be varied in 7¢ steps (at the sacrifice of uniformity) over a total range of

\$1.26 by judicious use of shims. Interaction effects also were noticed and measured between drums.

Various human and component mockups were studied in an effort to determine the effect of environmental changes and to establish safety factors. The maximum reactivity a human body could add to the system was found to be a little more than \$2.00, while the normal amount would be less than \$0.50. All other environmental changes resulted in reactivity changes of less than \$0.35.

The top grid-plate temperature coefficient was measured to be worth $-0.026\text{¢}/^{\circ}\text{F}$ without the internal beryllium reflectors attached, and $-0.034\text{¢}/^{\circ}\text{F}$ with the beryllium attached.

III. LOADINGS

A. LOADING APPROACH TO CRITICAL

To approach criticality in a safe manner, a planned procedure was adapted for all fuel loadings. The same general procedure for loading to critical was followed at the beginning of each phase of the program. Initially, the core vessel was loaded with 37 dummy Lucite rods, the reflector was unshimmed, and the two passive drums were rotated full in. The loading sequence was carried out in 12 steps, starting from one side of the core and working across to the other, following the order in which the fuel positions are numbered in Figure 1. In each loading step, a predetermined number of Lucite rods were replaced by fuel rods and the reactor was then assembled. Counts and signals were then recorded on all detector channels, and the points were plotted as an inverse multiplication curve of fuel rods vs inverse counts. The curve was then extrapolated to zero to find the predicted critical loading. In each case, the predicted number of rods needed to achieve criticality determined the size of the next loading increment as determined from Table 1. The Phase II loading sequence progressed as follows: 7, 3, 2, 3, 3, 2, 3, 3, 3, 1, 1, 1.

TABLE 1
FUEL LOADING CRITERIA

Loading Number	Maximum Loading Increment
1	1/4 of calculated critical loading
2	3/16 of extrapolated critical loading
3	1/8 of extrapolated critical loading
Subsequent Loadings	1/8 of extrapolated critical loading

Criticality was achieved in a slightly different manner in Phase I. After the twelfth loading, 31 fuel rods were in the core and criticality was extrapolated to 31.03 rods. A set of 1/8 in. beryllium shims was then added to the reflector and the reactor was brought to critical with an excess reactivity of 11.7¢. The Phase II loading proceeded to the 32nd rod with no shims and was brought to critical with an excess reactivity of 62.0¢. Assuming a fuel rod worth of \$1.00

and a set of shims to be worth about 42¢, the second configuration appears to be 8¢ less reactive.

B. LOADING TO FULL CORE

Each phase subsequently proceeded to a full core loading of 37 fuel rods with no shims on the reflector. The standard procedure for such an operation is to proceed in the subcritical region by rotating the passive drums out and continuing the approach to critical procedure. The fully loaded configuration provided a reference point of reproducibility between the two phases. Although the reflector had been completely dismantled between phases, the reproducibility was extremely good. The drum positions at critical differed by less than 2.0° in a region where the incremental drum worth is less than 1.5¢/° of rotation, giving a difference of 3¢ between phases.

IV. CORE REACTIVITY CONTROL

A. EXCESS REQUIREMENTS

Several related experiments were performed in an effort to determine closely the nuclear characteristics of the core. Flight system requirements dictate that the optimum excess reactivity be determined for the intended period and mode of operation. Sufficient reactivity must be present to override the various power and poison effects encountered at operational levels and still have a reasonable amount of excess reactivity on hand. The magnitudes of these various effects can only be approximated, so the final value of excess initially required may only be known within a range of 15 to 20%. For this reason, it is desired to set the core reactivity, which will be fixed in all future tests, to the calculated excess with an intermediate number of reflector shims in place. Then, as the various effects become defined more clearly, shims may be added or subtracted to compensate for errors in the estimated values. Initial measurements made with two shims in place have indicated that the excess reactivity is approximately \$1.50 higher than that required for the system.

Two approaches to lowering the excess reactivity seem to give promising results. The first approach is to replace several of the central fuel elements with similar elements having a lower hydrogen content. Because of the good moderating properties of hydrogen, a change of 8% in the hydrogen content of one fuel element results in lowering the reactivity by 20¢. Several low-N_H rods were substituted into the core and produced reactivity changes of the magnitudes desired.

The second approach to the problem involves the substitution of two or three dummy beryllium rods for fuel rods. The major advantage of the beryllium rods is their substantial weight savings. The details of these experiments are presented in the following paragraphs.

B. LOW-HYDROGEN FUEL LOADINGS

The 10 low-N_H fuel elements served a dual experimental purpose. As a group they served to lower the excess reactivity, and when measured singly they served to establish a hydrogen coefficient for the core. The primary consideration here is the cumulative loading and its effects on the system. In this

case, the low- N_H rods were substituted into the core for the standard elements, one at a time, until all 10 were in the core. After each substitution, the reactor was assembled and the change in reactivity was measured. In this manner, the incremental change in reactivity was determined with each loading, as well as the net cumulative effect of total change in N_H . Refer to the cross hatched positions in Figure 1 for the low- N_H loading. Table 2 summarizes the results of the cumulative loadings. It can be seen that seven low- N_H rods lowered the total excess by \$1.44 to make it \$3.36, and 10 rods lowered the excess by \$2.11 to a value of \$2.69. These values of total excess are in the range of flight system needs.

