TOWN OF PORTSMOUTH
ECONOMIC DEVELOPMENT COMMITTEE

2200 EAST MAIN RD • PORTSMOUTH, RHODE ISLAND 02871

November 4, 2008

Wind Turbine Impact Report

Due to concern for damage to the Town water tank near the Wind Turbine Generator (WTG) site, the Water Board requested a study be done to assess the potential for damage to the water tank in the event of WTG failure.

The Wind Blade Impact Analysis Report along with amplifying remarks from the WTG manufacturer (AAER) is attached.

In summary, the Impact Analysis and the manufacturer's amplifying remarks indicates that the probability of blade impact with the top corner of the tank is extremely remote (less than a thousandth of a percent) considering both the probability of WTG failure (by any mode) and the probability of blade failure that would cause ejection of a blade toward the turbine with impact on the most vulnerable tank top corner. Even in the remote event that this impact were to occur, the damage to the tank would not result in any major damage to the tank or appreciable water loss.

Respectfully,

Richard W. Talipsky
Chair

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Weekly Update: October 31, 2008

To the members of the Portsmouth Wind Turbine Project,

The project is on schedule for installation to be completed by December 31, 2008. The commissioning will take place the week of January 5th, and the final transfer of the wind turbine to the Town of Portsmouth is scheduled for January 12, 2009.

We stated this in our change order agreement with the Town where we also agreed to implement the changes needed for Net Metering. The project electrical engineer has submitted a detailed one-line diagram to National Grid depicting the location of the proposed poles for the new interconnection plan. The engineer is planning to meet this week with National Grid to go over the proposed location. The large 2000 kVA step-up transformer was delivered and installed this past week. It will serve to step up the voltage from the wind turbine's 690 volts to the higher 13.8 kV voltage of the distribution lines.

In addition, the Impact Analysis Report describing the overall effect that the wind turbine poses to the nearby water tank has also been completed and is enclosed with this update. The engineer conducting the study concluded that there is less than 2% probability that there would be a direct impact to the water tank by a blade separation that would possibly breach a top corner of the tank.

However, the 2% probability of damage by blade impact to the top corner of the water tank in the attached report represents the probability if *a failure occurs*. It does not include the probability of turbine failure by any mode—a probability of about one in a thousand based on historical failure occurrences of all types of wind turbines (or 0.1%). It also does not include the probability that the wind turbine will be at an azimuth where the blades are pointed toward the tank (a probability of about 20 degrees in 360 degrees (or 5.6%)) which gives an overall probability of occurrence that will cause damage to the tank of less than 0.0001% (2% X 0.1% X 5.6.%). Thus, it can be conservatively stated that the danger, if any, that the wind turbine poses to the water tank is remote.

Sincerely,

AAER USA, Inc.

Alexander Pichs,
Project Manager

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WIND BLADE IMPACT ANALYSIS

REPORT

October 13, 2008

Prepared for:

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October 13, 2008

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Subject: **Memorandum 2**
WIND BLADE IMPACT ANALYSIS REPORT

Dear Mr. Pichs:

In reference to our contract for professional services, I'm pleased to provide this report with the following conclusions:

1. My firm was engaged by Wind Smart, LLC, to perform this analysis and this report is completed under the original contract but addressed to AAER, as per your prior emails.
2. The scope of this report addresses the potential damage and failure possibilities of the wind tower project located in Rhode Island and impact to the adjacent water tank structure.
3. The final conclusion of this report is that the water tank structure is reasonably safe from wind turbine damage and is not expected to fail, provided there is no direct impact on the corner section located at the top of the tank. This is the area most vulnerable to stress concentration and would possibly fracture (i.e. breach the top corner of the tank) under a direct hit from a wind blade.
4. Not considering that any event of turbine failure is extremely remote, the possibility of this direct impact is approximated with less than 2% probability over the 20 year life of the wind tower for the case of blade separation failure, which is an even more remote possibility.

Please review this Memorandum and you may call me to discuss the details. My firm graciously appreciates your business and we look forward to working with your organization again.

