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IDO-17042

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NUCLEAR TECHNOLOGY BRANCHES
QUARTERLY REPORT
April 1-June 30, 1964

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IDO-17042
AEC Research and Development Report
Reactor Technology
TID-4500 (34th Ed.)
Issued: November 1964

NUCLEAR TECHNOLOGY BRANCHES QUARTERLY REPORT

FORMERLY -- MATERIALS TESTING REACTOR-ENGINEERING TEST REACTOR TECHNICAL BRANCHES
QUARTERLY REPORT

APRIL 1 - JUNE 30, 1964

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Contract AT(10-1) 205

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Previous Quarterly Reports in the MTR-ETR Series

<u>Quarter</u>		<u>Number</u>
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	<u>1963</u>	
1		IDO-16898
2		IDO-16917
3		IDO-16932
4		IDO-16977
	<u>1964</u>	
1		IDO-16994

SUMMARY

Fuel plates containing boron as dispersion in a 1-mil-thick duplex cladding were irradiated to 20 to 29 percent burnup of the U-235. Measurements showed changes in density and thickness equivalent to plates without boron. This technique appears to be a suitable method for incorporating boron in MTR-ETR type fuel plates.

A new comb design for ATR fuel elements shows promise of eliminating prior failures. An equation for calculating the deflection of ATR fuel elements under hydraulic forces was obtained from experimental determination of the effective moment of inertia.

The Advanced Test Reactor Critical Facility (ATRC) achieved criticality May 19, 1964.

New α -particle peaks in the decay spectra of U-235, based upon new high-resolution silicon surface barrier counter measurements, are proposed. The thermal activation cross section of Am-241 to 16-hour Am-242 was observed to be 770 barns, and the resonance activation integral to 16-hour Am-242 was observed to be 900 barns. Gamma spectra with a 3- x 3-inch NaI (TI) detector and with a Li-drifted Ge detector of 2 mm depletion depth and alpha spectra with a silicon solid state detector for Pa-231 are presented. Data from total neutron cross section measurements of Ta-182 are presented.

Neutron beam intensity measurements at 1.2×10^{-4} of operating power for the HT-1 beam hole in the MTR have been performed in anticipation of its planned utilization with the MTR velocity selector. Compared to its present location in HG-6, intensity gains of 14 over the Maxwellian region and 28 above the Maxwellian are indicated. The signal to background due to 1 to 2 MeV neutrons will be 28 and 56, respectively. Experimental neutron inelastic scattering measurements on powdered aluminum with and without Cd spacers show important effects due to multiple scattering, but structure in the scattering law persists when multiple scattering corrections are made. Preliminary first energy transfer moments for liquid argon show agreement with calculated values in contrast to the results obtained with liquid sodium.

A statistical analysis of the measured resonance interference in mixed uranium-238/thorium-232 systems showed that theoretical predictions of their effect, based on a multiresonance treatment of the Nordheim formulation, underestimate the interference. Interference in a typical metal system of these two absorbers could be as great as five percent.

The absorption resonance integral of Rh-103 is 1200 ± 100 barns after adjusting for energy dependence of ARMF weighting factors.

An initial study of the decay of Nd-149, produced by neutron capture, on Nd-148, has been carried out; and delayed state with a half-life of several microseconds has been identified. Measurements have been made on the characteristics of the decay of Ca-47 and of the branching ratio for the 2.18-MeV transition in the decay of Pr-144. Studies have been made to determine the energy calibration of the permanent-magnet spectrograph.

Empirical determination of the response of a strain gauge to a dynamic pressure surge was made over a transient pressure range from 400 psi to 5000 psi. Exploding wires in thin-walled cylinders produced the pressure surges.

Results are reported on the testing of over 300 transducers and cables to determine their transient radiation sensitivities. These tests were performed in the TRIGA Mark F Reactor on behalf of the Spert and STEP projects.

Random noise measurement to determine β/ℓ and $\ell/\bar{\beta}$ for several reactors is reported. A Xenon Simulator is described. This simulator was designed to solve, in real time, the equation describing the formation, decay, and burnup of I-135 and Xe-135 in a nuclear reactor.

Weldable strain gauges, attached to Spert I Oxide Core fuel pin cladding, are analyzed for apparent strain errors during a transient heat transfer condition. The result is compared with experimental evidence.

An IBM 7040 program which generates contour maps of neutron flux from the diffusion code PDQ-40 has been written and is in use. The output is a two dimensional map drawn by the Cal Comp digital plotter. PDQ-40 and TURBO-40 have both been speeded up by improving the tape positioning routines. The Multi-group diffusion code AIM-6 has now been converted to the 7040. A program to analyze gamma-spectra by least-squares determination of both intensities and energies of component spectra has been developed. Several smaller data analysis programs and an inventory control program have been written.

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I. REACTOR ENGINEERING

1. REACTOR FUELS AND MATERIALS DEVELOPMENT (W. C. Francis)

1.1 Use of B₄C + Al Foils in Fuel Plates (G. W. Gibson, B. G. Carlson, M. J. Graber)

A continuing problem in the fabrication of the fuel plates for the ETR fuel elements has been to obtain a uniform dispersion of the boron in the fuel plate. The present practice is to add boron to the uranium aluminum alloy; however, fuel element fabricators have had trouble in controlling the amount of boron present in the alloy and ensuring that it is distributed uniformly throughout the fuel plates. In a prior report [1], the preparation of a set of sample fuel plates, which had a 1-mil-thick duplex cladding of aluminum containing a dispersion of 3.5 weight percent B as B₄C under a 14-mil-thick coating of 1100 aluminum alloy, was given. The core material of these plates was an alloy 19 weight percent U fully enriched in aluminum 20 mils thick.

Sample fuel plates with the duplex cladding were irradiated in the L-51 position of the MTR and examined in the Hot Cell. The results of this examination are summarized in Table I-1.

The density and thickness measurements indicate that the plates have increased in volume slightly. However, these density changes are typical of those of other plates without boron which have been irradiated under identical conditions to similar levels of burnup [2]. The microhardness data of the matrix and fuel particles are similar to that obtained on other fuel plates, but, the increase in hardness observed in the cladding in the zones surrounding the B₄C particles is unusual. It is believed this increase in hardness is due to the diffusion of lithium or helium (formed by the transmutation of the boron) into the aluminum.

The microstructure of a typical irradiated plate is shown in Figure I-1. Figure I-2 is a photomicrograph made at higher magnification showing a B₄C particle encased in the void. The helium gas pockets surrounding the B₄C particles are clearly shown at the core-clad interface. This is of interest since it is believed that this is the first time that an identification of B₄C particles in an irradiated aluminum clad fuel plate has been made.

These results seem to indicate that this procedure is a suitable means for the dispersion of boron in the aluminum fuel plates for use in MTR-ETR type reactors. However, it will be necessary to fabricate full size fuel plates in order to determine if this technique produces a better dispersion of the poison than conventional procedures.

TABLE I-1

EFFECTS OF IRRADIATION ON THE PROPERTIES
OF SAMPLE FUEL PLATES CONTAINING B_4C + Al FOILS

Sample Number	80-2	80-7	80-10
Percent Burnup of original U-235	20	29	28
Density - g/cc			
Before	2.89	2.89	2.89
After	2.87	2.86	2.86
Change	-0.02	-0.03	-0.03
Thickness - mils			
Before	51	50	50
After	52	51	51
Change	+1	+1	+1
Microhardness - DPH			
Cladding			
Before (comparison plate - 46 DPH)			
After	54	50	48
Position 2[a]	223	249	187
Matrix			
Before (comparison plate - 36 DPH)			
After	116	123	122
Fuel			
Before (comparison plate - 181 DPH)			
After	302	334	386

[a] The cladding DPH measurements listed under Position 2 were made within 2 mils of the B_4C particles.

1.2 Hydraulic and Structural Studies upon ATR Fuel Elements (V. A. Walker, M. L. Griebenow, A. D. Kartchner, C. A. Moore)

Hydraulic tests upon ATR fuel elements, fabricated by welding the fuel plates to the side plates and by roll-swaging the fuel plates to the side plates, have been continued. The results of these tests are summarized in Table I-2. Based on these experiments, it has been concluded that: (a) the welded fuel elements appear satisfactory for large external channels, and (b) the roll-swaged fuel elements appear marginal. Motion of the fuel bundle as a function of flow rate has been observed as a result of the lateral differential pressures of about 2 psid between Channels 1 and 20 (the channels external to the external fuel plates). Further investigation of these observations, together with consideration of the resultant reactivity effect during reactor operations, is under-way.

Fig. I-1 Microstructure of a typical irradiated plate.

Fig. I-2 B₄C + Al layer between core and cladding showing B₄C particles surrounded by void.

TABLE I-2

RESULTS OF HYDRAULIC TESTING OF ATR FUEL ELEMENTS

Operating Conditions							
Fuel Element	Outside Channel Configuration	Instrumentation	Nominal	Maximum	Evidences of Failure	Post-Test Inspection	Remarks
DA-5B Welded No Vents	Channel 1 -- 0.108" Channel 20 -- 0.113" No lateral support top or bottom except T-bars.	Static Tubes 6" Pitot Tubes 12"	150°F 100 psid 655 gpm	150°F 243 psid 1050 gpm	At 1050 gpm test section ΔP increased while flow decreased. Velocity heads deviated from slope. Lateral pressures from 2-18 & 18-19 dropped.	Plate 12 failed. The element twisted counterclockwise & shifted toward Channel 1 at the top & toward Channel 20 at the bottom.	Maximum ΔP 's observed were: 2 $\rightarrow$ 1 33.6 psid 18 $\rightarrow$ 19 6.8 psid 19 $\rightarrow$ 20 41.0 psid 1 $\rightarrow$ 20 9.9 psid
DA-1B Welded Mark IV Vent Design	Channel 1 -- 0.108" Channel 20 -- 0.190" Bottom tied down. Top unsupported laterally.	Static Tubes 5" Pitot Tubes 7-1/2"	350°F 100 psid 850 gpm	400°F 211 psid 1265 gpm	Because of instrument failure, fuel element failure was not observed.	Top comb failed.	Maximum ΔP 's observed were: 1 $\rightarrow$ 2 2.0 psid 18 $\rightarrow$ 19 8.3 psid
DA-1B Welded Mark IV Vent Design	Channel 1 -- 0.108" Channel 20 -- 0.190" Bottom tied down & centered. Top semipositioned.	Static Tubes 5" Pitot Tubes 7-1/2" Transducers Strain Gauges	350°F 100 psid 875 gpm	425°F 203 psid 1295 gpm	Deviation of velocity heads from the slope. Lateral pressures deviated from the slope.	Top comb loose. Plate 1 broke away from the side plate. Fuel element shifted and bowed toward Channel 20.	A new comb (pinned clear through) was installed for this test. Plate 1 was beveled at the point of attachment where failure occurred.
DA-10B Welded Modified 3 Vent Design	Channel 1 -- 0.108" Channel 20 -- 0.190" Bottom of element tied down.	Static Tubes 8" Pitot Tubes 12"	350°F 100 psid 850 gpm	350°F 191 psid 1185 gpm	Deviation of entrance losses. Erratic velocity head measurements. A rerun at 1070 showed significant changes.	Bow in Plate 18 toward 19 of about 0.012 from 7 to 10 inches down from the top.	The Pitot tube in Channel 19 had slipped down 10" and restricted the channel just below the point of failure.
DA-10B Welded Modified 3 Vent Design	Channel 1 -- 0.108" Channel 20 -- 0.190" Bottom of element tied down.	Static Tubes 8" Pitot Tubes 12" Transducers	350°F 100 psid 850 gpm	350°F 196 psid 1185 gpm	Entrance losses deviated. Lateral pressures dropped, especially 18 $\rightarrow$ 2, 18 $\rightarrow$ 19, and 20 $\rightarrow$ 19.	Plate 18 failed toward 17 at the top. Top comb failed. Element shifted toward Channel 20 by approximately 0.040"	Since failure was only partial during the first run, the element was rerun. Uneven guides were used above the top comb.
DA-4A Roll-swaged Modified 3 Vent Design	Channel 1 -- 0.108" Channel 20 -- 0.063" Lower end box was firmly positioned & centered. Upper end box restricted laterally.	Static Tubes 17-1/2" Pitot Tubes 18-1/2" Transducers	350°F 100 psid 795 gpm	350°F 225 psid 1247 gpm	Test section ΔP went up and flow went down. Velocity heads, entrance losses, & lateral pressures all deviated. The transducers showed large movement of Plate 19.	Fuel element bowed toward Channel 20. Many plates buckled and many were loose. The top of the side plate peeled back into Channel 20.	To achieve the minimum channel spacing in Channel 20, a considerable amount was filed from the side plate, thus weakening the element appreciably.
DA-9A Roll-swaged Mark IV Vent Design	Channel 1 -- 0.108" Channel 20 -- 0.190" Lower end box allowed to move 0.013" toward Channel 20.	Static Tubes 15-1/2" Pitot Tubes 16-1/2" Transducers	350°F 100 psid 882 gpm	350°F 146 psid 1073 gpm	Velocity heads began to deviate. Lateral pressures from 18 to 19 & 19 to 20 increased greatly.	Fuel element shifted toward 20 by greater than 0.025". Plate 17 buckled near top vent. Many plates loose. Side plate peeled off into Channel 9.	Plates 17 and 18 were slightly loose before the test was begun.

1.21 ATR Fuel Element Comb Failures and Redesign. Three failures of the original design ATR fuel element upper combs have occurred during testing of the elements in a hydraulic test facility. The original comb has a rectangular cross section, $1/8 \times 1/2$ inch, and is 2.534 inches long. It is fabricated of type 6061-T6 aluminum. It has nineteen $3/8$ -inch-deep grooves to form twenty teeth which extend between interior fuel plates and outside of the outside plates. The combs are attached with four $1/16$ -inch-diameter stainless steel roll pins (two at each end) which extend through the first two fuel plates and into the third plate.

The first failure occurred during destruction testing of element DA-1B. The element was removed from the test section when a pressure measurement indicated some type of failure. A number of teeth were broken and the center portion had disintegrated. Since the element was not appreciably damaged, a new comb was installed with two $1/16$ -inch-diameter stainless steel pins extending through all of the plates. During subsequent destruction testing, the comb twisted about 30° to one side and several teeth were broken.

The third failure occurred during destruction testing of element DA-10B. Before starting the test, the comb was removed and reinstalled with $1/16$ -inch stainless steel pins as in the second test of element DA-1B. Again the comb was broken in several places.

After the three failures described in the foregoing, the comb was redesigned. The redesigned comb has a circular top with a $3/32$ -inch radius and tapers to a width of $1/8$ inch at the bottom. Thus, it is $1/16$ inch wider than the original comb; the length and depth are unchanged, and the comb is attached with two $1/16$ -inch-diameter pins extending through all the fuel plates. It is made of type 6061-T6 aluminum.

The new comb design has been tested on one element during destruction testing with no apparent damage. It will be further tested during the destruction testing of future elements.

1.22 ATR Fuel Element Deflection Test. A considerable amount of bending or bowing, normal to the longitudinal axis of the ATR fuel element, has been observed during hydraulic testing. This bending is caused by a difference in the hydraulic pressure in the two outside coolant channels. In order to write an equation relating transverse deflection at any point to differential pressure, it was necessary to determine an effective moment of inertia for the entire element. Since an element is comprised of two end-box sections with different cross sections and a fuel plate section, it was necessary to determine the effective moment of inertia experimentally.

