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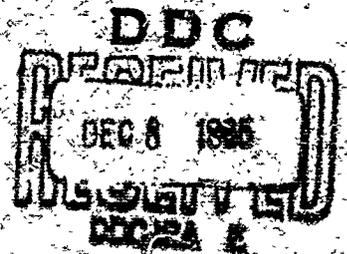
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EARLY PERFORMANCE DECREMENT IN PRIMATES  
FOLLOWING PULSED IONIZING RADIATION

EDWARD A. RICE, Captain, USAF

August 1965



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**EARLY PERFORMANCE DECREMENT IN PRIMATES FOLLOWING  
PULSED IONIZING RADIATION**

**EDWARD A. RICE, Captain, USAF**

## FOREWORD

This report was prepared in the Radiobiology Branch under task No. 571002. The paper was submitted for publication on 11 June 1965. The work was accomplished in 1965.

The experiments reported herein were conducted according to the "Principles of Laboratory Animal Care" established by the National Society for Medical Research.

The author wishes to express his appreciation to J. W. Poston of the Health Physics Division of the Oak Ridge National Laboratory for his assistance during this investigation and to John C. Mitchell and Kenneth A. Hardy of the USAF School of Aerospace Medicine for their invaluable comments and assistance.

This report has been reviewed and is approved.

*Harold V. Ellingson*  
HAROLD V. ELLINGSON  
Colonel, USAF, MC  
Commander

## ABSTRACT

A procedure to determine the early effects of ionizing pulsed radiation on primates is described in detail. Data were collected, before and after exposure to approximately 12,000 rads, on ten adult male primates (*Macaca mulatta*) trained in a shock-avoidance behavioral conditioning paradigm. Fatigability and performance efficiency were the two parameters tested. The primates were unable to perform a learned task (i. e., pulling a ring in response to a visual or auditory cue) after exposure to 12,000 rads (performance decrement). The onset time of the performance decrement varied from 1 to 3 minutes after the total dose was delivered, and the duration of the performance decrement varied from 5 to 70 minutes. All animals experienced fatigue during their postexposure work periods. The importance of the rate at which ionizing radiation is delivered—relative to (1) onset time of the decrement, (2) duration of the decrement, (3) severity of the decrement, and (4) homogeneity of biologic effects—is discussed.

## EARLY PERFORMANCE DECREMENT IN PRIMATES FOLLOWING PULSED IONIZING RADIATION

### I. INTRODUCTION

The first studies of radiation-induced performance decrement were conducted in 1952 (1), and there have been few investigations in this area since that time (2-9). The results of these studies indicated radiation produces a state of hyperactivity followed by debilitation and that these manifestations occur 1 to 3 minutes and 3 to 8 minutes, respectively, after delivery of the total radiation dose. Debilitation occurred with doses as low as 3,000 rads. Debilitation and hyperactivity are relative terms, and the exact meaning can be realized

only with reference to a specific task. In the past and present studies, debilitation was measured by the inability of the primate to perform a learned task within his established control values.

The minimum time in which the total radiation dose was delivered in the most recent study (9) was 25 msec. The delivery rate of nuclear weapons, however, is in the order of microseconds; therefore, if adequate assessment of the biologic effects resulting from such detonations is to be realized, it is imperative that we study these effects using a radiation source

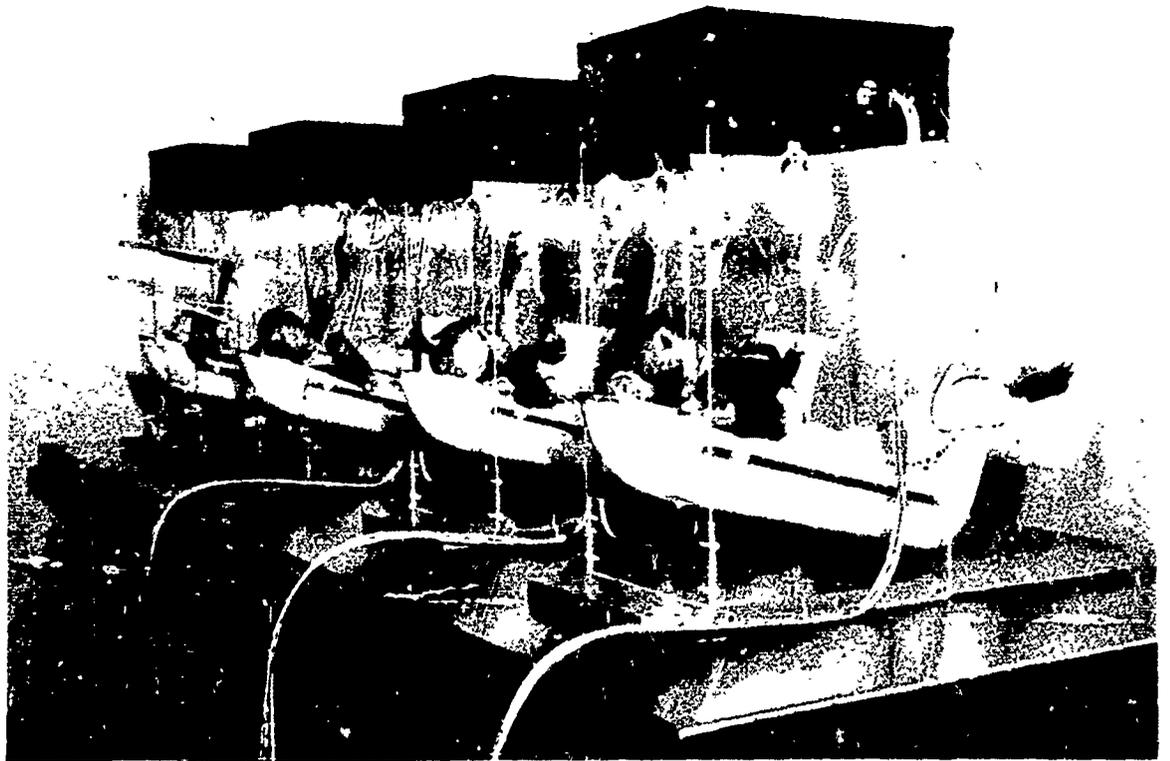


FIGURE 1

*Shock avoidance behavioral conditioning apparatus.*

that delivers its total radiation dose in microseconds. This study was designed to determine the early onset (within 5 minutes postexposure) of biologic effects resulting from exposure to mixed gamma and neutron radiation delivered in microseconds.

## II. METHODS

Ten adult male primates (*Macaca mulatta*), weighing 6 to 8 pounds each, were used.

### Training apparatus and technic

The apparatus used to train the primates to respond to a visual or auditory stimulus is illustrated in figure 1. Each animal was held securely in a couch, and the couch was placed in a psychomotor training apparatus. The training apparatus contained rings, which were in easy reach of the animal, and a cue-light or cue-speaker. An electrode attached to the

