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A MONTE CARLO SOLUTION TO THE PROBLEM OF SURVIVABILITY OF AMMUNITION STORES

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May 1979

US ARMY ARMAMENT RESEARCH AND DEVELOPMENT COMMAND
BALLISTIC RESEARCH LABORATORY
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The problem of survivability of ammunition stores given a hit is studied. This study models the propagation of the detonation through an ammunition store in a stochastic manner using the structure of percolation theory. This problem of propagation of detonation is found to fit into the model of a bond percolation problem. Our model predicts the average number of rounds lost per encounter, the standard deviation, and the probability distribution of reaction cluster size, as well as the cummulative probabilities, as functions of the inter-round interaction probability p. Our study shows that survivability requires that p

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be less than a critical probability P_c. We have also proposed a more general definition of the critical probability P_c.

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I. INTRODUCTION

The problem of survivability of ammunition stores is an important military problem. Ammunition stores make attractive targets for enemy fire, saboteurs and agents. Once an ammunition store sustains a hit, the problem arises of preventing the sympathetic reaction of other rounds in the store beyond those sustaining the direct hit. The sympathetic reaction of other ammunition rounds through detonation or rapid burning is usually referred to as the ammunition fratricide problem. Preventing ammunition fratricide is an important objective in the design of ammunition stores and compartments on board of military vehicles, ships, and aircraft[1]. Several approaches can be used to minimize ammunition fratricide in such stores.

a. Improved packaging and wrapping of the individual rounds by the use of a variety of shields and chemically treated packaging materials, and fire retardents. This might slow down or prevent the spread of reaction[2,3], and minimize the hazards of fire and cookoff[4].

b. The use of explosive fillers, propellants, and components which are less sensitive.

c. Stack separation of ammunition to minimize the losses.

The vulnerability analysis problem thus becomes: For a given ammunition store, or ammunition compartment design and given round conditions such as fillers and packaging (or equivalently for a given interaction probability p) what is the number of rounds lost per encounter with enemy fire given a hit? Secondly, what is the probability distribution of the number of rounds lost in an encounter, its mean and its standard deviation?

The problem of propagation of reaction through an ammunition store is analogous, from a mathematical point of view, to several physical problems arising in several diversified fields, and collected together under the banner of percolation theory. This theory finds application in the theory of dilute ferromagnets, in the spread of disease through an orchard of trees from an infected one, and the spread of viral

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[1] *Harry J. Reeves, "General Principles of Vulnerability Reduction of Stacked Ammunition," BRL Memo Report 2376, April 1974. (AD #920708L)*

[2] *Leonard Teitell and Harry Reeves, "Fire Retardant Packaging for Artillery Ammunition," BRL Memo Report 2490, August 1975. (AD #B009495L)*

[3] *Philip M. Howe and David Collis, "Effectiveness of Plastic Shields in Prevention of Propagation of Reaction between Compartmentalized Warheads," ARBRL-MR 2827, April 1978. (AD #B027466L)*

[4] *Philip M. Howe and W. Jackson, "Experimental Study of the Cookoff Hazard of Compartmentalized Tank Projectiles," BRL MR 2666, August 1976. (AD #B014010L)*

infections through a population from an infected person. Broadbent and Hammersley[5] gave a survey of such problems, and a vast body of literature exists describing many such problems, applications, and solution methods and results. To the above problems of percolation theory we add our present problem of the propagation of reaction through an ammunition store.

In Section II we describe briefly some of the basic definitions and problems in percolation theory, together with a brief description of some of the general results. In Section III we formulate our problem and indicate some of the differences from other percolation problems. We give a description of our basic model and the method of solution. In Section IV we apply our model to the problem of survivability of a number of two and three dimensional ammunition stores given that they sustained a hit. The results of such applications are given in tables and graphs. It has been found as a result of those studies that in order to prevent mass reaction in the ammunition store we need to keep the inter-round interaction probability p substantially lower than a critical value P_c, i.e., $p << P_c$. In Section V we summarize the results of our study and propose a generalized definition of the critical probability P_c. In the Appendix we give a listing of the developed code together with some directions on its usage.

II. ELEMENTS OF PERCOLATION THEORY

Percolation deals with the flow of fluid through a medium where the flow is controlled by a random process associated with the medium. By a medium we mean in general an infinite set of abstract objects called atoms or sites[6]. The sites (atoms) are connected together by paths along which the fluid flows. The paths are called bonds. Bonds are said to be oriented if they allow the flow of fluid in one direction only. A bond is said to be unoriented if it permits the fluid to flow in both directions. When the random process is associated with the bonds of the medium, the problem is called a bond percolation problem. A bond is blocked with probability $q = 1 - p$, and unblocked with probability p. When the random characteristics of the medium are placed on the sites (atoms) the problem is termed to be a site percolation problem. A site is blocked with probability $q = 1 - p$ and unblocked (or wet) with probability p. The coordination number Z for any regular medium is defined to be the number of bonds leaving any site. A set of unblocked atoms linked together through unblocked bonds is called a cluster. The percolation probability P(p) is defined as the probability that the fluid from a single source atom, chosen at random, will wet

---

[5] *S. R. Broadbent and J. M. Hammersley, "Percolation Processes," Proc. Camb. Phil. Soc., 53, p 629, 1957.*

[6] *V.K.S. Shante, and S. Kirkpatrick, "An Introduction to Percolation Theory," Advances in Physics, Vol. 20, p 325, 1971.*

infinitely many other atoms. Mathematically,

$$P(p) = \lim_{n \to \infty} P_n(p) \tag{1}$$

where $P_n(p)$ is the probability that a single source atom wets at least n other atoms. The critical probability P_c is defined as

$$P_c = \text{Supremum } [p | P(p) = 0] \ . \tag{2}$$

A number of theoretical results have been established by a variety of methods. For example the critical probability for both the site and/or the bond percolation problem on the square lattice is greater than or equal to 0.5. In fact, for the bond problem, it has been shown that the critical probability[7] for the square lattice $P_c = 0.5$ and for the cubic lattice $P_c = 0.254$. Shante and Kirkpatrick[6] gave a survey of these problems and results. Most of the results obtained in percolation theory were arrived at numerically via Monte Carlo methods. Vyssotsky, et. al.,[7] computed the critical probabilities for the bond percolation problem for a number of two dimensional lattices. Frisch, Hammersley and Welsh[8] obtained numerical estimates of the percolation probabilities for various two and three dimensional lattices. Dean[9] constructed a new computational method which effectively evaluates the limit in Equation (1) for an infinite lattice from a sequence of finite lattices. The limiting process in Equation (1) is the essence of the different computational methods and its evaluation is a major source of difficulty.

III. THE PHYSICAL AND COMPUTATIONAL MODEL

The problem of concern to us here is that of a stack of ammunition, arranged in a certain two or three dimensional lattice, receiving a hit which results in the initial detonation of a set of rounds (ISET) consisting of one or more rounds of ammunition. We assume that the set (ISET) consists of a randomly selected round and a subset of its first generation neighbors. The number of rounds in (ISET) is an input parameter (NINS) which one specifies. We are interested here in

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[7] *V. A. Vyssotsky, S. B. Gordon, H. L. Frisch and J. M. Hammersley, "Critical Percolation Probabilities (Bond Problem)," Phys. Rev. 123, No. 5, p 1566, 1961.*

[8] *H. L. Frisch, J. M. Hammersley, and D.J.A. Welsh, "Monte Carlo Estimates of Percolation Probabilities for Various Lattices," Phys. Rev. 126, No. 3, p 949, 1962.*

[9] *P. Dean, "A New Monte Carlo Method for Percolation Problems on a Lattice," Proc. Camb. Phil. Soc. 59, p 397, 1963.*

studying the propagation of the detonation in the stack (lattice) from the initial set (ISET) as a function of the interaction probability, P, of neighboring rounds achieving reaction. The quantities that we are interested in determining are:

a. The average number, $\bar{n}$ (mean), of rounds lost on a given test and the standard deviation, S_n, as functions of P. N is a random variable representing the cluster size of reacted rounds, and n represents the value that N assumes on a given experiment.

b. The cluster size of reacted rounds on a given trial and its probability mass function, i.e., $P(N = n, P)$.

c. The probability, $P_n(P)$, of at least n rounds reacting, i.e., $P_n(P) = P(N \geq n, P)$.

d. The probability $Q_n(P)$, that the number of reacting rounds is less than n, i.e., $Q_n(P) = 1 - P_n(P) = P(N < n, P)$.

The above problem of random propagation of the reaction through an ammunition lattice is seen to fit the model of an unoriented bond percolation problem as outlined in Section II. The lattices we usually deal with in this problem are finite rather than infinite, whereas when one deals with problems concerned with the physical properties of continuous media, such as alloys and crystals, the lattices under consideration have to be infinite. This is an important difference in our model and results in considerable simplification of the problem. The essence of the various computational Monte Carlo methods devised by Vyssotsky[7] et. al., Frisch[8] et. al., and Dean[9] revolve around the evaluation of the limit as $n \to \infty$ in Equation (1), in order to evaluate the percolation probability P(P) and the critical probability P_c.

We assume therefore that we have a certain two or three dimensional lattice which is regular and finite, although it may consist of a large number of sites (rounds). We assume that the reaction process starts with a set of neighboring round (ISET) reacting following a hit, and further assume that a round can only be initiated by an immediate neighbor. The search process is therefore limited to the first generation neighbors of the reaction front. Figure 1 shows the first generation neighbors of a site A (x,y) in a two dimensional square lattice. The lattice geometry is reflected by the way the neighbors of a typical round are defined. We further assume that each bond (site) has probability P of being unblocked (or wet). In our computational model this is achieved by using a random number generator to generate a continuous random variable r such that $0 < r < 1$, and r has a uniform probability density distribution $f_r(r_o)$. The sample space for r is partitioned into two events, (i) the event E_1 that the bond (site) is unblocked and propagates the reaction to a neighboring round, (ii) the

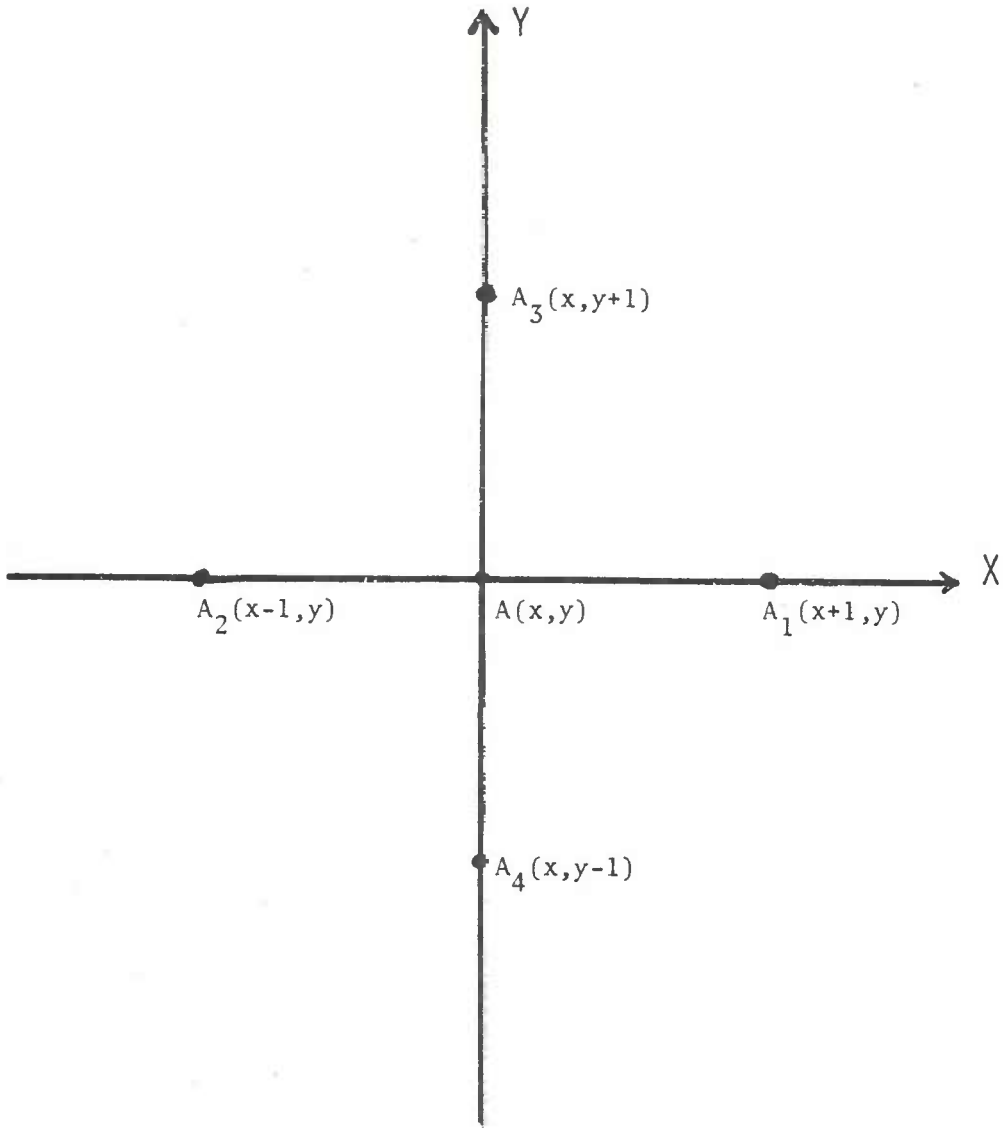


Figure 1: First Generation Neighors of a Node in a Square Lattice

event E_2 that the bond (site) is blocked and does not propagate the reaction to a neighbor. Equivalently the events can be termed 1 and 0 as shown in Figure 2. One such partition of the sample space into the above two events is:

If $r \leq p$ bond propagates the reaction (unblocked)

and if $r > p$ bond does not propagate the reaction (blocked).

