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NINETEENTH NUCLEAR ACCIDENT DOSIMETRY INTERCOMPARISON STUDY

August 9-13, 1982

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HIGHLIGHTS

The Nineteenth Nuclear Accident Dosimetry Intercomparison Study was held August 9-13, 1982, at the Oak Ridge National Laboratory using the Health Physics Research Reactor operated in the pulse mode to simulate nuclear criticality accidents. Participants from eight organizations measured neutron and gamma doses at air stations and on phantoms for three different shielding conditions. Measured results were compared to nuclear industry guidelines for criticality accident dosimeters which suggest accuracies of ±25% for neutron dose and ±20% for gamma dose. Seventy-two percent of the neutron dose measurements using foil activation, sodium activation, hair sulfur activation, and thermoluminescent methods met the guidelines while less than 40% of the gamma dose measurements were within ±20% of reference values. The softest neutron energy spectrum (also lowest neutron/gamma dose ratio) provided the most difficulty in measuring neutron and gamma doses. Results of this study indicate the need for continued intercomparison and testing of nuclear accident dosimetry systems and for training of evaluating personnel.

INTRODUCTION

The nineteenth in a series[1-4] of nuclear accident dosimetry (NAD) intercomparison studies was conducted at the Oak Ridge National Laboratory's (ORNL) Dosimetry Applications Research (DOSAR) Facility during August 9-13, 1982. Participants measured shielded and unshielded neutron and gamma doses greater than 0.2 Gy (20 rads) at air stations and on phantoms produced by operating the Health Physics Research Reactor (HPRR)[5] in the pulse mode to simulate nuclear criticality accidents. These results were compared to the results of other participants who made similar measurements under identical conitions and to reference doses[6] based on reactor spectral and operational data. This week-long study also included lectures, discussions, and demonstrations on relevant subjects such as neutron activation principles applied to accident dosimetry, calculation of dose from criticality accidents, criticality safety, radiation dose determination based on chromosome aberrations, medical aspects of radiation accidents, dose determined from hair and blood activation, problems and requirements associated with nuclear accident monitoring at participating facilities, and reviews of participants dosimetry systems. The intercomparison study program is included in Appendix A of this report. This study was approved for 16 units of continuing education credit (No. 82-20) by the American Board of Health Physics.

PARTICIPATION

Individual participants in the Nineteenth NAD Intercomparison Study, their affiliations, and the abbreviations used in this report to identify them are listed in Appendix B. A total of nine different organizations were represented by active participants or observers. Eight agencies made measurements and reported final results.

DESCRIPTION OF EXPERIMENTS

Nuclear criticality accidents on the order of 10^{16} fissions were simulated by operating the HPRR in the pulse mode. The neutron energy spectra and neutron-to-gamma dose ratios were changed for each of three pulses by operating the reactor bare, shielded with 20-cm of concrete, and shielded with 12-cm of Lucite. The fission yields in each case were sufficient to provide neutron and gamma doses greater than or equal to 0.2 Gy. Table 1 is a summary of experimental conditions for the three pulses.

Dosimeters were mounted on ring stands or tables for air station (area monitoring station) dose measurements and on BOMAB[7] phantoms for personnel monitoring. Both air stations and the centerlines of the phantoms were located 3m from the reactor vertical centerline. Figure 1 shows (without the HPRR moved into the experimental position) the arrangement of the phantoms and air stations for the unshielded pulse. Figures 2 and 3 show the experimental arrangement of phantoms, air stations, shields, and reactor for the concrete and Lucite-shielded pulses, respectively.

All three phantoms were arranged with their fronts facing the reactor. Phantom B was filled with a saline solution with a sodium concentration approximating that found in human blood (1.5 mg/ml). The irradiated saline solution was made available to participants after each pulse for dose measurements based on sodium activation analysis.[7-8] Phantoms A and C were filled with tap water.

DOSIMETERS USED IN THE INTERCOMPARISON

A general description of the types of radiation dosimeters used in this study and the abbreviations used to identify them are given below. All participating agencies reported some neutron doses based on neutron activation principles. All gamma dose measurements were made with LiF thermoluminescent dosimeters. Detailed descriptions of nuclear accident dosimetry systems and methods are available in the literature.[9-10]

GAMMA DOSIMETERS

Thermoluminescent Dosimeters (TLD) - All gamma dosimeters in this study were based on thermoluminescent properties of LiF. Metastable centers are produced when LiF is irradiated and, upon heating, light is emitted in proportion to the absorbed dose.

NEUTRON DOSIMETERS

1. Neutron Activation Systems (ACT) - Some materials (e.g., gold, copper, indium, sulfur) become radioactive when exposed to neutrons. By measuring the activity of exposed foils, neutron fluences over differential energy ranges can be estimated for the incident spectrum. Associated neutron doses can be obtained by applying fluence-to-dose conversion factors to the estimated fluences and summing over the range of energies encompassed by the activation foils. Some activation systems also use foils made of fissionable materials (e.g., plutonium, neptunium, uranium) which have fission cross sections with thresholds at different neutron energies. These systems are called Threshold Detector Units (TDU's) and are generally used for area monitoring.
2. Thermoluminescent Dosimeters (TLD) - Two types of thermoluminescent material (chips), one sensitive to gammas (^{7}LiF) and the other sensitive to neutrons and gammas (^{6}LiF), are simultaneously exposed to the simulated nuclear accident radiation fields. The response due to neutrons can be determined after both chips are analyzed. Various shields and absorbers are often placed near the chips to limit their exposure from a given direction to a selected range of neutron energies.
3. Sodium Activation (NaACT) - Samples from irradiated, saline-filled phantoms are analyzed for ^{24}Na activity by any of a variety of counting techniques. The dose received by a phantom is proportional to the activity per unit volume of solution and orientation of the phantom.
4. Human Hair Activation (HACT) - Samples of human hair are analyzed for ^{32}P activity following irradiation. This method is used to

determine the dose due to neutrons with energies greater than the ^{32}S threshold. The total neutron dose can be determined if the fast neutron dose fraction is known (En>2.7 MeV).

REFERENCE DOSIMETRY

Reference neutron and gamma doses in air and on phantoms are given in Tables 2 and 3, respectively. Reference neutron doses in air were obtained using fission yields determined by measuring the ^{32}P beta activity in a 22 gram sulfur pellet located at a fixed position near the reactor core and calculated dose-per-fission conversion factors at 3m from the reactor for the various HPRR spectra.[6] Reference neutron doses in air are given in terms of wet tissue kerma[11] and element 57 absorbed dose with the capture gamma component excluded. Element 57 refers to the central volume element of a tissue-equivalent cylindrical phantom.[12] This phantom is used to calculate the average absorbed dose in a volume element per unit incident neutron fluence. Neutron dose in volume element 57 is the highest for all volume elements in the phantom and represents the expected maximum measured value for each exposure in this study. Reference gamma doses in air were obtained by dividing neutron kerma in air by the neutron-to-gamma dose ratio at 3m from the reactor. The neutron-to-gamma dose ratio is based on measured results from the first eighteen NAD intercomparison studies.

The reference neutron and gamma doses on phantoms given in Table 3 were calculated by multiplying doses in air by appropriate air-to-phantom conversion factors developed from measured results of the first eighteen NAD intercomparison studies. These factors were applied only to neutron kerma and gamma dose values since element 57 dose represents the absorbed dose in a particular volume element of a tissue equivalent phantom. (It should be noted that the DOSAR staff recommends reporting kerma at air stations and element 57 dose to phantoms. In order that we might evaluate the doses reported by all participants, we have also provided reference values for kerma on the phantoms.)

MEASUREMENT RESULTS AND ANALYSIS

Final results of measurements reported by participants and evaluation of those results are shown in Tables 4 through 15 of this report. Tables 4-6 give neutron fluence measurements, neutron and gamma dose measurements, neutron-to-gamma dose ratios and detection systems used by participating agencies at air stations for each of the three pulses. Results of individual measurements made on phantoms and types of detection systems used for the three pulses are given in Tables 7-9. These tables also include results of sodium activation analysis using the simulated blood in phantom B.