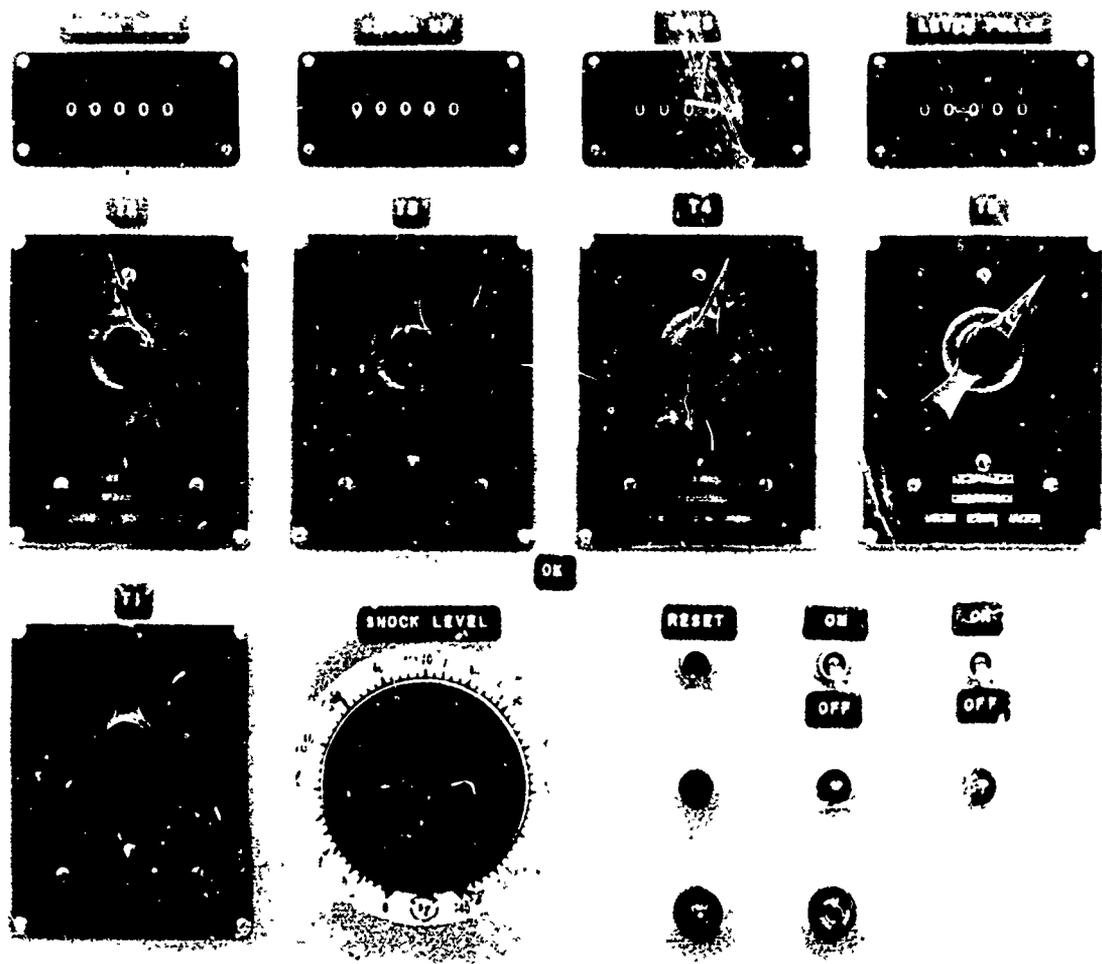


FIGURE 2

Training schedule panel. Shock-down counter indicates a shock when the animal holds the lever down for a period greater than that indicated by relay timer T2. T3 indicates the time required to pull the lever before a shock up is registered. The number of cues and lever pulls are registered. T4 is in series with T1 and prevents the resetting of T1. T1 indicates the interstimulatory period. Shock level is controlled by a variable transformer. T5 is in series with T2 and provides a shock for responses during the interstimulatory period.

primate's leg was used to deliver a current of 0.5 ma. A headholier attached to the training apparatus held the animal's head in a position advantageous to viewing the visual cue. A speaker attached to the training apparatus delivered sound to the primate. A panel displayed the number of stimuli delivered, the number of lever pulls made by the primate, and the number of shocks the primate received (fig. 2).

After the animal was properly placed in the training apparatus, the cue-presentation circuit was activated and the animal was presented a visual or auditory cue. The cue circuit remained activated until the animal pulled the ring. If the animal did not pull the ring within 6 seconds, a shock circuit was activated and the animal received a shock (0.5 ma.) that was

terminated either by the animal's pulling the ring or (after 2 seconds) by a monitor. The primate was considered fully trained when he avoided the shock 100% of the time in a work period. All primates used in this study were fully trained before being exposed to radiation.

The training diagrams demonstrate possible behavioral patterns.

#### Reactor facility

The health physics research reactor located at Oak Ridge National Laboratory, Oak Ridge, Tenn., was used (10). The reactor core with two animals in position is shown in figure 3.

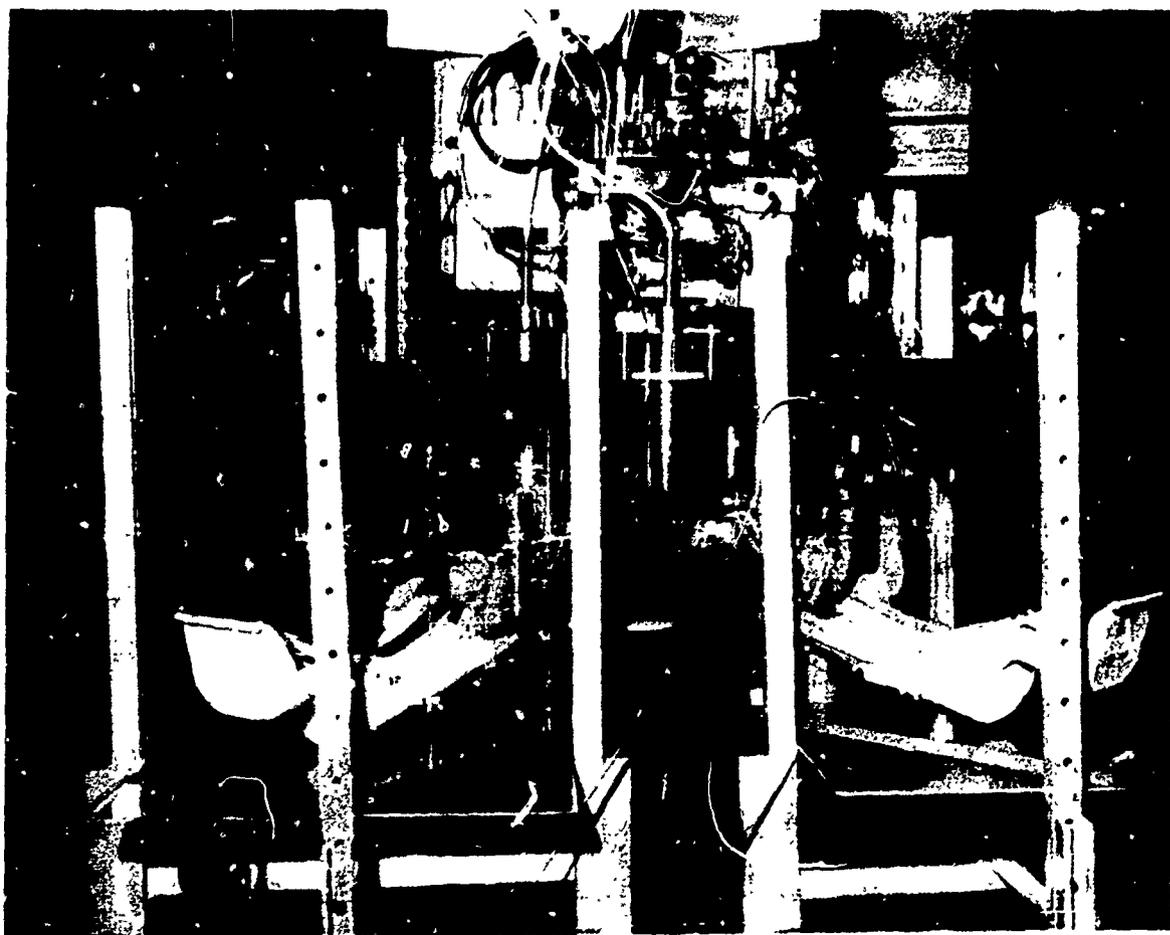
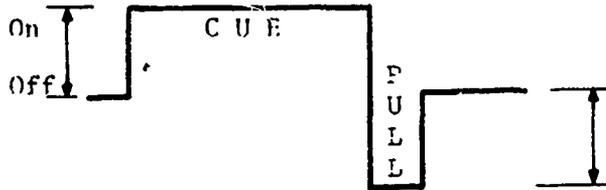


