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Empirical Correlation of Residual Gamma Radiation Resulting from Operation of the Health Physics Research Reactor

T. L. Chou
G. E. Ragan
C. S. Sims

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DEPARTMENT OF ENERGY

ORNL-6144

Contract No. DE-AC05-84OR21400

Health and Safety Research Division

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T. L. Chou*
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ORNL--6144

DE85 012075

Date Published - April 1985

* Taiwan Power Co., Radiation Laboratory, Shinmen, Taiwan, Republic of China

Oak Ridge National Laboratory
Oak Ridge, Tennessee 37831
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ACKNOWLEDGEMENTS

The authors take this opportunity to thank E. G. Bailiff for operating the reactor and G. R. Patterson for health physics support.

Empirical Correlation of Residual Gamma Radiation Resulting from Operation of the Health Physics Research Reactor

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Highlights

An empirical equation has been developed which gives gamma dose equivalent rate as a function of time, distance, and fission yield after a pulsed operation of Oak Ridge National Laboratory's (ORNL) unshielded Health Physics Research Reactor (HPRR). A related expression which is applicable to steady-state reactor operation has been mathematically derived from the aforementioned empirical equation. The two relations can be used to predict the gamma dose equivalent rate to within 25% for times between 1 minute and 90 minutes after reactor shutdown. Similar agreement is expected for up to several days. In most cases the relations are expected to overestimate the gamma dose equivalent rate.

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* Taiwan Power Co., Radiation Laboratory, Shinmen, Taiwan, Republic of China

INTRODUCTION

The Health Physics Research Reactor (HPRR) is a small, unmoderated fast reactor located at the Oak Ridge National Laboratory (ORNL) in Oak Ridge, Tennessee. The reactor may be operated in steady-state and in pulsed modes. The reactor is used in studying the biological effects of radiation and in neutron and gamma dosimetry development.[1] These applications require that the radiation produced by the reactor be well described under different operating conditions so that a known radiation dose can be administered to the experimental item.

Pulsed and high-power operations produce significant quantities of radioactive fission products. The radiation produced by the decay of these fission products must be considered in a complete description of the radiation produced by the reactor. In most cases, the radiation-dose contribution from the decay of fission products will be insignificant in comparison with the dose required for a given experiment. However, if a low dose is required soon after a pulsed or high-power operation of the reactor, the dose contribution from fission product decay may be significant. Also, personnel access to the reactor building is hampered by the presence of residual radiation after pulsed or high-power operation. For these reasons, a description of the residual radiation produced by pulsed and high-power operation of the reactor is useful.

An empirical relation which expresses the free-air gamma dose equivalent rate as a function of pulse yield (total number of fissions produced), time after pulse, and distance from the reactor has been developed and is the subject of this paper. A related expression has also been developed which is applicable to steady-state operation. The latter expression is mathematically derived from the former.

EXPERIMENTAL DESCRIPTION

The Reactor

The HPRR is located at the Dosimetry Applications Research (DOSAR) Facility at ORNL. Since the reactor is unshielded, it is remotely operated to prevent excessive personnel exposure during operation. The control building is located behind a hill and about 300 m from the reactor building.

Steady-state operation of the reactor can continue indefinitely at low power levels (less than 100 W). Higher power levels may be maintained for a limited time (e.g., 10 kW for 7.7 min.). Self-extinguishing pulses yielding up to 10^{17} fissions may be produced. Most pulses produced by HPRR yield between 10^{16} and 10^{17} fissions. The duration (full width at half maximum) of the pulses associated with these yields ranges from 900 down to 50 μs.

Instrumentation

A Geiger-Mueller gamma-ray dosimeter (Phillips No. 18509) with low neutron sensitivity[2] was used to measure the free air gamma dose. The high voltage supply (400 Vdc) and the preamplifier for the G-M counter were located in the reactor building. The pre-amplified signal was transmitted through aproximately 300 m of permanently installed electrical conduit (channel 1/62) to the control building where counting instrumentation was located. Two Tennelec TC545A counters were used to count the number of pulses coming from the detector. The use of two counters allowed counts of one minute duration to be taken every minute. The arrangement of the instrumentation is shown schematically in Fig. 1.

