Federal Aviation Administration

ANALYSIS OF THE RISK OF AN AIRBUS A380 HAND FLOWN BALKED LANDING PENETRATING THE FAA CODE E OFZ

Branch Study Report
AFS-440-BSR-03
September 2006

Flight Systems Laboratory

Executive Summary

The purpose of this study is to determine the probability of penetration of the FAA CAT I OFZ (Inner Transitional Surface) by an A380 during a hand-flown balked landing operation.

In AC 150/5300-13 CHG 8, the OFZ is specified to have a base width (Inner Approach Surface) of 400 feet for runways serving large airplanes. The inner-transitional OFZ surface rises vertically then 200 feet laterally from the center of the runway. The extent of this vertical rise is a function of both the runway threshold elevation above sea level and the most demanding wingspan of airplanes expected to use the runway. From the top of this vertical rise, the surface then slopes 6 (horizontal) to 1 (vertical) out to a height of 148 feet.

The study is intended to determine the risk of the A380 penetrating the FAA CAT I Inner-transitional OFZ during a hand-flown (flight director assisted) balked landing operation under typical environmental conditions.

The study applies extreme value analysis, a type of statistical analysis, to determine the penetration probability. The results of this analysis show that the probability of penetration is on the order of 4.5 E-07. (i.e., 4.5 in 10,000,000.)

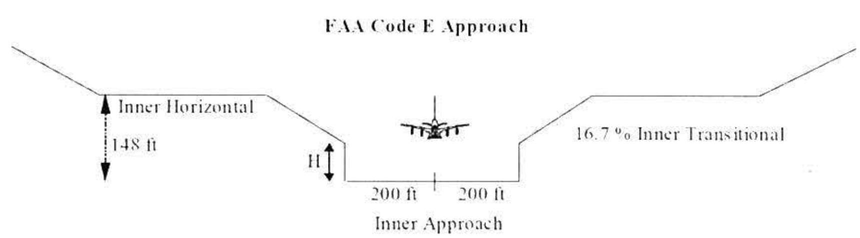
1.0 Introduction

The purpose of this study is to determine the probability of penetration of the FAA CAT I OFZ (Inner Transitional Surface) by an A380 during a hand-flown balked landing operation.

In AC 150/5300-13 CHG 8, the OFZ is specified to have a base width (Inner Approach Surface) of 400 feet for runways serving large airplanes (see Figure 1). At a distance 200 feet from the runway center the inner-transitional OFZ surface rises vertically on either side a distance H. The extent of this vertical rise (H) is a function of both the runway threshold elevation above sea level and the most demanding wingspan of airplanes expected to use the runway. From the top of this vertical rise, the surface then slopes 16.7%, 6 (horizontal) to 1 (vertical) out to a height of 148 feet.

The study is intended to determine the risk of the A380 penetrating the FAA CAT I Inner-transitional OFZ during a hand-flown (flight director assisted) balked landing operation under typical environmental conditions.

Figure 1



2.0 Test Plan

In order to determine the probability of penetration of the FAA OFZ we performed a series of tests of the balked landing operation using Airbus simulators in Toulouse and Berlin. These tests were designed to simulate the conditions of an Airbus A380 balked landing operation as closely as possible.

We performed 156 operational runs in Toulouse and 356 runs in Berlin all with professional flight crews. Of those 512 runs, 313 were hand flown balked landing operations (the other 199 were either actual landings, go-arounds that we not balked landings, or autopilot operations).

We had reason to believe that extreme crosswind conditions and very low balked landing initiation heights would increase the probability of OFZ penetration, so we included a disproportionate number of those cases in the test plan. The proportion of runs by crosswind speed and balked landing initiation height is indicated in Table 1.

Table 1

Initiation			Crosswind (knots)				
Height (ft)	0	10	18	21	23	25	Total
10	4%	8%	13%	2%	0%	6%	34%
40	3%	9%	8%	2%	6%	6%	35%
70	3%	8%	11%	0%	6%	3%	31%
Total	10%	26%	32%	5%	12%	15%	100%

For each run we measured aircraft position and orientation variables 15 times per second in order to determine the relationship between the A380 wing tips and the FAA OFZ Inner-transitional Surface.

