CEX-64.7

CIVIL EFFECTS STUDY

NEUTRON AND GAMMA-RAY LEAKAGE
FROM THE ICHIBAN CRITICAL ASSEMBLY

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Issuance Date: June 1966

CIVIL EFFECTS TEST OPERATIONS
U.S. ATOMIC ENERGY COMMISSION

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NEUTRON AND GAMMA-RAY LEAKAGE FROM THE ICHIBAN CRITICAL ASSEMBLY

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December 1965

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ABSTRACT

This experiment was a continuation of studies begun in 1956 to determine the radiation doses received by the survivors of the Hiroshima and Nagasaki nuclear detonations. The "Ichiban" critical assembly was designed and constructed at Los Alamos Scientific Laboratory to provide a simulant for the Hiroshima bomb with respect to radiation "leakage" and spectrum. It was operated at steady-state power levels while neutron and gamma-ray dose measurements were made. The results were corrected for room scattering and normalized to dose per fission. The first collision neutron dose measured at a distance of 9.5 meters was $7.7 \pm 0.3 \times 10^{-17}$ tissue rads per fission. Coupled with the mean dose per neutron of 1.14×10^{-9} rad/neutron/cm², this measurement represented a total fast neutron leakage of 0.77 ± 0.03 neutrons per fission.

ACKNOWLEDGMENTS

The authors wish to acknowledge the following IASL personnel who gave their patient assistance during the Ichiban leakage measurements: Gordon E. Hansen, Thomas F. Wimet, William Bernard, Raymond A. Pederson, Manuel B. Diaz, Wendell A. Biggers, and Jean K. Frame.

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Chapter 1

INTRODUCTION

Since 1956, the Oak Ridge National Laboratory Health Physics Division has conducted a study to determine the neutron and gamma-ray doses received by the survivors of the Hiroshima and Nagasaki nuclear detonations. Studies have included investigations of weapon fission yield and radiation leakage, geometrical factors such as the position of ground zero and height of the burst, and the radiation attenuation provided by air and by typical Japanese structures. Studies were made of these parameters during nuclear weapon tests,¹⁻⁴ Operation BREN,⁵ and other experiments. However, accurate yield and dose normalizations for Hiroshima were not possible since duplicates of that weapon were never test fired. Since the present test ban treaty forbids atmospheric testing of nuclear weapons, the "Ichiban" critical experiment was designed and built at the Los Alamos Scientific Laboratory to simulate the radiation leakage from the Hiroshima device. The purpose of the present research was to determine accurately the neutron and gamma-ray leakage per fission from this critical assembly. Comparison of these data with calculations made at IASL for the spherical geometry of "Ichiban" provides a test to determine if the calculations can be extended to the weapon configuration.

Measurements were made at the IASL Pajarito Site during steady-state operation of the critical assembly. Neutron dose measurements utilized Hurst proportional counters⁶ and threshold foil detectors.⁷ The neutron energy spectrum was determined, coarsely, from the threshold detector data and in more detail with a ⁶Li semiconductor diode neutron spectrometer.⁸ Neutron insensitive geiger counters^{9,10} and metaphosphate glass rods¹¹⁻¹³ were used for gamma-dose measurements. Variations in source output were normalized with a ²³⁸U fission counter, a BF₃ proportional counter, and sulfur pellets. Since the research utilized essentially all of the dosimetry systems currently in use at the DOSAR Facility of ORNL, this report will provide a comprehensive description of the systems not published previously.

The dose unit used in this research was "the first collision tissue rad" as defined in NBS Handbook 75. All dosimetry data were corrected with experimental data for room and air scattering and normalized to dose per fission. Angular and spatial measurements were made to assure that the data taken at 2 m were interpreted correctly. Neutron fluence leakage was determined directly with threshold foil detectors and a moderated BF₃ counter, and indirectly by dividing the dose per fission by the mean dose per neutron as calculated from the neutron energy spectrum.

Coupled with the air-dose curves determined during weapon tests and Operation BREN, these leakage data will facilitate the assignment of doses to the Hiroshima survivors. These dose values and the large number of clinical observations made in Japan by the Atomic Bomb Casualty Commission will ultimately constitute the largest single set of data available on the effects of nuclear radiation on human beings.

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Chapter 2

APPARATUS

2.1 KIVA

This leakage experiment was performed in Kiva number two of the Pajarito Site of Los Alamos Scientific Laboratory. The Kiva is a poured concrete building with a "T" shaped floor plan (Fig. 2.1). The main experimental area is a room 32 ft by 58 ft with a 20-ft-high ceiling. All walls are 10 in. thick with set-in glass bricks above 15 ft for illumination. The roof was of lighter construction. Neutron and gamma-ray scattering was excessive due to the heavy concrete walls and floor. Several other critical devices located within the room also perturbed the radiation field.

Except for the reactor controls used to operate the critical assembly, the equipment used in this experiment was located either in the Kiva or in a van trailer parked beside the control building. The trailer was equipped with air conditioning, desks, and both regulated and nonregulated electrical circuits. Temporary cables were strung between the trailer and the control room to connect with the underground cables to the Kiva. To alleviate noise associated with ground loops, regulated a-c power from the trailer was supplied to the equipment operating in the Kiva.

2.2 CRITICAL ASSEMBLY

The radiation source used for these measurements was the LASL "Ichiban" assembly (Fig. 2.2). To simplify the calculations of spectrum and leakage, "Ichiban" was built of concentric spheres of enriched uranium, reflector, and steel. This device was designed so that it would have nuclear properties similar to the Hiroshima weapon.

The "Ichiban" assembly consists of a massive steel spherical outer shell, 37.66 cm in outside radius. The fissile material (^{235}U) and reflector are disposed within. The assembly weighs about 2 tons.

A four-legged steel stand held the assembly such that the center was about 8 ft above the floor. The concentric steel and reflector spheres were divided into hemispheres that could be separated by hydraulically lowering the bottom ones which held the fuel. Nonoperational nuclear safety was assured by the low reactivity of the open configuration. Additional safety was provided by a cylinder of the steel and reflector which could be removed rapidly from the top hemisphere by a pneumatic actuator. When the sphere was assembled around the fuel, reactivity was controlled by a motor-driven cylinder of reflector and steel at the bottom. The assembly was critical when the sphere was closed, the top safety cylinder in, and the control element about 1 in. from total insertion.

Fig. 2.1--Kiva 2

Fig. 2.2--Ichiban Critical Assembly

A small hole through the lower hemisphere was provided for placing fuel samples into the core so that fission yield could be determined by chemical analysis. This hole was also used to hold a thermocouple during high level runs to ensure that the core temperature rise was not excessive. A rise of about 30°C was obtained during a 6-min run at a nominal power of 4 kw.

2.3 NEUTRON DOSIMETERS

2.3.1 Hurst Proportional Counter and Radsan

Low-level neutron dosimetry was performed with the Hurst proportional counter¹ which is a "Bragg-Gray chamber" lined with polyethylene 0.125 in. thick and filled with cyclopropane gas at a pressure of 50 cm Hg (Fig. 2.3). The counter is a cylinder about 5.5 in. long by 2.5 in. in diameter with a sensitive volume 1.625 in. long by 1.70 in. in diameter. Cyclopropane permits operation at lower anode potentials than ethylene but has the same ratio of carbon to hydrogen atoms in its molecule. Field tubes operating at 29% of the anode voltage define the length of the sensitive volume and improve the shape of the electric field. An internal alpha source mounted behind a shutter can be exposed by energizing a solenoid located outside the counter. A thin layer of silicon monoxide is plated over the alpha source to prevent counter contamination. Electrical connections to the anode and the field tubes are made through coaxial connectors located on one end of the counter.

Because energy resolution is a function of anode potential, an operating potential must be chosen which provides the required resolution while still providing adequate electron multiplication. If too low an electron multiplication is used, additional gain must be supplied by the pulse amplifier with a subsequent increase in noise. Typical operating voltages are between 1000 and 1500 volts depending upon the condition of the gas. Impure gas requires more voltage to produce the same multiplication resulting in poorer resolution. The counters used were refilled shortly before the beginning of the experiment and each exhibited an energy resolution of 6% or better.

Pulses from the counter are coupled through a coaxially mounted blocking capacitor to a hybrid nuvistor-transistor preamplifier (Figs. 2.4, 2.5). This preamplifier is a modification of one designed for use during Operation BREN. A nuvistor input stage provides high input impedance and low noise. Additional gain is provided by a low-noise silicon transistor which drives two cascaded emitter follower circuits. The first emitter follower uses a high-frequency germanium transistor to provide the signal for the preamplifier feedback circuit. A transistor with high-current gain is used as the second emitter follower to provide sufficient current to transmit the output signal over a coaxial cable of up to 1500 ft in length. Preamplifier gain is about 30. Low noise deposited carbon resistors are used where necessary and a well-regulated 9-volt power supply is used for the transistor circuits (Fig. 2.6). Filament voltage for the tube comes from a zener diode circuit which reduces the regulated 9 volts to 6 volts. The plate potential is supplied by a 67-1/2-volt battery.

Low voltage for the transistor stages of the preamplifier is supplied by a 12-volt full-wave rectifier located in a separate box which is connected to the preamplifier with a cable 10 ft long (Fig. 2.7). Also mounted in the box is the 67-1/2-volt battery for the nuvistor. To minimize noise pickup from the supply and interconnecting cable, the 9-volt regulator is located in the preamplifier housing. The gain stages are shielded from the regulator. A current regulator in the preamplifier housing is used as a line filter for noise from the solenoid cables (Fig. 2.8). An additional filter for the high voltage and the field tube voltage divider is located in the front of the preamplifier housing.