A summary of results of neutron dose measurements at air stations and on phantoms is given in Table 10. This table gives the average measured dose and experimental standard deviation from the mean by basic detection type (foil activation and Na activation), the dose averaged over all types of detection systems used, and reference doses. Measurements at air stations were made using activation methods (foil activation or TDU) for each of the three pulses. Phantom doses were measured using foil activation, sodium activation, TLD, or hair activation methods.

Table 11 shows the average measured neutron doses normalized to the reference kerma or element 57 dose values and associated percent standard deviations from the mean (in parentheses). The data in this table are based on data shown in Tables 4-9. Normalized dose gives an indication of the accuracy of the mean of a set of measurements (by basic detection method and averaged for all measurement methods) relative to the reference value. Percent standard deviation from the mean is a measure of precision and reflects agreement among individual measurements of the same dose.

Analysis of the average reported neutron doses for all dosimeter types (Table 11, column labeled "All") reveals that doses were more accurately measured at air stations and on phantoms for the concrete moderated spectrum than for the unshielded and Lucite shielded spectra. Measured neutron doses for the concrete moderated pulse averaged 0.96 times the reference doses for air station and phantom measurements compared to 0.89 and 1.22 times reference values for the bare and Lucite-shielded pulses, respectively. The normalized dose increased with decreasing spectral softness. This trend has been observed in previous intercomparisons[1-2] although unshielded neutron doses are usually measured more accurately than shielded neutron doses. The standard deviations from the mean ranged from 16 to 31% (average = 26%) for air station measurements and 15 to 23% (average = 20%) for phantom measurements. In both cases (air and phantom), measurements were more precise for the unshielded pulse (average = 16%) than for the shielded pulses (average = 27%). Neutron doses measured in air were more accurate but less precise than corresponding measurements on phantoms.

All neutron dose measurements at air stations were made using activation methods (foil activation or TDU). The average activation measured neutron doses varied from 0.90 to 1.20 times the reference values (average = 1.02) for air station measurements and 0.74 to 1.15

times reference values (average = 0.92) for phantom measurements. The concrete-shielded pulse was more accurately measured by activation methods than were the bare or Lucite-shielded pulses. Unshielded activation measured doses were more precise (average = 15%) than shielded doses (average = 27%). Average percent standard deviations from the mean were 26 and 20% for air station and phantom measurements, respectively, with phantom measurements being more precise than corresponding air station measurements.

Average neutron doses on phantoms determined by sodium activation methods ranged from 0.91 to 1.18 times the reference values. The most accurate and precise measurements using this technique were for the unshielded pulse. The average percent standard deviations from the mean ranged from 7 to 12% (average = 10%) with the lowest standard deviation being for the unshielded pulse. Based on accuracy and precision, sodium activation methods produced the best neutron dose measurements on phantoms. Analysis of TLD and hair activation measurements are included in Table 11, Column "All", since only one measurement by each method was reported for each of the three pulses.

Table 12 shows average gamma dose measurements at air stations and on phantoms, associated standard deviations from the mean, reference dose values, and measured and reference neutron-to-gamma dose ratios (D_n/D_γ). All reported gamma dose measurements were made with LiF TLD's. Measured neutron-to-gamma dose ratios are not given for phantom measurements since many participants reported element 57 dose for phantom measurements.

Average measured gamma doses normalized to the reference values and associated percent standard deviations from the mean for air station and phantom measurements are given in Table 13. Average measured gamma doses were higher than reference values by factors of 1.22 and 1.30 for air station and phantom measurements, respectively. The least accurate measurements were obtained for the Lucite shielded pulse (average normalized dose = 1.64) which produced the softest neutron energy spectrum and the lowest D_n/D_γ ratio of any configuration used in this study. Standard deviations from the means ranged from 9 to 30% (average = 19%) for air station measurements and from 13 to 20% (average = 17%) for phantom measurements.

Considering the composite of all reported results, Tables 11 and 13 show that neutron dose measurements in air and on phantoms were more accurate but less precise than corresponding gamma dose measurements. Average neutron doses were 1.02 times the reference values for air and phantom measurements while average gamma doses were 1.22 and 1.30 times reference values for air and phantom measurements, respectively. Gamma doses in air and on phantoms were more precisely measured (average standard deviations of 19 and 17%, respectively) than corresponding neutron doses in air and on phantoms (average standard deviations of 26 and 20%, respectively). Unshielded gamma doses were more accurate (1.06 times reference value) but with about the same precision (average standard deviation - 15% γ and 16% n) as unshielded neutron dose measurements (0.89 times reference value). Least accurate neutron and gamma dose measurements at air stations and on phantoms were made for the Lucite-shielded pulse.

A summary of average neutron fluence measurements at air stations is given in Table 14. These fluences were determined by participants using foil activation (including TDU) methods which provide some spectral definition of the neutron fields encountered during the study. This spectral information is important in dose determination since the relative contribution of a neutron to the total dose depends on its energy. No detailed analysis of these results is given in this report.

Table 15 shows measured and reference phantom-to-air station dose ratios[1-4] for neutron and gamma dose. Doses measured on phantoms were larger than those obtained at air stations by an average of 11% for neutrons and 68% for gammas. Neutron and gamma doses were larger on phantoms than at air stations for every shield configuration encountered in this study. Neutron dose measured on phantoms is greater because of reflected albedo neutrons from the phantoms. Measured gamma dose is increased on phantoms primarily due to the $^{1}H(n,\gamma)^{2}H$ reaction in the water that fills the phantom.

DOSIMETER PERFORMANCE RELATIVE TO REGULATORY CRITERIA

Nuclear criticality accident dosimetry guidelines[13-14] suggest accuracies of ±25% for neutron dose and ±20% for gamma dose. Figures 4-7 show graphically the performance of individual neutron and gamma dose measurements relative to the suggested guidelines at air stations and on phantoms for each of the three pulses. Measured doses normalized to the reference values are plotted for each participating organization. The solid line at 1.0 indicates the reference dose. The regulatory guidelines of ±25% for neutron dose and ±20% for gamma dose are shown as dashed lines and measurements meeting the guidelines will fall between these lines. A summary of the measured results relative to the regulatory guidelines is contained in Table 16. Figure 4 shows normalized neutron dose measurements at air stations by participating agency for each of the three pulses. The best results relative to the subject criteria were obtained for the unshielded pulse with 86% of the measurements meeting the criteria as compared to 75 and 50% for the concrete and Lucite-shielded pulses, respectively. Figure 5 shows normalized neutron dose measurements on phantoms by detector type and the average measured results for each participant. Based on individual measurements, the concrete-shielded pulse yielded the best results with 83% of the measurements meeting the guidelines compared to 73 and 56% for the unshielded and Lucite-shielded pulses, respectively. Considering the average measured results for each participant, all of the participants met the criteria for the unshielded and concrete-shielded pulses while only 50% of the average measurements met the criteria for the Lucite-shielded pulse. Normalized gamma dose measurements at air stations for each participating agency are shown in Figure 6. All of the measurements met the criteria for the unshielded pulse while none of the measurements for the Lucite-shielded pulse were within ±20% of the reference values. Figure 7 shows similar results for normalized gamma dose measurements on phantoms with the unshielded pulse producing the best values with 67% meeting the ±20% criteria as compared to 14 and 0% for the concrete and Lucite-shielded pulses, respectively. Figures 6 and 7 reveal that most of the gamma dose measurements which did not meet the guidelines were conservative (>1.20 times the reference values).

The composite results found in Table 16 show that 72% of the neutron dose measurements and only 39% of the gamma dose measurements met the subject guidelines. Poorest results were obtained for the Lucite-shielded pulse which provided the softest neutron energy spectrum and the lowest neutron-to-gamma dose ratio encountered in this study.

Only 53% of the neutron dose measurements and none of the gamma dose measurements satisfied the regulatory guidelines for this pulse.

COMPARISON TO PREVIOUS INTERCOMPARISON STUDIES

Results presented in the preceeding text for the Nineteenth NAD Intercomparison Study are consistent with the following statements which are based on an analysis of results from the previous studies:[1-4]

1. The precision of neutron dose measurements based on composite data has not improved as a function of time. The average percent standard deviation for unshielded neutron dose measurements made during the Nineteenth NAD Intercomparison Study (15%) is equal to the average of all eighteen previous intercomparisons. Average gamma dose precision measured for the unshielded pulse during this study (14%) was better than the average of the previous NAD Intercomparison studies (23%). Average percent standard deviations for shielded neutron and gamma dose measurements (≈22%) are consistent for all NAD intercomparison studies to date.