Respectfully Yours,

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Respectfully Submitted,

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WIND BLADE IMPACT ANALYSIS REPORT OUTLINE

1.0 Scope of Work

The purpose of this report is to investigate the possibility of a wind tower impacting an adjacent water tank structure. Since the water tank structure provides a lifeline service to a nearby community, the impact analysis report provides an engineering analysis of the various failure scenarios that could impact this structure.

1.1 Assignment and Objectives

A basic energy analysis using the Impulse-Momentum theory is provided to understand the scope of the loads and potential impact to the water tank structure. From the impulse-momentum equation, a force is estimated and its potential energy release on the structure is calculated.

The final result is to demonstrate whether there is a failure scenario that could result from the wind tower structure damaging the water tank.

2.0 Background of Wind Turbine-Tower Failures

Wind towers are susceptible (as any structure) to structural failure/collapse. The particular difference between a wind tower-turbine combination and a building is that this structure has a system of moving parts and is a power generation unit. Due to its complex mechanism and the fact that it has rotating parts (unlike a building/tower which is static), the failure mechanisms are complicated and intertwined with the mechanical system of the Nacelle. In this context, a summary of typical failure mechanisms is provided to simplify the overall understanding of these structures. These typical scenarios are derived from empirical experience based on actual field investigations for wind tower clients and power developers. As of the date of this report, there is no universal/central reporting of structural failures on wind towers in the industry. Industry information and overall statistics on wind tower failures are difficult to obtain and there are no industry reporting requirements on a national/international level. Reports are seldom published due to the confidential nature of these assignments, so first-hand knowledge is rare and difficult to obtain. A few notable references that discuss these scenarios are:

(a) *"Wind Energy Explained",* Manwell, McGowan, A.L. Rogers, John Wiley & Sons Publishers, Ltd, New York NY, 2002.

(b) *"Wind Energy Handbook",* Burton, Sharpe, Jenkins, Bossanyi, John Wiley & Sons Publishers, Ltd, New York NY, 2001.

2.1 Tower Collapse

A common cause of wind tower failure is the basic collapse of the tower. This occurs due to three primary causes:

i) Buckling and elastic instability of the tower shell

This is the result of a high diameter-thickness ratio (D/t). Most tower shells are designed for high D/t ratio to economize on the steel quantity. The end result is a "thin shell" that is potentially susceptible to buckling. Elastic instability occurs with a slight overstress of the tower shell and the entire tower will collapse. This has occurred most notably on towers with D/t > 300. The usual limit of D/t is 200 based on the US Steel codes, but we are permitted to exceed this limit with "structural analysis and explanation", which is part of the structural specifications for the wind turbine tower.

ii) Blade impact to the tower

In the remote event of turbine failure, blade impact is a very common cause of failure because the blades are rotating within close proximity to their tower shells. The blades deflect due to the wind load and can impact the vertical shaft of the shell. Due to the base of the tower normally engineered to a high degree of safety margin, the end result is a failure of the tower shaft, at mid-point, with the blade ripping the tower from underneath itself.

iii) Weld fatigue failure

A more common cause of failure occurs after 10-15 years of service life and with improper/inadequate maintenance of the tower shell. The typical tower has a service life of 20 years, and will undergo beyond 20 million cycles of wind loading and cyclic fatigue stress. Weld cracks can develop due to normal fatigue, and a small weld fracture/crack will propagate and create a “flaw” in the tower shell. However, weld fatigue can be prevented by adequate regular inspection and maintenance. In addition, because the base of the tower is engineered to a higher degree of safety, the probability of failure at the base is the least likely scenario to occur.

2.2 Rotor-Blade Separation

The separation of the rotor and blades is a past cause of wind tower failure. In this scenario the bolts and attachment system of the rotor to the blades is breached due to a variety of causes. Bolt loads may be exceeded due to excessive icing (winter loads), fatigue/fracture stress, and overspeed (discussed in 2.3). The end result is the blade separates from the tower rotor and flies off at excessive velocity. A typical blade weighs a minimum of 12,200 pounds (6 tons), and flying at 30 mph can cause serious damage. The AAER tower has a fail safe operation, or no stall system, as well as an icing detection system, which significantly reduces the possibility of blade separation. When there is excessive icing on the blades the SCADA system detects a problem because the power output is incongruent with the wind speed that is recorded by the anemometer. As a result the wind turbine shuts down automatically.