An array (IND) in this computational model keeps record of the status of each round in the lattice. Thus in our two dimensional bond problem IND (i,j) = + 1 if the reaction propagated to the round at (i,j), IND (i,j) = 0 otherwise. Our model is also capable of treating a site percolation problem which can be considered to simulate the case when the lattice consists of highly sensitive rounds (reaction probability one) mixed with inert rounds. The number of reactive rounds in the lattice L is pL. Thus in the case of a site percolation problem IND (i,j) = - 1, 0, or + 1. IND (i,j) = - 1 if the reaction front has not reached the round at (i,j) yet, IND (i,j) = 0 if the round at (i,j) is inert, and IND (i,j) = + 1 if the (i,j)th round achieved reaction.

The reaction process is initiated by randomly selecting a set (ISET) of neighboring rounds and assuming it to be already reacted. The number of rounds in the set (ISET) is an input parameter (NINS). If NINS is greater than one, then one of two subroutines DET2 or DET3 is called to select the remaining rounds that form the set (ISET). The number of rounds selected to be in ISET is less than or equal to NINS. The inequality applies sometimes if the first initially selected round lies on the grid boundary, and NINS is greater than what is feasible.

At a typical stage of the process the position of the reaction front is saved in arrays in terms of the rounds that form that front. The first generation neighbors of the rounds at the reaction front are examined and a determination is made of which subset of those rounds becomes part of the detonation front at the next stage. The process stops when this subset is the empty subset indicating no new rounds reacting. The number of rounds in the reaction cluster, n, is then recorded for the current trial and a new trial then initiated. After an input specified number of trials (NTRIAL), the mean cluster size $\bar{n}$, and the standard deviation S_n are computed. A histogram of the process is printed out in an input specified interval length (ISTEP). The distribution of cluster size and its probability mass function can be computed. The cumulative probabilities P_n (p) and Q_n (p) are printed out if input specified. The constructed code will also print out the reaction cluster and its heirarchy for a given case on a given trial if specified by the input.

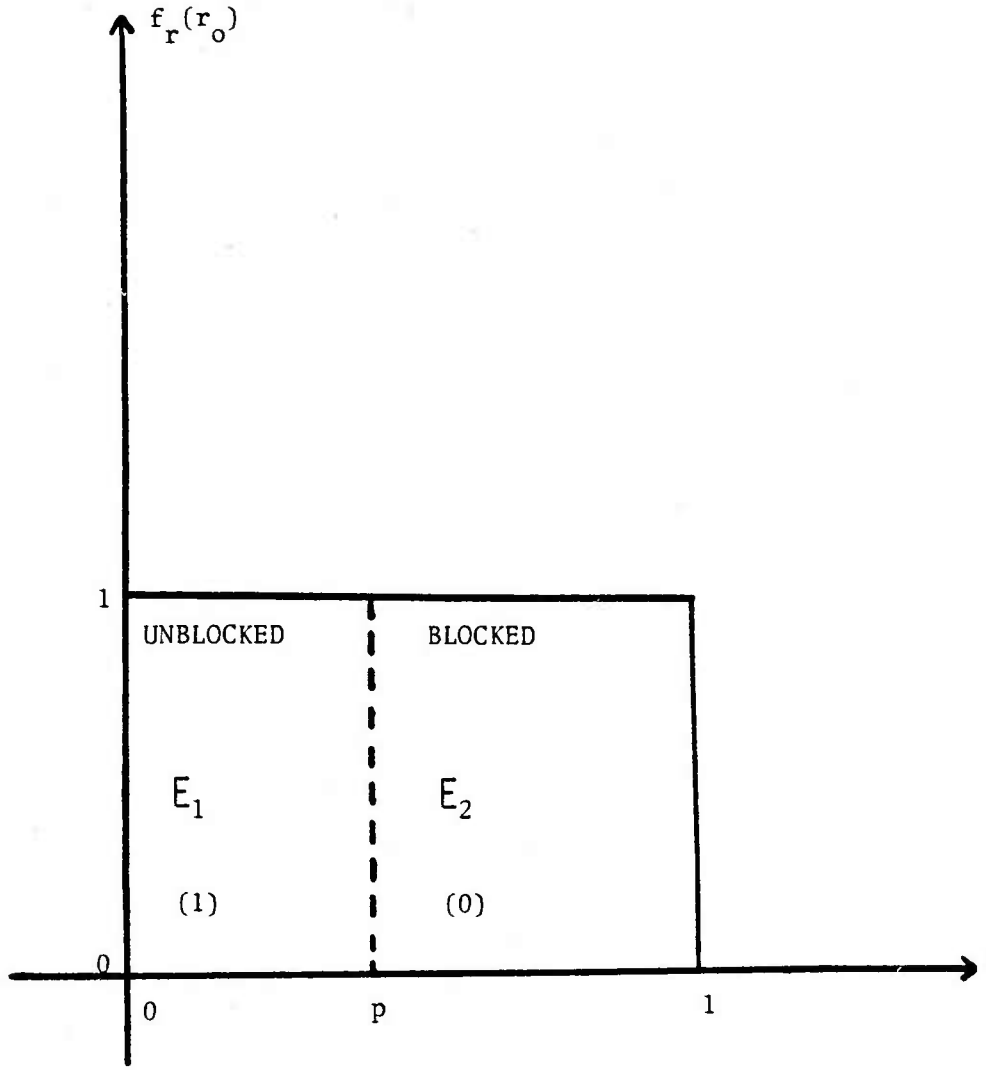


Figure 2: The Probability Density Function $f_r(r_o)$ and its Sample Space Partition to Events

IV. APPLICATION OF THE MODEL

The application of our computational model to the munition problem requires that we determine the minimum number of trials necessary for the various computed physical parameters to converge to their limiting values. The minimum number of trials is necessarily a function of the interaction probability p, and the lattice size L. Table I shows the mean cluster size $\bar{n}$ (the average number of reacted rounds per trial) and the standard deviation S_n as functions of the number of trials (abbreviated NTR) for the bond problem in a square lattice L = 20 x 20, for the cases p = 0.4, 0.5, and 0.6. Unless otherwise noted all our computational results assumed that the initial set (ISET) consisted of one round, i.e., NINS = 1. The results of similar calculations on two other lattices of 40 x 40 and 100 x 100 are also included in Table I. Figure 3 gives a graphical display of those results. It is seen from these calculations that on the average the number of trials NTR should be at least 25% of the lattice size L and preferably equal to L or larger. It is also seen from the table that for p = 0.4, the values of $\bar{n}$ and S_n are limited by the boundary of the lattice when L = 20 x 20, but both converge to their terminal values when the value of L is increased to the larger size lattices of 40 x 40 and 100 x 100. This becomes apparent from the last two columns of Table I, where values of $\bar{n}/L$ and S_n/L are given. The values of those variables decrease significantly due to the increase in the size of L, while $\bar{n}$ and S_n remain finite at about the same value in this case. We note here that p = 0.4 is less than the known critical probability $P_c = 0.5$. The cases of p = 0.5 and 0.6 show similar behavior with regard to the number of trials NTR needed for convergence, but the values of $\bar{n}$ and S_n continue to increase with the size of the lattice as would be expected since the interaction probability $p \geq P_c$ in this case.

A rough check can be made of the computed values of $\bar{n}$ and S_n in Table I. Assume that the random variable N representing the cluster size is drawn from a population with a distribution whose mean is μ and standard deviation σ. Let samples $S_1, S_2, \ldots\ldots, S_k$ of size m be drawn from that population. Let the mean of a typical sample be denoted by $\bar{N}$, and its standard deviation by S_n. Thus if the distribution of N is characterized by (μ, σ) then the distribution of $\bar{N}$ is characterized[10] by $(\mu, \sigma/\sqrt{m})$. In other words the distribution of the mean has the same mean as the original population and its standard deviation $S_{\bar{n}} = \sigma/\sqrt{m}$. In Table I the various samples have different sizes NTR, but if we consider the samples of sizes 100 to 800 then we find by using the mean sample size $\bar{m} = 414.29$:

(i) Case p = 0.4

Mean $(\bar{N})$ = 19.71; var $(\bar{N})$ = 1.6467; $\sqrt{\bar{m}}\ S_{\bar{n}}$ = 26.12; Mean (S_n) = 26.06.

[10] *W. J. Dixon and F. J. Massey, Jr., "Introduction to Statistical Analysis," p 45, McGraw-Hill, 1969.*

Table I. Dependance of the Mean Cluster Size $\bar{n}$ and Standard Deviation S_n on the Number of Trials, NTR, and Interaction Probability p, in a Randomly Initiated Lattice L

L	p	NRT	$\bar{n}$	S_n	$\bar{n}/L$	S_n/L
20X20	0.4	10	18.90	25.5	0.047	0.064
20X20	0.4	20	27.55	29.4	0.069	0.074
20X20	0.4	30	15.87	19.63	0.040	0.049
20X20	0.4	40	17.95	26.06	0.045	0.065
20X20	0.4	50	20.54	23.60	0.051	0.059
20X20	0.4	60	14.53	16.06	0.036	0.040
20X20	0.4	80	13.96	15.98	0.035	0.040
20X20	0.4	100	21.07	29.76	0.053	0.074
20X20	0.4	200	17.32	23.91	0.043	0.060
20X20	0.4	300	21.49	29.12	0.054	0.073
20X20	0.4	400	19.09	25.41	0.048	0.064
20X20	0.4	500	19.66	24.70	0.049	0.062
20X20	0.4	600	19.21	24.19	0.048	0.060
20X20	0.4	800	20.11	25.31	0.050	0.063
40X40	0.4	500	27.39	37.63	0.017	0.024
100X100	0.4	2500	29.91	41.83	0.003	0.004
20X20	0.5	10	63.60	94.18	0.159	0.235
20X20	0.5	20	136.85	92.46	0.342	0.231
20X20	0.5	30	100.97	104.06	0.252	0.260
20X20	0.5	40	109.08	102.60	0.273	0.257
20X20	0.5	50	119.36	106.76	0.298	0.267
20X20	0.5	60	137.07	105.25	0.343	0.263
20X20	0.5	80	107.30	97.72	0.268	0.244
20X20	0.5	100	111.15	98.68	0.278	0.247
20X20	0.5	200	123.86	105.18	0.310	0.263
20X20	0.5	300	120.33	105.53	0.301	0.264
20X20	0.5	400	112.00	102.25	0.280	0.256
20X20	0.5	500	112.49	107.20	0.281	0.268
20X20	0.5	600	119.12	104.49	0.298	0.261
20X20	0.5	800	118.81	103.40	0.297	0.259
40X40	0.5	500	405.98	387.95	0.254	0.242
100X100	0.5	2500	2032.68	2206.27	0.203	0.221
20X20	0.6	10	294.80	116.25	0.737	0.291
20X20	0.6	20	285.25	140.85	0.713	0.352
20X20	0.6	30	312.90	123.10	0.782	0.308
20X20	0.6	40	325.33	92.28	0.813	0.231
20X20	0.6	50	315.40	117.68	0.789	0.294
20X20	0.6	60	293.07	136.92	0.733	0.342
20X20	0.6	80	328.69	85.66	0.822	0.214
20X20	0.6	100	319.92	100.15	0.800	0.250
20X20	0.6	200	316.00	112.40	0.790	0.281
20X20	0.6	300	310.96	115.11	0.777	0.288
20X20	0.6	400	307.61	118.67	0.769	0.297
20X20	0.6	500	315.91	111.51	0.790	0.279
20X20	0.6	600	306.88	120.09	0.767	0.300
20X20	0.6	800	313.69	113.61	0.784	0.284
40X40	0.6	500	1355.39	399.05	0.847	0.249
100X100	0.6	2500	8757.02	2357.48	0.876	0.236

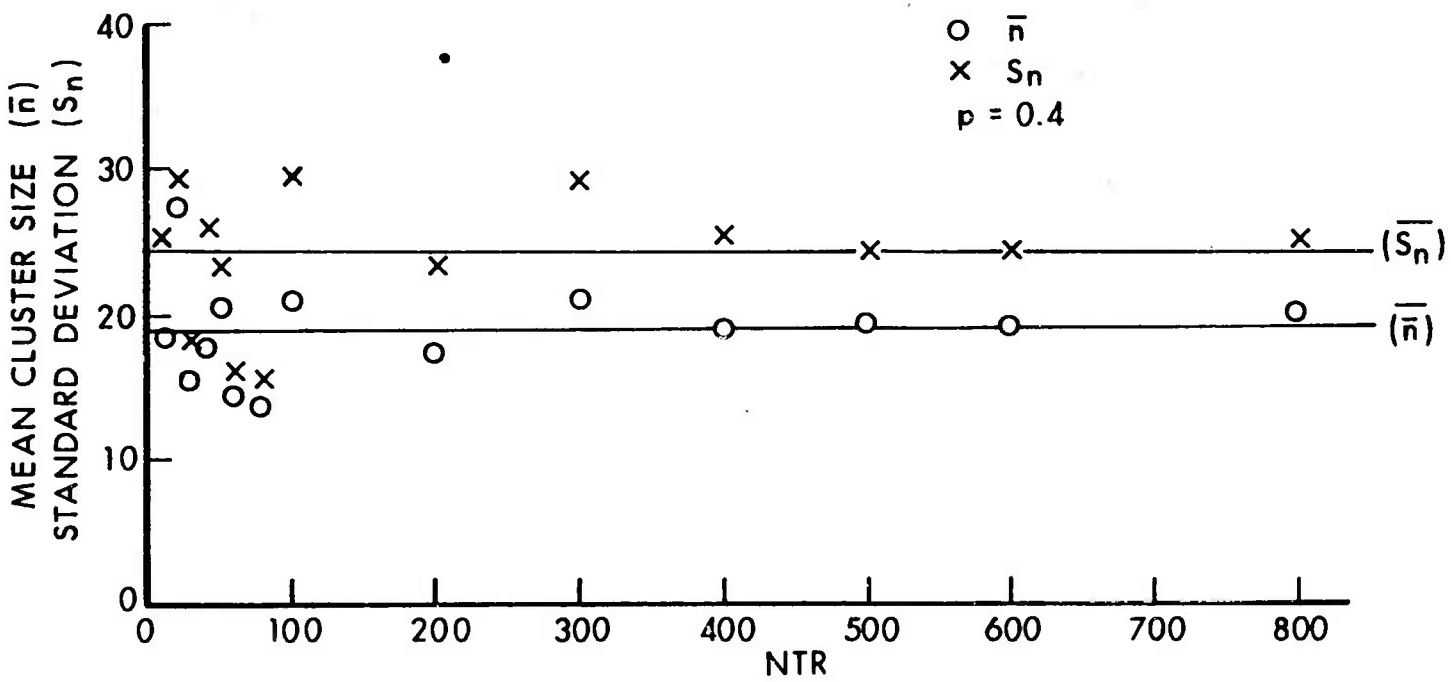


Figure 3: The Mean Cluster Size $\bar{n}$ and Standard Deviation S_n VS. Sample Size NTR, L = 20x20

(ii) Case p = 0.5

Mean $(\overline{N})$ = 116.82; Var $(\overline{N})$ = 20.7517; $\sqrt{m}\ S_{\overline{n}}$ = 92.72;
Mean (S_n) = 103.82.