TABLE 2
LOW- N_H FUEL LOADINGS

Low- N_H Rod Number	Substituted for Standard Rod Number	ΔN_H /Rod $\begin{smallmatrix} +0.05 \\ -0.15 \end{smallmatrix}$ ($\times 10^{22}$ /cc)	$\Delta \rho$ Worth (¢)
111	93	-0.28	-13.5
112	89	-0.57	- 7.2
113	107	-0.61	-21.9
114	110	-0.40	-15.7
115	102	-0.44	-31.9
116	106	-0.45	-21.0
126	105	-0.42	-22.8
127	103	-0.47	-19.7
128	88	-0.62	-23.0
129	81	-0.62	-24.2
		Average -0.49	-210.9

Following the cumulative loading, two sets of beryllium shims were affixed to all shimmable reflector surfaces, increasing the thickness to 2-1/8 in., and resulting in a \$0.90 increase in system reactivity. The low- N_H rods were then removed from the core and the regular fuel elements were replaced in their original positions. The total excess reactivity of the system was now raised to \$5.70.

Drum calibration and relative flux distributions were obtained for each of these three configurations in an effort to determine whether reflector shimming or loss of hydrogen in the central fuel positions have any effect on core buckling.

The following procedure was established and followed in obtaining the relative flux distributions. With the reactor disassembled, certain fuel elements were removed from the core and 1 cm² U²³⁵ foils were attached at designated positions (Figure 4). The fuel elements were then replaced in the core and the reactor was made critical. The foils were irradiated for 30 min near the top of the operating power range. As soon as possible after irradiation, the foils were removed and their activation was measured using a scintillation detector to count the gamma activity of the fission products. The counts were corrected for weight, background, and decay and were normalized to the center of the core. The results of these irradiations are shown in Figures 5 through 13. Radial traverses were made at the center and top planes, as were the circumferential traverses. Axial traverses were made at the center and peripheral positions, as indicated in Figure 4. An attempt to make the drum positions symmetrical during irradiations was reasonably successful as indicated by the circumferential mappings in Figures 7, 10, and 13.

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Figure 4. SCA-4C Foil Irradiation Positions

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 Figure 5. SCA-4C Axial Flux Distribution,
 No Shims, 10 Low- N_H Rods

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 Figure 6. SCA-4C Radial Flux Distribution,
 No Shims, 10 Low- N_H Rods

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Figure 7. SCA-4C Circumferential Flux Distribution, No Shims 10 Low- N_H Rods

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Figure 8. SCA-4C Axial Flux Distribution, 2 Shims Everywhere 10 Low- N_H Rods

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Figure 9. SCA-4C Radial Flux Distribution, 2 Shims, 10 Low- N_H Rods

3-30-64 7623-0142
Figure 10. SCA-4C Circumferential Flux Distribution, 2 Shims, 10 Low- N_H Rods

3-30-64 7623-0143
 Figure 11. SCA-4C Axial Flux
 Distribution, 2 Shims,
 37 Regular Rods

3-30-64 7623-0144
 Figure 12. SCA-4C Radial Flux Distribution
 2 Shims, 37 Regular Rods

3-30-64

7623-0145

Figure 13. SCA-4C Circumferential Flux Distribution,
2 Shims, 37 Regular Rods

3-30-64

7623-0146

Figure 14. SCA-4C Radial Flux Distribution, Both Curves
Adjusted to Same Average Flux
(Volume Weighted)

In studying these figures, two conclusions are apparent. Namely, adding shims to the reflector has no significant effect on the buckling, whereas substitution of the low- N_H rods into the core results in a definite lowering of the peak flux and a raising of the peripheral flux. Figure 14 shows a direct comparison of the two midplane radial traverses normalized to the same average flux. The significance of this flattening lies in the fact that a more level flux distribution means a better distributed power load among the fuel elements. In the peaked flux case, the center rods are carrying a disproportionate share of the load which leads to a greater possibility of those elements failing earlier than anticipated. The other flux mappings show no abnormalities, and the circumferential mappings are indicative of the reflector configuration.

In summary, we may conclude that the substitution of 10 low- N_H rods into the core causes a \$2.11 lowering of the total excess to a value of \$2.69. Addition of 1/4 in. of beryllium shims raises the excess back up to \$3.59 with no effect on core buckling. However, replacing the low- N_H elements with the regular fuel results in a higher peak flux and an excess reactivity of \$5.70.

C. BERYLLIUM ROD LOADING

Two dummy beryllium rods, identical in dimensions to the fuel rods, were placed at several positions in the core to determine their effect on reactivity, drum worths, and relative flux distribution. These beryllium rods weigh about 1 lb (463 gm) each, and thus represent a weight reduction of 2.3 lb/rod.

Initially one beryllium rod was placed in three different radial positions. The two beryllium rods were then measured together in three different positions (Figure 15). First they were placed in adjacent fuel positions, then diametrically opposite on the hexagonal flats, and finally on diametrically opposite corners of the fuel loading. A flux distribution study was conducted at the last configuration to ascertain whether any perturbations resulted from loading the beryllium rods. The only traverse showing anything significant was the circumferential plot in Figure 16. The radial and axial traverses were made at the standard positions (Figure 4) and were not truly significant since they did not include the local area of the beryllium loading. The circumferential flux is seen to be significantly unperturbed, and in this case some of the foils were attached directly to the beryllium rods.