2. Neutron doses from unshielded pulses have been measured more precisely than those from shielded pulses.

3. Considering precision and accuracy, overall performances of neutron and gamma dosimeters are better for unshielded pulses than for shielded pulses.

4. Neutron and gamma doses measured at air stations are more accurate than corresponding measurements made on phantoms.

CONCLUSIONS

Composite results of the Nineteenth NAD Intercomparison Study show that 72% of the reported neutron doses measured using foil activation, hair activation, thermoluminescent, and sodium activation methods satisfied the suggested nuclear accident dosimetry guidelines. Neutron doses measured using sodium activation methods were more accurate and precise than those made by any of the other methods. Ninety-two (92%) percent of the NaAct dose measurements met the nuclear accident dosimetry criteria. Only 39% of the reported gamma dose measurements satisfied the performance criteria. As in past studies, the greatest difficulty in measuring neutron and gamma doses occurred in radiation fields with soft neutron energy spectrum and high gamma component[1-4] (e.g., Lucite-shielded spectrum). This is evidenced by the fact that only approximately half (53%) of the neutron dose measurements and none of the gamma dose measurements for the Lucite-shielded pulse met the performance guidelines. The fact that none of the participating agencies met the existing neutron and gamma dose measurement accuracy criteria for all three pulses indicates that continued improvement in accident dosimetry development and evaluation is needed.

RECOMMENDATIONS

Many of the problems associated with analysis and intercomparison of measurements during past NAD studies have been because of a lack of consensus on the neutron dose reporting convention that was used. Lectures and discussions on this topic during this study succeeded in clarifying and specifying the conventions to be used. Improvements could still be made if only one convention (e.g., kerma) were specified for use for air station measurements and another (e.g., element 57 dose) for phantom dose measurements.

A continued need for training of dosimetry personnel and for dosimetry intercomparison studies has been expressed. The DOSAR staff has planned an accident dosimetry course to be conducted early in 1983.

The course will include lectures on accident dosimetry, criticality alarm monitoring, medical aspects of radiation accidents and experimental work which will allow participants to make neutron and gamma dose estimates based on activation (foil, blood sodium, hair) and thermoluminescent methods.

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Table 1. Summary of experimental conditions

Pulse No.	Date	Eastern Daylight Time	Pulse Yield,[a] 10^{16} fissions	Shield	Reactor to shield distance, m	Reactor to dosimeter distance,[b] m
1	8/10/82	1036	8.10	None		3
2	8/11/82	1034	6.04	20-cm concrete	1	3
3	8/12/82	1033	5.90	12-cm Lucite	2	3

[a]Based on sulfur pellet activation analysis.

[b]Dosimeters at area monitoring stations were located 3 m from the centerline of the HPRR. The centerlines of phantoms on which dosimeters were exposed were 3 m from the centerline of the HPRR.

Table 2. Reference neutron and gamma doses at air stations

Pulse No.	Shield	Pulse yield, 10^{16} fissions	Neutron dose, 10^{-2} Gy[a]		Neutron-to-gamma dose ratio[b]	Gamma dose, 10^{-2} Gy[c]
			Kerma	Element 57		
1	None	8.10	324	372	6.1	53
2	20-cm concrete	6.04	52	60	2.6	20
3	12-cm Lucite	5.90	30	35	1.1	27

[a]Calculated dose at 3 m from the reactor centerline based on HPRR reference dosimetry document ORNL/TM-7748. Units are 10^{-2} Gy (1 rad).

[b]Dose ratio at 3 m from the reactor based on measured results from the first eighteen nuclear accident dosimetry intercomparison studies.

[c]Neutron kerma divided by neutron-to-gamma dose ratio.

Table 3. Reference neutron and gamma doses on phantoms

Pulse No.	Neutron air-to-phantom conversion[a]	Neutron dose, 10^{-2} Gy		Gamma air-to-phantom conversion[a]	Gamma dose, 10^{-2} Gy[b]
		Kerma[b]	Element 57		
1	1.05	340	372	1.70	90
2	1.20	62[c]	60[c]	1.62	32
3	1.02	31	35	1.38	37

[a]Ratio of phantom-to-air dose based on measured results from the first eighteen nuclear accident dosimetry intercomparison studies.

[b]Product of conversion factor times the dose in air given in Table 2.

[c]Experimental error allows the kerma value to exceed the element 57 value.

Table 4. Measurements at air stations for pulse No. 1
Yield: 8.10 (10^{16}) fissions
Shield: None

Study group	Neutron dose, 10^{-2} Gy[a]	Gamma dose, 10^{-2} Gy	D_n/D_γ	10^{-12} x Neutron fluence, n/cm^2: Au, thermal	Pu, >1 keV	Np, >0.75 MeV	U, >1.5 MeV	S, >2.9 MeV	Cu >2 ev	In, thermal	In, fast	Detector system: Neutron	Gamma
Reference	324	53	6.1										
Reference	372[b]												
BPNL	330	52	6.4									Act	TLD
DOSAR	312	52	6.0	0.6	12.7	9.1	4.2	2.6[c]				TDU	TLD
ISAHP	312				4.6	4.8	1.2	2.6[c]				TDU	
LANL	324	62	5.2	1.2				1.8	7.8		5.6	Act	TLD
RFP	197			0.5				3.9	0.4	1.2	1.3	Act	
SRP	300	52	5.8					2.0	7.4	2.0	3.8	Act	TLD
Y-12	269			2.2				1.9			4.3	Act	

[a]Neutron doses represent wet tissue kerma unless otherwise indicated and are given in units of 10^{-2} Gy (1 rad).

[b]Neutron dose represents element 57 dose with the $^1H(n,\gamma)^2H$ component excluded.

[c]Fluence >2.5 MeV.

Table 5. Measurements at air stations for pulse No. 2
Yield: 6.04 (10^{16}) fissions
Shield: 20-cm concrete

Study group	Neutron dose, 10^{-2} Gy[a]	Gamma dose, 10^{-2} Gy	D_n/D_γ	10^{-10} x Neutron fluence, n/cm²								Detector system	
				Au, thermal	Pu, >1 keV	Np, >0.75 MeV	U, >1.5 MeV	S, >2.9 MeV	Cu >[illegible] ev	In, thermal	In, fast	Neutron	Gamma
Reference	52	20	2.6										
Reference	60[b]												
BPNL	55	18	3.1									Act	TLD
DOSAR	46	11	4.2	0.9	2.0	1.2	0.6	0.4[c]				TDU	TLD
GAT	22[b]	20	1.1	1.2				0.3			0.7	Act	TLD
ISAHP	51			1.0	1.5	0.3	0.4	0.3[c]				TDU	
LANL	58	23	2.5	1.2				0.3	3.6		0.9	Act	TLD
RFP	50			1.0				0.5	0.2	1.2	0.8	Act	
SRP	47	27	1.7					0.2	4.4	2.5	0.6	Act	TLD
Y-12	72			3.1				0.3			0.4	Act	

[a]Neutron doses represent wet tissue kerma unless otherwise indicated and are given in units of 10^{-2} Gy (1 rad).

[b]Neutron dose represents element 57 dose with the $^1H(n,\gamma)^2H$ component excluded.

[c]Fluence >2.5 MeV.

Table 6. Measurements at air stations for pulse No.3
Yield: 5.90 (10^{16}) fissions
Shield: 12-cm Lucite

Study group	Neutron dose, 10^{-2} Gy[a]	Gamma dose, 10^{-2} Gy	D_n/D_γ	10^{-10} x Neutron fluence, n/cm^2 Au, thermal	Pu, >1 keV	Np, >0.75 MeV	U, >1.5 MeV	S, >2.9 MeV	Cu >2 ev	In, thermal	In, fast	Detector system Neutron	Gamma
Reference	30	27	1.1										
Reference	35[b]												
BPNL	33	35	0.9									Act	TLD
DOSAR	37	39	1.0	1.3	1.4	0.1	0.6	0.4[c]				TDU	TLD
GAT	32[b]	52	0.6	1.9				0.4			0.7	Act	TLD
ISAHP	47			2.1	1.0	0.4	0.2	0.5[c]				TDU	TLD
LANL	50	49	1.0	2.6				0.3	1.6		0.9	Act	TLD
RFP	21			1.2				0.5	0.1	4.3	0	Act	

[a]Neutron doses represent wet tissue kerma unless otherwise indicated and are given in units of 10^{-2} Gy (1 rad).