3.0 Test Results

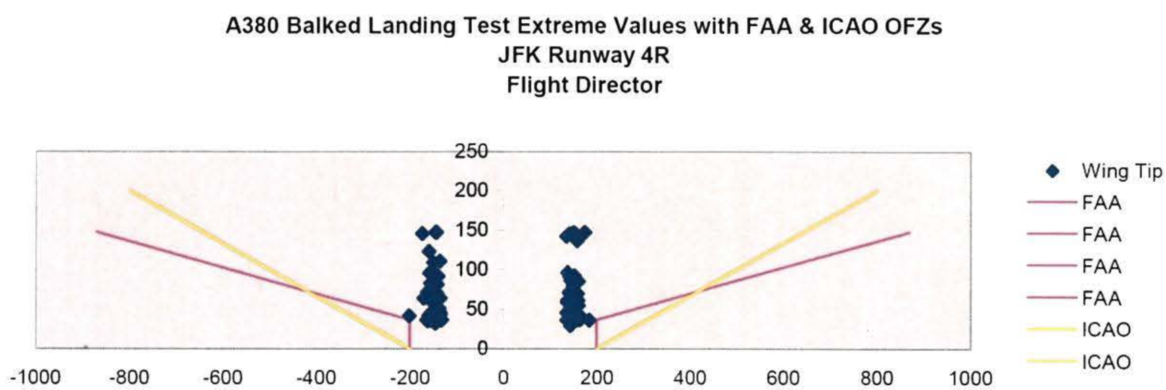
Since the FAA OFZ Inner-transitional Surface is (at least partially) a sloping surface, the relationship between the A380 wing tip and the surface varies by height even if the wing tip does not deviate laterally. For this reason, we normalized the measure of the distance from the wing tip to the OFZ surface. To do this, we defined a variable (called S) whose value is the percent lateral deviation of the wing tip between its nominal position and the FAA OFZ Inner-transitional Surface. That is, S is the actual wing tip deviation from nominal divided by the possible wing tip deviation, where *possible* means the distance from the wing tip to the surface when the aircraft is on track in the nominal position. For example, if the aircraft's lateral deviation from the nominal track is 0, the value of S is 0%. If the aircraft's left (or right) wing tip is touching the surface, the value of S is 100%. If the wing tip is exactly half way between nominal position and the surface, the value of S is 50%.

We calculated values for S for each data point along the aircraft's track starting with the initiation of the balked landing (taken to be when the throttle angle first exceeds 50°) and ending when the aircraft's lower wing tip has exceeded the 148 foot height of the sloping part of the Inner-transitional Surface (where the surface becomes horizontal) on its balked landing ascent. We then determined the maximum S value for each of the 313 balked landing runs.

For analysis purposes the variables of interest from the test data for each run are then: the maximum S value for the run, the crosswind speed, and the planned height at which the balked landing was initiated.

Figure 2 shows the left or right wing tip location for each maximum S related to the FAA OFZ surface in cross section. In the figure the height, H, is that calculated for runway 4R at KJFK (John F. Kennedy International Airport) in New York.

Figure 2



4.0 Analysis

Risk is the combination of

- the consequence (or severity) of a Hazard Event and the
- probability of its occurring within the Scenario of interest.

The purpose of the present study is to determine the probability component of the risk of the Hazard Event: an A380 wing tip penetrates the FAA OFZ Inner-transitional surface at least once during a Scenario operation.

<u>Analysis Preliminaries</u>

Here we establish five preliminary results that we will use in the analysis proper. First, we ensure that the Toulouse and Berlin data does not need to be analyzed separately. Second, we establish a reasonable estimate for balked landings. Third, we validate that crosswind speed and balked landing initiation height really do affect the value of S as we had suspected. Fourth, we compare the crosswind speeds used in the test with typical representative crosswind speeds to establish that test crosswind speeds are not representative. And finally, we compare the distribution of balked landing initiation heights used in the test with typical initiation heights to establish that test initiation heights are not representative

1. Toulouse and Berlin data should not be separated for analysis:

We performed both a Kolmogorov-Smirnov test and a Two-Sample Chi-Square test on the Toulouse and Berlin data to determine if they can be said to represent different distributions. The null hypothesis for each test was: the two sets of data represent the same distribution. The results of the two tests were consistent: each indicates that the null hypothesis should not be rejected. That is, there is no reason to separate the data for analysis since they appear to represent a single distribution.