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Figure 15. SCA-4C Be Rod Loadings,
Rods D1-D2

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Figure 16. SCA-4C Circumferential Flux Distribution,
No Shims, 2 Be Rods, 35 Regular Rods

The reactivity worths of the various loadings are summarized in Table 3. The beryllium rods are designated as D1 and D2. The beryllium rods had no observable effect on drum worths.

TABLE 3
BERYLLIUM ROD WORTHS

Case Number	Core Position		Total Worth (-\$)
	D1	D2	
1	10	—	1.66
2	28	—	1.30
3	37	—	0.65
4	37	30	1.56
5	20	30	1.57
6	31	1	1.24

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V. REFLECTOR STUDY

A. SCOPE AND PURPOSE

After determining the basic reactivity properties of the core, a detailed study of the properties of the beryllium reflector was necessary. Some of the phenomena which were investigated included the dependence of the control capabilities on the reflector thickness and total excess of the system, and the drum interaction effects which are present and how they must be compensated. Other experiments concerned the worth of the aluminum backings and supports and the shutdown margins of the system. All these problems concern, in some way, the final configuration that will be adapted to provide the optimum excess for the system.

As was stated in the introduction, the reflector is arranged in two halves pivoted at the bottom to fall away from the core. The reflector is octagonal in cross section, with the core vessel appearing as an inscribed circle (Figure 17). Of the eight segments of the reflector, four are in the form of hemicylindrical

Figure 17. SCA-4C Reactor
Cross Section

rotating drums with radii of 3-1/2 in. and maximum thickness of 1-7/8 in. when unshimmed. Two of the remaining four segments are initially 1-7/8 in. and shimmable, while the last two are fixed at 2-1/4 in. thick. The reflector separates along the axial plane bisecting the nonshimmable surfaces to fall away from the core.

For operational purposes, one-half of the reflector is designated as safety No. 1 and the other as safety No. 2. The two drums contained in each safety are designated as active drum and passive drum No. 1 and No. 2, depending in which safety they are contained. Active drum No. 2 is diametrically opposite of active drum No. 1 so that adjacent drums are active and passive. This provides for maximum symmetry of operation and should lessen the effects of drum interactions.

Each of the drums rotates through 135°, and the full-out position is such that the core sees a large leakage path through the vacated cavity. When full-in, the back of the drum completes the stationary reflector surface and the drum cavity is filled. Referring to Figure 17, each of the drums rotate out and away from the center of their safety so that the active and passive drums on opposite safeties are adjacent in the out position, while their vacated cavities are adjacent in the respective safeties. This rotational mode is referred to in section VB.

B. DRUM INTERACTION

The effects of drum interactions were noticed throughout the first phase of experiments, but their exact nature and magnitude was difficult to measure because of the symmetry of active and passive drum locations and the amount of excess reactivity available. Three measurable phenomena were finally isolated and measured late in the second phase of experiments. These effects are as follows:

- 1) The inner portion of active drum No. 1 increased in value as the passive drums were rotated in.
- 2) The total worth of passive drum No. 1 decreased in value, as measured with respect to the active drums, as passive drum No. 2 was rotated in.
- 3) With passive drum No. 2 rotated in 80° or more, a significant difference arose when measuring passive drum No. 1 against the two active drums.

Figure 18 illustrates the first point. In this case, the inner 45° of active drum No. 1 are calibrated in a series of different configurations wherein the passives were rotated to a series of more reactive positions. It is reasonable to assume that this effect of increasing worth is due to the higher relative flux seen by the active drum as the passives are moved in. It is tempting at this point to try to extrapolate to the configuration where both passive drums are full in and take the value obtained for the total worth of this portion of the drum at that configuration. However, this operation is not valid because of secondary interaction effects which will be shown later.

Figure 18. SCA-4C Drum Interaction

Table 4 summarizes the second and third effects. The second effect is actually a result of the first, as described above. That is, passive drum No. 2 is compared to the active drums in each case and, therefore, its worth appears to vary inversely with the active drums. This phenomenon was responsible for values of excess reactivity which were at first thought to be much higher than is actually the case. The excess reactivity was determined by finding the critical

TABLE 4
DRUM INTERACTION EFFECTS

Passive Drum No. 1 Total Worth With Passive Drum No. 2 At
Positions Shown

No Shim Case			
Passive Drum No. 1 Average Worth (\$)	Compared to		Passive Drum No. 2 Position (°)
	Active No. 1 (¢)	Active No. 2 (¢)	
2.48	+20	+18	135 (full out)
2.35	+ 5.2	+ 6.0	60
2.25	- 7.0	- 0.5	48
2.15	-20.5	- 7.5	35

positions of the active drums with both passive drums in the full-out position. The worth of the portion of the active drums remaining out was then added to the worth of the passive drums, as determined in the manner described above. In this case, the value of a passive drum was always measured with the other passive full out, with the result that the active drums were actually worth less than they were thought to be. In the extreme case, passive drum measurements of this type could differ by as much as \$0.50. Finally, a series of period measurement was taken with the passive and active drum positions interchanged, and the results showed that the total worth of the two passive drums was only \$0.06 greater than the combined worth of the active drums.

