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7. Author(s) J. D. Garner, R. F. Chandler, and E. A. Cook		
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16. Abstract

The costs of civil air transport emergency evacuation demonstrations using human subjects have risen as seating capacities of these aircraft have increased. Repeated tests further increase the costs and also the risks of injuries to participants.

A method to simulate such evacuations, by use of a computer model based on statistics from measured components of the escape path, has been developed. This model uses the General Purpose Simulation System (GPSS) computer programing language to represent various features of the escape process; e.g., seating and exit configurations, passenger mix, door-opening delays, time on escape slides, slide capacity, and redirection of passengers to equalize escape lines.

Results of simulated evacuations from the DC-10, L-1011, and B-747 aircraft and a military aircraft are reported. These results have been compared with results of certification demonstrations from the DC-10, L-1011, and B-747. Comparisons of exit size substitutions were evaluated as a means of estimating differences in escape potential for exit design optimization.

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   MEAN = 1.57     SD = 0.76                   FORWARD EXIT TIME FUNCTION
 1      FUNCTION    RN3,C32             FORWARD EXIT FUNCTION (TYPE I)
0,0/.00132,20/.01662,40/.06162,60/.13949,80/.24221,100/.35722,120
.47262,140
.57971,160/.67340,180/.75173,200/.81485,200/.86423,240/.90190,260/
.93005,280/.95070,300/.96562,320/.97625,340/.98373,360/.98894,380/
.99254,400/.99500,420/.99667,440/.99779,460/.99854,480/.99904,500/
.99937,520/.99959,540/.99974,560/.99983.580/.99989,600/1.0000,700
*   MEAN = 1.73    SD = .45                    FORWARD  SLIDE TIME
```

Figure 1. Example of the forward Type I exit function.

that elongates the top of the curve. Each evacuation pathway segment in the model references similar functions for random selection of passenger movement; i.e., time in each segment, until the passenger is on the ground.

The model limits the number of passengers allowed to occupy specific escape slides at one time to three on a single-lane slide, six on a double-lane slide, or to other numbers designated by the user. The length of an escape slide corresponds to the time-on-the-slide function in the model and, consequently, a delay could result in the rate at which passengers may enter the top of the slide.

The model has the capability to use differing mathematical routines, if needed, although none were used in this report. Such routines would be entered into the input listings along with the functions now used.

Transactions are accumulated in counting blocks that register passenger times, numbers of occupants using a facility (door, slide, etc.), and cumulative data during evacuations for each segment of the escape route. These data are then printed out in tabular or graphic form. The redirection of passengers in the cabin from longer waiting lines to an adjacent exit with shorter queues depends on the number programed for the shorter line to contain before transfers take place. The model assumes that passengers reach the shorter exit line before a gap in the escape line occurs. This exit reassignment is similar to volunteer passenger transfers that take place in evacuation demonstrations.

The time at which the last person reaches the ground at each exit is defined as the evacuation time, and the time at the exit with the longest evacuation time is defined as the total escape time. A number of runs on a particular configuration can be made to permit random selections to represent human performance variables on each run and to enable statistical statements of evacuation predictions. Runs of 10, 20, 40, 50, and 100 repeated model evacuations were examined to assess the number of runs needed to confidently display the built-in randomness. The optimum number of runs to allow adequate distribution appears to be between 20 and 40. For each configuration, 20 evacuations were made during the majority of the developmental simulations; this number appeared to provide satisfactory results.

Model Input Data Sources. A central source to obtain all evacuation data relating to transport aircraft does not exist. The aircraft manufacturers, airlines, FAA headquarters and field offices, the National Transportation Safety Board, and the Evacuation Research Unit at the Civil Aeromedical Institute (CAMI) each have limited information. The largest publication thus far is of data assembled by the Aerospace Industries Association (AIA) in their study of evacuations in 1967-68 (4). Assembly and publication of similar data since 1968 has not been accomplished but would be desirable to support the selection of quantitative data for computer inputs. This is especially true since most wide-bodied aircraft were evacuation certified during the early 1970's and are not included in the earlier AIA report.