2. The balked landing rate to use is less than 1.9 per 1000 landing attempts:

We compared Go-Around rates available from five European airports and from a sample of runway 14R at Chicago O'Hare airport (see Table 2). These rates are consistently around 1.9 Go-Arounds per 100 attempted landings. However, while every balked landing is a Go-Around, not all Go-Arounds are balked landings. And since we have no data for actual balked landing rates, we use the Go-Around rate as an upper bound. Anecdotal information indicates that the balked landing rate may be on the order of one-tenth the Go-Around rate.

Table 2

Go Around Rates

Airport	Year	Approaches	GA	GA per approach	Approaches/GA
LFPG	2003	257475	691	2.68E-03	373
LFPO	2003	103248	150	1.45E-03	688
LEBL	2002	135268	200	1.48E-03	676
LEBL	2003	140275	237	1.69E-03	592
LEMD	2002	183727	279	1.52E-03	659
LEMD	2003	189173	369	1.95E-03	513
LEPA	2002	80305	145	1.81E-03	554
LEPA	2003	84387	139	1.65E-03	607
TOTAL		**1173858**	**2210**	**1.88E-03**	**531**
KORD	**1998-2000**	**43960**	**84**	**1.91E-03**	**523**

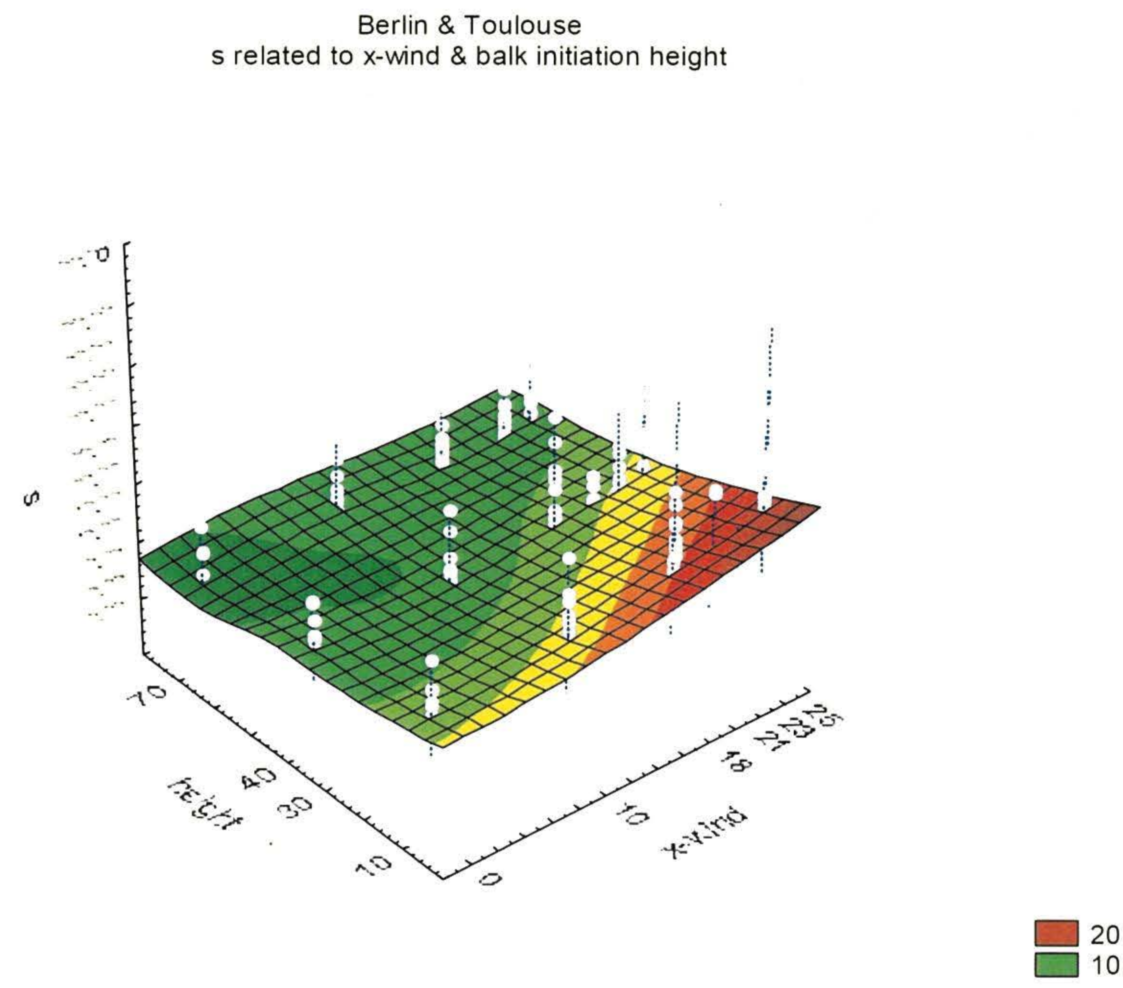
3. Crosswind and balked landing initiation height affect S:

In developing the test plan we believed that crosswind speed would have a significant effect on lateral deviation from the nominal track (measured by variable S) and that balked landing initiation height would have a significant effect (the lower the initiation height the greater the lateral deviation).

Figure 3 shows the graphical relationships among the three variables: S, Crosswind Speed, and Initiation Height. The colored surface is a smoothed surface created from the S means at each x-wind/height combination. The small circles represent actual S values at those x-wind/height coordinates.

The obvious conclusion from this data is that both higher crosswind speed and lower initiation height lead to greater S values. (S values are plotted in the vertical axis in Figure 3.)

Figure 3



4. Crosswind speeds used in the test are not representative:

Since we believed that higher crosswind speeds would affect lateral deviations (S), we included many more high wind speed runs in the test than would be typical in an actual airport operational environment. We did this to help us understand the relationship between crosswind speed and balked landing lateral deviation.

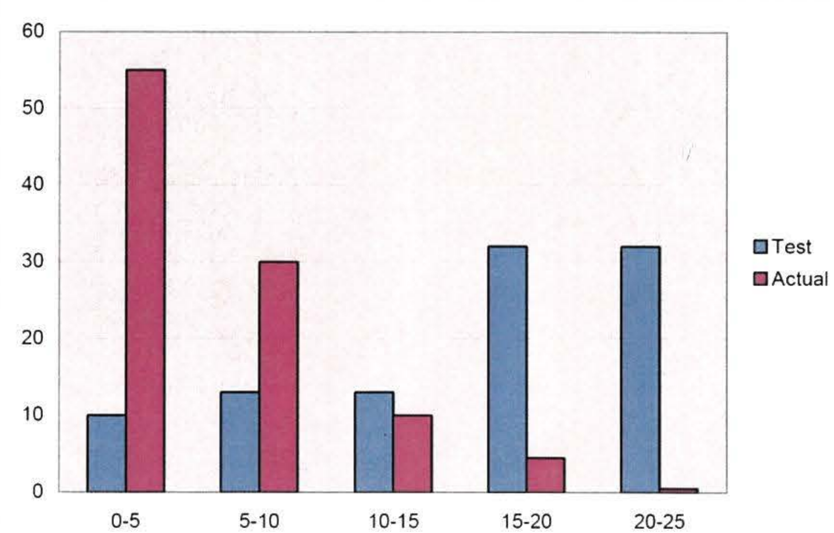
The analysis must therefore compensate for this imbalance by using an actual crosswind speed distribution, comparing it to the test distribution. The distribution we use as actual is from the table in Figure A4-7 of Appendix 4 to AC 120-28D. Table 3 lists the corresponding test and actual distribution values.