Effect number 3 seems to be of the second order and is a result of the rotational mode of the drums as discussed in the preceding section. Here, active drum No. 1 and passive drum No. 2 rotate in, facing each other, while active drum No. 2 rotates in from the opposite direction. In other words, the drum material is adjacent in the first case, while the vacated drum holes are adjacent in the second. Thus, rotating passive drum No. 2 in could be expected to have a larger effect on the local flux as seen by active drum No. 2, and indeed this seems to be the case.

To obtain the optimum drum calibrations for the flight configuration, i. e., to obtain the interaction effects which will then be present, the core was uniformly poisoned with boron splines in the fuel interstices so that the active

drums could be calibrated with the passive drums full in. It was found that this calibration coincided most nearly with the average drum calibration obtained with one passive drum full in and one full out. Many of the earlier calibrations were performed at this configuration and thus were used in determining values of reactivity quoted in the following sections.

C. DRUM CALIBRATIONS

The two active control drums were calibrated for a variety of different core and reflector configurations, and many of the early calibrations were later revised because of early failure to consider interaction effects and source influence. Because of the limited flux range available for operating, a stable period could only be run over approximately one decade. The supposed steady-state critical points were found at the bottom of this range initially and were later found to be slightly subcritical due to the source, a 1-c Pu-Be capsule placed on top of the core. Subsequently, the critical points were found at a higher source free level as determined by a source removal experiment. As discussed earlier, later calibrations also had to be corrected for drum interaction so that the final numbers obtained were relatively free of errors from these sources.

Figure 19 shows a matrix which has been partially completed by direct measurements and partially extrapolated. The experimental, combined, drum worth numbers are uncorrected for differences in flight and test configuration, but are adjusted within an experimental error band of $\pm 10\%$ for consistency.

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Figure 19. SCA-4C Drum
and Excess Worths

Some sample drum calibration curves are shown in Figures 20a, b, c, and d, where drum positions are plotted vs reactivity. The shape of these curves is representative and shows the expected approach to zero slope as the drum nears the full-in or full-out position. Similarly, Figure 21, showing the incremental drum worth vs drum position, is typical in that the peak is shifted toward the full-in position because of the increased worth as the local flux builds up and the leakage path grows smaller.

Figure 22 illustrates how various reactivity values react to the various shim configurations. From this figure and the matrix in Figure 19, it can be seen that the total worths of the active drums increase only slightly as shims are added to the passive and stationary surfaces. This increase may be ascribed to interaction effects.

D. EXCESS REACTIVITY

Referring to the total excess values in Figures 19 and 21, it can be seen that the fully shimmed 2-1/4 in. case differs by only \$1.26 from the minimum 1-7/8 in. case. This means that each 1/8 in. set of shims may be assigned an average value of approximately \$0.42 each. The drum shims are worth about 9¢ each, while the stationary reflector shims are smaller and worth about 5¢ each. The total excess numbers are adjusted within an error band of $\pm 20\%$ for consistency, but are uncorrected for flight system differences.

E. BUCKLING EFFECT ON DRUM WORTH

A number of experiments involved attempts to determine whether any change in drum worth resulted from a change in core buckling. Drum calibrations were performed with different core loadings, including 10 low- N_H rods, 2 Be rods, and a poison rod in the core. These loadings produced a variance of flux distributions, and any pattern of changing drum worth should have been apparent. However, even the poison rod in the center position produced no observable effect. The boron-loaded dummy element lowered the reactivity of the system by over \$3.00 and produced the most effective flux perturbation. Any changes in drum worth would have had to have been less than $\pm 5\%$, the limit of experimental error associated with the drum calibrations.

3-30-64 7623-0152
a. No Shims, 37 Regular Elements

3-27-64 7623-0153
b. One Shim (1/8 in.)
37 Regular Elements

3-24-64 7623-0154
c. Two Shims (1/4 in.), 37 Regular Elements

3-27-64 7623-0155
d. Three Shims (3/8 in.),
37 Regular Elements

Figure 20. SCA-4C Drum Calibrations

3-30-64

7623-0156

Figure 21. SCA-4C Incremental Drum Worth, 2 Shims

3-27-64

7623-0157

Figure 22. SCA-4C Shim Effects

F. NULL POINT ON ACTIVE DRUM

The null point, or zero slope, on a drum worth curve was determined by removing the in limit switch and calibrating active drum No. 1 through the full-in position. The results of this calibration are shown in Figure 23, where relative worth is plotted against drum position on an expanded scale. It can be seen that the null point is quite narrow and within 3.0° or 0.4% of the in position that had been used.

3-30-64 7623-0158
Figure 23. SCA-4C Drum Calibration, Null Point At In Position of Active Drum

G. DRUM SUPPORT WORTH

Passive drum No. 1 was removed from the machine to determine the worth of the aluminum drum support and backing. Critical points were found with the backing in the drum-in position, drum-out position, and with the backing removed from the machine. The results of these measurements are tabulated in Table 5. Although the control worth of the backing appears to be 6.5% , it is not necessarily true that 6.5% of the control drum worth is due to the backing. With the drum in position, the backing would have a large reduction in apparent flux and would be worth much less. However, this experiment does show that other portions of the safety and drum supports do have an effect on the system reactivity and should be considered in any normalization of results to the flight system configuration.