FIGURE 3

*Reactor with two primates in position.*

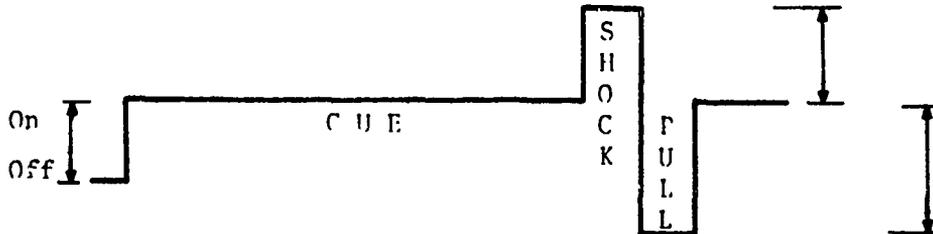
Training diagrams

1. Correct positive response:



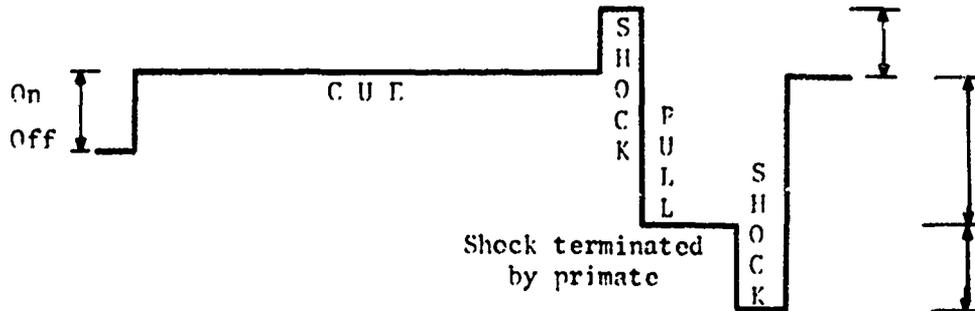
Visual or auditory stimulus terminated by primate

2. Nonavoidance. Escaping shock. Releasing ring:



Shock terminated by primate

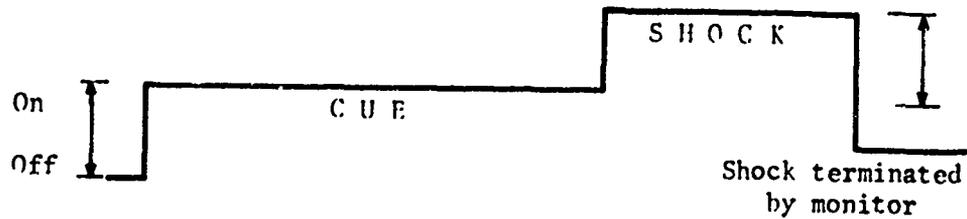
3. Nonavoidance. Escaping shock. Failure to release ring:



Shock terminated by primate

2d shock ring held too long

4. Nonavoidance. Failure to escape shock:



Shock terminated by monitor

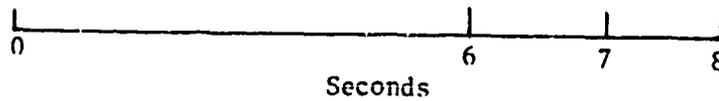


TABLE I  
Exposure schedule and dose level

Pulse No.	Date	Run No.	Reactor height	Power level	Dose at 40 cm. from center of core	Animal No.
1	17 Mar. 65	B65	1.25 m.	$6.00 \times 10^{16}$ fissions	12,117 r neutrons	G (R-33) H (S-33)
2	17 Mar. 65	B66	1.25 m.	$6.27 \times 10^{16}$ fissions	12,670 r neutrons	I (R-43)
3	17 Mar. 65	B67	1.25 m.	$6.42 \times 10^{16}$ fissions	12,974 r neutrons	J (R-47)
4	18 Mar. 65	B68	1.25 m.	$5.42 \times 10^{16}$ fissions	10,945 r neutrons	D (R-27) C (R-53)
5	18 Mar. 65	B69	1.25 m.	$5.61 \times 10^{16}$ fissions	11,329 r neutrons	E (R-57) F (U-46)
6	19 Mar. 65	B70	1.25 m.	$4.50 \times 10^{16}$ fissions	9,100 r neutrons	A (U-68) B (R-49)

#### Dosimetry

The nuclear radiation measurements that were used to estimate the neutron dose received by each primate were provided by Oak Ridge Laboratory personnel; a standard system was used to determine the total neutron doses (11). A Hurst threshold detector unit (containing  $\text{Pu}^{239}$ ,  $\text{Np}^{237}$ ,  $\text{U}^{235}$ , and  $\text{S}^{32}$  threshold detectors inside a  $\text{B}^{10}$  ball plus bare  $\text{S}^{32}$  pellets) was used to determine the neutron fluence ( $\phi$ ) and the first collision neutron dose (D). The first collision neutron doses as presented in table I were determined from the formula:

$$D = [1.4 (\phi_{\text{fm}} - \phi_{\text{m}}) + 2.4 (\phi_{\text{fp}} - \phi_{\text{f}}) + 3.0 (\phi_{\text{u}} - \phi_{\text{s}}) + 3.8 (\phi_{\text{s}})] \times 10^{-9}$$

Where the coefficients represent the average dose per neutron for the various energy regions weighted to a fast fission spectrum of neutron energies, the neutron fluence was determined from the formula:

$$\phi = \frac{(\gamma \text{CR}_f) \times \text{PF} \times 10^{10}}{(\gamma \text{CR}) \times \text{Wt}}$$

Where

$\phi$  = neutron fluence (n/cm.<sup>2</sup>) above a certain threshold energy E:

$\text{CR}_f$  = gamma count rate of the detector foil,

$\text{CR}$  = gamma count rate per gram per  $10^{10}$  n/cm.<sup>2</sup> above the threshold energy E,

Wt = weight of detector foil in grams,

PF = perturbation factor of  $\text{B}^{10}$  ball,

the neutron-to-gamma ratio was 7 to 1.

The details of each exposure are given in table I.

#### Performance efficiency and fatigability measurements

The animal's mean reaction time to 100 stimuli was used to measure performance efficiency, and the minimum and maximum mean reaction ranges were used to establish normal control limits. The mean reaction time of each response (i. e., all first responses, tenth responses, etc., over 10 or more work periods) was used to indicate the fatigue factor.

#### Data acquisition

*Work period.* Ten primates were identified with letters A through J. One hundred visual or auditory stimuli were presented to each animal in each work period. The response to each stimulus was recorded as the time required for animals A through J to respond after receiving the stimulus and was designated

$X_{A,1-100}^1$ ,  $X_{B,1-100}^1$ , and so forth. This resulted in 100 numeric values per animal per work period.

ANIMAL NO. A (R-33)

Response 1 thru 100	Work Periods (1 thru 10)										Fatigue Factor
	1	2	3	4	5	6	7	8	9	10	
1	$X_{A_1}^1$	$X_{A_1}^2$	$X_{A_1}^3$	$X_{A_1}^4$	$X_{A_1}^5$	$X_{A_1}^6$	$X_{A_1}^7$	$X_{A_1}^8$	$X_{A_1}^9$	$X_{A_1}^{10}$	$\bar{X}_{A_1} = \frac{\sum X_{A_1}^{1-10}}{10}$
100	$X_{A_{100}}^1$	$X_{A_{100}}^2$	$X_{A_{100}}^3$	$X_{A_{100}}^4$	$X_{A_{100}}^5$	$X_{A_{100}}^6$	$X_{A_{100}}^7$	$X_{A_{100}}^8$	$X_{A_{100}}^9$	$X_{A_{100}}^{10}$	$\bar{X}_{A_{100}} = \frac{\sum X_{A_{100}}^{1-10}}{10}$
	$\bar{X}_{A_{100}}^1$	$\bar{X}_{A_{100}}^2$	$\bar{X}_{A_{100}}^3$	$\bar{X}_{A_{100}}^4$	$\bar{X}_{A_{100}}^5$	$\bar{X}_{A_{100}}^6$	$\bar{X}_{A_{100}}^7$	$\bar{X}_{A_{100}}^8$	$\bar{X}_{A_{100}}^9$	$\bar{X}_{A_{100}}^{10}$	$\bar{\bar{X}}_{A_{1-100}} = \frac{\sum \bar{X}_{A_{1-100}}}{10}$
	Range of Baseline Data										Mean of Baseline Data

FIGURE 4

An example of the method used to reduce data from preirradiated work periods of animal No. A (R-33). X = numeric value; A = animal's designation; 1-10 = work period; 1-100 = response per work period. Example:  $X_{A_1}^1$  is the numeric value for work period No. 1, response No. 1, of animal A. The mean of means ( $\bar{\bar{X}}$ ) and the upper and lower ranges represent preirradiation performance efficiency data.

