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STUDY OF QUEUING THEORY IN SHELTER ENTRANCEWAY DESIGN

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U. S. Naval Civil Engineering Laboratory
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STUDY OF QUEUING THEORY IN SHELTER ENTRANCEWAY DESIGN

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by

D. B. Ryder

ABSTRACT

Experimental data is presented which tests the assumptions on which Technical Note N-423, Application of Queuing Theory to the Design and Location of Personnel Shelters, is based. A method outlining the development of design criteria of general usefulness is also given.

INTRODUCTION

An important problem in shelter design is insuring that the entrance of all assigned personnel into the shelter within a given interval of time has a high probability. Technical Note N-423, Application of Queuing Theory to the Design and Location of Personnel Shelters,[1] attacks this problem by applying techniques of queuing theory.

Assumptions inherent in these techniques have been tested experimentally, and the experimental results are discussed in this technical note. It should be noted that military personnel were utilized in performing the experiments, and that other commitments placed restrictions on the time as well as on the number of men available for experiments. However, results obtained indicate that more complete testing of assumptions as suggested in N-423 is not warranted.

ASSUMPTIONS

Assumptions made in Technical Note N-423 are as follows:

1. $g(t) = \mu e^{-\mu t}$, where $g(t)$ is the probability of an interval of time t between services, and μ is the service rate (the average number of persons passing through the entryway per unit time if persons are always waiting in line).

2. $f(t) = \lambda e^{-\lambda t}$, where $f(t)$ is the probability of an interval of time t between consecutive arrivals, and λ is the arrival rate (the average number of persons arriving at the shelter entranceway, or at the end of the queue at the entranceway, per unit time).

3. $\rho = \lambda/\mu \leq 0.9$, where ρ is the ratio of λ to μ.

4. $N \geq 100$, where N is the number of persons to be accommodated in the shelter.

5. The queue is single file.

6. Service is "first come, first served".

7. Transient effects can be ignored, and the steady state solution can be utilized.

EXPERIMENTAL PROCEDURE

Personnel were made available to NCEL by the Construction Battalion Base Unit. The multi-purpose protective shelter* of the Construction Battalion Center was also made available by the Disaster Recovery Training Division. Records of test runs were made by Esterline recorders and by movie camera.

Assumption 1 was tested by running groups of men single file into the shelter. Recorders equipped with push-buttons were stationed 60 feet from the shelter entranceway, immediately at the entranceway, and inside the shelter. As each man passed each station, the push-button was depressed, and a permanent record of the run was obtained on the recorder. In each run designed to check assumption 1, all participating personnel were lined up single file 60 feet from the entranceway, and at a signal from the officer in charge, personnel began moving into the shelter at normal military pace. Service was thus "first come, first served." Filmed records were obtained of personnel moving through the entranceway, and inside the shelter. The filmed records were obtained for purposes of checking the manually operated Esterline recorders. Figures 1, 2, and 3 show the location of the recording stations and the geometry of the shelter entrance.

Assumption 2 was tested by stationing men in such a way as to approximate the actual situation for which the CBC multi-purpose protective shelter is intended. The CBC Disaster Control Recovery Plan provided data on the intended staffing of the shelter. Probable locations of the staff personnel assigned to the shelter, which is intended for use as a control center in case of nuclear emergency, were determined, and test runs were set up to simulate a possible real situation.

Numbers of personnel expected to proceed to the shelter from various buildings on station having been estimated, available personnel were distributed into groups in proportion to these numbers for the test runs. Distances used in the test runs were scaled to the true distances from building to shelter in the ratio of one to four in order to facilitate actual testing operations. The groups were directed to remain at or near their respective stations, and were permitted to sit as well as stand while waiting. At a given signal, all personnel began moving toward the shelter at a normal military pace. Recorders were again stationed 60 feet from the shelter entranceway, at the entranceway, and inside the shelter. Filmed records were obtained of personnel moving through the entranceway, and inside the shelter.

Since the CBC multi-purpose shelter was located in a remote corner of the base, it was decided to simulate the case of a hypothetical shelter at a more centrally located site. Except for the different initial stationing of personnel, procedures were identical to those described previously.

The case of a multi-story building with adjacent shelter was also simulated by stationing groups of personnel so that 100-foot intervals between groups represented the difference between consecutive stories.

