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AIRCREW VULNERABILITY IN NUCLEAR ENCOUNTERS

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This Aeromedical Review has been reviewed and is approved for publication.

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A computational method (algorithm) is described which estimates probable mission outcome resulting from crew exposure to prompt neutron gamma radiation and/or residual fallout radiation. The threat scenario presupposes that: the crew has encountered one or more nuclear weapons; both aircraft and crew have survived the blast and thermal insults; and the aircraft is undegraded by the radiation (aircraft is survivable). Thus one is examining decreases in mission performance based upon crew irradiation only.

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AIRCREW VULNERABILITY IN NUCLEAR ENCOUNTERS

INTRODUCTION

Credibility of the concept of the triad of strategic forces in nuclear warfare is contingent upon sensible yet accurate vulnerability and survivability assessments. This is increasingly evident with the projection of fewer numbers of bomber aircraft and personnel.

Defense analysis affords a prediction capability for the outcome of a specified military encounter, where the force structure, the strategy, and tactics of both offensive and defensive deployment can be reasonably assumed. While entire military encounters have been analyzed using computer simulation (4), it is generally sufficient to study idealized circumscribed missions or mission segments such as a single bomber-SAM encounter, or air-to-air combat (7, 10) and measure the ability of the system to withstand exposure to one or more of the effects--blast, thermal, or ionizing radiation--from nuclear weapons. Thus when the effective hardness of the system or certain subsystem is less than the level of exposure (measured in psi, cal/cm^2, or absorbed dose in rads) the system is vulnerable to that hostile, manmade environment (1).

The objective of this analysis is to predict probable mission outcome resulting from crew exposure to neutron-gamma irradiation. The threat scenario presupposes that: the crew has encountered one or more nuclear weapons; both aircraft and crew have survived the blast and thermal insults; and the aircraft is undegraded by the radiation (aircraft is survivable). Both prompt and residual (fallout) radiation are included; thus one is examining decreases in mission performance based upon crew irradiation only!

CLINICAL OBSERVATIONS

Clinical observations of humans accidentally receiving high doses of high dose rate nuclear radiation and studies of Hiroshima and Nagasaki survivors, Marshall Island fallout, and large numbers of subhuman primate exposures reveal a characteristic symptom comple... The severity of symptoms is related to total dose and, to a slightly lesser degree, dose rate--i.e., the higher the dose and dose rate, the more severe the effect, and the sooner the time of onset.

These symptoms have been classically defined as:

1. The latent period - 3 to 7 minutes postradiation.

2. The initial (prodromal) reaction - 10 to 60 minutes.

3. The period of remission - partial recovery - 2 to 6 hours.

4. The premorbid period - delineation of likely type of death - 2 to 30 days (see Fig. 1).

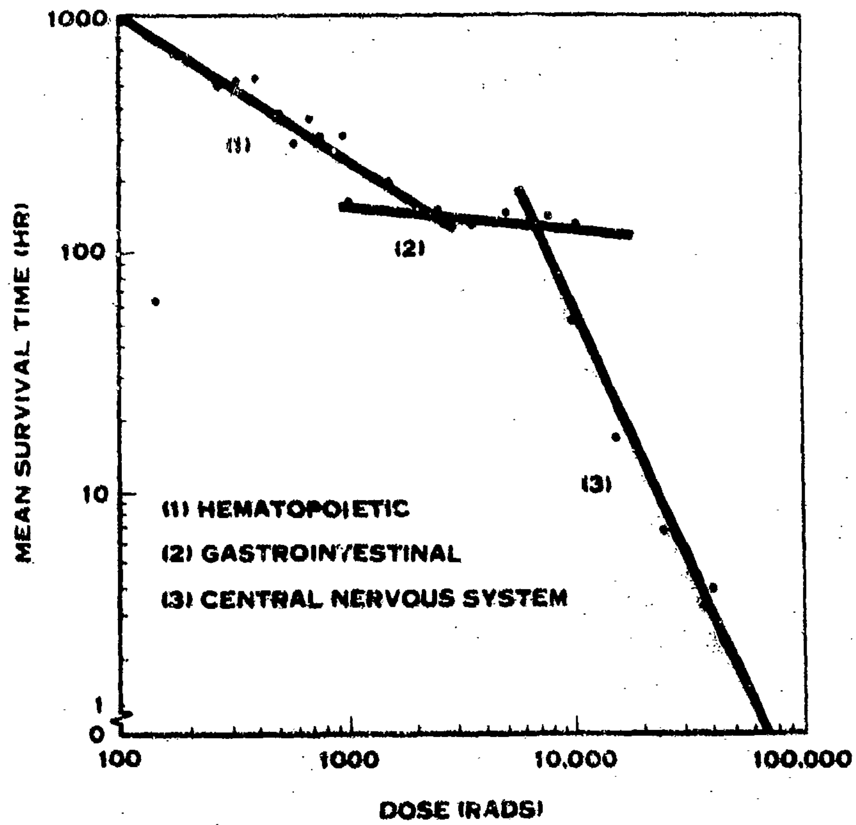

Figure 1. Mean survival time and modality of death as a function of radiation dose.

Phases 2 and 3 above are the ones of concern in mission vulnerability studies, since they degrade performance within the time span of a single mission. In a single mission time line for median lethal doses (350 to 450 rads) and/or greater doses, man will show varying signs and symptoms of acute gastrointestinal and neuromuscular distress (6). During the course of a military campaign lasting more than 4 or 5 days, death (phase 4) due to radiation will be a significant cause of personnel loss. However, when studying single missions less than 1 day duration, death is not a factor.

Gastrointestinal reactions include anorexia, nausea, vomiting, diarrhea, cramps, and dehydration. Neuromuscular symptoms include fatigability, listlessness, fever, and headache and are accompanied by hypotension, followed by hypotensive shock. The fulminating course of the syndrome involving all of these signs will usually not be seen unless the exposure dose is in the several thousand rad range (1000-5000 & >), or the period of observation exceeds 12 to 48 hours for lower doses (6).