**Baseline data.** Preirradiation baseline data were collected over 10 work periods. Each animal had 1,000 raw data points during this period (i.e., 10 points per period for 10 periods). The raw data points were entered in a matrix with 100 rows of 10 elements in each row. Each animal was his own control; therefore, no attempt was made to cross-reference the data. Figure 4 illustrates the simple matrix system used. Raw data points for 100 responses for animal number A are displayed vertically, and the work periods 1 through 10 are displayed horizontally.

### III. RESULTS

#### Performance efficiency and fatigability

The performance efficiency and fatigability curves are illustrated in figures 5 through 14. Pre-exposure and postexposure mean reaction values are plotted in milliseconds for each animal. An increase in reaction time beyond the pre-exposure control limits was observed for each animal after the pulse. The duration of the performance decrement (i.e., increase in reaction time beyond established control limits)

TABLE II

*Fatigability and performance efficiency*

Animal No.	Dose (rads)	Fatigue at response No.	Performance decrement onset (min.)	Performance decrement duration (min.)	Second decrement onset (min.)
A (U-68)	9,100	20	1	21	56
B (R-49)	9,100	20	1	16	—
C (R-53)	10,945	20	1	Observation period	—
D (R-27)	10,934	20	1	5	57
E (R-57)	11,329	30	3	9	—
F (U-46)	11,329	20	2	31	52
G (R-33)	12,117	20	1	Observation period	—
H (S-33)	12,117	10	3	Observation period	—
I (R-43)	12,670	4	1	31	35
J (R-47)	12,974	10	1	Observation period	—

was not constant; however, the general indication is that the duration increases with increased dose. The duration of the performance decrement was 5 minutes through the end of the observation period. A decrease in reaction immediately following exposure, "facilitory effect," was not observed. Nine out of the ten animals continued to respond to shock after exposure; however, animal No. H (S-33) did not respond to shock or to the visual stimulus after being exposed. In general, the performance decrement effect was consistent from animal to animal. All animals died within 24 hours postirradiation.

ANIMAL U-68 (9,100r)

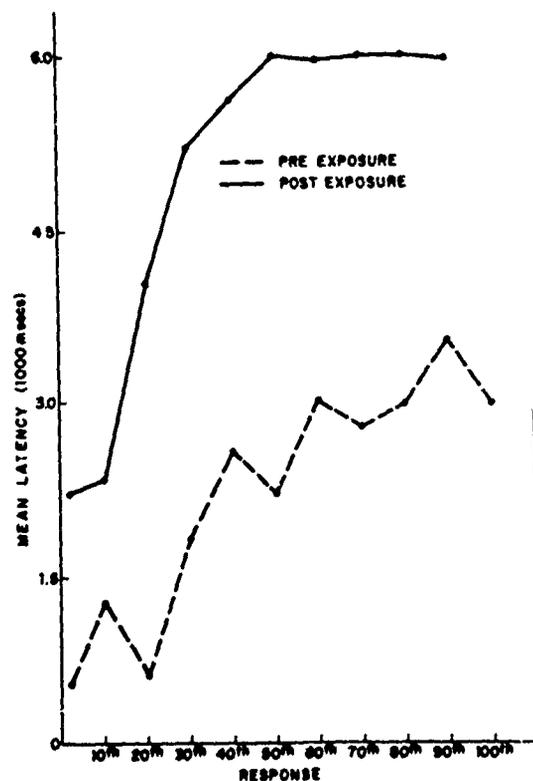


FIGURE 5A

The effects of pulsed ionizing radiation on the fatigability of a primate receiving 9,100 rads in 25  $\mu$ sec. Note the sharp increase in reaction time at the twentieth response.

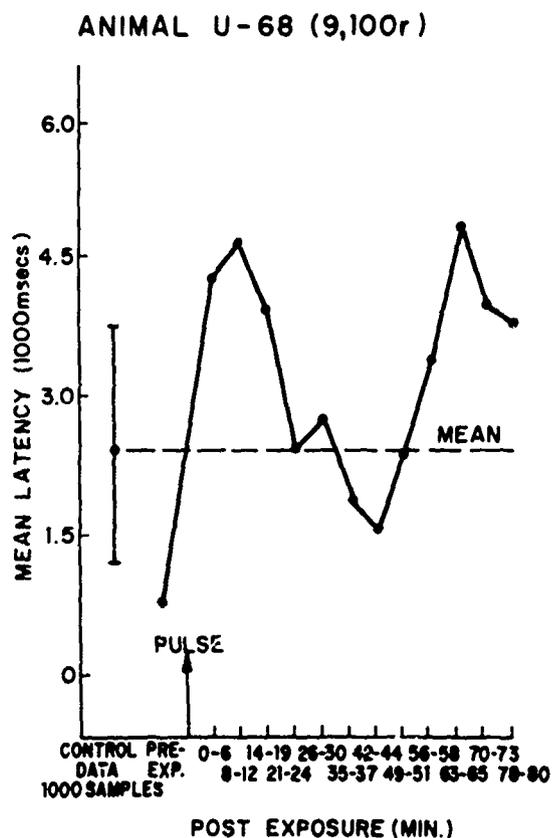


FIGURE 5B

The effects of pulsed ionizing radiation on the performance efficiency of a primate receiving 9,100 rads. Control data show the upper and lower ranges and the mean. Animal showed a performance decrement 1 minute postirradiation.

Also illustrated in these figures are the mean reaction time response periods of each animal. The question asked here is: How fast does the animal respond to each of the stimuli over many work periods? The postirradiation control data curve indicates the animals responded generally slower to the hundredth stimulus in a series than to the first. The fatigability curve postirradiation indicates the animals generally were fatigued after the twentieth stimulus. Fatigability and performance efficiency statistics are presented in table II.

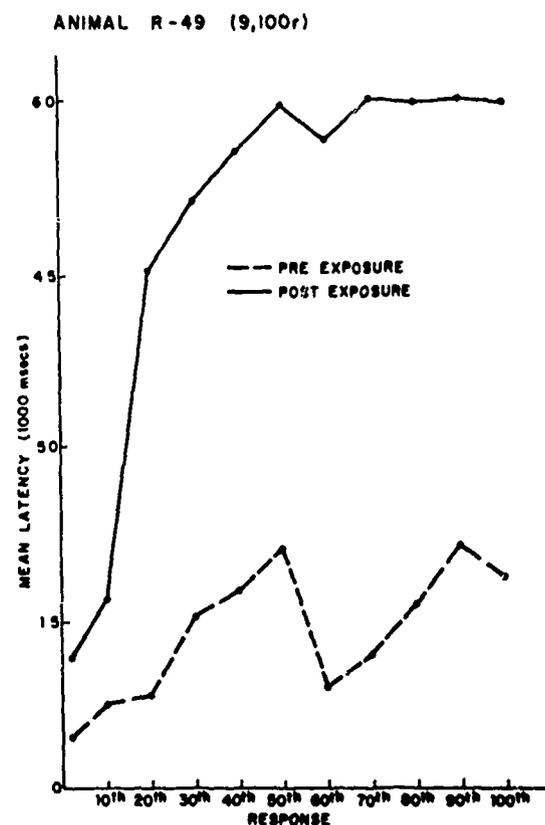


FIGURE 6A

Fatigue as a function of mean reaction time every tenth response.

#### Exposure to 9,100 rads

*Animal No. A (U-68).* Figure 5A illustrates the fatigability curve for this animal. At the twentieth response in postexposure work periods, the animal's reaction time increased sharply. Figure 5B illustrates the performance efficiency curve with control data consisting of the upper-lower mean reaction limits and the mean of means ( $\bar{X}$ ). This animal had a performance decrement at 56 minutes postirradiation that persisted throughout the observation period (80 minutes).