(iii) Case p = 0.6

Mean $(\overline{N})$ = 312.98; Var $(\overline{N})$ = 19.4847, $\sqrt{m}\ S_{\overline{n}}$ = 89.85;
Mean (S_n)= 113.08.

Figure 4 shows a plot of the probability mass function $P[N\varepsilon I, N_o]$ that the cluster size of reacted rounds, N, lies in an interval of length, I, centered at N_o for the case p = 0.4. The probability $P[N\varepsilon I, N_o]$ is plotted at the midpoint N_o for values of NTR = 50, 100, 200, and 400. The different points were connected by curves to facilitate comparison of the different cases. The curves for NTR = 100, 200, and 400 are almost identical. Figure 5 gives a comparison of the bar plots of the probability mass functions $P[N\varepsilon I, N_o]$ defined above for the three interaction probabilities p = 0.4, 0.5, and 0.6. Different symbols indicate the points of the different cases. The interval length in both Figures 4 and 5 is I = 20.

Table II gives the cumulative probability P_n (p) of clusters whose size is at least n for various values of n and corresponding to interaction probabilities of p = 0.4 to 0.6 in steps 0.02. The lattice in this case L = 100 x 100 and the detonation was started in the center of the lattice by a single round. Figure 6 shows plots of P_n (p) for a constant n as a function of the interaction probability p. Some of the columns of Table II were not plotted to avoid crowding the figure. The probability $Q_n(p)$ as a function of p may be derived from Table II as the complement of P_n (p). Table III gives the variations of $\overline{n}$, and S_n as functions of the interaction probability, p, for the above lattice. Table IV gives the cumulative probability P_n (p) for a square lattice L = 100 x 100 which is randomly initiated by a single round. A plot of P_n (p) for this case is given in Figure 7. Table V shows the variations of the mean cluster size, $\overline{n}$, and the standard deviation $S_{\overline{n}}$ for this lattice. Columns 5 and 6 of the table show that $d\overline{n}/dp$ has a maximum at p = 0.51, which is in the neighborhood of P_c. A comparison of Tables IV and V with Tables II and III shows the effect of random initiation versus central initiation. The differences are due to the effect of the boundary. Figure 8 shows the variations and comparison of the mean cluster size in a square lattice L = 100 x 100 as a function of p for the two modes of initiation and Figure 9 shows the standard deviation as a function of p for those two cases. Examination of Tables III, and V, and Figures 8, and 9 reveal the sharp rise in the growth rate of $\overline{n}$ as p increases past the critical value of p = 0.5. In fact numerical differentiation of the values of $\overline{n}$ given in Table V reveals that $d\overline{n}/dp$ has a maximum in the neighborhood of p = 0.51, and that $d^2\overline{n}/dp^2$ has a zero in that neighborhood. A more resolved calculation in that region might locate that maximum more closely.

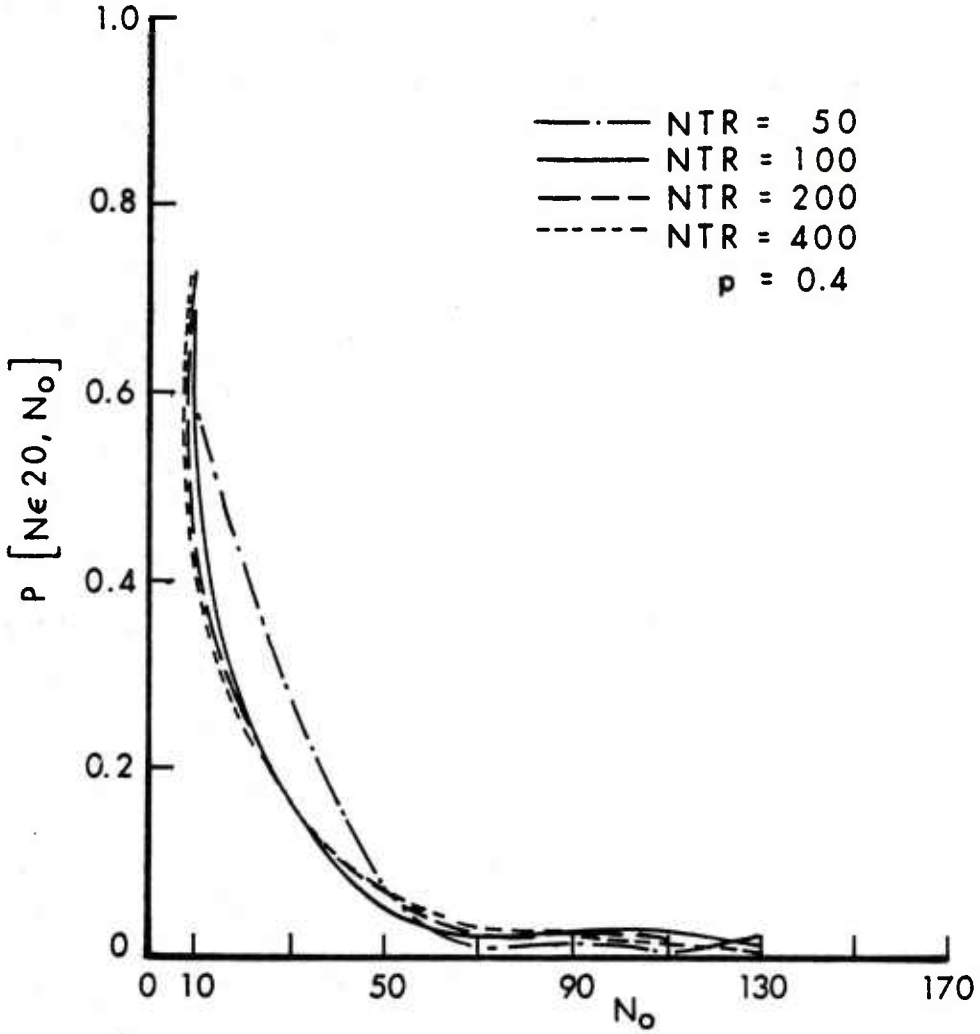


Figure 4: The Probability Mass Function $P[N\varepsilon I, N_o]$ that the Cluster Size N Lies in an Interval I Centered at N_o for Various Sample Size NTR

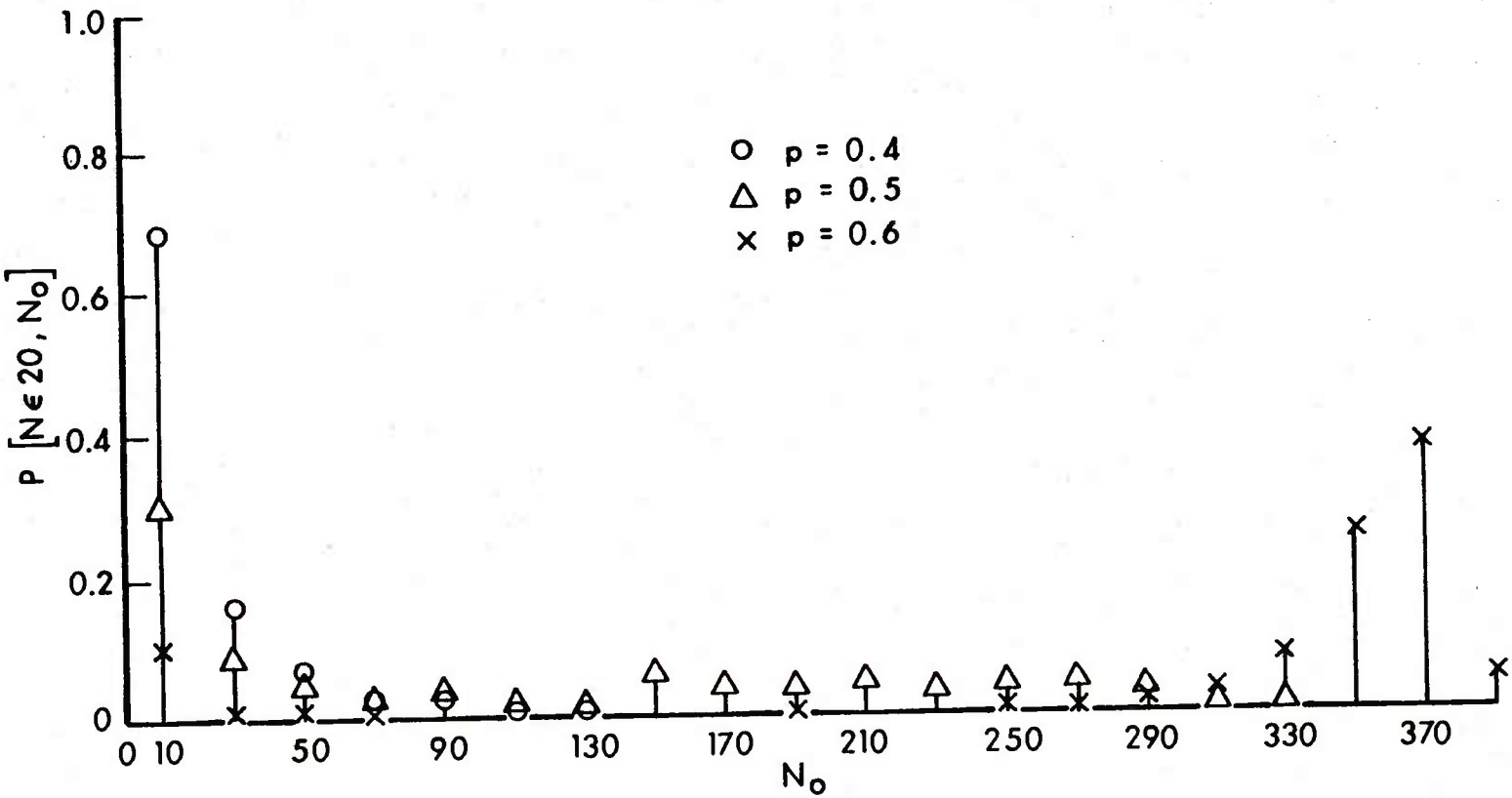


Figure 5: Comparison of the Probability Mass Functions $P[N \in I, N_o]$ for Three Interaction Probabilities

Table II. Cumulative Probability $P_n(p)$ of Clusters of at Least of Size n when the Interaction Probability is p for a Square Lattice L = 100 x 100, Centrally Initiated

p	$P_{91}(p)$	$P_{191}(p)$	$P_{291}(p)$	$P_{391}(p)$	$P_{491}(p)$	$P_{591}(p)$	$P_{691}(p)$	$P_{791}(p)$	$P_{891}(p)$	$P_{991}(p)$	$P_{1991}(p)$	$P_{2991}(p)$	$P_{3991}(p)$	$P_{4991}(p)$	$P_{5991}(p)$	$P_{6991}(p)$	$P_{7991}(p)$	$P_{8991}(p)$
.40	.09	.01	.00	.00	0	0	0	0	0	0	0	0	0	0	0	0	0	0
.42	.21	.06	.02	.01	0	0	0	0	0	0	0	0	0	0	0	0	0	0
.44	.34	.19	.12	.06	.04	.02	.01	.01	0	0	0	0	0	0	0	0	0	0
.46	.47	.35	.28	.22	.18	.14	.11	.09	.06	.05	0	0	0	0	0	0	0	0
.48	.64	.56	.51	.47	.44	.41	.39	.37	.35	.33	.15	.05	.01	0	0	0	0	0
.50	.74	.71	.69	.68	.67	.67	.66	.66	.65	.65	.58	.48	.34	.19	.07	0	0	0
.52	.81	.80	.80	.80	.79	.79	.79	.79	.79	.79	.79	.78	.77	.74	.66	.44	.02	0
.54	.85	.85	.85	.85	.85	.85	.85	.85	.85	.85	.85	.85	.85	.85	.85	.83	.69	0
.56	.91	.91	.91	.91	.91	.91	.91	.91	.91	.91	.91	.91	.91	.91	.91	.91	.90	.10
.58	.94	.94	.94	.94	.94	.94	.94	.94	.94	.94	.94	.94	.94	.94	.94	.94	.94	.89
.60	.95	.95	.95	.95	.95	.95	.95	.95	.95	.95	.95	.95	.95	.95	.95	.95	.95	.95