The following two elements were tested: (a) element DA-5B with solid side plates and (b) element DA-10B with three 2-inch-long windows in each side plate. The test consisted of simply supporting the shoe of each end-box creating a clear span of $64-3/16$ inches, and applying two loads of 56 pounds to the side plates at points six inches to the left and right of the center. An elastic deflection of 34 mils was measured at the center of each element; therefore, the windows have negligible effect on the effective moment of inertia of the element. The effective moment of inertia was calculated to be 1.72 in.^4 . Using this value, the deflection equation is given by:

$$y = \frac{P}{48E} \left[465x^4 - 597x^3 + 1505x^2 + 1,135,000x + 13,550 \right]$$

where: y = Deflection at any point in inches

P = Differential pressure between inside and outside channels in psi

E = Modulus of elasticity in psi

x = Distance from center of upper end-box shoe to point of deflection in inches ($56.85 \geq x \geq 7.35$).

1.23 ATR Hydraulic Studies. Initial hydraulic testing of ATR fuel elements indicated the necessity of slotting the side plates to relieve the lateral pressure gradients. The slotting allows flow between channels, and the resulting complex flow patterns make computer solutions of the hydraulic and heat transfer equations necessary. An IBM 7040 program has been written to solve the set of simultaneous hydraulic equations generated for a multivented element (continuity and energy balances) with a further stipulation for the normal set of equations that, at a vent, all channels in communication with the vent must be at the same pressure.

A series of isothermal hydraulic tests were run to determine the entrance and exit coefficients, verify the friction factor, and evaluate the accuracy of the computed results. The measured entrance coefficient for Channels 1 through 19 is 0.5. This value also works for the minimum Channel 20 thickness (0.063-inch), but as Channel 20 thickness becomes larger the apparent entrance coefficient increases. It is postulated that this is a result of an increase in drag around the portion of the upper end fitting that projects over Channel 20. The exit coefficient for Channels 2 through 19 is 0.7; and for Channels 1 and 20, it is 0.9. The friction factors vary from the predicted value by as much as ± 20 percent with the roll-swaged elements on the low side and the welded elements on the high side. The variation in friction factors observed in the hydraulic test was borne out by post-testing optical and electronic profilometer measurements. It is felt that part of their variation may be due to corrosion/erosion under environmental conditions.

Using the measured entrance and exit loss coefficients and the friction factor established for a particular fuel element, the flows calculated for Channels 2 through 18 correspond to the measurements within 5 percent. Channels 1, 19, and 20 vary in size at flow conditions due to the lateral pressures acting across the element as a whole and across Plate 19. (The effect in Channel 19 is small enough at reactor flow conditions to be marginal.) Currently, efforts are directed toward an analytical solution capable of predicting the deflections from the computed pressure differentials.

2. CRITICAL FACILITIES (E. E. Burdick)

2.1 Initial ATRC Experiments (N. C. Kaufman, J. W. Henscheid)

On May 19, 1964, the Advanced Test Reactor Critical Facility (ATRC) achieved its first criticality. The subsequent experimental program verified that the ATRC can be operated safely and within the limits established in the ATRC Safety Analysis Report [3]. During the course of this program, data for the evaluation of the core were obtained.

The first critical loading with 23.6 kg (27 fuel assemblies) was followed by a rod drop experiment [4] which indicated an 11 percent shutdown worth in the safety rods. The loading was then continued until the core contained a full loading of 40 fuel assemblies. The excess reactivity from fuel insertion was compensated by addition of hafnium neck shims. With all neck shims and all 40 assemblies (35 kg) in place, the reactor achieved criticality on May 21, 1964 with all outer shims at 110.8°.

Again, a rod drop experiment was performed. This experiment indicated that the shutdown worth of the safety rods was six percent. A flux map showed a symmetrical neutron distribution and provided a power calibration of the control instrumentation.

An experiment to measure the excess reactivity of the ATRC was performed using uniformly distributed natural boron in lucite strips as a poison to allow the withdrawal of all shims to their outer limits. This poisoning was done in steps to allow for a calibration by periods of the outer shim set. Experiments were then performed which used these reactivity-position curves to obtain the statistical weights of boron and of fuel in positions throughout the core. Table I-3 presents a summary of the results of these experiments.

A diagram of the ATRC as it was during this initial experimental program is shown in Figure I-3. The cruciform neck-shim housing shown in this figure is a temporary installation. This temporary housing duplicates the metal-water ratio of the permanent housing but requires remote, manual operation of the neck shims with the reactor in a shutdown condition. In mid-July the ATRC is to be shut down to permit the installation of the permanent neck-shim housing. It is not expected that the values for the parameters presented in this report will change significantly, although this presumption will be checked when operation resumes.

TABLE I-3

RESULTS OF INITIAL REACTIVITY EXPERIMENTS IN ATRC

<u>Excess Reactivity</u>	<u>\$</u>	<u>Percent^[a]</u>
Excess reactivity contained in all shims	8.9	6.7
Excess reactivity contained in 170 g built-in boron	11.5	8.6
Total excess reactivity	20.4	15.3
<u>Experiment Worths in Flow Tubes</u>		
51 U-Al, 13 Al rods ^[b] in NE (80.3 g U-235)	0.6	0.4
51 U-Al, 13 Al rods in E	0.9	0.6
51 U-Al, 13 Al rods in center	1.6	1.2
<u>U-235 Statistical Weights^[c]</u>	<u>\$/g U-235</u>	<u>Percent^[a]/g U-235</u>
Average in fuel annulus	1.3×10^{-3}	9.9×10^{-4}
In NE flow tube	3.6×10^{-3}	2.7×10^{-3}
In E flow tube	6.5×10^{-3}	4.9×10^{-3}
In center flow tube	1.1×10^{-2}	8.5×10^{-3}
<u>Aluminum Effects in Flow Tubes^[c]</u>	<u>\$/cu in. of Aluminum</u>	<u>Percent^[a]/cu in. of Aluminum</u>
In NE	3.1×10^{-3}	2.4×10^{-3}
In E	3.9×10^{-3}	2.9×10^{-3}
In center	7.9×10^{-3}	5.9×10^{-3}
<u>Natural Boron Statistical Weights</u>	<u>\$/g B(Nat)</u>	<u>Percent/g B(Nat)</u>
Average with 4-5 g/assembly	0.07	0.05
Average with 7-8 g/assembly	0.05	0.04

[a] While not strictly correct, all reactivity values in percent were obtained using $\beta = 0.75\%$.

[b] All rods are 0.187 in. in diameter, 48 in. long.

[c] All measured with #4, #5, and #6 neck rods inserted.

Fig. 1-3 Cross sectional diagram of ATRC core with temporary neck shim housing and center flux trap baffle.

3. REFERENCES

1. G. W. Gibson and W. C. Francis, Annual Progress Report on Fuel Element Development for FY 1962, IDO-16799 (August 1962).
2. G. W. Gibson, "Effect of Irradiation on the Densities of Aluminum-Uranium Fuels" in MTR-ETR Technical Branches Quarterly Report January 1-March 31, 1964, IDO-16994 (August 1964) p 10.
3. E. E. Burdick and J. W. Henscheid, Advanced Test Reactor Critical Facility Safety Analysis Report, IDO-16950 (July 1964).
4. K. V. Moore, Shutdown Reactivity by the Modified Rod Drop Method, IDO-16948 (March 1964).

II. NUCLEAR TECHNOLOGY

1. CROSS SECTIONS PROGRAM (M. S. Moore)

1.1 Fast Chopper (F. B. Simpson)

1.11 Total Neutron Cross Section of Ta-182 (G. E. Stokes, R. P. Schuman). Total neutron cross section measurements have been taken on Ta-182 from 5 to 100 eV. The sample was obtained by irradiating Ta-181 in the ETR for one cycle which gave approximately 1.1 percent conversion. The sample contained 7.78×10^{20} atoms/cm² of Ta-182. A plot of the preliminary data is shown in Figure II-1. These data indicate Ta-182 resonances at 6.0, 13.0, 16.1, 29.5, 31.0, 33.0, 49.8, 58.5, 61.7, 69.0, 73.3, 82.3, and 88.3 eV. There is also indication of resonances at 20.3, 35.0, and 39.5 eV; but due to large Ta-181 resonances at or near these energies, an exact determination will be difficult. The off-resonance cross section has not been corrected for contaminants, and is thus not an accurate representation of the Ta-182 cross section as shown. Additional measurements will be taken on the sample after one half-life of decay to aid in the analysis of the data.

Fig. II-1 Total cross section of Ta-182 from 5-100 eV, uncorrected for contaminants.

2. NUCLEAR CHEMISTRY (W. H. Burgus)

2.1 Alpha Spectrum of U-235 (R. P. Schuman)

In the course of checking out α -counting equipment and new high-resolution silicon surface barrier counters, an anomaly in the α spectrum of U-235 has been observed. The spectra were taken with very thin electroplated samples of highly

enriched U-235 using several different silicon surface barrier detectors. A typical spectrum, taken on a 99.91 percent U-235 sample, is shown in Figure II-2.

The energies of the U-235 α groups have been determined relative to the two major U-238 α groups (4.195 and 4.147 MeV) and the two major U-234 α groups (4.768 and 4.717 MeV) [1]. The errors in the energies are typically ± 3 keV plus the errors in the energies of the U-234 and U-238 standards.

Preliminary abundances of the α groups were determined from the spectra assuming that no U-235 α groups are obscured by the U-234 impurity in the sample. An α line at 4.407 MeV of roughly three percent abundance is proposed to account for the broadening observed on the high-energy side of the 4.380 MeV peak. The low abundance α group observed at 4.149 MeV with very poor statistics may be due to a trace of U-238 inadvertently introduced into the sample.

The energies and preliminary abundances of the U-235 α groups are summarized in Table II-1.

2.2 Am-241 Cross Sections (R. A. Deal, R. P. Schuman)

The purpose of this work is to obtain information useful in selecting irradiation parameters for irradiations of gram-size samples of Am-241 in which sufficient amounts of Am-242m will be induced to permit differential cross section measurements of the latter isotope with the aid of the MTR Fast Chopper. In the present experiment, the objective was to learn whether Cd-shielded irradiations, with lower 152-year Am-242m production and burnout, would yield a sample of higher Am-242m/Am-241 ratio than would unshielded irradiations. Two samples, each ≈ 0.03 mg of Am-241, were irradiated for one cycle in the same high-flux position in ETR. One sample was Cd-shielded, the other unshielded.

After irradiation, the Am samples were purified from fission products and plutonium by AmF_3 precipitations and by Dowex-1 column elutions with 12N LiCl and 10N HCl. The resulting unseparated Am + Cm fraction was examined by alpha pulse analysis. The Cm and Am were then separated by repeated α -hydroxy isobutyric acid elutions from Dowex-50 columns. The individual drops

Fig. II-2 Alpha spectrum of 99.91 percent U-235.

TABLE II-1

ENERGIES AND ABUNDANCES OF U-235 ALPHA GROUPS

Energy (MeV)	Abundance (%)
4.590	5.7
4.550	4.1
4.495	1.4
≈ 4.407	≈ 3.0
4.389	57.7
4.359	17.3
4.318	4.2
4.265	0.4
4.211	6.0
≈ 4.149	≈ 0.2

from the columns were analyzed by gamma spectrometry. The Am-241 was determined by counting its 60 keV γ , and the Cm-242 determined by counting its L - X-ray (see Figure II-3). Since the Cm-242 alpha activity is much greater than the Am-241 alpha activity, the L - X-rays of Am did not obscure those of Cm. The final samples were analyzed by α -pulse analysis. Each column separation gave about a 20-fold enrichment of Am with about an 80 percent yield. The final pure Am will be mass analyzed to determine the ratio of 152-year Am-242m to Am-241.

Fig. II-3 α -Hydroxy isobutyric acid elution curve for Am and Cm.

From the ratio of 162-day Cm-242 alpha activity to 458-year Am-241 alpha activity, as determined by silicon surface barrier alpha spectra, preliminary values of σ_{th} and R. I. for the activation of Am-241 to 16-hour Am-242 were determined. The cross sections were calculated assuming (a) that σ_c to 152-year/ σ_c to 16-hour is 1/15 and does not change with energy, (b) that 16-hour Am-242 decays 81 percent to Cm-242 and has no significant resonance capture and an 8000 barns thermal capture cross section, and (c) that 162-day Cm-242 does not capture significantly. With these assumptions, the thermal activation cross section of Am-241 to 16-hour Am-242 was observed to be 770 barns, and the resonance activation integral to 16-hour Am-242 900 barns.

2.3 Energy Levels in Ac-227 (R. N. Chanda, R. A. Deal)

The availability of a hundred mg sample of Pa-231 has provided an opportunity for study of energy levels in Ac-227 populated by Pa-231 decay. Here are reported preliminary results of level population by α and γ decay of Pa-231; later it is hoped to obtain confirmation of this data by observation of Ac-227 resulting from β decay of Ra-227.

Figure II-4 shows an α -spectrum taken with a solid state detector of 22 mm² area and 15 keV resolution. Thirteen α -groups are discernible in this spectrum. This can be compared with the 11 to 19 groups reported with a high-resolution magnetic spectrometer [2]. Gamma spectra were also taken with a 3- x 3-inch NaI(Tl) detector and with a Li-drifted Ge detector of 2 mm depletion depth. These are shown in Figures II-5 and -6, respectively. To complement these experiments, equipment is being assembled which will permit α - γ and α -e⁻ coincidence studies.

Fig. II-4 Pa-231 α -spectrum taken with surface barrier detector of 22 mm² area and 15 keV resolution. Energy scale ≈ 3.2 keV/channel. $E_0 = 4.23$ MeV.

Fig. II-5 Pa-231 γ -spectrum taken with 3-x 3-inch NaI (Tl) detector. Energy scale ≈ 2.5 keV/channel. Approximate γ -ray energies shown in keV.

Fig. II-6 Pa-231 γ -spectrum taken with 2 mm depletion depth Li-drifted Ge detector. Energy scale ≈ 1.3 keV/channel. Approximate γ -ray energies shown in keV.

3. INELASTIC SCATTERING (R. M. Brugger)

3.1 HT-1 Flux Measurements (R. M. Brugger)

In September, the MTR velocity selector is to be moved from its present hole, HG-6, to a high flux hole, HT-1, of the MTR. Since HT-1 is a through-hole, it is necessary to insert a source block or reflector into the hole that will scatter neutrons out. Measurements were conducted to determine the best size and shape of source blocks to give maximum thermal intensity while giving minimum fast intensity.

An aluminum liner was inserted into HT-1 from the south, through which sample source blocks could be inserted without becoming contaminated. At the north end of HT-1 were positioned a bare fission chamber to detect slow neutrons, a cadmium-covered fission chamber to detect epithermal neutrons, and a fission chamber in a nine-inch-diameter paraffin cylinder to detect 1 to 2 MeV neutrons [3]. The counting rates of these detectors were recorded while the reactor was at 1.2×10^{-4} of operating power and while the source blocks were slowly inserted.

Source blocks 3/8 inch thick at reflecting angles to the beam, and source blocks of varying thickness at right angles to the beam were tried. Figure II-7 shows a flux plot of the beam for a source block two inches thick at right angles to the beam. The 20-inch mark is at the center line of the reactor. Figures II-8 and -9 show the maximum intensities versus reflecting angle for the 3/8-inch-thick pieces and maximum intensity versus thickness for the right angle source blocks.

From these measurements it is concluded that reflection is not the important mechanism, but that moderation and flux peaking in the source block are quite important. The HT-1 hole when empty has a flux of 10^{14} n/cm² sec while the two-inch right angle block peaks the flux to 1.9×10^{14} n/cm²sec. With this block the thermal flux from the hole is 8×10^9 n/cm² sec (uncorrected for beam measurements with an isotropically calibrated foil), while the cadmium-indium ratio is 4.47. To give maximum thermal intensities and minimum fast intensities, the two-inch-thick right angle block is best.

These flux values from this block, compared to measured values at HG-6, indicate that when the velocity selector is moved the thermal intensity will be increased by 14; the intensity above the Maxwellian region will increase by 28; while the signal to fast background change (background arising from neutrons with energies greater than 1 MeV) will be by 28 and 56, respectively.

Fig. II-7 A flux plot of the beam for a source block two inches thick at right angles to the beam.