Experimental Data

Data were collected following five separate pulsed operations of the HPRR. The data consist of the counts registered in one minute intervals every minute for up to 90 minutes after each pulse. The detector was placed at different locations and the fission yield varied as shown in Table 1. The operation number and pulse number uniquely identify the reactor run for record keeping purposes.

The raw data were transformed in two ways. First, a dead time correction was made in accordance with

$$C = \frac{C_o}{1 - C_o\tau}$$

where

C = corrected count rate

C_o = observed count rate

τ = dead time.

The dead time was previously measured to be 10^{-6} minutes for the particular G-M counter used. However, count rates in excess of $1/\tau$ were observed in the first few minutes after some of the pulses. This indicates that the dead time is actually smaller than 10^{-6} min. In the absence of a better value for τ, 10^{-6} min. was used and the data from the first few minutes were discarded.

Second, a conversion from count rate to dose equivalent rate was made. The conversion factor used was 4,381 counts/mrem.* This is from a

* 1 rem = 10^{-2} Sv.

calibration of the G–M counter done in April, 1984 using a standard Co-60 source.

Results

Examination of the data was expected to reveal that:

1. The dose equivalent rate at a given distance from the reactor would be proportional to $t^{-1.2}$, where t is the elapsed time after a pulse;

2. The dose equivalent rate at a given distance and time would be proportional to the fission yield of the pulse;

3. The dose equivalent rate at a given time after a pulse would be inversely proportional to the square of the distance from the reactor.

The "$t^{-1.2}$ law" was expected[3] on the basis of theoretical considerations[4] and experimental observations of the decay of fission products created by momentarily exposing a 10–mil uranium disk to thermal neutrons.[5] This widely applicable law, when applied to fallout from nuclear weapons, holds to within 25 percent for times between 30 minutes and 200 days[6]. In order to verify the $t^{-1.2}$ law for the HPRR, least–squares fits of the form

$$y = at^{b}, \qquad (1)$$

where y(t) is the fitted curve, t is the time in minutes after a pulse, and a and b are the fitted parameters, were performed for each of the five data sets. The parameter b was found to vary between -1.07 and -1.25, depending on the time interval over which the data were fitted. Since a single equation applicable for all times of interest was desired, this result was taken to be a rough confirmation of the $t^{-1.2}$ law.

The proportionality of dose equivalent rate to fission yield was expected because the residual radioactivity is produced by fission products which are produced in proportion to the fission yield. This proportional relationship was confirmed by plotting the parameters "a" (which represent the dose equivalent rate at time t=1) from fits of the type of Eq.(1) against fission yield, n. The proportionality constant B was determined by a least squares fit of the form

$$y = Bn, \qquad (2)$$

to be

$$B = 3.75 \times 10^{-14} \ \frac{\text{mrem}}{\text{minute-fission}}.$$

The significance of B can more easily be seen by rewriting Eq.(2) as

$$D(n,1,3) = Bn \qquad (3)$$

where

$D(n,t,r)$ = the calculated dose equivalent rate in mrem/minute corresponding to fission yield n, time t, and distance r.

The "inverse-square law" is expected for a point source in a vacuum. It was also shown to be adequate for the HPRR, at least at 3, 6, and 9-meters. This was done in the following way. First the parameters "a" from fits of the type of Eq.(1) to the data collected at 6 and 9 meters were normalized to the same fission yield (based on the proportionality of dose equivalent rate to fission yield which had already been demonstrated). Then a least-squares fit of the form

$$y = cr^{d} \qquad (4)$$

was performed, where y(r) is the fitted curve, r is the distance in meters, and c and d are the fitted parameters. The value of the exponent d was found to be d = −2.07. This was taken to be a rough confirmation of the inverse-square law for present purposes.