2.3 Overspeed and E-stop Loads

Wind towers are designed to function within operational wind speeds of typically 8mph to 50 mph maximum. At 50 mph, the rotor is designed to stop rotation. There have been typically two systems to achieve this stop mechanism: (a) Soft Stop and (b) Hard Stop. As their names imply, the Soft Stop is a gradual deceleration of the rotor with internal braking mechanism. The Hard Stop is a sudden electronic brake that stops the rotor within a second. The Hard Stop is commonly referred to as an "e-stop" loading.

The Soft Stop is preferred because it causes less structural stress on the tower, however this has not always worked in the field. The reason is the braking system is not always functional and the blades are not stopped at 50 mph. The end result is "overspeed". Overspeed sends the rotor into excessive angular momentum and overloads the blade-rotor bolt connection. The end result is blade-rotor separation and tower collapse.

Many turbine designers then started the Hard Stop with a sudden brake that is applied at the trigger speed (i.e., 50 mph). This causes a sudden shock wave in the tower and could also result in the tower blade separation from the rotor, in addition to a complete tower collapse.

3.0 <u>Modes of Failure for AAER Wind Tower</u>

After reviewing the design documents provided on the AAER tower, nacelle, and blades, we have determined that the AAER Wind Tower is predominately safe. Although any of the wind tower failure scenarios are possible, and it is not possible to rule out any of them, the key point of this report is to address what impacts the survivability of the water tank structure. The tower is 244 feet away from the water tank, which is sufficiently far so as any possible scenario of the tower collapsing would not affect the water tank. This is noted on Figure A provided, that if the tower were impacted by a blade during normal operation, it would fail at approximately the mid-height and collapse at a safe distance from the water tank.

The primary mode of failure that could impact the water tank is blade separation and impact on the water tank structure. The D/t ratio for this tower is over 200, which does make the possibility of tower buckling an issue, but all wind towers exceed the D/t ratios normally prescribed by the American Institute of Steel Construction (AISC) and International Building Code (IBC). In addition, the AAER wind turbine's D/t ratio does not exceed 300, which reduced the likelihood of buckling under normal operating conditions and is able to withstand hurricane force wind gusts up to 59 m/s. The final point is that the water tank structure is not within striking range of the tower itself, based on the geometric analysis described above and contained in the attached Figure.

The authors note that the AAER product has an alternate, “soft-stop-type” braking mechanism, which virtually eliminates the hard stop mechanism in this tower which further reduces the possibility of blade separation. The braking system is described in detail in AAER’s document “A-1500 PLC Error List.” However, there have been (other non-AAER) documented cases of overspeed (wherein the braking system does not function, or fails) and the blades will detach at their respective bolt connections. We cannot ascertain whether this possibility is fully eliminated, and so therefore it does exist as a small probability of occurrence.

We have taken the worst case scenario and examined the possible impact to the water tank structure using conventional estimates for tower blade rotation, impact velocity, and included the weights and dimensions of the tower elements.

4.0 Impact Energy and Impulse Momentum Equations

Blade separation assumes the disconnection from the rotor at peak rotation angular velocity. The typical operational rotation is 18-20 rpm. The weight of the AAER turbine blade is 6800 kg.
Using a simple lumped mass model to estimate the rotational kinetic energy of the blade,

$\mathbf{\Omega}_{operational}$ = 18 rpm = 18 rev/min x 2π rad/rev x (1min/60s) = 1.885rad/s

$\mathbf{\Omega}_{Peak}$ = 25 rpm = 25 rev/min x 2π rad/rev x (1min/60s) = 2.618rad/s

Peak Rotational Kinetic Energy = $\mathbf{KE}_{peak} = \frac{1}{2}\mathbf{MR^2\Omega^2}_{Peak}$