A brief account of three different nuclear accidents (~5000 rad, ~1900 rad, ~800 rad) will serve to establish the dose-time course of symptomatology, and a summary is provided in Table 1.

TABLE 1. SUMMARY OF THREE NUCLEAR ACCIDENTS (ref. 6)

	Case I (D) ~800 rad	Case II (S) ~1900 rad	Case III (K) ~5000 rad
Ataxia and disorientation	No	No	Prompt
Shock	? Mild	No	Severe
Nausea and vomiting	Troublesome, 1-1 1/2 hr	Mild, 1 hr	Severe, 15 min
Diarrhea	No	Once, 4 hr	Severe, 45 min
Erythema, onset	3 days	24 hr	Immediate
Fever	Slight and irregular	Moderate and irregular	103.5° falling to normal in 12 hr
Hemoconcentration	Moderate and gradual	Moderate and gradual	Prompt and severe
WBC, total count	Rise to 16,000 in 24 hr	Rise to 18,000 in 24 hr	Rise to 28,000 in 12 hr
Lymphocytes	Drop to few hundred in 48 hr	Drop to near 0 in 24 hr	Complete disappearance in 10 hr
Renal impairment	3 days	24 hr	Immediate
Death	24 days	9 days	35 hr

"In retrospect, the clinical course of patient K (Case III - Table 1) can be divided into four rather distinct periods, differing in duration, symptomatology, and response to supportive therapy. The first period (lasting about 20 to 30 minutes) was characterized by his immediate physical collapse and mental incapacitation, which progressed to semiconsciousness and severe prostration. The second period (lasting about one and one-half hours) began with his arrival by stretcher at the emergency room of the hospital and ended with his transfer from the emergency room to the ward for further supportive therapy. This second period was characterized by such severe cardiovascular shock that death seemed imminent during the whole time. During this period he seemed to be suffering severe abdominal pain. The third period was about 28 hours in length and was characterized by enough subjective improvement to encourage continued attempts to alleviate his anoxia, hypotension, and circulatory failure. The fourth period began with the unheralded onset of rapidly increasing irritability and uncooperativeness, bordering on mania, followed by coma and death in approximately 2 hours. The entire clinical course lasted 35 hours from the time of radiation exposure to death." (11)

"The clinical courses of two other fatally injured patients deviated in some respects from that usually associated with the acute radiation syndrome, or at least showed exaggeration of some of the features of this illness. In both instances, the unusual reactions, or more correctly, the unusual degree of reactions, are believed to be related to the uneven irradiation of the body as well as to the magnitude of the radiation doses. Case I - Table 1, whose course was fulminating and relatively brief, showed paralytic ileus of such severity that it required continuous gastric suction. During the first 25 hours after the accident, the outstanding complaint was severe gastric distress, manifested by nausea and repeated episodes of retching and vomiting, beginning one and one-half hours after exposure. At times the patient retched and vomited almost continuously. During the second day, the nausea persisted, but the patient no longer vomited. He suffered from prolonged periods of hiccoughing during this day. There was no diarrhea or abdominal distention. Following this 48-hour period, the patient's appetite improved, and he ate well. Terminally, this patient went into circulatory collapse and just before death developed jaundice and mild hemorrhagic manifestations." (5)

"The other patient (Case II - Table 1) had a more gradually developing febrile course and showed complicated side reactions. In addition to mild diarrhea and abdominal distention, he manifested a severe stomatitis, which was biphasic in nature. The patient vomited within an hour of exposure and again several times in the next few hours. One loose diarrheal stool was passed four hours after exposure. Vomiting and nausea ceased completely within 12 hours, and the appetite was good for the next five days. The initial gastrointestinal reaction of this patient was not nearly so severe as that in Case I. On the sixth day, the patient became nauseated, vomited and complained of abdominal distention, which was unrelieved by enemata and rectal tubes. No peristaltic sound could be heard. He died without showing hemorrhagic phenomena clinically." (5)

PERFORMANCE MEASUREMENTS

Because acute gastrointestinal distress usually interferes with man's ability to function, these responses are likely to be the first radiation symptoms to accompany, if not cause, a decrement in performance (6). These measures of decrement (with respect to time into the mission, time of radiation exposures, and total dose) will define a mission-aborting impairment of the crew's ability to accomplish its designated military task. To quantitate the degree of performance decrement postradiation, trained monkeys, whose clinical response to radiation is essentially the same as that of humans, have been utilized in flight-simulating tasks involving control-precision dynamics (pitch and roll), visual, auditory and memory responses, as well as postirradiation emesis.

Visual or auditory studies require the animals to press an appropriate lever (Fig. 2). When nearly 100% of his responses are correct preradiation, prompt neutron-gamma exposures are made, and postradiation decrement is measured by time and dose.

Another measure of decrement is obtained by training animals to "fly" an equilibrium platform (Fig. 3) in both the pitch and roll axes. Again when performance is error free, pulsed radiation is delivered at various dose levels, and the degree of decrement is noted by dose and time.

Data obtained from these tasks (Fig. 4) indicate a pronounced decrement shortly after radiation. The time course of the quantitative performance measure generally parallels the time course of the clinical symptomatology of significance; however, the early transient performance incapacitation, observed shortly after irradiation, occurs before the clinical gastrointestinal symptomatology becomes overt.

