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THE TISSUE EQUIVALENT PROPORTIONAL COUNTER NEUTRON MONITOR

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ABSTRACT

The Tissue Equivalent Proportional Counter (TEPC) is a sensitive area monitoring instrument that can be used either "in place" at fixed locations or as a portable neutron exposure measuring device. The system was developed to monitor low levels of neutron radiation exposure and has the capability of accurately measuring neutron exposure rates as low as 0.1 mrem/hr. The computerized analysis system calculates the quality factor which is important for situations where the neutron to gamma ratio may vary significantly and irregularly such as in fuel fabrication or handling facilities.

The TEPC monitoring system utilizes an advanced model of the Rossi-type tissue equivalent (TE) spherical counter connected to a computerized data acquisition and processing system which may be programmed to read out in excess of 200 work locations. The neutron dose is accumulated on a real time basis and after the "proton drop point" is established, dose rates can be read out at any time for the dose accumulated over a fixed period of time.

The complete computerized TEPC system is described, detection limits and accuracy discussed and examples of the use of the system under operational conditions in a plutonium fuel fabrication facility are detailed. Development of improved TEPC gas filled counters and modification of the system into versatile portable instruments are also discussed. Because of the ability of this system to compute the quality factor data from the energy distribution evaluated in the pulse height analysis unit this may be the only instrument currently available that provides the "dose equivalency" neutron exposure information as recommended by ICRP-26.

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THE TISSUE EQUIVALENT PROPORTIONAL COUNTER NEUTRON MONITOR

INTRODUCTION

One of the most difficult monitoring problems during the development of nuclear energy is the determination and subsequent control of neutron exposures. Personnel neutron exposures are often estimated through indirect monitoring techniques such as the use of the neutron-to-gamma ratio. However, this technique cannot be used during fabrication of plutonium enriched mixed oxide fuels for fast reactors due to the frequent variations in the neutron-to-gamma ratio. Whereas the gamma dose rate may remain relatively constant, the neutron dose rate often can vary greatly depending on fuel inventory and geometry. Although the neutron exposure can be estimated from personnel dosimeters, this method is not totally satisfactory as current limits of detection for personnel dosimeters require exposures of one month or more. Measurements of this duration are not conducive to the use of administrative controls to correct high exposure situations to prevent over exposure of personnel.

The difficulty and necessity for measuring low neutron exposures is further compounded by several additional factors:

1. Increased throughput rates at fuel fabrication facilities will require the handling of larger inventories which will increase neutron exposures.
2. Increased plutonium content, due to the use of mixed oxide fuels containing higher percentages of plutonium oxide, will cause higher neutron exposures.
3. Fabrication of fuel from high exposure plutonium compositions which have increased neutron yields will also increase the neutron exposure.
4. The National Council on Radiation Protection Measurements (NCRP) has recently issued a public release stating that the maximum permissible neutron dose may be further reduced by a factor of 3 to 10.

Thus the increased potential for higher neutron exposures during the manufacture of plutonium containing fuels, coupled with the expected decrease in already low personnel exposure limits and design criteria, will require the development of new neutron monitoring instrumentation. At the Hanford Engineering Development Laboratory (HEDL), in Richland, Washington, a computerized neutron monitoring system is being developed using Tissue Equivalent Proportional

Counters (TEPCs) which are shown in Figure 1. This system will allow more accurate determination of low neutron exposures at over 200 locations on a real time basis.

TEPC DETECTOR CONSTRUCTION AND OPERATION

The heart of the computerized TEPC neutron monitoring system is a Rossi-type[1,2] spherical proportional counter constructed of tissue equivalent (TE) plastic (Shonka type A-150)[3,4] and filled with tissue equivalent gas. Since the basic TEPC detector has been used for years and has been described in detail in the literature,[1,2,5] only a brief description of the counter and its operation will be given here. Details of the tissue equivalent plastic and gas compositions are contained in ICRU Report 26[6].

The 2 1/4 inch tissue equivalent sphere, depicted in Figure 2, is contained in a pressure vessel with a valve for admitting the tissue equivalent gas at about 25 torr pressure. Neutrons interact with the tissue-equivalent plastic walls of the counter creating charged particle secondaries (mostly protons or hydrogen ion recoils). These charged particles interact with the TE gas in the spherical cavity producing pulses in the proportional counter which are detected at the central anode. A helical grid surrounds the central anode to maintain uniform gas multiplication along the length of the anode wire. The detected pulse height is proportional to the energy lost by the charged particle secondaries in traversing the spherical gas cavity. The absorbed rad dose is defined as 100 ergs of energy absorbed in 1 gram of material. Since the proportional counter measures the energy released by neutron secondaries into a known mass of tissue-equivalent gas, the Tissue Equivalent Proportional Counter directly measures the absorbed neutron dose.

Gas pressure within the counter is adjusted so that the mass stopping power is the same as a tissue sphere 2 micrometers in diameter. With low gas density, charged particle secondaries lose little energy traversing the gas cavity, and the particles have nearly constant linear energy loss or transfer (LET). This allows calibration of the counter. Protons have a maximum LET or linear energy loss rate of 98 keV/micrometer in water or tissue. The most energy which can be absorbed in the gas cavity is a proton with an LET of 98 keV/micrometer traversing the cavity diameter and depositing 98 keV/micrometer x 2 micrometers (path length) or 196 keV of energy. Thus, the largest pulse height