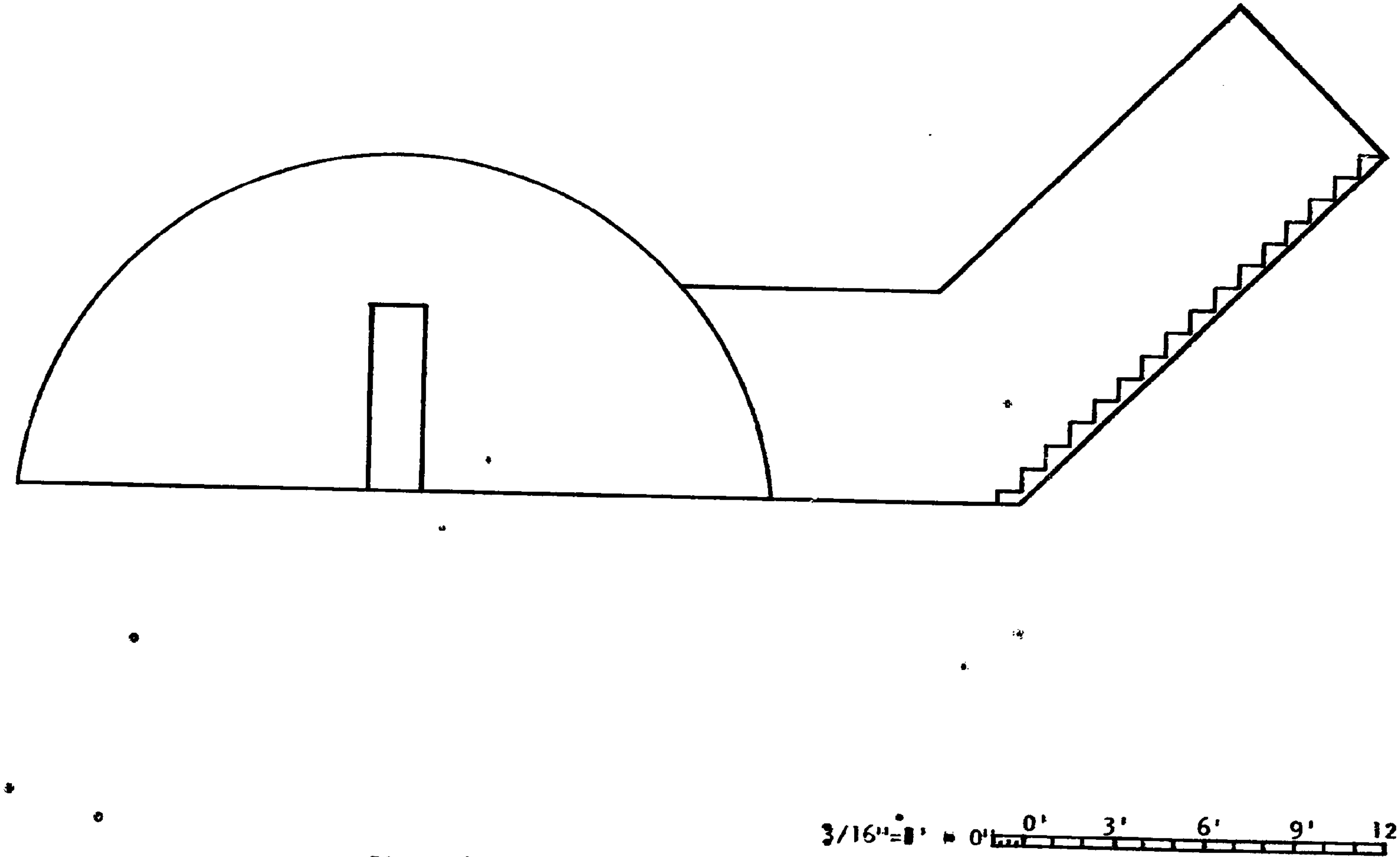

Figure 1. Cross section - shelter entrance.

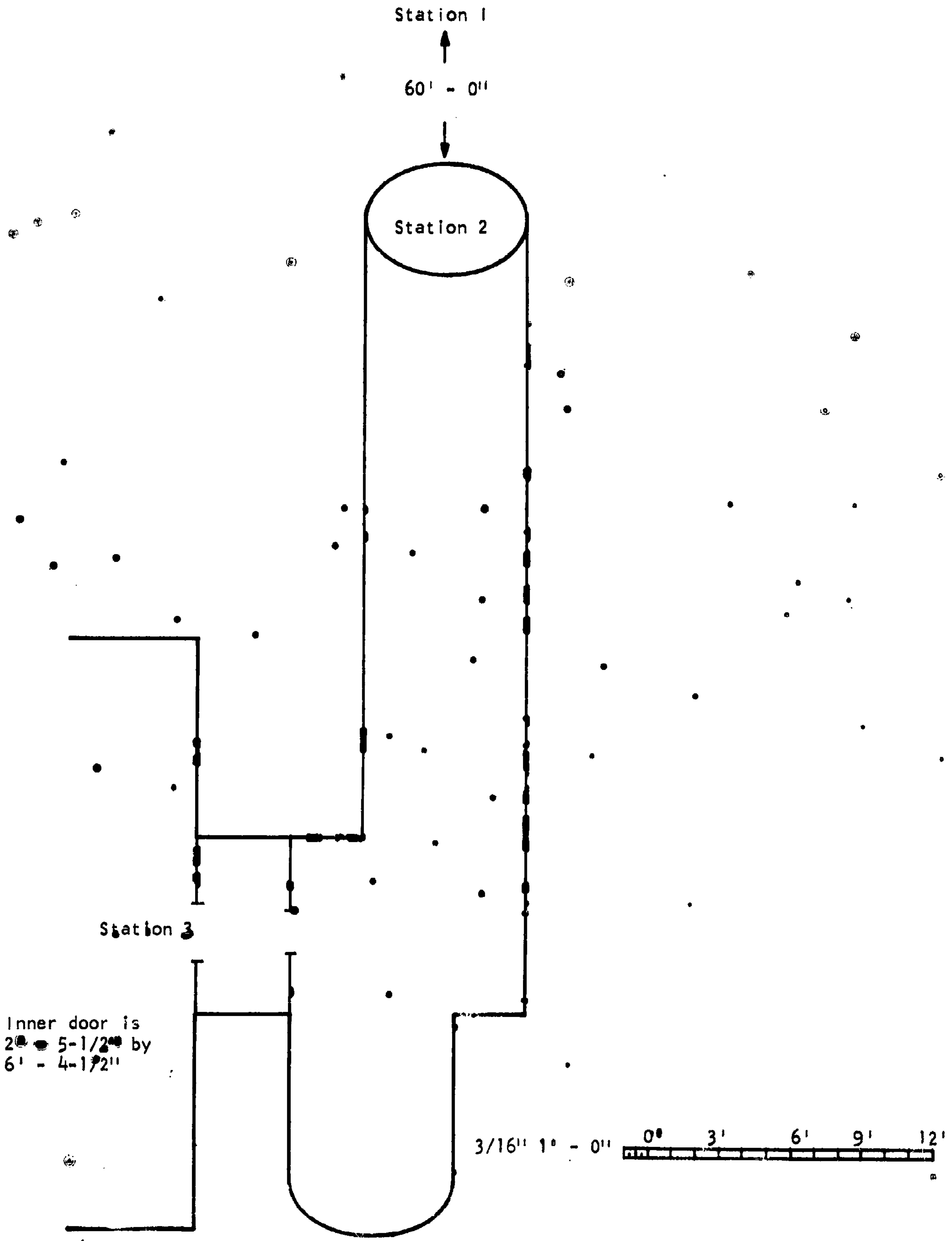

Figure 2. Plan view - shelter entrance.

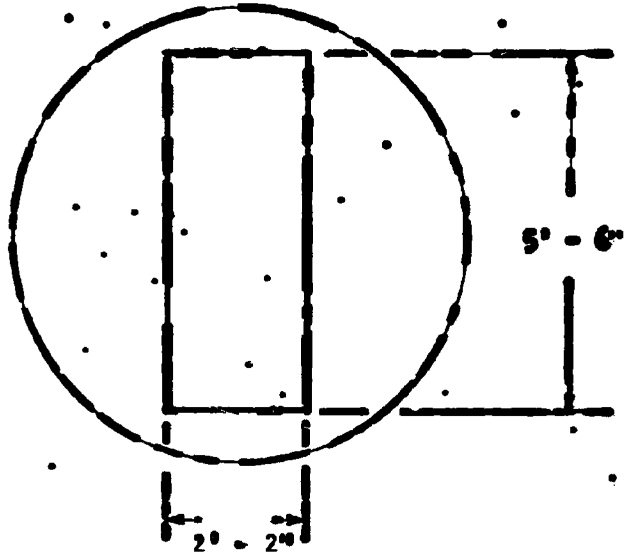

Figure 3. Cross section - hatch at station 2.

Service was "first come, first served" for all runs, and all queues were single file.