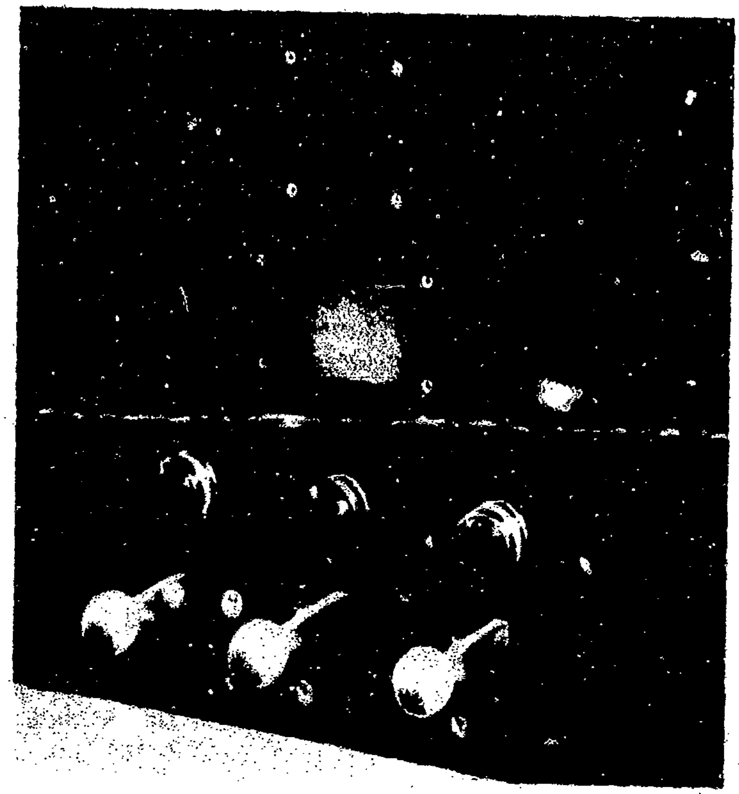

Figure 2. Test panel for visual and auditory studies.

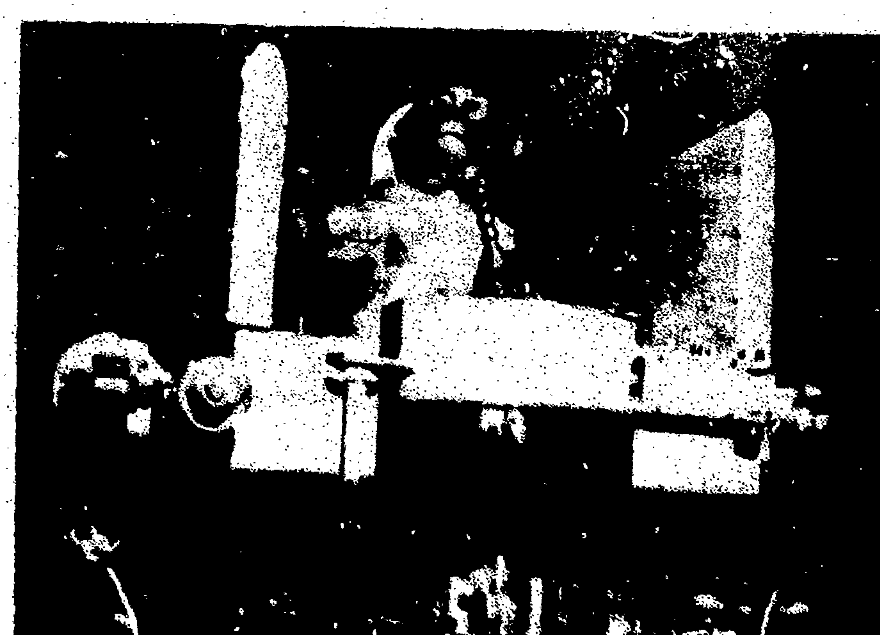

Figure 3. Primate equilibrium platform.

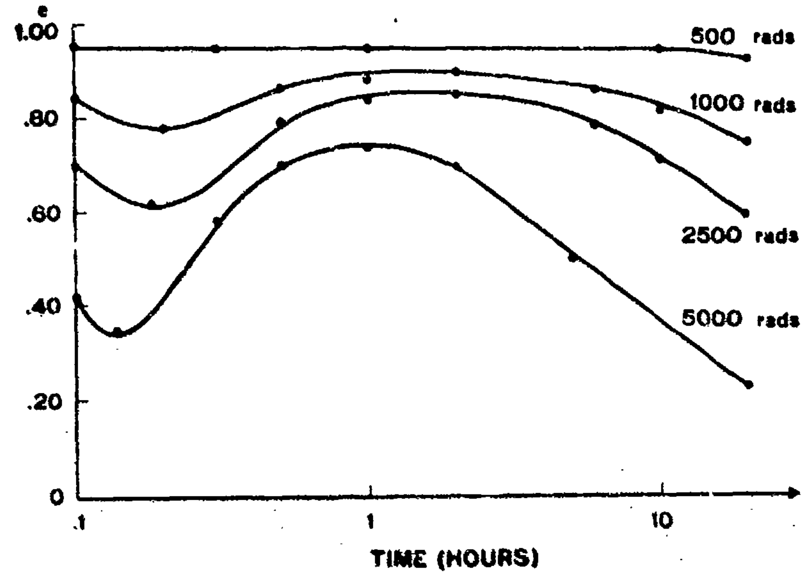

Figure 4. Laboratory task performance e (efficiency) as a function of time after irradiation and dose. The performance measure e refers to percent correct response on the visual/ auditory task, and percent of time within trained limits per unit time on the equilibrium platform task.

These data indeed provide quantitative measures of performance impairment, so that predicting the probability of accomplishing a designated mission, based upon crew vulnerability, is realistic, warranted, and sobering.

For supralethal doses (900-5000 rad) postradiation performance is almost exclusively based on monkey data and four human accident case reports (9). Thus, until there is an actual nuclear confrontation, laboratory-simulated flight tasks using monkeys provide the most realistic assessment for war-gaming or modeling crew vulnerability in a nuclear environment. However, there is evidence indicating monkey-man comparability on these simple laboratory tasks.

