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Analysis of Debris Trajectories at the Scaled Wind Farm Technology (SWiFT) Facility

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Analysis of Debris Trajectories at the Scaled Wind Farm Technology (SWiFT) Facility

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Executive Summary

Sandia National Laboratories operates the Scaled Wind Farm Technology Facility (SWiFT) on behalf of the Department of Energy Wind and Water Power Technologies Office. An analysis was performed to evaluate the hazards associated with debris thrown from one of SWiFT's operating wind turbines, assuming a catastrophic failure. A Monte Carlo analysis was conducted to assess the complex variable space associated with debris throw hazards that included wind speed, wind direction, azimuth and pitch angles of the blade, and percentage of the blade that was separated. In addition, a set of high fidelity explicit dynamic finite element simulations were performed to determine the threshold impact energy envelope for the turbine control building located on-site. Assuming that all of the layered, independent, passive and active engineered safety systems and administrative procedures failed (a 100% failure rate of the safety systems), the likelihood of the control building being struck was calculated to be less than 5/10,000and ballistic simulations showed that the control building would not provide passive protection for the majority of impact scenarios. Although options exist to improve the ballistic resistance of the control building, the recommendation is not to pursue them because there is a low probability of strike and there is an equal likelihood personnel could be located at similar distances in other areas of the SWiFT facility which are not passively protected, while the turbines are operating. A fenced exclusion area has been created around the turbines which restricts access to the boundary of the 1/100 strike probability. The overall recommendation is to neither relocate nor

improve passive protection of the control building as the turbine safety systems have been improved to have no less than two independent, redundant, high quality engineered safety systems. Considering this, in combination with a control building strike probability of less than 5/10,000, the overall probability of turbine debris striking the control building is less than 1/1,000,000.

ACKNOWLEDGMENTS

DOE Wind and Water Power Technologies Office provided funding for this report.

DRAFT

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NOMENCLATURE

DOE	Department of Energy
SNL	Sandia National Laboratories
SWiFT	Scaled Wind Farm Technology Facility
WWPTO	Department of Energy Wind and Water Power Technologies Office
rpm	Revolutions per minute

1. INTRODUCTION

Sandia National Laboratories (SNL) operates the Scaled Wind Farm Technology Facility (SWiFT) on behalf of the Department of Energy (DOE) Wind and Water Power Technologies Office (WWPTO). An analysis was performed to evaluate the hazards associated with debris thrown from one of SWiFT's wind turbines, assuming a failure.

1.1. Purpose of Analysis

Debris throw from an operating turbine is a notable hazard. The purpose of this analysis was to evaluate the **worst case scenario** of debris thrown and striking a person in an **unmitigated situation assuming a failure of the turbine and/or rotor blade**. The precursors required to reach this failure were not assessed in this analysis but are considered as part of a complete hazards analysis for the Engineered Safety Work Planning and Controls of SWiFT, performed separately.

1.2. About SWiFT

SNL operates the SWiFT facility on behalf of the DOE WWPTO. It is located on the Reese Technology Center in Lubbock, TX. The principal assets of the facility are three wind turbines that have been modified for research. Two of the turbines are owned by DOE/SNL and the third is operated by SNL on behalf of Vestas Wind Systems, a wind turbine manufacturing company. The turbines have a hub height of 32.5 meters, a rotor diameter of 27 meters and a maximum height of 46 meters. The turbines are oriented as shown in Figure 1. Two meteorological towers are installed 67.5 meters south of the wind turbines and the turbine control building is located 120 meters northwest of the DOE/SNL2 wind turbine (turbine closest to the control building). Access to the site is along the roads shown in Figure 1 and a perimeter fence surrounds the turbines and meteorological towers as shown by the blue line.