Passenger flow rates through Type I (24 x 48 in) and Type A (42 x 72 in) exits, described in the Federal Aviation Regulations (25.807), and used in the GPSS model, were derived from the results of an evaluation performed by CAMI in Oklahoma City (5). Overall flow rates through Type I exits averaged 46.8 passengers/min or 1.28 s/passenger. The overall rate for the Type A exit averaged 126.2 passengers/min or 0.48 s/passenger. A ratio of 2.6 has been used for Type A exit escape rates and appears in the GPSS as 10/26. The computer derives the Type A flow rate by dividing the mean Type I flow rate, entered as parameter function 1 (1.57 s/passenger), by 2.6, which maintains the ratio. The resulting Type A flow rate is 0.60 s/passenger and remains in use in the GPSS program until a more representative rate is established for validation of the model.

Calculation of passenger flow rates during the evacuations can be performed either by using the total time from test start to the last out or by considering the time from the first passenger out until the last has evacuated.

Thus, the overall flow rate for an exit is defined by the following ratio:

$$\frac{\text{Time (s) from start signal to last passenger on ground}}{\text{No. passengers evacuated}} = \text{Average overall flow rate (s/passenger)}$$

Continuous flow rate is defined as:

$$\frac{\text{Time (s) from first passenger on ground to last passenger on ground}}{\text{No. passengers} - 1} = \text{Average continuous flow rate (s/passenger)}$$

GPSS General Format. Appendix A is a typical GPSS evacuation program showing the analysis of 527 passengers evacuating a B-747 aircraft through five Type A exits. The first entries in Appendix A, four statements of model operational instructions, are followed by seven Function entities. The Functions permit computations of discrete functional relationships between an independent variable and dependent values of the function. For the B-747 evacuation, these functions are probabilistic distributions from which random

Table 2 lists results of a series of six simulated evacuations, each the average of 20 runs, on the L-1011 aircraft with 356 or 411 passengers. The objective of the runs was to comparatively evaluate a Type I exit vs. a Type A exit in the aft exit position in combination with three other Type A exits on the L-1011. Three of these simulations were comparable to aircraft evacuation demonstrations, the results of which are noted for comparison in Table 2.

TABLE 2. Evacuation Times and Conditions of GPSS Simulation of an L-1011 Evacuation (20 Computer Runs; Exit-Opening Time = 13 s)

No. Pax.	Exits Used A	Exits Used I	Intracabin Redirection Yes	Intracabin Redirection No	Average Total Evacuation Time (s)	Average Total Evacuation Time (Range (s)
356	3	1	-	N	93.5[1]	77.4 - 120.0
356	3	1	Y	-	84.9[2]	77.8 - 90.8
356	4	-	-	N	83.6	77.6 - 89.3
356	4	-	Y	-	79.6	76.7 - 83.9
411	4	-	-	N	83.6	77.6 - 89.3
411	4	-	Y	-	79.6[3]	76.7 - 83.9

[1]Total evacuation time for an actual demonstration was 101.1 s.
[2]Total evacuation time for an actual demonstration was 82 s.
[3]Total evacuation time for an actual demonstration was 89.7 s.

Table 3 consists of groups of 20 simulation runs and shows the total average escape times on a DC-10 with 391 passengers with two variables in the simulated conditions. Exit No. 2 (Type A) simulated a delayed exit-opening time of 50 s, with and without redirection of passengers in the cabin. The other variable shown is a blocked aft exit (Type A), with and without redirection.

TABLE 3. Evacuation Times and Conditions of GPSS Simulation of a DC-10 (20 Computer Runs; 391 Passengers)

Exits Used A	Exits Used I	Intracabin Redistribution Yes	Intracabin Redistribution No	Average Total Evacuation Time (s)	Average Total Evacuation Time Range (s)	Exit-Opening Time (s) 1	2	3	4
3	1	-	N	112.0	100.0 - 122.0	13	50	13	13
3	1	Y	-	92.5	88.9 - 96.6	13	50	13	13
3	1	Y	-	90.2	85.8 - 93.2	13	50	13	13
3	1	-	N	85.0	76.0 - 99.0	13	13	13	13
2	1	-	N	144.0	130.0 - 162.0	13	13	13	--*
2	1	Y	-	114.0	110.0 - 118.0	13	13	13	--*
3	1	Y	-	82.0	77.0 - 88.0	13	13	13	13
3	1	Y	-	90.2	85.8 - 93.2	13	13	13	13

*The aft Type A (Exit 4) was blocked.