COMPUTATIONAL METHOD

Assume P_o planes "fly out" in a retaliatory nuclear strike. At some time t after the initiation of the strike, P(t) planes remain in the striking force where $P(t) \leq P_o$. The ratio $P(t)/P_o$ is then the surviving fraction, s(t), of aircraft at any time t. To provide the desired vulnerability/survivability assessment for aircrews in a man-made nuclear environment, s(t) in a nuclear environment must be determined.

To determine s(t), let $\lambda(t)$ be the average rate at which aircraft are lost in the operations plan in unit time at time t for a given mission or sortie. Then $\lambda(t)P(t)$ is the average number of planes lost per unit time at time t in the mission. That is:

$$\frac{dP(t)}{dt} = -\lambda(t)P(t) \tag{1}$$

Dividing both sides of equation 1 by P_o yields

$$\frac{ds(t)}{dt} = -\lambda(t)s(t), \tag{2}$$

the basic equation in the analysis.

Equation 2, an ordinary differential equation, has the solution:

$$\frac{ds(t)}{s(t)} = -\lambda(t)dt$$

or

$$\int_0^t \frac{ds(t)}{s(t)} = \int_0^t -\lambda(t)dt$$

but

$$\int_0^t \frac{ds(t)}{s(t)} = \ln[s(t)] - \ln[s(o)] = \ln[s(t)]$$

since $s(o) = P(o)/P_o = P_o/P_o = 1$. Then

$$s(t) = \mathrm{EXP}\left(-\int_0^t \lambda(t)dt\right) \tag{3}$$

Thus, if $\lambda(t)$ is a known function of time, $s(t)$ can be unambiguously determined. The function $\lambda(t)$ is defined as the average loss rate function and is pivotal to the analysis.

$\lambda(t)$, the average rate of aircraft loss per unit time at time t in a given mission, may be attributable to a multiplicity of causes. For this analysis, consider only the aircraft losses resulting from crew performance failure due to radiation received during or just prior to the course of a mission. So, $\lambda(t)$ is the average rate of aircraft loss in unit time at time t in the given mission due to irradiation of the crew, and $s(t)$ then is the surviving fraction at time t assuming that the only insult to the aircraft-crew combination is the radiation dose absorbed by the crew.

Aircraft loss refers to aircraft no longer capable of accomplishing its designated mission--i.e., if it is on course, but has fallen unacceptably far behind the mission time line, it is unacceptably off course, a mission-critical task has been failed (e.g., refueling, weapon delivery), or there is total loss of aircraft control.

In general, $\lambda(t)$ depends on the ability of the crew to perform its assigned flight tasks, which can be severely degraded based upon the time of irradiation and the magnitude of the dose absorbed. Clearly $\lambda(t)$ cannot be determined by direct human experimentation employing lethal doses of radiation; so it is estimated for fighter and bomber missions using the radiation effects data described previously in this review.[1]

Strategic and tactical missions are easily divisible into mission phases: takeoff, climbout, cruise, refueling; and it is possible to relate distinct flight crew duties to each of these phases. For example, a key question is, "Suppose a B-52 crew were so incapacitated by radiation that they could score only 0.25 on either the visual and/or auditory task or the equilibrium platform (pitch and roll) tasks. What is the probability that the crew so incapacitated could accomplish refueling according to standard operating procedures?"

Personnel with aircrew experience (rated crew members) and knowledge of nuclear weapon radiation effects provide probability estimates with little variability. Rand Corporation studies conclude that decreased dispersion of estimates is correlated with an increased probability that the estimate is accurate (3). Thus, the use of such phase estimates to assess the impact of radiation on a military mission has merit. B-52 bomber and F-1?4 interceptor mission scenarios have been examined, and curves were constructed relating the probability of mission phase completion (p) to laboratory task performance (e) for such typical mission phases.

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[1]The use of radiomimetic drugs on humans performing simulated missions may at some future time be feasible.

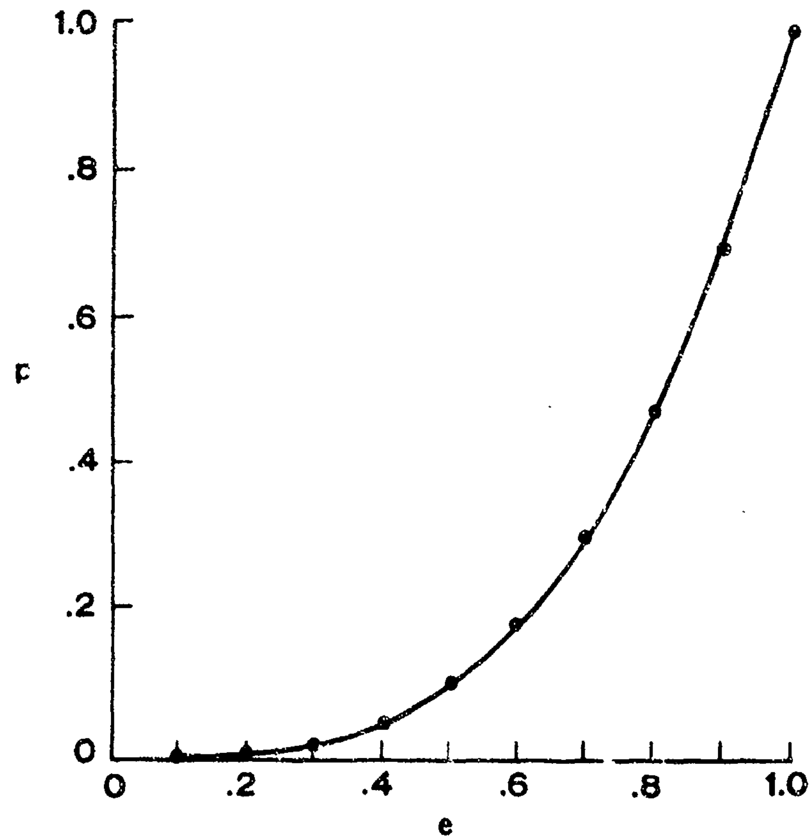


Figure 5. A p (= probability of phase completion) versus e (= laboratory task performance score) curve for the refueling phase of a B-52H mission.