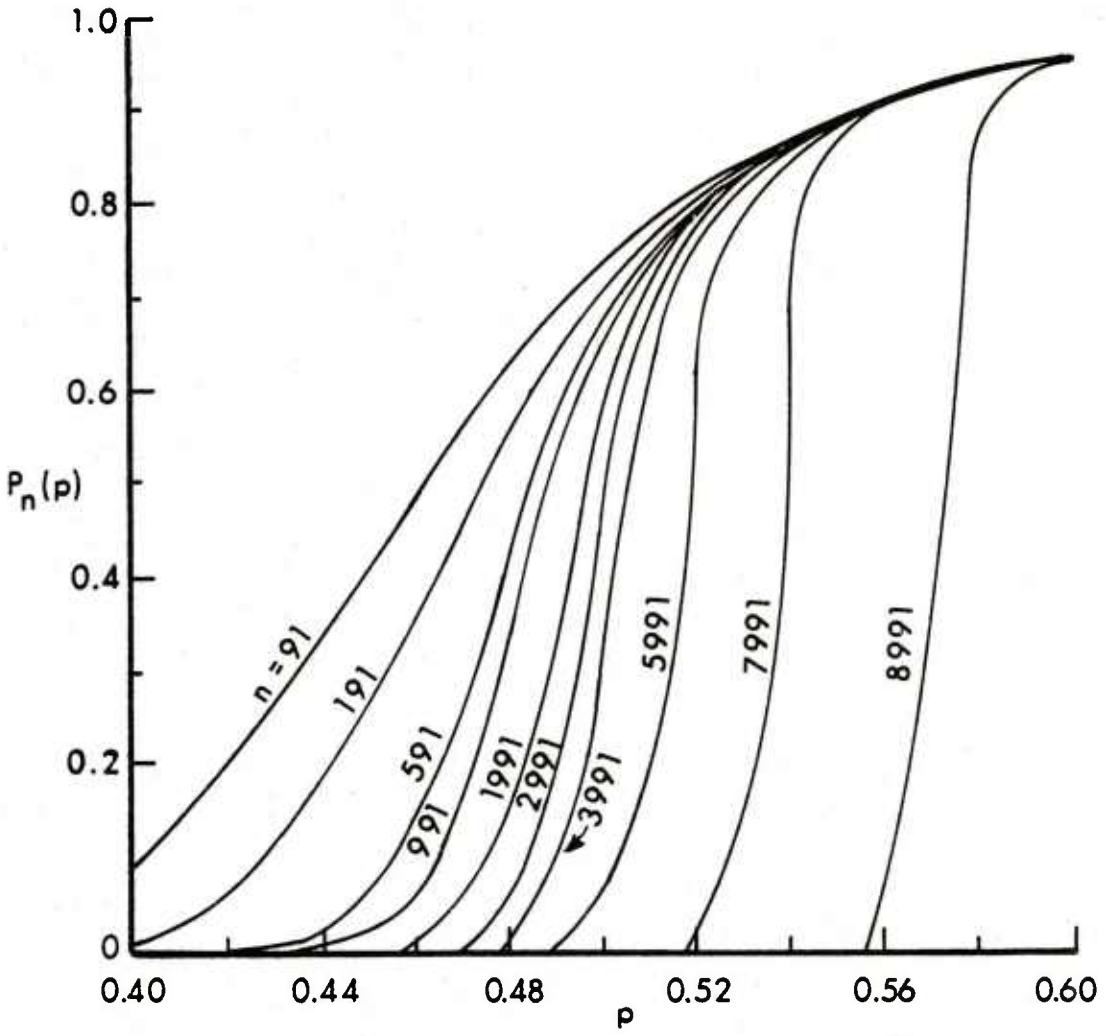


Figure 6: Cumulative Probability Mass Distribution $P_n(p)$, L = 100x100, Centrally Initiated

Table III. Variations of the Mean $\bar{n}$ and the Standard Deviation S_n in a Square Lattice L = 100 x 100, Centrally Initiated

p	NTR	$\bar{n}$	S_n	$\bar{n}/L$	S_N/L
0.40	2500	32.98	46.27	0.003	0.005
0.42	2500	54.82	78.83	0.005	0.008
0.44	2500	105.59	156.37	0.011	0.016
0.46	2500	240.67	360.02	0.024	0.036
0.48	2500	827.23	1036.91	0.083	0.104
0.50	2500	2646.77	2216.54	0.265	0.222
0.52	2500	5390.39	2913.57	0.539	0.291
0.54	2500	6973.17	2957.45	0.697	0.296
0.56	2500	7987.42	2581.81	0.799	0.258
0.58	2500	8596.88	2203.51	0.860	0.220
0.60	2500	8895.52	2100.34	0.890	0.210

Table IV. Cumulative Probability $P_n(p)$ of Clusters of at Least of Size n when the Interaction Probability is p for a Square Latice L = 100 x 100, Randomly Initiated

p	$P_{91}(p)$	$P_{191}(p)$	$P_{291}(p)$	$P_{391}(p)$	$P_{491}(p)$	$P_{591}(p)$	$P_{691}(p)$	$P_{791}(p)$	$P_{891}(p)$	$P_{991}(p)$	$P_{1991}(p)$	$P_{2991}(p)$	$P_{3991}(p)$	$P_{4991}(p)$	$P_{5991}(p)$	$P_{6991}(p)$	$P_{7991}(p)$	$P_{8991}(p)$
0.40	.08	.01	.0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0.42	.18	.05	.02	.01	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0.44	.30	.14	.07	.03	.02	.01	.00	.00	.00	0	0	0	0	0	0	0	0	0
0.46	.44	.29	.22	.16	.12	.09	.07	.06	.04	.03	0	0	0	0	0	0	0	0
0.48	.57	.48	.42	.37	.33	.30	.27	.24	.21	.19	.08	.03	.01	0	0	0	0	0
0.50	.70	.65	.62	.59	.58	.55	.53	.52	.51	.51	.41	.33	.24	.16	.06	0	0	0
0.52	.79	.77	.76	.75	.75	.74	.74	.73	.73	.73	.71	.69	.68	.65	.59	.41	.03	0
0.54	.85	.84	.84	.84	.84	.84	.84	.84	.84	.83	.83	.83	.83	.83	.83	.82	.69	0
0.56	.89	.89	.89	.89	.89	.89	.89	.89	.89	.89	.89	.89	.89	.89	.89	.89	.89	.10
0.58	.93	.93	.93	.93	.93	.93	.93	.93	.93	.93	.93	.93	.93	.93	.93	.93	.93	.89
0.60	.93	.93	.93	.93	.93	.93	.93	.93	.93	.93	.93	.93	.93	.93	.93	.93	.93	.93

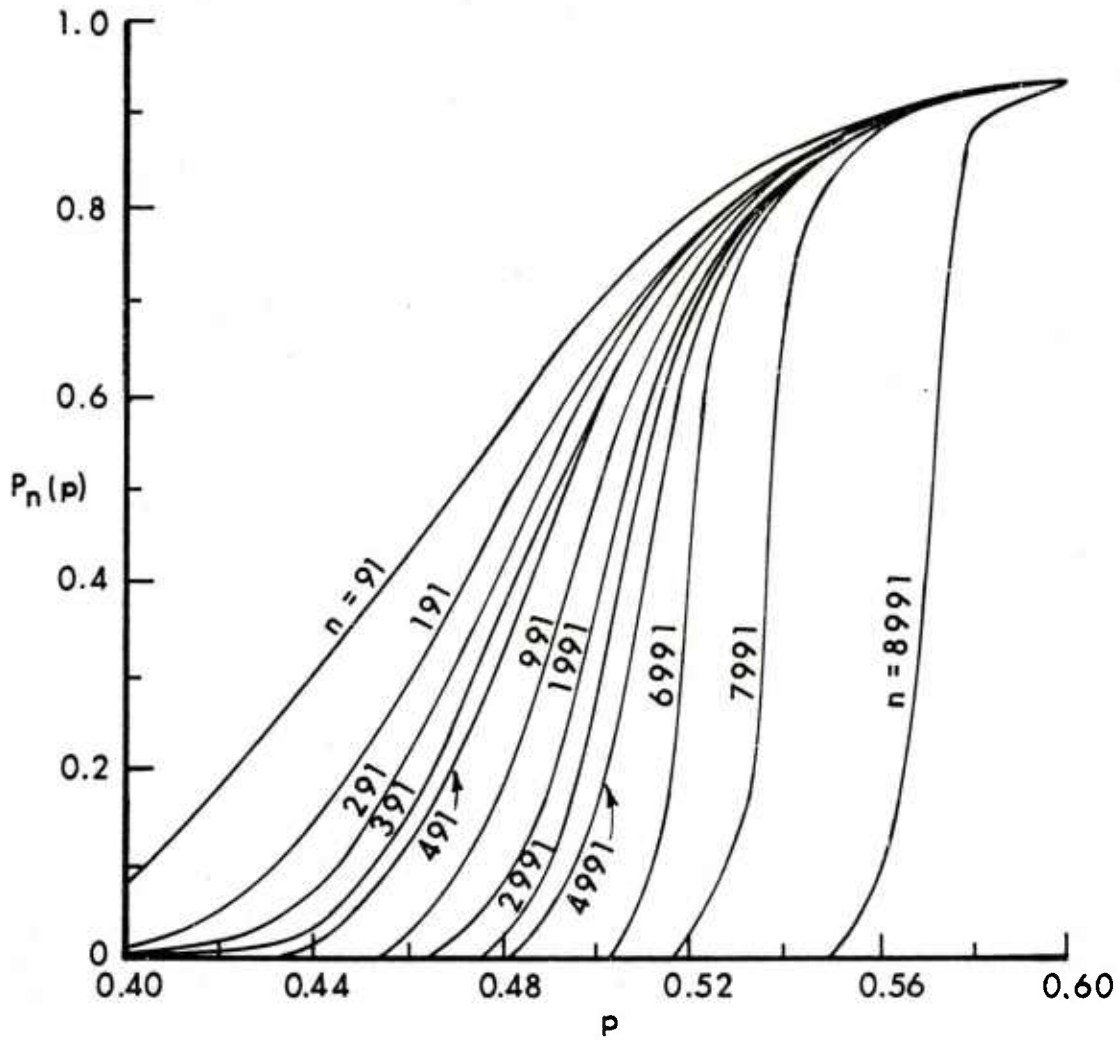


Figure 7: Cumulative Probability Mass Distribution $P_n(p)$, L = 100x100, Random Initiation

Table V. Variation of the Mean $\bar{n}$ and Standard Deviation S_n in a Square Lattice L = 100 x 100, Random Initiation

p	NTR	$\bar{n}$	S_n	$d\bar{n}/dp$	$d^2\bar{n}/dp^2$
0.40	2500	29.91	41.83		
				970	
0.42	2500	49.31	70.96		4.0275×10^4
				1775.5	
0.44	2500	84.82	123.99		17.675×10^4
				5310.5	
0.46	2500	191.03	300.16		65.3975×10^4
				18390	
0.48	2500	558.83	849.92		276.5125×10^4
				73692.5	
0.50	2500	2032.68	2206.27		345.7375×10^4
				142840	
0.52	2500	4889.48	3176.54		-222.98×10^4
				98244	
0.54	2500	6854.36	3075.74		-238.985×10^4
				50447	
0.56	2500	7863.3	2743.59		-92.9025×10^4
				31866.5	
0.58	2500	8500.63	2374.12		-95.235×10^4
				12819.5	
0.60	2500	8757.02	2357.48		