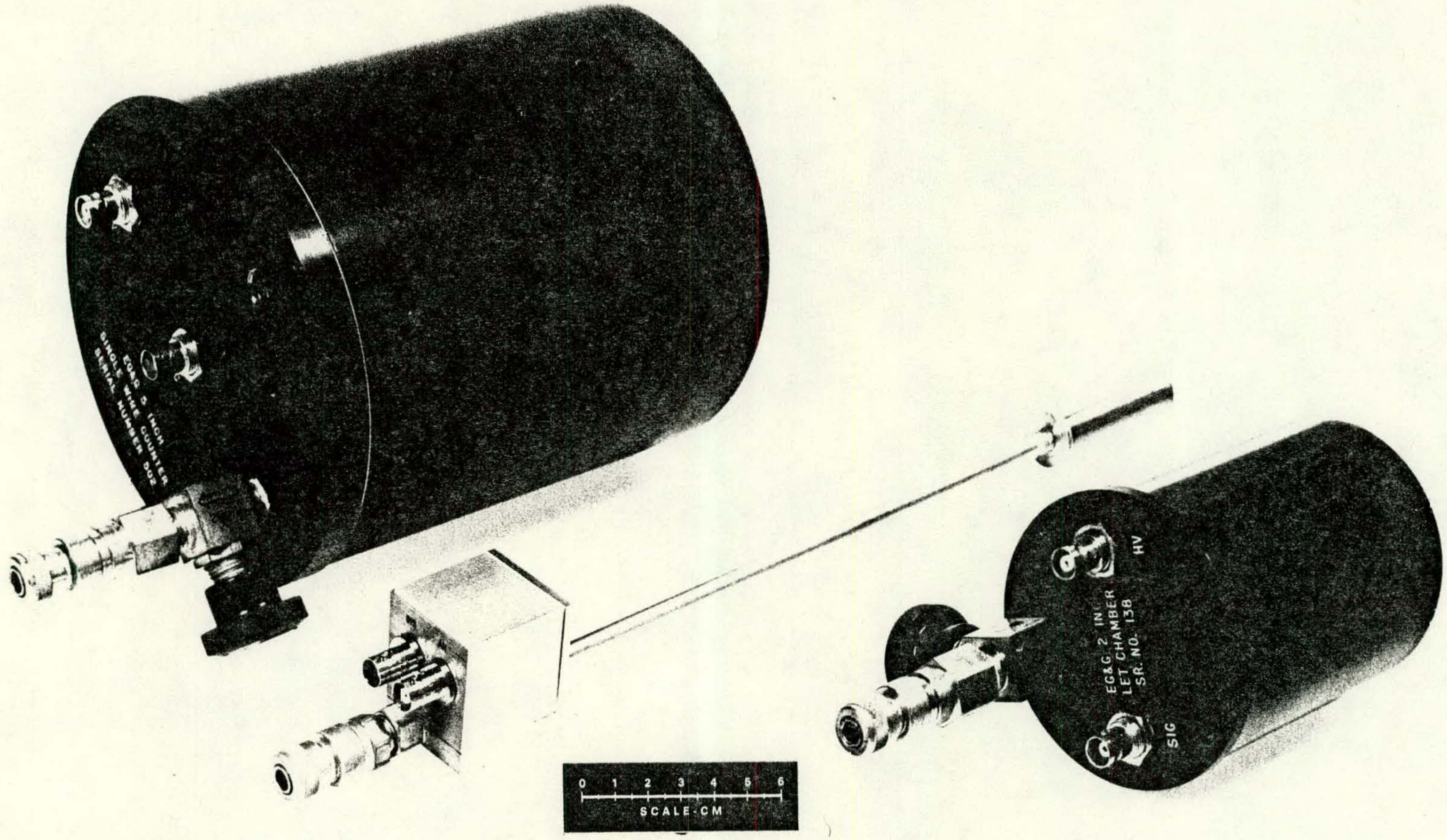

FIGURE 1. Typical Tissue Equivalent Proportional Counters (TEPCs)--Shown Are the 5", 1/2", and 2" models. (Photo No. BN745123-3)