Figure 5 shows a p versus e curve for the refueling phase (20 minutes) of a B-52 mission. The curve depicts, for example, that if the crew is incapacitated (degraded) to such a level that they can perform at only 0.50 efficiency on the standard laboratory tasks, then there is only a 0.10 probability of completing refueling. This p versus e statement assumed that the level of incapacitation, scaled by e, remains constant throughout the phase (p = 0.10 if e = 0.50 for refueling when e = 0.50 throughout the entire phase--20 minutes). In reality, e is rarely constant postirradiation. To determine the time-varying function $\lambda(t)$ from the "static" p versus e estimates, it is assumed that loss rates observed at any given time are a function of the e value at that time; i.e., $\lambda(t) = f[e(t)]$. Other relationships are conceivable. It is possible that residual effects of prior incapacitation as well as current incapacitation will be reflected in the current loss rate. Mathematically, this can be expressed as

$$\lambda(t) = f\left(\int_0^t h(t,u)e(u)du\right)$$

where the current loss rate $\lambda(t)$ is viewed as a weighted integral with $h(t,u)$ the weighting function of current and prior $e(u)$ values (incapacitation values). Examination indicates plausible $h(t,u)$ functions will not significantly alter the outcome of the analysis. It should be noted that $h(t,u) = \delta(t-u)$, where δ is the Dirac delta function, provides the case that $\lambda(t) = f[e(t)]$.

In Figure 4, e is described as a function of t and since the p versus e curves give p as a function of e, p can be expressed as a function of t. The probability that the crew will accomplish that portion of a mission phase between time t_1 and t_2 is $s(t_2)/s(t_1)$. It can be shown that there exists t* and t** between t_1 and t_2 such that

$$\frac{s(t_2)}{s(t_1)} = \text{EXP}\left[-\lambda(t^*)(t_2 - t_1)\right] = p(t^{**})^{\frac{t_2 - t_1}{T}}$$

where T is the duration of the mission phase. Therefore,

$$\lambda(t) = -\ln p(t)/T \tag{4}$$

Equation 4 gives λ as a function of p and/or t. Therefore, knowing λ as a function of t, s(t) can be determined using equation 3.

The curves in Figure 4, performance score e on a laboratory task as a function of t, time after a prompt nuclear radiation exposure, are well fitted by equations of the form:

$$e_1(t) = \text{EXP}[-C(t-t_1)]\left\{\text{EXP}[-A(t-t_1)] + L\left(1-\text{EXP}[-B(t-t_1)]\right)\right\} \quad \text{For } t \geq t_1$$

$$e_1(t) = 1 \quad \text{For } t \leq t_1 \tag{5}$$

where the coefficients A, B, C, and L are functions of the dose of radiation received, and t_1 is the time of burst. These curves fit the postirradiation performance data and were derived from a very simple model of radiation-induced performance incapacitation. The term $\text{EXP}[-A(t-t_1)]$ represents the acute incapacitation of the animal. This acute incapacitation is countered by homeostatic mechanisms which are described by the term $L(1-\text{EXP}[-B(t-t_1)])$. The term $\text{EXP}[-C(t-t_1)]$ represents the slow, inexorable decompensation of performance after a lethal dose. It may be fortuitous that the above model is relatively effective. Nevertheless, the above equations are computationally useful; and further, the model describes a practical hypothesis not unsupported by the literature. Data points and the fitted equations are provided in Figure 6. Similarly the equation coefficients are listed in Table 2 for the doses at which data have been obtained. Coefficients for additional doses were derived by linearly interpolating between the given coefficients.

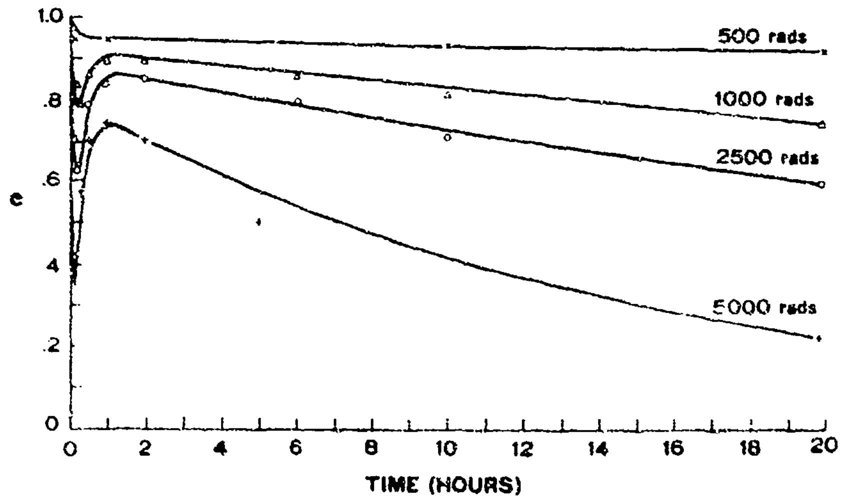


Figure 6. Laboratory task performance data points and fitted curves. x = data points for 500 rads, Δ = data points for 1000 rads, o = data points for 2500 rads, + = data points for 5000 rads.

