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# AREA RADIATION MONITOR AT THE INTENSE PULSED-NEUTRON SOURCE†

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## ABSTRACT

A tissue-equivalent ionization chamber with associated circuitry has been developed for area radiation monitoring in the Intense Pulsed-Neutron Source (IPNS) facility at Argonne National Laboratory. The conventional chamber configuration was modified in order to increase the electric field and effective volume thereby achieving higher sensitivity and linearity. The instrument provides local and remote radiation level indications and a high level alarm. Twenty-four of these instruments were fabricated for use at various locations in the experimental area of the IPNS-1 facility.

## Introduction

The pulsed neutron source is a research facility which has unique instrumentation requirements particularly in regard to area radiation monitoring. The facility consists of a 500 MeV rapid cycling proton synchrotron and a 500 MeV linac injector to provide an intense pulsed beam of protons. The protons interact in a depleted uranium target to provide intense pulses of neutrons. The neutrons are moderated and then utilized in a wide variety of material science research programs.

The synchrotron operates at pulse rates up to 45 Hz with a pulse duration of 100 nsec. The resulting duty factor of $4.5 \times 10^{-6}$ requires a radiation monitor with the capability of accurate response to very high instantaneous dose rates. The peak dose rate during the 100 nsec proton pulse due to a combined field of fast and slow neutrons, and $\gamma$ rays, is 22,000 rem/hr or an average of 100 mrem/hr at the maximum rate of 45 pulses/sec. This instrument linearly measures the time averaged dose rate due to a combined fast and slow neutron and $\gamma$-ray field over the range of 0.25 - 100 mrem/hr. Therefore, radiation monitors for this area must have a linear response over a range greater than eight orders of magnitude.

## Design Considerations

Tissue equivalent ionization chambers should be filled with a gas mixture which has a constitution similar to that of tissue. The ratio of nitrogen to hydrogen in tissue is about 0.4 by weight. Maximizing the neutron sensitivity and the ratio of neutron to $\gamma$-ray sensitivity leads to the choice of high pressure hydrogen as the primary chamber filling gas. Therefore, the new chamber is filled with 0.55 atm of $N_2$ and 19.45 atm of $H_2$. At thermal energies only about 25% of the radiation dose in tissue is due to hydrogen via the $^{1}H(n,\gamma)^{2}H$ reaction. The remaining dose is due to the nitrogen via the $^{14}N(n,p)^{14}C$ reaction.

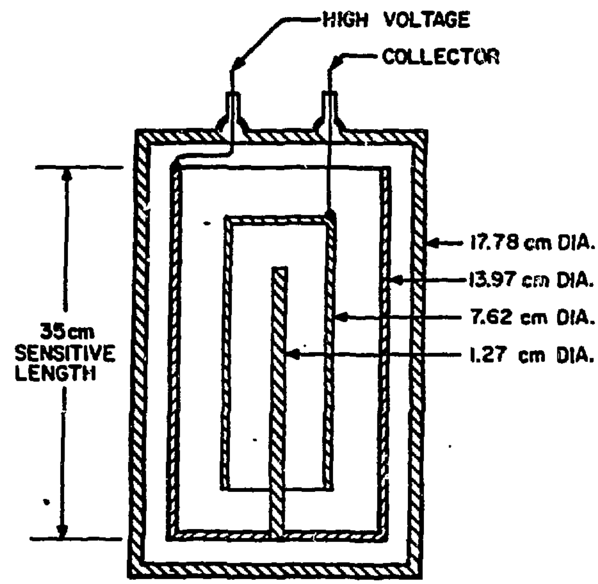


Fig. 1. Cross section of new ionization chamber. Introduction of center post increased the active volume by 13%. Increasing the diameter of the collector electrode decreased the distance between the collector and high voltage electrodes, thereby reducing recombination losses.

A cross section of the new chamber, LND model no. 50430, is shown in Fig. 1. This is a modified version of LND chamber[1] model no. 50413 which is hydrogen-filled to a pressure of 18 atm. The chamber is cylindrical with a length of 40 cm and a diameter of 18 cm. The outside shell which is made of 3 mm carbon steel is the containment vessel for the high pressure gas and an electrical shield for the high voltage and collector electrodes. Connections to the electrodes are through seals on the top face of the chamber. The high voltage electrode is a cup with a diameter of about 14 cm and the collector electrode is an inverted cup 7.62 cm in diameter.