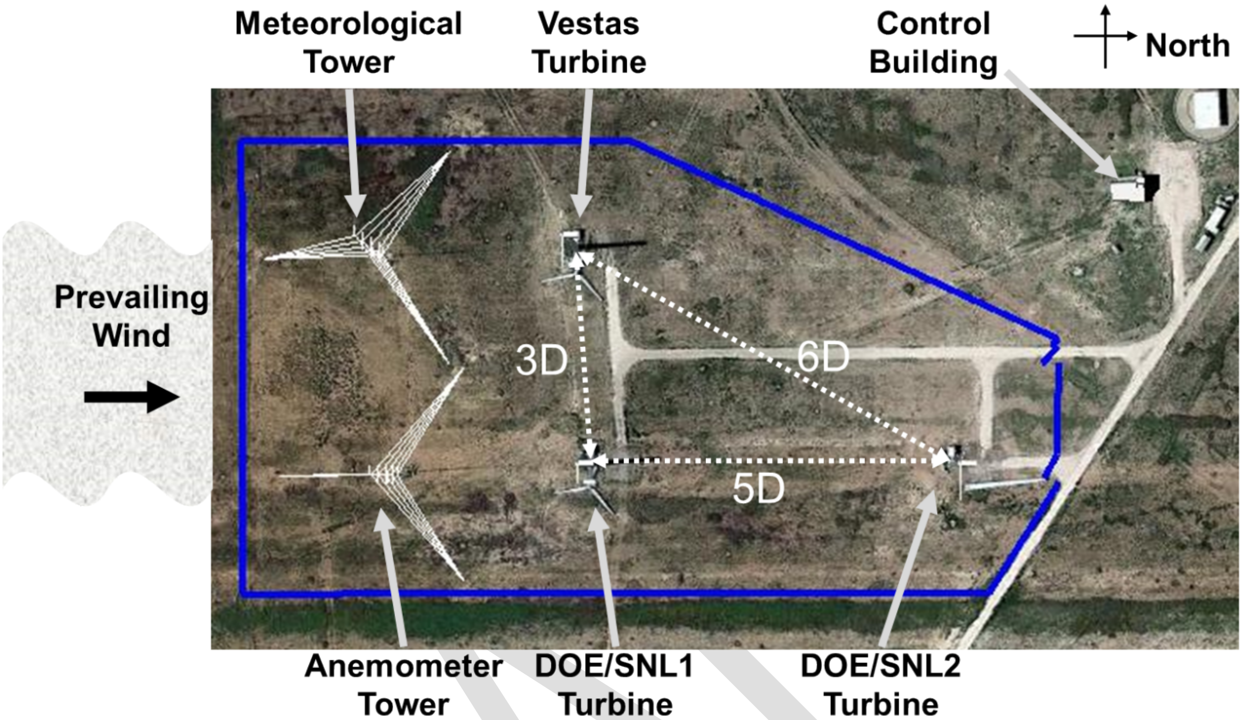

Figure 1. Layout of SWiFT Facility with perimeter fence shown in blue and the distance between each turbine shown as multiples of the rotor diameter of 27 meters ("D").

The nameplate power rating of the turbines is 300 kW and the normal operating speed is 43.9 revolutions per minute (rpm). In an overspeed situation controlled by the active safety systems, the maximum rotational speed of the rotor is 52.7 rpm (120% of nominal). Assuming failure of the safety systems and the passive pitch mechanism, the rotor could not accelerate beyond 220 rpm based on the results of a compressible aerodynamics analysis shown in Figure 2. The analysis showed that as the Mach Number approaches 0.7 there is a dramatic increase in drag force with a slight increase in lift which therefore stops the rotor acceleration and limits the maximum rotor speed.

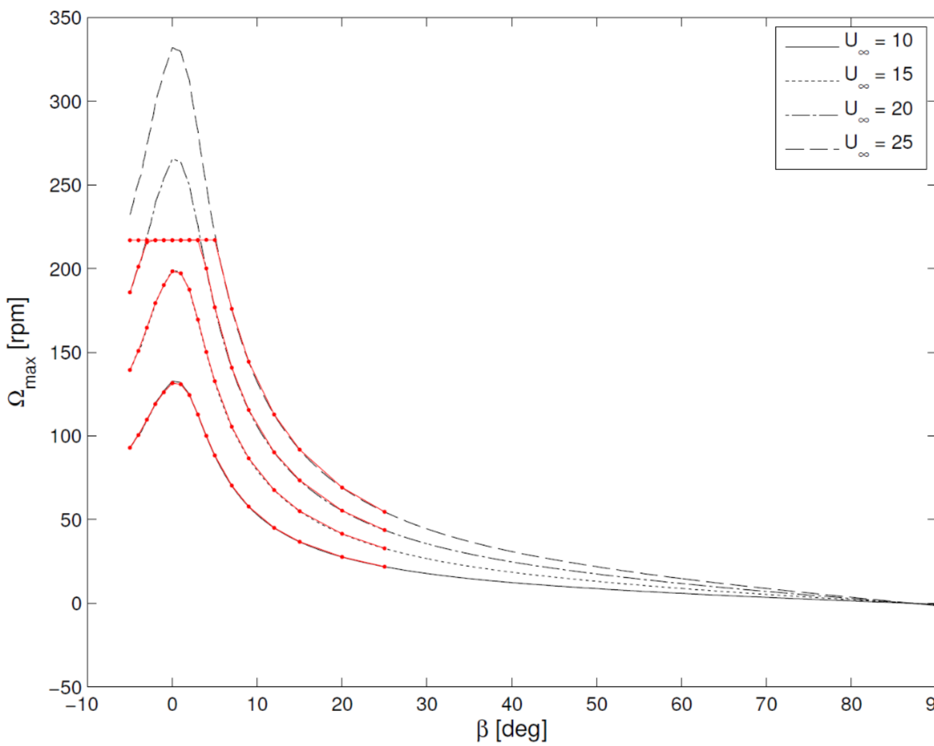

Figure 2. Maximum rotation speed of free-wheeling rotor with incompressible results shown in black and compressible results shown in red.