Table 4 lists three sets of 20 evacuation simulations that compare evacuation times for: (1) 355 passengers through three Type A and either a Type I (24 x 48 in with a single slide) or a Type B (32 x 72 in with a double slide) exit in the forward position, and (2) 375 passengers through three Type A exits and a Type B exit in the forward position.

TABLE 4. Evacuation Times and Conditions of GPSS Simulation of a DC-10 to Compare Type I and Type B Exit Times (20 Computer Runs)

Exits Used I[1]	A	B[2]	No. Pax	Intracabin Redirection Yes	No	Average Total Evacuation Time (s)	Average Total Evacuation Time Range (s)
1	3	-	355	-	N	106.0	94.0 - 119.0
-	3	1	355	-	N	58.0	55.0 - 61.0
-	3	1	375	Y	-	73.4	67.9 - 79.4

[1]Single-lane slide used.
[2]Double-lane slide used.

Special Applications of the GPSS Evacuation Model. The GPSS model was used to simulate a unique evacuation of 114 passengers from a military command post aircraft. In lieu of flight attendants, military personnel working aboard the aircraft at other duties were assigned to prepare the exits for evacuation. The time required for them to reach the exits from their respective work stations was added to door/slide preparation time. Groups of 25 passengers were evacuated from each exit, one exit at a time, to obtain basic input data for statistical controls. The test results (Table 5) were applied to the flow rate determinations for computer functions. Results of simulated evacuations through five and nine Type A exits are shown in Table 6. The total evacuation times and number of passengers out each exit were averaged from 50 computer runs for each exit configuration.

TABLE 5. Evacuation Time-Path Data Obtained From Evacuations of 25 Passengers From a Military Command Post Aircraft

Test No.	Exit	Time to Exit (s)	No. Pax Out Exit	Time 4th Pax Out Exit (s)	Time 8th Pax Out Exit (s)	Time Last Pax Out Exit (s)
1	L-2	7.1	9	22.2	25.5	27.0
2	L-1	6.8	9	22.2	24.6	26.0
3	R-1	9.2	9	24.0	27.0	28.5
4	R-2	5.3	16	21.0	24.3	31.5
5	L-3	9.2	16	25.2	30.6	42.0
6	R-3	5.4	16	--	20.4	30.0
7	R-4	6.8	16	23.4	29.4	40.5
8	L-5	9.6	16	24.0	29.4	40.0
9	R-5	5.6	9	25.2	31.2	33.0

TABLE 6. GPSS Computer Model Evacuation Simulation Results: Escape by 114 Passengers From a Command Post Aircraft via 5 and 9 Exits

Exit No.	Total Evacuation Time (s)	Average No. Evacuees Through Exit
	5 Exits	
R-1	35.34	23.1
R-2	36.72	25.5
R-3	39.45	23.2
R-4	34.70	22.9
R-5	32.47	19.3
	9 Exits	
R-1	28.90	12.4
R-2	31.49	11.4
R-3	36.33	11.8
R-4	28.37	12.7
R-5	28.37	13.2
L-1	28.10	13.2
L-2	28.82	13.4
L-3	35.88	12.6
L-5	28.80	13.3

A second use of the GPSS evacuation model was as a new aircraft design tool. Two exit configurations and three passenger loads for each configuration were presented for exit optimization in a new civil air transport aircraft. The existing five-exit model program was adjusted to a three-exit program by bypassing operational statements for two nonessential exits. Three Type A exits, and one Type I and two Type A exits in combination, were evaluated, each with 208, 248, or 309 passengers. Table 7 displays the evacuation times for the exit combinations and load factors given. It can be seen that 30 percent less time was required for evacuation with the three Type A exits.