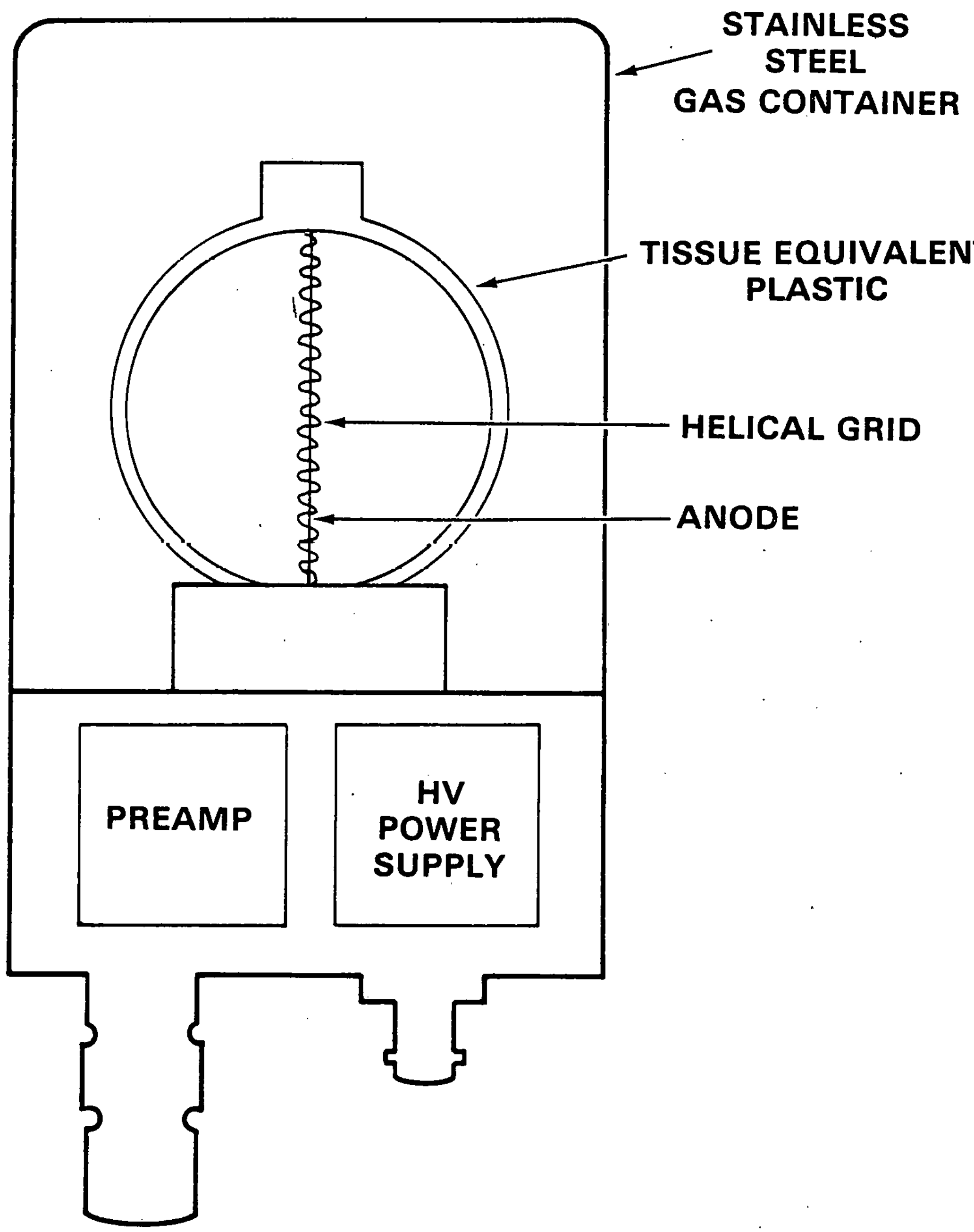

FIGURE 2. Cross Section of a Tissue Equivalent Proportional Counter. (Photo No. 8007846-1)

is an absorbed energy of 196 keV. This is the "proton drop point," which, by convention, is the inflection point on the pulse number plot verses pulse height. as shown in Figure 3.

Curve B of Figure 3 shows a typical pulse height spectrum from a TEPC detector exposed to 1.4 MeV neutrons. Curve C is obtained by multiplying the event distribution (or counts per channel) recorded from a multichannel analyzer times the channel number and is proportional to the energy deposited, or the dose. Curve A represents the data from ^{60}Co gamma rays. Neutron and gamma induced events can be separated on the basis of event size. Thus the minimum point 1 is selected as the lower limit of neutron events. This works well unless the photon rate is sufficient to produce pulse pile-up. Several rads/hr of gamma are required to produce pulse pile-up.

Multiplying the number of events of a given size by the energy gives the absorbed energy distribution in the TE gas, which is a direct measure of the absorbed dose. Following the nomenclature in ICRU-26[6], this may be stated mathematically as:

$$\frac{D}{\text{rad}} = \frac{100D}{\text{Gy}} = 1.602 \times 10^{-8} \sum_{h_1}^{h_2} \left(\frac{c \cdot hN(h)}{\text{MeV}}\right) \left(\frac{\rho}{\text{gcm}^{-3}}\right)^{-1} \left(\frac{V}{\text{cm}^3}\right)^{-1}$$

where h is the measured pulse height exposed as channel number, N(h) is the number of pulses accumulated in channel h, h_1 and h_2 are the limits in pulse height between which the absorbed dose is determined, ρ is the gas density, V is the sensitive volume of the cavity, and c is the calibration relating energy to channel number, determined from the proton drop point.

Neutron quality factors can also be determined from TEPC measurements by using H. H. Rossi methods which are outlined in the literature.[1,2,5,7] The neutron dose equivalent is found by multiplying the measured absorbed neutron dose by the quality factor. In most situations the quality factor is approximately 10.

TEPC DEVELOPMENT PROGRAM

The TEPC detector currently in use with the computerized TEPC neutron monitoring system is an advanced model developed under contract with EG&G*.

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*EG&G; 130 Robin Hill Road; Goleta, California 93107, USA