ABSOLUTE FAST NEUTRON DOSIMETER

Fig. 2.3--Hurst Proportional Counter

Fig. 2.4--Radsan Preamplifier

Fig. 2.5--Hurst Proportional Counter Mounted on Preamplifier Assembly

Fig. 2.6--Nine-Volt Regulator

Fig. 2.7--Twelve-Volt Power Supply

Fig. 2.8--Solenoid Current Regulator

Pulses from the preamplifier go to the Radsan dose integrator which was originally designed by Wagner and Hurst. The circuits were later modified by De Lorenzo.² This instrument is identified by the ORNL model number Q 1955-1R0-2R0 (Fig. 2.9). Contained in the unit are a linear amplifier, four discriminators, a binary scale of sixteen, a decade scaler with scale of 10^4 , an interval timer, a high-voltage supply, and a power supply for the solenoid.

When used with the remote preamplifier, the first stage of the linear amplifier provides more gain than necessary so the input is bypassed to the fine gain control to reduce the gain to approximately 3000. Output pulses up to 100 volts can be produced by the amplifier. The amplifier output is connected to four discriminator circuits set at 5, 10, 20, and 40 volts. Discriminator outputs are coupled to a four-bit binary in such a way that amplifier pulses between 5 and 10 volts produce a "two" count in the binary. Similarly, the pulses between 20 and 40 volts and those above 40 volts produce signals in the binary worth 4 and 8 counts respectively. The output of the binary circuit is transmitted to a decade scaler with three decades of electronic scaling preceding a four-decade register.

The coarse gain control on the amplifier is used primarily for checking the discriminator settings so the control has a section that switches the discriminator outputs into the decade scaler one at a time. Thus, the 5-volt discriminator is connected directly to the decade scaler on the lowest gain setting. Increasing the gain by a factor of two connects the 10-volt discriminator to the scaler. The gain control position which is four times the minimum connects the decade scaler to the 20-volt discriminator while the next factor of two connects the 40-volt discriminator. The maximum coarse gain setting is used for normal operation and is a factor of 32 greater than the minimum setting. With the gain switch in the "operate" position, the output of the four-bit binary operates the decade scaler.

When the proper running time is chosen, the Radsan will record dose rate in mrad per hour. An internal glow transfer tube scaler is used as the timer with a variable frequency multivibrator providing the clock pulses. Because the timer will stop only when factors of ten are reached, the input frequency is varied to produce the desired timing interval. Short, medium, and long time cycles are available which normally run 22, 220, 2200 sec.

The high-voltage supply in the Radsan is a well-regulated, low-noise supply with adequate output current to operate the counter and field tube voltage divider network. Output from the high-voltage supply is variable from 800 to 1500 volts and is transmitted to the counter over a high-voltage coaxial cable such as RG 59/U or RG 11/U.

To operate the alpha-source solenoid on the counter, a low-voltage supply is built into the Radsan which is turned on when the coarse gain switch is in any position other than "operate". However, when the solenoid circuit includes a current regulator to decrease noise, the internal supply does not provide sufficient voltage; therefore, an external supply capable of supplying 1 amp at voltages as high as 25 volts is used instead of the internal supply (Fig. 2.10). A multisecondary filament transformer with the secondary windings in series supplies power to a bridge rectifier circuit with a condenser input LC filter. To control the output voltage, the transformer primary operates through a variable autotransformer from the power line. Output voltage and current are monitored by meters. When several neutron dosimeters are used simultaneously, the supply has a switch for sequential operation of five solenoids.

For the neutron dose leakage measurements of "Ichiban," two Radsans and two solenoid supplies were used. A single switch was arranged to start both Radsans simultaneously as the noise caused by the internal timer clock is

Fig. 2.9--Radsan Integrator and Solenoid Power Supply

Fig. 2.10--Solenoid Power Supply

avoided when both units are started simultaneously. A third Radsan and two additional proportional counters were available as replacements.

2.3.2 Threshold Foil Detectors

For measuring neutron fluence and dose leakage during high power runs, the ORNL threshold detector system was used.³ Six foils are used in this system. Two 1-mil-thick by 7/16-in.-dia. gold foils are used with one of the foils enclosed in cadmium; the difference in activation of the two foils is related to the thermal neutron fluence. Three fissile foils that contain 3 g of ^{239}Pu , 5 g of ^{238}U , and 0.4 g of ^{237}Np are each encapsulated in copper cans 15/16 in. in diameter by 3/32 in. thick. During use, they are enclosed in a 30-mil-thick cadmium cup and a 1.65 gm/cm² ^{10}B sphere. The ^{10}B shield provides an artificial threshold of 1 kev for the ^{239}Pu foil and shields all the fissile foils from thermal neutrons. Effective threshold energies for ^{237}Np and ^{238}U are 0.75 and 1.5 Mev respectively. The remaining foil in the system is a 22-g sulfur pellet for the $^{32}\text{S}(\text{n},\text{p})^{32}\text{P}$ reaction with a threshold at 2.5 Mev.

After exposure, the gamma activities of the gold foils are measured with a 1-in. x 1 1/2-in. NaI(Tl) scintillation crystal and the beta particles from the sulfur pellets are detected with a 1 3/4-in.-dia. by 1/6-in.-thick plastic phosphor. Fission product gamma rays from the fissile foils are measured with a counter that consists of two 4-in.-dia. by 2-in.-thick NaI(Tl) crystals facing each other. The crystals are separated by a sample slide and two conical lead filters to prevent exposure of the crystals to soft gamma rays from ^{237}Np that might overload the detector or amplifier. All of these counting systems are calibrated with ^{137}Cs sources.

Operating voltages for the scintillation counters are provided by a well-regulated, low-noise supply and are independently adjustable to control photomultiplier gain. Pulses from the detectors are amplified by a double delay line linear amplifier. Amplifier gain is set so that the pulse height selector has a range of 2 Mev. For fission foil counting, the PHS is set to provide an energy bias of 1.2 Mev to exclude the ^{238}Np gamma rays resulting from thermal neutron capture in ^{237}Np . Output pulses from the amplifier PHS circuit are recorded by a 2-mc transistorized scaler. The same high-voltage supply, amplifier and scaler are used on all three counting systems. Lead shields enclose the detectors to reduce background.

2.3.3 Semiconductor Diode Detectors

A count-rate system was designed to supplement the fission-foil detectors when greater sensitivity was required.⁴ A gold-silicon surface-barrier diode with a sensitive area of 3.5 cm² was made neutron-sensitive by placing thin fissile targets next to its sensitive surface. The detector was insulated in fluoroethene, mounted in a 0.025-in. cadmium cup, and placed inside a ^{10}B shield (Fig. 2.11). The targets consisted of approximately 2 mg of ^{238}U and ^{237}Np , and 20 μg of ^{239}Pu , each electro-deposited on a 30-mil-thick nickel mount. The bias voltage for the diode was supplied by a 15-volt battery through a 500-K Ω load resistor. Both battery and load resistor were mounted inside the box of an integrating preamplifier which was used with a double-differentiating linear amplifier (ORNL Type A-8). The diode was attached directly to the preamplifier using RG 174/U cable and a BNC connector. The PHS output of the amplifier was registered on a 2 Mc transistorized scaler.

Fig. 2.11--Semiconductor Diode Detector

2.4 NEUTRON ENERGY SPECTRUM MEASUREMENTS

2.4.1 Lithium-6 Neutron Spectrometer

The Ichiban neutron energy spectrum was measured with a ${}^6\text{Li}$ spectrometer⁵ consisting of two closely spaced surface-barrier detectors, one of which had 2 cm² of its sensitive surface coated with a 90 $\mu\text{g}/\text{cm}^2$ layer of ${}^6\text{Li}$. The charged particle detectors have sensitive areas of 2.4 cm² and were mounted in nonhydrogenous lavite rings. Miniature connectors provided connections to the diodes which were hermetically sealed in a nickel-plated brass can. The inside of the brass can was lined with approximately 1/8 in. of the "teflon" to absorb electrons resulting from gamma interactions in the brass. During use, a ${}^{10}\text{B}$ can enclosed the spectrometer to prevent undesired thermal neutron events. In addition, a second spectrometer unit having no ${}^6\text{Li}$ coating was used to determine the background caused by neutron interactions with the silicon detectors.

Signals from the detectors were summed and amplified by ORTEC Model 101 preamplifiers and an ORTEC Model 201 NS main amplifier. Power to operate the preamplifiers and summing circuit which were located in the Kiva was provided by an ORTEC Model PS 120 Remote Supply. An Oregon Model A2A power supply, variable from 0-300 volts, was used to provide bias voltages for the detectors which were normally operated at 100 volts. Signals from each preamplifier and their sum signal were transmitted to the trailer via low capacitance (RG 63/U) coaxial cables. The preamplifier pulses served as inputs for two ORNL A-8 double-differentiating linear amplifiers while the sum pulse was further amplified with the main amplifier. The A-8 amplifier outputs were fed through cross-over discriminators and operated a tunnel diode coincidence circuit that had a resolving time of 100 nsec. If the preamplifier pulses occurred within the resolving time of the coincidence circuit, a 2- μsec , 4-volt pulse was generated to operate the linear gate of a Nuclear Data Model 101 analyzer so that the corresponding sum pulse from the main amplifier could be recorded. Figure 2.12 shows the spectrometer components that were located in the Kiva.

2.4.2 Threshold Detectors

While the sandwich neutron spectrometer provided detailed measurement of the neutron energy spectrum, coarse measurements were also made using the threshold detector system described in Section 2.3.2.

2.4.3 Semiconductor Diode Detectors

Additional neutron spectrum data was obtained using the fission foil targets on the semiconductor diodes. This equipment was described in Section 2.3.3.