TABLE 7. Averages of Evacuation Times for Exit Combinations and Passenger Load Factors Proposed for a New Design Transport Aircraft (20 Computer Runs)

Exits Used I	Exits Used A	Average Evacuation Times (s), No. Pax 208	248	309
1	2	87.19	99.70	120.40
0	3	62.89	70.49	83.32

The chart listing the number of passengers using each exit demonstrates the effect of passenger transfers to exits with faster escape rates. The transfers are particularly evident with the smaller Type I exit in the forward position combined with two Type A exits when compared with the configuration of three Type A exits as shown in Table 8.

TABLE 8. Effect of Passenger Transfers Showing Average Number Out Each Exit (20 Computer Runs)

No. Pax	Exits		
	3 Type A		
	Forward	Overwing	Aft
208	68.65	71.22	68.13
248	82.48	83.10	83.42
309	102.48	104.04	102.48
	1 Type I and 2 Type A		
	Forward	Overwing	Aft
208	42.75	95.75	69.50
248	51.00	114.28	82.72
309	63.68	140.95	104.37

IV. Discussion.

The program of civil air transport evacuation simulation was undertaken to provide a better understanding of the factors that influence evacuation. Existing certification procedures for demonstrating the safe evacuation potential of an aircraft have proven costly and may result in injury to the participants. The present simulation model program is designed with the exit and slide segments of an evacuation as the major determining factors for total evacuation times. In addition, redistribution or reassignment of passengers to equalize waiting lines to escape contributes significantly to the total evacuation time and this is included in the program. The effects of adverse conditions, such as smoke, fallen ceiling panels, and debris in the aisles, on evacuation times have not been simulated because of the lack of available data for any specific condition.

The knowledge gained from the evacuation demonstrations and accident histories has provided a valuable source of information on which judgments for simulation can be based. Criteria must be determined for the simulation that will provide assurance of adequate escape potential from civil transport aircraft and detect factors inimical to escape and survival. The GPSS-language computer model has the potential to simulate much more sophisticated entities than are shown in this report. An example is the inclusion of the effects of crew effort on evacuation times. Graded on a scale from 1 to 10, a Factor could be entered that would directly influence passenger flow rates through an exit. Computer runs could be made with both easy and low effort (grade 1) to the most enthusiastic effort (grade 10) to evaluate the effects of crew effort. Of course, data would be required to establish the delay function of the Factor. Another example would relate to exit design evaluations to establish optimum distances between exits while considering exit capacities to provide optimization of a total aircraft exit configuration. Until encumbrances on passenger movement to exits override the limiting flow rates, modeling exit flow and escape slide patterns will provide adequate evacuation performance evaluations. Although some rudimentary information is available on interior cabin movement by individual passengers, group tests will be required to substantiate data for more precise simulations.

V. Conclusions.

1. The capability and potential of the GPSS evacuation model have reached the stage in development that allows it to closely simulate actual evacuations from current transport aircraft. With refined inputs, based on additional test results, the model may provide a valid means to certify evacuation systems or evaluate escape system designs while the aircraft are in the early planning stages.

2. A group knowledgeable in evacuation simulation should develop a program to provide the data and formulate simulation criteria for potential use as a certification and/or design tool.

3. All evacuation tests, research, and actual performance data should be assembled at one source and analyzed to obtain pertinent material for model input functions.

4. A final model should be refined and subjected to a rigorous validation process.

5. A practical, validated, evacuation simulation model should then be considered for acceptance as a certification and/or design tool.