VALIDITY OF EXPERIMENTAL PROCEDURES IN TESTING ASSUMPTIONS

Comment upon the validity of experimental procedures used in testing assumptions is warranted. Is it realistic to simulate actual behavior in a nuclear emergency by stationing groups of personnel on foot at different distances from the shelter entranceway to await a warning signal? In view of many unknowns, this seemed to be the best that could be done. No provision has been made for method of transportation to the CBC control center in case of alert. The CBC Disaster Recovery Training Division Officer expressed the belief that personal vehicles would be utilized, and the reduction of distances in the ratio of one to four tends to make allowance for this. In view of the various destinations to which personnel would proceed and the present level of training of personnel, the chaos which would occur during an actual emergency makes it difficult to formulate a realistic model. Only in the event that a high level of training is attained, with frequent drills, can a realistic approximation to the actual situation be made. Even then, if arrival records of an actual base wide drill were obtained, these records would serve only for CBC and for the control center as presently located. Nevertheless, the results obtained in the experiments performed do have significant bearing on the problem of proper shelterway design, and a discussion of the implication of these experiments is presented in a following section.

It should also be pointed out that assumption 4 was not enforced in some of the experimental runs. Sufficient personnel were not available on these occasions. In developing the mathematics of Technical Note N-423, this assumption was made subsequent to assumptions 1 and 2, and because indications are that assumptions 1 and 2 are invalid in themselves, the failure to enforce this assumption is not of great importance.

EXPERIMENTAL RESULTS

Experimental runs were made as follows:

Run 1: Thirty-nine men were stationed single file with the front of the queue initially 60 feet from the shelter entrance. On signal, the men moved into the shelter.

Run 2: Forty men were distributed in groups in proportion to the expected distribution of personnel assigned to the shelter in event of actual emergency, and these groups were stationed so as to preserve the ratio between distances travelled to the shelter for the experimental run and the real event. A group of six men was stationed

500 feet from the shelter; 3 men, 1160 feet from the shelter; one man, 1580 feet from the shelter; two men, 1720 feet from the shelter; two men, 1850 feet from the shelter; 22 men, 2275 feet from the shelter; one man, 2315 feet from the shelter; one man 2400 feet from the shelter. On signal, the men moved into the shelter.

Run 3: Same as run 2, except that 21 men were stationed 2275 feet from the shelter entrance.

Run 4: To simulate the case of a three-story building with adjacent shelter, groups of 13 men were stationed at 100 feet from the shelter entrance, at 200 feet, and at 300 feet. On signal, the men moved into the shelter.

Run 5: Same as run 4, except that the men were stationed at 400 feet from the shelter entrance, at 500 feet, and at 600 feet.

Run 6: Same as run 4, except that the men were stationed at 700 feet from the shelter entrance, at 800 feet, and at 900 feet.

Run 7: Same as run 1, except that 58 men participated.

Run 8: The case of a centrally located shelter was simulated. Sixty-four men were distributed in groups in proportion to the expected distribution of personnel assigned to the shelter in event of an actual emergency, and these groups were stationed so as to preserve the ratio between distances travelled to the shelter for the experimental run and the real event. A group of 35 men was stationed 240 feet from the shelter; 3 men, 410 feet from the shelter; 2 men, 780 feet from the shelter; 5 men, 1040 feet from the shelter; 3 men, 1100 feet from the shelter; 2 men, 1270 feet from the shelter; 3 men 1550 feet from the shelter; 3 men, 1580 feet from the shelter; and 8 men, 1840 feet from the shelter. On signal, the men moved into the shelter.

Run 9: Same as run 8, except that a high explosive was detonated in the immediate area of the shelter, and all personnel with private vehicles near the shelter were directed to move them approximately 150 yards farther away from the shelter before the run started and before the signal to move into the shelter had been given. Personnel were told that the high explosive would be detonated at an unspecified time after the signal to move into the shelter had been given. It was felt that the knowledge that no danger was imminent contributed to the orderly and expeditious manner in which personnel moved into the shelter on other runs. Run 9 was designed to see if an element of uncertainty regarding personal safety would have any effect on the men.

Run 10: Same as run 8, except that all men participated. A group of 57 men was stationed 240 feet from the shelter; 5 men, 410 feet from the shelter; 4 men, 780 feet from the shelter; 8 men, 1040 feet from the shelter; 6 men, 1100 feet from the shelter; 5 men, 1270 feet from the shelter; 5 men, 1550 feet from the shelter; 5 men, 1580 feet from the shelter; and 16 men, 1640 feet from the shelter. On signal, the men moved to the shelter.

Run 11: Same as run 4, except that 64 men were stationed 100 feet from the shelter; 28 men, 200 feet; and 16 men, 300 feet. This run was set up so as to insure that a relatively long queue would form.

For runs 1 through 6, wind was from the west (perpendicular to the direction of travel) at 1 to 3 knots, temperature varied between 62 degrees Fahrenheit and 65 degrees Fahrenheit, barometric pressure was 30.00 in and steady, and there was no cloud cover. For runs 7 through 11, wind was from the west at 13 to 18 knots, temperature was 59 degrees Fahrenheit, barometric pressure was 30.02 in and steady, and there was no cloud cover. Ages of participating personnel varied between 50 and 17 with a mean age of 21 years. Terrain was level except for one ditch which was easily stepped over.

The data obtained from the experimental runs is presented in Tables 1 through 11 in Appendix A. Station 1 refers to the recorder 60 feet from the shelter entrance; station 2, to the recorder at the shelter entrance; and station 3, to the recorder inside the shelter. Time is measured from the instant the signal directing personnel to proceed into the shelter is given, and each entry in the table refers to an arrival at a station.

ANALYSIS OF EXPERIMENTAL RESULTS

Data from runs 6 and 7 is analyzed to test assumption 1. As was recommended in Technical Note N-423, a chi-square test was performed. A service is considered to have occurred when a man arrives at station 3. For run 6, arrivals at station 3 between 25.0 seconds and 74.9 seconds inclusive are treated in terms of 50 subintervals of 1 second each. For run 7, arrivals between 20.0 seconds and 94.9 seconds inclusive are treated in terms of 75 sub-intervals of 1 second each. In the following analysis, x_k refers to the number of arrivals in a sub-interval, $P(x_k)$ to the Poisson probability of x_k arrivals in a sub-interval, I to the number of subintervals, and A_k to the actual number of sub-intervals with x_k arrivals. Thus, theoretically, the product of I and $P(x_k)$ should be equal in value to A_k.

2	2	0.490	24.50	24	0.010
3	3	0.095	4.75	5	0.013

TOTAL $$\Lambda = \sum_{k=0}^{3} \frac{(I \cdot P(x_k) - A_k)^2}{I \cdot P(x_k)} = 0.072$$

If the service rate is normally distributed about x = 1.64, there are three chances in four that Λ will be less than 0.102. Since Λ = 0.072<0.102, there is no reason to object to an assumption of normally distributed service rates on the basis of the experimental data.