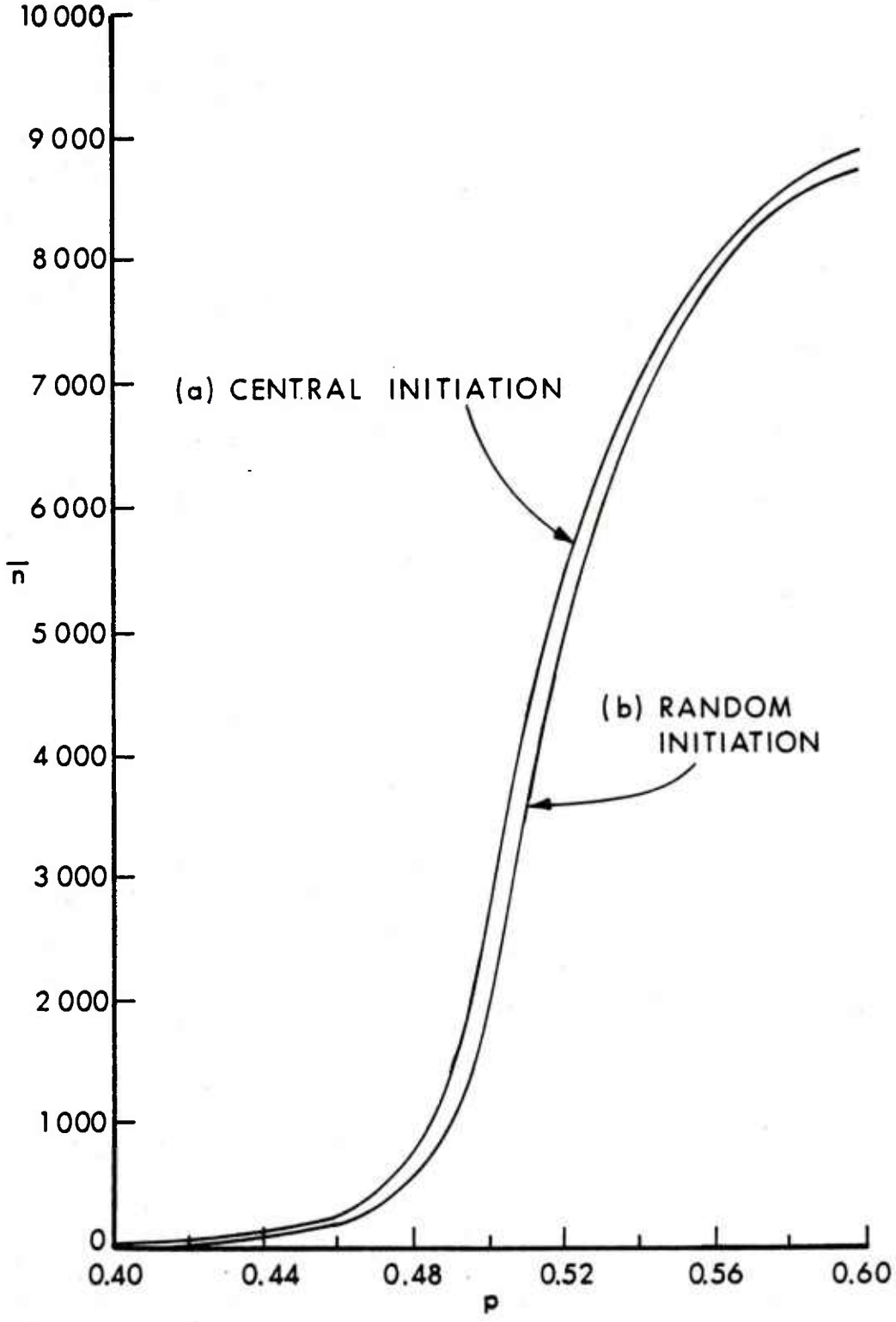


Figure 8: Mean Cluster Size Versus p in a Square Lattice

L = 100x100

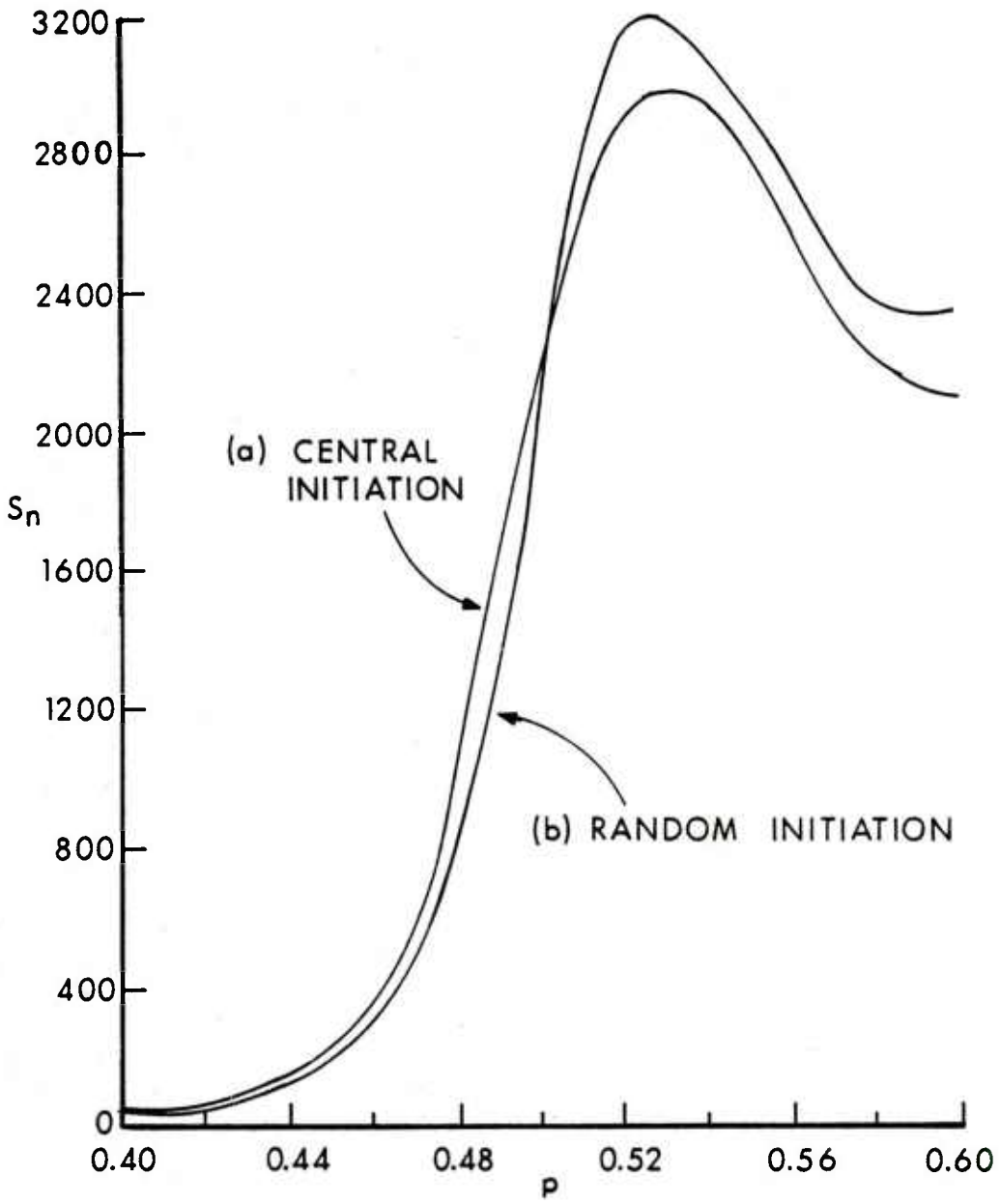


Figure 9: Standard Deviation Versus p in a Square Lattice

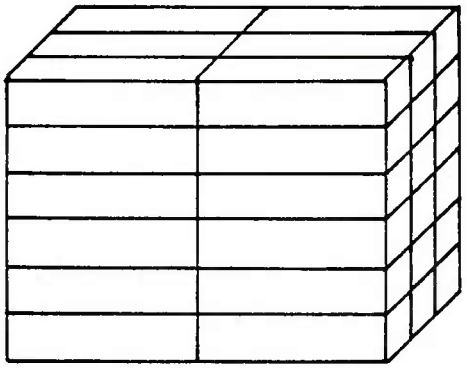
L = 100x100

Figure 9 remarkably shows that the standard deviation curves for the two modes of initiation cross at the critical value of p = 0.5.

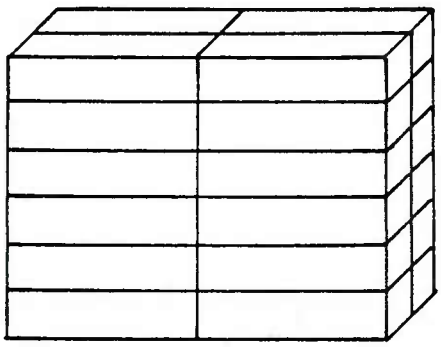
The cost of conducting full scale tests on ammunition stores is high, hence, experimentally one can conduct tests on small scale stack configurations such as those shown in Figures 10 and 11. The results of such tests are then used to extrapolate and make predictions for the larger stores. Alternatively one can utilize the results of the small scale test to compute the interaction probability p for the lattice of interest, and then utilize the present model to predict the survivability (or vulnerability) of ammunition stores of any size. Such calculations can be performed quickly and economically. Table VI shows the results of a calculation for a three dimensional lattice $L_1 = 2 \times 3 \times 6$ which is shown schematically in the top of Figure (10a). The above table shows a parametric study in terms of p, of the probability $Q_n(p)$ that the cluster size of reacted rounds is less than n. In some sense $Q_n(p)$ can be considered as a measure of survivability (or vulnerability) of the ammunition store. Figure 12 shows a plot of the probability mass function $Q_2(p)$ which is the probability that the detonation of an initial round in the stack will not propagate to other rounds. Table VII shows the probability $Q_n(p)$ for the lattice $L_2 = 3 \times 2 \times 10$ shown in Figure (11a). The equation

$$P_n(p) + Q_n(p) = 1$$

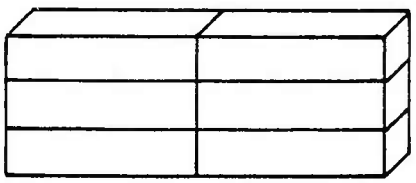
can be used in conjunction with the above tables to infer the probability $P_n(p)$. Figure 13 shows a plot of $Q_2(p)$ as a function of p for the pallet in Figure (11a), which is the probability that the reaction does not propagate beyond the initial round. Table VIII gives the mean cluster size $\bar{n}$ and the standard deviation S_n for lattices L_1 and L_2 as functions of p. Figure 14 shows a standard storage magazine for the 155mm projectile partially full, and containing 36 x 40 x 3 ammunition boxes. We applied the present model to study the vulnerability of this magazine in terms of the interaction probability p. The magazine was assumed to be full, and containing $L_3 = 40 \times 40 \times 5$ boxes. Table IX shows the probability $Q_n(p)$ for L_3 for values of p from 0.10 to 0.55 in increments of 0.05 and for values of n from 11 to 7891 in steps of 10 at first and 100 later on. Table X reveals the large increase in the growth rate of $\bar{n}$ as p increase again past the critical probability for the cubic lattice. As a matter of fact $d\bar{n}/dp$ has a maximum in the neighborhood of p = 0.325 as can be seen by numerically differentiating the values of $\bar{n}$ in Table X. Two factors influence the value of p at which $d\bar{n}/dp$ has a maximum, first the resolution of the calculations, and secondly the effect of the boundary due to the finiteness of our lattice. A smaller step in p would result in a more accurate location of the maximum of $d\bar{n}/dp$. A second more resolved calculation with smaller steps in p and greater number of trials placed the maximum value of $d\bar{n}/dp$ at p = 0.305.



(a) 36 BOXES
(STANDARD PALLET SIZE)

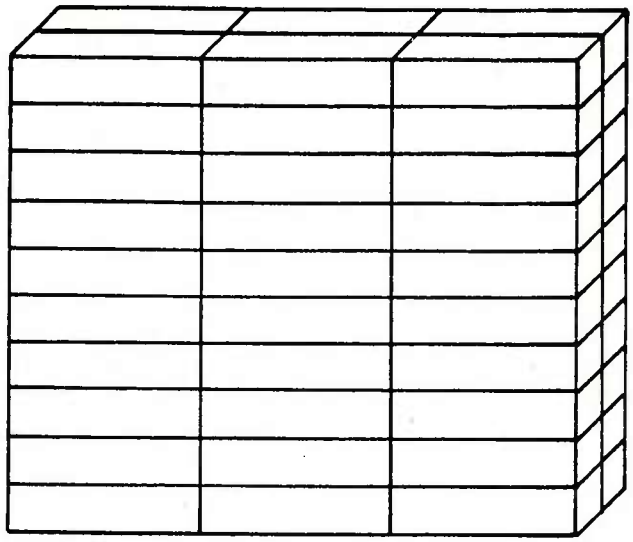


(b) 24 BOXES

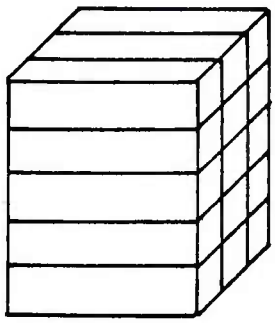


(c) 6 BOXES

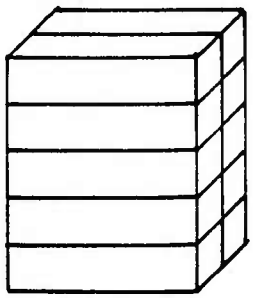
Figure 10: Stack Configurations Used for 81mm Tests



(a) 60 BOXES



(b) 15 BOXES
(STANDARD PALLET SIZE)



(c) 10 BOXES

Figure 11: Stack Configurations Used for 105mm Tests

Table VI. The Probability Q_n (p) that the Cluster Size of Detonated Rounds is Less than n, for a 2 x 3 x 6 Pallet.

N \ P	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
1	0	0	0	0	0	0	0	0	0
2	0.60	0.44	0.20	.15	0.04	0.02	0.01	0	0
3	0.90	0.60	0.36	0.21	0.07	0.03	0.01	0	0
4	0.97	0.74	0.45	0.27	0.09	0.04	0.01	0	0
5	0.98	0.83	0.54	0.31	0.09	0.04	0.01	0	0
6	0.99	0.88	0.60	0.35	0.10	0.05	0.01	0	0
7	0.99	0.93	0.66	0.37	0.11	0.06	0.01	0	0
8	1	0.94	0.70	0.39	0.12	0.06	0.01	0	0
9	1	0.95	0.75	0.41	0.12	0.06	0.01	0	0
10	1	0.96	0.77	0.44	0.14	0.06	0.01	0	0
11	1	0.96	0.80	0.47	0.14	0.06	0.01	0	0
12	1	0.98	0.84	0.47	0.17	0.06	0.01	0	0
13	1	0.99	0.84	0.50	0.20	0.06	0.01	0	0
14	1	1	0.88	0.52	0.21	0.06	0.01	0	0
15	1	1	0.91	0.55	0.22	0.07	0.01	0	0
16	1	1	0.92	0.58	0.23	0.07	0.01	0	0
17	1	1	0.93	0.59	0.24	0.07	0.01	0	0
18	1	1	0.94	0.60	0.27	0.07	0.01	0	0
19	1	1	0.95	0.62	0.29	0.07	0.01	0	0
20	1	1	0.97	0.67	0.31	0.07	0.02	0	0
21	1	1	0.98	0.69	0.31	0.08	0.02	0	0
22	1	1	0.98	0.73	0.31	0.08	0.02	0	0
23	1	1	0.99	0.75	0.33	0.09	0.02	0	0
24	1	1	0.99	0.77	0.35	0.09	0.02	0	0
25	1	1	1	0.81	0.38	0.10	0.02	0	0
26	1	1	1	0.84	0.40	0.11	0.02	0	0
27	1	1	1	0.86	0.41	0.11	0.02	0	0
28	1	1	1	0.87	0.43	0.12	0.02	0	0
29	1	1	1	0.90	0.47	0.13	0.02	0	0
30	1	1	1	0.92	0.51	0.14	0.02	0	0
31	1	1	1	0.95	0.57	0.16	0.02	0	0
32	1	1	1	0.99	0.66	0.21	0.02	0	0
33	1	1	1	0.99	0.73	0.25	0.03	0	0
34	1	1	1	0.99	0.83	0.36	0.06	0.01	0
35	1	1	1	1	0.88	0.55	0.15	0.02	0
36	1	1	1	1	0.95	0.80	0.35	0.11	0.2