Fig. II-8 The maximum intensities versus reflecting angle for the 3/8-inch-thick pieces.

Fig. II-9 The maximum intensity versus thickness for the right angle source blocks.

3.2 Powder Aluminum (R. M. Brugger, P. D. Randolph)

The inelastic scattering from aluminum powder was measured using the velocity selector and the powdered aluminum samples described in the January-March 1964 MTR Quarterly Report. This sample is made of 18 sintered blocks, each 2 x 0.25 x 0.46 inches, which are stacked vertically with 0.020-inch cadmium spacers between each 0.25-inch-high block. The purpose of the Cd spacers was to reduce the effects of multiple scattering in the sample. The transmission of this sample when oriented at 45° to the beam is 0.87. Data were taken at incident energies of 0.02, 0.04, and 0.06 eV with the cadmium spacers in place. The runs were then repeated with the Cd spacers removed. The data of the experiment were converted to reduced partial differential cross section $S(\kappa, \hbar\omega)$, and then averaged, for all except the elastic case, over increments of $\log \kappa^2$, as described in the January-March 1964 MTR Quarterly Report.

Figure II-10 shows the reduced partial differential cross section for elastic scattering ($\hbar\omega = 0$) for the runs both with and without cadmium spacers. The strong peaks are due to Bragg scattering from the crystal planes whose Miller indices are shown at the bottom of the figure. The effect of the cadmium in reducing multiple scattering is clearly evident. Since aluminum is an almost completely coherent scatterer, the cross section should be very small or zero at κ values below that of the lowest Bragg peak. The data show that there is still an appreciable amount of scattering in this region, mostly due to multiple scattering. It is seen that the cadmium reduces the total scattering in this region by as much as 30 to 40 percent. For larger κ values the multiple scattering becomes less and the Cd has correspondingly less effect.

Figure II-11 shows the complete scattering law for aluminum (with the cadmium spacers in place) out to an energy transfer of 0.058 eV ($\epsilon = 2.0$). The scattering law shows structure in its κ values as the Bragg peaks of Figure II-10. For larger energy transfer $\epsilon \geq 1$, maxima are still present in the scattering law, though reduced in size; but are displaced in κ , the maxima at these ϵ 's being located where the minima occur for small ϵ . At small energy transfers, the observed structure is explained by using the momentum conservation condition $\kappa \pm q = 2\pi\tau$ where τ is a lattice vector of the reciprocal lattice and q is the wave vector of a phonon excited in the material. For a given Brillouin zone

Fig. II-10 Reduced partial differential cross section for elastic scattering in aluminum powder. The plot includes the results at incident energies of 0.02, 0.04, and 0.06 eV both with and without cadmium spacers in the sample.

at large κ it is seen that the Cd has an appreciable effect indicating that some multiple scattering is still present.

3.3 Liquid Argon (P. D. Randolph)

An experiment on liquid argon at -186°C has been performed using the velocity selector. This was done at 0.02, 0.04, and 0.1 eV. A new sample holder was then built containing Cd sheets inside, spaced 0.75 inch apart, to try to reduce multiple scattering effects, and further data at 0.02, 0.04, and 0.6 eV taken. This latter data have not yet been completely processed. The earlier data taken without the cadmium were converted to a diffraction pattern and compared with similar results obtained by X-rays. The pattern disagrees with the X-ray results in that the positions of the diffraction maxima and minima are displaced. The explanation of this discrepancy has not yet been found. Preliminary measurements of the first energy transfer moment of argon, however, agree with calculated ones. This is in contrast to the liquid sodium results in which the first moment disagreed markedly from the theoretical values.

of the reciprocal lattice and a single acoustical branch of the dispersion relation, the cross section will have a finite value only at those κ values lying in the range $|2\pi\tau - q| \leq \kappa \leq |2\pi\tau + q|$. Outside this range the cross section is zero. Since in a powder sample, several Brillouin zones and more than one branch of the dispersion relations are being examined simultaneously, the cross section has minima rather than going to zero. At the larger energy transfer, the shift of the maxima has not yet been satisfactorily explained.

Measurements of the first moment of the energy transfer $\langle \epsilon' \rangle$ have been made from the scattering law for both the sample with Cd and the sample without Cd. Figure II-12 shows the results. At small κ values, the moment is larger than the theoretical value. The use of the cadmium has a marked effect in improving the agreement with theory at all κ values. At small κ there is still an appreciable discrepancy, though the Cd makes a large improvement. Even

Fig. II-11 Reduced partial differential cross section for aluminum powder with cadmium spacers containing the data at 0.02, 0.04, and 0.06 eV incident energies. The points are the results of averaging over 20 equal increments in $\log k^2$.

Fig. II-12 First moments of the energy transfer for aluminum powder for the sample with and without cadmium.

4. REACTOR EXPERIMENTS (E. Fast)

4.1 Resonance Absorption of Neutrons in Mixtures of Th-232 and U-238 (W. K. Foell)

4.11 Uncertainty Analysis. A detailed statistical uncertainty analysis has been applied to the measurements of interference between resonances of Th-232 and U-238 [4]. Because the experimental techniques used in the measurements were based on a difference method,

many possible systematic errors were canceled, resulting in a small uncertainty in the results. The analysis showed that the theoretical predictions of interference, which were systematically lower than the measured values throughout the entire range of concentrations, fall outside the limits of uncertainty assigned to the experiment. Since these limits of uncertainty have been assigned on a firm basis, it must be concluded that the calculations, based on a multiresonance treatment of the Nordheim formulation, underestimate the amount of interference.

One deficiency of the calculation, of course, is that it was practical to include only a few selected pairs of interfering resonances; if all slightly interfering resonances were taken into account, the calculated interference would increase. However, because the most prominent resonances of uranium and thorium were included in the calculation, it is felt that the inclusion of all the resolved resonances could increase the total fractional interference by no more than 10 to 20 percent. It is realized, also, that accidental overlap may occur in the unresolved range. Assuming that these two possibilities together would increase the fractional interference by approximately 25 percent, the calculations would still underestimate the interference by slightly more than a factor of two.

A second and possibly more serious cause for underestimating the interference may lie in the use of the narrow resonance approximation in the moderator terms of the first-flight coupled equations. This approximation, which is inherent in the present formulation of the Nordheim treatment [5], is based on the assumption that a single collision with a moderator nucleus will cause it to hurdle the energy range of interest; however, the practical width of a pair or group of resonances such as those encountered in the present work is quite large. For this reason, a collision with a moderator nucleus may not remove a neutron from the energy range of interest; hence, absorption in a higher energy resonance may actually cause a deficiency in the number of neutrons entering the fuel lump at the energy of the lower resonance. A further theoretical investigation of the effect is anticipated in collaboration with F. Adler, using more exact solutions of the transport equation [6].

4.12 Higher Density Systems. For experimental reasons, the U-238/Th-232 powdered dioxide samples studied had relatively low absorber densities (less than 6 g/cm³ in the samples of highest concentration). In a reactor, the density of both fertile materials would be greater. Calculations, identical to those performed for the experimental samples, were carried out for cylindrical samples containing U-238 and Th-232 metals of approximately theoretical density. The results showed that the fractional interference approaches three percent for

rods of large radius. If these values were then to be corrected on the basis of the experimental work performed with the samples of lower density, it would be necessary to multiply the calculated results by a factor of approximately 2.5. The interference in a typical U-238/Th-232 system might, therefore, be significant. In a metal rod of one centimeter radius, for example, the effect could amount to five percent. Due to their lower densities, the effect should be less in a mixture of the oxides. Because such interference could compromise the advantages to be gained from a mixed system, this phenomenon should definitely be considered in future work on binary systems.

4.2 Resonance Integral of Rh-103 (J. J. Scoville, E. Fast)

A tentative value of the resonance absorption integral of Rh-103 was reported previously [7]. In further analysis a factor was determined to correct for the energy dependence of the reactor weighting function. The measurements were made relative to gold standards whose primary neutron absorption occurs at 4.906 eV, compared to 1.257 eV for the rhodium resonance. The difference in weighting function between these two energies leads to a correction factor of 1.09 for the ARMF-II with the cadmium shield facility in place. Applying this factor results in a resonance integral for rhodium of 1200 ± 100 barns. This value is in reasonable agreement with the 1100 barns obtained from the literature as an average of calculated results [8].

5. THEORETICAL PHYSICS (H. L. McMurry)

5.1 Brownian Model for Liquid Methane (G. W. Griffing)

The experiments^[9] of Y. D. Harker and R. M. Brugger on the scattering of slow neutrons for liquid methane indicate that at large momentum transfers, their results agree with that obtained from computations assuming the liquid can be treated as a gas. However, at small momentum transfers there are deviations from computations for a gas. One model, which has been considered and rejected in attempting to explain the experimental results, consisted of assuming that the liquid could be thought of as clusters of methane molecules of various sizes.

A more promising model consists of the following: The vibrational and rotational modes have the same degrees of freedom as in a gas. The translational motion is assumed to undergo Brownian motion. The analytical formulation for this model has been completed and shows that gaseous behavior will result at large momentum transfers. Methods for computations of the resulting formula are being developed. Comparisons of this model will be made with the experiments.

6. LOW-ENERGY NUCLEAR PHYSICS -- DECAY SCHEME STUDIES (R. L. Heath, J. E. Cline)

6.1 Decay of Nd-149 (L. D. McIsaac, R. G. Helmer)

The radioactive nuclide ${}_{60}\text{Nd}^{149}$ decays by electron emission with a half-life of 1.7 hours to levels in ${}_{61}\text{Pm}^{149}_{88}$ which in turn decays with a half-life of 54 hours to Sm-149. The only previous reports on the radiations from the decay

of Nd-149 are the internal-conversion-electron studies of Rutledge et al [10] and the scintillation studies of Gopinathan and Joshi [11].

All of the samples used in this study were produced from neodymium oxide enriched to 88 percent in Nd-148. Irradiations were carried out in the Materials Testing Reactor in fluxes of 1×10^{13} and 2×10^{14} neutrons-sec⁻¹-cm⁻². Even when counted only a few minutes after an irradiation, the Nd-151 (12 minutes) activity was not observable. Spectra obtained one day after an irradiation showed the presence of small amounts of Nd-147, Pm-149, and Pm-151. In all the experiments, care was taken to use samples that contained a minimum amount of these contaminant activities.

This section summarizes the results obtained to date. More experiments are planned.

6.11 Conversion Electrons. Internal-conversion electrons were observed with a set of three 180°, uniform-field, magnetic spectrographs with photographic detection. The spectrographs, which span the energy ranges 2 to 95, 5 to 450, and 10 to 900 keV, have been described previously [12]. A recent calibration of these instruments is discussed in Section II-6.4. The Nd-149 sources were made by vacuum evaporation of neodymium oxide onto graphite blanks. These blanks were irradiated for two hours in a flux of 2×10^{14} neutrons-cm⁻²-sec⁻¹. Usually, the blanks were placed in a spectrograph about 30 minutes after the irradiation. Several sources were made and used.

Three separate experiments were carried out in order to assure that no systematic errors were introduced into the neodymium line energies. In the first case, calibration plates of Ir-192 and Ta-182 were taken before and after a set of Nd-149 plates. In the second experiment, iridium was evaporated onto a blank before the neodymium was evaporated. By varying the exposure times, visible lines were obtained on the same plate from both activities. By this method any possible systematic errors involving the difference in source positions and reference notch measurements [12] were eliminated. The third calibration check came from plates with Nd-149, Ta-182, and Ta-183 lines. The tantalum lines came from evaporation of a part of the tantalum filament used in making the source.

The energies of the conversion lines observed and their interpretations are listed in Table II-2. The results of the "internal" calibrations with Ir-192 or Ta-182 and Ta-183 in the sources are given in Tables II-3 and -4. All average gamma-ray energies for Ta-182, Ta-183, and Ir-192 agree with the "best" values (column 4) to within 1 part in 10^3 . It is, therefore, believed that the energies of the Nd-149 gamma rays, computed from conversion lines, are accurate to at least 0.2 percent or 0.1 keV, whichever is larger. The internal consistency among the Nd-149 energies should be 0.05 percent or 0.1 keV. Several lines that are not listed were observed on two or three plates, but they have not been interpreted unambiguously.

The methods used to determine relative conversion-line intensities from spectrograph plates have been discussed in Reference 12. Densitometer traces of three plates were made. From these traces the relative intensities listed in column 3 of Table II-5 were computed. These calculations include corrections of the areas of the lines for the emulsion sensitivity and for the variation in transmission with position on the plate. The density-exposure relationship [12, 13] was assumed to be linear, except as noted in Table II-5, for the range of densities used.

TABLE II-2

INTERNAL-CONVERSION LINES OBSERVED ON Nd-149 PLATES

Electron Energy	Assignment	Transition Energy	Average
23.07	L ₂	30.09	
23.59	L ₃	30.05	
28.68	M ₃	30.04	30.0
30.61	L ₁ and L ₂ for 38.1		
31.62	or M ₁ and N ₁ for 32.1		
	or K lines for 75.8 and 76.8		
29.25	K	74.45	
67.26	L ₂	74.28	
67.80	L ₃	74.26	
72.89	M ₂	74.35	
74.24	N ₂	74.50	74.4
51.78	K	96.98	
89.66	L ₁	97.09	
95.38	M ₁	97.03	
97.01	N ₁	97.35	97.0
69.12	K	114.32	
106.91	L ₁	114.34	
107.87	L ₃	114.33	
112.68	M ₁	114.33	
114.14	N ₁	114.48	114.3
94.06	K	139.26	
131.82	L ₁	139.25	139.3
110.71	K	155.91	
148.49	L ₁	155.92	155.9
143.59	K	188.79	
181.63	L ₁	189.06	
187.19	M ₁	188.84	188.8
146.91	K	192.11	

TABLE II-2 (Continued)

INTERNAL-CONVERSION LINES OBSERVED ON Nd-149 PLATES

Electron Energy	Assignment	Transition Energy	Average
184.86	L ₁	192.29	192.2
153.77	K	198.97	
191.78	L ₁	199.21	
197.00	M ₁	198.65	198.9
163.03	K	208.23	208.2
200.70	L ₁	208.13	
166.11	K	211.31	
204.03	L ₁	211.46	
209.76	M ₁	211.41	
210.95	N ₁	211.29	211.4
168.84	K	214.0	214.0
195.07	K	240.27	
232.94	L ₁	240.37	
238.73	M ₁	240.38	240.3
222.50	K	267.70	
260.41	L ₁	267.84	
266.02	M ₁	267.67	267.7
225.08	K	270.28	270.3
230.36	K	275.56	275.6
243.05	K	288.25	288.2
281.46	K	326.66	326.7
378.74	K	423.94	423.9
496.36	K	541.56	541.6
239.15	K from Pm-149	286.00	286.0

TABLE II-3

Nd-149-- GAMMA ENERGIES FROM Nd + Ir PLATES

Ir-192 Lines				Nd Lines			
Line Energy	Assignment	E_γ	Best Values [14, 15, 16]	Line Energy	Assignment	E_γ	Average
58.05	K - Pt	136.43	136.33 $\pm$ 0.02	51.78	K	96.98	97.0
123.07	L ₂ - Pt	136.33					
124.69	L ₃ - Pt	<u>136.24</u>		68.99	K	114.19	
	average	136.33		106.93	L ₁	114.36	114.3
131.95	K - Os	205.85	205.79 $\pm$ 0.02	166.00	K	211.20	211.2
193.44	L ₂ - Os	205.82					
194.85	L ₃ - Os	205.71					
203.51	M ₃ - Os	<u>205.96</u>					
	average	205.84					
217.60	K - Pt	295.98	295.93 $\pm$ 0.03				
282.58	L ₂ - Pt	295.84					
284.64	L ₃ - Pt	<u>296.19</u>					
	average	296.00					
230.05	K - Pt	308.43	308.46 $\pm$ 0.03				
295.29	L ₂ - Pt	<u>308.55</u>					
	average	308.49					
238.18	K - Pt	316.54					
303.11	L ₂ - Pt	316.37	316.50 $\pm$ 0.03				
304.91	L ₃ - Pt	<u>316.46</u>					
	average	316.46					
389.84	K - Pt	468.22	468.0 $\pm$ 0.1				