Although run 11 was not intended as a check on assumption 1, data from this run can be used to further investigate the assumption that service rates are normally distributed about a mean value. If, in addition to the 50 sub-intervals from runs 1 and 7, arrivals in run 11 between 25.0 seconds and 174.9 seconds inclusive are treated in terms of 60 sub-intervals of 2.5 seconds each, there is still no reason to object to the assumption of normally distributed service rates. Furthermore the values of $I \cdot P(x_k)$ are of greater magnitude lending more confidence to the use of the usual approximation to the discrete χ^2 frequency function.

k	x_k	$P(x_k)$	$I \cdot P(x_k)$	A_k	$\frac{(I \cdot P(x_k) - A_k)^2}{I \cdot P(x_k)}$
0	0	0.0335	3.68	4	0.028
1	1	0.3798	41.78	41	0.015
2	2	0.5050	56.00	56	0.000
3	3	0.0817	8.99	9	0.000

TOTAL $$\Lambda = \sum_{k=0}^{3} \frac{(I \cdot P(x_k) - A_k)^2}{I \cdot P(x_k)} = 0.043$$

If the service rate is normally distributed about x = 1.636, there are four chances in five that Λ will be less than 0.064.

Data from runs 2 through 6 and 8 through 9 was analyzed to test assumption 2. An arrival is considered to have occurred when a man arrives at station 1. For runs 2 and 3, arrivals between 0.0 seconds and 599.9 seconds inclusive are treated in terms of 5-second intervals; for runs 4 and 5, arrivals between 0.0 seconds and 119.9 seconds inclusive are treated in terms of 2-second intervals; for run 6, arrivals between 0.0 seconds and 179.9 seconds inclusive are treated in terms of 3-second intervals; and for runs 8 and 9, arrivals between 0.0 seconds and 359.9 seconds inclusive are treated in terms of 5-second intervals.

Run 2

k	x_k	$P(x_k)$	$I \cdot P(x_k)$	A_k	$\frac{(I \cdot P(x_k) - A_k)^2}{I \cdot P(x_k)}$
0	0	0.717	86.0	105	4.20
1	1	0.239	28.7	7	16.41
2	2 or more	0.044	5.3	8	1.38

TOTAL $\Lambda = \sum_{k=0}^{2} \frac{(I \cdot P(x_k) - A_k)^2}{I \cdot P(x_k)} = 21.99$

Run 3

k	x_k	$P(x_k)$	$I \cdot P(x_k)$	A_k	$\frac{(I \cdot P(x_k) - A_k)^2}{I \cdot P(x_k)}$
0	0	0.723	86.8	106	4.25
1	1	0.235	28.2	2	24.34
2	2 or more	0.042	5.0	12	9.80

TOTAL $\Lambda = 38.39$

Run 4

k	x_k	$P(x_k)$	$I \cdot P(x_k)$	A_k	$\frac{(I \cdot P(x_k) - A_k)^2}{I \cdot P(x_k)}$
0	0	0.522	31.3	42	3.66
1	1	0.339	20.3	3	14.74
2	2 or more	0.139	8.3	15	5.41

TOTAL $\Lambda = 23.81$

Run 5

k	x_k	$P(x_k)$	$I \cdot P(x_k)$	A_k	$\frac{(I \cdot P(x_k) - A_k)^2}{I \cdot P(x_k)}$
0	0	0.522	31.3	41	3.01
1	1	0.339	20.3	2	16.50
2	2 or more	0.139	8.3	17	9.12

TOTAL $\Lambda = 28.63$

Run 6

k	x_k	$P(x_k)$	$I \cdot P(x_k)$	A_k	$\frac{(I \cdot P(x_k) - A_k)^2}{I \cdot P(x_k)}$
0	0	0.522	31.3	45	6.00
1	1	0.339	20.3	2	16.50
2	2 or more	0.139	8.3	13	2.66
TOTAL					$\Lambda = 25.16$

Run 8 and Run 9

0	0	0.4[illegible]1	29.6	55	2[illegible].80
1	1	0.366	26.4	3	20.[illegible]0
2	2 or more	0.233	16.1	14	2.70
TOTAL					$\Lambda = 45.20$

For each of these cases, if the arrival rate is truly Poisson, there is one chance in a thousand that Λ will exceed 10.8.

IMPLICATIONS OF EXPERIMENTAL RESULTS

Experimental results strongly imply that queuing theory with Poisson input and exponential service times is of limited usefulness in designing shelter entranceways. For the shelter entrance tested, indications are that a mean service rate (0.65 entries/sec for the case tested) holds, and use of a mean service rate for design purposes should suffice. The problem of arrival rate is not so simple. Although it does seem reasonable that rates of travel under emergency conditions are normally distributed about some mean value for walking and running given distances, it is difficult to test this assumption experimentally. Nevertheless, given approximate locations of personnel with respect to shelter, design criteria to insure the entrance of assigned personnel can be adequately developed if use of a mean value for walking and running given distances is made to determine arrival rates.

A slightly modified version of the design method developed at NCEL for inclusion in Navdocks P-81, Part 2[2], is applicable. An example is utilized to illustrate the method. For this example, Figure 4 shows the