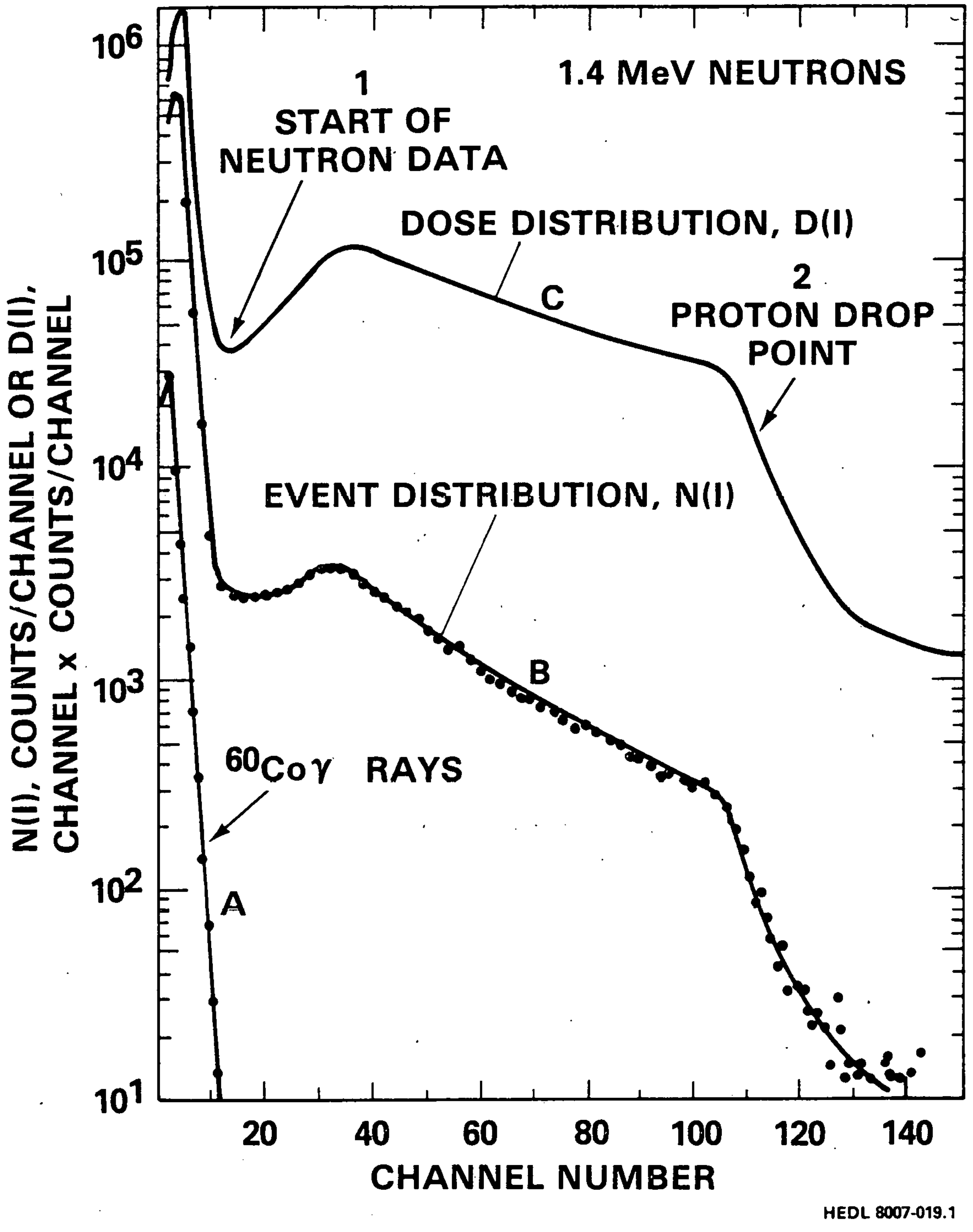

FIGURE 3. Pulse Height Spectra from a Tissue Equivalent Proportional Counter Exposed to 1.4 MeV Neutrons. (Photo No. 8007846-3)

These detectors incorporate the following improvements:

1.) Increased Longevity. One of the major disadvantages of older model TEPCs was the requirement for refilling with TE gas at least weekly due to contamination of the counter gas which was evidenced by gain shifts. Gas degradation products came from counter components with lesser products being admitted through poor seals. Newly developed TEPCs have incorporated improved TE plastic molded components and seals.

With the old detectors, gain changes of 40% and greater were evidenced in less than seven days and detectors ceased to function after one month of operation. The newly developed TEPCs showed gain changes of 2 to 8% during the first week and leveled off to only from 11 to 22% after 18 months of operation without refilling. These counters still exhibited good resolution and sensitivity. We consider this a major breakthrough for the practical use of TEPCs in measuring radiation exposure.

2.) Simplified Electronics. Newly developed TEPCs have their preamp and High Voltage power supply incorporated into the base of the counter as shown in Figure 2. This simplification in required components should reduce system and wiring costs.

3.) Remotely Activated Calibration Source. Newly developed models have an internal ^{244}Cm alpha source which may be activated remotely for calibration checks. This will enable an auto analyze system mode to perform calibration checks of the equipment on off shift hours without operator assistance.

The maximum sensitivity or detection level achievable with a TEPC is a function of the TE detector surface area. Three different diameter spherical detectors are currently being evaluated; a 5 inch, the 2 1/4 inch, and a one-half inch which is useful under restricted geometry situations. The 2 1/4 inch size is used for most of our measurements. It usually requires a minimum of eight hours of counting in minimal exposure areas for accurate determination of the proton drop point or for quality factor analyses. After the proton drop point is established, reasonably accurate measurements can be performed at 0.1 mRem/hr levels. A program is currently underway to define the minimum levels of detection, minimum variances and the reliability of the instrument when operated at neutron dose rates to which future facilities will be required to control operational personnel exposure.

SYSTEM OPERATION

A Nuclear Data 6600 Multi-Parameter Data Acquisition and Analysis System is used to acquire, display, and analyze the neutron spectra from the TE detectors. This system, which is shown in Figure 4 is a computerized pulse height analysis system capable of determining absolute neutron absorbed dose and quality factors from a number of locations simultaneously. The present system is designed for use in a mixed oxide fuel fabrication laboratory at HEDL.

A schematic of the neutron monitoring system components is shown in Figure 5. Briefly, the system operates as follows:

1.) The TE detector provides a signal proportional in magnitude to the total resultant ionization incurred when a neutron traverses the counter.

2.) A high voltage power supply and preamp are built into the base of the TE detector to provide high voltage to the anode and to provide initial signal amplification.

3.) Signals from the preamp are routed first to an amplifier and then to the gated analog router (GAR) which routes the signal to the appropriate memory location allowing simultaneous data acquition from several detectors. Lower level discriminators, built into each GAR are used to reduce low-level energy noise thereby decreasing deadtimes.

4.) Using the Rossi model for linear energy transfer (LET) distributions, the absolute neutron absorbed dose and the quality factor are determined for each detector.

Total system capacity is 384 detectors or monitoring locations--four detectors may be handled by each GAR; four GARs may be routed to each analog to digital converter (ADC); up to eight ADCs can be interfaced with each display and acquisition system (DAS); and three DASs can be interfaced to the ND6600.

Software for the current system is written in FORTRAN IV and allows two modes of operation:

1.) Auto Analyze. Allows automatic data acquision, storage of spectra to disc, calculation of neutron dose rates, and printout without operator assistance. This operational mode was designed primarily for detector calibration and measurement of background during off shift hours.