*Animal No. B (R-49).* Figure 6A illustrates fatigue at approximately the twentieth response in postexposure work periods. In

ANIMAL R-49 (9,100r)

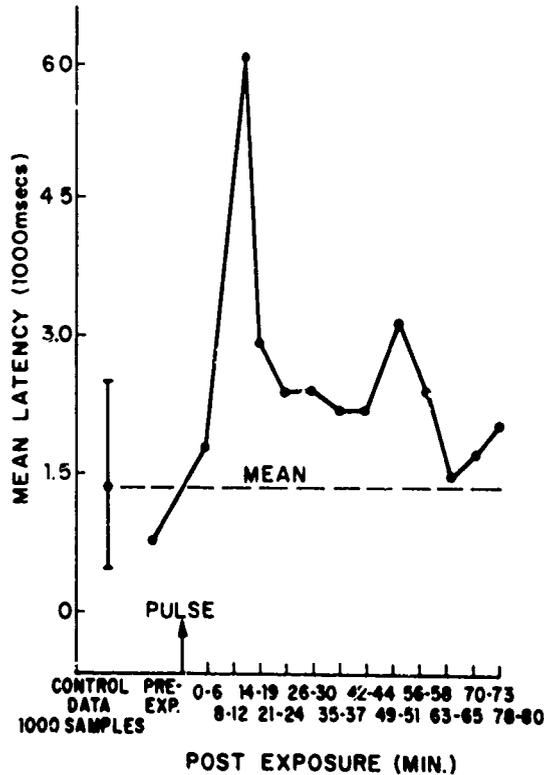


FIGURE 6B

Performance efficiency curve with pre-exposure control data. The pre-exposure mean reaction time was recorded at the reactor site 1 minute prior to pulse. Exposure duration, 25  $\mu$ sec. Note recovery 24 minutes postexposure.

figure 6B, a performance decrement can be noted at 1 minute postexposure, and a return to pre-exposure reaction time can be noted by 24 minutes postexposure.

**Exposure to 10,945 rads**

Animal No. C (R-53). The fatigability curve in figure 7A indicates fatigue at approximately the twentieth response in postexposure work periods. A performance decrement, which remained throughout the observation period, can be noted at 1 minute postexposure in figure 7B.

ANIMAL R-53 (10,945r)

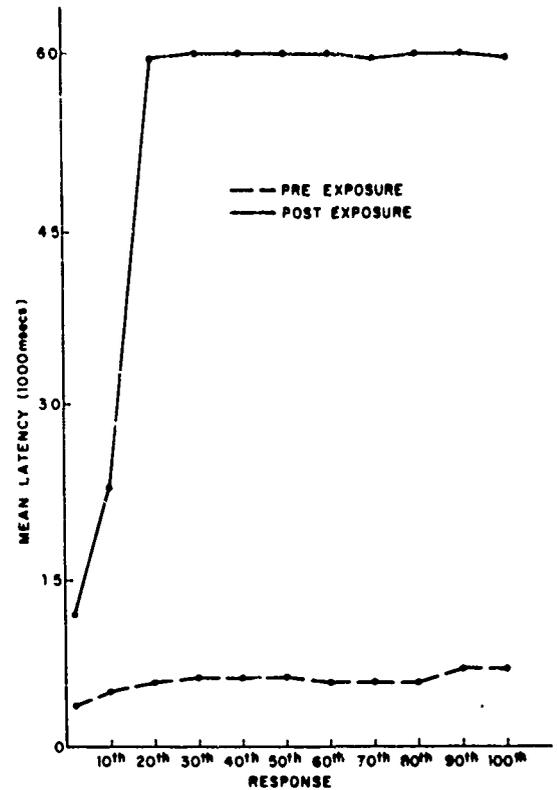


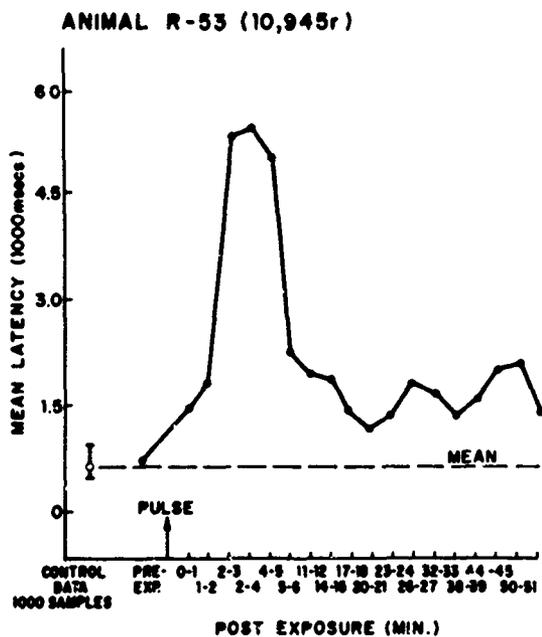
FIGURE 7A

Fatigue as a function of mean reaction time of every tenth response.

Animal No. D (R-27). The fatigability curve in figure 8A indicates fatigue at approximately the twentieth response in postexposure work periods. In figure 8B, the animal's performance efficiency curve indicates a 5-minute performance decrement 1 minute postexposure; a second performance decrement occurred 57 minutes postexposure.

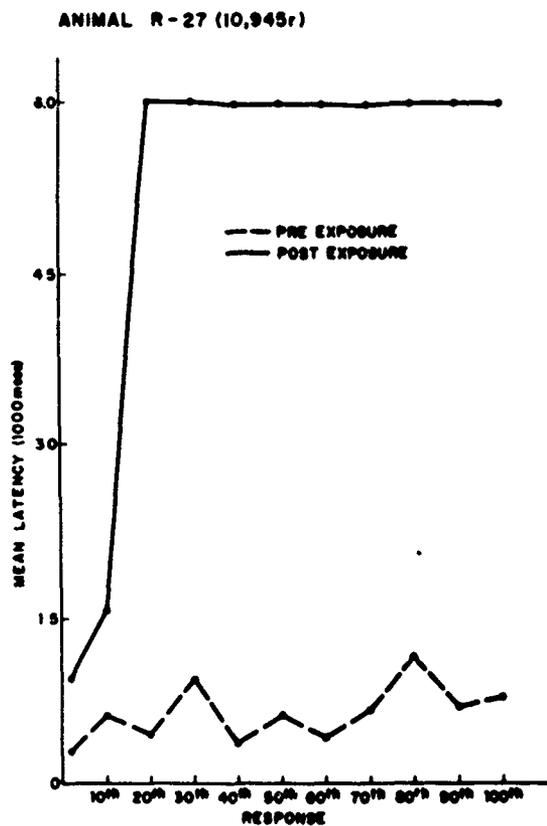
**Exposure to 11,329 rads**

Animal No. E (R-57). Figure 9A illustrates fatigue at approximately the twentieth response in postexposure work periods. In figure 9B, a performance decrement can be noted 3 minutes after the pulse.



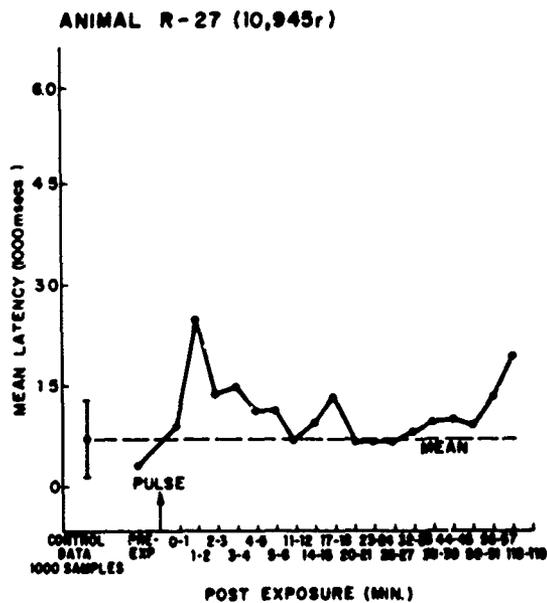
**FIGURE 7B**

Performance efficiency curve with pre-exposure control data. The pre-exposure mean reaction time was recorded at the reactor site 1 minute prior to pulse. Exposure duration, 25  $\mu$ sec. Note partial recovery after 11 minutes.



**FIGURE 8A**

Fatigue as a function of mean reaction time of every tenth response.



**FIGURE 8B**

Performance efficiency curve with pre-exposure control data. The pre-exposure mean reaction time was recorded at the reactor site 1 minute prior to pulse. Exposure duration, 25  $\mu$ sec. Note recovery and second decrement.