TABLE II-4

Nd-149 + Ta-182 + Ta-183
PLATES II-95, -96, and -97

Ta-182				Nd-149			
Line Energy	Assignment	E_γ	Bent Crystal Values ^[17]	Line Energy	Assignment	E_γ	Average
15.07	K	84.58		22.94	L ₂	29.96	
74.47	L ₃	<u>84.67</u>		23.55	L ₃	30.01	
	average	84.62	84.67	28.53	M ₃	29.89	30.0
53.57	L ₁	65.66		29.19	K	74.43	
62.88	M ₁	65.69		67.22	L ₂	74.24	
65.18	N ₁	<u>65.77</u>		74.04	N ₂	74.30	74.3
	average	65.70	65.74				
55.65	L ₁	67.74		51.72	K	96.92	
57.55	L ₃	<u>67.75</u>		89.61	L ₁	97.04	97.0
	average	67.75	67.74				
30.60	K	100.11		69.05	K	114.25	
88.49	L ₂	100.03		106.76	L ₁	114.19	
89.82	L ₃	100.02		107.77	L ₃	114.23	
97.73	M ₃	100.00		112.60	M ₁	114.25	
99.67	N ₃	<u>100.09</u>		113.97	N ₁	114.31	114.25
	average	100.05	100.09				
44.11	K	113.62	113.66	96.96	K	139.16	139.2
				110.68	K	155.88	155.9
				143.45	K	188.65	
				181.61	L ₁	189.04	188.8
				146.85	K	192.05	192.1
				153.71	K	198.91	198.9
				162.82	K	208.02	
				200.53	L ₁	207.96	208.0
				165.96	K	211.16	
				203.85	L ₁	211.28	
				209.61	M ₁	211.26	211.2
				194.89	K	240.09	
				232.71	L ₁	240.14	
				238.61	M ₁	240.26	240.1
				222.43	K	267.63	
				260.16	L ₁	267.59	267.6
				224.90	K	270.10	270.1

Ta-183			
Line Energy	Assignment	E_γ	Bent Crystal Values ^[17]
34.36	L ₁	46.45	46.48
45.88	N ₁	46.47	
40.46	L ₁	52.55	52.59
38.38	K	107.89	107.93

TABLE II-5

RELATIVE INTERNAL-CONVERSION-ELECTRON INTENSITIES

Transition Energy	Line	Intensity			
		Spectrograph		Solid-State Detector	Adopted Value
		Photographic Plates	Solid-State Detector		
74.3	K	0.17			0.2
97.0	K	0.16			0.16
	L	≤ 0.04			≤ 0.04
114.3	K	2.6 ^[a]	2.6	2.6	2.6
	L	0.24	0.43	0.37	0.35
155.5	K	0.05		≈ 0.04	0.05
188.8	K	≤ 0.05		0.05	0.05
192.2	K	≤ 0.03			≤ 0.03
198.9	K	≤ 0.04		0.05	0.05
208.2	K	0.06			0.06
	L	0.03			0.03
211.4	K	0.55	0.72	0.52	0.55
	L	0.11		0.11	0.11
240.4	K	0.42	0.32	0.30	0.33
	L	0.13		0.04	0.06
267.6	K	0.11		0.05	0.06
270.2	K	0.06		[0.03]	0.03
288.2	K	0.02			0.02
326	K	0.03		< 0.04	0.03
424	K	0.01			0.01

[a] Photographic density of about 1.5. Intensity calculated from linear density-exposure relation and then increased by a factor of 1.5.

In another experiment a surface-barrier-type, silicon, electron detector was placed in one of the spectrographs. The detector had a 1/32-inch-wide slit in front of it to define the electrons accepted. The detector was driven along the focal plane of the spectrograph and its output recorded, after amplification, in a multichannel analyzer. The spectra taken with the slit at the peaks of prominent conversion lines were analyzed. After correction for the variation in transmission with position, the results of these measurements were listed in column 4 of Table II-5.

An electron spectrum taken with a surface-barrier-type, silicon, electron detector is shown in Figure II-13. The components shown and their relative intensities are listed in column 5 of Table II-5. In several regions the resolution is not sufficient to separate the conversion lines. In these cases the spectrographic results have been used to aid in identification and in estimation of the relative intensities. Although there is undoubtedly a large amount of scattering in the source and backing, the shape of the 69-keV line (K-114) does not appear any wider than is expected for this detector. In the computation of these line intensities, it has been assumed that the area of a peak is proportional to the electron intensity with a constant of proportionality which is independent of the electron energy.

In column 6 of Table II-5, the adopted relative intensities are shown.

Fig. II-13 Electron spectrum of Nd-149 sample taken with silicon electron detector. Energies are in keV.

6.12 Gamma Rays. Gamma-ray spectra were measured with a NaI(Tl) scintillation spectrometer, which has been described [18], and with a lithium-drifted germanium detector. Due to its much better resolution, the germanium

detector can be used to resolve gamma rays not observable in the NaI spectrum. However, the small volume of this detector (2 mm thick by 1 cm diameter) results in large Compton distributions. Since the variation of the photopeak efficiency with energy is not precisely known, only approximate intensities were obtained.

Two gamma-ray spectra taken with a lithium-drifted germanium detector are shown in Figures II-14 and -15. Figure II-14 indicates the large number of gamma rays above 660 keV. It is known that several of these gamma rays are from Pm-149 and Nd-147. This region will be studied more carefully after modification of the electronics system which is used with this detector.

The photopeaks in Figure II-15 were fitted with gaussian functions to determine their positions and areas. The underlying Compton distributions were approximated with straight lines. The photopeak positions were used to determine the gamma-ray energies. Before and after the neodymium run, Eu-152 and Cs-137 calibration spectra were measured. The resulting energies are shown in Table II-6. They agree satisfactorily with the spectrograph energies (to within 1 part in 500).

The photopeak areas were used to determine the relative intensities of gamma rays of approximately the same energy. The variation of the photopeak

Fig. II-14 Gamma-ray spectrum obtained with lithium-drifted germanium detector.

Fig. II-15 Gamma-ray spectrum obtained with lithium-drifted germanium detector

TABLE II-6
TRANSITION ENERGIES

<u>Spectrograph</u>	<u>Ge Detector</u>	<u>Coincidence Spectra</u>
30.0		
		59
74.4	≈ 75	
97.0		
114.3	114.3	
139.3		
155.9	155.6	
188.8	188.7	
192.2		
198.9		
208.2		
211.4	} 211.0	
214.0		
240.3	240.6	
267.7	} 269.5	
270.3		
275.6		
288.2		≈ 285
326.7	326.6	
	349.0	
	≈ 365	≈ 365
		≈ 385
423.9	423.9	
	443.8	
		≈ 495
541.6	540.8	
	556.5	
	633	
	655.1	

efficiency with energy was determined approximately from the known efficiency of a NaI crystal and by comparing the areas of the more intense peaks with those of the same peaks in a NaI(Tl) scintillation spectrum (Figure II-16). From this relative efficiency curve, the relative photon intensities in column 2 of Table II-7 were obtained.

The gamma-ray spectrum of a Nd-149 sample measured with a 3- x 3-inch NaI(Tl) crystal is shown in Figure II-16. The decomposition into individual components is shown. Two bremsstrahlung components are used to approximate the effect from those beta rays (≈ 1.5 MeV) to levels of 200 to 300 keV and those (≈ 1.2 MeV) to levels of 500 to 700 keV. The intensities of the bremsstrahlung components were computed from the known intensity of the 655-keV gamma ray (see $4\pi\beta\text{-}\gamma$ coincidence results) and from the spectra of sources of Y-91 and Pr-143 of known disintegration rates. The gamma-ray shapes are from a computer program of R. L. Heath [19]. The intensities and positions of the more intense gamma rays were determined with the aid of a spectrum-fitting program which allows the energies of the gamma rays as well as their intensities to vary [a]. The positions of the weaker transitions were fixed at the values calculated from their energies. The intensities of several of these transitions were "fixed" at a certain fraction of that of a neighboring gamma ray in those cases where such a ratio was available from the Ge detector data. The resulting intensities are given in column 3 of Table II-7. These values have been normalized to percent of decays by use of the results of the $4\pi\beta\text{-}\gamma$ experiments described later.

6.13 Internal-Conversion Coefficients. By proper normalization of the relative intensities in Tables II-5 and -7, the internal-conversion coefficients of several of the transitions can be determined. This normalization was carried out by use of a mixed source of Nd-149 and In-113m. The gamma-ray and electron spectra from this source are shown in Figure II-17, and the resulting relative intensities are listed in Table II-8. A conversion coefficient of $\alpha_K = 0.4$ was used for the In-113m transition [20]. The resulting α_K values are given in Table II-9 along with the K/L ratios computed from the data in Table II-7.

One of the more sensitive indications of a gamma-ray multipolarity is the relative intensity of the three L shell conversion lines. For several transitions, these ratios were estimated by visual examination of the spectrograph plates. These ratios are also listed in Table II-9.

[a] This program is being written by G. A. Jayne of the Applied Mathematics Section. It varies the gamma-ray energies by a "direct search" technique and calculates intensities by a linear least-squares method.

Fig. II-16 Gamma-ray spectrum, of Nd-149 measured with 3- x 3-inch NaI(Tl) detector.

TABLE II-7

RELATIVE INTENSITIES OF GAMMA RAYS BELOW 660 keV
(The values in the brackets were assumed in the fit.)

Energy (keV)	Intensity	
	Ge Detector	NaI(Tl) Detector
655	8.4[a]	8.4
633	0.3	[0.3]
556	1.3	[1.1]
541	6.8[a]	6.8
490	---	0.4
444	1.5	1.6
424	7.4[a]	7.4
385	---	0.5
365	≈ 0.5	0.8
349	1.2	[1.7]
326	3.5	4.8
288	---	4.5
270	{ 15.7[a]	{ 15.7
267		
240	4.0	4.8
211 (+208 +214)	26.2[a]	26.2
198	---	3.6
188 (+191)	1.2	[1.2]
156	---	5.9
139	---	0.5
114	18.9[a]	18.9
97	---	1.4
74	---	2.1
59	---	0.5

[a] These values were used to determine the photopeak efficiency for the germanium detector.

Fig. II-17 Gamma-ray and electron spectra of mixed source of Nd-149 and In-113m.

TABLE II-8

GAMMA-RAY AND CONVERSION-ELECTRON
INTENSITIES FROM SOURCE OF Nd-149 + In-113m

Transition	Gamma Ray	Line	Conversion-Electron
In ^{113m} -393	≡ 1.00	K	≡ 0.40
Nd ¹⁴⁹ -655	0.128		
Nd ¹⁴⁹ -541	0.111		
Nd ¹⁴⁹ -211		K	0.055
Nd ¹⁴⁹ -114		K	0.24

The theoretical internal-conversion coefficients [21, 22] are also given in Table II-9 for dipole and quadrupole transitions. The multiplicities deduced are shown in the last column. Since the relative intensity of the 267- and 270-keV transitions is not known, they were treated as a single gamma ray. The low value of α_K implies that at least one transition has E1 character. If the M2 assignment for the 240-keV transition is correct, this transition should have a measurable half-life. See the $4\pi\beta\text{-}\gamma$ coincidence results which follow for an experiment which demonstrates this long half-life.

TABLE II-9

INTERNAL-CONVERSION COEFFICIENTS

Transition (keV)	Coefficient	Experimental Value	Theoretical Values ^[c]				Multipolarity	
			M1	E2	E1	M2		
30	L ₁ /L ₂	< 1	11	0.004	1.7	13	E ₂ (< 2% M1 mixture)	
	L ₂ /L ₃	≥ 0.5 and ≤ 2	5	0.7	0.65	0.15		
97	L ₁ /L ₃	> 3	60	0.25	4.1	5.4	M1 or any E1 + M2 mixture	
	L ₁ /L ₂	> 2	12	0.3	5.0	8.3		
114	α _K	0.83 ± 0.1 ^[a]	0.94	0.79	0.17	8.0		
		0.9 ± 0.2						
	K/L	4.8 ± 1.6 ^[b]	7.4	1.65	7.0	4.3		
		6.5 ± 1.5						
	L ₁ /L ₃	> 20	66	0.37	5	6	M1 (< 2% E2 mixture)	
155	α _K	0.06 ± 0.03	0.40	0.34	0.075	2.6	E1	
211	α _K	0.14 ± 0.05	0.165	0.13	0.031	0.86	M1 (with < 20% E2 mixture) or 90% E1 + 10% M2	
	K/L	6.6 ± 1.4 ^[b]	6.9	3.7	7.2	5.5		
		+2.5 5.0 -0.8						
	L ₁ /L ₃	> 5	50	1.3	7.7	11		
267 + 270	α _K	0.03 ± 0.01	0.085	0.063	0.016	0.39	One or both E1	
326	α _K	0.04 ± 0.03	0.052	0.032	0.010	0.20	M1 + E2 (any mixture) or E1 (with < 30% M2 mixture)	
240			M1	E2	M3	E1	M2	E3
	α _K	0.51 ± 0.15	0.12	0.090	2.2	0.021	0.59	0.31
	K/L	≥ 5	6.9	4.1	5.0	7.2	5.8	2.3
	L ₁ /L ₃	> 3	14	1.3	3.8	8.4	8.5	0.6

[a] From Reference 11.

[b] From Reference 10.

[c] From References 21 & 22.

6.14 4π β - γ Coincidence Measurements. Several measurements were carried out with the 4π β - γ coincidence system which has been described previously [23]. The intensity of the 655-keV transition in percent of decays was measured by comparing the gamma-ray emission rate of a source determined by scintillation spectrometry with its disintegration rate determined by 4π β - γ coincidence techniques. Nd-149 sources having a thickness of a few $\mu\text{g}/\text{cm}^2$ were mounted on gold-coated VYNS plastic film [24]. When corrected for the delayed 240-keV transition (see below), the results indicate an intensity for the 655-keV transition of (8.4 ± 0.4) percent. The photon intensities in Table II-7 are, thus, given in percent of decays.

The decay of one Nd-149 source as recorded on the gamma-ray channel of the 4π β - γ equipment was followed for more than ten half-lives. The data, shown in Figure II-18, were analyzed to determine the half-life. A value of (1.73 ± 0.01) hours was obtained.

The 4π β - γ coincidence system was also used to investigate the possibility that the 240-keV transition has a relatively long lifetime. The amplifier output

Fig. II-18 Data for Nd-149 half-life measurement.

of the gamma channel was fed to a 512-channel analyzer. The output of the coincidence circuit was used to turn the analyzer off for each coincident event (ie, in anticoincidence mode). The spectra of the Nd-149 are shown in Figure II-19 with the anticoincidence gate on and off. Since the resolving time of the coincidence circuit is $2\tau = 4 \mu\text{sec}$, it is apparent that the 240-keV transition has a lifetime in the μsec range. Further measurements are anticipated to more accurately determine this lifetime.

6.15 Gamma-Gamma Coincidences. Gamma-gamma coincidence measurements were made with a 256 x 256 channel, two-parameter analyzer. The two 3- x 3-inch NaI(Tl) detectors, each located 8 cm from the source, were placed at right angles and a Cd-covered lead wedge used to eliminate Compton scattering between crystals. The signals from each crystal were amplified such that the spectrum presented to each side of the analyzer covered the energy range from 0 to 800 keV. The coincidence circuit used to gate the analyzer had a resolving time of $2\tau \approx 120 \text{ ns}$.

Fig. II-19 Gamma-ray spectrum of Nd-149 demonstrating the long lifetime of the 240-keV transition.