2.5 GAMMA-DOSE MEASUREMENTS

2.5.1 Phil Dosimeter

The Phil gamma-ray dosimeter is a Phillips Model 1850901 Geiger-Mueller counter suitably shielded with lead, tin, and fluorothene to make its response per roentgen more uniform at low photon energies (Fig. 2.13).^{6,7} This dosimeter has inherent low sensitivity for fast neutrons with some response to thermal neutrons that can be reduced by an additional ${}^6\text{Li}$ shield.

Signals from the detector were amplified by two cascaded emitter followers that provided sufficient current amplification to transmit pulses over 1500

Fig. 2.12--Lithium-6 Neutron Spectrometer Components that Were Located in the Kiva

THERMAL NEUTRON SHIELD

PROBE ASSEMBLY

Fig. 2.13--Phil Gamma-Ray Dosimeter

feet of low capacitance coaxial cable (Fig. 2.14). Output pulse height was limited to 9 volts by the 10-volt preamplifier power supply. Signal, high voltage, and preamplifier operating voltage were transmitted to the detector on a four-conductor cable from the power supply box described in Section 2.3.1. The 10-volt potential for the preamplifier was obtained from a zener diode circuit operating from the 12-volt rectifier. Detector high voltage was supplied by a blocking oscillator converter (Fig. 2.15). The high-voltage output of the converter was rectified, filtered, and regulated with a 400-volt corona discharge tube. A feedback arrangement used the current through the corona tube to control the blocking oscillator. Although somewhat noisy, this supply was adequate for operating the Phil.

Output pulses from two of these detectors were transmitted over coaxial cables to the instrument trailer and read out on decade scalars. Sensitivity varied from counter to counter over a range from 75 to 90 counts per minute per mr/hr, therefore, careful calibration was required. The maximum dose rate the Phil could measure was limited to about 1 R/hr by the counter dead time. The minimum dose rate measurable was limited by statistical considerations and background.

2.5.2 Metaphosphate Glass Microdosimeters

Silver metaphosphate glass rods 1 mm in diameter by 6 mm long were used to measure the gamma-dose leakage during high power runs.^{8,4} Gamma-ray irradiation of silver-activated glass produces luminescence centers which yield orange light when the glass is exposed to ultraviolet light. The number of luminescence centers produced is linearly related to absorbed dose up to 10^4 rads. Toshiba II rods, manufactured by the Tokyo Shibura Electric Company of Japan, were used. This glass is identified as "low z" since lithium and boron replace the potassium and bromium which are used in "high z". Lower doses can be measured with "low z" glass because it has greater sensitivity and lower predose luminescence than "high z" glass. The presence of Li, B, and Ag in the glass makes it sensitive to thermal neutrons so a ^6Li shield is used when the rods are exposed in a mixed neutron-gamma field. The shield has an outer diameter of 0.345 in. and is 0.490 in. long with inner dimensions of 0.125 in. dia. by 0.270 in. deep. It is press formed from a mixture of 90% LiF and 10% polytetrafluoroethylene and has a total weight near two grams. Each shield holds three microdosimeters without photon energy response shields and one when such a shield is used.

The reader used to measure the luminescence of the irradiated rods consists of three basic parts: a UV light source, a chuck to hold the glass rods, and a photomultiplier to detect the orange light. A modified Bausch and Lomb reader was used for these experiments.

2.6 NORMALIZATION CHANNELS

2.6.1 Fission Counter

The principal means of normalizing the radiation output of the critical assembly was an Amperex B300D fission counter plated with 20 mg/cm² of natural uranium. Its dimensions were 4 1/2 in. x 4 3/4 in. x 1 7/8 in. thick with a sensitive area of about 60 cm². During use, the counter was enclosed in a 30-mil-thick cadmium can to reduce counts due to thermal fissioning of the 0.7% ^{235}U present in the uranium liner.

A preamplifier designed to have good line driving characteristics and high gain combined with low radiation sensitivity was used. It was constructed with ceramic capacitors, carbon resistors, and nuvistor vacuum tubes (Fig. 2.16).

Fig. 2.14--Phil Preamplifier

Fig. 2.15--Phil High Voltage Supply

Fig. 2.16--Normalized Fission Counter Preamplifier

The preamplifier was conventional except for the nuvistors which allowed the circuit to be built in a box 2 in. x 2 5/8 in. x 1 5/8 in. Two input gain stages were coupled to a cathode follower that provided signal for the output and feedback circuits. The output stage used two tubes as a White cathode follower that provided sufficient current gain for transmitting signals over long coaxial cables. Preamplifier gain was 100 for pulse rise times of 0.2 μ sec. Less gain and faster rise times could have been obtained by decreasing the size of the resistor in the feedback network.

Preamplifier power and counter high voltage were provided by a special power (Fig. 2.17). The filament supply had a transistor voltage regulator to improve preamplifier gain stability and was variable so that filament voltage could be adjusted to compensate for losses in the cable between the power supply and preamplifier. Series regulators in the high-voltage supply provided 300 volts for the counter anode and plate voltage for the preamplifier. Plate voltage was variable from 75 to 150 volts, but it was set, normally, at 120 volts. This was reduced to 90 volts by a filter circuit in the preamplifier box. A front panel meter with appropriate switching allowed the counter voltage, plate voltage, and filament voltage and current to be checked routinely. A single multiconductor cable carried voltage from the power supply to the preamplifier and returned the output signal to the power supply chassis.

The detector signal was transmitted from the power supply over a coaxial cable to a special transistorized double-differentiating amplifier.^{9,10} Although output pulse widths as short as 100 nsec could have been used with this amplifier, a 500-nsec pulse width was sufficient for this application. Some of the detector pulses produced preamplifier output signals sufficient to overload the main amplifier so an attenuator was used at the amplifier input. In addition, the attenuator provided proper termination for the coaxial cable and reduced amplifier response to "cable noise". The amplifier output signal went to an ORNL designed transistorized integral-differential discriminator chosen for high speed operation. Discriminator output pulses operated a 100-mc scaler. All circuit components were designed or selected to operate satisfactorily at counting rates up to 10^5 counts per second.

2.6.2 BF₃ Counter

One of two back-up systems used for source output normalizations was a BF₃ proportional counter enclosed in a cylindrical paraffin neutron moderator. This same counter was used as the primary normalizing channel during Operation BREN. Its sensitivity was too great to allow its satisfactory use during all of the Ichiban runs. Because the energy response of the counter was known,¹¹ it was also used for an approximate measurement of neutron leakage.

A 1.5-cm-dia. BF₃ proportional counter was used. It was mounted in an aluminum cylinder 37 cm long by 4 cm dia. with the remaining space in the aluminum tube filled with paraffin. This arrangement is used, typically, in conjunction with the Hansen-McKibben long counter. The moderator used was a paraffin-filled aluminum cylinder 37 cm long by 22.5 cm dia. equipped with an axial hole for the counter.

The counter was used with a modified ORNL A1A preamplifier. For improved signal transmission properties, a White cathode follower was used in the preamplifier output. A high-voltage filter and load resistor for the counter were mounted inside the preamplifier box. The 2800-volt counter anode potential came from the Baird-Atomic Model 319 power supply via RG 11/U coaxial cable. Preamplifier power was supplied from the main amplifier over a multiconductor cable that also carried the signal to the amplifier. After further amplification by an A1 linear amplifier operated at 0.5 mc bandwidth, the signal operated

Fig. 2.17--Power Supply for the Normalization Fission Counter Preamplifier

a 2-mc transistorized scaler and a linear count-rate meter. The count-rate meter output operated a Brown recorder to provide an analog display of reactor power level.

2.6.3 Sulfur Pellets

The second back-up normalization channel utilized sulfur pellets located in a reproducible position on the critical assembly during each run. These sulfur pellets were identical to those used in the threshold detector system as described in Section 2.3.2.

2.7 SPATIAL DOSE-DISTRIBUTION MEASUREMENTS

Spatial dose-distribution studies were made with the Phil and glass rods for gamma rays and with the Radsan and sulfur pellets for neutrons. These detectors and associated equipment are described in Sections 2.5.1, 2.5.2, 2.3.1, and 2.3.2.

For measurements of scattered radiation, it was necessary to shield the detectors from "direct" radiation. The neutron shield was a truncated cone 46 cm long with a small diameter of 3 cm and a large diameter of 12 cm (Fig. 2.18). It contained approximately 20 lbs of paraffin intimately mixed with 3 lbs of borax for thermal neutron absorption. A lead brick sufficed as the shield for gamma scattering measurements.

An additional means of measuring the direct dose leakage from Ichiban was provided by personnel of "J" division of IASL who installed a collimator on the floor 9.45 m from the critical assembly. The collimator consisted of a four-sided truncated pyramid of steel with a 3.5-in. axial hole and was aimed directly at Ichiban while measurements were made with Radsan and Phil dosimeters (Fig. 2.19).

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Fig. 2.18--Borated Paraffin Shield

Fig. 2.19--Neutron Collimator

Chapter 3

PROCEDURES

3.1 NEUTRON-DOSE MEASUREMENTS

3.1.1 Hurst Proportional Counters

Hurst proportional counters were used with Radsan pulse integrators for neutron dosimetry measurements. To ensure correct integration, the Radsan discriminators were calibrated daily with a pulser which delivered a step-function pulse with exponential decay similar to the pulses generated by the proportional counters. The pulser signal was fed into the Radsan amplifier, and the resulting output was monitored with an oscilloscope that had a calibrated vertical amplifier. With the coarse gain control at the 5V setting, the amplifier output was set at 5 volts and the 5-volt discriminator adjusted so that its output was half the maximum counting rate. This procedure was repeated for the 10V, 20V, and 40V gain settings and discriminators. The preamplifier output was connected to the Radsan input via approximately 1200 ft of cable between the Kiva and the control trailer. A second cable transmitted high voltage to the counter. The anode potential was adjusted to operate the counter in the proportional region. With the amplifier coarse gain control set at 5V, the alpha-source shutter in the counter was opened and a multichannel analyzer was used to examine the resulting pulse height distribution and counter resolution. Then, the fine gain was increased so that essentially all the alpha pulses were above the 5V discriminator setting so that the maximum count rate from the alpha source could be determined. The "operating" fine gain setting was obtained by adjusting the count rate to be half the maximum rate which placed the 5 Mev alpha peak at approximately 5 volts output. To use the dosimeter, the alpha source shutter was closed and the coarse gain control set at "operate". Since the "operate" gain setting was a factor of 32 times higher than the 5V setting, the lower level cutoff was 5 Mev/32 or approximately 0.16 Mev.