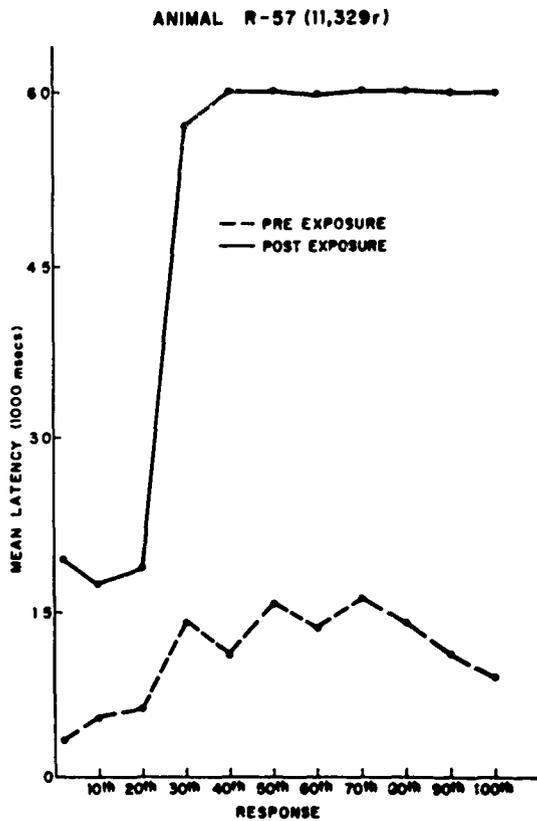


FIGURE 9A

Fatigue as a function of mean reaction time of every tenth response.

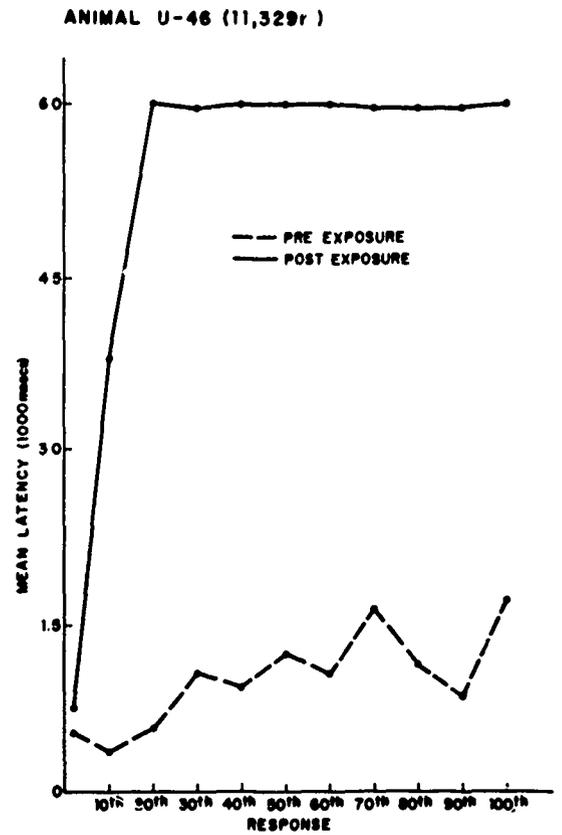


FIGURE 10A

Fatigue as a function of mean reaction time of every tenth response.

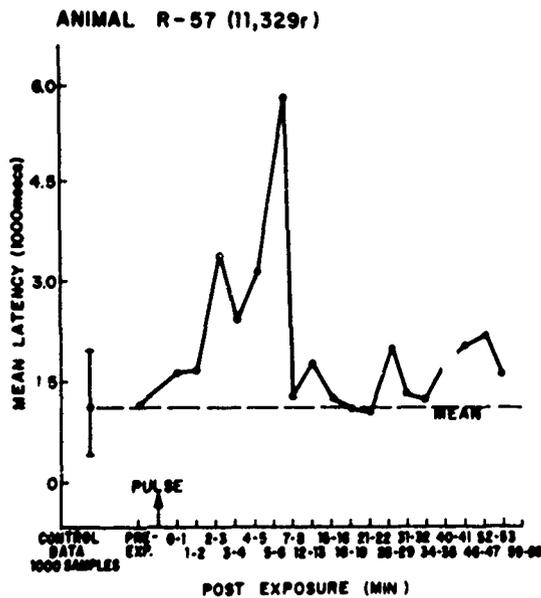
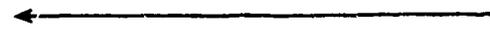


FIGURE 9B

Animal No. F (U-46). The fatigability curve in figure 10A illustrates fatigue at the twentieth response in postexposure work periods. In figure 10B, the performance efficiency curve illustrates a performance decrement at 2 minutes postexposure that persisted for 31 minutes; a second decrement occurred at 52 minutes postexposure.



Performance efficiency curve with pre-exposure control data. The pre-exposure mean reaction time was recorded at the reactor site 1 minute prior to pulse. Exposure duration, 25  $\mu$ sec. Note recovery after 12 minutes.

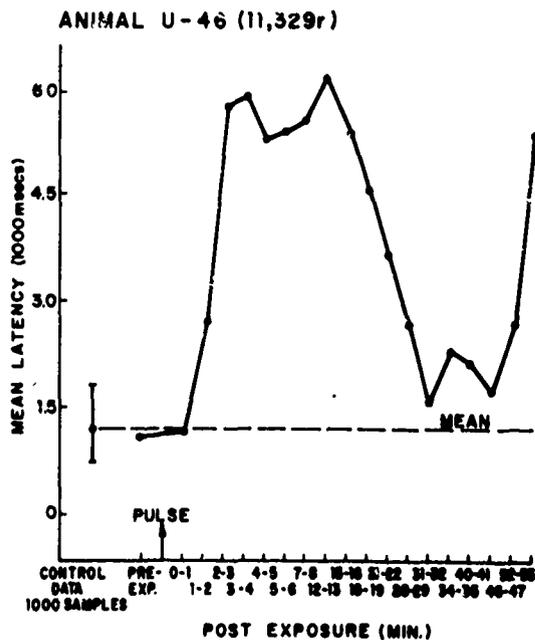


FIGURE 10B

Performance efficiency curve with pre-exposure control data. The pre-exposure mean reaction time was recorded at the reactor site 1 minute prior to pulse. Exposure duration, 25  $\mu$ sec. Note brief recovery at 31 minutes.

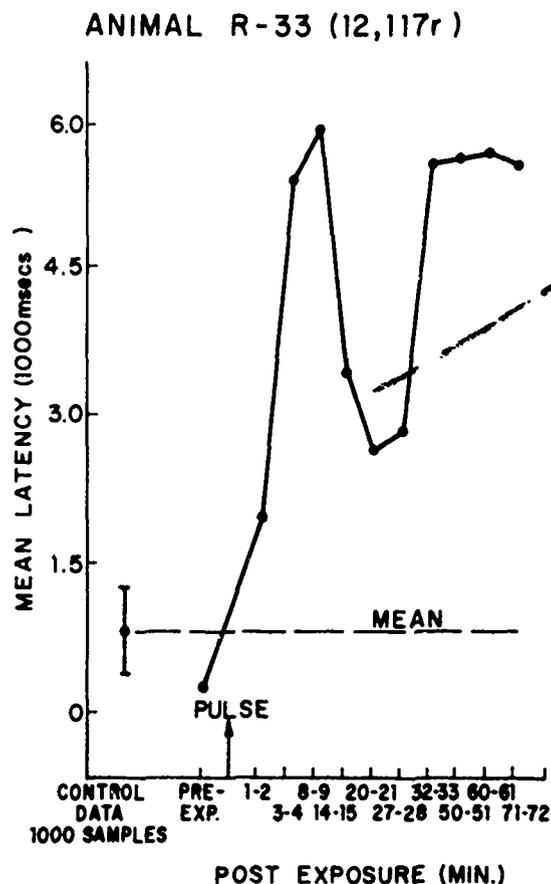
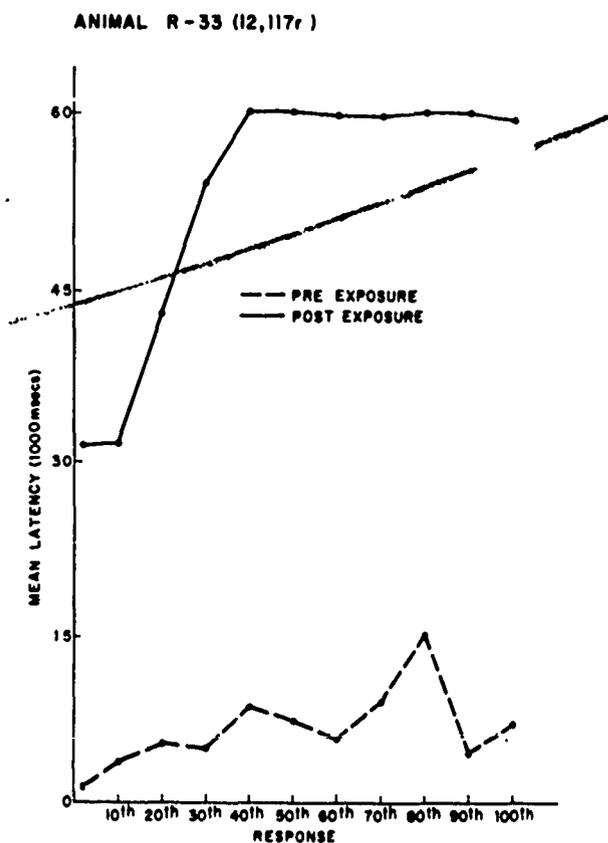