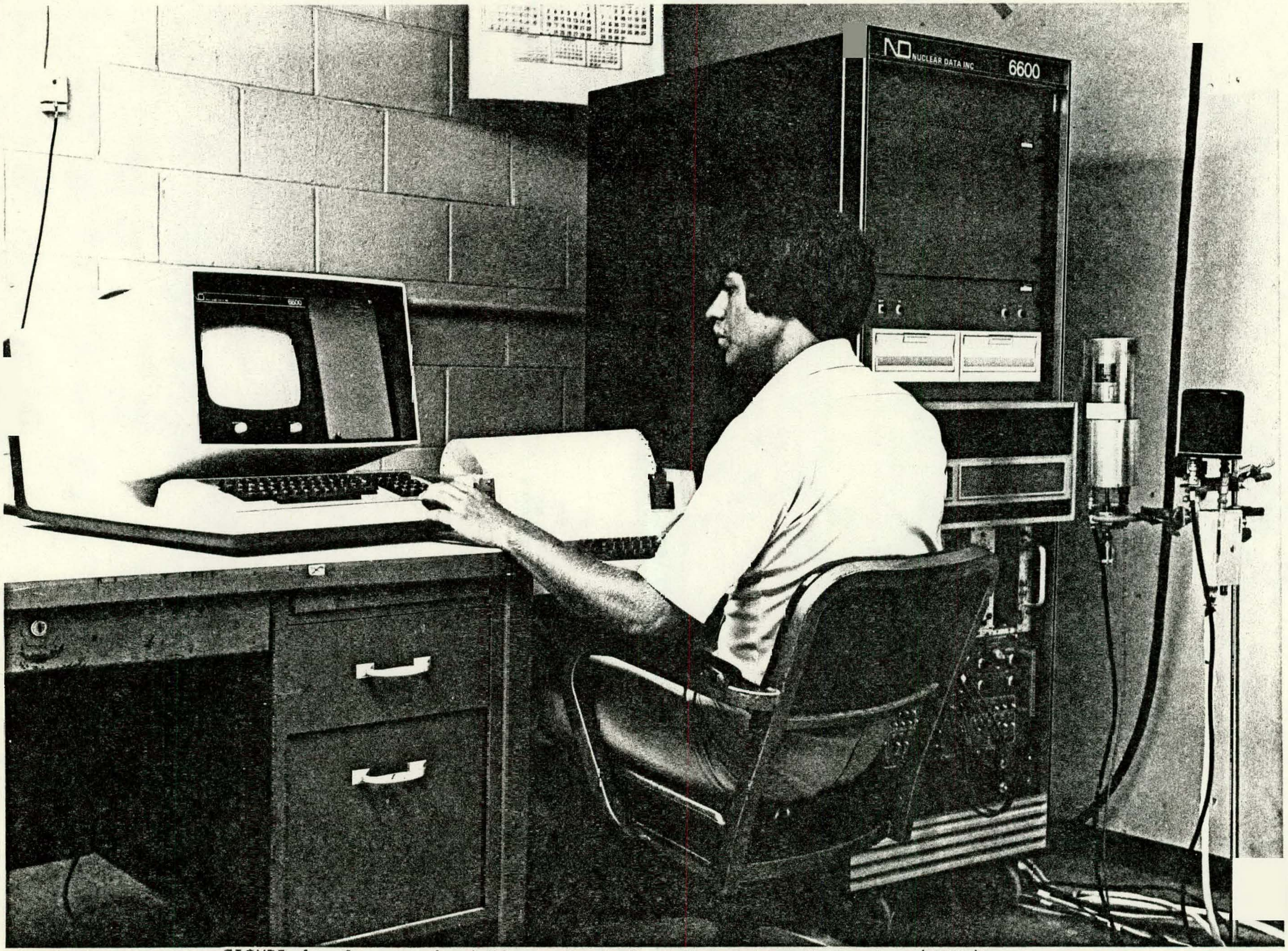

FIGURE 4. Computerized Tissue Equivalent Proportional Counter (TEPC) Monitoring System. (Photo No. 8007434-1CN)

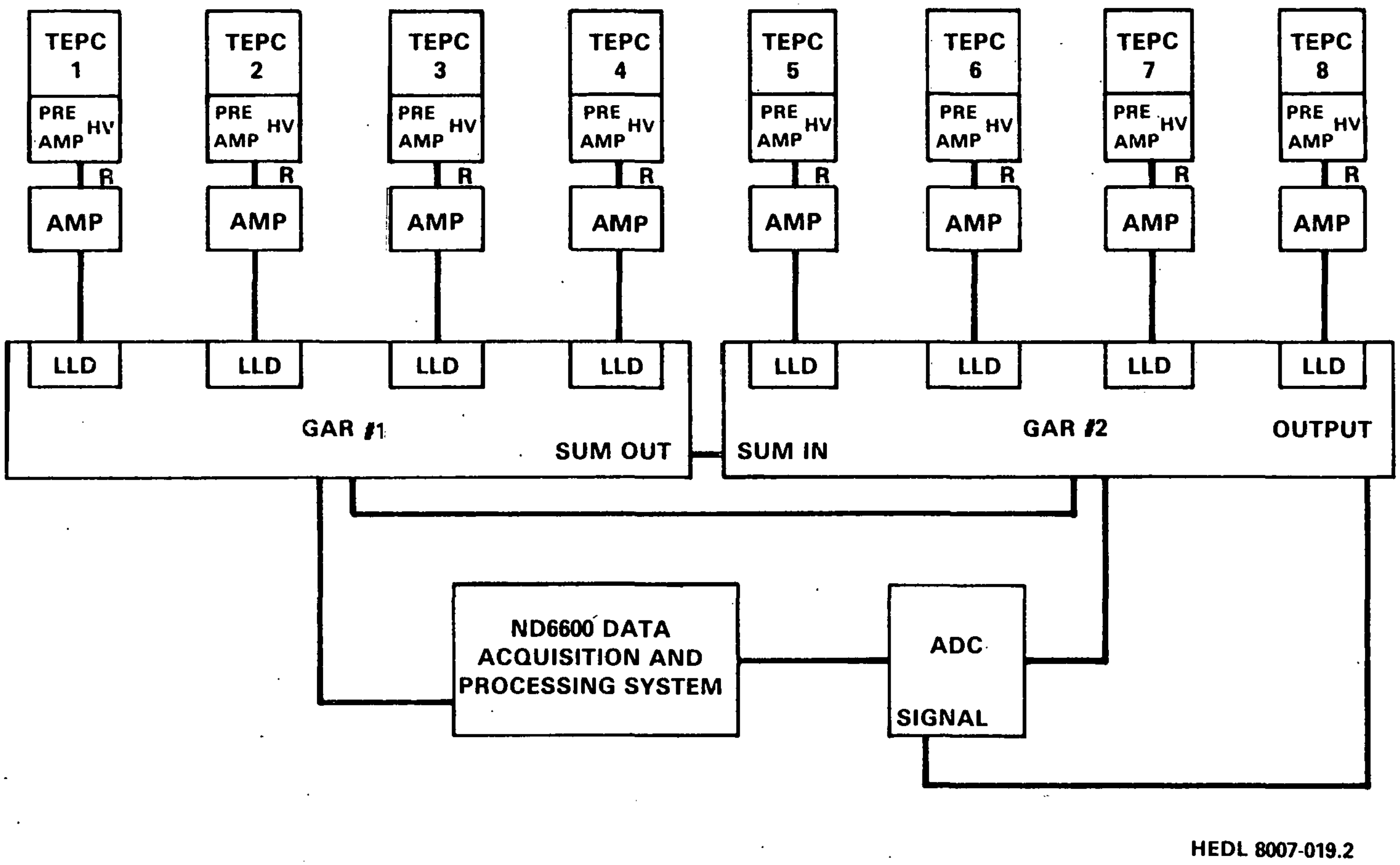

FIGURE 5. Wiring Schematic for the TEPC Neutron Monitoring System. (Photo No. 8007846-2)

2.) Manual. Operator initiates and monitors each step in the counting sequence.