TABLE 2. RADIATION RESPONSE COEFFICIENTS

Dose (rads)	A	B	C	L
500	8	8	0.001	0.95
1000	8	5	0.010	0.92
2500	10	4	0.020	0.89
5000	25	4	0.065	0.80

Limited experimentation has been completed on the crew effects following exposure to multiple nuclear weapons (2). These data, however, suggest use of the following calculational procedures. Suppose there are two events, one occurring at time t_1 and the other occurring at time t_2. Then, at time t the combined performance score can be expressed as

$$e_c(t) = e_1(t)\, e_2(t) \tag{6}$$

where $e_i(t)$; i = 1,2 represents the functional relationship between the score e and time after burst t as in Equation 5. This last equation is easily generalized to situations involving more than two bursts.

At present no experimental data are available for low dose rate fallout radiation to construct e vs t curves such as those in Figure 4. A careful review of the Marshall Islands data and the descriptive medical literature, including that pertaining to radiotherapy, suggests that there is no acute phase of performance incapacitation attributable to low dose rate irradiation; rather a slow decompensation of performance occurs in response to the total accumulated dose (8). This slow decompensation can be represented by a single exponential term $e(u) = \mathrm{EXP}[-Cu]$ where C takes the same values given in Table 2 for a weapon exposure. So that, if R rads are delivered between $t = t_1$ and $t = t_2$, use the equation

$$t_1^* = \frac{t_1 + t_2}{2}$$

$$e_1(t) = \mathrm{EXP}[-C(t - t_1^*)] \quad \text{For } t \geq t_1^*$$

$$e_1(t) = 1 \quad \text{For } t \leq t_1^* \tag{7}$$

to estimate the performance score e at time t. The term $(t_1 + t_2)/2 = t_1^*$ is used to implement the concept that an accumulated dose is causative of the performance decrement; so t_1^* represents the time of occurrence of the fallout dose. Equations can be written for situations involving multiple fallout doses as was done for the multiple burst case.

The computations just described using the estimation algorithm for mission analysis are too lengthy to accomplish by hand, but they can be readily executed by a simple program on a small digital computer. The flow diagram for such a program is shown in Figure 7.

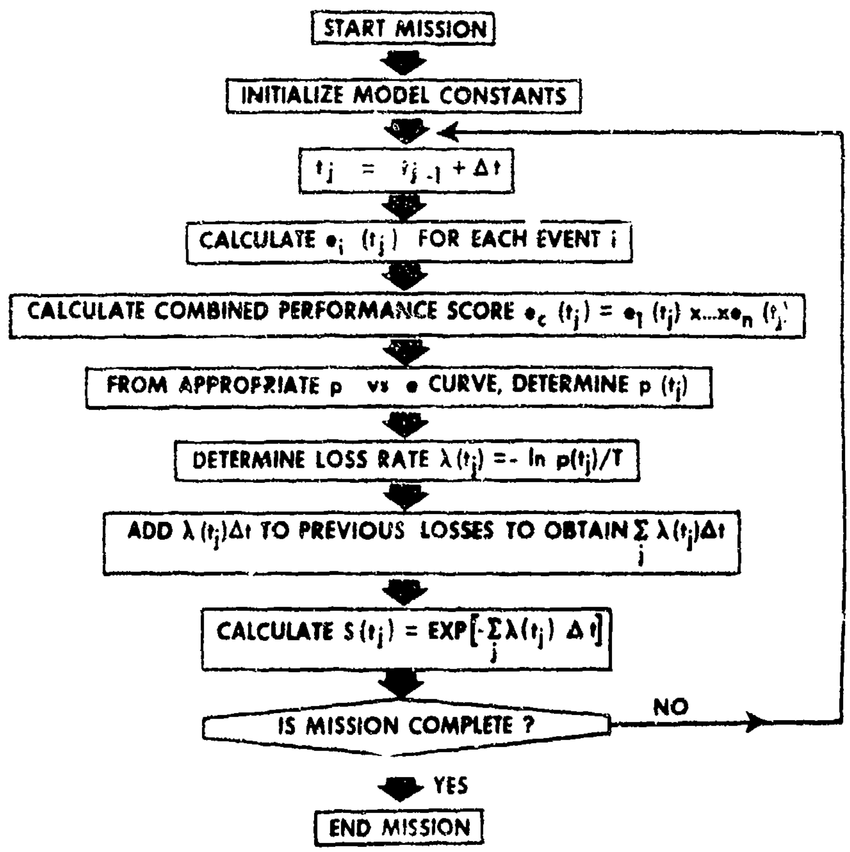


Figure 7. Flow diagram of the estimation algorithm computations.

MISSION AND THREAT SCENARIO

A hypothetical B-52 mission and the attendant nuclear threat will illustrate the application and capability of the estimation algorithm technique. The mission provided consists of takeoff (TO), climbout (CO), level flight (LF), refuel (RF), go-low (GL), and penetration (PN) phases.[2] The B-52H considered has six crew members: pilot, co-pilot, navigator, radar navigator, EW officer, and gunner. Mission completion culminates at the end of the penetration phase, and the assigned mission required hitting surface targets using air-to-ground missiles and gravity bombs. The mission phase details are as follows:

---

[2]Different assigned scenarios will require different phase divisions, and a more detailed breakout of crew duties can be elected depending on the analytical needs and the data available.

Takeoff (TO): This phase lasts 5 minutes from start of the acceleration roll to a flying condition for the generally heavily loaded aircraft. It is a period of extreme concentration and activity requiring accurate response for maintaining proper directional attitude and transition to an airborne condition.

Climbout (CO): This phase lasts 55 minutes. The plane maintains climbing attitude until it reaches its cruising altitude. Crew activity is less intense than during takeoff, and errors can be corrected. Frequent and periodic checks of instruments and controls are made.

Level Flight (LF): This phase lasts 5 hours with little crew activity, and autopilot may be used for the actual flight operations. Periodic checks of instruments, navigation check points, and fuel consumption calculations are required on a routine basis.