The dosimeters were calibrated by exposure to a one-curie PuBe source that had an output of $1.855 \pm 0.043 \times 10^6$ neutrons per second as determined by the National Bureau of Standards. During calibration, the source was positioned such that neutrons emerging from its cylindrical sides impinged on the front ends of the detectors. The PuBe source output had been investigated previously with a Hansen-McKibben long counter and found to be uniform around its circumference and only slightly lower from the ends than from the sides. Therefore, the neutron flux at the center of each detector was calculated using a simple inverse square correction on the source output. By using a recently published neutron dose conversion factor of $4.0 \pm 0.2 \times 10^{-9}$ rad/neutron/cm²,¹ the first collision tissue dose rate due to neutrons was calculated to be 0.59 mrad/hr for a source-to-detector distance of 60 cm. A typical dosimeter reading during this calibration procedure was 0.664 mrad/hr; therefore, all experimental data taken with this particular dosimeter was corrected by the ratio 0.59/0.664 or 0.887.

Ichiban dose-leakage measurements were made with the critical assembly operating in the steady-state mode at low power. Care was taken to reject noise pulses. During some of these runs, the output of the 5-volt discriminator of one of the Radsans was recorded on a separate scaler. Since the 5-volt discriminator triggered for all acceptable pulses, recording its output allowed a simple analysis of the statistical uncertainties of the dose-rate measurements. A large number of dosimeter readings were taken at each experimental position to ensure good counting statistics. For convenience in normalizing data, the Radsan variable timer was adjusted to provide "medium" timing intervals of 200 sec rather than the standard 220. All measurements were normalized initially to dose per fission counter count and ultimately to dose per fission in the core.

To compare the Ichiban leakage measurements with air-dose curves obtained during weapon tests and Operation BREN, it was necessary to distinguish between radiation emerging from the core and that scattered from the concrete floor, walls, and ceiling of the Kiva. It was also necessary to make measurements far enough away from the critical assembly so that point-source, point-detector geometrics could be approximated. Point-source considerations required that measurements be made at a distance of at least 7.5 m or ten times the outer diameter of the critical assembly. For these reasons, the Hurst dosimeters were exposed inside the IASL collimator at a distance of 9.45 m from the center of the core. In this way, the "direct" neutron dose leakage from the Ichiban assembly was measured in the best geometry possible under the circumstances.

An additional series of measurements was performed to confirm the collimator results by using the borated paraffin cone described in Section 2.7. The Hurst dosimeters were exposed 9 ft above the floor at horizontal distances of 2, 3, and 4 m both with and without the cone so that the "direct" neutron dose rate could be determined by subtraction. These "direct" neutron dose results were compared with the collimator results.

3.1.2 Threshold Detectors

Hurst threshold detector systems were used for neutron dosimetry studies during high power runs of short duration. The fission foils were counted in an ORNL-type fission foil counter described in Section 2.3.2.

Prior to use, this counting system was set up using a detailed checkout procedure. Amplifier pulse shape and gain were checked using a pulser and an oscilloscope; then, 100 mv input pulses were used with sufficient gain to obtain 100 volt output pulses. The pulser was operated at settings of 100, 90, 80, etc., while the amplifier output pulses were examined with a multichannel analyzer. The resulting pulse height spectra were typed out and plotted versus pulser settings to check amplifier linearity. The linearity of the pulse height selector (PHS) was tested by setting both pulser and PHS at 50.0 and adjusting the amplifier gain until the PHS output yielded half maximum counting rate of 30 counts per sec. Using this gain setting, the pulser was set at 100, 90, 80, etc., and the PHS adjusted to yield 30 counts per sec in each case. These pulser and PHS settings were plotted and if necessary, slight adjustments were made with the PHS zero control.

Once the amplifier was operating satisfactorily, the scintillation counters were connected to the parallel preamplifier inputs and the high voltage turned on. Again using the multichannel analyzer, the gains of the two counters were matched by adjusting the high voltages until the photopeaks of a ^{137}Cs source overlapped. A dynamic range of 2 Mev was selected by adjusting the amplifier gain so that at an integral discriminator setting of 33.0 volts, half of all pulses due to the total absorption of the 0.66-Mev gamma rays were counted.

This was accomplished using the multichannel analyzer by placing the amplifier output in anticoincidence with the PHS discriminator. With the PHS set at 33.0 volts, the amplifier gain was adjusted until the output was "cutoff" in the center of the ^{137}Cs photopeak by the anticoincidence pulses. A scaler was used to measure the count rate of the PHS output for these conditions. This procedure was repeated for the detectors operating separately and then together. Typical count rates were 200-250 counts per sec separately and 500 counts per sec together. Routine gain standardizations were performed by periodically checking these check rates at 33.0 volts PHS with the ^{137}Cs source. This standardization method was satisfactory since for a scintillation counter with average resolution, the change in count rate with respect to amplifier gain near the ^{137}Cs photopeak was about 10.1; i.e., a 1% drift in gain resulted in a 10% change in the integral count rate.

Calibration of the fission foils was achieved by exposure to known fluences of fast neutrons above the respective threshold energies and counting the fission products generated as a function of time at a discriminator setting of 60.0 volts (1.2 Mev). This work was published separately² but will be described here briefly.

A gold-silicon surface barrier detector was mounted in a 0.025-in.-thick cadmium cup and placed inside 1.65 gm/cm² ^{10}B shield to simulate the conditions in which fission foils were normally exposed. The detector was made neutron sensitive by placing thin fissile targets of ^{238}U , ^{237}Np , and ^{239}Pu next to its sensitive surface. The efficiency of the detector was found to be 0.81 counts per fission by irradiating it with known fluences of 14.8 Mev neutrons. Finally, the detector was exposed to neutrons from the Health Physics Research Reactor using separate runs for each of the various fissile targets. Several Hurst threshold detectors containing standard-sized fission foils were irradiated simultaneously in the same geometry. Fission product decay curves were determined for the three fissile materials using the fast neutron fluences as measured with the diode detector and the weights and gamma count rates of the standard fission foils. The decay curves describe as a function of time the gamma activities of the foils per gram per 10^{10} neutrons per cm² above their respective threshold energies (Fig. 3.1). To simplify the use of the decay curves, $N(t)$ was defined for all three fission foils as follows:

$$N(t) = \frac{C(t) \times 10^{10}}{Wt \times \phi}$$

where: ϕ = neutron fluence above the threshold energy, neutron/cm²
 $C(t)$ = gamma count rate of the foil at time t
 $N(t)$ = gamma count rate per gram per 10^{10} neutron/cm² above $E_{\text{threshold}}$

Fast neutron fluences were determined for the Ichiban measurements using the following relationship:

$$\phi = \frac{C(t) \times C.F. \times P.F. \times 10^{10}}{Wt \times N(t)}$$

where C.F. was the counter factor or relative counter efficiency compared with the ORNL standard fission foil counter with which the decay curves were generated. Another correction factor (P.F.) for the perturbation of the neutron fluence by the ^{10}B shield was necessary because the computed cross sections for the foils took into account only the $^{10}\text{B}(n,\alpha)^7\text{Li}$ reaction and made no estimate for neutron scattering. The recommended factors for the measurement of fission spectrum neutrons were 1.15 for Np and 1.1 for ^{238}U , and these factors were used in the evaluation of the Ichiban data.

Fig. 3.1--Normalized Decay Curves for Fission Foil Threshold Detectors

Due to the inherent low sensitivity of the threshold detectors, it was not possible to expose them inside the collimator at 9.45 m from the Ichiban core. TDU measurements were made by exposing several units 2 m from the core and 9 ft above the floor during high-power runs of short duration. During one of the runs, a TDU was exposed behind the borated paraffin cone to correct for scattered radiation by subtraction from an unshielded unit. The detectors were retrieved from the Kiva as soon as possible and the fission foils counted as a function of time at a PHS of 1.2 Mev. Fast neutron fluences were calculated as described previously and first collision neutron doses were calculated from the fluence data as follows:

$$D = \left[1.04(\phi_{pu} - \phi_{np}) + 2.29(\phi_{np} - \phi_u) + 2.96(\phi_u - \phi_s) + 3.49(\phi_s) \right] \times 10^{-9}$$

where the coefficients represent the average dose per neutron for the various energy regions weighted to the Ichiban neutron energy spectrum as measured with the ^6Li spectrometer (see Section 4.3.2). The results were normalized to dose per fission and compared with the Radsan measurements at 2 m.

3.1.3 Semiconductor Diode Detectors

Since there was speculation that the maximum operating power of the Ichiban assembly might not produce sufficient activities in the fission foils, several surface-barrier detectors equipped with fissile targets were used to obtain "back-up" TDU data. These detectors offered the advantage of integrating neutron fluences over long, low-power runs since individual fission events were counted rather than the gamma rays from the fission products generated. Two diode detectors equipped with Pu, Np, or U targets were exposed during six low-power runs. This provided two separate runs each for the three target materials to check reproducibility. The count-rate data were normalized to the fission counter and were ultimately converted to neutron fluences per fission counter count using known detector efficiencies. First collision doses per fission counter count were calculated from these data in the same manner as from the TDU data.