The activity of the source was maintained constant within a factor of two during the measurement by replacing with new source material. The age of the source material used was between one and four hours. A total of about 10^7 coincidence events were accumulated during the run. The results are summarized in Table II-10, and a few of the coincidence spectra are shown in Figures II-20 through -22. These and other spectra were analyzed with the aid of computer programs to generate gamma-ray shapes, to gain-shift spectra, and to compute intensities.

TABLE II-10

GAMMA-GAMMA COINCIDENCE RESULTS

(An X represents an observed coincidence relationship and an O, one which is not observed. A blank indicates a lack of definitive information.)

	59	74	96	114	156	189	192	198	211	268	288	327	349	365	385	424	444	490	541	556	656
59			X	X					X	X		O				O			O		O
74		X		X				X		X			X								
96				X															O		O
114					X					X	X	X	O			X	O		X	O	O
156										X		O				O			O		O
189, 192									X	X			X	X						X	
198																					
211, 208									X	X		X					X		X	X	
214																					
268, 270										X		O	O	O	X	O	O	X	O	O	
288												O		X		O			O		O
327													O	O		O	O		O	O	O
349														O		O	O		O	O	O
365																O	O		O	O	O
385																O	O		O	O	O
424																	O		O	O	O
444																			O	O	O
490																		X			X
541																				O	O
556																					O

6.16 Beta-Gamma Coincidence Measurements. Beta-gamma coincidence measurements were made with a 1/2- x 1-inch anthracene crystal used as the electron detector. Several of the spectra are shown in Figure II-23. These results indicate that the 541- and 655-keV transitions are both preceded by a beta transition of about 1100 keV. The 424-keV transition (and those of 325- and 270-keV) are preceded by a beta branch of about 1200 keV. There is no observable difference between the highest energy beta transitions in coincidence with the 211- and 114-keV gamma rays and the singles. This suggests that any ground-state beta transition is weak.

6.17 Decay Scheme. The proposed partial decay scheme is shown in Figure II-24. The portion of the scheme on the left is considered to be well verified. The portion on the right is consistent with the experimental results but cannot be completely verified. No attempt has been made to include the transitions above 660 keV.

Fig. II-20 Gamma-gamma coincidence spectra. The ranges spanned by the second detector are noted for each curve. Dotted curve represents estimate random coincidences and dashed curve represents calculated bremsstrahlung intensity.

This level scheme has a large number of combinations of gamma-ray energies that must be equal. These combinations are compared in Table II-11. All energies are from spectrograph measurements unless otherwise noted. Most of the coincidence relationships in this decay scheme are illustrated in Figures II-20 through -22.

The ground-state spins of Nd-149 and Pm-149 have been measured to be $5/2$ [25] and $7/2$ [26], respectively. If the shell model description of these nuclei is correct, these states would be expected to result from coupling of several $f_{7/2}$ neutrons and a single $g_{7/2}$ proton, respectively. Therefore, the parities shown in the figure are to be expected.

The M2 character of the 240-keV transition suggests that the 240-keV state has spin and parity of either $3/2^-$ or $11/2^-$. Two possible sets of spins are consistent with the observed multipolarities, and one of these two spins is shown. Other combinations of spins might also be possible.

Fig. II-21 Gamma-gamma coincidence spectra. The ranges spanned by the second detector are noted for each curve.

Fig. II-22 Gamma-gamma coincidence spectra. The ranges spanned by the second detector are noted for each curve. Dotted curve represents estimate random coincidences and dashed curve represents calculated bremsstrahlung intensity.

Fig. II-23 Beta-gamma coincidence spectra.

TABLE II-11

COMPARISON OF SUMS OF TRANSITION ENERGIES WITH ENERGIES OF CROSS-OVER TRANSITIONS AND OTHER SUMS

E_1 (keV)	E_2 (keV)	E_{sum}	E_3
97.0	+ 114.3	= 211.3	211.4
114.3	+ 155.9	= 270.2	270.3
30.0	+ 240.3	= 270.3	270.3
114.3	+ 423.9	= 538.2	538.1[c]
211.4	+ 326.7	= 538.1	
267.7	+ 270.3	= 538.0	
188.8	+ 349.0[a]	= 538	
114.3	+ 288.2	= 402.5	402.6[c]
188.8	+ 214.0	= 402.8	
114.3	+ 74.4	= 188.7	188.8
74.4	+ 214.0	= 288.4	288.2
114.3	+ 541.2	= 655.5	655.1[a]
211.4	+ 443.8[a]	= 655.2	655.1[a]
211.4	+ 556.0[a]	= 767.0	
"402.6" level	+ 365.0[b]	= 768.0	

[a] Energy from Ge detector data.

[b] Energy from coincidence spectra.

[c] Average energy sum.

Fig. II-24 Proposed partial decay scheme for Nd-149. Energies are in keV. Probable multipolarities are shown for several transitions as well as the intensities in percent of decays (in parentheses). Each of the two alternate sets of possible spins and parities are consistent with the data reported herein.

6.2 Decay of Ca-47 (W. W. Black)

This experiment was undertaken with the purpose of clearing up some of the controversial details concerning the decay of Ca-47. It has been known for some time [20] that Ca-47 decayed by beta emission to the ground state and to a 1300-keV excited state of Sc-47. The 1300-keV level is depopulated by a 1300-keV gamma ray to the ground state and by a gamma-ray cascade consisting of 800- and 500-keV transitions. The gamma rays of this cascade will be referred to as γ_1 and γ_2 as indicated in Figure II-25. Sc-47, in turn, decays by beta emission to Ti-47. Until recently, no information was available to indicate the order of emission in the cascade. Recently, however, two groups have reported information on the order of emission in the cascade. Langer, Spejewski, and Wortman [27], in the course of measuring the shape of the highest energy beta group of Ca-47, reported another beta-ray branch which was presumed to populate the first excited state of Sc-47. They report an end point energy of 1486 ± 10 keV for this group which would indicate that the first excited state is at about 500 keV. They also report the following relative beta-ray intensities: 15.8 percent for the 1979-keV beta group, 1.8 percent for the 1486-keV beta-group, and 82.4 percent for the 671-keV beta group. Fuschini, Gadjokov, Maroni, and Veronesi [28] have made gamma-gamma directional correlation measurements and gamma-gamma polarization directional correlation measurements on the γ_1 - γ_2 cascade. They apparently presumed the spins and parities shown in Figure II-25. Then, from the gamma-gamma directional correlation data, they calculate two possible values for the M1-E2 mixing ratio, δ , of the $5/2 \rightarrow 3/2$ transition. The results of the polarization measurements were interpreted as determining the correct δ and then as being consistent with an 800-keV first excited state.

Fig. II-25 The decay chain $\text{Ca-47} \rightarrow \text{Sc-47} \rightarrow \text{Ti-47}$ showing the level structure of Sc-47 and Ti-47. All energies are in keV.

Fuschini et al [28] also measured the half-life of Ca-47 to be 6.8 days which is considerably longer than any other reported value. Langer et al [27] measured the half-life to be (4.7 ± 0.1) days, which is in good agreement with the values listed in Reference 26.

Lyon and Handley [29] have reported the intensity of the 1300-keV transition to be about 14 times the intensity of the 800- and 500-keV transitions. If 82 percent of all Ca-47 decays proceed in the 671-keV beta branch,

this factor of 14 means that the absolute intensity of γ_1 is less than six percent of all decays. Thus, even a minute amount of beta feeding to the first excited state of Sc-47 will result in γ_2 being considerably more intense than γ_1 . A value of 1.8 percent for the intensity of the intermediate beta group would require the 500-keV transition to be about 1.25 times more intense than the 800-keV transition.

It was felt that with present techniques available in this laboratory, an intensity ratio considerably closer to 1 than 1.25 could be measured and, therefore, could provide information on the proper sequence of this cascade. Furthermore, the data obtained would provide a better value of the half-life of Ca-47.

6.21 Experimental Procedure. The activity was produced by irradiating 10 mg of normal CaCO_3 in a flux of $\approx 2 \times 10^{14}$ neutrons-cm⁻²-sec⁻¹ for three days. To ensure that no short-lived activities were present, chemistry was not performed until two days after irradiation. Then the material was precipitated twice as calcium carbonate to remove any long-lived contaminants. A portion of the activity was deposited on plastic backing and positioned 10 cm from a 3- x 3-inch NaI(Tl) crystal. A 1.185 g/cm² Be absorber was placed directly over the crystal to reduce the effects of the β radiation. Under these conditions a series of gamma-ray spectra were taken over a period of a month. The only contaminant observed was a very small amount of Cr-51, which emits a single 323-keV gamma ray. Therefore, all gamma-ray intensity analyses were done at energies greater than 350 keV. A combined Ca-47 and Cs-137 spectrum was also taken to establish the relative pulse heights for determining the energies of the transitions.

6.22 Data Analysis. From the available spectra the Ca-47 + Cs-137 spectrum and three Ca-47 spectra (hereafter referred to as spectrum I, II, or III) were chosen for extensive computer analysis. Figure II-26 represents a typical spectrum used for data analysis. Three programs were used. One [30] fits the photopeak of a gamma-ray spectrum with a "modified-gaussian" to determine the "exact" channel location of the center of the photopeak. The second program [a] enables the analyzation of a complex spectrum into its individual gamma-ray components. It determines the "best" photopeak position by a direct search method and the intensities by a linear least-squares subroutine. The program includes a subroutine for generating gamma-ray shapes which applies peak-to-total and

[a] Program for complex gamma-ray spectrum decomposition by direct-search and least-squares methods written by G. A. Jayne.

Fig. II-26 Gamma-ray spectrum from Ca-47 and Sc-47. Energies are in keV.

absorption corrections so that the total number of gamma-ray emissions corresponding to each transition may be obtained. The third program [a] allows gain-shifting of a spectrum to some new pulse-height scale.

The data were analyzed with several objectives in mind. Namely, to try to determine the half-life of Ca-47, the location of the first excited state of Sc-47, the transition energies of both Sc-47 and Ti-47, and to establish the accuracy of the computer programs being used by means of consistency checks.

First, the channel locations of the photopeaks in all the spectra were determined. These results are given in Table II-12. The ratio of the positions of the 1300- and 662-keV photopeaks places the photopeak of the 1300 gamma ray in channel 127.10 on a scale where 661.6 keV falls in channel 66.16. With the 1300-keV photopeak in channel 127.10, the channel location for all other photopeaks using the pulse-height ratios shown in Table II-12 can be calculated. The results for the channel locations and energies are given in Table II-13.

To find the half-life of Ca-47, the area under the 1300 photopeak was

TABLE II-12

CHANNEL LOCATIONS OF PHOTOPEAKS

Spectrum	Peak Location (Channels)					Ratio of Pulse Heights			
	1300	800	662	500	160	1300/800	1300/662	1300/500	1300/160
Ca-47 + Cs-137	127.16	80.36	66.19	49.23	16.73	1.582	1.921	2.583	7.601
I	126.96	80.33	---	49.31	16.60	1.581	---	2.575	7.648
II	126.02	79.66	---	48.93	16.48	1.582	---	2.576	7.647
III	126.40	79.88	---	49.08	16.54	1.582	---	2.575	7.642

[a] Program for gain-shifting pulse-height scales of multichannel analyzer spectra written by G. A. Cazier.

TABLE II-13

CHANNEL LOCATIONS AND
ENERGIES ON STANDARD GAIN SCALE

Transition In	Channel Position	Energy (keV)
Sc-47	127.10	1299 $\pm$ 6
Sc-47	80.36	808 $\pm$ 4
Sc-47	49.36	489 $\pm$ 3
Ti-47	16.62	156 $\pm$ 3

measured for spectra I, II, and III. These three points were least-squares fit to the straight line $\ln N = \ln N_0 - \lambda t$. The result for the half-life is (4.52 ± 0.05) days.

In order to determine the relative intensities of the gamma rays emitted in the decay of Ca-47, the data were gain-shifted to position the 1300-keV photopeak in channel 127.16. The gain-shifted spectra were then analyzed into their individual gamma-ray components.

Table II-14 gives the pertinent figures for each component. The peak-to-total ratios used to calculate the absolute intensities listed in Table II-14 are estimated to have a maximum error at any given energy of two percent. Since the measured intensities of the 500- and 800-keV gamma rays agree to within four percent, it cannot be said which is the more intense. Hence, their order of emission cannot be determined. If it is assumed that the intensities are of equal magnitude and that γ_2 is internally converted, the internal-conversion coefficient can be calculated knowing the intensity of the intermediate beta group. Taking the intensity of the intermediate beta group to be 1.8 percent, α is calculated to be about 0.25. Since present evidence for the spins of the states involved indicates that the first transition involves a spin change of one and the second involves a spin change of two, this value of α is three or four orders of magnitude larger than would be expected. Thus, the gamma-ray intensities measured in this experiment would indicate that the intensity of any intermediate beta group must be less than 0.3 percent in contrast to the value of 1.8 percent previously reported.

TABLE II-14

RELATIVE INTENSITIES OF
GAMMA RAYS EMMITED IN DECAYS OF Ca-47

Spectrum	Peak Location (Channels)			Intensities $\times 10^{-7}$ (Counts)			Normalized Intensities		
	1300	800	500	1300	800	500	1300	800	500
I	127.14	80.29	49.35	9.662	0.8808	0.8420	1.000	0.0912	0.0872
II	127.14	80.27	49.34	8.281	0.7577	0.7197	1.000	0.0915	0.0869
III	127.15	80.19	49.35	5.237	0.4790	0.4569	1.000	0.0914	0.0872

Turning to the performance of the computer programs used in this analysis, there are several comparisons that may be made. First of all, the high degree of reproducibility of the pulse-height ratios, from spectrum to spectrum in Table II-12, indicates that the photopeak locations were determined with good accuracy. Comparison of Tables II-13 and -14 indicates the accuracy with which absolute channel locations were determined. The values of column 2, Table II-12, were determined by a peak-fitting routine. They were then gain-shifted to channel

127.16. The values listed in column 2 of Table II-14 were found from these gain-shifted spectra by a search routine which is an entirely different method from that of peak fitting. It can be seen that the results agree to within a few hundredths of a channel. Two observations can be made concerning the intensity measurements. First, the normalized intensities compare well from spectrum to spectrum. Second, if the gamma-ray shape generating routine is accurate and the separation of the complex spectra into their individual gamma-ray components is also accurate, then the absolute intensities listed in Table II-14 should give good values for the half-life of Ca-47. The data from columns 5, 6, and 7, Table II-14, were each least-squared to a straight line of the form $\ln N = \ln N_0 - \lambda t$. The results of the least-squares calculations are given in Table II-15. Columns 4, 6, and 8 of Table II-15 are calculated values using the coefficients determined from the least-squares fits. Table II-16 gives the half-lives resulting from this analysis. The values agree well with the measured value of (4.52 ± 0.05) days.

TABLE II-15

RESULTS OF LEAST-SQUARES CALCULATIONS FOR HALF-LIFE

Spectrum	Time (hours)	1300-keV Transition		800-keV Transition		500-keV Transition	
		Log of Count Rate	Calculated Log of of Count Rate	Log of Count Rate	Calculated Log of of Count Rate	Log of Count Rate	Calculated Log of of Count Rate
I	0	2.267	2.267	2.168	2.172	2.127	2.128
II	24.33	2.114	2.112	2.025	2.019	1.974	1.973
III	95.98	1.656	1.656	1.567	1.569	1.519	1.519

TABLE II-16

HALF-LIFE DETERMINATIONS

Transition	Half-Life (days)
1300	4.54
800	4.60
500	4.55

6.23 Conclusions. This work has been unsuccessful in its attempt to determine the order of emission of the 808- and 489-keV gamma rays in Sc-47. However, it has established that the relative intensity of an intermediate beta-ray group must be much less than the 1.8 percent previously reported, and that the recently reported value of 6.8 days for the half-life of Ca-47 is too long. Also, it is felt that more precise values of the transition energies and relative intensities in Sc-47 and Ti-47 have been obtained.