TABLE 5
EFFECT OF REMOVING A DRUM AND BACKING
FROM THE REFLECTOR

Reactivity Effect (¢)	Configuration
0.0	Drum and backing in place (drum-out position)
-18.5	Drum removed (backing in drum-in position)
-25.0	Drum removed (backing in drum-out position)
-35.0	Drum removed (backing removed)

H. SAFETY ELEMENT CALIBRATION

Calibration of a safety element was obtained over much of its range by using the period bump technique with the active drum on the opposite safety as the balancing element. Measurements were made from the full-up position (90°) to a position of 79°. The full-down, or scram, position is 75°. The calibration curve is shown in Figure 24, with extrapolation to the scram position showing a total control worth of approximately \$5.90 with both drums full in.

Because of the limited amount of excess reactivity available with both drums out on safety No. 1, only a few points could be obtained on the calibration for this configuration. These few points do indicate a more shallow slope, and the reader may attempt to extrapolate a total control worth. This curve originates at a value of \$4.50 below the drums-in curve on Figure 27 because this number represents the total worths of the two drums.

I. SHUTDOWN MARGINS

An important parameter in the flight system will be the shutdown margins, or the amount of reactivity necessary to make the reactor critical from a given configuration. The values shown in Figure 25 are for the regular fuel loading, and any reduction in core reactivity may be added to these numbers.

Figure 24. SCA-4C Safety Calibration, No Shims

Figure 25. SCA-4C Drum and Safety Shutdown Margins

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VI. ADDITIONAL NUCLEAR CHARACTERISTICS

A. REMAINING PHYSICS PARAMETERS

With the immediate questions concerning major reactivity regulation settled, some of the other parameters of the reactor may now be discussed. The various parameters studied include hydrogen and samarium coefficients, β/l , grid plate worths, and various human and component mockups. These somewhat diversified experiments will be discussed in the remaining sections of this report.

B. HYDROGEN WORTH

Several experiments have provided insight into the part hydrogen plays in the system. During the fuel loadings the Lucite rods were seen to be worth three-fourths of a fuel rod in the later stages. The low- N_H rod loadings, both cumulative and individual, demonstrated how even a small change in hydrogen content results in a large reactivity change. Other experiments were performed which showed a characteristic axial dependence on hydrogen in the core.

Table 6 shows that a Lucite rod is worth more than \$2.16 with respect to void when surrounded by fuel, whereas a fuel rod is only worth \$2.80. The chemical composition of Lucite is $C_5H_8O_2$, and its N_H is 5.64×10^{22} Hatoms/cc or 1.41×10^{25} atoms/rod. It can then be calculated that the value of $\Delta k/k/\Delta N_H/N_H$ is 0.595 at the center of the core and 0.297 at position No. 7 (periphery).

TABLE 6
FUEL WORTHS

Fuel Rod Number	Weight U235 (gm)	Fuel to Lucite (¢)	Fuel to Iron (\$)	Fuel to Void (\$)	Position (center)
93	129.5	74	2.16	-2.89	10
83	128.4	49	-	-1.57	7
117	129.3	52	-	-	32
116	129.0	47	-	-	37

The 10 low- N_H rods were loaded into the center fuel position individually to obtain an average value for the hydrogen coefficient at this position. The results of the loadings are summarized in Table 7. It can be seen that considerable scattering (because of a large uncertainty in N_H values) is present, but a final value of $31.4\text{¢}/0.5\Delta N_H$ with a mean deviation of 3.69¢ is indicated. Using these numbers, it is calculated that this small change in hydrogen has a larger effect of $1.05 \pm 0.12 \Delta k/k / \Delta N_H / N_H$, being intermixed with fuel.

TABLE 7
INDIVIDUAL LOW- N_H ROD WORTHS

Rod Number	$\Delta N_H^{+0.5}_{-1.5} (\times 10^{22})$	Rod Worth (¢)	Worth/ 0.5×10^{22} (¢)
111	-0.28	-14.5	-24.2
112	0.48	13.2	13.2
113	0.48	30.7	30.7
114	0.38	26.7	33.4
115	0.48	30.0	30.0
116	0.38	22.4	28.0
126	0.38	25.7	32.1
127	0.28	23.0	38.3
128	0.48	33.5	33.5
129	0.38	25.8	32.3

Two experiments were conducted on the axial worth of hydrogen. The first determined axial worth for the whole core and utilized 50 Lucite rods 1.22 in. long and 0.135 in. in diameter, placed in the core interstices. The positions of these rods were varied axially by use of aluminum spacers. The total weight of the Lucite was 16.2 gm and the total hydrogen content was 7.8×10^{23} atoms. A subsequent experiment determined the axial worth at the center position. A special segmented fuel rod was furnished with a nonhydrided segment which could be substituted for a normal N_H segment at any of the 12 positions. Table 8 summarizes the data from these experiments, while Figure 26 illustrates the axial dependence in the two cases.

TABLE 8
AXIAL WORTH OF HYDROGEN

Height of Bottom of H Vehicle (in.)	Fuel Segment Worth (¢)	$\Delta k/k/\Delta N_H/N_H$ For Fuel Segment	Lucite Rod Worth (¢)	$\Delta k/k/\Delta N_H/N_H$ Lucite
0	- 8	0.26	2.5	0.014
1.2			11.0	0.63
2.4	-24	0.77	12.5	0.71
3.7			14.5	0.83
4.9	-35.6	1.14	16.5	0.94
7.3			13.0	0.74
8.0	-23.2	0.77		
9.8			7.5	0.43
11.0	- 8.0	0.26

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Figure 26. SCA-4C Axial Worth of Hydrogen

C. SAMARIUM POISON WORTH

A series of experiments has given insight into the effect of distributing samarium oxide (Sm_2O_3) uniformly throughout a SNAP 10A core. The studies were designed to measure the concentration coefficient and the radial position dependence in the core. Two groups of empty cladding tubes, coated internally with the poison material, were furnished with a group of bare fuel rods for these experiments.