2. DEBRIS TRAJECTORY ANALYSIS

To drive site-wide emergency planning and risk analysis, calculations were performed assuming debris was thrown from the wind turbines in an unmitigated overspeed, worst-case-scenario.

2.1. Analysis Assumptions

The purpose of this analysis was to evaluate the **worst case scenario** of debris thrown and striking a person in an **unmitigated situation assuming a failure of the turbine and/or rotor blade.** Assumptions for the worst case scenario are as follows:

- Turbine is holding blade pitch to zero degrees
- Controller does not respond properly to an overspeed situation
- Controller activity relay and watchdog both fail to open on the e-stop circuit
- The two overspeed analog circuits both fail to open
- Turbine pitch and brake system fail to stop the turbine
- Workers on site fail to depress any of the seven emergency stop buttons
- Once at steady state rpm an imbalance force is applied to the rotor (such as a wind gust from a different direction) that initiates breakage of the blade
- The blade breaks perfectly (debris become separated from the blade while retaining original shape and do not loose kinetic energy during fragmentation)
- After impact, the debris travels a distance while sliding to a rest

2.2. Analysis Approach

The calculation of a worst case debris throw was challenging because of the complex variable space that includes wind speed (utilizing historical data from the site), wind direction (utilizing historical data from the site), azimuth and pitch angles of the blade, and percentage of the blade that separated. Therefore, the results were calculated utilizing a Monte Carlo analysis. One-million samples were created at random in the variable space (wind speed, wind direction, azimuth angle, rotor speed, blade section). A throw trajectory was calculated for each sample including air drag and one rotation of the debris about its center of gravity during the throw trajectory.

The analysis focused on nominal and overspeed conditions as shown in Figure 3. In nominal conditions, the turbine is operating as intended and the rotor speed linearly increases as a function of wind speed until reaching 43.9 rpm at a wind speed of 8 m/s. After this point the turbine regulates rotor speed at 43.9 rpm up to a wind speed of 20 m/s at which point the turbine automatically shuts down.

In overspeed conditions, it is assumed that all control and safety devices have failed and the rotor has reached the maximum freewheeling speed possible for a given wind speed. From a wind speed of 0 m/s until 16.6 m/s the maximum freewheel speed is calculated utilizing the maximum tip speed ratio (ratio of rotor blade tip velocity to wind speed) of 18.7 which results in the linearly increasing rotor speed. At a tip speed ratio of 18.7 the aerodynamic forces on the inboard and outboard sections of the rotor blade are balanced and further rotor acceleration is not possible. Once the rotor speed reaches 220 rpm, the flow becomes compressible and aerodynamic drag increases rapidly thereby preventing further acceleration of the rotor.

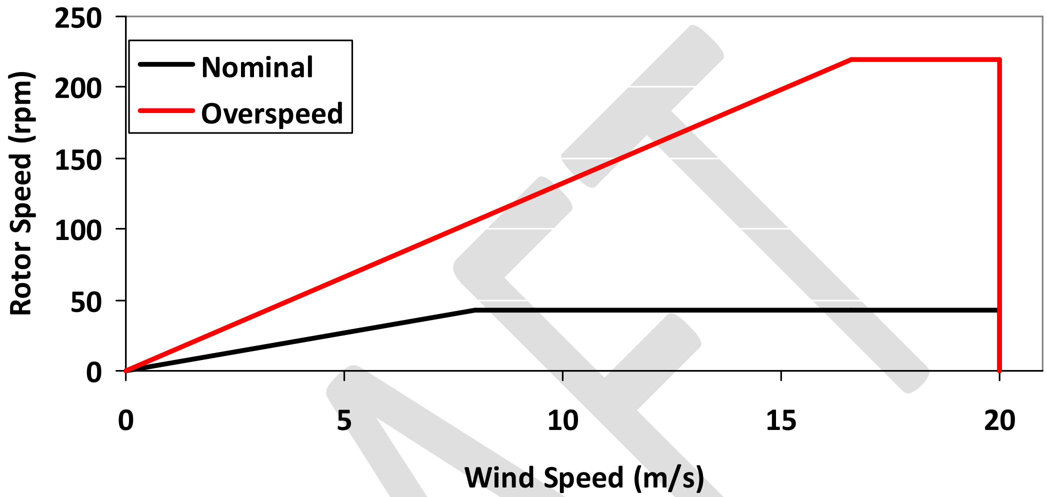

Figure 3. Nominal and Overspeed rotor speed as a function of wind speed.