Both modes of operation will allow either a predetermined lapsed time to be set for counting or interrogation at any time during the counter interval. The system has been programmed to alarm when the specified preset dose is exceeded allowing corrective actions to be taken.

RESULTS

Prototypes of the TEPC neutron monitoring system have been used to measure the neutron absorbed dose and to verify shielding effectiveness studies at a variety of situations in plutonium fuel fabrication facilities. Because of the continuing trend toward lowering allowable occupational exposure limits, the development efforts have geen directed to obtaining the lowest practicable limit of detection.

The neutron monitoring system was used to measure neutron dose equivalent rates from a Fast Flux Test Facility (FFTF) driver subassembly, shown in Figure 6, fabricated at HEDL for the Fast Breeder Reactor. The measured FFTF subassembly was comprised of 217 fuel pins assembled in a compact hexagonal array and contained 7.3 kg of plutonium as a mixed oxide (25% PuO_2 - 75% UO_2). Measurements, were made with the detector located at the midplane of the 36-inch long fuel region. The neutron exposures shown in Table 1 were measured on five different days at six different distances from the subassembly. Although the subassembly location was fixed during the period of the measurements, other fuel components were being moved during the fabrication process. Thus some of the fluctuation in results can undoubtedly be attributed to variations in background caused by adjacent fuel movements.

TABLE 1

Neutron Dose Equivalent Rates from "A" Type FFTF Subassembly

	Dose Equivalents in mRem/hr					
	Distance to Counter Center (inches/cm)					
Date	2.1/5.33	6/15.2	12/30.5	24/61.0	36/91.4	48/122
12/11	24.4	10.9		2.5		0.91
12/12	23.4	10.8		2.5		0.95
12/15	24.7	11.4		2.8		0.82
12/18			5.3	2.1	1.2	0.71
12/19			5.2	2.0	1.2	0.74
Average	24.17	11.03	5.25	2.38	1.2	0.83

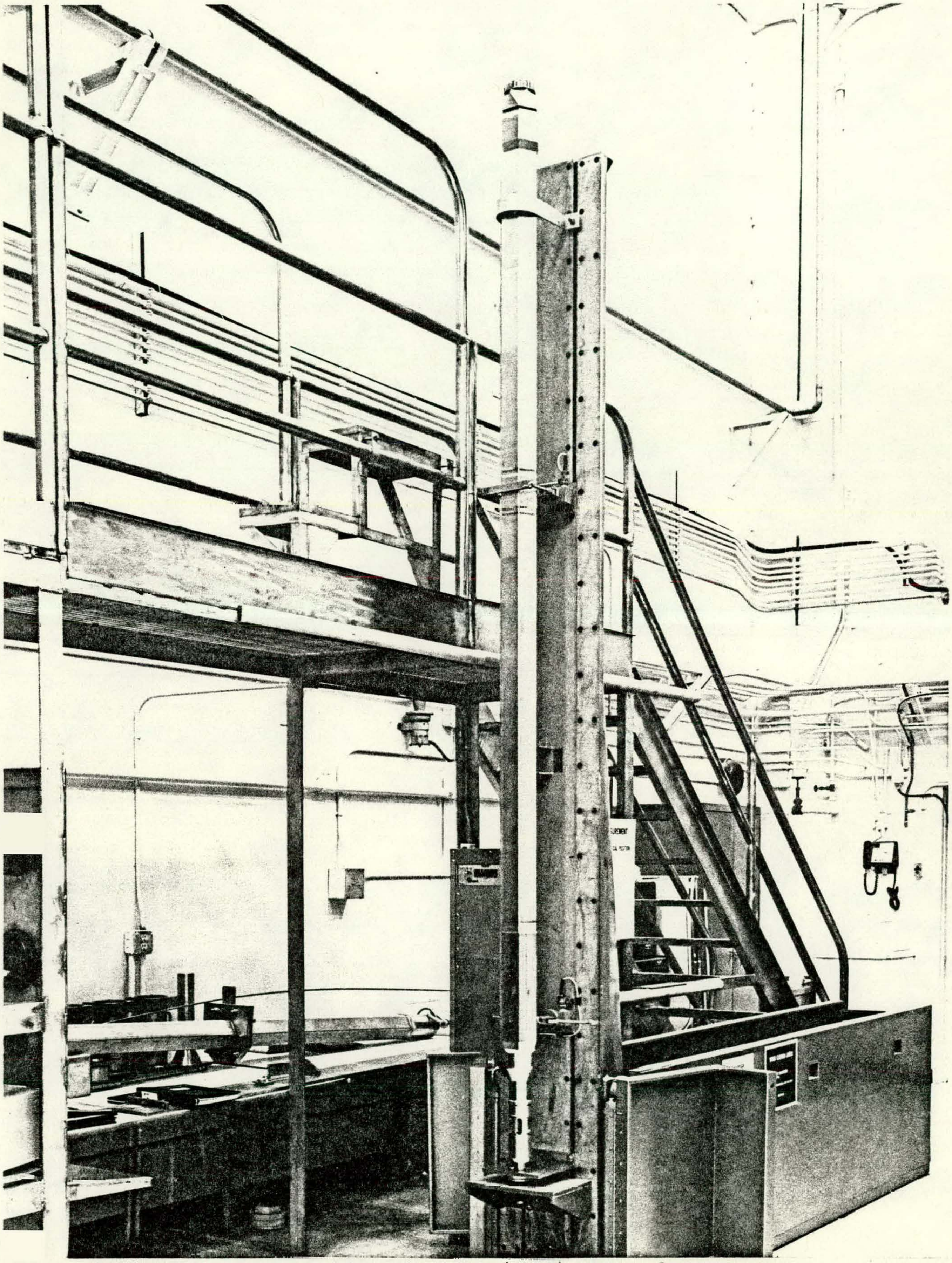

FIGURE 6. Fast Flux Test Facility (FFTF) Driver Subassembly. (Photo No. 766997-5cm)

Agreement among results is good considering the possible sources of error with the largest variation in results being about 17 1/2 percent at the 24 inch distance. Variations in the results at the closer distances were generally within 3 percent of the average. The gamma dose associated with these measurements varies widely from about three times the neutron dose at positions near the surface to about equal or slightly less than the neutron component at four feet away.