An important performance criterion for ionization chambers is linearity of response as a function of radiation field intensity. However, as field intensity increases, recombination losses increase. The percentage loss in ionization current due to recombination may be expressed by[2]

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$$\frac{I-I_s}{I_s} = \frac{\beta n P^2 d^4}{6\mu^2 V^2} \times 100\% \qquad (1)$$

in which $$n = \frac{I_s}{e\, v_c}, \qquad (2)$$

and,

$I$ = current in A,

$I_s$ = measured saturation current in A,

$\beta$ = proportionality constant in $cm^3$ sec/ion-pair,

$n$ = ion pairs/$cm^3$ sec formed in the chamber,

$P$ = *pressure in atm,*

$d$ = electrode separation in cm,

$u$ = mobility for ions in $cm^2$ atm/Vsec,

$V$ = applied voltage in volts,

$e$ = charge of the electron, and

$v_c$ = active volume of the chamber.

Equation (1) states that recombination losses are inversely proportional to the square of the voltage applied to the electrodes, directly proportional to the fourth power of the distance between the electrodes, and directly proportional to the square of the pressure. We modified LND model no. 50413 by inserting a high voltage electrode center post into the volume of the collector cup and by increasing the collector electrode diameter from 4.75 cm to 7.62 cm. Insertion of the center post increased the sensitive volume by 13%. The increase in diameter of the collector electrode decreased the distance between the collector and high voltage electrodes by 44%. A pressure of 20 atm and a collector voltage of 5 kV is used in the new chamber instead of 18 atm and 3 KV which was recommended by LND for model 50413. Using Eqs. (1) and (2), the percentage loss in ionization current due to recombination at a dose rate of 22,000 rem/hr is calculated to be 6.6% for the new chamber and 62% for the original model no. 50413. Thus, calculations show that as a result of these modifications ionization current losses due to recombination were reduced by about 10 times.

Table 1. The response of the new chamber is calculated for neutron energies ranging from 0.025eV to 6.5 MeV. The calculated response which is listed in the right-hand column is plotted in Fig. 2.

| Neutron Energy | $D_{tot}$ $10^{-9}$ rem/nv | $I_{meas}$ $10^{-14}$ A/nv | $I_{corr}$ $10^{-14}$ A/nv | Neutron flux (nv) per mrem/hr | Response $10^{-13}$ A/mrem/hr |
|---|---|---|---|---|---|
| 0.025 eV | 1.09 | | 0.116 | 260 | 3.1 |
| 100 eV | 1.36 | | 0.146 | 208 | 3.0 |
| 1 keV | 1.27 | | 0.136 | 192 | 2.6 |
| 30 keV | 3.73 | | 0.400 | 80 | 3.2 |
| 240 keV | 12.1 | 1.1 | 1.[illegible]0 | 18 | 2.3 |
| 1 MeV | 23.7 | 3.5 | 4.27 | 7.2 | 3.1 |
| 2 MeV | | 5.0 | 5.74 | 7.8 | 4.5 |
| 5 MeV | | 4.6 | 5.28 | 7.2 | 3.8 |
| 6.5 MeV | | 4.1 | 4.70 | 7 | 3.3 |

In order to estimate the neutron response of the new chamber in A/mrem/hr as a function of energy, calculations were made for nine energies over the range 0.025 eV to 6.5 MeV. The results are shown in Table 1. Values of ionization current/unit neutron flux (the $I_{meas}$ column) at five neutron energies were furnished by LND for the 18 atm hydrogen-filled chamber no. 50413. The $D_{tot}$ column lists calculations by Yampol'skiy[3] for the total dose in tissue due to capture and scattering reactions in hydrogen and nitrogen for neutron energies from 0.025 eV to 1 MeV. We corrected the $I_{meas}$ values to give $I_{corr}$ by adding to $I_{meas}$ the percentage of the nitrogen capture reaction in $D_{tot}$ at 240 keV and an additional percentage for the increase in hydrogen pressure from 18 to 19.45 atm. The four lower energy values of $I_{corr}$ are the result of multiplying $I_{corr}$ at 240 keV by the ratio of $D_{tot}$ to $D_{tot}$ at 240 keV. $I_{corr}$ was then multiplied by values in the column headed nv/mrem/hr to give the response in the last column in A/mrem/hr. The values in the column nv/mrem/hr account for the biological effect of neutron radiation as a function of neutron energy.[4] The response in the last column was plotted and is shown in Fig. 2. The average of the response is 3.2 x $10^{-13}$ A/mrem/hr for an energy range of 0.025 eV to 6.5 MeV. Calculations showed that the effect of scattering and capture of neutrons in the chamber walls was negligible.