2.3. Trajectory Analysis Results

In Figure 4 and Figure 5, the debris throw distances for the nominal and overspeed cases, respectively, are shown as a function of distance and presented on a histogram plot. This histogram plot divides the distance between minimum and maximum throw distance into one-hundred equally sized distance bins. The number of samples that fall within each bin was calculated and then normalized by one-million total samples. The result showed the percentage of total samples which fell within each bin (summation of all of the bins would equal 100%). From these results, the 95th percentile of debris throw was calculated at 136 and 249 meters for the nominal and overspeed cases, respectively, as shown by the dashed vertical line.

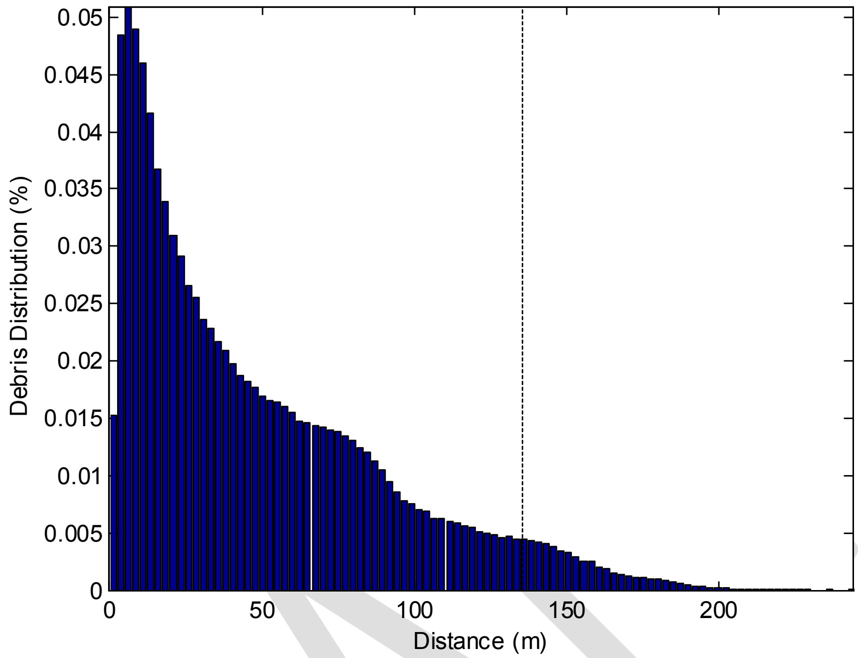

Figure 4. Nominal operating debris throw histogram of one-million analytical samples separated into one-hundred bins. All were normalized by the total number of samples. 95th percentile distance is shown by the dashed line at 136 meters.

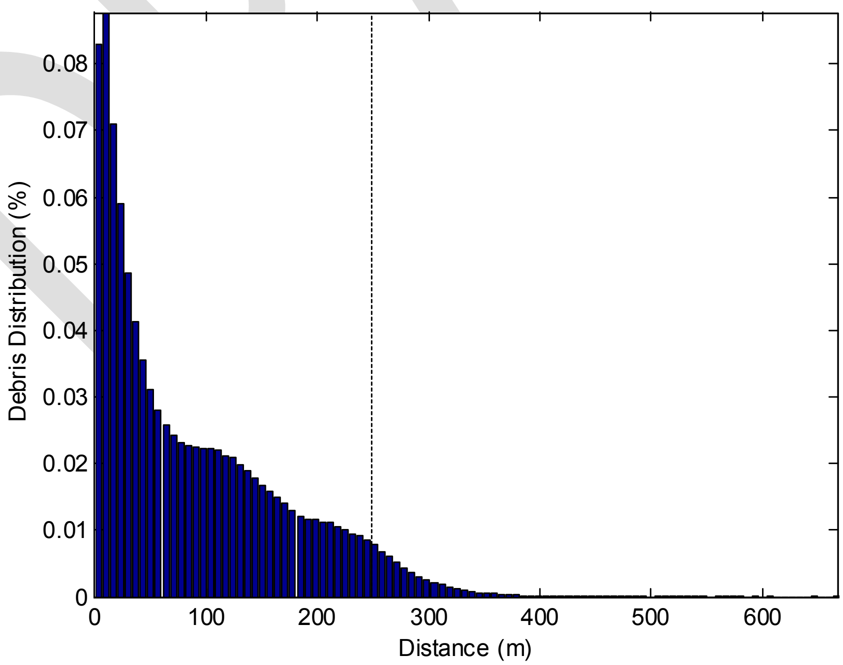

Figure 5. Overspeed debris throw histogram of one-million analytical samples separated into one-hundred bins. All bins were normalized by the total number of samples. 95th percentile distance is shown by the dashed line at 249 meters.