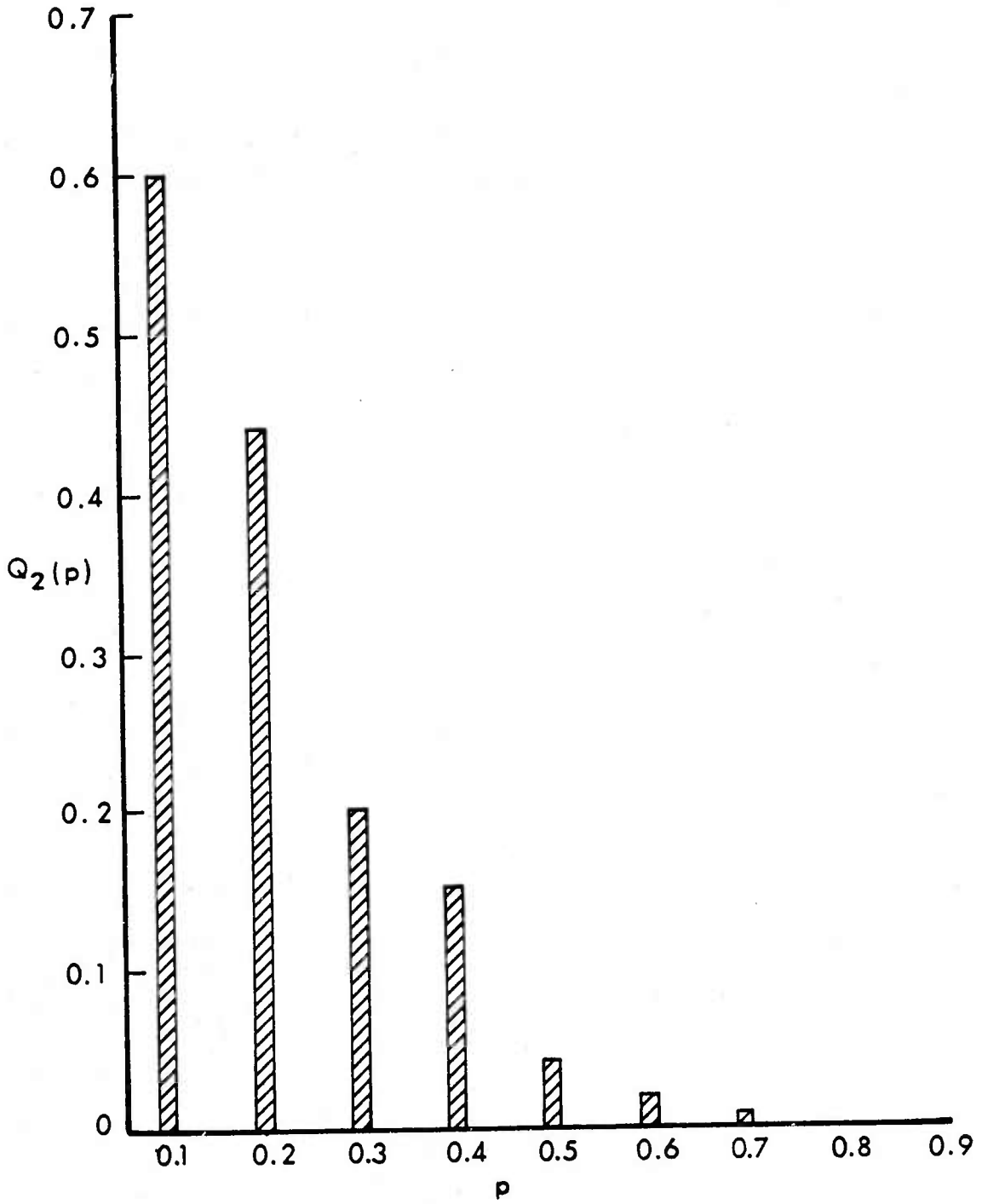


Figure 12: The Probability that the Detonation does not Propagate Beyond the Initial Set VS. p,in a Lattice L_1 = 2x3x6

Table VII. The Probability Q_n (p) that the Cluster Size of Reacted Rounds is Less than n, for L = 3 x 2 x 10 Pallet.

n \ p	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
1	0	0	0	0	0	0	0	0	0
2	0.63	0.41	0.21	0.13	0.03	0.02	0	0.01	0
3	0.91	0.53	0.36	0.22	0.04	0.03	0	0.01	0
4	0.96	0.69	0.46	0.25	0.05	0.04	0	0.01	0
5	0.97	0.75	0.52	0.27	0.06	0.04	0	0.01	0
6	0.99	0.82	0.60	0.31	0.06	0.04	0	0.01	0
7	1	0.88	0.66	0.33	0.06	0.04	0	0.01	0
8	1	0.90	0.70	0.36	0.07	0.04	0	0.01	0
9	1	0.93	0.76	0.37	0.09	0.04	0	0.01	0
10	1	0.94	0.78	0.39	0.09	0.04	0	0.01	0
11	1	0.95	0.83	0.42	0.09	0.04	0	0.01	0
12	1	0.96	0.84	0.42	0.11	0.04	0	0.01	0
13	1	0.97	0.84	0.46	0.13	0.04	0	0.01	0
14	1	0.98	0.86	0.47	0.13	0.04	0	0.01	0
15	1	0.99	0.87	0.50	0.14	0.04	0	0.01	0
16	1	0.99	0.88	0.53	0.16	0.04	0	0.01	0
17	1	0.99	0.89	0.54	0.18	0.04	0	0.01	0
18	1	1	0.90	0.54	0.18	0.04	0	0.01	0
19	1	1	0.90	0.56	0.20	0.04	0	0.01	0
20	1	1	0.91	0.58	0.22	0.05	0	0.01	0
21	1	1	0.93	0.60	0.22	0.06	0	0.01	0
22	1	1	0.94	0.61	0.22	0.06	0	0.01	0
23	1	1	0.95	0.61	0.22	0.06	0	0.01	0
24	1	1	0.95	0.64	0.23	0.06	0	0.01	0
25	1	1	0.96	0.68	0.23	0.06	0	0.01	0
26	1	1	0.96	0.70	0.25	0.06	0	0.01	0
27	1	1	0.97	0.73	0.25	0.06	0	0.01	0
28	1	1	0.97	0.73	0.26	0.06	0	0.01	0
29	1	1	0.97	0.74	0.27	0.06	0	0.01	0
30	1	1	0.97	0.76	0.28	0.06	0	0.01	0
31	1	1	0.97	0.77	0.29	0.07	0	0.01	0
32	1	1	0.98	0.78	0.30	0.07	0	0.01	0
33	1	1	0.99	0.79	0.30	0.07	0	0.01	0
34	1	1	1	0.79	0.31	0.08	0	0.01	0
35	1	1	1	0.81	0.32	0.09	0	0.01	0
36	1	1	1	0.82	0.32	0.10	0	0.01	0
37	1	1	1	0.82	0.33	0.10	0	0.01	0
38	1	1	1	0.83	0.33	0.11	0	0.01	0
39	1	1	1	0.85	0.35	0.11	0	0.01	0
40	1	1	1	0.87	0.38	0.12	0	0.01	0
41	1	1	1	0.88	0.39	0.12	0.01	0.01	0
42	1	1	1	0.88	0.41	0.12	0.02	0.01	0
43	1	1	1	0.89	0.43	0.12	0.02	0.01	0

Table VII. (Cont'd) The Probability Q_n (p) that the Cluster Size of Reacted Rounds is Less than n, for L = 3 x 2 x 10 Pallet.

n \ p	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
44	1	1	1	0.89	0.44	0.13	0.02	0.01	0
45	1	1	1	0.91	0.45	0.13	0.02	0.01	0
46	1	1	1	0.92	0.46	0.13	0.02	0.01	0
47	1	1	1	0.93	0.49	0.14	0.02	0.01	0
48	1	1	1	0.95	0.52	0.14	0.02	0.01	0
49	1	1	1	0.96	0.54	0.15	0.02	0.01	0
50	1	1	1	0.97	0.59	0.16	0.02	0.01	0
51	1	1	1	0.99	0.62	0.17	0.02	0.01	0
52	1	1	1	0.99	0.67	0.18	0.02	0.01	0
53	1	1	1	1	0.70	0.20	0.02	0.01	0
54	1	1	1	1	0.76	0.23	0.02	0.01	0
55	1	1	1	1	0.79	0.28	0.02	0.01	0
56	1	1	1	1	0.86	0.34	0.03	0.01	0
57	1	1	1	1	0.90	0.41	0.03	0.02	0
58	1	1	1	1	0.95	0.52	0.10	0.02	0
59	1	1	1	1	0.97	0.67	0.24	0.05	0
60	1	1	1	1	1	0.87	0.47	0.16	0

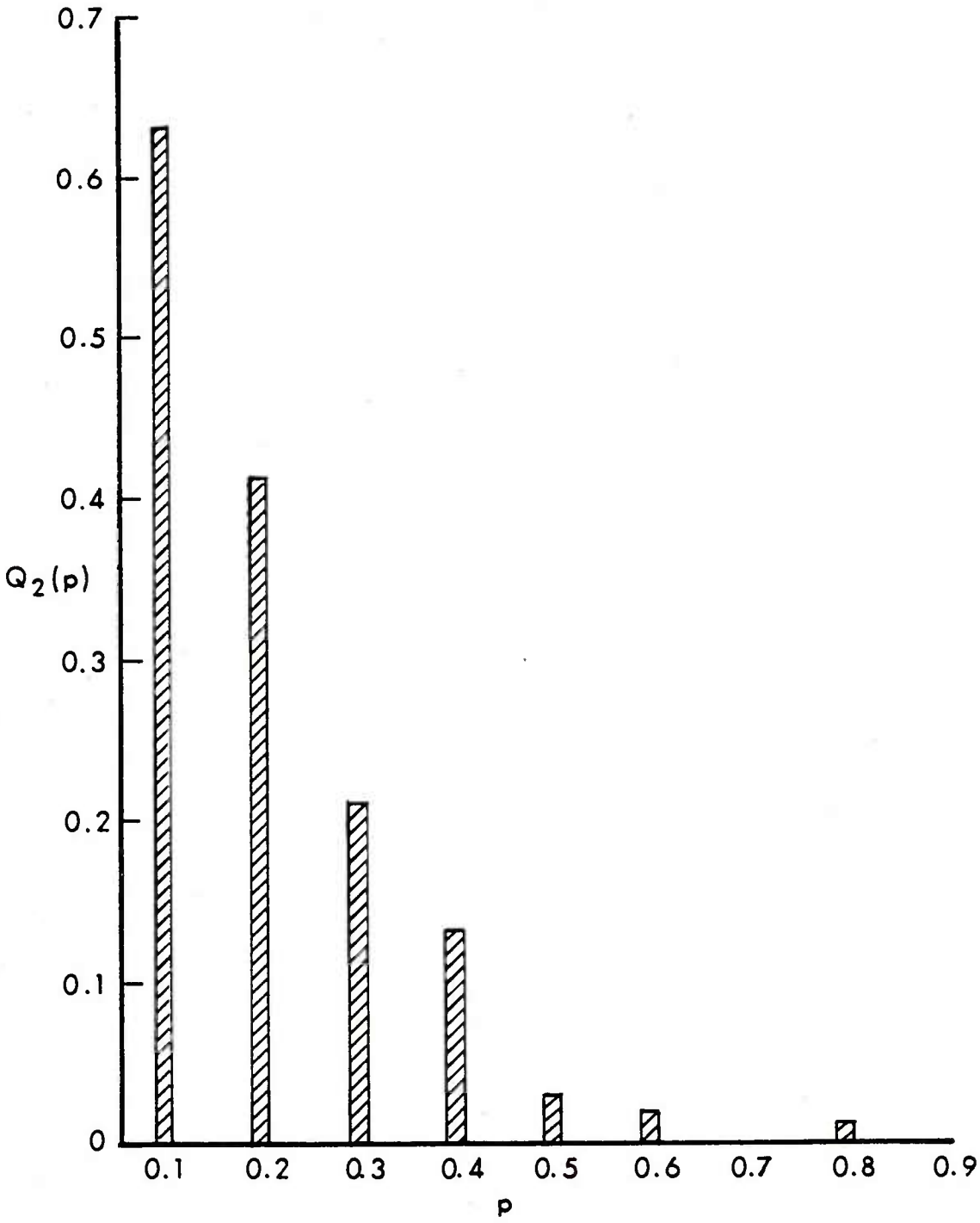


Figure 13: The Probability that the Detonation does not Propagate Beyond the Initial Set VS. p, in a Lattice L_2 = 3x2x10

Table VIII. Variations of the Mean $\bar{n}$ and Standard Deviation S_n for Lattices L_1 and L_2

p	$\bar{n}(L_1)$	$S_n(L_1)$	$\bar{n}(L_2)$	$S_n(L_2)$
0.1	1.59	0.98	1.56	0.97
0.2	2.82	2.58	3.36	3.24
0.3	6.14	5.63	6.83	7.43
0.4	13.52	10.29	18.41	15.64
0.5	24.42	10.72	39.43	17.59
0.6	31.51	8.17	52.55	13.18
0.7	35.04	3.72	58.74	4.14
0.8	35.70	2.49	59.21	5.88
0.9	35.99	0.12	60.00	0.07

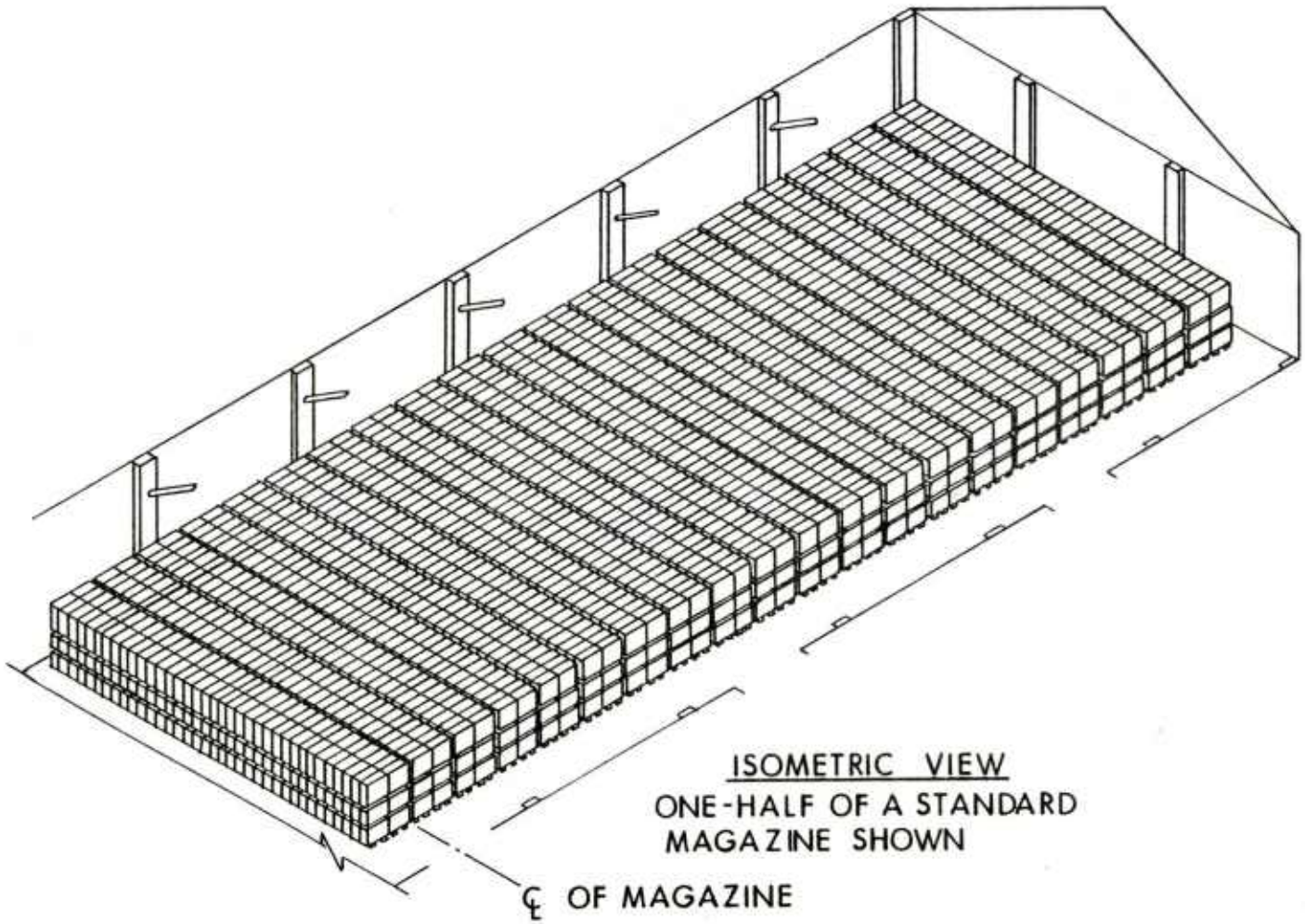


Figure 14: Standard Magazine Storage Procedures for 155mm Projectile

Table IX. The Probability Q_n (p) that the Cluster Size of Reacted Rounds in a 40 x 40 x 5 Store is less than n