FIGURE 11B

Performance efficiency curve with pre-exposure control data. The pre-exposure mean reaction time was recorded at the reactor site 1 minute prior to pulse. Exposure duration, 25  $\mu$ sec. Note performance decrement persisted throughout observation period.

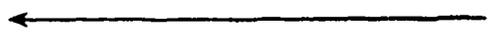


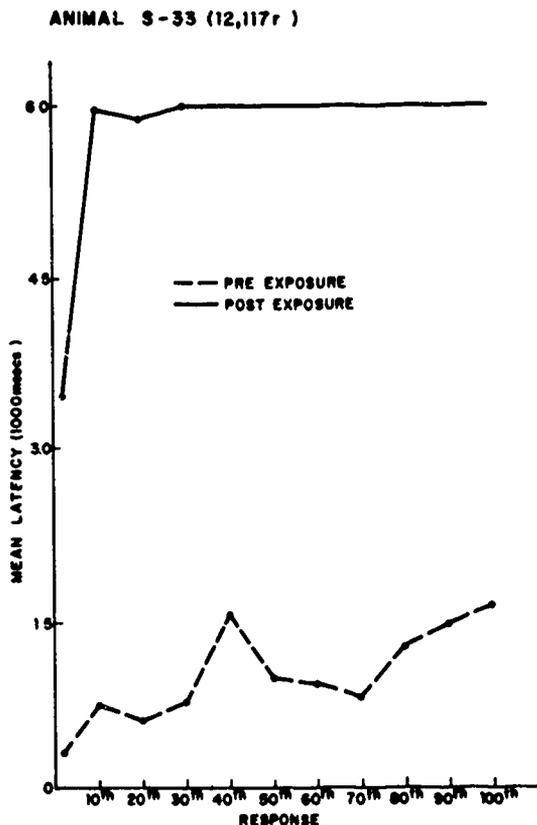
FIGURE 11A

Fatigue as a function of mean reaction time of every tenth response.

**Exposure to 12,117 rads**

*Animal No. G (R-33).* The fatigability curve in figure 11A illustrates fatigue at approximately the twentieth response. The performance efficiency curve in figure 11B illustrates a performance decrement at 1 minute postexposure that persisted throughout the 72-minute observation period.

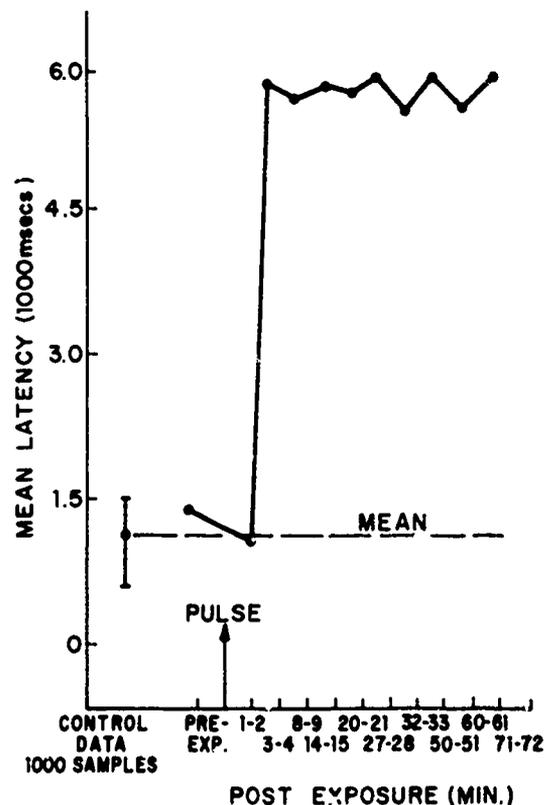
*Animal No. H (S-33).* The fatigability curve in figure 12A illustrates fatigue at approximately the tenth response. The performance efficiency curve in figure 12B illustrates a performance decrement at 3 minutes postexposure that persisted throughout the 72-minute observation period.



**FIGURE 12A**

*Fatigue as a function of mean reaction time of every tenth response.*

**ANIMAL S-33 (12,117r)**



**FIGURE 12B**

*Performance efficiency curve with pre-exposure control data. The pre-exposure mean reaction time was recorded at the reactor site 1 minute prior to pulse. Exposure duration, 25  $\mu$ sec. Note no recovery during observation period. This animal did not respond to shock.*

*Animal No. I (R-43).* The fatigability curve in figure 13A indicates fatigue after the third or fourth response in postexposure work periods. In figure 13B, the performance efficiency curve illustrates a performance decrement 1 minute postexposure that persisted for 50 minutes and a second decrement, occurring at 35 minutes postexposure, that ended 60 minutes later.

**Exposure to 12,974 rads**

*Animal No. J (R-47).* The fatigability curve in figure 14A indicates fatigue at the

ANIMAL R-43 (12,670r)

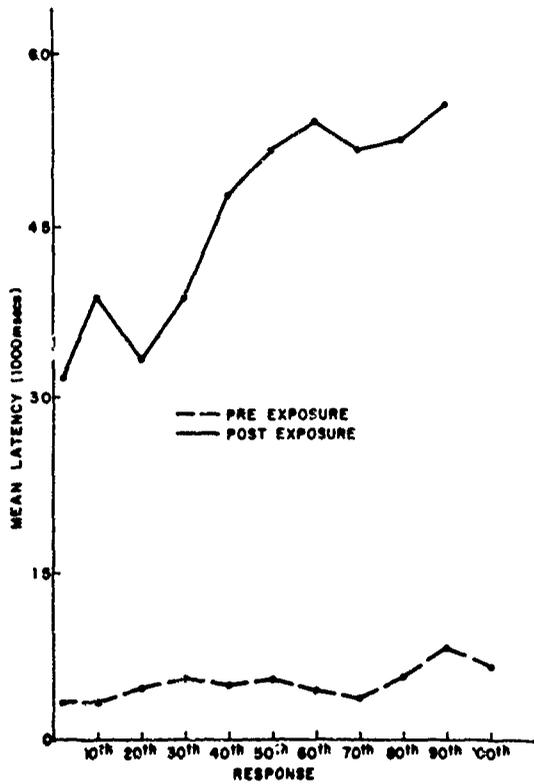


FIGURE 13A

Fatigue as a function of mean reaction time of every tenth response.