Table 3

Speed	Test	Actual
0-5	10	55
5-10	13	30
10-15	13	10
15-20	32	4.5
20-25	32	0.5

And Figure 4 displays the same information graphically. Note that the test wind value of 10 knots represented 26% of the values and is divided between the 5-10 and 10-15 categories here giving 13% in each for a balanced comparison.

Figure 4



5. Distribution of balked landings by initiation height is not representative:

The FAA AFS-420 Chicago O'Hare Land and Hold Short study data indicate that almost all go-arounds are initiated above 70 feet (about 97%) and that certainly far less than 10% of them are initiated below 15 feet. But the very small sample size of go-arounds at low altitudes in this data (combined with the fact that these are go-arounds and not specifically balked landings) prevents us from using them to find accurate distributions for balked landings initiated below 70 feet.

However, data supplied to Airbus from five airlines it surveyed give a more detailed distribution of actual balked landing initiation heights. Table 4 compares the actual balked landing initiation heights distribution estimates from the Chicago Study and the Airbus Data with the distributions of initiation heights from the test data.

Table 4

Source	Overall Go-Around Rate per 1000 Approaches	Percent of Go-Arounds Initiated Below 70 Feet	Percent of Go-Arounds Initiated Below 50 Feet	Percent of Go-Arounds Initiated Below 15 Feet
Chicago Study	1.9	3%	not available	not available
Airbus Data	1.6	7%	4%	2%
Test Data	--	94%	70%	19%

<u>Probability of OFZ Penetration</u>

To calculate the probability that an A380 wingtip penetrates the FAA Code E OFZ (Inner Transitional Surface) we use a three step methodology.

- First, we establish the Scenario of Interest. This is the scenario to which the probability applies. And it includes attribute assumptions such as crosswind distribution, initiation height distribution, and type of landing.
- Second, we use the data to develop a distribution of maximum S values for the Scenario of Interest.
- And third, we use this distribution to estimate probability that S > 100%, that is, that a wing tip penetrates the Code E OFZ surface under the Scenario of Interest.

Scenario 1 (artificial crosswinds, actual initiation heights)

1. Establish Scenario 1

In this scenario we assume the actual crosswind distribution is the same as that used in the 313 test runs. But we assume that the initiation height distribution is that of the Airbus airline data [ ]. We must emphasize the crosswind distribution is an artificial assumption based on the relationship between the actual crosswind speeds and those used in the test (see Analysis Preliminary 4 above).

Since (a) the proportion of higher crosswind speeds in the test is much higher than in actual conditions and (b) the relationship between that variable and the variable S is such that higher crosswind speeds are directly related to higher values of S (see Analysis Preliminary 4), then we would expect this scenario to lead to a higher probability of OFZ penetration than one using wind actual conditions.

Assumptions:

- A hand-flown balked landing has occurred, as in the test.
- Crosswind speeds are those of the test (not actual distributions)
- Balked landing initiation heights are those of the actual Airbus airline data

2. Develop a Distribution for Maximum S for Scenario 1

Next, we use classical Extreme Value Theory to develop a distribution for the maximum S values. This theory provides the two things. First, it provides a family of distributions (called GEV, or General Extreme Value distributions) that model block maximums such as those of the variable S. Second, it provides the justification for using a GEV distribution to extrapolate beyond the range of the maximum S values found in the test data.

The family of GEV distributions is described by the distribution function:

$\mathrm{GEV}(x) = \exp\left\{-\left[1+\xi\left(\frac{x-\mu}{\sigma}\right)\right]^{-1/\xi}\right\}$, where μ is the location parameter, σ is the scale parameter, and ξ is the shape parameter. Changing the value of any one of the parameters provides a different member of the family of GEV distributions.

We actually develop two GEV distributions, one for each of two categories of initiation height. We use only two categories in order to maintain a relatively large sample size in each category. We develop one distribution for initiation heights less than or equal to 50 feet and another for initiation heights above 50 feet. We chose the break at 50 feet to balance the number of runs below and above the break in the test data with the number below and above in the Airbus airline data[1].

We use the test data and a standard extreme value technique (extreme value maximum likelihood estimation) to estimate the three parameter values for each of the two specific distributions that fit our data.