Having confirmed the expected trends of the data (1, 2, and 3 above), we are left with an equation of the form

$$D(n,r,t) = knt^{-1.2}\, r^{-2}, \qquad (5)$$

where the only parameter to be determined is k. The equation

$$k = \frac{D(n,r,t)}{nt^{-1.2}\, r^{-2}} \qquad (6)$$

should hold for any values of n, r, and t. Equation (3) gives a value for D(n,1,3) which was determined on the basis of the three data sets collected at 3 meters.

Combining Eq. (3) and Eq. 6) gives

$$k = \frac{D(n,1,3)}{n1^{-1.2}\ 3^{-2}}$$

$$= \frac{Bn}{n3^{-2}}$$

$$= 9B$$

$$= 3.33\ x10^{-13}\ \frac{\text{mrem}}{\text{minute-fission}}$$

Finally, we have

$$D(n,r,t) = 3.38 \times 10^{-13}\ nt^{-1.2}\ r^{-2} \qquad (7)$$

where

n = fission yield

t = time after pulse in minutes

r = distance from reactor in meters

D(n,r,t) = dose equivalent rate in mrem/minute

Equation (7) gives the dose equivalent rate as a function of fission yield, distance from the reactor and the time after a pulse.

For steady-state reactor operation, the following expression has been derived (see Appendix):

$$D(N,r,t,t_o) = 1.69 \times 10^{-12}\ Nr^{-2}\ [t^{-0.2} - (t+t_o)^{-0.2}]\ t_o^{-1} \quad (8)$$

where

t_o = operating time in minutes

N = steady-state fission yield

t = time after shutdown in minutes

$D(N,r,t,t_o)$ = dose equivalent rate in mrem/minute.

Taking into account the relationship between fission rate, Nt_o^{-1}, and reactor power, Eq. (8) can be rewritten as

$$D(P,r,t,t_o) = 3140\ Pr^{-2}\ [t^{-0.2} - (t+t_o)^{-0.2}] \quad (9)$$

where

p = reactor power in kW.

Figures 2 and 3 show comparisons of the measured dose equivalent rate and the value calculated by Eq. (7) for each of the five pulses listed in Table 1. Table 2 shows a comparison between measured and calculated values at approximately 26 hours after a pulse. Agreement is within 25% in every case thus far examined.

Figure 4 shows a comparison between the dose equivalent rate calculated from Eq. (8) and values measured after a steady-state operation. Equation (7) is also shown in the figure in order to demonstrate that Eq. 7 and Eq. 9 are equivalent at times much greater than the duration of reactor operation. The data in Figure 4 is from reactor operation number 2772 which was a 2 kW steady-state operation for 20 minutes.

This corresponds to a fission yield of 7.44 x 10^{16}. Agreement between measured and calculated values is within 25%.

The empirical correlations (Eq's 7 and 9) overestimate the dose equivalent rate in most cases (see Fig's. 2, 3, and 4). This could be due to the fact that the dead time used was greater than the actual dead time.

CONCLUSIONS

An empirical equation (Eq. 7) has been developed which gives the gamma dose equivalent rate as a function of time, distance, and fission yield after a pulsed operation of the HPRR. A related expression (Eq. 9) which is applicable to steady-state reactor operation has been mathematically derived from Eq. (7). Equation 7 and Eq. 9 can be used to predict the gamma dose equivalent rate to within 25% for times between 1 minute and 90 minutes after pulsed and steady-state operations, respectively. Similar agreement is expected for up to several days. In most cases the empirical correlations are expected to overestimate the dose-equivalent rate.

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Table 1. Variation of pulse yields and detector locations.