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APPENDIX A

TYPICAL GPSS EVACUATION PROGRAM

```
 1          GENERATE  ,,,527,,1C                                                       70
 2          TRANSFER  .200,,FWDA  FORWARD TYPE A EXIT EXPECTS 1/5                       71
 3          TRANSFER  .250,,MIDA  SECOND TYPE A EXIT EXPECTS 1/5                        72
 4          TRANSFER  .333,,AFTA  THIRD TYPE A EXIT EXPECTS 1/5                         73
 5          TRANSFER  .500,,AFT1  FOURTH TYPE A EXIT EXPECTS 1/5                        74
 6          TRANSFER  ,ADDL       FIFTH TYPE A EXIT EXPECTS 1/5                         75
 7    FWDA  ASSIGN    4,1                                                    CB160740   76
 8          ASSIGN    5,2              FIRST EXIT, SLIDE NBR ASSIGNED P5     CB160750   77
 9          ASSIGN    6,2              OPPOSITE SIDE E&S NBR ASSIGNED P6     CB160760   78
10          ASSIGN    9,21                                                   CB160770   79
11          ASSIGN    1C,22                                                  CB160780   8C
12          ASSIGN    1,1                                                               81
13          TRANSFER  ,EXIT                                                  CB160790   82
14    MIDA  ASSIGN    4,4                                                    CB160800   83
15          ASSIGN    5,5                                                    CB160810   84
16          ASSIGN    6,5                                                    CB160820   85
17          ASSIGN    9,24                                                   CB160830   86
18          ASSIGN    1C,25                                                  CB160840   87
19          ASSIGN    1,2                                                               88
20          TRANSFER  ,EXIT                                                  CB160850   89
21    AFTA  ASSIGN    4,7                                                    CB160860   90
22          ASSIGN    5,8                                                    CB160870   91
23          ASSIGN    6,8                                                    CB160880   92
24          ASSIGN    7,6         OVERWING-RAMP PATH IS NUMBERED   6 IN P7   CB160890   93
25          ASSIGN    9,27                                                   CB160900   94
26          ASSIGN    10,28                                                  CB160910   95
27          ASSIGN    1,3                                                               96
28          TRANSFER  ,EXIT                                                  CB160920   97
29    AFT1  ASSIGN    4,10                                                   CB160930   98
30          ASSIGN    5,11                                                   CB160940   99
31          ASSIGN    6,11                                                   CB160950  100
32          ASSIGN    9,30                                                   CB160960  101
33          ASSIGN    1C,31                                                  CB160970  102
34          ASSIGN    1,4                                                              103
35          TRANSFER  ,EXIT                                                  CB160980  104
36    ADDL  ASSIGN    4,13                                                   CB160990  105
37          ASSIGN    5,14                                                   CB161000  106
38          ASSIGN    6,14                                                   CB161010  107
39          ASSIGN    9,33                                                   CB161020  108
40          ASSIGN    1C,34                                                  CB161030  109
41          ASSIGN    1,5                                                              110
42          TRANSFER  ,EXIT                                                  CB161040  111
43    EXIT  TEST GE   N2,114                                                           112
44   BEGIN  ENTER     P4          ENTER AISLES AWAITING DOORS                          113
45          ADVANCE   FN2         DOOR-MECHANISM DELAY, USING P4 ALSO        CB161120  114
46          LEAVE     P4                                                     CB161130  115
47          QUEUE     P9                                                     CB161140  116
48          LINK      P1,FIFO,AAA                                                      117
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49   AAA    GATE NU    P5              HOLD FOR EXIT REASSIGNMENT
50          UNLINK     P1,AAA,1
51          TEST GE    Q*9,K0,SEZ                                      CB161170
52          TEST NE    P9,21,NOONE                                     CB161180
53          TEST NE    P9,24,NOFOR                                     CB161190
54          TEST NE    P9,27,NOSEV                                     CB161200
55          TEST NE    P9,30,NOTEN                                     CB161210
56          TEST NE    P9,33,NOTHT
57   NOONE  TEST L     Q*V$SIDE2,K0,ONE4                               CB161220
58          TRANSFER   ,ASGN2                                          CB161230
59   ONE4   TEST E     Q*V$SIDE4,K0,SEZ                                CB161240
60          TRANSFER   ,ASGN4                                          CB161250
61   NOFOR  TEST L     Q*V$SIDE1,K0,FOR2                               CB161260
62          TRANSFER   ,ASGN1                                          CB161270
63   FOR2   TEST E     Q*V$SIDE2,K0,FOR4                               CB161280
64          TRANSFER   ,ASGN2                                          CB161290
65   FOR4   TEST E     Q*V$SIDE4,K0,SEZ                                CB161300
66          TRANSFER   ,ASGN4                                          CB161310
67   NOSEV  TEST E     Q*V$SIDE1,K0,SEV2                               CB161320
68          TRANSFER   ,ASGN1                                          CB161330