ANIMAL R-47 (12,974r)

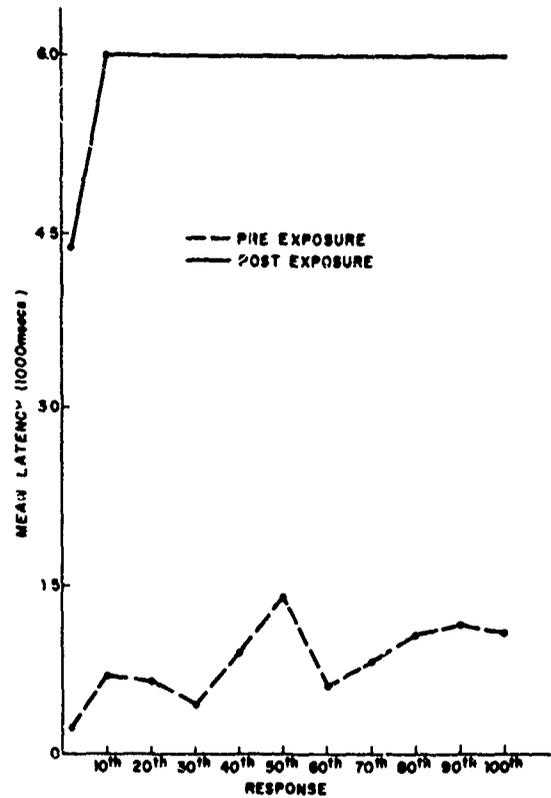


FIGURE 14A

Fatigue as a function of mean reaction time of every tenth response.

ANIMAL R-43 (12,670r)

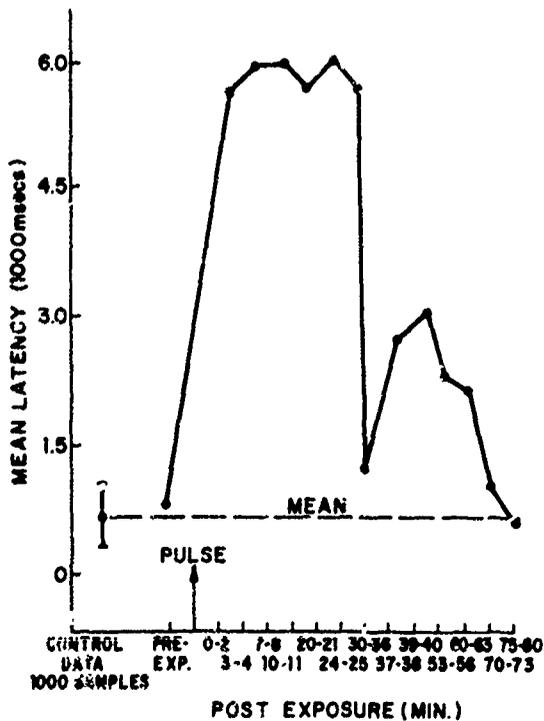


FIGURE 13B

Performance efficiency curve with pre-exposure control data. The pre-exposure mean reaction time was recorded at the reactor site 1 minute prior to pulse. Exposure duration, 25  $\mu$ sec. Note very brief recovery at 50 minutes postexposure and second recovery at 75 minutes postexposure.

tenth response in postexposure work periods. In figure 14B, the performance efficiency curve illustrates a performance decrement at 1 minute postexposure that persisted throughout the 44-minute observation period.

#### IV. DISCUSSION

The data reported here indicate the biologic changes resulting from radiation exposure to be related to dose-rate and to the gamma and neutron ratio; hence, the radiation source used in assessing the biologic effects from atomic detonations should duplicate the rate of radiation delivery expected from such detonations. The data presented in this paper indicate that increasing the rate at which ionizing radiation is delivered to biologic systems will (1) affect the onset time at which behavioral changes will appear; (2) affect the duration of the behavioral changes; (3) decrease the intraspecies variation and produce a more consistent behavioral effect; (4) lower the total dose necessary to produce behavioral changes; and (5) produce a greater behavioral change with lesser total dose.

The questions of importance, when considering the effects of radiation on the performance of military personnel, are: (1) If there is an early performance decrement from exposure to nuclear detonation, then how much corrective action time will there be before the onset of the decrement? (2) What is the duration of the performance decrement? (3) Is recovery sufficiently complete to permit continuation of the mission or the participation in later missions? (4) Are all sensory systems involved in the decrement and, if they are not, can the tasks required of military personnel be designed to use sensory systems less sensitive to ionizing radiation? (5) Can the concept of radiation-induced decrement be used as an offensive weapon? If it can, what is the minimum radiation dose required to produce this effect?

These questions have great military significance in both offensive and defensive use of nuclear weapons. Attempts to answer them by using a radiation source with a delivery rate much greater than that expected from atomic detonations were based on the assumption that

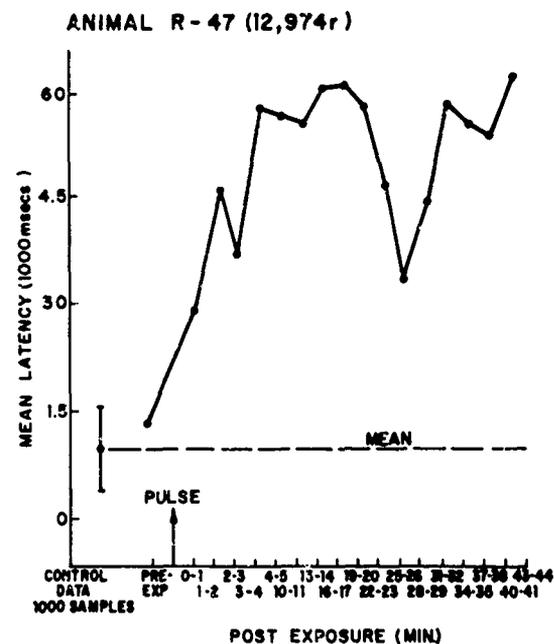


FIGURE 14P

Performance efficiency curve with pre-exposure control data. The pre-exposure mean reaction time was recorded at the reactor site 1 minute prior to pulse. Exposure duration, 25  $\mu$ sec. Note no recovery from decrement.

the rate at which the radiation was delivered was not important in arriving at tolerance figures. Our experimental data indicate that the delivery rate is very important and that the 80,000-rad figure reported as necessary to produce total decrement (12) may be excessive. Even though this investigation did not reveal a figure for total performance decrement, the decrement produced here with approximately 12,000 rads suggests a trend that indicates the figure to be lower than 80,000 rads. The results reported indicate there is produced an early decrement in the performance of a task requiring the visual and auditory systems, and the beginning of which could be sufficiently short to preclude corrective action prior to the onset of the decrement. Further, the duration of this decrement is sufficiently long that it may prohibit successful accomplishment of missions requiring periodic visual and auditory vigilance.

In previous studies, there exists a wide variation in response of primates to radiation

exposure. In this respect, the results reported here are very encouraging. The heterogeneous effects of ionizing radiation reported in previous experiments may account for the rather high dose required to produce performance decrements.

One of the major problems confronting military planners when considering radiation-induced decrement as an offensive weapon is the size of the weapon that would be capable of supplying sufficient radiation to induce performance decrement in an acceptable percent-

age of enemy personnel within a predetermined geographic area. Obviously, the genesis of one's thinking on this problem is the total dose required to produce this effect in an acceptable percentage of enemy personnel. The larger this figure, the greater the physical configuration of the radiation source. The data presented here suggest that increasing the rate at which ionizing radiation is delivered may lower the total dose required to produce performance decrement. Additional experiments are being designed to determine the exact radiation requirement to produce this effect.

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13 ABSTRACT A procedure to determine the early effects of ionizing pulsed radiation on primates is described in detail. Data were collected before and after exposure to approximately 12,000 rads, on ten adult male primates ( <u>Macaca mulatta</u> ) trained in a shock-avoidance behavioral conditioning paradigm. Fatigability and performance efficiency were the two parameters tested. The primates were unable to perform a learned task (i.e., pulling a ring in response to a visual or auditory cue) after exposure to 12,000 rads (performance decrement). The onset time of the performance decrement varied from 1 to 3 minutes after the total dose was delivered, and the duration of the performance decrement varied from 5 to 70 minutes. All animals experienced fatigue during their postexposure work periods. The importance of the rate at which ionizing radiation is delivered--relative to (1) onset time of the decrement, (2) duration of the decrement, (3) severity of the decrement, and (4) homogeneity of biologic effects--is discussed.			

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