Operation number	Pulse number	Pulse yield, fissions	Distance from reactor, m
2752	971	5.48×10^{15}	3
2752	972	1.24×10^{16}	3
2759	977	5.49×10^{16}	3
2760	978	4.66×10^{16}	6
2763	979	5.80×10^{16}	9

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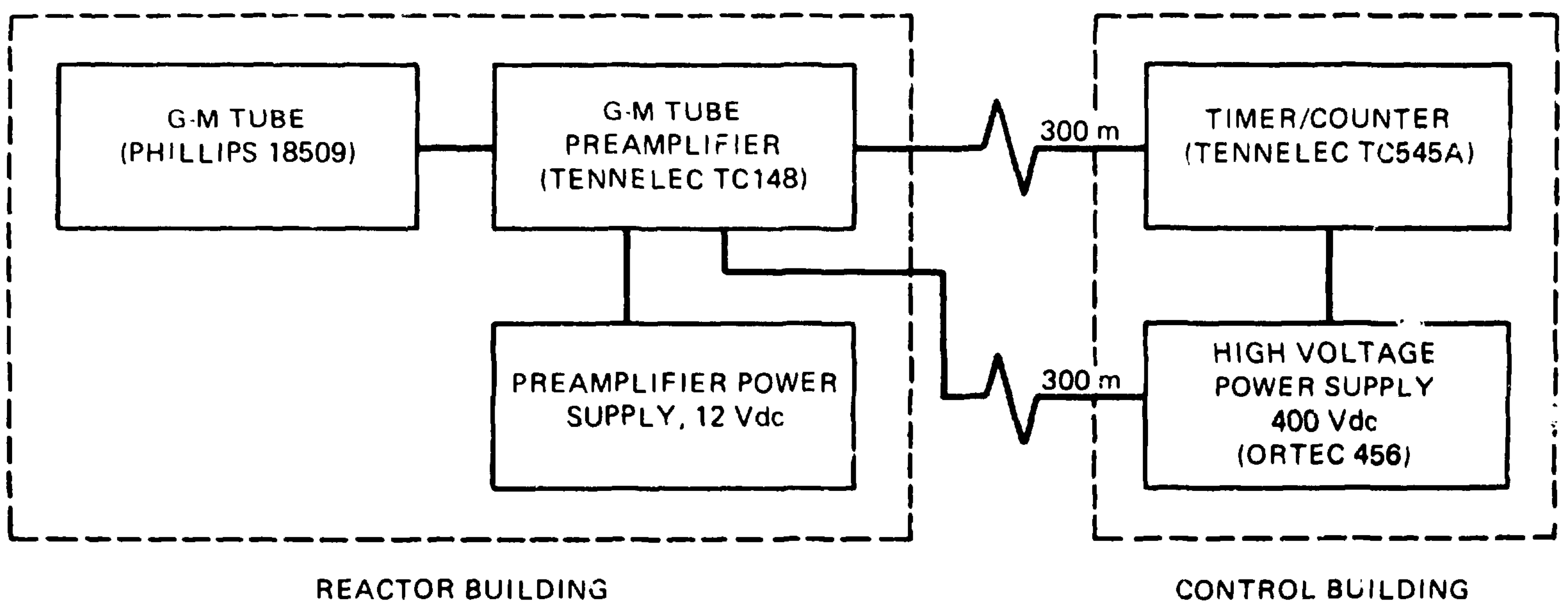