Refueling (RF): This phase lasts 20 minutes. Intense concentrated activity is required as the aircraft rendezvous with the tanker, and the actual transfer of fuel from one plane to the other necessitates intense concentration to maintain critical flight attitude.

Go-Low (GL): This phase lasts 30 minutes. Prior to penetration over enemy territory navigation must be computed and closely checked. This task requires rapidity of action and mental clarity. Long-range weapons aimed at softening enemy defenses are released during this period.

Penetration (PN): This phase lasts 2 hours and involves high-performance low-level flight over enemy territory. Concentration on the flying effort is confounded by a requirement to observe for potential enemy threats. Twenty turn points are assumed to be executed during this phase as the crew works its way toward bomb run over target.

RESULTS

The p versus e curves for each of the phases are shown in Figure 8. These curves conform to the equation $p = e^{N}$ where N is an appropriate real-valued exponent. Use of these equations to fit the probability estimates has a very interesting and practical consequence. If $S_i(t)$ and $S_j(t)$ are surviving fractions at time t due to radiation exposures i and j, respectively, then the surviving fraction at time t due to irradiation with both doses is $S_{ij}(t) = S_i(t)\ S_j(t)$. Thus, if $p = e^{N}$ is used in our analytic procedure, the effects of radiation appear as independent events, an intuitively appealing, possibly conservative result. Practically the multiplication rule $S_{ij}(t) = S_i(t)\ S_j(t)$ simplifies treatment of multiple dose cases. The time line for the mission is shown in Figure 9 and simply involves the sequential performance of the phases listed above. Using the phases listed above

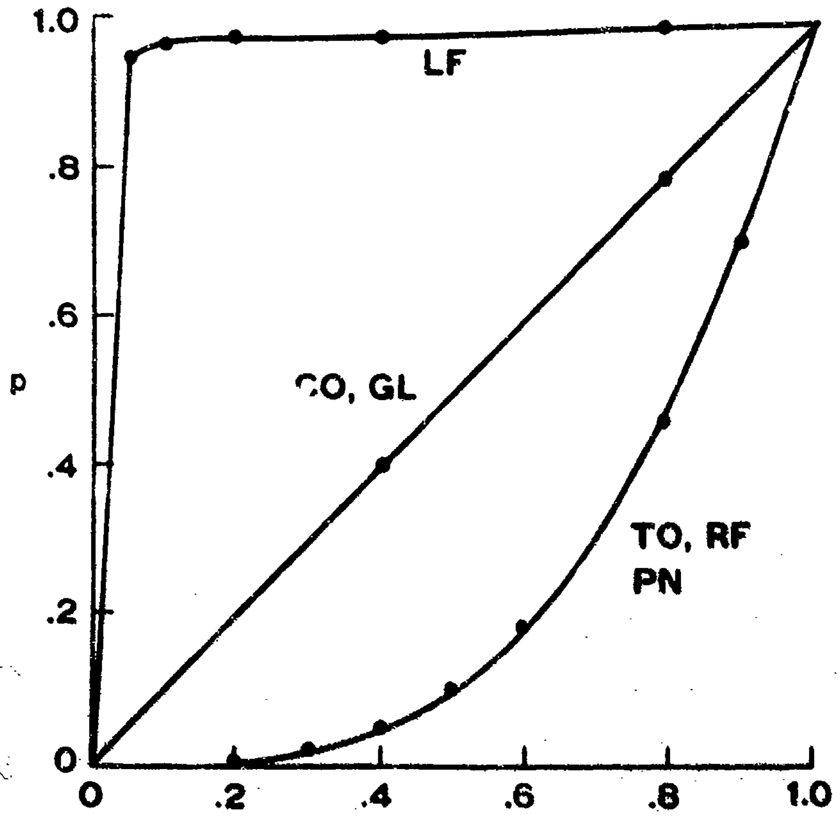
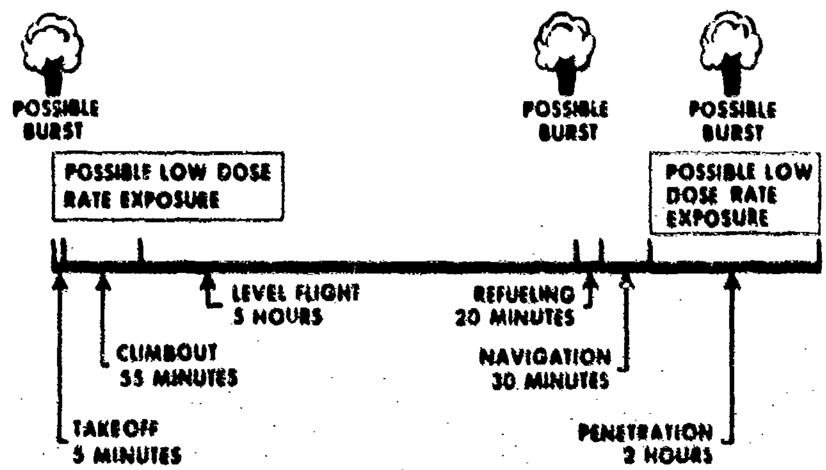


Figure 8. p versus e curves for a hypothetical B-52H mission.

and their p versus e curves, one can study several missions with other configurations--missions with more than one refueling operation, or a longer penetration phase.[3] Now consider the cases of nuclear exposures received just before takeoff; just before refueling; and 1 hour into penetration; with absorbed doses of 0 rads, 500 rads, 1000 rads, 2500 rads, and 5000 rads. Additionally two low-dose-rate exposures are treated: the first exposure starts at takeoff and is complete 2 hours later; the second exposure is encountered at the start of penetration and lasts throughout the penetration phase. These threats are diagrammatically represented in Figure 9. Surviving fractions at the end of the penetration phase (mission completion) are presented in Table 3 from which all dose combinations can be calculated using $S_{ij}(t) = S_i(t)\ S_j(t)$. Representative computer outputs are given in Figures 10 through 12.