M = 6.8 Tonnes = 6,800 kg

R = mean radius to the c.g. of the blade (assume $\mathbf{R}_{blade}$x ½) = 37.25m/2 = 18.75m

$$KE_{peak} = \tfrac{1}{2} MR^2\Omega^2_{Peak} = \tfrac{1}{2}\,(6800\ kg)(18.75m)^2(2.618\ rad/s)^2$$
$$= \underline{8.193x10^6 kg\text{-}m^2/s^2}$$

$KE_{translational} = \tfrac{1}{2}\ M\ V^2$ = KE of impact from the blade travel velocity

For translational kinetic energy, we shall assume a mild travel velocity of 20 mph, which converts to 10m/s. This is probably underestimated, but gives a reasonable conclusion with regard to the rotational KE:

$$KE_{translational} = \tfrac{1}{2}\ M\ V^2 \quad = \tfrac{1}{2}\,(6800\ kg)(10m/s)^2 = \underline{0.340x10^6\ kg\text{-}m^2/s^2}$$

Clearly, the velocity of rotation outweighs the translational contribution.

If we add these two,

$$KE_{TOTAL} = KE_{translational} + KE_{peak} = \underline{8.533x10^6\ kg\text{-}m^2/s^2}$$

Impact Energy = Work

KE = $\int F dr$

Linear Impulse Momentum Theory for Translational Rigid Body Impact

<u>Impulse = Change in Momentum</u>

$$F\ dt = \Delta\{P\}$$

This simplifies to

$$F \times \Delta t = (MV) + (Mr\Omega)$$

$$F = [(MV) + (Mr\Omega)] / \Delta t$$

Assume $\Delta t = 0.1$ ***sec(1/10 second)***

$$F_{impact} = (6800\ kg)(10m/s)/0.1\ sec +$$
$$(6800\ kg)(18.75m/2)(2.618rad/s)/0.1\ sec$$
$$= 2{,}348{,}975\ kg\text{-}m/s^2 = 239{,}447\ N = 239.5\ kN$$

F_{impact} = 239.5kN = 54 kips = 54,000 lbs. of impact

5.0 Failure Points on the Water Tank

The critical point on the water tank is the corner point at the top of the tank. This is based on an examination of the Portsmouth water tank structure documents and stress analysis and design requirements for similar water tank structures which shows the corner points are the usual areas most vulnerable to fracture.

A point impact load of 54 kips is not an impossible force to resist but if it occurs at the critical point of the water tank, it would cause a breach of the tank structure. The damage is predicted to be isolated to the top corner of the tank and is not expected to cause any tank collapse that would cause appreciable loss of the tank's water volume.

The tank walls are less susceptible to this point force because this would require the blade to have a perfectly horizontal impact on the water tank wall, which is highly unlikely given the configuration of the tank's physical surroundings and the expected trajectory of a failed blade, to the water tank structure.

The bottom of the tank is even less likely to take a direct hit because this would require the blade to perfectly hit the tank at the base moment connection to the foundation (also a critical point of failure). Due to the tank's physical surroundings and the expected trajectory of a failed blade, this is less probable because the blade would most likely hit the ground and disintegrate before it hit the tank.

As a final note, the top of the corner junction to the water tank is the most susceptible, and this would suffer damage, under a direct hit from the blade with an impact load of 54 kips (or higher). Not considering that any event of turbine failure is extremely remote, the likelihood of this specific scenario itself upon turbine failure, is a low probability (much less than 2%) as compared to the other possible scenarios of the blade hitting the ground or missing the water tank altogether.