6.3 Branching Ratio of 2.18-MeV Gamma Ray in Decay of Pr-144 (L. D. McIsaac)

The branching ratio for the 2.18-MeV gamma ray in the decay of 17.5-min Pr-144 has been measured using $4\pi\beta$ counting techniques. Carrier free Pr-144 was separated from its parent Ce-144 by the multiple extraction of the latter into HDEHP [31]. Further purification and concentration was accomplished by coprecipitation of Pr-144 with $\text{Fe}(\text{OH})_3$ and removal of the iron by ether extraction. For each branching-ratio measurement, two sources of known volume were prepared from a purified Pr-144 solution. All sources were deposited on 0.5 mg/cm^2 Al-coated Mylar. The intensity of the two sources differed by about a factor of

100. The more intense source was used for gamma-ray emission rate measurements by scintillation spectrometry [32] while the weaker was analyzed in a 4π beta chamber for absolute disintegration rate determination. Since the beta rays associated with the decay of Pr-144 are so energetic the 4π counting was assumed to be 100 percent efficient. To minimize errors associated with decay, both beta- and gamma-ray measurements were taken simultaneously.

The results of four independent measurements indicate that the absolute intensity of the 2.18-MeV transition, with its estimated uncertainty, is 0.77 ± 0.04 percent.

6.4 Calibration of Permanent-Magnet Spectrographs (R. G. Helmer)

A discussion of the calibration of the 180° , uniform-field, magnetic spectrographs has been presented previously [12]. Since the last report, the source holders in two of the spectrographs (54 and 123 gauss) have been replaced with a resultant change in source positions. This required a redetermination of the calibration parameters B , x , and y (see Figure 22 of Reference 12).

The spectrographs were calibrated from a set of plates obtained with sources of Ir-192 and Ta-182. The "true" gamma-ray energies were taken as an average of the values reported in References 15, 16, 33, and 34 for Ir-192 and Reference 35 for Ta-182. The true energies of the internal-conversion-electron lines were then determined by use of the atomic electron binding energies in Reference 36.

In the calibration process, the values of the parameters were varied until an acceptable set of parameters was obtained. The criterion for acceptability was that the energies of the conversion lines computed from the parameters agree with the true values to within 1 part in 10^3 , except at the low-energy end of each plate.

The results are shown in Figure II-27 where E is the "true" electron energy and ΔE is $E - E(B, x, y)$. The error bars indicate the uncertainties quoted in References 15, 16, 33, 34, or 35. These results indicate that, in the future, computed energies $E(B, x, y)$ should be accurate to about 1 part in 10^3 , if there is no systematic error.

The sources used in this study were made by vacuum evaporation of the sample onto a graphite blank. The sample and graphite were irradiated in a flux of about 2×10^{14} neutrons-cm $^{-2}$ sec $^{-1}$ and used as the source. The sources were 0.010 inch wide and 0.6 inch long.

Fig. II-27 Calibration results for three spectrographs. The parameters B , x , and y are defined in Reference 35.

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III. INSTRUMENT DEVELOPMENT

1. DETECTOR DEVELOPMENT (S. D. Anderson)

1.1 Capsule Dynamic Pressure Measurements (R. H. Meservey)

Capsules designed for use in the Spert Capsule Driver Core have insufficient room between the fuel pin, which they enclose, and the capsule wall for a low radiation sensitivity pressure transducer. Since it is necessary to measure the dynamic pressure created inside the capsule by the expanding fuel pin, other methods of pressure measurement were investigated. Strain gauges were chosen because a direct relationship exists between the pressure within a thin-walled cylinder and the strain in the walls of the cylinder. Since a direct analytical approach to the response of a strain gauge to a dynamic pressure within a cylinder was not available, it was decided to determine this empirically.

An open-ended aluminum cylinder, five inches long with an inside diameter of 1.8 inches and a wall thickness of 0.1 inch, was used in the first phase of the testing program. The electrical explosion of a copper wire mounted along the axis of the cylinder created a line source of dynamic pressure within the cylinder. All of the tests were conducted in a water environment.

The magnitude and shape of the pressure pulse produced inside the capsule by the exploding wire was determined by mounting a Crystal Research explosion immersion hydrophone approximately midway between the axis and the wall of the cylinder. By changing the voltage on the capacitor bank, which was discharged into the copper wire to explode it, and also changing the diameter of the wire, the pressure inside the capsule could be varied. In these tests, the peak pressure was varied from 400 to 3000 psi. These pressures have a rise time (0-100 percent) of three microseconds and a duration of 67 microseconds. The pressure was also measured outside the capsule by mounting a similar hydrophone one inch from the outside of the capsule wall.

Three types of gauges were installed to measure circumferential strain on the capsule. These were weldable, semiconductor, and foil gauges. For a thin-walled cylinder

$$\epsilon = \frac{PD}{2Et}$$

where: ϵ = strain in walls

P = pressure inside cylinder

E = Young's Modulus

D = cylinder diameter

t = wall thickness.

The above expression was used to calculate the pressure inside the capsule from the strain indicated by each of the gauges.

All gauges showed good response to the dynamic pressure inside the capsule. Strain-versus-time curves from each gauge have the same general shape as the pressure-versus-time curve. Rise time (0-100 percent) of the strain gauges was approximately 10 microseconds. Durations of about 55 microseconds and maximum strain rates of 100 inch/inch/sec were encountered. It was noticed that foil gauges become defective and begin to give erratic results after a few shots at a capsule pressure of only 1000 psi. Other gauges developed this behavior at approximately 3000 psi.

The second phase of this series of tests was conducted in a water-filled barrel 600 feet in back of building CF-688. Aluminum capsules of approximately the same diameter and wall thickness as the one discussed above, but having a length of five feet, were instrumented with strain gauges and tested. A line source of dynamic pressure was created in these capsules by placing a three-foot length of Primacord inside a heavy walled stainless steel tube and placing this along the axis of the capsule. The Primacord was detonated with an electric blasting cap. Peak pressures in this series of tests ranged from 400 to 5000 psi. These pressures have rise times (0 to 100 percent) of 10 microseconds and durations of 120 microseconds.

Four types of strain gauges have been used on these capsules. These are weldable, foil, wire, and semiconductor gauges. Results from these tests are similar to those obtained from the previous tests. As in the tests with the five-inch capsule, the foil gauges cannot be depended upon to give reliable data after one or two shots. Most of the strain gauges will indicate a pressure inside the capsule which is within 10 percent of that measured by a hydrophone within the capsule. Strain gauges installed on thin-walled aluminum capsules usually become defective when the dynamic pressure inside reaches a peak of around 3000 psi. This pressure corresponds to a strain in these capsule walls of about 2000 μ inch/inch.

The results of the tests show quite clearly that the dynamics of an aluminum capsule which is immersed in, and, therefore, damped by water, are favorable to the measurement of pressure with strain gauges. For the pressures expected in the Capsule Driver Core a water-damped aluminum capsule does not have radial vibration modes or other dynamic characteristics which prevent the use of strain gauges as pressure measuring devices.

1.2 Transient Radiation Sensitivities of Nonnuclear Transducers (F. D. Terry)

Recent investigations of transient radiation effects on nonnuclear transducers were conducted at the General Atomics' TRIGA Mark F Reactor. Items included in the investigations were strain gauge, piezoelectric, inductive, and photoresistive transducers as well as electrical cables. In all, approximately 300 samples were tested, with the majority of samples receiving more than one test. Complete data from the tests cannot be included in this short report, but a brief summary of some of the test results is presented in the following paragraphs.

1.21 Transient Radiation Effects on Electrical Cables. When subjected to transient radiation fields, the electrical cables behaved approximately as charge generators, shunted by a parallel RC circuit. The generated charge was apparently produced by free secondary electrons which were collected by or ejected from conductors. The shunt resistance, R, represents the resistance

of the cable insulation. The conductivity of the insulation is significantly decreased by transient radiation. Changes in the cable capacitance, C, are reported by other experimenters to be small.

It was found that single conductor cables produced positive charge proportional to the conductor diameter. The charge was not significantly affected by variations in insulation thickness (from 0.0015 to 0.051 inch), but was affected by the type of insulation and conductor material used. Coaxial cables produced less charge than single conductor cables of equivalent size. The magnitude and polarity of the charge produced by the coaxial cables depended upon the composition of the cable insulation and conductor, and upon the relative dimensions of the jacket, shield, insulation, and conductor. Test results indicate that, in a given radiation field, it should be possible to optimize the relative dimensions of these cable components such that the generated charge would be considerably reduced. Generally speaking, coaxial cables with the smallest overall diameter produced the least charge.

1.22 Transient Radiation Effects on Strain Gauge Transducers. Spurious signals were produced in strain gauge transducers by:

- (1) Spurious currents which are believed to be produced by secondary electron absorption in and ejection from conductors.
- (2) Changes in the resistance of all insulation materials, the strain gauge element, and lead cable conductors, caused by gamma heating and radiation-induced changes in the free charge carrier densities.
- (3) Thermal strains produced by gamma heating of the various components used in the construction of the transducer housing.

Tests showed that radiation-induced current and resistance change effects in typical foil strain gauges were roughly equal, and that the proper choice of lead cable significantly reduced the generated spurious signals. Measured resistance changes in the test samples could be accounted for by radiation-induced changes in the conductivities of cable and strain gauge insulations and the calculated gamma-heating-induced resistance changes in the strain gauge and lead cable conductors. However, other radiation effects, such as changes in the free charge carrier densities of the conductors, may also be quite important.

It was found that radiation-induced current and resistance change effects could be reduced by proper electrical compensation techniques. A 90 percent cancellation of the generated spurious signals was attained by utilizing balanced two and four "exposed" arm Wheatstone bridge circuits with low impedance paths to ground (Figure III-1).

1.23 Transient Radiation Effects on Piezoelectric Crystal Transducers. Spurious signals were produced on piezoelectric transducers by:

- (1) Spurious charge resulting from free secondary electrons which are absorbed by or ejected from conductors.

TWO "EXPOSED" ARM BRIDGE

FOUR "EXPOSED" ARM BRIDGE

Fig. III-1 Compensating bridge circuits for use in transient radiation fields.

- (2) Pyroelectric properties of the crystals which resulted in charge production proportional to the gamma ray and neutron heating of the crystals.
- (3) Thermal strains in the transducer produced by gamma heating of the various housing components.
- (4) Capacitance and shunt resistance changes which affected the gain and low frequency RC time constant of the circuit when cathode follower amplifiers were used. The effects of radiation-induced capacitance and resistance changes were markedly reduced by using charge amplifiers with the crystal transducers.

The spurious charge produced by 11 types of unhusd piezoelectric crystals are tabulated in Table III-1. Q_1 is the charge produced in the lead cable and Q_2 is the charge produced in the crystal. The temperature of the crystals was not monitored in the radiation field and, therefore, the charge produced by pyroelectric effects in the crystals cannot be accurately determined.

TABLE III-1
RADIATION-INDUCED CHANGE IN PIEZOELECTRIC CRYSTALS

Radiation Field:	Peak Flux Dose	Neutron		Gamma Ray		
		1.6×10^{16}	nv	2.3×10^7	rads/sec	
		1.9×10^{14}	nvt	2.8×10^5	rads	
Crystal Material	Physical Description	Pressure Sensitivity ($\frac{\text{Cb}}{\text{psi}}$) p	Q_1 ($\frac{\text{Cb}}{p}$)	Q_2 ($\frac{\text{Cb}}{p}$)	Total Charge ($\frac{\text{Cb}}{p}$)	Equivalent Pressure (psi)
ADP	1/8" cube	3.33	+1,380	+1,820	+3,200	970
Barium Titanate	1/8" cube	2.49[a]	+1,380	+9,320	+10,700	4,300
Barium Titanate	1/2" cube	52.4[a]	+1,380	+131,600	+133,000	2,540
PZT-4	1/8" cube	6.58[a]	+1,380	+25,800	+27,200	4,150
Lithium Sulphate	1/8" cube	1.10	+1,380	-3,830	-2,450	2,230
Tourmaline	1/4" disk, 0.025" thick	0.47	+1,380	-5,850	-4,470	9,500
Tourmaline	1/2" disk, 0.047" thick	1.88	+1,380	+20,600	+22,000	11,700
Tourmaline	1/2" disk, 0.094" thick	1.88	+1,380	+4,620	+5,000	3,200
Quartz	1/8" cube	0.14	+1,380	+640	+2,020	14,500
Electra-mite ^[b] 1400	1/8" cube	9.2	+1,380	-17,600	-16,200	1,760
Electra-mite ^[b] 1500	1/8" cube	11.0	+1,380	-13,700	-12,300	1,110
Piezite II ^[b]	3/8" disk, 0.1" thick	0.21	+1,380	-9,140	-8,760	41,700
Piezite VI ^[b]	3/8" disk, 0.1" thick	41.9	+1,380	+56,100	+57,000	1,370
Piezite X ^[b]	3/8" disk, 0.1" thick	1.22	+1,380	-8,740	-7,360	5,020
HI-T Ceramic ^[b]	1/8" cube	11.5	+1,380	+53,100	+54,500	4,750

[a] Values were measured in an isotropic, dynamic pressure field and have not been verified from reports of other experimenters.

[b] Trade names: Electra-mite -- Electra Scientific
Piezite -- Endevco
HI-T Ceramic -- Gulton

However, it is possible to calculate the approximate temperature change which the crystals would undergo from gamma heating by the formula:

$$\Delta T \approx K \frac{\gamma}{c_p}$$

where: $K = 2.39 \times 10^{-6}$ cal/g-rad

γ = incident gamma dose in rad

c_p = specific heat of the crystal.

Tourmaline would also undergo significant thermal neutron heating because of its boron content. Calculated pyroelectric effects agreed in polarity and approximately in magnitude with Q_2 for most crystals. However, because of the degree of uncertainty of the calculated pyroelectric effects, it was not possible to separate the pyroelectric effects from those caused by the collection and ejection of secondary electrons. The calculations do show that pyroelectric effects can be an important source of spurious charge.

Because of the nature of the radiation-induced spurious signals in piezoelectric crystals, it is felt that the best method of compensating for these effects is the utilization of "dummy" elements and balanced circuit configurations (see Figure III-2). Equal radiation-induced spurious signals from the two elements would then be canceled by the differential amplifier. If the two spurious signals are accurately known, even though they may not be equal, it should be possible to adjust the amplifier gains such that the signals cancel. A test of this compensation technique was performed using a pair of X cut-X face, and X cut-Z face quartz crystals. The quartz crystals were chosen because of their low pyroelectric coefficients. The X cut-Z face crystal is essentially insensitive to applied pressure and can thus be used with the X cut-X face crystal in a pressure field to compensate for radiation effects. Better than two decades of spurious signal cancellation were obtained by this technique.

1.24 Transient Radiation Sensitivities of Inductive and Photoresistive Transducers. Test results on inductive pressure and velocity transducers are contained in Table III-2. The Kaman pressure transducers were modified

Fig. III-2 Compensated piezoelectric crystal circuit.

TABLE III-2

RADIATION-INDUCED SPURIOUS SIGNALS IN INDUCTIVE-TYPE TRANSDUCERS

Type Device	Manufacturer	Model	Range	Peak Radiation Flux			Maximum Induced Equivalent Pressure or Velocity	Radiation-Spurious Signal % of full scale
				Fast Neutron	Thermal Neutron	Gamma Ray (Rads/sec)		
Pressure Transducer	International Resistance	70-6214-3607	10K psi	1.9×10^{14}	9.4×10^{14}	1.9×10^6	+16.9 psi	0.169
Pressure Transducer	Kaman Nuclear	K-1200	1K psi	4.0×10^{15}	1.2×10^{16}	2.3×10^7	-0.97 psi	0.097
Pressure Transducer	Kaman Nuclear	K-1300	1K psi	4.0×10^{15}	1.2×10^{16}	2.3×10^7	-1.2 psi	0.12
Velocity Transducer	M B Electronics	11		1.9×10^{14}	9.4×10^{14}	1.9×10^6	-0.024 in./sec	---
Velocity Transducer	Sanborn	7LV3		1.9×10^{14}	9.4×10^{14}	1.9×10^6	-0.0091 in./sec	---

by the manufacturer specifically for use in transient radiation fields. The Sanborn velocity transducers were tested in a balanced circuit configuration (ie, the coil in the transducer was center tapped to electrical ground). The balanced circuit configuration reduced the radiation-induced spurious signals by approximately one decade.