[b]Neutron dose represents element 57 dose with the $^1H(n,\gamma)^2H$ component excluded.

[c]Fluence >2.5 MeV.

Table 7. Measurements on phantoms for pulse No. 1
Yield: 8.10 (10^{16}) fissions
Shield: None

Study Group	Neutron dose, 10^{-2} Gy[a]	Gamma dose, 10^{-2} Gy	^{24}Na activity, Bq/ml[b]	Basis for estimating Neutron dose	Basis for estimating gamma dose
REFERENCE	340	90			
REFERENCE	372[c]				
DOSAR	380[c]	103	43.7	NaAct	TLD
DOSAR	314[c]			HAct	
LANL	330[c]	105		Act	TLD
LANL	374[c]		41.6	NaAct	
RFP	223			Act	
RFP	342			TLD	
RFP	242	125		Act	TLD
RFP	288			NaAct	
SRP	240	80		Act	TLD
SRP	339	87	52.2	NaAct	TLD
Y-12	318	74		NaAct	TLD

[a]Neutron doses represent wet tissue kerma unless otherwise indicated and are given in units of 10^{-2} Gy (1 rad).

[b]3.7×10^{10} Bq = 1 Ci

[c]Neutron doses represents element 57 dose with the $^1H(n,\gamma)^2H$ component excluded.

Table 8. Measurements on phantoms for pulse No. 2
Yield: 6.04 (10^{16}) fissions
Shield: 20-cm concrete

Study Group	Neutron dose, 10^{-2} Gy[a]	Gamma dose, 10^{-2} Gy	^{24}Na activity, Bq/ml[b]	Basis for estimating	
				Neutron dose	Gamma dose
REFERENCE	62	32			
REFERENCE	60[c]				
DOSAR	47[c]	22	8.1	NaAct	TLD
DOSAR	60[c]			HAct	
GAT	62[c]	40		Act	TLD
LANL	56[c]	40		Act	TLD
LANL	58[c]		10.6	NaAct	
RFP	59			Act	
RFP	91			TLD	
RFP	35	40		Act	TLD
RFP	57			NaAct	
SRP	53	36		Act	TLD
SRP	51	41	11.3	NaAct	TLD
Y-12	66	44		NaAct	TLD

[a]Neutron doses represent wet tissue kerma unless otherwise indicated and are given in units of 10^{-2} Gy (1 rad).

[b]3.7×10^{10} Bq = 1 Ci.

[c]Neutron dose represents element 57 dose with the $^{1}H(n,\gamma)^{2}H$ component excluded.

Table 9. Measurements on phantoms for pulse No. 3
Yield: 5.90 (10^{16}) fissions
Shield: 12-cm Lucite

Study Group	Neutron dose, 10^{-2} Gy[a]	Gamma dose, 10^{-2} Gy	^{24}Na activity, Bq/ml[b]	Basis for estimating: Neutron dose	Basis for estimating: Gamma dose
REFERENCE	31	37			
REFERENCE	35[c]				
DOSAR	36[c]	54	8.0	NaAct	TLD
DOSAR	62[c]			HAct	
GAT	32[c]	57		Act	TLD
LANL	54[c]	57		Act	TLD
LANL	46[c]		7.6	NaAct	
RFP	28			Act	
RFP	39			TLD	
RFP	38	62		Act	TLD
RFP	37			NaAct	
Y-12		74			TLD

[a]Neutron doses represent wet tissue kerma unless otherwise indicated and are given in units of 10^{-2} Gy (1 rad).

[b]3.7×10^{10} Bq = 1 Ci

[c]Neutron dose represents element 57 dose with the $^{1}H(n,\gamma)^{2}H$ component excluded.

Table 10. Summary of results of neutron dose measurements at air stations and on phantoms

Pulse No.	Dosimeter location	Neutron dose, 10^{-2} Gy[a]			
		Activation[b], kerma/el 57	Sodium, kerma/el 57	All[c], kerma/el 57	Reference, kerma/el 57
1	Air	292±46[d]/		292±46/	324/372
2	Air	54±9/22[e]		54±9/22[e]	52/60
3	Air	38±12/32[e]		38±12/32[e]	30/35
1	Phantom	235±10/330[e]	315±26/377±4	285±50[f]/350±33[g]	340/372
2	Phantom	49±12/59±4	58±8/53±8	59±17[f]/57±6[g]	62/60
3	Phantom	33±7/43±16	37[e]/41±7	36±5[f]/46±12[g]	31/35

[a]Values are average doses based on data shown in Tables 4-6 (air) and Tables 7-9 (phantoms) and are given in units of 10^{-2} Gy(1 rad).

[b]Includes foil activation and threshold detector unit data.

[c]Average of results for all measurement methods.

[d]Mean ± one standard deviation.

[e]One measurement reported.

[f]Includes one measurement made by TLD.

[g]Includes one measurement based on hair activation.

Table 11. Normalized average measured neutron doses and associated percent standard deviations[a]

Pulse No.	Shield	Dosimeter Location	Normalized dose (percent standard deviation)[b]		
			Activation	Sodium	All[c]
1	None	Air	0.90(16)		0.90(16)
2	20-cm concrete	Air	0.96(30)		0.96(30)
3	12-cm Lucite	Air	1.20(31)		1.20(31)
1	None	Phantom	0.74(14)	0.96(7)	0.87(15)
2	20-cm concrete	Phantom	0.87(21)	0.91(12)	0.95(22)
3	12-cm Lucite	Phantom	1.15(26)	1.18(12)	1.24(23)

[a]Based on data shown in Tables 4-9.

[b]Average reported measured dose divided by the reference value (percent of standard deviation from the mean).

[c]Includes results for all measurement methods.

Table 12. Summary of results of gamma dose measurements at air stations and on phantoms

		Gamma dose, 10^{-2} Gy[a]		D_n/D_γ	
Pulse No.	Dosimeter Location	TLD[b]	Reference	Measured[c]	Reference[d]
1	Air	55± 5[e]	53	5.3±1.0	6.1
2	Air	20± 6	20	2.7±0.9	2.6
3	Air	44± 8	27	0.9±0.3	1.1
1	Phantom	96±19	90		
2	Phantom	38± 7			
3	Phantom	61± 8	37		

[a]Values are average doses based on data shown in Tables 4-6 (air) and Tables 7-9 (phantoms) and are given in units of 10^{-2} Gy(1 rad).

[b]All reported gamma measurements were made with LiF dosimeters.

[c]Average of all reported neutron kerma measurements divided by the average of all reported gamma dose measurements.

[d]Data from Table 2.

[e]Mean ±one standard deviation.

Table 13. Normalized average measured gamma doses and associated percent standard deviations[a]

Pulse No.	Shield	Dosimeter Location	Normalized dose (percent standard deviation)[b]
1	None	air	1.04(9)
2	20-cm concrete	air	1.00(30)
3	12-cm Lucite	air	1.63(18)
1	None	phantom	1.07(20)
2	20-cm concrete	phantom	1.19(18)
3	12-cm Lucite	phantom	1.65(13)

[a]Based on data given in Table 12.

[b]Average reported measured dose divided by the reference value (percent of standard deviation from the mean).

Table 14. Summary of neutron fluence measurements at air stations

Pulse No.	10^{-10} x Average neutron fluence, n/cm^2 [a]								
	Au, Thermal	Pu, >1 keV	Np, >0.75 MeV	U, >1.5 MeV	S, >2.5 Mev	S, >2.9 Mev	Cu >2 ev	In, Thermal	In, fast
1	1.1±0.8	8.7±5.7	7.0±3.0	2.7±2.1	2.6±0.0	2.4±1.0	5.2±4.2	1.6±0.6	3.8±1.8
2	1.4±0.8	1.8±0.4	0.8±0.6	0.5±0.1	0.4±0.1	0.3±0.1	2.7±2.2	1.9±0.9	0.7±0.2
3	1.8±0.6	1.2±0.3	0.3±0.2	0.4±0.3	0.5±0.1	0.4±0.1	0.9±1.1	4.3	0.5±0.5

[a]Average fluences based on data given in Tables 4-6.