By directly utilizing the debris impact locations (i.e., where each of the one-million samples land), the results showed that when considering debris throw from the Vestas turbine (worst case) 99.9% of the debris fell within the Reese Technology Center fence 320 meters to the west, as shown in Figure 6. Further, when considering debris throw from the SNL1 turbine (worst case) 74.5% of debris fell within the Texas Tech University leased property with boundaries to the north, south, east and west.

The likelihood of debris striking a worker/bystander (represented by a 0.2 meter squared area) was analyzed. Probability contours of strike from this analysis are shown in Figure 6. In this figure, the debris throw samples are shown as red dots and the probability contours of strike are blue lines. A probability contour line represents a set of locations where a person would possess an equal probability of strike. Probability contours of one in: one-hundred, one-thousand, ten-thousand, one-hundred-thousand and one-million are shown. A person located beyond a probability contour line has a probability of being struck that is **less** than the probability associated with that nearest contour. The frequency distribution of the wind direction manifests in an oval shape of the contours that are wider generally in the east-west direction (rotor plane in predominant wind direction) and narrower in the north-south direction.

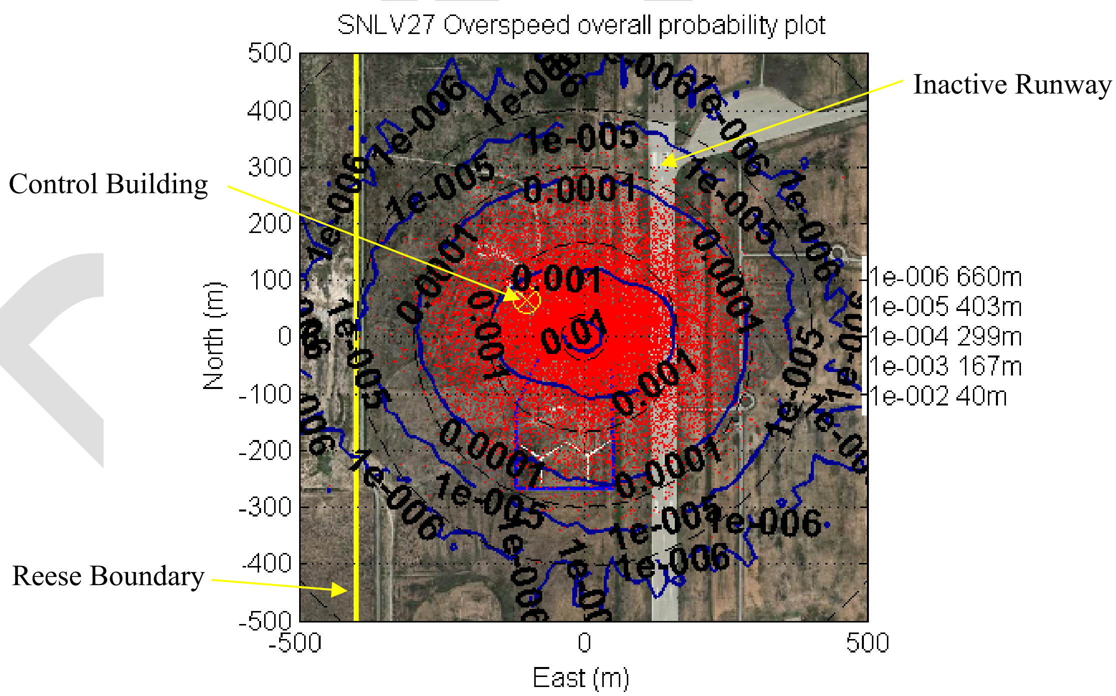

Figure 6. Overspeed case debris throw samples (red dots) with probability contours of debris strike (blue line). Probability maximum radii are shown in the text box.

Table 1 lists the maximum radius of the debris strike probability contours for the nominal and overspeed cases with and without sliding of the debris after impact. Results show that the maximum distance to have a debris strike probability below 1/1,000 is 110 meters for the nominal case and 167 meters for the overspeed case when sliding after impact is included. When only concerned with the initial impact (due to the significant reduction of kinetic energy after impact) the boundary for 1/1,000 is 97m and 82m, respectively.

Table 1. Debris strike probability boundaries for nominal and overspeed case assuming sliding after impact.

Case	1/100	1/1,000	1/10,000	1/100,000	1/1,000,000
Nominal w/Sliding	34m	110m	167m	204m	230m
Nominal No Sliding	31m	97m	157m	187m	215m
Overspeed w/Sliding	40m	167m	299m	403m	660m
Overspeed No Sliding	26m	82m	272m	354m	444m

3. CONTROL BUILDING BALLISTICS ANALYSIS

3.1. Finite Element Analysis

The preceding analysis assessed the risk of debris throw and debris strike to an on-site bystander. The final evaluation assessed the location and design of the control building, located to the northwest of the field site and within 120 meters of the DOE/SNL #2 turbine. There were two aspects to this analysis. First, a conservative analysis was performed to assess the strength of the building to resist the impact of a blade in a worst case scenario. Second, the debris strike probabilities were calculated and binned by the order of magnitude of the energy at impact to assess the survivability of a worker located within the control building.