A Giannini photopot was the only photoresistive device tested. The transient radiation caused a decrease in the resistance of the photoresistive semiconductor material from 390 K ohms to less than 550 ohms when irradiated in the TRIGA Mark F maximum flux position.

1.3 Spert I Fuel Pin Cladding Strain [a] (P. H. Hofine)

The Detector Development Section installed strain gauges on the Spert I Oxide Core fuel pins of serial numbers 4-3115 and 4-152. The axial gauges were Microdot [b] weldable-type SG-102-2A-20 with a nominal resistance of 60 ohms. They were temperature compensated for 304 SS and supplied with 20-foot integral leads. The circumferential gauges were similar except for being supplied preformed with a 0.25-inch radius of curvature.

The circumferential gauges were mounted 21.0 inches from the bottom of each fuel pin. An axial gauge was mounted directly above the circumferential gauge with the center of the axial gauge 22.0 inches from the bottom of each fuel pin. A second axial gauge was mounted on each fuel pin at the same level and 90° around the fuel pin from the first axial gauge.

The initial installation was tested by applying axial tensile forces to the ends of the fuel pins. By assuming a thin wall tube, theory will predict the value of strain that should be indicated by the strain gauges. The measured values of strain differ from the computed values because the uranium meat in the fuel pins was neglected when the strains were calculated. During this test all the strain gauges gave consistent readings except for the axial gauge located

[a] Summary of private correspondence with G. E. McGlothlin.

[b] Microdot Inc., 220 Pasadena Ave., South Pasadena, California.

90° from the circumferential gauge on the fuel pin, serial number 4-3115. The readings from this gauge were very erratic. Examination revealed no visible defect in the mounting of this gauge. This leads to the conclusion that the gauge was defective before it was mounted. There is no indication that the output from the other gauges should be in error.

During actual reactor tests, there are two major contributors of error in the strain gauge outputs. The first of these, radiation-induced output, would not exceed the equivalent of 100 to 150 μ inch/inch of strain in the flux fields typical of Spert I [1, 2].

The second source of error is lack of dynamic temperature compensation of the strain gauge. (This lack of compensation results because the temperature of the strain gauge filament will lag that of the fuel pin surface by the thermal time constant of the strain gauge mounting.) Thermocouples with a construction similar to that of the strain gauges were installed to determine the thermal time constant, but they failed from water absorption before the required short-period transients could be run.

The strain gauge installation remained intact and the gauges operated successfully through the 2.2 msec destructive test. The maximum error caused by transient temperatures during these tests can be found from the equation

$$\epsilon_t = t_1 \alpha_p + t_2 \left[\frac{C_f}{G} - \alpha_f \right] \quad (1)$$

where:

ϵ_t = apparent strain (error in output);

t_1 = fuel pin surface temperature above ambient;

α_p = linear temperature coefficient of expansion for the fuel pin;

t_2 = strain gauge filament temperature above ambient;

C_f = temperature coefficient of resistivity of the strain gauge;

G = gauge factor;

α_f = linear temperature coefficient of expansion for the strain gauge.

The condition which achieves static temperature compensation is

$$\alpha_p = \alpha_f - \frac{C_f}{G} \quad (2)$$

Equation (1), for a temperature compensated gauge, reduces by substitution of Equation (2) to

$$\epsilon_t = \alpha_p (t_1 - t_2) \quad (3)$$

where α_p is about 18 μ inch/inch per degree centigrade for the fuel pin cladding. On the 2.2-msec destructive transient, t_1 does not exceed about 10°C until after

the fuel pin cladding strain has achieved an indicated maximum of 1600 $\mu\text{inch/inch}$ which occurs about 10 msec after peak power. During this time, even if there is no thermal transfer to the strain gauge, the maximum temperature induced error is 180 $\mu\text{inch/inch}$. At the same time the maximum radiation induced error is 150 $\mu\text{inch/inch}$ for a total maximum error of 330 $\mu\text{inch/inch}$ or 20.5 percent. The indicated strain for this destructive test is in good agreement with the thermal strain calculated from the known reactor characteristics [a].

The results of the laboratory and reactor tests show that this was a successful strain gauge installation and the gauges gave a true indication of the strain in the fuel pin cladding.

2. INSTRUMENTATION ANALYSIS (Ned Wilde)

2.1 Experimental Measurement of β/ℓ for the ATRC Critical Facility (R. P. Morrell)

Five samples of reactor noise data for the ATRC Critical Facility were recorded and analyzed to determine the noise spectral density for different drum positions. From the noise spectra, the values of β/ℓ for the various drum positions were computed, along with their respective standard deviations, by a least-squares-fit method [3]. The results are tabulated in Table III-3, and the computed values of β/ℓ are shown as a function of drum rotation in degrees in Figure III-3. The lines through the points in the figure cover the 95 percent confidence values.

TABLE III-3

RESULTS OF β/ℓ MEASUREMENTS
FOR ATRC CRITICAL FACILITY

Drum Rotation (Degrees - ± 0.40)	Reactor Power (Watts)	Computed β/ℓ (rad/sec)	Standard Deviation (rad/sec)
13.0	10.1	163.8	1.82
47.2	12.0	151.3	2.62
78.3	12.7	135.6	3.01
107.5	19.0	117.6	3.82
137.9	26.9	106.9	1.87

Fig. III-3 ATRC β/ℓ versus drum rotation. Lines through points show 95 percent confidence values.

2.2 Measurement of ℓ/β for Spert III, ARMF-I, and PBF Reactors (J. C. Hamilton, R. P. Morrell)

The value of ℓ/β was measured for each of three reactors: Spert III, ARMF-I, and PBF. These measurements were made using random noise techniques. This technique is analogous to that used in determining the transfer function of a linear system. A band-limited white noise source, which is wide-band compared to the system under test, is applied to the system input; and the system output signal is analyzed to determine the spectral density function. Under these conditions the spectral density function has the same form as the squared modulus of the system transfer function.

[a] Private correspondence with J. F. Koenig.

For an $\ell/\bar{\beta}$ measurement on a low-power nuclear reactor, the driving function is the fission process in the core which has been shown to be white and also wide-band compared to the reactor transfer function. For low-power operation, the assumption of linearity can be made without sacrificing significant accuracy.

The noise signal containing the output spectral density of the reactor is obtained from a compensated ionization chamber placed sufficiently near the reactor core. These signals were analyzed above the 1 to 5 cps range on the low-frequency end, since it was known from reactor physics calculations that the pole corresponding to $\bar{\beta}/\ell$ for the reactor was well above 5 cps.

A spectral density function was obtained for the Spert III reactor at three different power levels. The analyzer results for these runs are shown as experimental data in Figure III-4. The results for ARMF-I and PBF are shown in Figures III-5 and -6, respectively. A hand fit to these functions was found to be too crude to provide a sufficiently accurate determination of $\bar{\beta}/\ell$ in each case, so a least-squares fit was made on each one by the method described in a previous report [3]. The least-squares fit is shown as the solid line through each function. The experimental data shown in Figures III-4, -5, and -6 have, of course, been corrected for instrumentation response. The results of these $\ell/\bar{\beta}$ measurements are tabulated in Table III-4.

Fig. III-4 Power density spectra for Spert III reactor at three power levels. Accuracy on experimental data points show 90 percent confidence values.

Fig. III-5 ARMF-1 -- power density spectrum.

Fig. III-6 Power density spectrum for Spert Power Burst Facility.

TABLE III-4
RESULTS OF $\ell/\bar{\beta}$ MEASUREMENTS

Reactor	Power Level	$\bar{\beta}/\ell$ [a]
Spert III	10 Watts	$401.7 \pm 2.0\%$ [b]
Spert III	50 Watts	$397.7 \pm 2.4\%$
Spert III	100 Watts	$427.8 \pm 4.2\%$
Spert III	Avg. (10, 50, 100) Watts	$409.0 \pm 2.8\%$
ARMF-I	40 Watts	$107.3 \pm 5.3\%$
PBF	100 Watts	$400.5 \pm 2.9\%$

[a] Units of $\bar{\beta}/\ell$ are radians/sec.

[b] Percentage error for one standard deviation (68% conf.).

2.3 Xenon Simulator (S. R. Gossmann, A. W. Hauf)

An all-electronic Xenon Simulator has been completed, tested, and put into service in the analog computer facility. This unit is designed to solve, in real time, the space-independent differential equations describing the formation, decay, and burnup of I-135, and Xe-135 in a nuclear reactor. Because of the real-time capability, the unit is a simulator. Provisions have also been made to operate the Xenon Simulator on a time scale compressed by a factor of 1000. This time scale change allows studies of xenon transients to be performed in times ranging from several seconds to several minutes rather than hours. The real-time capability is important for studies in which the reactor kinetics and reactor control system dynamics must also be considered.

The input to the Xenon Simulator is a voltage proportional to the thermal neutron flux. The output is a voltage proportional to the reactivity worth in dollars of the xenon concentration.

The equations solved by the simulator are:

$$\begin{aligned} T_X \dot{D}_X + D_X &= -F \gamma_X \sigma_X T_X \phi - \sigma_X T_X \phi D_X + (T_X/T_I) D_I \\ T_I \dot{D}_I + D_I &= -F \gamma_I \sigma_X T_I \phi, \end{aligned}$$

where:

D_X = $-F \sigma_X X$ xenon reactivity in dollars

F = f/β ($1 + \sigma_a/\sigma_f$)

X = C_X/Σ_f modified xenon concentration

C_X = xenon concentration in atoms/cc

f = reactor thermal utilization factor, $f < 1$

β = delayed neutron fraction, $0.0064 < \beta < 0.0080$

σ_a/σ_f = U-235 microscopic capture and fission cross sections in barns, $\sigma_a/\sigma_f = 0.1924$

Σ_f = U-235 macroscopic fission cross section in cm^{-1} (actual value not required)

T_X = Xe-135 mean life (time constant), $T_X = 47,847$ seconds

γ_X = Xe-135 yield = 0.002

σ_X = Xe-135 microscopic absorption cross section, $2.8 \times 10^{-18} \text{ cm}^2$

ϕ = thermal neutron flux, $\phi \leq 5 \times 10^{14} \text{ nv}$

$D_I = -F \sigma_X I$ = "iodine reactivity" in dollars

$I = C_I/\Sigma_f$ = modified iodine concentration

C_I = iodine concentration in atoms/cc

T_I = I-135 mean life, $T_I = 34,843$ seconds

γ_I = I-135 yield, $\gamma_I = 0.061$.

The values of σ_a/σ_f , γ_X , σ_X , γ_I , f , and β listed above are nominal values used as reasonable estimates during the design phase. Other values of these parameters are quite easily incorporated by recalculating the setting of certain coefficient potentiometers. The values of T_I and T_X are fixed. The value of ϕ quoted above is the maximum thermal neutron flux for which the unit is designed. The flux may, of course, be a constant or an arbitrary function of time.

A simplified circuit diagram of the Xenon Simulator is shown in Figure III-7. The various symbols shown are identified on the figure. The extremely large time constants, T_I and T_X , are realized by amplification of the basic RC time constants of 100 seconds. This is accomplished by establishing high closed-loop circuit gains through the use of both positive and negative feedback. For instance, the closed-loop equation for the iodine circuit is

$$T_I (k_I \dot{D}_I) + (k_I D_I) = -\left(\frac{R_{2I}}{R_I} A_I\right) P_I (k_\phi \phi)$$

where:

$(k_\phi \phi)$ = input voltage

$(k_I D_I)$ = output voltage

$\left(\frac{R_{2I}}{R_I} A_I\right)$ = closed-loop dc gain

P_I = pot setting or attenuation factor

T_I = closed-loop circuit time constant.

Formulas For Pots

$$P_1 = \frac{100}{A_I} \frac{k_I}{k_\phi}$$

$$P_{1x} = \frac{8 T_x \gamma_x F \sigma_x}{A_x} \frac{k_x}{k_\phi}$$

$$P_{2x} = \frac{200 T_x \gamma_x F \sigma_x}{A_x} \frac{k_x}{k_\phi}$$

$$P_{3x} = \frac{300 T_x \sigma_x}{A_x} \frac{k_x}{k_\phi}$$

Time Constant Amplification Factors

$$A_I = 1 / \left(\frac{R_{2I}}{R_{1I}} - 1 \right)$$

$$A_x = 1 / \left(\frac{R_{2x}}{R_{1x}} - 1 \right)$$

Circuit Time Constants

$$T_I = R_{3I} C_I A_I \left(1 + \frac{R_{2I}}{R_{1I}} + \frac{R_{2I}}{R_I} + \frac{R_{2I}}{R_{3I}} \right)$$

$$T_x = R_{3x} C_x A_x \left(1 + \frac{R_{2x}}{R_{1x}} + \frac{R_{2x}}{R_{x2}} + \frac{R_{2x}}{R_{x3}} + \frac{R_{2x}}{R_{3x}} \right)$$

Voltage Amplitude Scale Factors

$$k_\phi = \frac{100}{\phi_{\max}} \left(\frac{\text{Volts}}{nV} \right), \quad k_x = \frac{100}{D_{x\max}} \left(\frac{\text{Volts}}{\text{Dollars}} \right)$$

$$k_I = \frac{100}{D_{I\max}} \left(\frac{\text{Volts}}{\text{Dollars}} \right)$$

$$*C_x = *C_I = \begin{cases} 10 & \text{For Real Time} \\ 0.01 & \text{For 1000/1 Time Scale Change} \end{cases}$$

All resistance in megohms

All capacitances in microfarads

PPC-6-A-6085

Fig. III-7 Simplified circuit diagram of Xenon Simulator.

The key circuit parameter which allows the realization of $T_I = 34,843$ seconds is A_I given by

$$A_I = 1 / \left(\frac{R_{2I}}{R_{1I}} - 1 \right).$$

The time constant, T_I , is given by

$$T_I = R_{3I} C_I A_I \left(1 + \frac{R_{2I}}{R_{1I}} + \frac{R_{2I}}{R_I} + \frac{R_{2I}}{R_{3I}} \right),$$

or alternatively by

$$T_I = R_{3I} C_I A_I \left(2 + \frac{1}{A_I} + \frac{R_{2I}}{R_I} + \frac{R_{2I}}{R_{3I}} \right).$$

Note that A_I can be made arbitrarily large by adjusting R_{1I} arbitrarily close to the value of R_{2I} . Since T_I is approximately proportional to A_I , it is possible to obtain an arbitrarily large T_I . In this instance, however, R_{2I} , R_I , R_{3I} , and C_I were selected so that the closed-loop gain, $A_I R_{2I} / R_I$, would not be too high after having adjusted R_{1I} (and hence A_I) to the value required to obtain $T_I = 34,843$.

All components used in the circuit are of analog computer quality. The resistors are all noninductive, wire wound, and have extremely low-temperature coefficients. The capacitors are polystyrene and also have very small temperature coefficients. Because of the careful choice of components and component values, the Xenon Simulator is a very precise piece of equipment. As an example of the errors to be expected, the following two tables list the theoretical voltages and the measured values of the corresponding voltages at the analog computer

patchboard. Table III-5 simulates a reactor start-up with initial values of xenon and iodine equal to zero. This condition represents the worst operational condition of the simulator because of the extremely small voltages and resulting small currents. Table III-6 simulates the buildup of xenon from equilibrium conditions following a reactor shutdown. Operationally, this is a better condition for the simulator because of the large voltages and currents. The significantly smaller errors listed

in Table III-6 are, therefore, more representative of the inherent accuracy of this unit, since start-up transients are usually of less interest than shutdown transients.