n \ p	0.10	0.15	0.20	0.25	0.30	0.35	0.40	0.45	0.50	0.55
11	1	0.94	0.80	0.56	0.36	0.18	0.12	0.09	0.05	0.02
21	1	0.99	0.90	0.67	0.41	0.19	0.12	0.09	0.05	0.02
31	1	1	0.94	0.73	0.44	0.19	0.12	0.09	0.05	0.02
41	1	1	0.97	0.77	0.45	0.19	0.12	0.09	0.05	0.02
51	1	1	0.98	0.81	0.46	0.20	0.12	0.09	0.05	0.02
61	1	1	0.99	0.83	0.47	0.20	0.12	0.09	0.05	0.02
71	1	1	1	0.85	0.48	0.20	0.12	0.09	0.05	0.02
81	1	1	1	0.86	0.49	0.20	0.12	0.09	0.05	0.02
91	1	1	1	0.88	0.49	0.20	0.12	0.09	0.05	0.02
191	1	1	1	0.95	0.53	0.20	0.12	0.09	0.05	0.02
291	1	1	1	0.98	0.55	0.20	0.12	0.09	0.05	0.02
391	1	1	1	0.99	0.57	0.20	0.12	0.09	0.05	0.02
491	1	1	1	1	0.58	0.20	0.12	0.09	0.05	0.02
591	1	1	1	1	0.60	0.20	0.12	0.09	0.05	0.02
691	1	1	1	1	0.61	0.20	0.12	0.09	0.05	0.02
791	1	1	1	1	0.62	0.20	0.12	0.09	0.05	0.02
891	1	1	1	1	0.62	0.20	0.12	0.09	0.05	0.02
991	1	1	1	1	0.64	0.20	0.12	0.09	0.05	0.02
1991	1	1	1	1	0.70	0.20	0.12	0.09	0.05	0.02
2991	1	1	1	1	0.82	0.20	0.12	0.09	0.05	0.02
3991	1	1	1	1	0.95	0.20	0.12	0.09	0.05	0.02
4991	1	1	1	1	1	0.20	0.12	0.09	0.05	0.02
5991	1	1	1	1	1	0.29	0.12	0.09	0.05	0.02
6991	1	1	1	1	1	1	0.33	0.09	0.05	0.02
7491	1	1	1	1	1	1	1	0.67	0.05	0.02
7891	1	1	1	1	1	1	1	1	1	1

Table X. The Mean Cluster Size $\bar{n}$ and the Standard Deviation S_n for a 40 x 40 x 5 Store

p	$\bar{n}$	S_n	$d\bar{n}/dp$	$d^2\bar{n}/dp^2$
0.10	2.03	1.70		
			25.4	
0.15	3.30	3.65		1200
			85.4	
0.20	7.57	11.83		10620
			616.4	
0.25	38.39	78.65		427260
			21979.4	
0.30	1137.36	1482.97		1076500
			75804.4	
0.35	4927.58	2448.49		-1023132
			24647.8	
0.40	6159.97	2317.35		-228676
			13214.0	
0.45	6820.67	2118.38		-46312
			10898.4	
0.50	7365.59	1617.13		-88836
			6456.6	
0.55	7688.42	1125.93		

V. CONCLUSIONS

A simple stochastic model has been developed using the framework of percolation theory. The model can be used to treat both an unoriented bond percolation problem and/or a site percolation problem. The bond problem formulation is the more useful for the study of the problem of survivability (vulnerability) of ammunition stores and magazines given a hit. The application of the model to a specific store or magazine requires only a knowledge of the geometry and the interaction probability p. Small scale tests can determine the interaction probability and a calculation with our model will determine the survivability (vulnerability) of an ammunition store for the given interaction probability. Such calculations reduce the need for many of the large scale tests, result in substantial savings, and can be performed rather quickly. The use of a sometimes desired large sample size, to improve the accuracy of the results would only add marginally to the cost of the calculations. Furthermore, the present model provides a probability mass distribution for each cluster size together with the mean cluster size $\bar{n}$ and the standard deviation S_n for a given interaction probability p.

The results of our sample calculations on both two and three dimensional lattices indicate that ammunition store survivability dictates that the interaction probability, p, be kept less than the critical probability P_c for the lattice in question and preferably $p \ll P_c$. The critical probability for the two dimensional square lattice, $P_c = 0.5$. For this case our calculations on L = 100 x 100 show that if $p < 0.4$ then the average number of rounds lost per encounter is less than 30, and the probability of keeping the losses less than or equal to 90 rounds is 0.92. For the three dimensional cubic lattice $P_c = 0.254$ our calculations on the lattice L_3 indicate that if we keep $p \leq 0.2$ then on the average we lose less than 8 rounds per encounter and with probability of 0.90 our losses are less than 21 rounds. Our results here show that the mean cluster $\bar{n}$ takes a sharp rise as p increases through P_c. The experimental investigations[2,3] cited show that the interaction probability p can be reduced by a variety of methods such as the treatment of packaging materials with suitable chemicals, such as fire retardant, by the use of coatings around the charges, the use of less sensitive fillers or by increasing the separation distances between rounds.

The present model can be used for a parametric study, in terms of p, of the survivability of a given ammunition store or magazine. Such calculations were performed here for the lattices L = 100 x 100, L_1 = 2 x 3 x 6, L_2 = 3 x 2 x 10, and L_3 = 40 x 40 x 5. Although for the purposes of this report the results of our calculations on L_3 were done in steps of 10 and 100, it is a simple matter to perform such calculations in more details and with more resolution for a case of specific interest.

Finally our results suggest that $d\bar{n}/dp$ has a maximum at the critical value of p, i.e., $p = P_c$. If we generalize our observation and define

for a given lattice, the critical probability to be the value of the interaction probability p for which $d\bar{n}/dp$ is a maximum, then our results suggest that for the lattice L = 100 x 100, $P_c \approx 0.51$ and for the lattice L_3 = 40 x 40 x 5, $P_c \approx 0.305$ as was indicated by our detailed calculations. The fact that the third dimension of this lattice is small makes this lattice behave intermediately between an infinite square and an infinite cube lattice. We have not incorporated any calculations for a site percolation problem, or any calculations for a bond problem where the initial reaction set consists of more than one round (NINS > 1), in order to keep the size of this report to a reasonable level. Possible modifications of this model would make the interaction probability a function of the relative orientation of the rounds to each other and/or make it a function of the physical conditions at the detonation front.

Finally we included in this report an Appendix containing a listing of our computer program which is written in Fortran IV. The Appendix contains an explanation of the symbols and some helpful hints for its usage. The code is rather easy to use for an analyst with some knowledge of probability and with a mathematical background. Knowledge of percolation theory is desirable although not absolutely necessary. Blind usage of the code by a person with primarily programming interest can lead to amazing and spectacular results and is therefore not recommended.

ACKNOWLEDGMENTS

The author expresses his gratitude to Dr. Philip Howe who interested him in this problem and pointed out the relationship of this problem with percolation theory. The author is also indebted to Mr. Ralph Shear who proposed one of the early versions of the model and provided several technical discussions.

APPENDIX

The following is a listing of the code developed on the basis of the model outlined in the body of this report. The code consists of the main program called PROGRAM MAIN, and two subroutines DET 2 and DET 3 which are used in two or three dimensions, when the number of rounds detonating on the initial hit is greater than one. DET 2, or DET 3 selects the initial detonation set. To use the code in one dimension with two or more detonations initially an analogous subroutine DET 1 would have to be added.

The usage of the code requires six input cards written in the appropriate format

Card 1:

ITYPE Variable indicating type of problem desired

ITYPE = 0 for a Bond problem
ITYPE =-1 for a Site problem
IDIM = 1, 2, or 3 depending on the dimensions of the problem
IX, IY, IZ = number of nodes in the x, y, or z direction respectively
NTRIAL = number of trials desired per case.

Card 2:

NNP = Number of different interaction probabilities desired
Q(k) = An array representing the interaction probabilities desired.

Card 3:

NINS = Number of initiation sites (rounds) desired on the initial hit
ISTEP = Number of rounds desired per step or block in sorting reaction clusters.

NUM = Number of cluster sizes for which cumulative probabilities are desired.

Card 4:

ITALLY(L) = An array representing cluster sizes for which cumulative probabilities are desired.

Card 5:

NQP = Number of probabilities for which certain hierarchy of reaction clusters is desired to be printed.
QP(I) = An Array of probabilities for which the hierarchy of reaction clusters is desired to print.

Card 6:

NCY = Number of cycles for which the hierarchy of reaction cluster is desired per probability
NPCY(I) = An array representing the cycles on which the hierarchy of reaction cluster is desired for each QP(I) value.