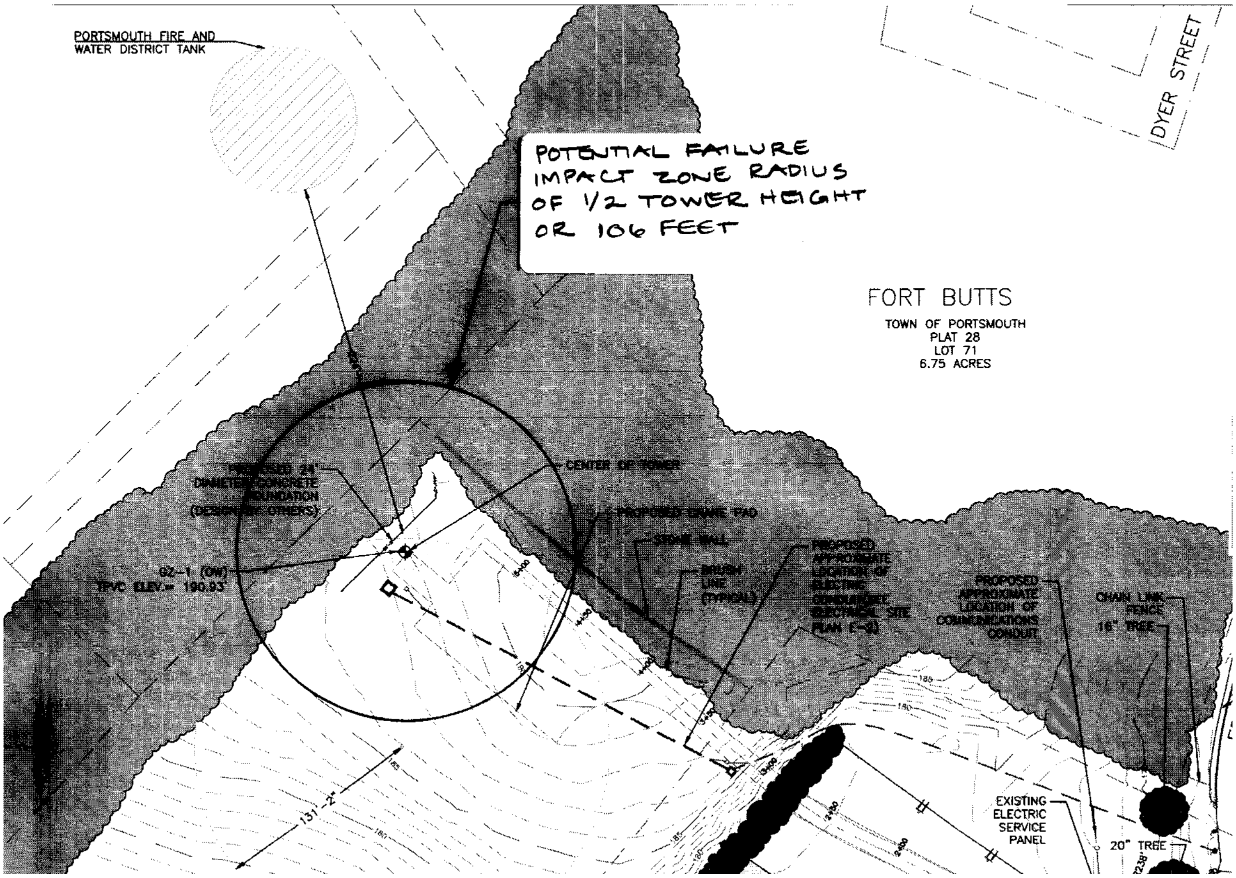
6.0 Conclusions

In conclusion:

1. *The scope of this report addresses the potential damage and failure possibilities of the wind tower project located in Rhode Island and impact to the adjacent water tank structure.*

2. *The final conclusion of this report is that the water tank structure is reasonably safe from wind turbine damage and is not expected to fail, provided there is no direct impact on the corner section located at the top of the tank. This is the area most vulnerable to stress concentration and would possibly fracture (i.e. breach the top corner of the tank) under a direct hit from a wind blade.*

3. *Not considering that any event of turbine failure is extremely remote, the possibility of this direct impact is approximated with much less than 2% probability over the 20 year life of the wind tower for the case of blade separation failure, which is an even more remote possibility.*



<u>Figure A</u>: If the tower is struck by the blade, the potential failure impact zone will be within a radius equal to one half the tower height or 106 feet from the tower.