[b]One standard deviation from the mean. No standard deviation indicates that results were reported by only one participant.

Table 15. Comparison of doses measured on phantoms with those measured at air stations

Pulse No.	Shield	Ratio of phantom dose to air station dose			
		Neutron		Gamma	
		Measured[a]	Reference[b]	Measured[c]	Reference[b]
1	None	1.05±0.25[d]	1.05	1.75±0.38	1.70
2	20-cm concrete	1.16±0.42	1.20	1.90±0.67	1.62
3	12-cm Lucite	1.11±0.44	1.02	1.39±0.31	1.38

[a]Based on data given in Tables 4 - 9 for all reported dose measurements.

[b]Based on experimental data obtained during the previous 18 intercomparison studies.

[c]Based on data given in Table 12 for all reported dose measurements.

[d]One standard deviation from the mean.

Table 16. Summary of final measured results relative to regulatory criteria

Pulse number	Dosimeter location	Neutron measurements		Gamma measurements	
		Number of measurements	Number meeting criteria[b]	Number of measurements	Number meeting criteria[b]
1	Air	7	6 (86)	4	4 (100)
2	Air	8	6 (75)	5	3 (60)
3	Air	6	3 (50)	4	0 (0)
1	Phantom	11	8 (73)	6	4 (67)
2	Phantom	12	10 (83)	7	1 (14)
3	Phantom	9	5 (56)	5	0 (0)
Total		53	38 (72)	31	12 (39)

[a]Criteria presented in ANSI N13.3 which suggest accuracies of ±25% for neutron doses and ±20% for gamma doses.

[b]Number of measurements meeting the above mentioned criteria (percent meeting criteria).

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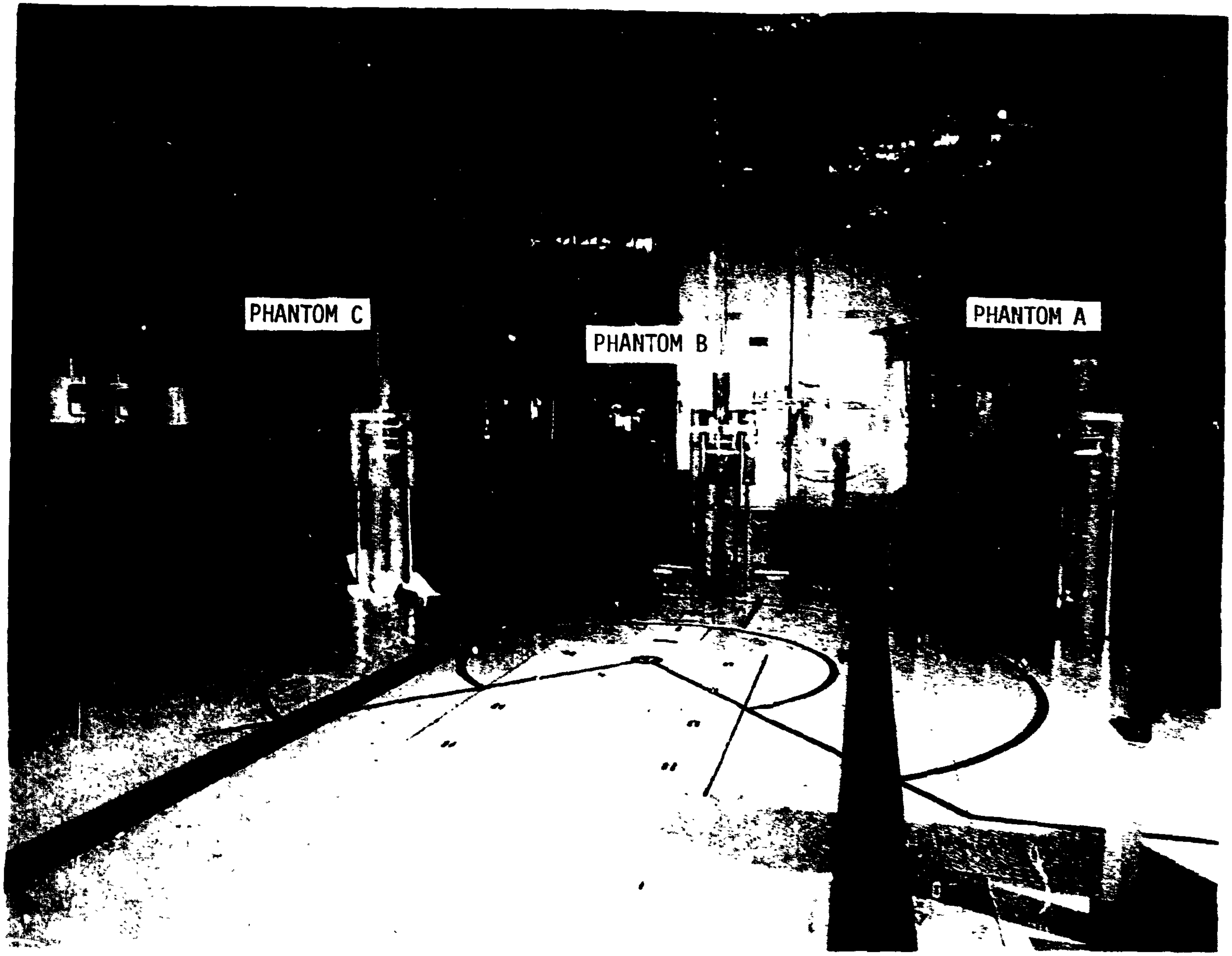

Fig. 1. Experimental arrangement for pulse No. 1

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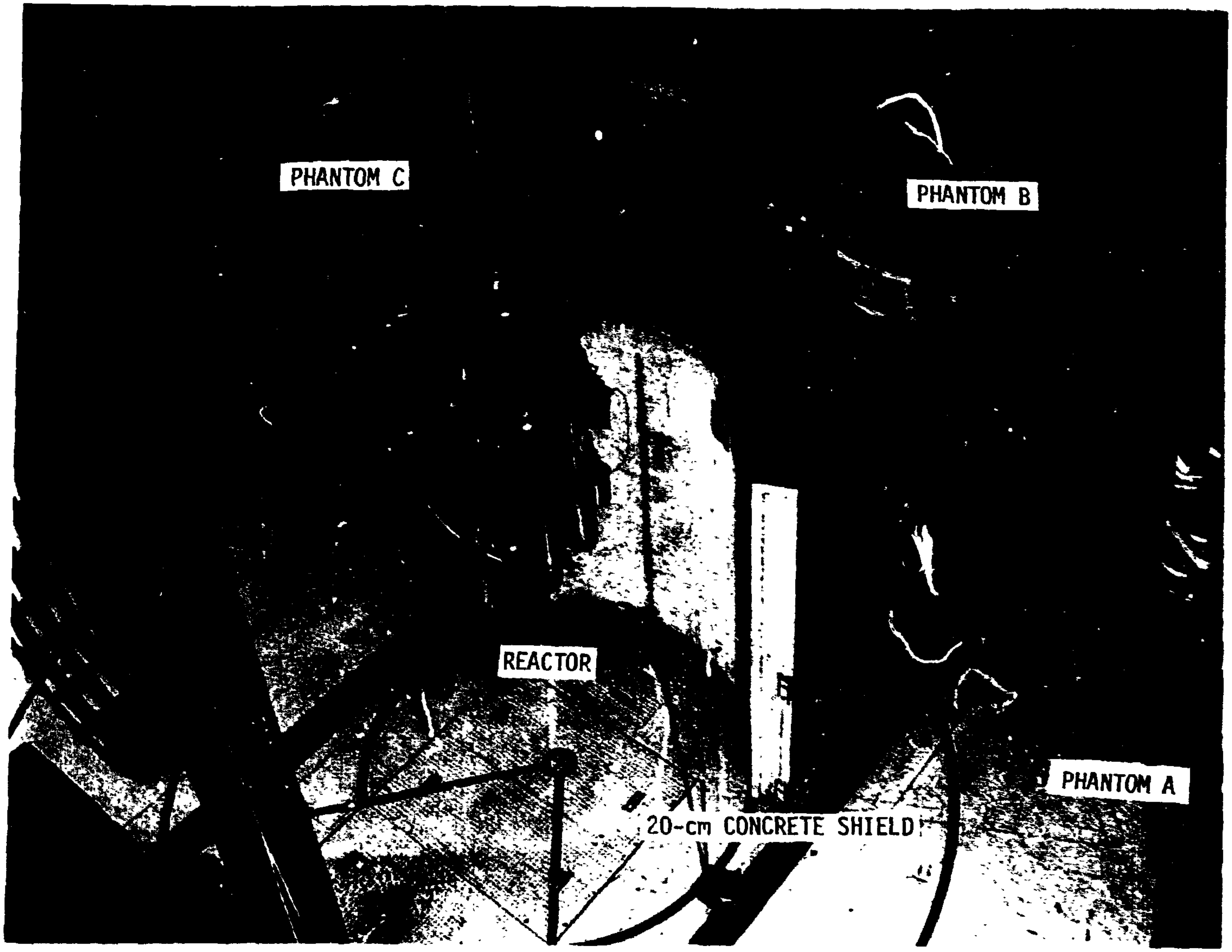