TABLE III-5

XENON BUILDUP
FOLLOWING REACTOR START-UP

Time t (sec)	Calculated $k_X D_X$ (volts)	Measured $k_X D_X$ (volts)	% Error
0	0	0	0
300	-0.217	-0.218	0.46
600	-0.407	-0.408	0.25
3600	-1.874	-1.878	0.21
5700	-2.648	-2.654	0.23

TABLE III-6

XENON BUILDUP FOLLOWING REACTOR SHUTDOWN

t (sec)	Calculated $k_X D_X$	Calculated $k_I D_I$	Measured $k_X D_X$	Measured $k_I D_I$	% Error in D_X	% Error in D_I
0	-17.238	-100.00	-17.238	-100.00	0	0
600	-31.038	-98.290	-31.056	-98.280	0.0580	0.0100
1200	-44.415	-96.615	-44.428	-96.606	0.0293	0.0093
1800	-57.428	-94.965	-57.464	-94.961	0.0627	0.0042
2400	-70.020	-93.344	-69.970	-93.349	0.0714	0.0054
3000	-82.220	-91.750	-82.169	-91.759	0.0620	0.0098
3600	-94.055	-90.184	-93.991	-90.199	0.0680	0.0166

The Xenon Simulator is designed for use with the analog computer; consequently, the unit is controlled in its various modes of operation (Initial Condition, Hold, Operate) by the computer control switches. The input-output terminals are located on the computer patchboard. Overall system specifications can be summarized as follows:

Maximum Neutron flux -- 5×10^{14} nv

Maximum Xenon -- arbitrary

Maximum Iodine -- arbitrary

Initial conditions of Xe and I -- arbitrary

Error in start-up simulation -- less than 1 percent

Error in shutdown simulation -- less than 0.1 percent

Fig. III-9 Photograph of amplifier illustrating package design.

4. REFERENCES

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IV. MATHEMATICAL ANALYSIS AND MACHINE COMPUTATIONS

1. CONTOUR PLOT SUBROUTINE (CØNPLT) (S. T. Bennion -- PPCO 40.0303)

A subroutine has been written for the IBM 7040 computer to automatically prepare contour maps. This subroutine provides a means of representing the values assigned to the mesh points of a two dimensional grid in the form of contour lines. These contour lines, representing distinct levels within the range of the maximum and minimum values over the whole grid, form a contour map of the area defined by the grid. The contour map is prepared on the CALCOMP digital plotter from a magnetic tape of plotting commands generated on the IBM 7040 computer by the CØNPLT subroutine in conjunction with the PLØT subroutine (PPCO program number 40.0163). The primary function of the CØNPLT subroutine is to determine where the different contour levels are to be drawn on the two dimensional grid and to call upon the PLØT routine to generate the actual plotting commands on magnetic tape.

The method used by the routine to construct a contour line representing a particular level involves a complete scan of the array of grid values. This scan determines which pairs of adjacent mesh points have values that bracket the particular level desired. The result of this scan is the location of the intersection points on the grid lines projected on the plane, which represents the level requested parallel to the base grid; the intersection being that of the plane intersected with a surface fitted over all of the grid values.

The points of intersection are obtained by straight line interpolation and are then joined together in a systematic manner by short, straight lines to form the contour line. It is apparent that a grid with a large mesh point spacing will produce very jagged contour lines. The design of this particular routine is primarily for grids of a large number of mesh points (up to 20,000) and a small mesh point spacing. In writing the routine, emphasis has been placed on speed, both on the computer and the plotter. Even for very large problems, the program appears to be almost completely tape bound on the IBM 7040 computer.

The routine allows the user to provide the values of the levels to be plotted in any manner desired. In addition, two computational methods are provided that will automatically compute the contour levels and print out their values (on the listed output) when given an estimate, N, of the number of levels desired. One method computes N equally spaced contour levels. The other method computes approximately N levels; the value of the minimum level is a suitably rounded number near the minimum value, and the level increment is a power of ten times one of the scale factors; 1.0, 2.0, 2.5, or 5.0. The second method is preferred since it provides values which are easily read, transcribed, or manipulated. The choice of which method to be used is a user option.

Another option provided in the routine for the user is that of either plotting the whole grid, or just certain rectangular subregions. Since the grid values are not destroyed, the whole grid or any subregions of it can be plotted in any time sequence, dependent only upon the user's controlling program.

Whether or not the whole grid or a subregion of it is plotted, the actual area plotted is scaled to fit within 10 inches on the y axis and 30 inches on the x axis of the plotter. This scaling is necessary to ensure that the contour map will not exceed the bounds of the plotter and will not be so large as to consume excessive computer and plotter time.

The contour plot subroutine has been incorporated in a new program PDQCP (PPCO program number 40.0302) which reads and prepares contour maps of the flux data from the merge tape generated by the two dimensional neutron diffusion program, PDQ (PPCO program number 40.0018). The PDQCP program is in the production stage at this time and will permit the use of the neutron diffusion program to obtain contour maps of the computed fluxes until the contour plot routine can be incorporated in the PDQ program itself.

Figure IV-1 is an example of a contour map that was prepared from the two dimensional thermal flux data of a LOFT core design study computed by the

Fig. IV-1 Contour map prepared from two dimensional thermal flux data of a LOFT core design study computed by neutron diffusion program, PDQ.

neutron diffusion program, PDQ. The grid is indicated by the axis drawn about the region of 6084 mesh points. The example required 1.5 minutes of computer time to read and scan the data and generate the magnetic tape of plotting commands. The plotter required nearly three minutes to draw the contour map. Both the computer and plotter times seem to be heavily dependent upon the number of levels per contour map and the length of the contour lines per level since the problem is almost completely tape bound.

2. INVENTORY CONTROL PROGRAM (Stephen E. Nugent -- PPCO 40.0191)

The Inventory Control Program is a 7040 COBOL program which when completed will create and maintain four files of information on magnetic tape. These files are the purchase order file, the store's file, the vendor file, and the buyer's file. A wide variety of reports will be generated from these files, some weekly, some monthly, and some both weekly and monthly. The program will also generate a monthly work tape which will be used by Finance to distribute costs to the various charge numbers.

2.1 The Purchase Order File

The purchase order (PO) file contains all "open" purchase orders, check requests, and contracts. By "open" it is meant those files which have not been fully received and "closed". A weekly report called "Purchase Transactions-Expedites-Exceptions" is generated from this file. This report lists all purchase orders which were closed during the week, all check requests which were closed during the week, all contract releases which were closed during the week, and all open PO's that are to be expedited or that are delinquent. All this information is listed in vendor number order so that it enables the store keepers to go through the report vendor by vendor and take any necessary action.

2.2 The Store's File

The store's file is by far the most important and most useful file that is maintained by this program. This file records and controls the "balance-on-hand" of every store's stock item. There are several weekly and monthly reports that are generated for this file.

2.21 Price Comparison Report. Weekly, this report lists all stock items which had a PO whose unit price varied more than a certain percentage of the previous PO on that item. Monthly, this report lists all stock items whose average price varied by more than a certain percentage.

2.22 Volume and Dollar Summary of Warehouse Transactions. This report lists for each stock class the beginning balance, total issues, receipts, and adjustments for the period, the ending balance, the ending average investment, and the forecasted sales and inventory for the next month.

2.23 Reorder Report. The content of this report is based on extensive statistical calculations. It tells the buyers when it is time to reorder each stock item and how much to order. It lists each stock item whose balance on hand and machine-computed-usage-forecast indicates that it should be reordered at

report time. Additional items printed included the machine-computed current balance on hand, the machine-computed usage forecast, the minimum and maximum quantity, the machine-computed lead time (time from reorder report to receipt), the machine-computed economic order quantity, the quantity on back order, the quantity due in, the machine computed quantity to buy, and the total price of the quantity to buy. The IBM Impact Manual was used as the main reference of forecasting usage and setting order quantity and order point.

2.24 Store's Activity Listing. This report lists for each stock item, all issues, receipts, back orders, PO's, and adjustments during the period. Each month these individual issues, receipts, and adjustments are stored on a tape which is used by Finance to distribute costs and to write their six-month historical report.

2.25 Summary of Procurement Actions. This report lists total purchases from vendors in each of the four main classes: government agency, small business, big business, and educational. Each of these is broken down into several subclasses.

2.26 No Activity Store's Items. This lists all items that had not been issued during the current month, along with the date last issued, balance on hand, and the last average usage.

2.27 Store's Stock Out Record. The last report generated by the store's file is the "Store's Stock Out Record" which lists all items that went on back-order during the month.

2.3 The Vendor File

2.31 Vendor Performance Report. The vendor file will contain information about each of Phillips' vendors, and on the basis of this information a monthly report will be generated which will enable the buyers to evaluate the performance of each of these vendors. This report is called the "Vendor Performance Report". It will list, for each vendor, for the current six months and the last six months, the number of orders placed, the total value of these orders, the number of orders completed, the number of orders completed with more than one receiver, the number of receivers on orders completed, the number of purchase order line items completed, the number of line items completed past due, and the percent of line items completed past due.

2.4 The Buyer's File

2.41 Buyer's and SBA Report. This report will list, for each buyer, the number of purchase orders and check requests for the month, the total amount of these, and the year-to-date number and amount of purchase orders. It will also list some small business association information such as the number of orders awarded to small business and to big business.

2.5 Procedure

At the end of each day all the purchase orders, receivers, issues, contracts, and check requests for that day are read into the 7040 and put through an extensive error checking procedure which will list out any errors that may be present so that they may be corrected by the warehouse people during the next day's run. Even though there may be an error on a purchase order or

other transaction, it is still retained on the daily tape along with the correct transactions and listed out each day with error messages until it is either corrected or deleted. This makes it almost impossible for the correction to be overlooked or forgotten.

At the end of each week the daily tape is run through what is called the "Prewrite Run.". This run takes each transaction on the daily tape that does not have any errors, and generates transactions on another tape in a form that can be sorted in the order of the purchase order file so that this file can be updated. For example, for a receiver, the corresponding purchase order must be found in the PO file and the received quantity deducted from the quantity due in on that order. There are also new purchase orders and check requests that must be added to the file. This tape is then sorted and the purchase order file update run is made. The "Purchase Transactions-Expedites-Exceptions" report is written at this time.

The purchase order file update run generates transactions to the other three files on separate tapes, and each of these tapes is sorted. For example, a store's file transaction must be generated for each store's item receiver so that it can add to the balance on hand for that item in the store's file. Vendor and buyer's file transactions must be generated for all new purchase orders and for all completed purchase orders. Issues are passed directly onto the store's transaction tape since they do not affect the purchase order file at all.

The store's file update is made next, and all the weekly reports from this file are generated. The vendor and buyer's file transaction tapes are saved since updates are made to these files monthly.

At the end of each four-week period the reorder report calculations are made in the store's file and the reorder report is written. At the end of each month all other monthly reports from the store's file are generated. Also at the end of the month all the month's vendor and buyer's transaction tapes are merged onto one tape which is sorted and the vendor and buyer's files are updated and the reports are written from these files.

There also will be facilities to make a wide variety of adjustments to all four of these files both during the weekly runs and during the monthly runs so that any malfunction can be easily and quickly corrected. The user must be able to, if necessary, make changes to any part of any file.

3. SHIFTY GAMMA FITTER (G. A. Jayne, G. A. Cazier)

A FORTRAN program (PPCO 40.0205) for the IBM 7040 has been written to determine the intensities of standard spectra present in a composite spectrum obtained from a gamma-ray scintillation spectrometer.

The count in Channel i of the composite spectrum can be represented by

$$y_i = \sum_{j=1}^N B_j S_{ij}$$

where N is the total number of standard spectra present, B_j is the intensity of standard spectrum j , and S_{ij} is the count in channel i of standard spectrum j .

An initial linear least-squares fit is used to determine the B_j 's. Since the exact gain of each standard spectrum is not known, all specified standards are gain-shifted by ratios of $1 \pm \Delta R_j$, where ΔR_j is an input ratio increment for standard j , in an attempt to find a better fit to the composite, again in a least squares sense.

This cycle, consisting of gain-shifting the specified standards by given ratios, and of fitting to determine the B_j 's, is repeated with finer and finer sets of ΔR_j 's until no significantly better fit to the composite can be found.

4. REACTOR CODES DEVELOPMENT (K. R. Dickey)

Improvements have been made in the magnetic tape positioning routines in the PDQ (two dimensional steady state neutron diffusion) and TURBO (two dimensional neutron diffusion and depletion) codes. Both of these codes store large amounts of data on magnetic tape and require a considerable amount of tape positioning during the computation. By making use of the trapping capability of the 7040 computer through the Input-Output Control System furnished with the monitor, tape positioning routines have been coded that allow up to four tapes to be positioned simultaneously with arithmetic computation. At certain points in the computation, the tape positioning time has been halved by the use of these routines. In order to take complete advantage of the overlapped tape positioning, slight additional modifications will be made to the codes.

The AIM-6 (Atomics International Multi-Group Diffusion Code for the 7090) has been converted to the 7040 computer. Due to the larger core storage requirements of the 7040 monitor system, the program storage arrangement of the AIM-6 code had to be changed. With these changes of core storage, all the capability and options of the original code remain unchanged.

5. SPERT IV STABILITY STUDY (G. A. Cazier -- PPCO 40.0025)

A computer program (PPCO 40.0025) has been prepared to assist in the stability study of Spert IV. Data from ion chambers at Spert IV are recorded in analog form on FM magnetic tape. It is desired to calculate the standard deviation of the data. To make the data acceptable to the 7040 computer the data are processed through an analog to digital converter, thus producing a digital tape which can be read by the computer. The digital tape is prepared in BCD form with 2048 three-digit words per record. The first 48 words of each record are used to convert the remaining data to engineering units.

The standard deviation is computed with double precision arithmetic from the relationship:

$$\sigma = \sqrt{\sum_{i=1}^N \frac{(x_i - \bar{x})^2}{N}}$$

where

$$\bar{x} = \frac{\left(\sum_{i=1}^N x_i \right)}{N} .$$

6. DATA ERROR RETURN (R. L. Coates -- PPCO 40.0218)

Frequently, programs written for the IBM 7040 are submitted for data processing with several sets of data to be run at one time. If an error due to key punching or card handling is encountered on a particular set of data, the program is terminated and all the subsequent sets of data are left unprocessed.

For this reason error recovery subroutines have been written (see PPCO 40.0218) which when an error occurs during one problem set (eg, bad data) the user has the capability of continuing with the next problem set without terminating the program.

7. COMBINATION CROSS SECTION CONVOLUTION PROGRAM (COMBCCO) (N. H. Marshall -- PPCO 40.0297)

This code computes theoretical total and fission cross section curves from input parameters using the Reich-Moore multilevel formula. Total cross sections may also be computed using the Breit-Wigner single level formula. The data may be Doppler and/or resolution broadened, or both. This code allows the cross sections of up to five different isotopes to be computed simultaneously and combined into a single output curve. The program is in "debug" stage.

8. MULTILEVEL CROSS SECTIONS CONVOLUTION PROGRAM (MLCNVL) (N. H. Marshall -- PPCO 40.0117)

This code computes theoretical total and fission cross section curves from input parameters using the Reich-Moore multilevel formula. The data may be Doppler broadened and/or resolution broadened, or both. The program is complete and write-ups are available.

9. BURST FITTING PROGRAM (BURFIT)
(N. H. Marshall -- PPCO 40.0139)

This code computes and convolutes theoretical data using the model

$$f(y) = \left[A + B(y-y_0) \right] e^{-\left(\frac{y-y_0}{\sigma_0} \right)^2} + \left[C + D(y-y_1)^2 \right] e^{-\left(\frac{y-y_1}{\sigma_1} \right)^2} .$$

The program allows automatic plotting of output data. The code is complete and operational.