The output is simple and easy to understand. The IH BLOCK contains a histogram of the process in the number of trials (NTRIAL) specified in steps of ISTEP. The mean cluster size and the standard deviation (SIGMA or SIGALT) are printed. PNP( ) and QNP( ) stand for $P_n(p)$ and $Q_n(p)$ as outlined in the text of the report. The hierarchy of reaction clusters is printed out if input specified for the desired interaction probabilities and for the desired cycles. Some of the input is printed at the end of the run.

```
      PROGRAM MAIN (INPUT,OUTPUT,TAPE5=INPUT,TAPE6=OUTPUT)
  200 FORMAT(1H ,20(I4,2X))
  201 FORMAT(1HO,' MEAN NO. OF DET. =',FB.2,' SIGMA =',FB.2,' SIGALT =',
     1 FB.2)
  202 FORMAT(1H ,2(I4,2X))
  203 FORMAT(1HO,'R=',I4,2X,'T=',I4,2X,'V=',I4,2X,'NDET='I4)
  204 FORMAT(1H ,I4)
  205 FORMAT(1H ,E12.5)
  206 FORMAT(1H ,' Q =',FB.2,//)
  207 FORMAT(1H ,' ***** IH BLOCK *****',//)
  208 FORMAT(1HO,'Q=',F5.2,'  NCT=',I5)
  209 FORMAT(' R=',I4,' T=',I4,' V=',I4,'NDET=',I4//(' X=',I3,2X,'Y=',I3
     1,2X,'Z=',I3,5X))
  210 FORMAT(1H1)
  211 FORMAT(1HO,'IX=',I3,5X,'IY=',I3,5X,'IZ=',I3,5X,'NTRIAL=',I5,5X,'ST
     1EP SIZE=',I3,5X,'NO. OF INITIAL DETONS.=',I3)
  215 FORMAT(6I5)
  220 FORMAT(I5,(10F5.2))
  221 FORMAT (I5,10F5.2)
  222 FORMAT(2I5/ (2I5,5X))
  223 FORMAT(16I5)
  224 FORMAT(1HO,'***THIS IS A SITE PROBLEM***ITYPE=-1')
  225 FORMAT(1HO,'***THIS IS A BOND PROBLEM***ITYPE= 0')
  227 FORMAT(1H ,'PNP(',I4,') =',F5.2,5X,'QNP(',I4,') =',F5.2,5X,'TOTAL
     1=',I5)
      INTEGER B(6), C(6),D(6),SVNDET
      DIMENSION ND(2000),Q(25),QP(10),NPCY(10),ITA(60)
      DIMENSION P(900),IH(900),ITALLY(60),PNP(60),  NTOTAL(60),QNP(60)
      COMMON/COORD/R(1000),T(1000),V(1000)
      INTEGER AR(1000),AT(1000),AV(1000),R,T,V
      COMMON/KIWAN/INO(40,40,5)
      LEVEL 2,IND
      B(1)=1$B(2)=-1$B(3)=0$B(4)=0$B(5)=0$B(6)=0
      C(1)=0$ C(2)=0$ C(3)=1$ C(4)=-1$ C(5)=0$ C(6)=0
      D(1)=0$ D(2)=0$ 0(3)=0$ D(4)=0$D(5)=1$ D(6)=-1
      IP = 1
      NCT = 1
C     *** ITYPE=-1 FOR A (SITE) PROBLEM***ITYPE=0 FOR A (BOND) PROBLEM***
      READ 215,ITYPE,IDIM,IX,IY,IZ,NTRIAL
      READ 220, NNP,(Q(K),K=1,NNP)
      READ 215, NINS,ISTEP,NUM
      READ 223,(ITALLY(L),L=1,NUM)
    2 READ 221,NQP,(QP(I),I=1,NQP)
      READ 223,NCY,(NPCY(I),I=1,NCY)
      NP=IX*IY*IZ/ISTEP$XNP=NP$JJ=1$IPR=1$ NCOUNT=0 $ STEP=ISTEP
      DO 1 MP=1,NP
      XMP=MP
      P(MP) =STEP*XMP
      IH(MP)=0
    1 CONTINUE
    5 DO 7 II = 1,IX
      R(II)=0
    7 CONTINUE
      DO 9 IJ = 1,IY
      T(IJ)=0
    9 CONTINUE
      DO 11 IK= 1,IZ
      V(IK)=0
   11 CONTINUE
      DO 20 IB = 1,IX
```

```
      DO 18 IC = 1,IY
      DO 16 ID= 1,IZ
      IND(IB,IC,ID)=ITYPE
   16 CONTINUE
   18 CONTINUE
   20 CONTINUE
      VB=0.
      I=0
      NACDET = 1
      IT = 1
      T(1)=1 $ V(1)=1 $ NBILOS=0
   25 ETA=RANF(I)
      Z=100.*ETA
      R(NACDET) = INT(Z)
      IF(R(NACDET) .GT. IX .OR. R(NACDET) .LT. 1) GO TO 25
      IF(IDIM .EQ. 1) GO TO 31
   27 ETA=RANF(I)
      Z=100.*ETA
      T(NACDET) = INT(Z)
      IF(T(NACDET) .LT. 1 .OR. T(NACDET) .GT. IY) GO TO 27
      IF (IDIM .EQ. 2) GO TO 31
   29 ETA = RANF(I)
      Z = 100. * ETA
      V(NACDET) = INT(Z)
      IF(V(NACDET) .LT. 1 .OR. V(NACDET) .GT. IZ)GOTO 29
   31 NR=R(1)
      IF(NR .EQ. 1 .OR. NR .EQ. IX) NBILOS=NBILOS+1
   32 MT=T(1)
      IF(IDIM .EQ. 1)GOTO 33
      IF(MT .EQ. 1 .OR. MT .EQ. IY) NBILOS=NBILOS+1
      NV=V(1)
      IF(IDIM .EQ. 2) GOTO 33
      IF(NV .EQ. 1 .OR. NV .EQ. IZ) NBILOS=NBILOS+1
   33 MAXDET=2*IDIM+1-NBILOS
      IND(NR,MT,NV) = 1
      NINSTR=MINO(NINS,MAXDET)
      IF(NINS.GT. 1 .AND.IDIM.EQ.2)CALL DET2(NINSTR,IX,IY,IZ)
      IF(NINS.GT. 1 .AND. IDIM .EQ. 3)CALL DET3(NINSTR,IX,IY,IZ)
      NVRDET=NINSTR
      NACDET=NINSTR
      NEWDET = 0
      NEIBOR=2*IDIM
      IF (ABS(Q(JJ)-QP(IPR)).LE.0.001.AND.NCT.EQ.NPCY(IT)) WRITE(6,208)
     1 Q(JJ),NCT
   30 DO 60 K=1,NACDET
      SVNDET=NEWDET
      DO 50 L=1,NEIBOR
      MU=R(K)+B(L)
      NU=T(K)+C(L)
      NAU = V(K) + D(L)
      IF(MU.LT.1.OR.MU.GT.IX)GO TO 50
      IF(NU.LT.1.OR.NU.GT.IY)GO TO 50
      IF(NAU .LT. 1 .OR. NAU .GT. IZ)GOTO 50
      IF(IND(MU,NU,NAU) .NE. ITYPE)GOTO 50
      ETA=RANF(I)
      IF(ETA .GT. Q(JJ))GO TO 40
      IND(MU,NU,NAU) =1
      NEWDET = NEWDET + 1
      IF(NEWDET.GT.1000)GOTO999
      AR(NEWDET) = MU
```

```
      AT(NEWDET) = NU
      AV(NEWDET) = NAU
       GOTO 50
   40 IND(MU,NU,NAU)=0
   50 CONTINUE
      NDET = NEWDET - SVNDET
      IF(ABS(Q(JJ)-QP(IPR)).LE..001 .AND.NCT.EQ.NPCY(IT))GOTO51
      GO TO 60
   51 IF (SVNDET .EQ. NEWDET) GO TO 52
      IB = SVNDET + 1
      WRITE(6,209)R(K),T(K),V(K),NDET,(AR(J),AT(J),AV(J),J=IB,NEWDET)
      GO TO 60
   52 WRITE(6,203)R(K),T(K),V(K),NDET
   60 CONTINUE
      NVRDET = NVRDET + NEWDET
      IF(NEWDET .EQ. 0) GO TO 70
      DO 65 K=1,NEWDET
      R(K)=AR(K)
      T(K)=AT(K)
      V(K) = AV(K)
   65 CONTINUE
      NACDET = NEWDET
      NEWDET = 0
      GO TO 30
   70 NVRDET = NVRDET + NEWDET
      XV = NVRDET
      ND(NCT) = NVRDET
      VB=VB+XV
      IF(NCT .EQ. NTRIAL) GO TO 100
      IF(NCT .EQ. NPCY(IT)) IT = IT + 1
      NCT = NCT + 1
      NACDET = 1
      DO 75 II = 1,IX
      R(II) = 0
   75 CONTINUE
      DO 80 IJ = 1,IY
      T(IJ)=0
   80 CONTINUE
      DO 85 IK=1,IZ
      V(IK)=0
   85 CONTINUE
      DO 96 IB = 1,IX
      DO 95 IC = 1,IY
      DO 90 ID=1,IZ
      IND(IB,IC,ID) =ITYPE
   90 CONTINUE
   95 CONTINUE
   96 CONTINUE
      T(1)=1 $ V(1)=1 $ NBILOS=0
      GO TO 25
  100 XNN=NCT
      XMEAN = VB / XNN
      SIG=0. $ SIGXSQ = 0.
      DO 110 J=1,NTRIAL
      X = ND(J) $ XSQ = X * X
      SIG = SIG + (X - XMEAN) **2 $ SIGXSQ = SIGXSQ + XSQ
  110 CONTINUE
      SIGSQ=SIG/XNN $ SIGSQAL = SIGXSQ/XNN - XMEAN * XMEAN
      SIGMA=SQRT(SIGSQ) $ SIGALT = SQRT(SIGSQAL)
      NPP=NP-1
```

```
      DO 13D IL=1,NCT
      X = ND(1L)
      IF(X .LE. P(1)) GO TO 111
      GO TO 112
  111 IH(1)=IH(1)+1
      GO TO 13C
  112 CONTINUE
      DC 12D NX=1,NPP
      IF(X .GT. P(NX) .AND. X .LE. P(NX+1)) GO TO 113
      GO TO 120
  113 IH(NX+1)=IH(NX+1)+1
      GO TO 130
  12D CONTINUE
  13D CONTINUE
      WRITE(6,21D)
      WRITE(6,2D6)Q(JJ)
      WRITE(6,207)
      WRITE(6,20D)(IH(J),J=1,NP)
C     COMPUTES NO. OF TIMES THE NUMBER OF DETONATIONS IS G.E. THAN ITALLY(K)
      DO 134 K=1,NUM
      DO 133 IADD=1,NP
      IAD = IADO* ISTEP
      IF (IAD .LT. ITALLY(K)) GO TO 133
      NCOUNT = NCOUNT + IH(IADD)
  133 CONTINUE
      PNP(K)=FLOAT(NCOUNT)/FLOAT(NTRIAL) $QNP(K) =1.0-PNP(K)
      NTOTAL(K) =NCOUNT $NCOUNT =D
      ITA(K)= ITALLY(K) -ISTEP +1
  134 CONTINUE
  136 WRITE(6,201)XMEAN,SIGMA,SIGALT
      WRITE(6,227) (ITA(L),PNP(L),ITA(L),QNP(L),NTOTAL(L),L=1,NUM)
  137 IF(NNP .EQ. JJ)GOTO 150
      IF (Q(JJ) .EQ. QP(IPR)) IPR = IPR + 1
      JJ = JJ + 1
      NCT = 1
      DO 135 IE=1,NP
      IH(IE)=0
  135 CONTINUE
      DO 14D IK=1,NTRIAL
      NO(IK)=D
  14D CONTINUE
      GO TO 5
  15D WRITE(6,211)IX,IY,IZ,NTRIAL,ISTEP,NINS
      IF(ITYPE .EQ.-1)WRITE(6,224)
      IF(ITYPE .EQ .D)WRITE(6,225)
      GOTO 16D
  999 WRITE(6,998)NEWDET
  998 FORMAT(' INCREASE ARRAY  DIMENSIONS  NEWDET=',I5)
  160 STOP
      END
      SUBROUTINE DET2(NINSTR,IX,IY,IZ)
      COMMON/KIWAN/IND(4D,4C,5)
      LEVEL 2,IND
      COMMON/COORO/R(100D),T(10D0),V(100D)
      INTEGER R,T,V
      DO 40 J=2,NINSTR
      JCOUNT=J
      I=D$ ITERAT=C
   30 ZETA=RANF(I)
      ITERAT=ITERAT+1
```

```
      IF(ITERAT .GE. 25)GOTO 41
      IF (ZETA.LE. 0.25) GOTO 31
      IF(ZETA .LE. 0.50) GOTO 32
      IF(ZETA .LE. 0.75) GOTO 33
      IF(ZETA .LE. 1.00) GOTO 34
   31 R(J)=R(1)+1
      IF(R(J) .GT. IX)GOTO 30$T(J)=T(1)$V(J)=V(1)
      IXR=R(J)$IYT=T(J)$IZV=V(J)$IF(INO(IXR,IYT,IZV).EQ.1)GOTO30$GOTO 39
   32 R(J)=R(1)-1
      IF(R(J) .LT.1)GOTO 30$T(J)=T(1)$V(J)=V(1)
      IXR=R(J)$IYT=T(J)$IZV=V(J)$IF(INO(IXR,IYT,IZV).EQ.1)GOTO30$GOTO 39
   33 T(J)=T(1)+1
      IF(T(J) .GT. IY)GOTO 30$ R(J)=R(1)$V(J)=V(1)
      IXR=R(J)$IYT=T(J)$IZV=V(J)$IF(INO(IXR,IYT,IZV).EQ.1)GOTO30$GOTO 39
   34 T(J)=T(1)-1
      IF(T(J) .LT. 1) GOTO 30$R(J)=R(1)$V(J)=V(1)
      IXR=R(J)$IYT=T(J)$IZV=V(J)$IF(INO(IXR,IYT,IZV).EQ.1)GOTO30$GOTO 39
   39 INO(IXR,IYT,IZV)=1
   40 CONTINUE
      GOTO 42
   41 WRITE(6,300)ITERAT,JCOUNT
  300 FORMAT(1HO,'ITERAT=',I3,5X,'NINSTR=',I3)
   42 RETURN
      ENO
      SUBROUTINE OET3(NINSTR,IX,IY,IZ)
      COMMON/KIWAN/INO(40,40,5)
      LEVEL 2,INO
      COMMON/COORO/R(I000),T(1000),V(1000)
      INTEGER R,T,V
      00 40 J=2,NINSTR
      JCOUNT=J
      I=0$ ITERAT=0
   30 ZETA=RANF(I)
      ITERAT=ITERAT+1
      IF(ITERAT .GE. 25)GOTO 41
      IF(ZETA.LE. 0.16667) GOTO 31
      IF(ZETA.LE. 0.33333) GOTO 32
      IF(ZETA.LE. 0.50000) GOTO 33
      IF(ZETA.LE. 0.66667) GOTO 34
      IF(ZETA.LE. 0.83333) GOTO 35
      IF(ZETA.LE. 1.00000) GOTO 36
   31 R(J)=R(1)+1
      IF(R(J) .GT. IX)GOTO 30$T(J)=T(1)$V(J)=V(1)
      IXR=R(J)$IYT=T(J)$IZV=V(J)$IF(INO(IXR,IYT,IZV).EQ.1)GOTO30$GOTO 39
   32 R(J)=R(1)-1
      IF(R(J) .LT. 1)GOTO 30 $T(J)=T(1) $V(J)=V(1)
      IXR=R(J)$IYT=T(J)$IZV=V(J)$IF(INO(IXR,IYT,IZV).EQ.1)GOTO30$GOTO 39
   33 T(J)=T(1)+1
      IF(T(J) .GT. IY) GOTO 30 $R(J)=R(1) $V(J)=V(1)
      IXR=R(J)$IYT=T(J)$IZV=V(J)$IF(INO(IXR,IYT,IZV).EQ.1)GOTO30$GOTO 39
   34 T(J)=T(1)-1
      IF(T(J) .LT. 1) GOTO 30 $R(J)=R(1) $V(J)=V(1)
      IXR=R(J)$IYT=T(J)$IZV=V(J)$IF(INO(IXR,IYT,IZV).EQ.1)GOTO30$GOTO 39
   35 V(J)=V(1)+1
      IF(V(J) .GT. IZ)GOTO 30 $R(J)=R(1) $T(J)=T(1)
      IXR=R(J)$IYT=T(J)$IZV=V(J)$IF(INO(IXR,IYT,IZV).EQ.1)GOTO30$GOTO 39
   36 V(J)=V(1)-1
      IF(V(J) .LT. 1) GOTO 30$R(J)=R(1) $T(J)=T(1)
      IXR=R(J)$IYT=T(J)$IZV=V(J)$IF(IND(IXR,IYT,IZV).EQ.1)GOTO30$GOTO 39
   39 INO(IXR,IYT,IZV)=1
```

```
 40 CONTINUE
    GOTO 42
 41 WRITE(6,300)ITERAT,JCOUNT
300 FORMAT(1HO,'ITERAT=',I3,5X,'NINSTR=',I3)
 42 RETURN
    END
```

LIST OF SYMBOLS

p	interaction probability
$P(p)$	percolation probability
r	random variable
r_o	value assumed by the random variable r
IND(i,j)	an array to represent the status of the lattice nodes
L	lattice
ISET	initial reaction set
N	random variable representing cluster size
n	value assumed by random variable N
$\bar{n}$	mean value of n
S_n	standard deviation
μ	population mean
σ	population standard deviation
m	sample size
$P[N \varepsilon I, N_o]$	probability that N lies in an interval of length I centered at N_o
$P_n(p)$	cumulative probability of clusters at least of size n
$Q_n(p)$	cumulative probability of clusters whose size is less than n

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