3.2 GAMMA-DOSE MEASUREMENTS

3.2.1 Phil Gamma Dosimeters

The Phil was used for most of the gamma-ray measurements.³ Wagner found that the response of this dosimeter from 200 keV to 1.25 MeV was approximately proportional to exposure in roentgens. Its response above 1.25 MeV was determined with monoenergetic gamma rays obtained from a number of proton-induced resonance reactions which were run on the ORNL 5 MeV Van de Graaff accelerator.⁴ The results of this work indicated that the dosimeter had an average response from 0-8 MeV of $5.2 \pm 1.3 \times 10^6$ counts per tissue rad which was equivalent to about 86 cpm/mrad/hr.

During the Ichiban leakage experiments, the Phil dosimeters were routinely calibrated with a ^{60}Co source placed 60 cm from the detectors. This source had been calibrated with an accuracy of $\pm 3\%$ at the National Bureau of Standards. Using this source, the sensitivity of the dosimeters used was approximately 80 cpm/mr/hr, and this value was used to convert the Ichiban data to dose rates.

The Phil dosimeters were positioned in the same geometry as the proportional counters during low, steady-state operations of the Ichiban assembly. Detector signals were transmitted to the trailer via RG 63/U coaxial cables and recorded on decade scalars. Gamma-dose rates were obtained by normalizing the count-rate data to the fission counter and dividing by the calibration constant of 80 cpm/mr/hr.

Several attempts were made to determine the "direct" gamma-dose leakage from the core. First, a Phil was exposed inside the collimator which was used during the neutron leakage measurements; however, the collimator proved to be such a copious source of neutron capture gamma rays that it was useless as a gamma-ray collimator. A more successful "direct" gamma-dose measurement was made at the 2 m position by exposing 2 Phils, one in air, and the other behind the borated paraffin cone with the addition of 2 in. of lead between the cone and the detector. The Phil readings were normalized to the fission counter and the "direct" gamma-ray leakage was obtained by taking the difference between the unshielded and shielded results.

3.2.2 Metaphosphate Glass Rods

Measurements of gamma-dose leakage were made with glass microdosimeters during the two runs used for determining the neutron spectrometer background. For both runs, the rods were positioned in low scatter holders 2 m from the center of the core and 9 ft above the floor. Each station consisted of 3 rods wrapped in thin paper strips and enclosed in ^6Li shield. The dosimeters were recovered as soon as possible to decrease exposure to residual gamma rays from the core. Evaluation was performed with a Bausch and Lomb reader at ORNL after completion of the Ichiban leakage studies. Gamma doses were normalized to the fission counter and compared with the Phil gamma-dose measurements.

3.3 NEUTRON SPECTRUM MEASUREMENTS

3.3.1 Lithium-6 Sandwich Spectrometer

The fast neutron energy spectrum of the Ichiban device was determined using a Love-type spectrometer⁵ consisting of 2 closely-spaced surface-barrier detectors, one of which was coated with a thin layer of ^6LiF . Prior to the Ichiban leakage experiment, the response of the spectrometer was investigated using 2.95 Mev neutrons from the D(d,n)He reaction. An energy resolution of 300 kev full width at half maximum was obtained with an efficiency of approximately 10^{-6} .

Ichiban neutron energy spectrum measurements required that the detectors and preamplifiers be operated in the Kiva while the main amplifier, coincidence circuit, and analyzer were located in the trailer. The summed pulse from the detectors and the individual preamplifier pulses that served as inputs to the coincidence circuits were transmitted approximately 1200 ft to the trailer via coaxial cable. Initial calibration of the coincidence circuit was accomplished using the internal pulser of the main amplifier that was calibrated in units of Mev. The main amplifier was attached to the preamplifiers in the Kiva and the pulser operated at the chosen lower level discriminator setting of 1.6 Mev. The preamplifier output pulses were amplified by the A-8 amplifiers on the trailer and routed to the input discriminators of the coincidence circuit. The discriminators were set to half-trigger with these pulses so that pulses greater than 1.6 Mev originating in both detectors within the resolving time of 100 nsec satisfied the logic and a 2- μsec gate pulse enabled the 256-channel analyzer to accept the corresponding sum pulse. With this calibration completed, the main amplifier was reinstalled in the trailer for regular operation. Final adjustments were made by placing a neutron source in a moderator near the detector to obtain a "thermal" neutron peak. With the gain settings used, the peak of the thermal neutron response was recorded in channel 138 which indicated a sensitivity of approximately $4.6/138$ or 0.033 Mev per channel. A dynamic range of 8 Mev was obtained by adjusting the post amplifier bias until the thermal peak was lowered to channel 15.

The detectors were placed inside a ^{10}B shield and positioned 2 m from the Ichiban core and 9 ft from the floor. Spectral data were accumulated during 4-hr periods with the critical assembly operating at a nominal power of 100 watts. Identical runs were made using the background spectrometer unit for subtraction of undesired (n,p) and (n, α) reactions in the silicon detectors. Finally, the net data were corrected for cross section to obtain neutron energy spectra.

3.3.2 Threshold Detectors

In addition to its application to dosimetry, the Hurst threshold detector system was useful in estimating the shape of the neutron energy spectrum of the Ichiban device. The threshold detector data provided spectral information in four energy regions: the ^{239}Pu foil measured essentially the total "fast" neutron fluence above 1 kev while the ^{237}Np , ^{238}U , and ^{32}S detectors measured the total fluences above 0.75, 1.5, and 2.5 Mev respectively. By subtracting one from the other, the neutron energy spectrum was described in the regions 1 kev to 0.75 Mev, 0.75 to 1.5 Mev, 1.5 to 2.5 Mev, and above 2.5 Mev. This technique provided an independent measurement of the Ichiban neutron energy spectrum.

3.3.3 Semiconductor Diode Detectors

These detectors were used to obtain backup TDU data including spectral and dose information. See Section 3.1.3 for procedures.

3.4 SPATIAL DOSE DISTRIBUTIONS

A number of sulfur pellet and glass rod detectors were exposed around the outer steel surface of the critical assembly to determine if the radiation leakage was isotropic. Additional detectors were exposed at 1-m intervals from 1 to 4 m along a string tied between the assembly and a far wall and the results were compared with Radsan and Phil measurements. The ^{32}P activities of the sulfur pellets were counted after allowing 24 hr for the decay of ^{31}Si which was formed by the $^{32}\text{S}(n,\alpha)^{31}\text{Si}$ reaction. The glass rods were evaluated later at ORNL.

3.5 NORMALIZATION CHANNELS

3.5.1 Fission Counter

The primary normalization channel used during the Ichiban leakage experiment was the cadmium-covered uranium fission counter described in Section 2.6.1. It was firmly mounted on the support structure approximately 1 m from the center of the core. The fission counter preamplifier and power supply were operated in the Kiva and output pulses from the preamplifier were transmitted via coaxial cable to the main amplifier located in the trailer. Main amplifier gain was set with the coarse control at maximum and the fine control at midrange. A neutron source was placed near the counter and the amplifier output pulses were displayed on an oscilloscope. The input attenuator was adjusted so that none of the input pulses overloaded the amplifier. This gain adjustment was made at the input attenuator rather than with the amplifier gain controls to optimize the signal-to-noise ratio. Once the amplifier gain was set, the pulse height selector was adjusted to bias against alpha pulses due to the natural activity of the uranium counter lining. This bias setting resulted in a low energy cut-off of about 10 Mev for the fission fragments while providing ample discrimination against gamma rays from a ^{60}Co source.

The total counts from the fission counter were recorded for each run with a 100-Mc scaler. In addition, a separate 2-Mc scaler was used to obtain count-rate normalization data during the 20 and 200-sec Radsan and Phil measurements.

A routine calibration was performed before and after each run by placing a PuBe source in a reproducible position on the counter and taking a 10-min count.

3.5.2 BF_3 Counter

A BF_3 proportional counter enclosed in a cylindrical paraffin moderator was used as a back-up normalization channel during low-level Radsan and Phil measurements. The BF_3 counter and its amplifier, preamplifier and high-voltage supply were installed on a catwalk in the Kiva approximately 35 ft from Ichiban. PHS pulses from the amplifier were transmitted via coaxial cable to the trailer where readout was accomplished with a 2-Mc scaler and a linear count-rate meter that operated a Brown recorder. A neutron source was placed near the counter and a H.V. versus count-rate curve was generated to determine the proper operating voltage. With the counter operating at the selected setting of 2800 volts, the amplifier gain was adjusted until none of the neutron-induced pulses overloaded the amplifier output. Finally, a PHS versus count-rate curve was run with a ^{60}Co source next to the counter. An operating PHS setting of 15 volts was selected because it permitted counting of nearly all neutron pulses while discriminating effectively against gamma-ray pulses.

In addition, this counting system was used to estimate the neutron fluence leakage 2 m from the core during a low-power run. The counter was calibrated with the PuBe source. Leakage was calculated by dividing the BF_3 counts/fission counter count by the calibration factor of 3.05 counts/neutron- cm^2 .

3.5.3 Sulfur Pellets

Sulfur pellets weighing approximately 22 g each were exposed in a reproducible position on the outer steel surface of the Ichiban assembly during each run. These detectors were limited to measuring integrated source output and were unsuitable for normalizing power variations during Radsan and Phil measurements. The pellets were counted on the previously described plastic scintillation counter at least 24 hr after exposure to allow decay of the 2.65 hr ^{31}Si activity. Sulfur pellet activities were corrected to cpm ICR (initial counting rate at time zero) and compared with the fission counter counts for each run. A constant factor of fission counter counts per cpm ICR on the corresponding sulfur pellet gave assurance that the primary normalization channel was operating properly.