The Terminal Ballistics Technology Department (5431) at SNL performed an assessment of the capability of the control building to withstand an impact from a fragment of the turbine blade. Multiple high fidelity explicit dynamic finite element simulations were performed with various blade fragment masses and impact velocities to investigate the control building's susceptibility to perforation.

A representative section of the building is shown in Figure 7 [2-3]. The section consisted of a 26 gage zinc-aluminum coated steel corrugated layer with a 1.1 cm thick oriented strandboard (wood) underlayment. Both layers were supported by 25.4 cm roof rafters with 61 cm separation. Only the region between two roof rafters was considered in the finite element simulations because during perforation the loads were localized to a region centered around the impact point of the blade fragment. In addition, the worst case impact scenario that generates the largest stresses in the roof/wall layers occurred for impacts between the rafters. The air voids between the strandboard and steel sheet metal due to the corrugation were compressed out during an impact. As a result, the corrugated sheet metal layer was modeled as a flat metal sheet. A section near the tip of the full turbine blade was used in the impact simulations with actual blade geometry. The density was adjusted to vary the mass of the blade fragment. It was assumed that the blade remains fully intact and undamaged during impact.

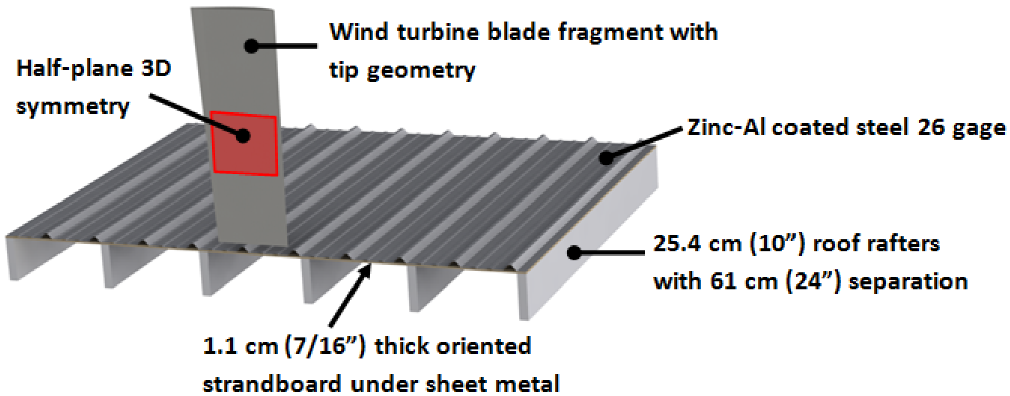

Figure 7. Control building debris strike initial model.

Johnson-Cook plasticity [4] and fracture models [5] were used to represent the response of the steel sheet metal layer. The Johnson-Cook fracture model provided the equivalent plastic strain where failure initiated in the material as functions of the ratio of the mean normal stress and the von Mises stress, strain rate, and temperature. The effects of temperature were not included as significant changes in temperature are not expected during an impact scenario. The response of the strandboard layer was approximated using a perfectly plastic model with material properties obtained from [6-7].

A simulation matrix was established to investigate the effects of impact speed and blade mass on the resulting damage to the representative building layer. Blade fragment masses of 5, 10, 50, and 100 kg and impact velocities of 5 to 50 m/s were considered. The range of impact velocities considered were dependent on the blade mass. For example, for a 5 kg blade mass, impact velocities of 20 to 50 m/s were considered, whereas, in the 100 kg case, velocities of only 1 to 4 m/s were considered.

For each blade mass, the impact velocity at which the blade causes failure to initiate in the sheet metal layer was estimated. The term “failure” here was defined as separation of the sheet metal layer such that two new surfaces were generated. It was assumed that once failure initiated in the sheet metal layer, then the blade fragment was able to reach the inside of the control building and the subsequent complex mechanical behavior of the roof panel and interactions of the blade fragment with the internal structures of the control building were not modeled. A threshold velocity-mass map was determined by fitting a curve through the impact threshold velocities obtained from the simulation matrix. The threshold impact energy was then computed using the velocity-mass map. Figure 8 illustrates damage of the representative building layer due to a 10 kg fragment impacting at 15 and 20 m/s. For the 15 m/s case, the blade did not puncture the sheet metal layer. However, at an impact velocity of 20 m/s, the blade punctured or caused failure in the sheet metal layer.