Fig. 1 Arrangement of Detector Instrumentation

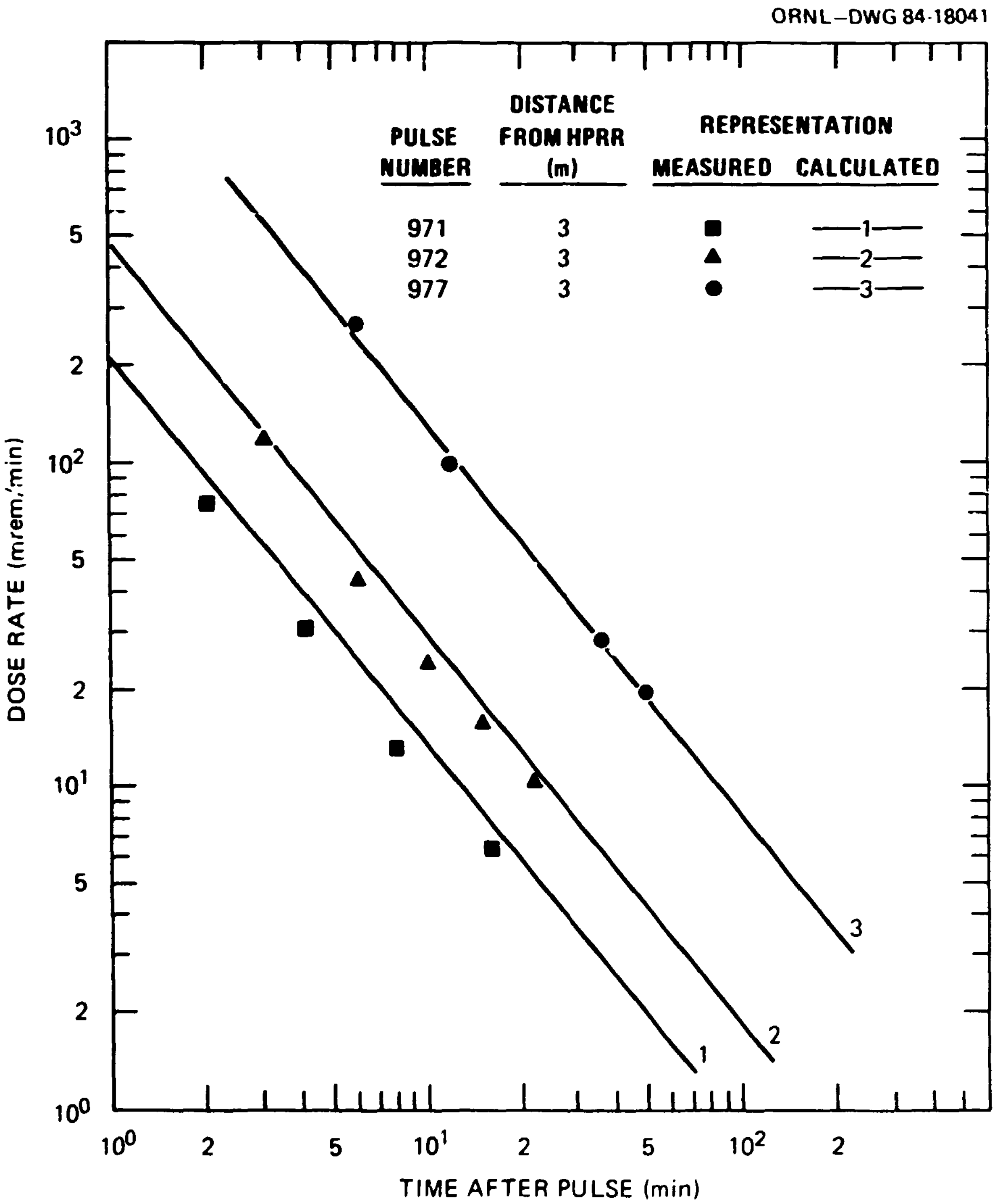

Fig. 2 Comparison of measured and calculated dose-equivalent rates at 3 meters from HPRR.