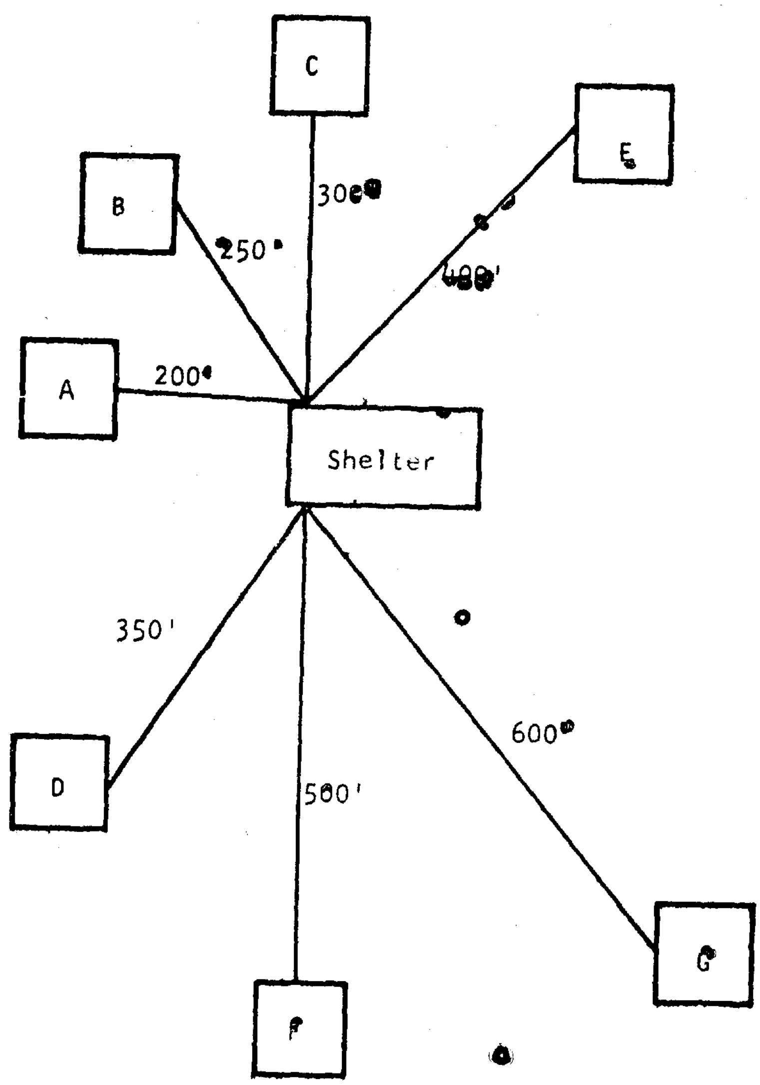

Figure [illegible]. Centrally located shelter.

distribution of work spaces for the assigned occupants. Distances to shelter, numbers of persons, etc., for each building are shown in Table 1 of Appendix B, while the example is given in Table 2. Results of the application of the method to the experimental runs are presented in Table 3 of Appendix B and are considered satisfactory.

Appropriate travel rates and service rates for use with this design method are found in "Design of Entrance Systems for Personnel Protective Shelters",[3] but no information for travel rates immediately at the entranceway could be found. Here a reduction of speed was noticed during the experimental runs. It is not clear if this was due to the fear of hitting the metal perimeter of the relatively narrow entrance, if the change from level ground to stairway had some effect, or if some other circumstance contributed to the bottleneck. At any rate, velocity for this 2 foot interval was computed to be about 1.5 feet/second. This value was obtained by dividing 60 feet by the average number of men between Station 1 and Station 2 once steady state conditions had been reached on run 41, and then multiplying this value by the mean service rate. This average computed value is utilized in the calculations of Table 3 of Appendix B.

For this design method to have general usefulness, more information is needed regarding velocity of persons through a variety of hatchways and openings. Effect of both cross-sectional area and slope of the opening with respect to ground level should be studied. All that is needed for such a study is a series of mockups and a group of 50 men or more.

Also needed is more information regarding queue density as a function of velocity. In order to compute lengths of queues at different times, it is necessary to know the average amount of space occupied by a person in the queue. This information could be collected during the hatchway - velocity test. A group of 100 men or more would then be needed in order to provide adequate data, however.

Further implications were that training is of great importance in insuring the entrance of assigned personnel. Proper utilization of personnel shelters can occur only with orderly behavior through familiarization of each individual with the action to be taken in the event of immenent emergency, through proper traffic control, etc.

It can be tentatively stated that minimization of distances to the probable locations of assigned personnel is of greater importance than the maximumization of the area of shelter entrances for most situations. The fact that there was little problem in servicing the men even though distances from the shelter were scaled from 4 to 1 indicates that, for shelters located on a station where assigned personnel may be expected to originate from several locations, more can be gained from proximity of the shelter to these locations than from the provision of larger entrances or more entrances. This fact is further substantiated by the speed with which all personnel gained entrance to the shelter in runs 8 through 10 as opposed to runs 2 and 3.

FINDINGS

1. Two fundamental assumptions on which Technical Note N-423, Application of Queuing Theory to the Design and Location of Personnel Shelters, is based did not hold true for the cases experimentally tested.

2. A step-by-step arithmetic procedure provides reasonable accuracy in predicting arrival time for personnel.

3. More information regarding velocity of personnel through hatches and openings and density of queues is needed.

4. It is extremely difficult to simulate emergency conditions in so far as movement of personnel is concerned.

CONCLUSIONS

It is concluded that:

1. The step-by-step arithmetic procedure presented in this note can be adopted for use in shelter siting and entranceway design at the present time.

2. Experimental work to determine velocity of personnel through hatches and openings and also to determine the density of queues should be performed.

ACKNOWLEDGEMENTS

The work of CDR E. A. Quarterman, USNR, in serving as officer in charge of the experiment is acknowledged. His enthusiasm and energy contributed greatly to its success.

The cooperation of CAPT E. J. Ralph, Officer in Charge, Construction Battalion Base Unit, U. S. Naval Construction Battalion Center is also acknowledged.

Finally, the cooperation of the men participating in the experiment is acknowledged.

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2. Navdocks P-81, Part 2, Personnel Shelters and Protective Construction, Department of the Navy, Bureau of Yards and Docks, Washington, D. C. (To be published).

3. Armour Research Foundation, No. K158, Final Report, Part I, Design of Entrance Systems for Personnel Protective Shelters, Chicago, Illinois, December 1959. (SECRET).

APPENDIX A

TABLE 1

Run 1

Station 1	Station 2	Station 3
3.1 sec	13.0 sec	21.2 sec
4.3	14.0	22.3
5.1	15.1	23.2
6.0	16.3	24.9
6.8	17.2	26.0
7.4	18.9	28.0
8.1	20.0	29.0
8.9	21.1	30.9
9.6	22.7	31.9
10.2	24.0	34.6
10.8	25.2	35.4
11.3	26.5	36.6
12.1	27.8	37.7
12.5	29.3	38.9
13.2	30.5	39.6
13.7	31.6	40.8
14.1	33.0	41.5
15.1	34.0	43.9
15.5	35.1	44.9
16.1	37.1	46.1
17.0	38.3	47.8
17.9	40.1	49.9
18.7	41.8	51.5
19.6	43.1	53.1
20.2	44.4	54.9
21.1	46.1	56.1
22.2	47.7	58.2
23.7	49.4	60.0
24.8	50.9	61.1
25.8	52.0	62.2
27.0	53.8	63.3
27.6	55.1	66.0
28.3	56.5	68.1
29.2	58.3	70.9
30.1	60.0	72.5
31.8	61.7	74.1
32.8	63.2	75.4