69   SEV2   TEST E     Q*V$SIDE2,K0,SEV3                               CB161340
70          TRANSFER   ,ASGN2                                          CB161350
71   SEV3   TEST E     Q*V$SIDE3,K0,SEV4
72          TRANSFER   ,ASGN3                                          CB161370
73   SEV4   TEST E     Q*V$SIDE4,K0,SEZ
74          TRANSFER   ,ASGN4
75   NOTEN  TEST E     Q*V$SIDE1,K0,TEN2
76          TRANSFER   ,ASGN1                                          CB161390
77   TEN2   TEST L     Q*V$SIDE2,K0,TEN3
78          TRANSFER   ,ASGN2
79   TEN3   TEST L     Q*V$SIDE3,K0,SEZ                                CB161400
80          TRANSFER   ,ASGN3                                          CB161410
81   NOTHT  TEST L     Q*V$SIDE1,K0,THT3
82          TRANSFER   ,ASGN1
83   THT3   TEST E     Q*V$SIDE3,K0,SEZ
84          TRANSFER   ,ASGN3
85   ASGN1  ASSIGN     4-,3            SEND PAX TO NEXT EXIT FORWARD   CB161420
86          ASSIGN     5-,3                                            CB161430
87          ASSIGN     6-,3                                            CB161440
88          DEPART     P9                                              CB161450
89          ASSIGN     9-,3                                            CB161460
90          QUEUE      P9                                              CB161470
91          QUEUE      P10                                             CB161480
92          DEPART     P10                                             CB161490
93          TRANSFER   ,SEZ                                            CB161500
94   ASGN2  ASSIGN     4+,3            SEND PAX TO NEXT EXIT AFT       CB161510
95          ASSIGN     5+,3                                            CB161520
96          ASSIGN     6+,3                                            CB161530
97          DEPART     P9                                              CB161540
98          ASSIGN     9+,3                                            CB161550
99          QUEUE      P9                                              CB161560
100         QUEUE      P10                                             CB161570
101         DEPART     P10                                             CB161580
102         TRANSFER   ,SEZ                                            CB161590
103  ASGN3  ASSIGN     4-,6                                            CB161600
104         ASSIGN     5-,6                                            CB161610
105         ASSIGN     6-,6                                            CB161620
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106         DEPART    P9                                                          CB161630
107         ASSIGN    9-,6                                                        CB161640
108         QUEUE     P9                                                          CB161650
109         QUEUE     P10                                                         CB161660
110         DEPART    P10                                                         CB161670
111         TRANSFER  ,SEZ                                                        CB161680
112  ASGN4  ASSIGN    4+,6                                                        CB161690
113         ASSIGN    5+,6                                                        CB161700
114         ASSIGN    6+,6                                                        CB161710
115         DEPART    P9                                                          CB161720
116         ASSIGN    9+,6                                                        CB161730
117         QUEUE     P9                                                          CB161740
118         QUEUE     P10                                                         CB161750
119         DEPART    P10                                                         CB161760
120         TRANSFER  ,SEZ                                                        CB161770
121  SEZ    QUEUE     P5          BEGIN EXIT DELAY-INTERVALS                      CB161780
122         SEIZE     P5                                                          CB161790
123         DEPART    P9                                                          CB161800
124         MARK      8                                                           CB161810
125         ADVANCE   V*5                                                         CB161820
126         RELEASE   P5                                                          CB161830
127         TEST E    P4,7,QUE4   PATH 7 INCLUDES OVERWING SEGMENT, 6 IN P7      CB161850
128         ASSIGN    7,6                                                         CB161860
129         QUEUE     P7                                                          CB161870
130         ENTER     P7          ENTER STORAGE FOR OVERWING RAMP                 CB161880
131         ADVANCE   V*7                                                         CB161890
132         LEAVE     P7                                                          CB161900
133         DEPART    P7                                                          CB161910
134  QUE4   QUEUE     P4                                                          CB161920
135         ENTER     P5          ENTER STORAGE FOR SLIDE TIME                    CB161930
136         ADVANCE   V*4                                                         CB161940
137         LEAVE     P5                                                          CB161950
138         DEPART    P4                                                          CB161960
139         DEPART    P5                                                          CB161970
140         SAVEVALUE P5,M1       RECORD THE LATEST TOTAL TIME FOR EACH PATH      CB161990
141  TERM   TERMINATE 1                                                           CB162000
     *                            STORAGE CAPACITIES LISTED NEXT                  CB162010
```