Fig. 2. Experimental arrangement for pulse No. 2 (20-cm concrete shield).

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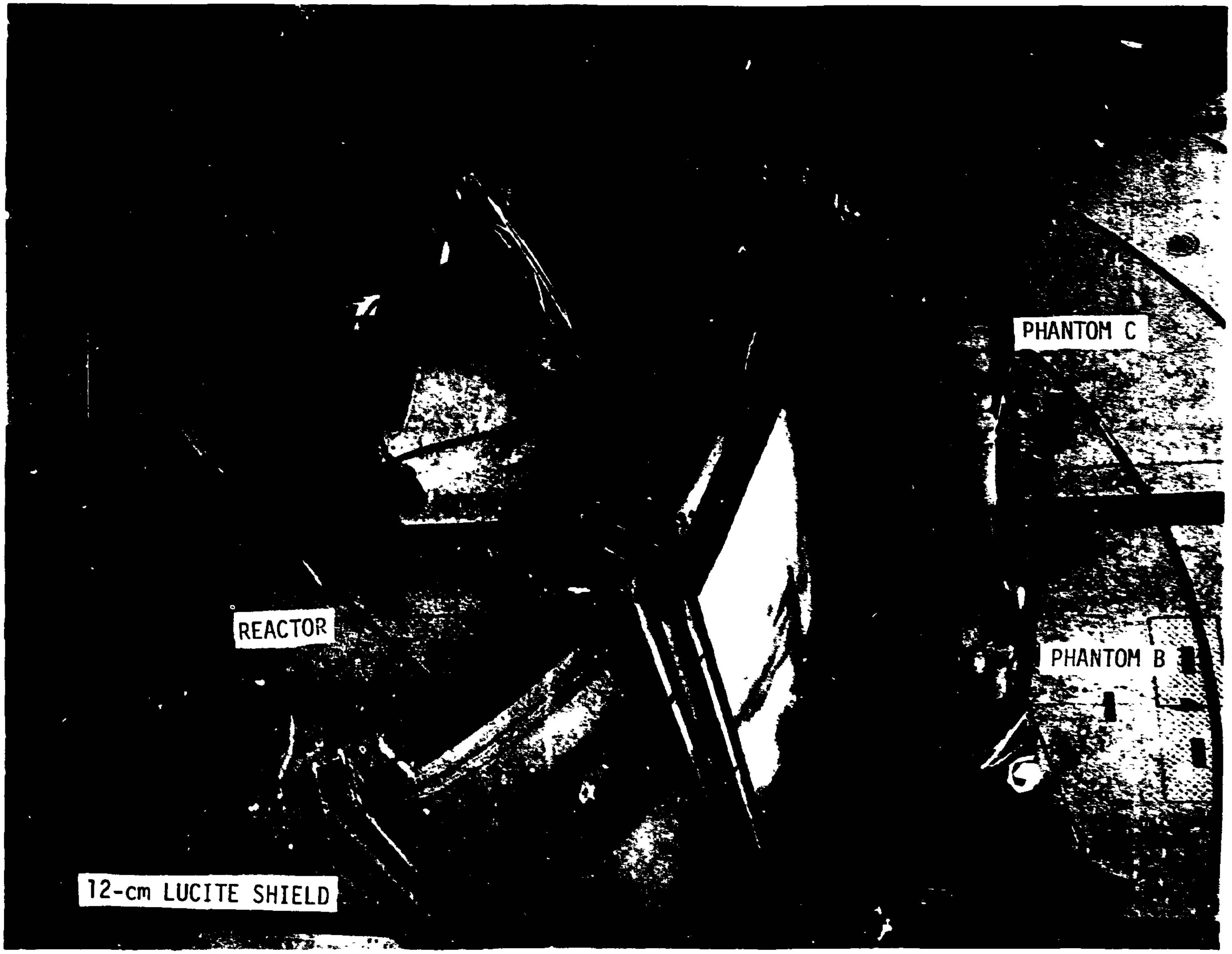

Fig. 3. Experimental arrangement for pulse No. 3 (12-cm Lucite shield).