The first experiment entailed the reactivity measurement of five tubes containing various concentrations of samarium oxide. The concentrations were determined by destructive chemical analysis of the tubes after the completion of the reactivity measurements. The cladding tubes are referred to as the X-tubes because of their numbering sequence. The concentrations of Sm_2O_3 in mg/in. contained in the cladding tubes are indicated in Table 9.

TABLE 9
SAMARIUM CONTENT OF X-TUBES

Tube Number	Samarium Content (mg/in.)
X-6	0
X-8	3.92
X-10	7.86
X-13	13.01
X-14	14.99

A bare fuel rod was placed in each tube in turn, and the reactivity worths were measured in the center fuel position in the SCA-4 core. Figure 27 illustrates the results which yield a concentration coefficient of 0.95¢/mg/in. in the center position. The extreme concentrations were also measured in third and fourth ring corner positions, resulting in the additional curves shown in in the figure.

Although some radial dependence data were obtained with the X-tubes, it was desirable to obtain a larger effect to reduce the uncertainty in the peripheral measurements. A second group of cladding tubes was provided for this purpose. This group consisted of five tubes with no samarium content and five

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Figure 27. SCA-4C Samarium Concentration Worths

tubes containing nominal loadings of the poison material (7.54 mg/in. of Sm_2O_3 average). These 10 are referred to as the cluster tubes and are accompanied by five bare fuel rods.

The fuel rods were first loaded into the cladding tubes containing no poison and placed in the desired radial positions. After determining the critical configuration, the unpoisoned tubes were replaced with the tubes containing samarium and the reactivity difference was found.

An inspection of the core diagram (Figure 1) reveals that all fuel positions fall into one of six radial categories corresponding to six average radial distances from the center of the core. These positions are referred to by ring number and corner or flat position, with the center element comprising the first ring. The number of test elements used varied from one position to the next and was determined by considerations of symmetry and proximity to open drums. For a given radial worth measurement, the test elements were placed in the same ring, symmetrically on the flats or symmetrically on the corners.

Figure 28 shows the radial worth curves thus generated. It is seen that the center-to-corner traverse lies above the center-to-flat traverse, as might be expected for a noncircular core. As seen from the center, the core appears to be smaller when looking toward the flats and larger when looking toward the corners.

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7623-0163

Figure 28. Cladding Tube Worths in SCA-4C Core

The X-tube measurements agree well with the center-to-corner traverse as shown in the figure. Subsequent experiments performed in the SCA-4A critical machine indicate samarium worths are 8 to 10% higher when measured in the actual flight cores. The difference is most likely caused by a slightly different neutron energy distribution in the region of the samarium resonance, brought about by differences in hydrogen content in the two cores.

D. GRID-PLATE MATERIAL WORTH

An effort was made to determine the relative worths of grid plates of different materials. The materials of interest were stainless steel, Hastelloy C, and Invar. Each of these materials has its advantages, and its effect on the systems reactivity could possibly determine which would be adapted for the flight system.

Early indications were that the material containing more nickel would have a much greater effect on the reactivity of the system because of the greater reflecting properties of nickel. However, the grid plates are not of sufficient volume to have much of an effect, since they are only 1/8 in. thick and 9 in. in diameter and contain 37 pin indexing holes and many more larger coolant flow holes. Indeed, measurements indicated that the Hastelloy C and Invar plates were identical in reactivity, and the stainless plate was worth approximately 3¢ less. The effect of removing a plate was approximately 15¢. An additional measurement showed by comparison that 3/4 in. of solid beryllium above the core was worth 90¢.

E. BERYLLIUM INSERT EXPERIMENT

The worth of the internal beryllium was determined by measuring the reactivity effect of removing one and then two of the inserts. The inserts were worth \$1.00 each, giving a total worth of \$6.00 for the internal beryllium.

F. FAT MAN EXPERIMENT

One of the conditions considered in nuclear safeguards is the so-called fat man accident. This experiment was conducted to obtain reactivity worth data of a simulated human body acting as a reflector. Several approaches were undertaken in mocking up the classical fat man.

The first mockup consisted of a stack of paraffin slabs placed beside and on top of the reactor. The stack of paraffin weighed about 80 lb, and in the first case was placed tangentially to the core as closely as possible (about 5 in.), with the stack about the same height as the core. The total reactivity worth in this configuration was found to be only 14¢. The stack of paraffin placed on top of the reactor was found to be worth 90¢.

The second approach was the adding of Lucite shims to the shimmable reflector surfaces. The results of this procedure are shown in Table 9 and

indicate more than \$1.25/in. as the initial incremental worth when placed on all reflector surfaces. This value cannot be applied easily to a human body because it couldn't be distributed as efficiently as the shims.