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Chapter 4

RESULTS

4.1 NORMALIZATION RESULTS

The four systems used for normalizing source output were: (1) a natural uranium fission counter; (2) a sulfur pellet located in a reproducible position; (3) a BF_3 proportional counter in a cylindrical paraffin neutron moderator; and (4) an ion chamber which functioned as part of the Ichiban control system. The output of the fission counter was recorded with two separate scalers, one for short periods equal to the length of time that the dosimeters were operated and one for the entire length of each run. In some cases, the integrated count was all that was necessary when all detectors were operated for the total length of the run. The BF_3 counter and sulfur pellets functioned only as backup normalization channels with the sulfur ineffective at low power levels and the BF_3 inoperative at high levels. A relatively high gamma response made the ion chamber readings suspect for normalization purposes so it was used only to control the power level of the Ichiban device.

Most of the Ichiban leakage results are presented in this section in tabular form. The data do not represent the total taken but are averages of that taken during single runs. Certain numbers such as those necessary for calculating the statistical variations in the Radsan readings are not presented in these tables. All statistical limits shown represent one standard deviation and include the propagation of all known sources of error. In some cases the uncertainties include estimates of error in positioning the detectors.

Table 4.1 summarizes most of the normalization data taken during the Ichiban leakage measurements. Good agreement was obtained between the fission counter and the sulfur pellets as is evidenced by the average value of $1.09 \pm 0.01 \times 10^{-4}$ cpm ICR/FC count.

4.2 NEUTRON ENERGY SPECTRUM RESULTS

4.2.1 Lithium-6 Spectrometer

The neutron spectral data were accumulated in a 256 channel analyzer with a sensitivity of about 0.033 Mev/channel which yielded an energy range of about 8 Mev. Since the ^6Li spectrometer had an energy resolution of 300 kev, the data reduction was accomplished in groups of 3 channels, i.e., at 1 Mev or channel 30, net counts from channels 29, 30, 31 were summed and corrected for the $^6\text{Li}(n,\alpha)^3\text{H}$ cross section at 1 Mev. The resulting differential neutron energy spectrum (Fig. 4.1) was evaluated with a computer using a "least squares" program. Also shown is the HPRR spectrum, normalized to the same total number of neutrons. As can be seen, the massive casing caused the Ichiban neutron energy spectrum to be considerably softened such that the mean dose per neutron was only 1.14×10^{-9} rad/neutron/cm². This number was obtained by weighting the differential spectra to the first collision tissue dose curve from NBS Handbook 75. The differential neutron energy spectrum was also used to weight

Fig. 4.1--Neutron Energy Spectra of HPRR and Ichiban

the TDU cross sections and dose per neutron values, and the dose lost below the 5-volt discriminator of the Radsans.

4.2.2 Spectrum Measurements Using Threshold Detectors

As can be seen from Table 4.7, the differential fluence between 1 kev and 0.75 Mev as measured with the threshold detectors was 3146/4043 or 78% of the total fast neutron leakage from the Ichiban device. Approximately 19% of the total leakage was between 0.75 Mev and 1.5 Mev while only about 3% was above 1.5 Mev. These measurements corroborated the ^6Li spectrometer results in that the Ichiban neutron energy spectrum was considerably softened when compared with spectra from an unshielded fission source like the HPRR.

Table 4.1--NORMALIZATION DATA

Date	Run	Ion chamber, amps	Fission counter counts	Sulfur pellet, cpm ICR	Total fissions
11-30	1A	1.8×10^{-10}	552		
11-30	1B	2.32×10^{-9}	4,828		
12-1	2A	2.1×10^{-9}	3,056		
12-1	2B	2.24×10^{-9}	4,026		
12-1	2C	2.2×10^{-9}	3,056		
12-1	2D	2.2×10^{-9}	3,717		
12-2	3A	2.25×10^{-9}	2,278		
12-2	3B	2.1×10^{-9}	2,411		
12-2	3C	3.8×10^{-9}	5,572		
12-3	4A	6×10^{-7}	6,000,794	633 ± 7	
12-4	5A	6×10^{-7}	6,000,187	660 ± 7	
12-7	6A	6×10^{-7}	6,000,011	652 ± 7	
12-8	7A	6×10^{-7}	6,000,045	656 ± 8	
12-9	8A	1.2×10^{-6}	1,000,945	107 ± 3	
12-9	8B	1.2×10^{-6}	511,000	55 ± 2	
12-9	8C	3×10^{-6}	5,028,371	559 ± 7	
12-9	8D	3×10^{-6}	23,407,660	2608 ± 24	
12-10	9A	3×10^{-6}	4,009,552	443 ± 7	
12-10	9B	1.2×10^{-6}	1,515,082	157 ± 4	
12-10	9C	3×10^{-6}	7,125,100	738 ± 9	
12-11	10A	3×10^{-5}	7,768,360	843 ± 10	$2.29 \pm 0.07 \times 10^{16}$
12-14	11A	8×10^{-9}	7,839		
12-14	11B	6×10^{-5}	15,412,781	1781 ± 15	$4.60 \pm 0.14 \times 10^{16}$

4.2.3 Spectrum Measurements Using Semiconductor Diode Detectors

Although originally designated as "back-up" units for the threshold detectors, the fission foil diodes were used during the Ichiban leakage experiment and the results are shown in Table 4.2. These results are in excellent agreement with the TDU results in Table 4.7.

Table 4.2--NEUTRON FLUENCE AS MEASURED WITH SEMICONDUCTOR DIODE DETECTORS

Target	Neutron/cm ² /F.C. count		
	"In air"	Behind shield	"Direct"
²³⁹ Pu	5798 ± 185	1628 ± 103	4170 ± 212
²³⁷ Np	1032 ± 52	(Scattering factor taken from TDU data)	882 ± 44
²³⁸ U	137 ± 7	(Scattering factor taken from TDU data)	116 ± 6

4.3 NEUTRON-DOSE LEAKAGE RESULTS

4.3.1 Hurst Proportional Counters

As was mentioned in Section 3.1.1, the Radsans had a low-energy cutoff for protons of 0.16 Mev which was necessary to discriminate against gamma-ray pulses in the Hurst proportional counters. Therefore, it was necessary to "weight" the neutron dose lost below the 5-volt discriminator versus the neutron energy spectrum of the Ichiban device. Table 3 in NBS Handbook 75 lists the per cent, *f*, of energy spent in the counter by recoil protons losing less than the bias energy, *B*, for a variety of bias energies and fast neutron energies. For the 0.16 Mev bias energy, *f* was plotted versus neutron energy and a smooth curve drawn so that points from the curve could be weighted to the differential neutron energy spectrum of the Ichiban device as measured with the ⁶Li spectrometer. This correction technique revealed that 48% of the fast neutron dose leakage from Ichiban was lost below the 5-volt discriminator of the Radsans. While this fraction may seem excessive, the corresponding losses for HPRR measurements were approximately 15%. Table 4.3 presents all of the Radsan data taken during the Ichiban leakage experiments, and Table 4.4 contains the averaged results corrected for bias energy losses.

The Radsan "direct" measurements were plotted as R^2/D versus *D* for distance of 2, 3, 4, and 9.46 m, the latter figure having been measured in the collimator. As can be seen in Fig. 4.2, good agreement was obtained between the collimator data and that taken at 2 m. This agreement indicated that source-to-detector geometry at a distance of 2 m was satisfactory for comparisons between Radsan and TDU measurements.

4.3.2 Threshold Detectors

Interpretation of the threshold detector data required that the cross sections of the various foils be weighted for the Ichiban neutron energy spectrum as measured with the ⁶Li spectrometer because the Ichiban spectrum was considerably softened by the massive steel and reflector enclosure. In addition, it was necessary to weight the dose per neutron for each of the four TDU energy regions to the Ichiban spectrum. Additional values are shown for spectra typical of Godiva-type reactors like the HPRR.