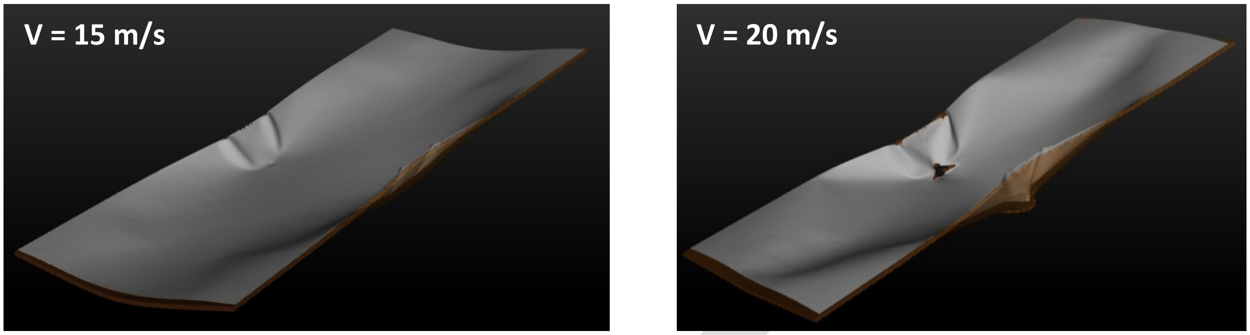

Figure 8. 10 kg blade fragment control building strike examples with survival shown at V = 15 m/s and puncture (failure) shown at V = 20 m/s.

The resulting impact energy threshold map is shown in Figure 9. The results show that for small debris (less than 5% of blade mass) the building would be survivable for impact energies within a 1 kJ magnitude. For larger debris, the threshold drops to a 100 J magnitude.

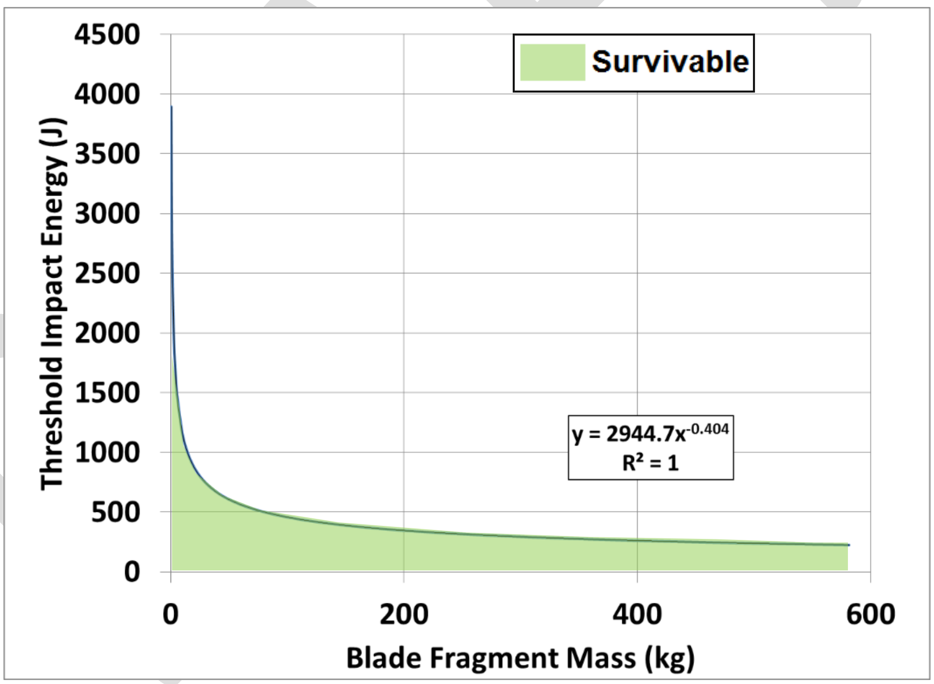

Figure 9. Threshold for energy of impact as a function blade mass.

3.2. Debris Strike Probability

To assess the survivability of the control building, the threshold for energy of impact was integrated with the previous debris strike calculations. The debris strike calculations were separated by the magnitude of energy at impact with the ground without sliding after impact. Table 2 lists the maximum radial distance at overspeed for the probability of debris strike shown in the first column and the energy level shown in the first row. The “All Energies” column is the non-binned distance for all one million samples. Sliding was not included because the scenario modeled, representing the worst case, was a direct vertical impact to the control building for which no sliding would occur.

Table 2. Overspeed debris strike calculations separated by energy level.

Overspeed	All Energies	0-1 kJ	1-10 kJ	10-100 kJ	100-1000 kJ	+1000 kJ
1E-02	26m	N/A	N/A	N/A	19m	N/A
1E-03	81m	N/A	N/A	29m	70m	37m
1E-04	272m	N/A	39m	237m	239m	74m
1E-05	354m	101m	153m	327m	341m	136m
1E-06	444m	156m	192m	414m	435m	272m

Table 3 shows the distribution of debris strike energy levels for each operating case. Results showed that the debris strike energy distribution shifted higher as the rpm increased. A small percentage of the debris was less than 1 kJ in all cases. The specific probabilities of debris strike of the control building as a function of energy magnitudes and operating cases is shown in Table 4. **The results showed that the probability of control building strike without sliding is highest for the overspeed case at 5/10,000 and 4/10,000 for the nominal case.** In comparison to the control building strength, the overall magnitudes of debris strike are such that the control building cannot be counted to provide passive engineered safety.