34.0	64.9	76.8
35.2	66.6	78.0

TABLE 2

Run 2

Station 1	Station 2	Station 3
92.2 sec	106.0 sec	115.5 sec
93.1	107.2	116.4
93.9	108.6	117.3
94.6	109.8	118.8
95.2	110.8	120.1
95.8	112.4	121.8
352.7	362.5	369.5
364.7	376.0	384.4
365.3	377.3	385.6
431.1	444.6	453.7
432.0	446.0	456.0
437.4	449.1	458.8
438.1	450.4	460.0
439.2	452.0	461.1
448.6	459.8	467.3
449.8	461.7	471.2
451.4	463.6	473.5
452.2	465.0	474.9
453.0	466.2	475.7
453.6	467.7	476.5
453.9	468.8	477.6
454.4	470.3	478.6
454.9	471.5	479.9
455.6	472.9	481.9
456.0	474.2	483.0
456.5	457.6	485.1
456.9	477.4	486.8
457.9	478.8	487.5
458.8	480.4	488.7
459.9	481.8	489.7
460.9	483.2	490.8
461.8	484.8	492.8
462.6	486.4	494.2
463.3	487.6	495.8
463.9	489.5	498.0
464.8	491.0	500.2
466.7	492.7	501.9

501.8	511.6	520.2*
579.9	592.5	604.9
581.3	594.0	606.2

TABLE 3

Run 3

Station 1	Station 2	Station 3*
81.5 sec	93.8 sec	97.6 sec
82.4	95.4	98.8
83.0	96.6	100.2
83.7	97.8	101.8
85.5	99.0	103.0
85.9	100.3	104.8
331.6	352.0	354.9
335.4	358.2	362.0
336.8	359.6	363.7
381.5	406.4	409.5
382.2	407.6	411.5
384.9	411.0	415.4
386.5	412.3	416.9
387.9	413.8	418.3
437.6	461.2	462.1
438.7	462.5	464.0
439.8	463.8	465.5
456.9	479.5	480.6
458.0	480.9	482.0
462.5	486.5	488.5
463.6	487.7	491.1
466.2	490.0	492.9
467.1	491.1	493.6
467.7	492.7	495.0
468.8	493.8	496.5
469.7	495.8	498.0
470.1	497.1	500.0
470.7	498.7	501.5
471.1	500.4	502.9
472.1	501.4	504.3
473.4	503.1	506.0
474.0	505.0	507.3
474.7	506.3	509.0
475.5	508.6	509.9

476.6	509.7	512.4
478.3	510.9	514.3
494.9	520.0	522.4
551.8	576.7	581.4
552.6	577.8	583.1

*Reference to movie records indicate the Esterline records for Station 3 as given here are 6 seconds too fast.

TABLE 4

Run 4

Station 1	Station 2	Station 3
6.2 sec	16.6 sec	25.1 sec
7.0	18.1	26.4
7.7	19.6	27.5
8.6	20.6	28.4
9.3	21.6	29.3
10.3	23.0	30.2
11.3	23.2	31.2
12.1	26.0	32.0
12.9	26.9	33.7
13.9	28.1	35.1
14.8	29.1	36.6
15.6	30.5	38.1
16.0	32.1	39.3
30.7	43.1	52.1
31.5	44.2	53.0
32.2	45.3	54.0
32.9	46.4	54.8
33.5	47.5	55.7
34.4	48.9	56.8
35.0	49.9	57.9
35.8	51.3	59.1
36.6	52.6	60.1
37.4	53.9	61.6
38.2	55.1	62.5
39.0	56.3	63.6
39.7	58.0	65.4
49.5	61.6	69.7
50.2	62.9	71.4
51.0	64.1	72.8
52.0	65.5	73.9

53.0	66.9	75.0
53.6	68.3	76.2
54.5	69.9	77.3
55.7	71.1	79.8
56.8	72.4	80.6
58.4	74.3	83.1
59.0	74.9	84.3
60.4	77.0	85.6
61.4	78.7	88.1

TABLE 5

Run 5

Station 1	Station 2	Station 3
56.0 sec	68.1 sec	76.9 sec
57.0	69.2	78.0
57.9	70.4	79.1
58.5	71.5	79.8
59.4	72.6	80.6
60.4	74.2	82.1
61.3	75.5	83.0
62.3	76.7	84.4
63.1	77.7	86.6
64.3	78.8	88.2
65.5	80.4	89.3
66.3	82.0	91.0
67.2	83.4	91.8
79.4	92.9	101.7
80.4	94.0	102.7
81.4	95.2	103.5
82.3	96.9	105.0
83.4	98.2	106.1
84.2	99.2	107.1
84.8	100.2	108.5
85.5	101.3	109.5
86.1	102.5	111.0
87.0	104.0	112.4
87.7	105.4	113.0
88.5	106.0	115.2
89.3	107.9	115.6
100.4	112.4	121.4
101.6	113.8	123.9
102.5	115.3	125.1
103.8	116.4	126.3

105.2	118.6	127.7
106.1	120.1	129.3
107.4	121.8	131.6
108.5	123.2	133.0
109.5	124.4	134.2
110.3	125.9	135.2
111.2	127.3	136.3
112.6	128.6	136.9
113.7	130.0	139.4

TABLE 6

Run 6

Station 1	Station 2	Station 3
112.0 sec	128.9 sec	137.8 sec
112.9	130.2	138.9
113.8	131.1	139.8
114.8	132.6	141.1
115.9	134.1	142.2
117.0	135.3	144.3
117.8	136.8	145.6
119.0	138.3	146.8
119.7	139.3	149.0
120.4	140.5	150.1
121.1	142.5	151.3
121.8	144.3	152.4
122.9	146.1	154.3
135.1	153.5	162.1
135.9	154.7	163.1
136.8	155.8	164.0
137.7	157.1	165.5
138.5	158.2	166.4
139.5	159.4	168.1
140.4	160.9	169.3
141.6	162.5	170.4
142.7	163.6	171.1
143.2	164.7	172.3
144.4	165.9	174.1
145.1	167.0	175.3
145.8	168.3	177.0
161.4	177.9	186.1
162.9	179.8	189.0
163.9	181.2	190.2

165.4	183.1	191.5
167.3	184.5	194.3
169.0	187.1	196.0
172.0	188.5	198.1
173.3	190.3	199.3
174.3	191.9	200.3
176.1	193.3	202.5
177.0	194.8	204.3
178.7	197.1	205.6
179.4	197.8	206.9

TABLE 7

Run 7

Station 1	Station 2	Station 3
1.5 sec	10.7 sec	17.8 sec
2.3	11.3	18.7
2.8	12.2	19.9
3.7	13.6	21.6
4.5	14.8	23.4
5.3	15.7	26.8
6.1	16.6	28.2
6.9	17.4	29.4
7.5	18.3	30.3
8.3	20.1	31.4
9.1	21.3	33.2
9.7	23.3	34.5
10.3	24.7	35.8
11.4	26.2	36.9
12.2	28.3	38.1
12.7	29.3	39.4
13.1	30.0	40.2
13.5	31.3	40.9
14.2	32.8	41.6
15.1	34.3	43.7
16.1	36.2	47.8
17.0	37.2	48.4
17.6	38.4	49.7
18.3	39.5	50.5
20.0	40.5	51.8
20.8	41.9	52.7
21.4	43.5	53.5
22.0	44.7	54.4