POSSIBLE BURST EXPOSURES: 0, 500, 1000, 2500, 5000, rads
POSSIBLE LOW DOSE RATE EXPOSURES: 0, 100, 250, 500, rads

Figure 9. Time line of hypothetical B-52 mission and threat scenario.

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[3]For instance, if there is a p versus e curve, $p = f_T(e)$, for some phase or mission segment with duration T, then the p versus e curve for a comparable phase but with duration T' is simply $p = f_{T'}(e) = [f_T(e)]^{T'/T}$.

TABLE 3. MISSION COMPLETION SURVIVING FRACTIONS

Dose (rads)	Surviving fraction: Prompt dose: Takeoff	Prompt dose: Refueling	Prompt dose: Penetration	Fallout dose: Takeoff	Fallout dose: Penetration
100				0.99	1.00
250				0.98	1.00
500	0.61	0.73	0.93	0.96	1.00
1000	0.24	0.34	0.78		
2500	0.09	0.15	0.64		
5000	0.00	0.02	0.44		

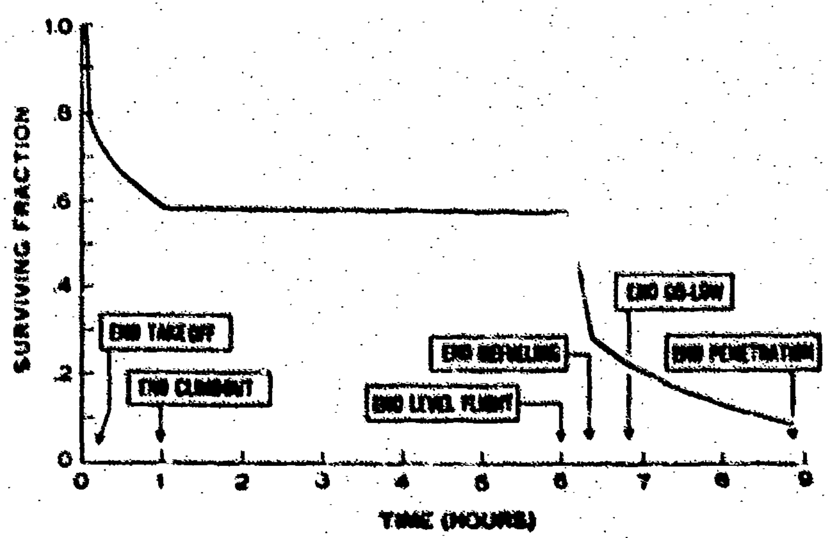

Figure 10. Surviving fraction as a function of time for 2500 rads (burst dose) received at takeoff.

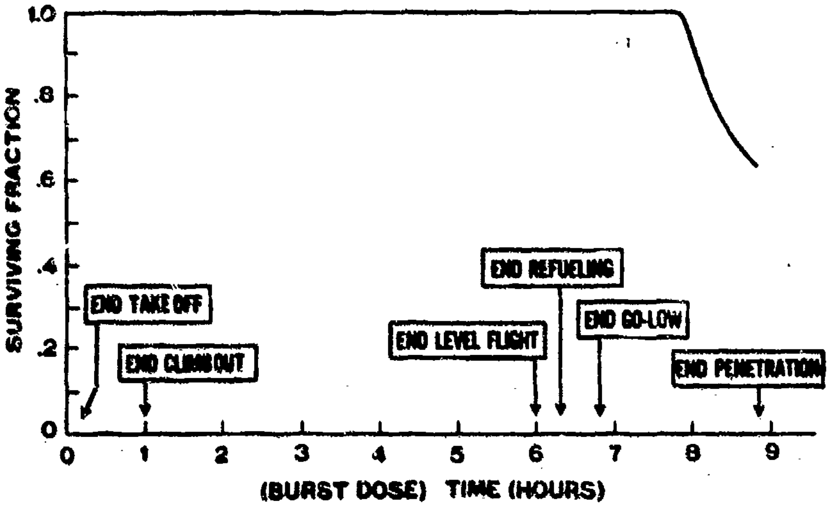

Figure 11. Surviving fraction as a function of time for 2500 rads (burst dose) received 1 hour into penetration.

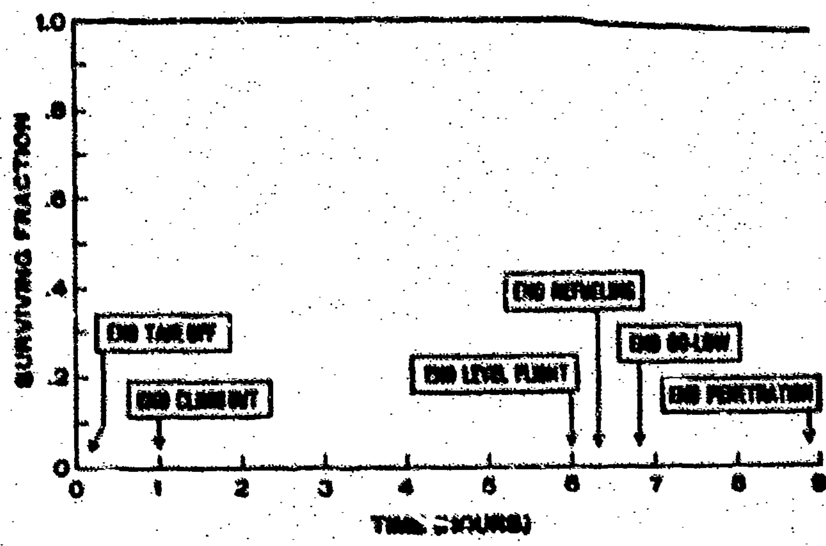

Figure 12. Surviving fraction as a function of time for 250 rads (fallout) received starting at takeoff and complete 2 hours later.

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