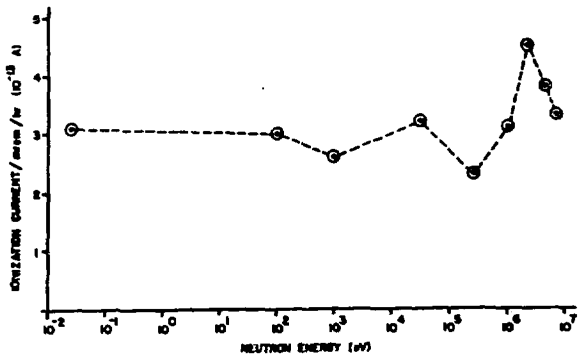



Fig. 2. The Response column of Table 1 is plotted as a function of neutron energy. The calculated neutron response of the new chamber averages 3.2 x $10^{-13}$ A/mrem/hr for an energy range of 0.025 eV to 6.5 MeV.

The γ-ray sensitivity for the new chamber was calculated and found to be 1.3 x $10^{-12}$ A/mrem/hr for 1 MeV γ rays. The ratio of neutron to γ-ray effective dose is estimated to be 10 or more at the IPNS-1 facility. Therefore, there is no danger of the γ-ray induced current overwhelming the neutron induced current. Because the major portion of γ rays are above 100 keV, reduced sensitivity at low energies due to absorption in the chamber walls will introduce negligible error.

## Measured Response of New Chamber

The measured neutron response of the new chamber at six neutron energies is shown in Fig. 3. The chamber current/mrem/hr is plotted as a function of neutron energy from 0.08 MeV to 4.5 MeV. The Fast Neutron Generator facility at ANL was used as the source of neutrons. At this facility protons are accelerated onto a lithium target to produce monoenergetic neutrons. The proton beam intensity was adjusted to provide six known neutron energies. A fission counter was used to determine the neutron flux density. The average response over the energy range from 0.3 MeV to 4.5 MeV is $4.5 \times 10^{-13}$ A/mrem/hr which is somewhat higher than the average response of the calculated value of $3.4 \times 10^{-13}$ A/mrem/hr. Two factors contribute to the higher average response than was calculated: 1) Increase in sensitive volume of the modified chamber (13%) and 2) increase in dose due to $\gamma$ rays (3% of the neutron dose).

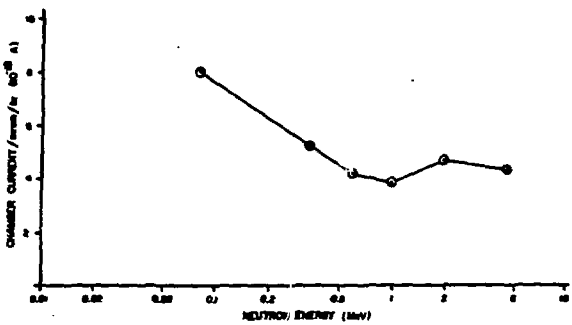
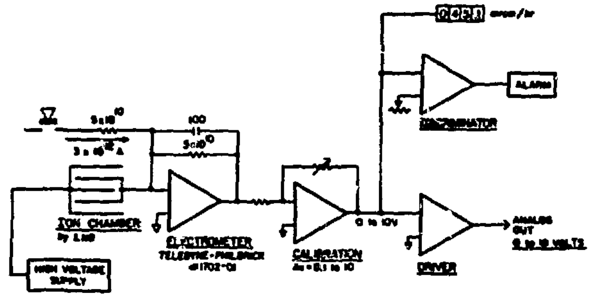


Fig. 3. The measured neutron response of the new chamber averages $4.5 \times 10^{-13}$ A/mrem/hr over the energy range of 0.3 MeV to 4.5 MeV.

## Electronics

The electronic circuitry for the new chamber is shown schematically in Fig. 4. The electrometer stage is a parametric amplifier which has an input bias current of $\pm 2 \times 10^{-15}$A. Because the new chamber has a sensitivity of $4.5 \times 10^{-13}$ A/mrem/hr for neutrons this corresponds to an error of less than $\pm 0.01$ mrem/hr. The input offset voltage for the electrometer stage is $\pm 10\ \mu V/^{o}C$ which results in an error of less than $\pm 0.004$ mrem/hr for a $\pm 10^{o}C$ variation in temperature. A test current of $3 \times 10^{-12}$ A is provided for checking the chamber sensitivity and testing the electronics. The calibration stage which has a potentiometer-controlled gain allows calibration of the instrument so that 10 V at the output is equal to 100 mrem/hr as indicated on the local digital panel meter. An analog output is provided for the IPNS-1 central control system. A relay contact output is also sent to the central control system for indicating whether the discriminator set level has been exceeded.




BLOCK DIAGRAM OF AREA RADIATION MONITOR

Fig. 4. The calibration stage nullifies differences between monitors caused by differences in the chambers and in the high-meg feedback resistors. The calibration potentiometer is adjusted so that 10V at the output is equal to 100 mrem/hr. The average dose rate in mrem/hr is indicated by the local digital panel meter.