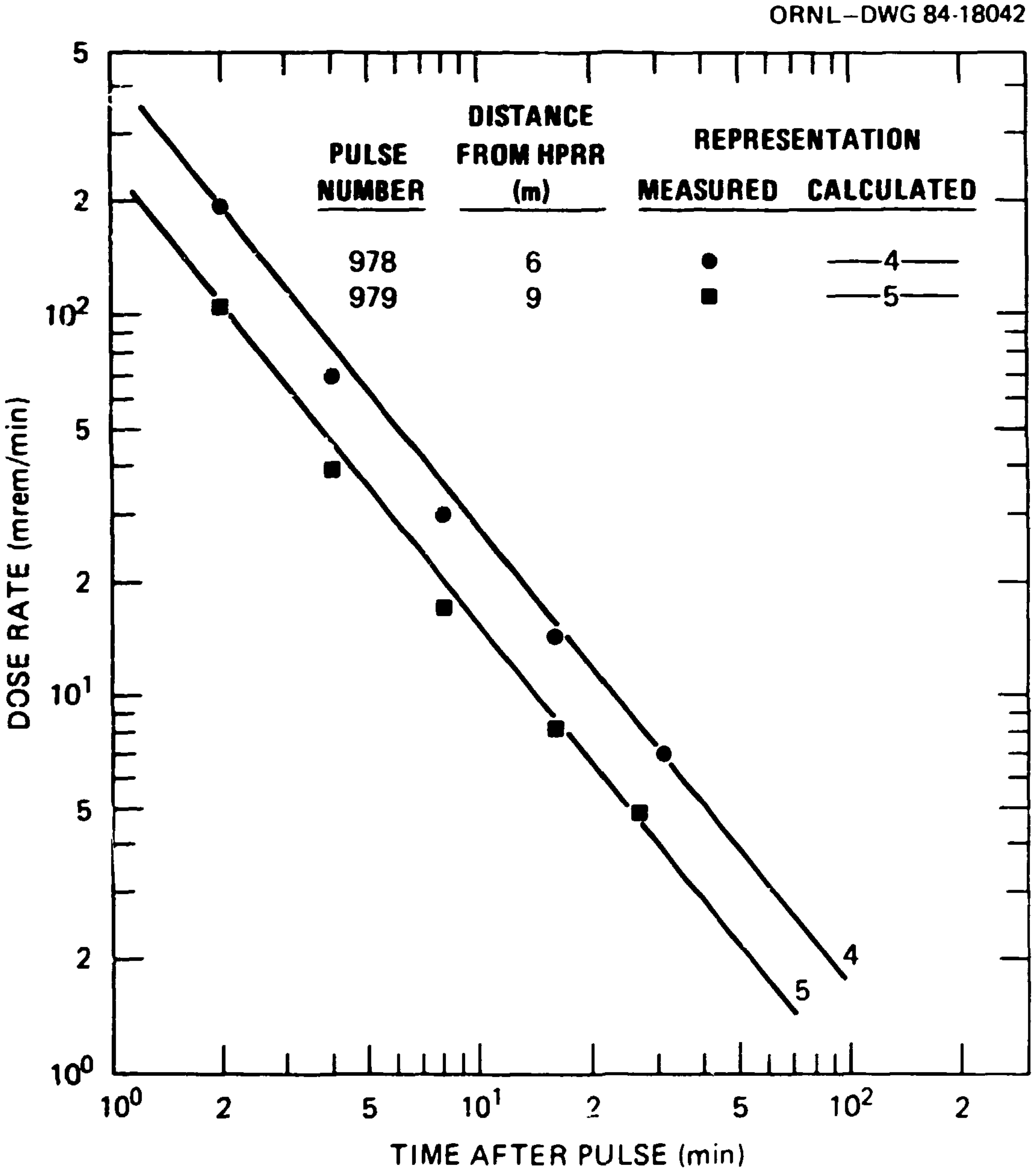

Fig. 3 Comparison of measured and calculated dose-equivalent rates at 6 and 9 meters from HPRR.