The most realistic mockup consisted of 200 lb of Lucite pellets and paraffin blocks filling a pair of coveralls which were placed in various positions around the reactor (Figures 29a and b). The most significant effect resulted from placing the dummy in a standing position on the reactor table with the body leaning over the top of the core and the arms extended around the reactor. The measured worth was 84¢.

The worth of hands in the drum voids was found by filling a pair of rubber surgeon's gloves with Lucite pellets (Figures 29 c and d) and jamming them into the passive drum voids with the passive drums in the out position. Each glove contained approximately 440 gm of Lucite, and the combined worth measured in this way was found to be \$1.11.

It may be concluded from the foregoing that a human body in maximum contact with the reactor and with hands in the drum voids will add a maximum of \$2.15 worth of reactivity to the system if a factor of 15% is added to measured worths to account for a possible difference in reactivity between Lucite and a human body. The results are summarized in Table 10.

TABLE 10
HUMAN MOCKUP RESULTS

Configuration		Worth (\$)
80 lb stack of paraffin	Tangential Above	+0.14
1/8 in. Lucite shim		+0.90
1/4 in. Lucite shim		+0.25
3/8 in. Lucite shim		+0.53
200 lb Lucite dummy		+0.74
2 Lucite hands in drum voids		+0.84
		+1.11

a.

b.

c.

d.

7623-0164

Figure 29. Human Mockup

G. VACUUM TANK AND SHIELD MOCKUPS

A thin reflector built of rectangular plates 1/2-in. thick was placed around the reactor so to circumscribe it at various radii. Plates of Lucite were used to simulate a hydrogenous reflector, and iron and aluminum plates were used to simulate chamber walls. A concrete block reflector was also constructed to simulate cell walls. The measured worths are plotted in Figure 30 as a solid angle cubed and are tabulated in Table 11. A rough estimate for a full chamber can be made by extrapolating the curve in Figure 30 to the solid angle cubed value of unity.

Figure 30. SCA-4C Circumscribed Reflector Worth

A lithium hydride shield similar to the flight shield was placed in position above the core, and its effect was measured at various axial configurations. The shield was positioned at 2-3/8 in. and 3-3/8 in. above the core and at 3-3/8 in. with a 1-1/2 in. paraffin block placed between it and the core to

TABLE 11
CHAMBER MOCKUP RESULTS

Material	Thickness (in.)	Radius (in.)	Worth (β)
Lucite	1/2	19.7	12.5
Lucite	1/2	22.6	8
Lucite	1/2	34.1	3
Lucite	1/2	45.5	1
Lucite	1	22.6	15
Aluminum	1/2	22.6	4
Aluminum	1/2	34.1	2.5
Aluminum	1	22.6	5
Iron	1/2	22.6	10.5
Iron	1/2	34.1	3
Iron	1	22.6	17
Concrete blocks 18 in. high	3-5/8	17	45
by 3-5/8 in. thick	7-1/4	17	57.5

simulate plenum and head components. The measured reactivity worths were \$0.25, \$0.16, and \$0.87 respectively.

H. β/ℓ MEASUREMENT

The ratio of the effective delayed neutron fraction to prompt neutron lifetime was measured by frequency analysis of the reactor noise spectra. A value of 1107 sec^{-1} was obtained for β/ℓ , corresponding to a prompt lifetime of $7.2 \mu \text{ sec}$ if a value of 0.008 is taken for β .

I. SHUTDOWN FLUX DETERMINATION

It is desirable to know the ratio of the shutdown-to-source thermal flux levels and the relative flux levels with the safeties up and safeties down with all drums out. Indium foils, 1 in.^2 , were irradiated in an attempt to determine these flux levels. The irradiation of foils at the shutdown condition (no source present) did not yield counting rates much above background, and no significant ratio of source-to-shutdown level was obtained. However, with the source

present the foils were sufficiently activated to give a significant number of counts which determined that raising the safeties increased the thermal flux level by a factor of two. An upper limit can be set for the no-source shutdown level of 0.037 times the flux with the source in place. Anything greater than this would have been detected.

The following equation was used to calculate the saturation activity of the foils:

$$A_S = A \frac{e^{\lambda t}}{1 - e^{-\lambda T}} \frac{\lambda \tau}{1 - e^{-\lambda \tau}}$$

where

A_S = saturation activity

A = counted activity

t = time elapsed between irradiation and start of count

T = period of exposure to radiation

τ = duration of counting interval

λ = decay constant of indium

VII. GRID-PLATE TEMPERATURE COEFFICIENT

The top grid-plate temperature coefficient has been measured on the SCA-4C reactor assembly. The experiment was conducted with the stainless-steel top grid plate with the internal beryllium unattached.

The grid plate was heated by a standard G.E. heater cable controlled through a 20-amp variac, and was insulated from fuel, air, and core vessel by Fiberfrax paper insulation. The plate was insulated sufficiently to allow it to reach temperatures in excess of 550°F with a heater current of 6.5 amp before heating of the fuel became significant. A group of 10 chromel-alumel thermocouples was utilized to monitor grid plate, fuel, core vessel, and reflector temperatures. Four thermocouples were attached to the grid plate at various radial positions. Three thermocouples were attached to fuel elements near the top of the core. The elements monitored were in positions 10 (center), 27 (1/2 radius), and 37 (full radius). (Refer to Figure 1 for the fuel positions.) Two thermocouples were attached to the inner surface of the core vessel near the top, and one was attached to the reflector. The thermocouple signals were conducted to the control room through an interconnecting thermocouple cable and read out on two instruments. The most representative grid plate thermocouple was connected to a strip charge recorder, and the others were connected through a selector switch to a Wheelco temperature indicator. A full set of readings could be recorded in less than 15 sec.