For this scenario, for the initiation heights less than or equal to 50 feet, case 1, the parameter values the estimation technique yields are:

$\mu = 7.9065$, $\sigma = 6.2897$, and $\xi = 0.3656$ with standard errors 0.5126, 0.4516, and 0.0786 respectively. We call this distribution GEV1.

And for the initiation heights above 50,case 2, feet the parameter values the estimation technique yields are:

$\mu = 4.2574$, $\sigma = 2.5920$, and $\xi = 0.0161$ with standard errors 0.3039, 0.2231, 0.0824 respectively. We call this distribution GEV2.

3. Estimate the probability that S > 100% for Scenario 1

We estimate the probability that S > 100%, given that a hand-flown balked landing has been attempted under this scenario by calculating the area under each GEV density function (GEV1 and GEV2 for cases 1 and 2 respectively) to the right of 100, multiplying each of these areas by the probability of each case occurring given a balked landing has occurred. Table 5 summarizes the calculation.

Table 5

Case	Initiation Height	Probability of Case Given Balked Landing	Penetration Probability Given Case	Resultant Probability Given Balked Landing
1	≤ 50 feet	7/169 = 0.04142	6.3 E-03	2.6 E-04
2	> 50 feet	162/169 = 0.95858	2.7 E-13	2.6 E-13
			Total (Both Cases)	2.6 E-04

The total probability is 2.6 E-04 (meaning, 2.6 multiplied by 10 to the negative fourth power), given this scenario: that a hand-flown balked landing has occurred and the test crosswind and actual initiation height conditions are used. This estimate is likely high due to the use of the artificially high crosswind distribution.

[1] We tested break values of both 40 and 60 feet also, and obtained results similar to those using a 50 foot break (about 4.8 E-07 for 40 and 60 versus 4.1 E-07 for 50 feet). Note that for a break of 50 feet there were only 7 data points (out of 169) below in the Airbus airline data, but there were 219 (out of 313) below in the test run data.

However, it does provide an upper bound estimate for the actual OFZ penetration probability.

The 313 flight simulator test runs used three airports: John F. Kennedy International Airport (KJFK), Denver International Airport (KDEN), and Benito Juárez International Airport in Mexico City, Mexico (KMEX). The results in scenarios 1 and 2 assume the environmental conditions at those locations. Also, the values for the height, H, (see Figure 1) vary because of the differences in elevation of the three airports. The value of H decreases when the MSL altitude increases. Therefore, the KJFK altitude (4 feet MSL) provides the greatest value for H.

In order to compare the results for Scenario 1 to those using a uniformly high value for H, we analyzed the KJFK runs separately. The resultant probability given a balked landing for the KJFK runs was 1.85 E-04. This is slightly smaller than the total resultant probability calculated for Scenario 1: 2.60 E-04 (see Table 5). This leads us to conclude that the results are not biased by lower values of H at the higher altitude airports in the study.

Scenario 2 (actual crosswinds, actual initiation heights)

1. Establish Scenario 2

In this scenario we assume the actual initiation height distribution is the same as that of the Airbus airline data, and that the crosswind distribution is the actual distribution given in Analysis Preliminary 4 above.

And since (a) the proportion of high crosswinds in the test is much greater than in actual conditions and (b) the relationship between this variable and the variable S is such that lower crosswind speeds are directly related to higher values of S (see Analysis Preliminary 4), then we would expect this scenario to lead to a somewhat lower probability of OFZ penetration than one found in Scenario 1.

Assumptions:

- A hand-flown balked landing has occurred, as in the test.
- Balked landing initiation heights are the actual ones of the Airbus airline data (not the test distribution).
- Crosswind speeds follow the actual distribution (not the test distribution)

2. Develop a Distribution for Maximum S for Scenario 2

Next, we use classical Extreme Value Theory as in Scenario 1, except now we develop four distributions of the maximum S values: one for each of four combinations of two initiation heights and two crosswind speeds. The two crosswind speed categories are 0 – 20, and 20 and above knots.

Next we develop four GEV distributions, one for each initiation height/crosswind speed category. Table 6 summarizes the parameter values for the four distributions.