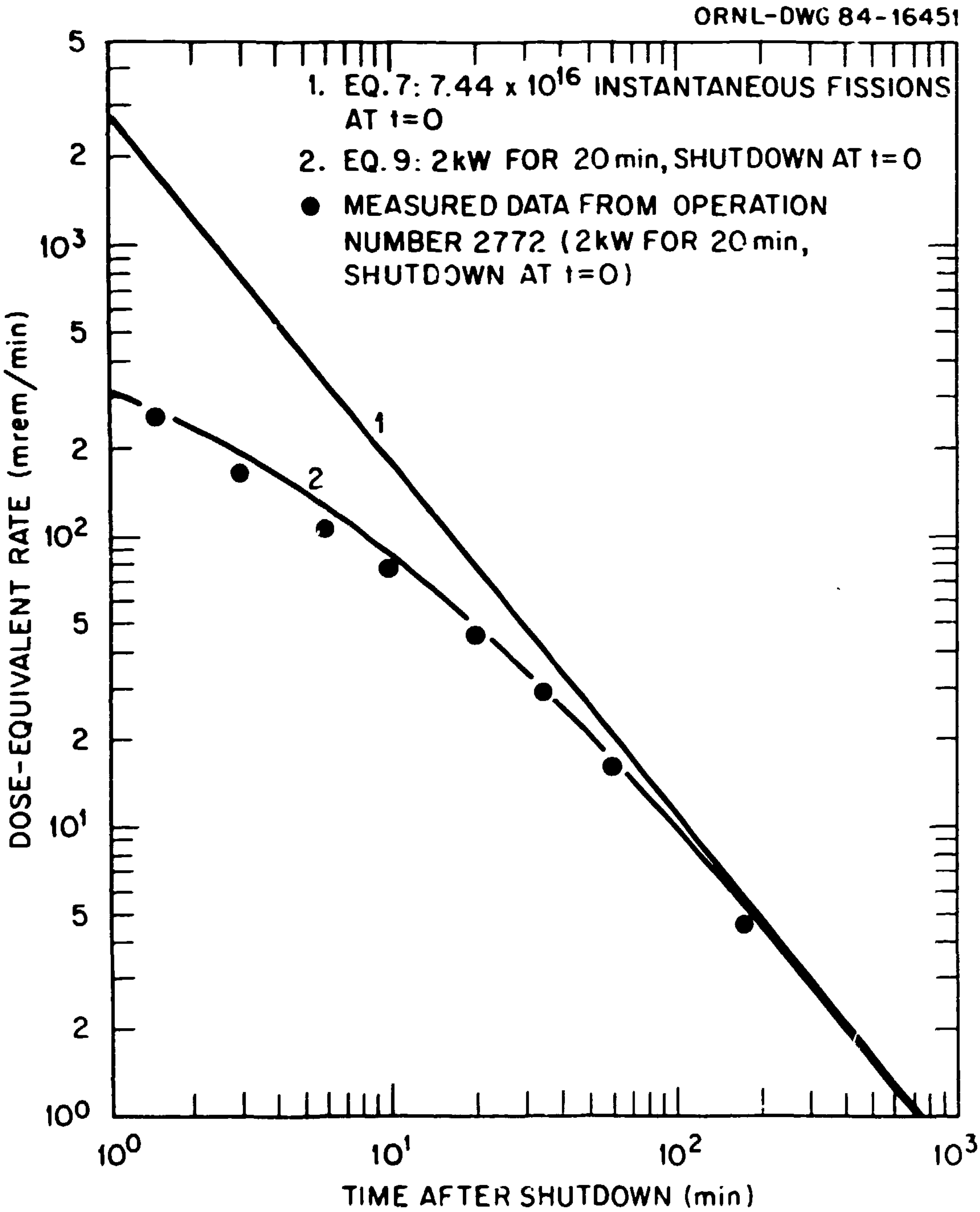

Fig. 4 Comparison of measured and calculated dose-equivalent rates after a steady-state operation of the HPRR.

APPENDIX

Appendix

Derivation of Equations (8) and (9)*

Suppose that the reactor operates at steady state for t_o minutes and fissions occur at the rate of R per minute. This situation is depicted in Fig. A-1. The fission products produced during the time interval dt contribute to the total dose equivalent rate at time t in accordance with

$$dB = k(Rdt)r^{-2}(t-\tau)^{-1.2} \quad \text{(A-1)}$$

which is merely a restatement of Eq. (7) in differential form. The total dose-equivalent rate at time t is found by integrating Eq. (A-1) over the duration of the reactor operation.