A second example of the use of the TEPC monitoring system, involved measuring the neutron dose equivalent rate at various distances from a Model 60 insert containing 120 FFTF fuel pins using four different detectors. The Model 60 insert, shown in Figure 7, is a hexagonally arranged bundle of stainless steel tubes used to transport fuel pins. The active fuel length within the insert is about 36 inches. Fuel pins within the measured insert contained a higher percentage of plutonium giving rise to a total source mass of approximately 5 kg of plutonium. Results of these measurements are shown in Table 2.

TABLE 2

Neutron Dose Equivalent Rates from a Model 60 Insert Containing 120 FFTF Fuel Pins

Dose Rates in mrem/hr

2.1 inches		12 inches		36 inches		6 inches			
#2	#4	#3	#1	#3	#1	#2	#4	#3	#1
14.5	15.0	3.41	3.96	1.08	0.92	7.78	8.36	7.98	8.93
15.3	14.8	3.47	3.48	1.00	0.91				
14.3	14.9	3.48	3.55	1.06	0.89				
14.7	14.9	3.45	3.66	1.05	0.91	(Average)			

It is of interest to compare the dose rates obtained from different detectors measuring the same effective source. Maximum deviation in measurements among detectors is about 20 percent with most of the measurements being within 5 percent. This variation in measurements between different detectors is comparable to the variation in results obtained on different days with a single detector. All of these measurements had to be made under actual operating conditions in a fuel fabrication facility where other fuel was being moved near or occassionally stored temporarily within the effective measurement capability of the monitoring system. Thus, most of the variations in measurements can be attributed either to shifting backgrounds or to the asymmetry in the radiation environment around the source.

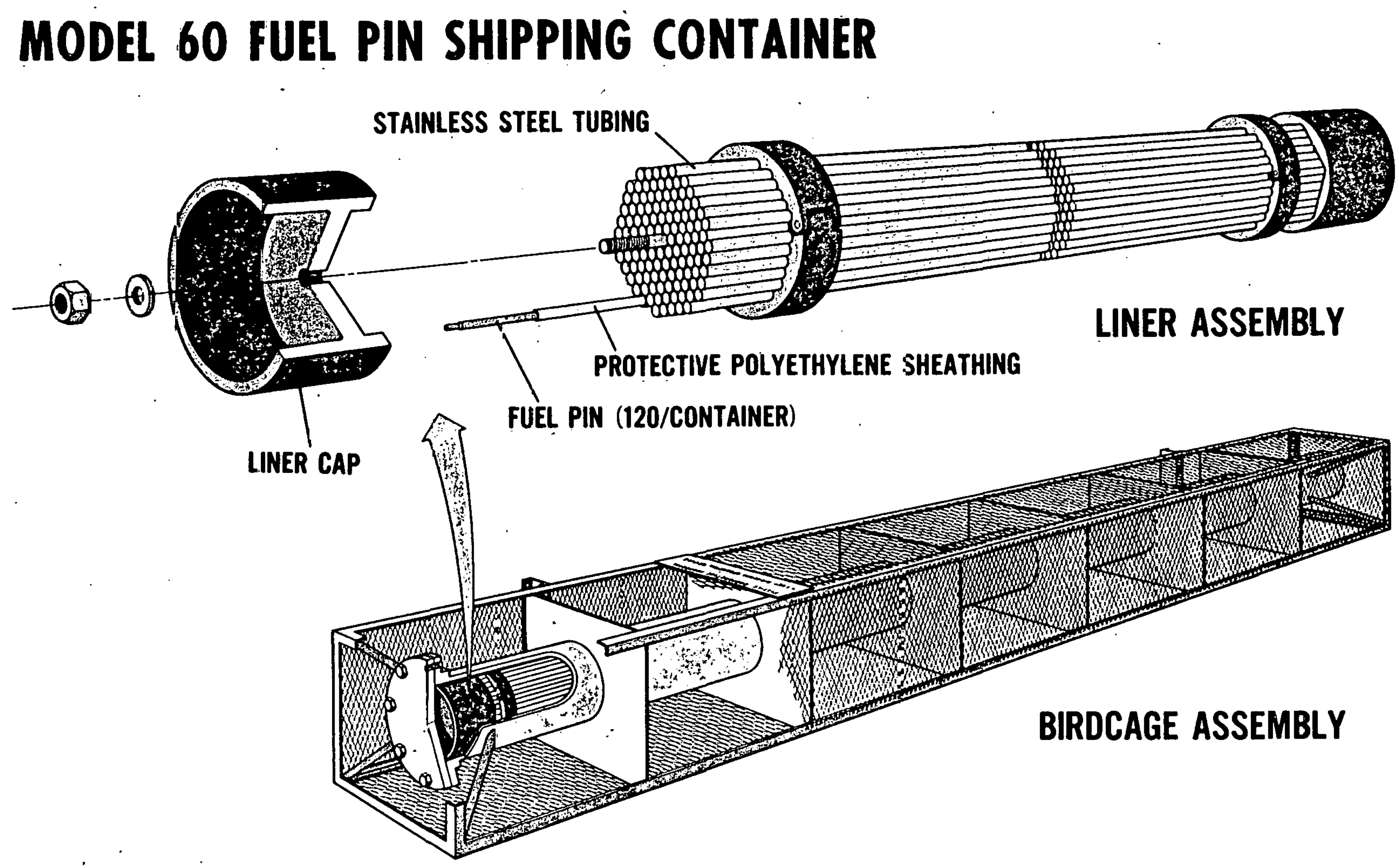

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FIGURE 7. Model 60 Shipping Container Used to Transport Up to 120 Fuel Pins. (Photo No. 734043-1CN)

The TEPC monitoring system has also been used to measure relatively low level occupational exposures such as the background exposures in the fuel storage area shown in Figure 8. This pit storage area is comprised of cylindrical holes which are approximately 14 feet deep, steel lined, and surrounded by concrete. Three foot steel extension tubes were located over each cylindrical hole. Completed subassemblies or up to two Model 60 inserts (each containing 120 fuel pins) were stored vertically in each hole. For these measurements, TEPC detectors were located at floor level and at 12 and 24 inches above the floor level, centered between the three foot high steel extensions. A fourth detector was centered over one of the extension tubes. The results of these measurements are shown in Table 3. To assure undisturbed conditions and to improve statistics, each of the two measurements shown represents 42 hours of data accumulation which were recorded over successive weekends.