Table 6

Case	Distribution	Initiation Ht.	Crosswind	μ	σ	ξ
a	GEVa	≤ 50 feet	≤ 20 knots	7.4363	6.1541	0.3598
b	GEVb	≤ 50 feet	> 20 knots	8.7922	6.2355	0.4229
c	GEVc	> 50 feet	≤ 20 knots	3.9029	2.5699	0.0912
d	GEVd	> 50 feet	> 20 knots	5.2678	2.2798	0.1692

3. Estimate the probability that S > 100% for Scenario 2

We estimate the probability that S > 100%, given that a hand-flown balked landing has been attempted under this scenario by calculating the area under each GEV density function (GEVa, GEVb, GEVc, and GEVd) to the right of 100 and multiplying each of these areas by the likelihood of the case.

Table 7

Case	Initiation Ht./ (Probability)	Crosswind/ (Probability)	Probability of Case Given Balked Landing	Penetration Probability Given Case	Resultant Probability Given Balked Landing
a	≤ 50 feet (0.04142)	≤ 20 knots (0.995)	0.0412	5.7 E-03	2.35 E-04
b	≤ 50 feet (0.04142)	> 20 knots (0.005)	0.0002	9.8 E-03	1.96 E-06
c	> 50 feet (0.95858)	≤ 20 knots (0.995)	0.9538	8.6 E-08	8.20 E-08
d	> 50 feet (0.95858)	> 20 knots (0.005)	0.0048	0.0 E-00	0.0 E-00
				Total (all cases)	2.37 E-04

Thus, P(S > 100%) = 2.37 E-04, given this scenario: that a hand-flown balked landing has occurred and the actual crosswind and actual initiation height conditions are used. Since the actual crosswind distribution was used (as opposed to the artificially high test conditions used in Scenario 1) the estimate here in Scenario 2 (2.37 E-04) is somewhat smaller than that of Scenario 1 (2.6 E-04), and in addition provides a validation in that the values are reasonably close.

We note that these probability estimates are conditional. That is, they are the probabilities *given* a balked landing has occurred. To arrive at the overall risk factor, they must be multiplied by the probability that a balked landing occurs. We show this calculation in the next section.

5.0 Conclusion

Based on the two scenarios analyzed, we can calculate a reasonable upper bound on the probability of ICAO Code E OFZ penetration. Table 6 summarizes the probability estimates from the two scenarios. It is important to recall that these are conditional probabilities. That is, they are probabilities of OFZ penetration given that a hand-flow balked landing has occurred. We must factor in the probability of a hand-flown balked landing occurring to complete the calculation.

Table 6

Scenario	Penetration Probability*
1	2.60 E-04
2	2.37 E-04

*Given hand-flow balked landing.

Each of these probabilities was developed using assumptions that would tend to produce higher rather than lower values. They differ primarily because of the variations in the sets of runs used to fit the various distributions.

To calculate a reliable upper bound on the OFZ penetration probability, we make these further assumptions:

1. Use the smaller and more precise of the two scenario probabilities (2.37E-04).
2. Use the balked landing rate of Analysis Preliminary 2, which is actually 1.9 balked landings per 1000 landing attempts.
3. Focus only on OFZ penetrations due to balked landings, assuming that normal landing produce effectively no penetrations.

The probability of hand-flown A380 FAA OFZ penetration during a balked landing (OFZP) is given by:

P(OFZP) = P(Balk)•P(OFZP | Balk) + P(no Balk) •P(OFZP|no Balk).

Which reduces to: P(OFZP) = P(Balk)•P(OFZP | Balk), since P(OFZP|no Balk) is effectively zero. That is, no Balk (i.e., normal landings) produce effectively zero penetrations by assumption 3 above.

Since, P(OFZP | Balk) = 2.37E-04, by assumption 1 above.
And, P(Balk) = 1.9 E-03, by assumption 2 above.
Then, P(OFZP) = 4.50 E-07.

That is, an estimate of an upper bound for the probability of an A380 FAA Code E OFZ penetration during a hand-flown balked landing is determined to be 4.50 E-07.