Table 3. Distribution of debris strike energy magnitudes as a function of RPM.

RPM	0-1 kJ	1-10 kJ	10-100 kJ	100-1,000 kJ	1,000kJ+
Nominal	2%	13%	40%	45%	0%
Overspeed	2%	11%	36%	44%	7%

Table 4. Control building debris strike probabilities as a function of energy levels.

RPM	All Energies	0-1 kJ	1-10 kJ	10-100 kJ	100-1000 kJ	+1000 kJ
Nominal	4E-04	7E-08	2E-06	2E-04	2E-04	N/A
Overspeed	5E-04	6E-06	4E-05	9E-05	3E-04	9E-06

3.3. Options for Improving Control Building Survivability

Although the data indicates a low probability of strike and perforation, to be thorough, potential options for improving the control building survivability were examined. First, the building could be retrofitted with ballistic resistant paneling to increase the threshold impact energies associated with building perforation. There are commercial vendors that sell storm paneling used for hurricane protection. As an example, a 0.63 cm thick panel provides more protection than 9 cm of plywood [8]. One option would be to replace the existing strandboard layer in the building with one or more layers of storm paneling of suitable thickness. The windows could be protected with a polycarbonate hurricane panel. These sort of modifications would provide an added perforation resistance, but do not address the building's ability to resist an impact from a structural standpoint.

The failure mode associated with building collapse due to an impact would require a different type of protection system. Mitigating the structural failure mode would require stopping the blade fragment before it impacts the building. This system could be in the form of a separate wall or a catch net. This protection system would be more costly as it would require new construction.

4. RECOMMENDATIONS

4.1. Summary

Assuming that all passive and active engineered safety systems and administrative procedures fail (a 100% failure rate of the safety systems), boundaries for debris strike probabilities were shown to be approximately 40 meters for 1/100 and 167 meters for 1/1,000 events. The control building overall debris strike probability was shown to be 5/10,000 or less. Analysis of the control building shows that the building offers some protection from low energy debris, but does not provide significant survivability in the event of a significant debris strike.

4.2. Recommendations

1. Although there are options to improve the ballistic resistance of the control building, the recommendation is not to pursue them because there is a low probability of strike and an equal likelihood that personnel could be located at similar distances in other areas of the SWiFT facility which are not passively protected. Further, it is anticipated that a significant structural enhancement (likely replacement of the control building) would be required to passively control all impact scenarios and the result would not significantly change the overall probability for workers to be struck assuming they may not happen to be in the control building.
2. A fenced exclusion area (installed around the turbines) will restrict access to the area of higher (1/100) strike probability as a passive engineered safety system.
3. If future R&D testing using the turbines involves heightened likelihood of failure leading to thrown debris, strengthening of the control building and increasing access restrictions to the surrounding area and adjacent inactive runway should be considered.
4. The overall recommendation is to neither relocate nor improve the control building as the turbine safety systems have been improved to have no less than two redundant, high quality engineered safety systems (failure of 1/1,000 if a normal engineered system or 1/10,000 if a certified engineered safety system). Additionally, a strike probability of less than 5/10,000 results in an overall probability of being struck at less than 1/1,000,000.

5. REFERENCES

1. Scott Larwood, *SWiFT Fragment Analysis*, University of the Pacific, Stockton, CA, March 2015.
2. Icon Construction, Sandia modular office drawings, June 2012.
3. Lazenby & Associates, Inc., Structural calculations, June 2012.
4. G. R. Johnson and W. H. Cook, A constitutive model and data for metals subjected to large strains, high strain rates, and high temperatures, *Seventh International Symposium on Ballistics*, The Hague, The Netherlands, April 1983.
5. G. R. Johnson and W. H. Cook, Fracture characteristics of three metals subjected to various strains, strain rates, temperatures, and pressures. *Engineering Fracture Mechanics*, **21**(1):31-48, 1985.
6. Forest Products Laboratory, Wood Handbook – Wood as an Engineering Material, General technical report *FPL-GTR-190*, Department of Agriculture, Forest Service, 2010.
7. S. R. Reid and C. Peng, Dynamic uniaxial crushing of wood, *International Journal of Impact Engineering*, **19** (5-6):531-570, 1997.
8. Strongwell HS Storm Panel vs. Plywood, http://www.strongwell.com/products/ballistic-and-storm-panels/, May 2015.

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