TABLE 3

Neutron Dose Equivalent Rates In the Pit Storage Area

	Dose Rates in mrem/hr			
Measurement	Floor level	12 inches	24 inches	38 inches*
#1	0.20	0.12	0.25	0.18
#2	0.22	0.10	0.21	0.10
Average	0.21	0.11	0.23	0.14

*The detector was placed above the pit and centered over the pit hole while the other locations were equidistant between two tube extensions.

DISCUSSIONS AND CONCLUSIONS

The TEPC has been under development at Hanford for nearly ten years as an area monitor and research tool. It has proven to be accurate in measuring neutron dose rates as low as 0.1 to 0.2 mRem/hr and should be able to provide "real time" neutron monitoring at these levels on a daily basis. Improved TEPC models which were developed for HEDL under a developmental contract with EG&G, have operated successfully for over 2 years without refilling--eliminating the weekly TE gas refilling requirement which has slowed the acceptance and use of older model TEPC detectors.

The computerized neutron monitoring system described has the potential of monitoring up to 384 separate locations in a nuclear facility. Software has been developed to allow automatic monitoring of work stations without operator

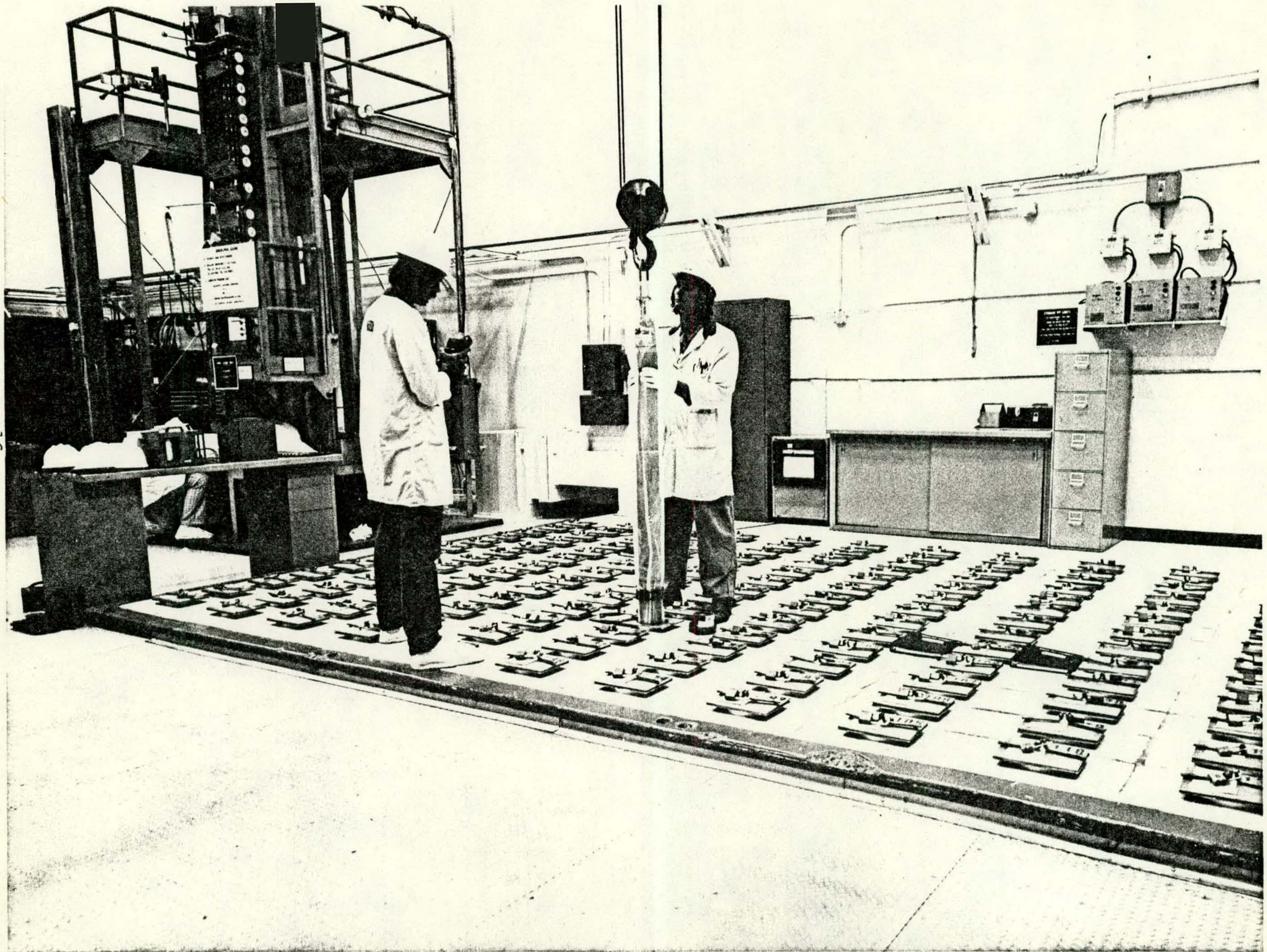

FIGURE 8. Pit Storage Area Used to Store Fuel Assemblies and Model 60 Inserts. (Photo No. 766619-1CN)

assistance or the system may be interrogated anytime during the counting interval. The system may be preset to alarm when a preset dose rate has been exceeded.

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