Fig. 4.2-- $R^2 D$ Versus R for Ichiban Fast Neutron Dose Leakage

Table 4.3--NEUTRON-DOSE RESULTS OBTAINED WITH RADSAN

Run	Radsan readings	Conversion factor	Dose rate, mrad/hr	Fission counter, counts 200/sec	Dose/F.C. mrad/count	Remarks
1B	1.035 $\pm$ 0.016	0.815 $\pm$ 0.037	0.844 $\pm$ 0.041	325 $\pm$ 7	1.44 $\pm$ 0.08 $\times 10^{-4}$	D = 9.46 m, in collimator
2A	19.88 $\pm$ 0.05	0.887 $\pm$ 0.039	17.632 $\pm$ 0.769	271 $\pm$ 6	3.615 $\pm$ 0.176 $\times 10^{-3}$	D = 2.0 m, without cone
	17.967 $\pm$ 0.048	0.995 $\pm$ 0.034	17.158 $\pm$ 0.789	271 $\pm$ 6	3.517 $\pm$ 0.178 $\times 10^{-3}$	D = 2.0 m, without cone
2B	4.578 $\pm$ 0.024	0.887 $\pm$ 0.039	4.061 $\pm$ 0.179	303 $\pm$ 6	7.446 $\pm$ 0.357 $\times 10^{-4}$	D = 2 m, with cone
	20.807 $\pm$ 0.044	0.955 $\pm$ 0.034	19.871 $\pm$ 0.755	303 $\pm$ 6	3.643 $\pm$ 0.153 $\times 10^{-3}$	D = 2 m, without cone
2C	3.588 $\pm$ 0.0223	0.887 $\pm$ 0.039	3.183 $\pm$ 0.121	329 $\pm$ 7	5.380 $\pm$ 0.261 $\times 10^{-4}$	D = 3 m, with cone
	11.883 $\pm$ 0.042	0.955 $\pm$ 0.034	11.348 $\pm$ 0.431	329 $\pm$ 7	1.917 $\pm$ 0.083 $\times 10^{-3}$	D = 3 m, without cone
54 2D	3.036 $\pm$ 0.020	0.887 $\pm$ 0.039	2.693 $\pm$ 0.118	338 $\pm$ 6	4.426 $\pm$ 0.212 $\times 10^{-4}$	D = 4 m, with cone
	8.110 $\pm$ 0.034	0.955 $\pm$ 0.034	7.745 $\pm$ 0.294	338 $\pm$ 6	1.273 $\pm$ 0.053 $\times 10^{-3}$	D = 4 m, without cone
3A	4.578 $\pm$ 0.030	0.877 $\pm$ 0.039	4.061 $\pm$ 0.183	292 $\pm$ 8	7.721 $\pm$ 0.401 $\times 10^{-4}$	D = 2 m, with cone
	20.446 $\pm$ 0.064	0.955 $\pm$ 0.034	19.526 $\pm$ 0.762	292 $\pm$ 8	3.713 $\pm$ 0.175 $\times 10^{-3}$	D = 2 m, without cone
3B	19.872 $\pm$ 0.163	0.877 $\pm$ 0.039	17.626 $\pm$ 0.776	272 $\pm$ 7	3.600 $\pm$ 0.184 $\times 10^{-3}$	D = 2 m, without cone
	18.592 $\pm$ 0.057	0.955 $\pm$ 0.034	17.755 $\pm$ 0.675	272 $\pm$ 7	3.626 $\pm$ 0.163 $\times 10^{-3}$	D = 2 m, without cone
3C	1.527 $\pm$ 0.016	0.738 $\pm$ 0.042	1.127 $\pm$ 0.048	529 $\pm$ 10	1.19 $\pm$ 0.056 $\times 10^{-4}$	D = 9.46 m, in collimator
7A	155.63 $\pm$ 0.48	1.211 $\pm$ 0.067	188.47 $\pm$ 10.4	8624 $\pm$ 34	1.214 $\pm$ 0.067 $\times 10^{-4}$	D = 9.46 m, in collimator

Table 4.4--AVERAGED RADSAN RESULTS CORRECTED FOR BIAS ENERGY LOSSES

Distance	Neutron dose/F.C. count $\times 10^3$		
	"In air"	Behind cone	"Direct"
2 m	6.906 ± 0.135	1.447 ± 0.051	5.46 ± 0.144
3 m	3.658 ± 0.158	1.027 ± 0.050	2.63 ± 0.166
4 m	2.429 ± 0.100	0.845 ± 0.040	1.58 ± 0.108
9.46 m (in collimator)			0.232 ± 0.013

Table 4.5--SPECTRUM-WEIGHTED CROSS SECTIONS FOR THRESHOLD DETECTORS

Foil	$E_{\text{Threshold}}$	"Effective" cross sections	
		Ichiban	HPRR
^{239}Pu	1 kev	1.45 b	1.8 b
^{237}Np	0.75 Mev	1.31	1.6
^{238}U	1.5 Mev	0.44	0.54
^{32}S	2.5 Mev	0.11	0.23

Table 4.6--SPECTRUM-WEIGHTED DOSE/NEUTRON VALUES FOR THRESHOLD DETECTORS

Energy region	Spectrum-weighted dose/neutron values	
	Ichiban	HPRR
0 to 0.75 Mev	1.02×10^{-6} mrad/neutron/cm ²	1.4×10^{-6} mrad/neutron/cm ²
0.75 Mev to 1.5 Mev	2.32	2.4
1.5 Mev to 2.5 Mev	2.88	3.0
Above 2.5 Mev	3.4	3.8

Threshold detector units were exposed during two separate high-power runs of 5-min duration. Two TDU's were used during the second of these runs, one in air and one behind the borated paraffin shield for scattering corrections. The resulting neutron fluences were normalized to the fission counter and are summarized in Table 4.7.

Table 4.7--NEUTRON-FLUENCE RESULTS FROM TDU MEASUREMENTS
(ALL AT D = 2 M, H = 9 FT)

Foil	Neutron/cm ² /F.C. count		
	"In air"	Behind shield	"Direct"
²³⁹ Pu (1 kev)	5376 ± 6	1333 ± 4	4043 ± 7
²³⁷ Np (0.75 Mev)	1097 ± 13	200 ± 10	897 ± 16
²³⁸ U (1.5 Mev)	145 ± 3	22 ± 3	123 ± 4
³² S (2.5 Mev)			72 ± 3

To determine the neutron fluence in each energy region, the paraffin shielded values were first subtracted from those "in air" to determine "direct" leakage. Then, the fluences above the various threshold energies were successively subtracted to obtain differential fluences. Finally, the dose per fission counter count was calculated from the differential fluences and the weighted dose conversion factors as shown in Table 4.8.

Table 4.8--DOSE LEAKAGE CALCULATED FROM THRESHOLD DETECTOR DATA

Energy region	Differential fluence, neutron/cm ² /F.C. count	Mrad/neutron/cm ²	Mrad/F.C.
1 kev to 0.75 Mev	3146	1.02 x 10 ⁻⁶	3.209
0.75 to 1.5 Mev	774	2.32 x 10 ⁻⁶	1.796
1.5 to 2.5 Mev	51	2.88 x 10 ⁻⁶	0.147
Above 2.5 Mev	72	3.40 x 10 ⁻⁶	0.245
Total			5.397 x 10 ⁻³

It is interesting to note the good agreement between the "direct" neutron dose/F.C. results as measured at 2 m with TDU's and Radsans. This agreement between two independent neutron dosimetry systems added considerable confidence to the neutron leakage results.

4.4 GAMMA-DOSE LEAKAGE RESULTS

Although the primary objective of the Ichiban experiment was to determine the neutron leakage, gamma-dose measurements were also made and presented in Table 4.7. One measurement was attempted at the 2 m position by exposing a Phil

dosimeter behind the paraffin cone with the addition of 2 in. of lead between the cone and the detector. The result corroborated suspicion that nearly all the gamma dose came from neutron capture in the floor and walls of the Kiva and that the gamma/neutron dose ratio of radiation actually emerging from the Ichiban assembly was less than 5%.

Table 4.9--GAMMA-DOSE RESULTS

Distance	Dose, mr/F.C. count	
	Phil	Glass
2 m	1.203 $\pm$ 0.016	1.07 $\pm$ 0.09
3 m	1.028 $\pm$ 0.028	0.805 $\pm$ 0.037
4 m	0.941 $\pm$ 0.025	1.07 $\pm$ 0.17
2 m (behind shield)	1.07 $\pm$ 0.03	

4.5 ANGULAR AND SPATIAL DISTRIBUTION

Sulfur pellets and glass rods were exposed at various distances from the core and around the circumference of the outer steel surface of the assembly to determine if the radiation leakage was isotropic. Although there were small variations in these measurements, there were no gross perturbations that could cause large errors in the calculation of leakage per fission.

4.6 NEUTRON LEAKAGE CALCULATIONS

As mentioned in Section 3.5.2, a moderated BF₃ counter was used to obtain a rough estimate of the neutron fluence leakage 2 m from the core during a low power run. A standard PuBe source was used to calibrate the counter in terms of counts per neutron/cm²; however, no attempt was made to correct for room and floor scattering. After "weighting" the counter response to the Ichiban neutron energy spectrum, a leakage of 0.62 neutrons per fission was obtained.

At the 2 m position, good agreement was obtained among the Radsan, TDU, and diode measurements; however, for the sake of neutron leakage calculations, the collimator results were deemed most reliable. At a distance of 9.46 m from the core, the first collision tissue dose rate due to neutrons was 0.232×10^{-3} mrad per fission counter count with an accuracy of $\pm 4\%$. Coupled with the mean dose per neutron of 1.14×10^{-9} rad/neutron/cm², and after an inverse square extrapolation to the center of the core, this measurement represented a total fast neutron leakage of 0.766 neutrons per fission:

$$\frac{(0.232 \times 10^{-3} \text{ mrad/F.C. count}) (4 \times 3.1416 \times 946^2)}{(2.9845 \times 10^9 \text{ fissions/F.C. count}) (1.14 \times 10^{-6} \text{ mrad/neutron/cm}^2)} = 0.77$$

It should be noted that a calculation based on the 2 m "direct" data would result in a fast neutron leakage only 5% higher than the 0.77 figure. The decision to use the collimator data for final leakage calculations was made on the basis of the data shown in Fig. 4.2.

Tables 4.10 and 4.11 summarize neutron leakage calculations made at LASL by Wendell Biggers and Gordon Hansen respectively. Biggers' results were calculated using a Monte Carlo code and predicted a total fast neutron leakage of 0.57 neutrons per fission, whereas Hansen's multigroup calculations predicted a total fast neutron leakage of 0.81 neutrons per fission.

It is interesting to compare the neutron leakage from the Ichiban assembly to that from the Health Physics Research Reactor which is a bare, unmoderated reactor. The fast neutron leakage from the HPRR is 1.3 neutrons per fission with a mean dose per neutron of 2.6×10^{-9} rad/neutron/cm².

Work is continuing to implement these Ichiban leakage results with existing air dose curves to determine the doses received by the survivors of the Hiroshima detonation. Hopefully, these dose values and the large number of clinical observations made in Japan by the Atomic Bomb Casualty Commission will ultimately constitute the largest single set of data available on the effects of nuclear radiation on human beings.