---

* This development parallels a similar one in Samuel Glasstone, Principles of Nuclear Reactor Engineering, Van Nostrand Co., Inc., Princeton, pp. 118-120., 1955.

$$D = \int_{-t_o}^{0} kRr^{-2}\ (t-\tau)^{-1.2}\ d\tau$$

$$= 5\ kRr^{-2}\ [t^{-0.2} - (t + t_o)^{-0.2}]$$

$$= 5\ kNr^{-2}\ [t^{-0.2} - (t + t_o)^{-0.2}]\ t_o^{-1} \qquad \text{(A-2)}$$

where

$N = Rt_o$, the steady-state fission yield.

Equation (A-2) is the basis of Eq. (8).

Alternatively, since the rate of fission product production is related to the reactor power by

$$R = XP$$

where

P = reactor power in KW

$X = 1.85 \times 10^{15}$ fissions/(KW-min),

Eq (A-2) can be rewritten as

$$D = 5kXPr^{-2}\ [t^{-0.2} - (t + t_o)^{-0.2}] \qquad \text{(A-3)}$$

Equation (A-3) is the basis of Eq. (9).

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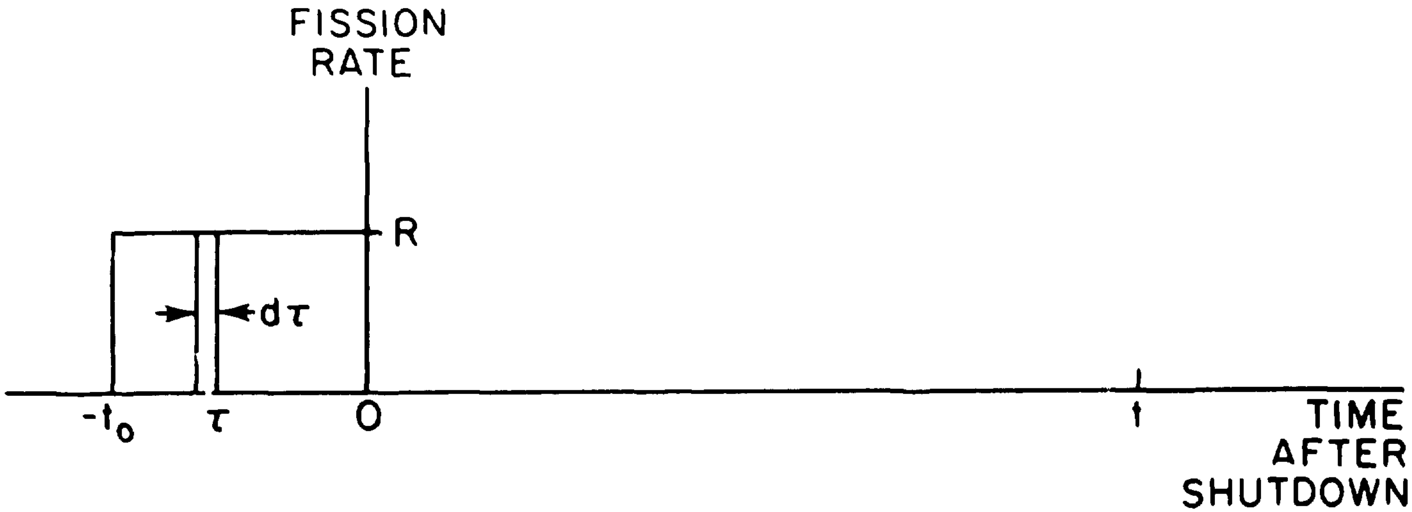

Fig. A-1 Depiction of Steady-state Reactor Operation

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74. Gary Zeman, AFRRI, Naval Medical Command, Bethesda, Maryland 20814
75. Office of Assistant Manager for Energy Research and Development, Department of Energy, Oak Ridge Operations Office, Oak Ridge, TN 37831

76-102. Technical Information Center, Department of Energy, Oak Ridge, TN 37831