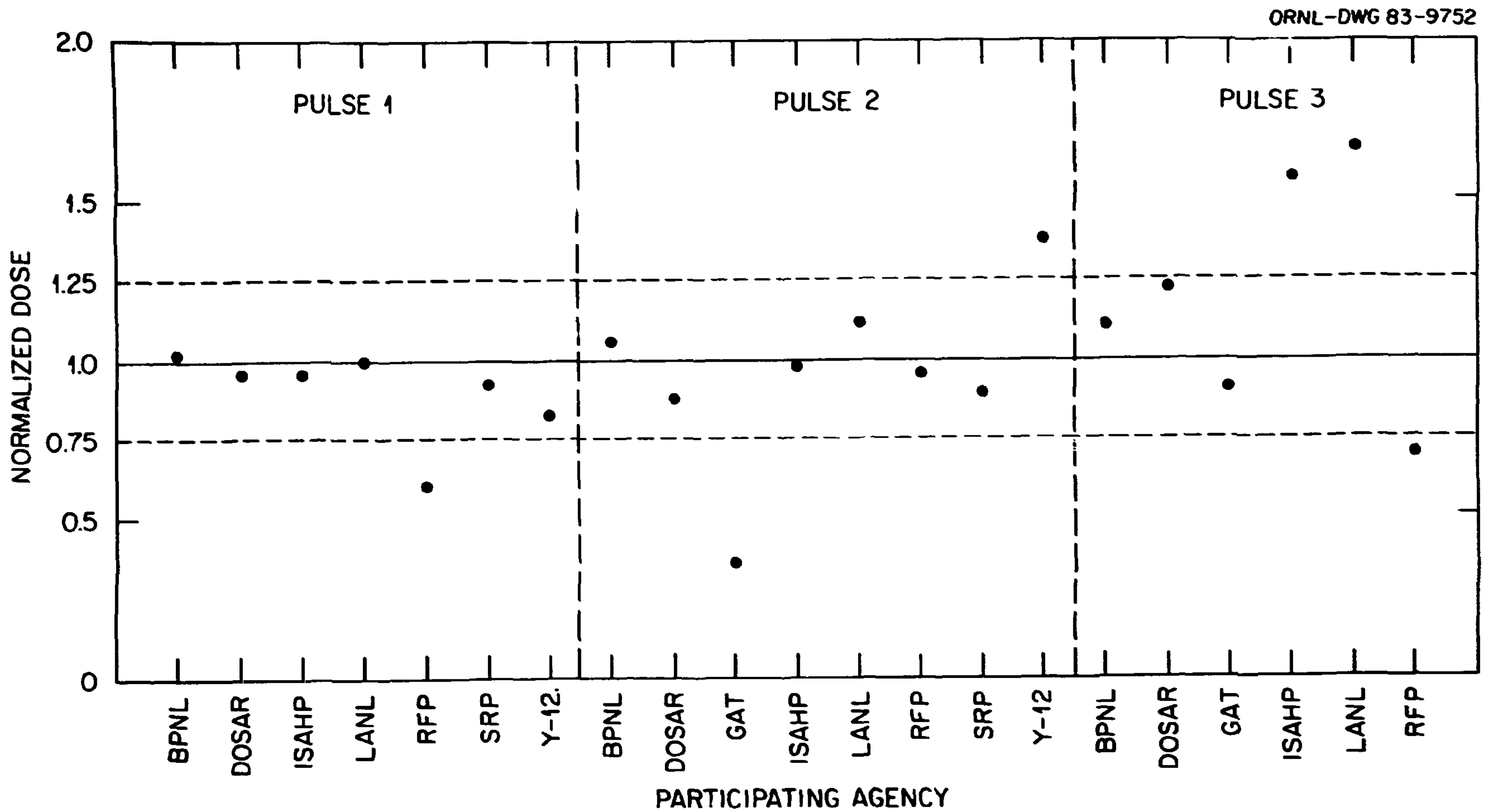

Fig. 4. Neutron dose measurements at air stations divided by the reference doses for each of the three pulses. Regulatory guidelines for neutron dose accuracy are shown as dashed lines.

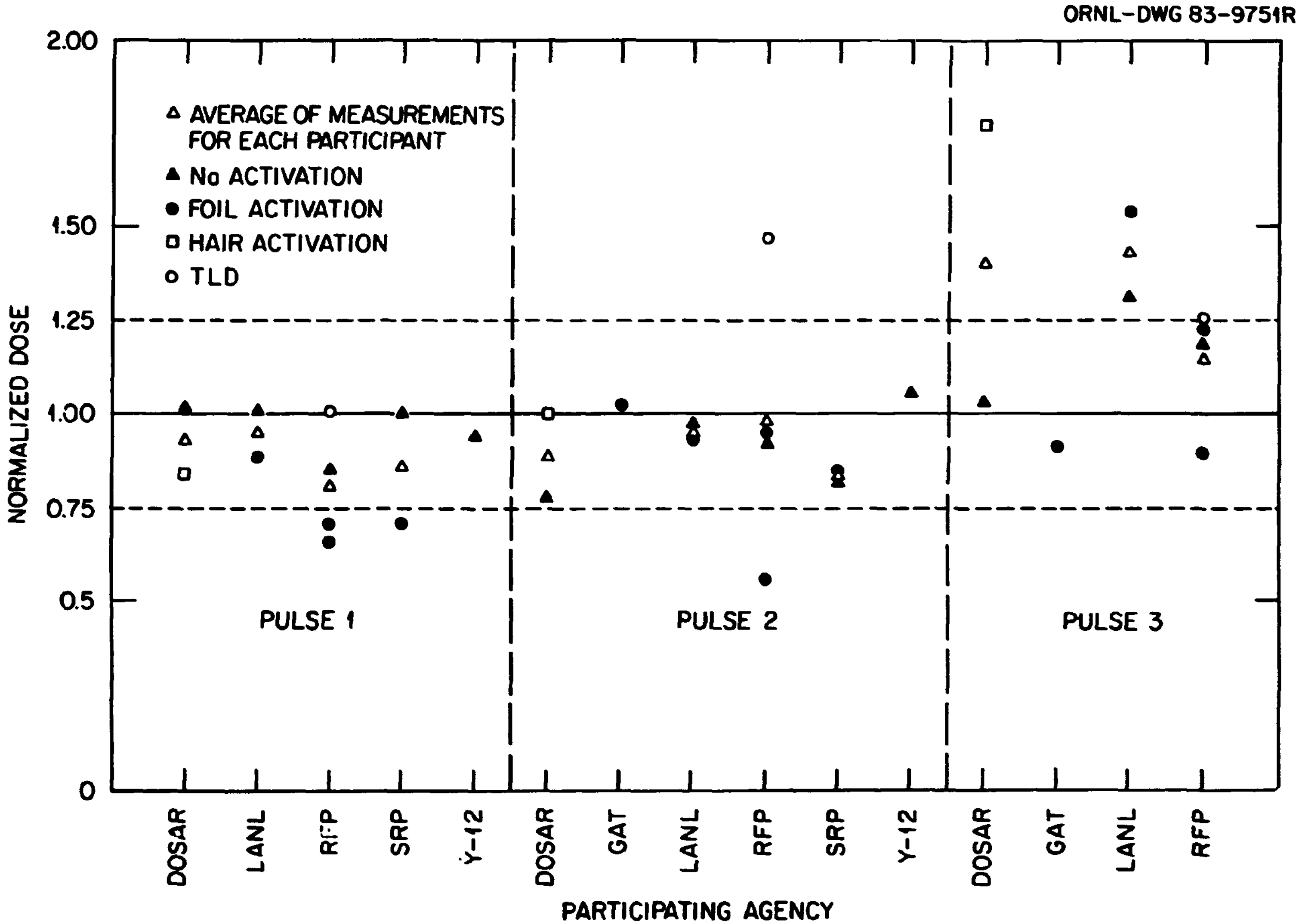

Fig. 5. Neutron dose measurements on phantoms divided by the reference doses for each of the three pulses. Regulatory guidelines for neutron dose accuracy are shown as dashed lines.

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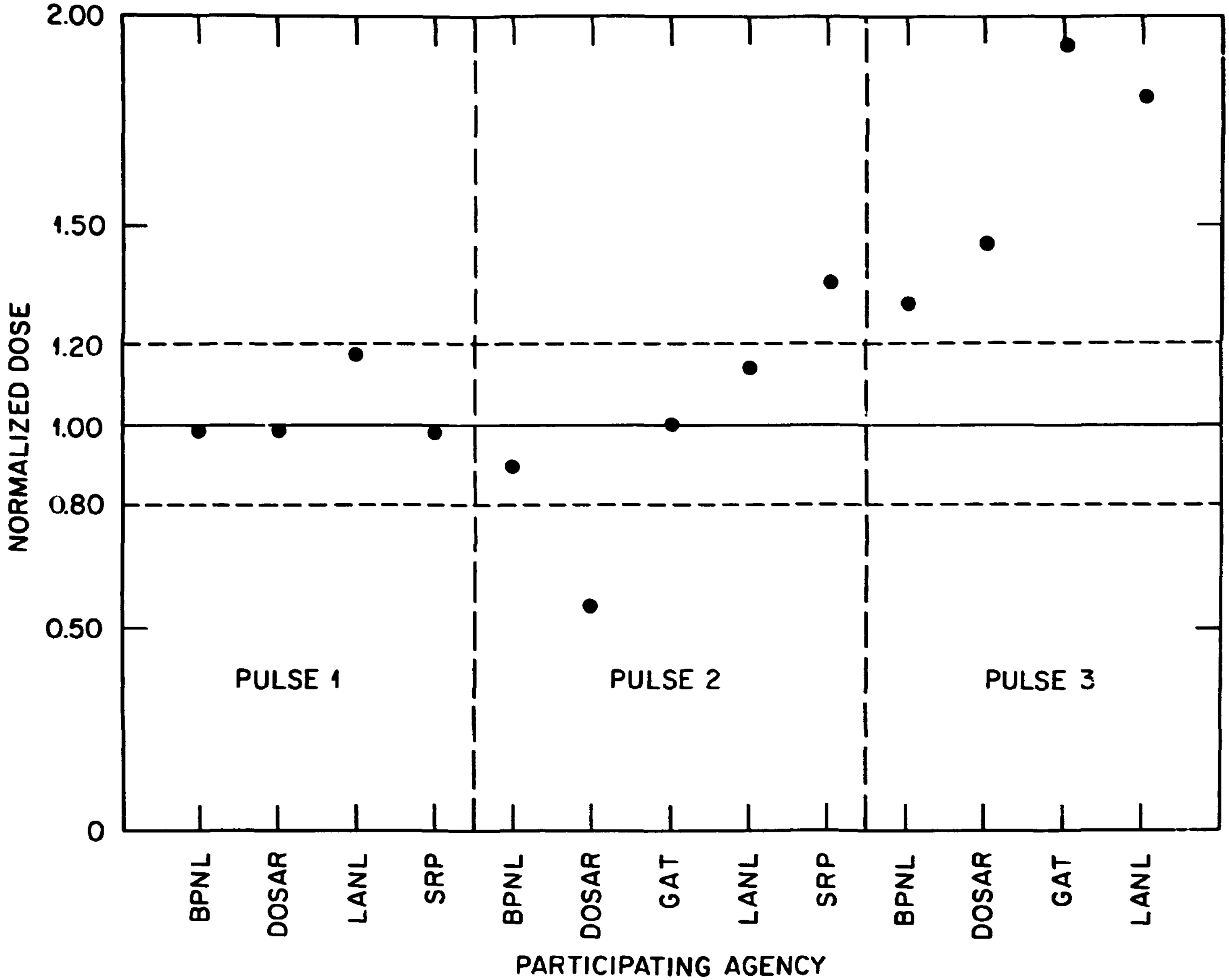

Fig. 6. Gamma dose measurements at air stations divided by the reference doses for each of the three pulses. Regulatory guidelines for gamma dose accuracy are shown as dashed lines.