## Calibration

A 5 Ci PuBe neutron source and a 0.7 Ci $^{137}Cs$ $\gamma$-ray source were used to calibrate the assembled monitors. For the geometry used in the calibration, the dose rate for the neutron source is known to $\pm 5\%$ and the dose rate for the $\gamma$-ray source is known to $\pm 1\%$. For the 24 instruments, the chamber current ranged from 4 to $6 \times 10^{-13}$ A/mrem/hr for neutrons and 0.9 to $1.1 \times 10^{-12}$ A/mrem/hr for $\gamma$ rays. The differences in current from chamber to chamber were due to slight variations in the calibration geometry, to differences in the chambers, and to differences in the electronics in which high-meg resistors were used. The calibration stage in the electronics nullified these differences.

## Packaging

A photograph of the area radiation monitor is shown in Fig. 5. The center of the ionization chamber is about 1.25 meters above floor level. The electronics and high voltage supply are housed in an air tight metal container which is gasketed to the chamber face. Desiccants within the container keep the relative humidity low thus minimizing leakage currents on the surfaces of insulators. Audible and visible alarms are mounted at the top of the instrument. The power supply and battery pack are mounted on the pedestal. The batteries are sized such that the instrument operates for about eight hours in case of AC power failure.

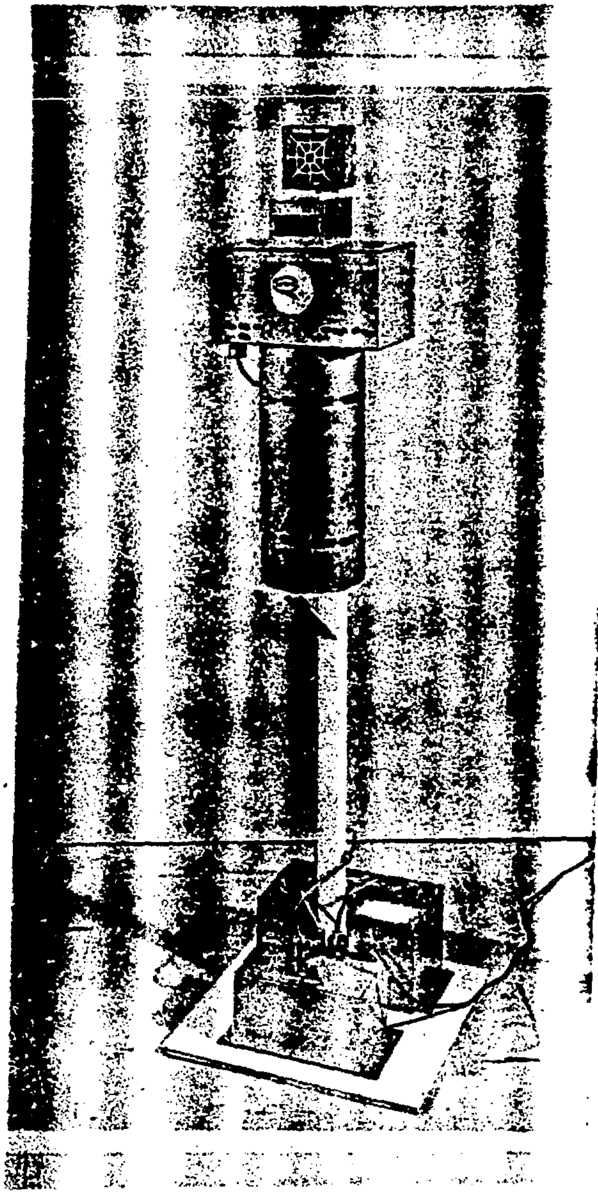


Fig. 5. The center of the ionization chamber is about 1.25 meters above floor level. An audible and visible alarm is mounted at the top of the instrument. The power supply and battery pack are mounted on the pedestal.

## Conclusions

A radiation monitor has been developed which clearly meets the special requirements of a pulsed neutron source. These requirements are:

1) Measure the time average dose rate due to a combined fast and slow neutron and $\gamma$-ray field.

2) Respond linearly over an integrated range of 0.25 to 100 mrem/hr.

3) Respond linearly to peak dose rates of 22,000 rem/hr.

In addition, the monitors provide the following:

1) A local meter to indicate the average dose rate.

2) An audible and visible alarm and a relay contact output whenever dose rate exceeds a preset level.

3) An analog output signal compatible with the IPNS Central Control system for beam shutdown, steering, or focusing.

4) Continuous operation via rechargeable batteries in case of AC power failure.

Twenty-four monitors have been fabricated, checked out, and calibrated. Fifteen of these are installed and operating satisfactorily at the IPNS-1 facility.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