22.6	46.1	55.6
23.5	47.5	57.3
24.3	49.0	58.5
25.3	50.3	59.7
26.0	51.9	61.1
26.6	52.8	62.3
27.4	54.3	65.8
28.4	55.9	66.7
29.5	56.7	68.0
30.1	57.7	69.1
31.0	59.2	70.1
31.5	60.8	71.3
32.3	62.0	72.5
33.1	63.4	74.4
33.6	65.3	75.7
35.2	66.5	77.4
36.1	67.8	78.6
37.0	69.3	80.5
38.0	71.3	83.0
39.2	72.6	84.2
40.2	74.1	87.0
41.3	75.3	89.3
43.0	77.2	90.5
44.2	78.3	91.5
45.4	80.5	94.5
46.1	81.3	95.7
47.4	83.3	96.9
48.9	84.9	98.3
50.5	85.6	99.4
54.7	87.5	102.5

TABLE 8

Run 8

Station 1	Station 2	Station 3
41.8 sec	56.6 sec	68.7 sec
49.4	61.5	70.6
50.4	62.8	72.1
51.1	63.4	73.2
52.1	64.5	74.2
53.0	65.5	76.2
53.9	66.8	77.3
54.6	68.0	78.3

55.1	69.3	79.3
56.0	70.4	80.3
56.5	71.4	81.2
57.1	72.9	82.5
57.7	74.1	83.5
58.6	75.1	84.5
59.4	76.2	88.5
60.3	77.2	89.5
60.8	77.7	90.5
61.9	79.0	93.1
62.5	80.1	94.2
62.9	81.0	95.1
64.0	83.5	96.5
65.2	85.0	97.4
66.3	86.7	100.0
67.1	88.2	101.2
67.6	90.1	102.1
67.9	91.0	103.6
69.2	92.9	104.8
70.1	94.1	106.1
71.0	95.4	107.3
72.5	97.0	108.2
73.0	98.3	109.3
73.9	99.9	110.5
75.1	101.3	113.2
76.2	102.7	114.6
77.6	104.2	116.1
82.1	106.1	117.1
82.8	107.3	118.3
83.4	108.4	119.4
188.3	202.8	226.0
189.0	203.6	227.4
- *	229.7	243.9
- *	230.8	245.1
- *	231.7	246.5
- *	232.6	249.0
- *	233.5	250.0
247.3	259.0	273.7
248.1	260.8	275.1
248.6	261.7	276.5
253.2	262.7	278.2
254.1	263.4	280.1
297.9	310.4	321.9
299.0	311.3	323.0
300.6	312.6	324.6

341.3	353.1	364.2
342.7	354.7	366.2
343.8	355.8	367.3
344.3	357.0	369.0
345.6	358.1	370.2
346.0	359.2	371.5
346.9	360.6	372.9
347.6	362.6	374.1
348.2	363.3	375.2
349.0	364.1	376.4
349.3	364.8	377.8

*Lost five pieces of data.

TABLE 9

Run 9

Station 1	Station 2	Station 3
36.9 sec	48.0 sec	58.6 sec
37.4	48.7	59.6
38.1	49.9	60.6
43.0	55.1	65.3
44.1	57.3	67.7
45.0	58.3	69.0
45.6	59.1	70.0
45.9	60.0	70.8
46.1	61.4	72.6
46.7	62.5	73.5
46.9	63.4	75.9
47.5	64.9	77.2
47.8	66.2	78.6
48.7	68.1	79.8
49.0	68.7	82.5
49.8	70.0	84.1
50.2	72.4	84.8
50.9	74.1	85.7
51.1	75.8	86.6
52.1	77.8	87.8
53.1	79.6	88.9
54.2	80.8	89.9
54.5	81.9	91.0
55.3	83.1	92.7

56.1	84.9	94.0
56.7	86.1	95.3
57.0	87.6	96.2
57.3	89.6	100.8
57.9	91.1	103.0
60.2	92.1	104.6
61.3	93.3	106.4
61.9	95.6	107.4
62.7	97.0	108.4
63.0	98.1	109.3
63.4	100.1	110.2
84.3	101.7	112.5
85.5	102.5	113.5
86.3	104.0	115.3
210.1	221.5	237.9
212.4	222.3	238.8
213.5	225.1	239.7
216.1	226.1	240.8
216.8	228.4	242.0
217.9	229.2	244.0
- *	231.0	245.1
282.2	296.6	312.3
282.7	298.0	313.4
283.8	299.0	315.1
285.4	300.1	316.3
285.9	301.0	318.2
299.8	310.9	324.8
301.0	311.7	326.0
301.7	312.7	327.5
324.2	335.3	346.1
325.2	337.2	347.3
326.4	338.5	348.3
327.6	340.2	351.9
328.0	341.2	352.8
329.0	342.1	354.2
329.9	343.4	355.3
330.9	344.5	356.3
330.6	346.0	357.9
331.1	347.1	359.1
332.1	351.1	360.2

*Lost one piece of data.

TABLE 10

Run 10

Station 1*	Station 2	Station 3
	40.0 sec	50.6 sec
	41.6	52.1
	42.4	53.1
	43.2	54.4
	44.3	55.1
	45.3	56.0
	47.1	58.0
	47.2	59.0
	49.9	60.3
	50.9	61.1
	52.6	62.7
	53.8	64.4
	55.1	65.3
	56.6	67.6
	58.3	69.1
	59.3	70.4
	60.8	70.8
	61.8	71.5
	62.9	74.2
	64.8	75.9
	65.7	77.1
	69.4	78.7
	70.3	80.7
	71.3	82.8
	73.1	84.1
	73.9	85.0
	75.0	86.1
	77.1	88.2
	78.7	88.9
	79.6	89.9
	81.2	91.3
	82.4	94.1
	83.8	95.1
	85.6	96.2
	86.8	97.1
	88.1	97.4
	89.5	98.9
	91.0	101.4
	93.0	102.8

94.2	104.5
95.5	105.8
96.3	107.1
97.7	109.4
99.0	110.8
100.1	112.3
100.9	113.4
103.8	115.0
105.9	116.5
107.9	118.4
109.1	119.8
111.9	120.7
113.2	122.0
114.8	123.2
115.6	124.5
116.9	126.0
118.1	127.6
119.2	129.4
120.7	130.4
122.2	132.1
123.3	133.1
124.7	134.1
125.5	135.8
208.8	220.1
209.9	220.8
210.8	221.6
212.1	222.3
226.3	235.4
226.9	236.7
227.8	240.0
230.0	240.9
230.9	242.3
232.1	243.5
233.2	247.1
234.1	248.2
272.4	283.7
273.2	289.6
274.4	285.9
275.3	286.9
276.8	288.0
277.8	289.9
279.0	291.1
280.3	292.7
281.9	295.4
282.8	297.0
284.0	298.1

308.4	319.0
309.4	320.4
329.7	340.9
330.8	344.0
331.9	345.2
333.1	346.6
347.3	356.0
348.1	357.5
348.8	358.4
353.4	363.8
355,0	366.4
356.7	367.3
358.2	368.7
359.3	370.1
360.9	372.0
362.0	373.1
363.9	374.2
365.5	375.3
368.1	376.3
372.1	379.7
372.5	380.9
374.4	382.2
375.8	383.9
376.7	385.9
377.8	386.9
379.4	388.8

*No data obtained at Station 1.