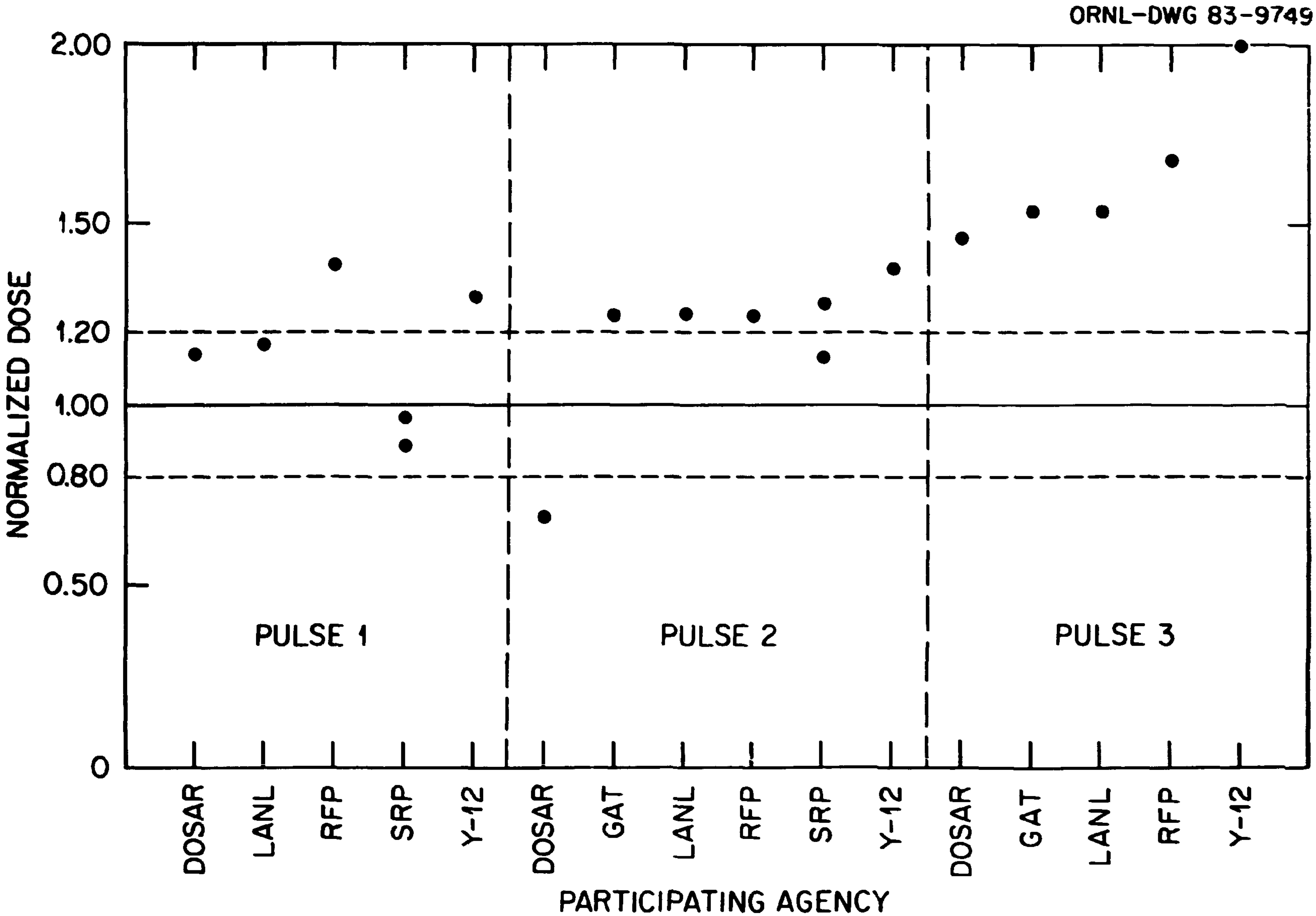

Fig. 7. Gamma dose measurements on phantoms divided by the reference doses for each of the three pulses. Regulatory guidelines for gamma dose accuracy are shown as dashed lines.

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APPENDIX A

PROGRAM

NINETEENTH NUCLEAR ACCIDENT DOSIMETRY INTERCOMPARISON STUDY

August 9-13, 1982

Date	Time	Activity
August 9	9:00 AM	Welcome, P. S. Rohwer (ORNL)
	9:15	Orientation, C. S. Sims (ORNL)
	9:30	Review of Nuclear Accident Dosimetry Intercomparison Program R. E. Swaja (ORNL)
	10:00	Tour of Control Room and Reactor Building
		LUNCH
	1:00 PM	Lecture: *Nuclear Accident Dosimetry* - R. E. Swaja (ORNL)
	2:00	Lecture: *Application of Neutron Activation Principles to Nuclear Accident Dosimetry* - R. T. Greene (ORNL)
	3:00	Preparation for Pulse No. 1
August 10	8:00 AM	Final setup of dosimetry for Pulse No. 1
	9:00	Observation of pulse operation of HPRR
	10:00	Pulse No. 1 (unshielded)
	10:30	Group photograph
	11:00	Collect dosimeters
		LUNCH
	1:00 PM	Lecture: *Radiation doses Due to Nuclear Accidents* - C. S. Sims (ORNL)
	2:00	Analysis of data and preparation for Pulse No. 2 - Demonstration of blood sodium activation analysis

Date	Time	Activity
August 11	8:00 AM	Final setup of dosimeters for Pulse No. 2
	9:00	Review of participant dosimetry system- R. W. Martin (Los Alamos National Laboratory)
	10:00	Pulse No. 2 (20-cm concrete shield)
		Lecture: *Fundamentals of Criticality Safety* - C. M. Hopper (Y-12)
	11:00	Collect Dosimeters
		LUNCH
	1:00 PM	Lecture: *Determination of Radiation Dose Based on Chromosome Aberrations* L. G. Littlefield (ORAU)
	2:00	Analysis of data and preparation for Pulse No. 3 - Demonstration of hair activation analysis
August 12	8:00 AM	Final setup of dosimeters for Pulse No. 3
	9:00	Review of participant dosimetry system - W. H. Carlton and C. D. Strain (Savannah River Plant)
	9:30	Review of Participant dosimetry system - J. M. Aldrich (Rockwell International - Rocky Flats Plant)
	10:00	Pulse No. 3 (12-cm Lucite shield)
		Discussion: Requirements and problems associated with nuclear accident monitoring at participating facilities.
	11:00	Collect dosimeters
		LUNCH
	1:00 PM	Lecture: *Medical Aspects of Radiation Accidents* - K. F. Hubner (ORAU)

Date	Time	Activity
August 12	2:00 PM	Analysis of data
	7:00	Dinner at the Steak and Ale Restaurant in West Knoxville
August 13	9:00 AM	Discussion: Reporting final doses for analysis of intercomparison study results - C. S. Sims and R. E. Swaja (ORNL)
	9:30	Presentation of preliminary dose estimates and discussion of results
	10:30	Final Critique

APPENDIX B

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