The results of the critical runs are illustrated in Figure 31, where reactivity is shown as a function of average grid-plate temperature. Three different critical runs were made as indicated in the figure. On the first run, the plate was brought directly to the maximum temperature. On the second and third runs, the temperature was increased incrementally with thermal equilibrium being attained at each step. More scattering is noticed in the first case because separate continuous plots were maintained for drum position and grid plate temperature. The data points shown are a result of cross plotting at representative points.

The four temperature regions indicated in Figure 31 are applicable to the first and second runs. These four regions indicate fuel temperatures below 75°F, below 100°F, below 150°F, and above 150°F, respectively.

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Figure 31. SCA-4C Grid-Plate
Temperature Coefficient

In defining the average temperatures used here, account must be taken of temperature gradients present throughout the experiment. It was found that a 20°F temperature gradient from center to periphery prevailed on the grid plate through Region II. As the temperature entered Region III, various points on the periphery of the plate began to conduct heat to the core vessel, resulting in an increased gradient. By the time the average grid-plate temperature reached the upper limit, the gradient had increased to approximately 80°F. Therefore, the average temperature in the lower regions is generally within 3 to 5% of the extremes, while in the higher regions it is within 10 to 20% of the extremes. The fuel temperatures remained uniform until the core vessel began to heat in the upper regions, after which the peripheral rods began to heat more quickly.

The effect of fuel heating is apparent on the third run as illustrated in Figure 31. This run consumed more time than the others, and fuel temperatures followed the grid plate temperature a little more closely. Presumably, the decreasing slope in this case can be accredited to the added effect of fuel heating.

Figure 31 data yield an effective temperature coefficient of reactivity of $-0.026\text{¢}/^{\circ}\text{F}$ over the range of 75 to 575 $^{\circ}\text{F}$. As inferred earlier, this effect is the result only of movement of the fuel as a result of the thermal expansion of the grid plate coupled to the fuel by the indexing pins. An attempt was made to calculate the probable effect of having the internal beryllium reflectors also attached to the grid plate. The effect of moving the internal reflectors was found by shimming them in their extreme positions and measuring the change in core reactivity. This change was found to be 14.5¢ with an average radial movement of 0.020 in. each. Converting this to ¢/in. and multiplying by the thermal radial expansion of the grid plate in in./ $^{\circ}$ at the proper radius, an additional effect of $-0.008\text{¢}/^{\circ}$ was obtained. If this result is added directly to the measured temperature coefficient, a final result of $-0.034\text{¢}/^{\circ}$ is obtained.

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APPENDIX
SCA-4 FUEL DATA*

Element Number	Total Weight of Rod (gm)	Total Weight of Uranium (gm)	U ²³⁵ Enrichment (%)	H(%)	Av. N _H For Rod -0.1
81	1398.04	138.53	93.15	1.83	6.62
82	1394.95	138.71	93.15	1.81	6.43
83	1388.56	137.72	93.25	1.83	6.56
84	1399.02	138.74	93.15	1.82	6.53
85	1398.39	138.50	93.15	1.81	6.52
86	1397.64	138.53	93.15	1.81	6.52
87	1398.02	138.70	93.25	1.81	6.52
88	1397.25	138.57	93.15	1.81	6.52
89	1397.27	138.45	93.20	1.79	6.47
90	1396.95	138.57	93.15	1.79	6.51
91	1398.33	138.72	93.15	1.78	6.42
92	1399.07	139.03	93.15	1.78	6.39
93	1399.07	139.01	93.15	1.77	6.38
94	1399.66	138.85	93.20	1.78	6.42
95	1387.54	137.61	93.20	1.84	6.58
96	1390.64	138.95	93.20	1.78	6.41
97	1397.57	137.80	93.17	1.78	6.43
98	1407.76	138.79	93.17	1.81	6.57
99	1398.91	137.23	93.17	1.79	6.46
100	1389.68	136.19	93.17	1.80	6.49
101	1398.68	137.49	93.17	1.80	6.50
102	1396.97	137.18	93.17	1.76	6.34
103	1404.21	137.47	93.13	1.87	6.57
104	1403.04	136.94	93.13	1.77	6.42
105	1388.00	135.79	93.17	1.79	6.42
106	1388.93	137.87	93.15	1.80	6.45
107	1400.70	139.38	93.15	1.78	6.51
108	1378.93	136.87	93.15	1.77	6.37
109	1410.00	138.7	93.13	1.77	6.55
110	1410.00	138.7	93.13	1.76	6.40
111	1393.00	136.8	93.17	1.86	6.69
112	1405.74	138.97	93.18	1.81	6.54
113	1398.81	138.56	93.15	1.75	6.31
114	1395.30	138.21	93.15	1.78	6.42
115	1402.82	137.48	93.13	1.80	6.53
116	1406.29	138.52	93.17	1.81	6.56
117	1407.75	133.88	93.13	1.79	6.54

NOTE: Recent measurements indicate that the values given above for N_H average about 0.08 high. The core average is 6.40 instead of 6.48.

*AI-TDR-7164