Table 4.10--ICHIBAN NEUTRON SPECTRUM CALCULATIONS
(PER ONE FISSION NEUTRON BORN)

Longwalk Energy group in Mev		Neutrons/Mev
1.500 + 01	1.400 + 01	8.70×10^{-7}
1.400 + 01	1.300 + 01	1.42×10^{-6}
1.300 + 01	1.200 + 01	9.14×10^{-7}
1.200 + 01	1.100 + 01	2.74×10^{-6}
1.100 + 01	1.000 + 01	6.71×10^{-6}
1.000 + 01 - 9.500 + 00		6.71×10^{-6}
9.500 + 00 - 9.000 + 00		1.10×10^{-5}
9.000 + 00 - 8.500 + 00		1.34×10^{-5}
8.500 + 00 - 8.000 + 00		2.01×10^{-5}
8.000 + 00 - 7.500 + 00		3.53×10^{-5}
7.500 + 00 - 7.000 + 00		5.79×10^{-5}
7.000 + 00 - 6.500 + 00		5.79×10^{-5}
6.500 + 00 - 6.000 + 00		1.07×10^{-4}
6.000 + 00 - 5.500 + 00		6.76×10^{-5}
5.500 + 00 - 5.000 + 00		1.22×10^{-4}
5.000 + 00 - 4.500 + 00		1.48×10^{-4}
4.500 + 00 - 4.000 + 00		2.43×10^{-4}
4.000 + 00 - 3.500 + 00		3.24×10^{-4}
3.500 + 00 - 3.000 + 00		2.97×10^{-4}
3.000 + 00 - 2.500 + 00		6.49×10^{-4}
2.500 + 00 - 2.000 + 00		1.26×10^{-3}
2.000 + 00 - 1.500 + 00		1.85×10^{-3}
1.500 + 00 - 1.000 + 00		7.18×10^{-3}
1.000 + 00 - 7.000 - 01		4.53×10^{-2}
7.000 - 01 - 4.000 - 01		1.24×10^{-1}
4.000 - 01 - 2.000 - 01		2.89×10^{-1}
2.000 - 01 - 1.000 - 01		3.63×10^{-1}
1.000 - 01 - 7.000 - 02		3.14×10^{-1}
7.000 - 02 - 4.000 - 02		6.20×10^{-1}
4.000 - 02 - 2.000 - 02		1.58×10^0

Table 4.10--continued

Longwalk Energy group in Mev	Neutrons/Mev
2.000 - 02 - 1.000 - 02	7.56×10^{-1}
1.000 - 02 - 7.000 - 03	1.78×10^{-1}
7.000 - 03 - 4.000 - 03	4.78×10^{-1}
4.000 - 03 - 2.000 - 03	1.21×10^0
2.000 - 03 - 1.000 - 03	5.87×10^0
Total fast neutron leakage = 0.57 neutrons per fission.	

Table 4.11--ICHIBAN NEUTRON SPECTRUM CALCULATIONS
(PER ONE FISSION NEUTRON BORN)

Energy Interval	Neutrons/Mev
<u>Mev</u>	
3.0 - 15	1.80×10^4
1.4 - 3.0	4.49×10^{-3}
0.9 - 1.4	2.74×10^{-2}
0.4 - 0.9	1.25×10^{-1}
0.1 - 0.4	4.27×10^{-1}
<u>kev</u>	
17 - 100	1.04×10^0
3 - 17	9.64×10^{-1}
0.55 - 3	2.47×10^0
<u>ev</u>	
100 - 550	4.69×10^0
30 - 100	1.49×10^1
10 - 30	3.19×10^1
3 - 10	5.74×10^1
1 - 3	8.85×10^1
0.4 - 1	1.04×10^2
0.1 - 0.4	7.07×10^2
Thermal	2.77×10^1
Total fast neutron leakage = 0.81 neutrons per fission.	

CIVIL EFFECTS TEST OPERATIONS REPORT SERIES (CEX)

Through its Division of Biology and Medicine and Civil Effects Test Operations Office, the Atomic Energy Commission conducts certain technical tests, exercises, surveys, and research directed primarily toward practical applications of nuclear effects information and toward encouraging better technical, professional, and public understanding and utilization of the vast body of facts useful in the design of countermeasures against weapons effects. The activities carried out in these studies do not require nuclear detonations.

A complete listing of all the studies now underway is impossible in the space available here. However, the following is a list of all reports available from studies that have been completed. All reports listed are available at the prices indicated, from the Clearinghouse for Federal Scientific and Technical Information, U. S. Department of Commerce, Springfield, Va.

- CEX-57 1, The Radiological Assessment and Recovery of Contaminated Areas, C. F. Miller, 1960, \$0.75
- CEX-58 1, Experimental Evaluation of the Radiation Protection Afforded by Residential Structures Against Distributed Sources, J. A. Auxier, J. O. Buchanan, C. Eisenhauer, and H. E. Menker, 1959, \$2.75
- CEX-58 2, The Scattering of Thermal Radiation into Open Underground Shelters, T. P. Davis, N. D. Miller, T. S. Ely, J. A. Basso, and H. E. Pearce, 1959, \$0.75
- CEX-58 7, AEC Group Shelter AEC Facilities Division, Holmes & Narver, Inc., 1960, \$0.50
- CEX-58 8, Comparative Nuclear Effects of Biomedical Interest, C. S. White, I. G. Bowen, D. R. Richmond, and R. L. Corsbie, 1961, \$1.00
- CEX-58 9, A Model Designed to Predict the Motion of Objects Translated by Classical Blast Waves, I. G. Bowen, R. W. Albright, E. R. Fletcher, and C. S. White, 1961, \$1.25
- CEX-59 1, An Experimental Evaluation of the Radiation Protection Afforded by a Large Modern Concrete Office Building, J. F. Batter, Jr., A. L. Kaplan, and E. T. Clarke, 1960, \$0.60
- CEX-59 4, Aerial Radiological Monitoring System I Theoretical Analysis, Design, and Operation of a Revised System, R. F. Merian, J. G. Lackey, and J. E. Hand, 1961, \$1.25
- CEX-59 4 (Pt II), Aerial Radiological Monitoring System Part II Performance, Calibration, and Operational Check-out of the EG&G Arms-II Revised System, J. E. Hand, R. B. Guillou, and H. M. Borella, 1962, \$1.50
- CEX-59 4 (Pt. III), Aerial Radiological Monitoring System, Part III Electronic Processing of ARMS-II Data, J. E. Hand and H. M. Borella, 1965, \$1.00
- CEX-59 7B (Pt II), Experimental Radiation Measurements in Conventional Structures Part II Comparison of Measurements in Above-ground and Below-ground structures from Simulated and Actual Fallout Radiation, Z. G. Burson, 1964, \$1.50
- CEX-59 7B (Pt III), Experimental Radiation Measurements in Conventional Structures Part III The Attenuation of Air-scattered Radiation in a Basement, Z. G. Burson, 1965, \$1.00.
- CEX-59 7C, Methods and Techniques of Fallout Studies Using a Particulate Simulant, W. Lee and H. Borella, 1962, \$0.50
- CEX-59 13, Experimental Evaluation of the Radiation Protection Afforded by Typical Oak Ridge Homes Against Distributed Sources, T. D. Strickler and J. A. Auxier, 1960, \$0.50
- CEX-59 14, Determinations of Aerodynamic-drag Parameters of Small Irregular Objects by Means of Drop Tests, E. P. Fletcher, R. W. Albright, V. C. Goldizen, and I. G. Bowen, 1961, \$1.75
- CEX-60 1, Evaluation of the Fallout Protection Afforded by Brookhaven National Laboratory Medical Research Center, H. Borella, Z. Burson, and J. Jacovitch, 1961, \$1.75
- CEX-60 3, Extended- and Point-source Radiometric Program, F. J. Davis and P. W. Reinhardt, 1962, \$1.50
- CEX-60 5, Experimental Evaluation of the Fallout-radiation Protection Afforded by a Southwestern Residence, Z. Burson, D. Parry, and H. Borella, 1962, \$0.50
- CEX-60 6, Experimental Evaluation of the Radiation Protection Provided by an Earth-covered Shelter, Z. Burson and H. Borella, 1962, \$1.00
- CEX-61 1 (Prelim.), Gamma Radiation at the Air-Ground Interface, K. O'Brien and J. E. McLaughlin Jr., 1963
- CEX-61 4, Experimental Evaluation of the Fallout-radiation Protection Provided by Selected Structures in the Los Angeles Area, Z. G. Burson, 1963, \$2.25
- CEX-62 01, Technical Concept—Operation BREN, J. A. Auxier, F. W. Sanders, F. F. Haywood, J. H. Thorngate, and J. S. Cheka, 1962, \$0.50
- CEX-62 02, Operation Plan and Hazards Report—Operation BREN, F. W. Sanders, F. F. Haywood, M. I. Lundin, L. W. Gilley, J. S. Cheka, and D. R. Ward, 1962, \$2.25
- CEX-62 03, General Correlative Studies—Operation BREN, J. A. Auxier, F. F. Haywood, and L. W. Gilley, 1963, \$1.00
- CEX-62 2, Nuclear Bomb Effects Computer (Including Slide-rule Design and Curve Fits for Weapons Effects), E. R. Fletcher, R. W. Albright, R. F. D. Perret, Mary E. Franklin, I. G. Bowen, and C. S. White, 1963, \$1.00
- CEX-62 11, Distribution of Weapons Radiation in Japanese Residential Structures, J. S. Cheka, F. W. Sanders, T. D. Jones, and W. H. Shimpagh, 1965, \$1.00
- CEX-62 13, Post Pulse Gamma-radiation Spectrum—Operation BREN, J. H. Thorngate and E. T. Loy, 1966, \$1.00
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