TABLE 11

Run 11

Station 1	Station 2	Station 3
2.7 sec	11.9 sec	21.1 sec
3.5	13.8	23.5
4.3	14.8	24.7
4.9	15.5	25.8
5.8	16.7	26.8
6.5	17.6	28.4
7.5	18.6	29.3
8.3	19.8	30.1

9.3	21.5	31.1
10.5	22.9	32.8
11.6	24.7	34.0
12.6	25.5	36.4
13.0	26.7	38.9
14.0	28.1	40.1
15.1	29.2	41.1
15.9	30.2	42.3
17.0	31.8	43.1
17.8	33.3	44.0
18.7	35.1	45.6
19.6	36.6	46.8
20.5	38.8	49.2
21.8	39.9	50.7
23.1	43.4	52.0
24.4	44.0	53.1
25.6	45.5	54.8
26.4	47.3	56.2
27.7	48.6	57.8
- *	49.8	59.7
30.7	51.7	61.1
31.8	53.1	62.5
32.9	54.0	63.9
34.5	55.6	65.6
35.6	56.8	67.4
36.1	57.4	69.0
36.9	59.0	70.0
37.9	60.5	71.1
39.0	62.8	72.4
40.5	64.8	74.4
41.4	66.0	75.7
42.6	67.4	77.7
43.8	68.8	79.4
44.7	69.9	80.4
46.0	71.2	82.4
47.2	72.5	83.7
48.0	73.6	84.8
49.6	74.6	87.0
50.4	75.7	88.0
51.4	76.7	89.2
51.8	77.3	90.6
52.7	80.2	92.2
53.1	83.0	93.2
54.4	84.8	95.8
55.0	85.8	97.3
56.2	87.5	98.9

57.3	89.4	101.0
58.0	91.2	102.1
59.0	93.3	102.9
59.7	94.8	105.8
62.0	95.9	110.7
63.3	97.9	111.5
64.2	99.8	112.9
67.0	101.5	114.1
67.9	103.3	115.1
68.8	104.9	116.2
70.7	106.5	117.9
71.2	107.8	118.7
72.1	109.5	119.7
73.2	110.4	122.3
74.6	112.0	123.4
75.2	113.7	124.7
76.0	115.3	125.9
76.8	117.3	126.9
78.4	118.7	128.3
79.7	120.0	129.7
80.8	123.1	131.1
82.5	124.0	134.5
84.2	124.7	136.2
85.8	126.2	138.8
86.8	127.7	140.0
87.8	128.4	142.6
88.8	131.1	143.9
90.2	133.3	145.5
91.5	134.2	146.8
92.8	135.4	148.4
93.9	136.5	149.6
95.1	138.6	150.6
96.8	140.0	151.6
98.5	141.3	152.8
100.7	143.2	154.9
102.5	144.7	156.2
104.7	146.6	157.6
105.8	147.8	158.0
112.0	148.3	162.6
113.6	150.1	164.0
114.7	151.8	165.2
116.3	153.4	166.6
118.0	155.1	168.1
119.1	156.2	170.4
120.1	157.5	171.0
121.1	159.0	171.9

122.6	161.2	172.8
124.9	162.4	175.1
125.6	163.3	176.7
127.4	165.1	178.5
129.1	166.2	179.9
130.1	167.4	180.8
131.1	168.3	181.8
132.3	169.2	185.7

*Lost one piece of data.

APPENDIX B

TABLE 1

Location	Number of Personnel	Distance to Shelter	Travel Rate	Time to Shelter
A	40	200 feet	6 MPH	23 sec
B	10	250	6	28
C	5	300	6	34
D	25	350	6	40
E	10	400	6	45
F	5	500	6	57
G	5	600	6	68

TABLE 2

Location	Number of Personnel	Time to Reach End of Queue	Time Elapsed Since Last Group Arrived at End of Queue**	Number Serviced During Elapsed Time	Number in Queue Immediately Before Present Group Arrives	Length of Queue Immediately Before Present Group Arrives
A	40	23 sec*	--	--	0	0 feet
B	10	28	5 sec	4	36	108
		16	--	--	40	120***
C	5	34	11	8	42	126
		20	--	--	50	150***
D	25	40	17	12	43	129
		25	2	1	54	162
		21	--	--	55	165
E	10	45	22	16	64	192
		24	1	1	79	237
		19	--	--	80	240***
F	5	57	34	25	65	195
		35	12	9	81	243
		29	6	4	86	258
		28*	5	4	86	258
G	5	68	40	29	62	186
		47	19	14	77	231
		42	14	10	81	243
		41*	13	10	81	243

Total Time = $41 + \frac{(86)(3)}{2.2} + \frac{50}{4.4} = 170$ seconds.

Design Travel Rate immediately at shelter entrance: 1.5 MPH.

Design Travel Rate inside shelter: 3.0 MPH.

Personnel density in single file queue: 1 man/(3 ft).

Length of shelter entrance to be traversed inside shelter: 50 feet.

* Designates final value (as opposed to trial value).

** Time elapsed since last group arrived at the end of the queue is computed by subtracting the previous maximum final value in the column labeled "Time to Reach End of Queue" from the present value in this column.

*** No need to find a final value since any final value in the column labeled "Time to Reach End of Queue" will be less than some previous final value.

TABLE 3

Results of Design Method Compared With Observed Results

Run	Predicted Time of Arrival of All Personnel at Station 3*	Actual Time of Arrival of All Personnel at Station 3
2	731 sec	606.2 sec
3	731	589
4	100	88.1
5	168	139.4
6	236	206.9
8	397	377.8
9	397	360.2
10	410	388.8
11	200	185.7

*Data used in computation of this column is as follows:

Travel rate outside shelter: 4.4 ft/sec

Travel rate immediately at shelter entrance: 1.5 ft/sec

Travel rate inside shelter: 4.0 ft/sec

Distance to be travelled inside shelter: 48 ft

Personnel density in single file queue: 1 man/(2.3)ft

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