Potential Effects of the Interaction between Marine Mammals and Tidal Turbines – An Engineering and Biomechanical Analysis

Thomas Carlson[1], Rich Jepsen[2], Andrea Copping[1]

[1]Pacific Northwest National Laboratory
Seattle, WA USA
thomas.carlson@pnnl.gov
andrea.copping@pnnl.gov

[2]Sandia National Laboratories
Albuquerque, NM USA
rajepse@sandia.gov

Abstract— The deployment of tidal turbines in coastal waters raises questions about the potential risk to marine animals from strike by rotating blades. Of particular concern are marine mammals that are already facing threats from other human activities as well as climate change. Regulators in the US who are charged with permitting the installation of tidal turbines have sought additional information to guide biological assessments of blade strike to marine mammals.

This study determined a "worst case" scenario for interaction between a marine mammal and a tidal turbine, focusing on the highly endangered Southern Resident Killer Whale in the U.S. and an open-centred tidal turbine (OpenHydro) proposed for deployment. The analysis combined a finite element modelling of the forces from the turbine blade with information on the biomechanical analysis of the marine mammal tissues, in order to estimate the potential results of a blade strike. Supported by ancillary data, this analysis is being used to inform permitting of a tidal energy project in Puget Sound, Washington, U.S. Analyses are underway to further develop this and related analyses to include three tidal turbine designs and three marine mammal species.

***Keywords*— tidal energy, marine mammals, finite element analysis, biomechanical tissue properties, Southern Resident killer whale.**

I. Introduction

Understanding the interaction of marine mammals with tidal devices is an important step to assuring that development of marine energy does not cause harm to animals that may also be under stress from climate change and other human activities. In the United States and other nations, permitting (consenting) processes frequently focus on potential harm to marine mammals ([1] [2]). The study discussed in this paper was conceived to assist with permitting of a tidal installation where a small population of highly endangered resident orcas (*Orcinus orca* - killer whales) (Fig. 1). The process of this research, and the initial outcomes reported here, are believed to be a useful approach to inform the marine energy industry, researchers, regulators, and stakeholders in the absence of extensive data on interactions between marine mammals and operating marine energy devices.

Fig. 1 Endangered Southern Resident Killer Whale (SRKW) pictured in Puget Sound, Washington

Our team set out to analyse the mechanics and biological consequences of a tidal turbine blade strike on a Southern Resident Killer Whale (SRKW) native to the Pacific Northwest region of the U.S. This analysis supports an estimate of the potential level of injury from a turbine blade-animal interaction. The results of this analysis are being used to assist in determining the risk to the SRKW population in the permitting process for a pilot tidal energy project.

II. Approach

The limited number of marine energy devices deployed worldwide, and even more limited studies of direct interactions of marine mammals with tidal turbine blades, do not allow for straight-forward estimates of the potential risk to the animals from an encounter with a turbine blade. At the start of this research, the National Oceanic and Atmospheric Administration – the U.S. governmental agency tasked with the protection of the SRKW population - agreed that the likelihood of a SRKW randomly encountering the two 6 meter open-centre OpenHydro tidal turbines proposed for deployment in Puget Sound is negligibly small ([3] [4] [5]). The present study starts from that premise.

This study has taken a weight of evidence approach, with a combination of engineering analyses for those aspects of the turbine blade interaction that can be modelled, informed by biomechanical information on marine mammal tissues to withstand injury. Ancillary information on effects of blunt force head trauma in other animals, and real world experience with stranded and captive whales from marine veterinarians, provided supporting evidence. The steps to this approach are summarized in

Fig**. 2 OpenHydro tidal turbine design.**

TABLE 1.

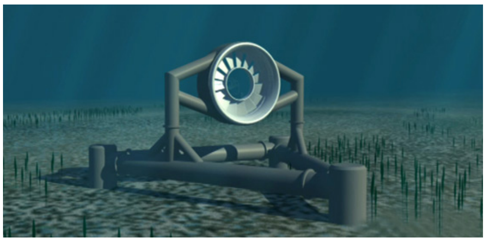

Fig. 2 OpenHydro tidal turbine design.

TABLE 1
THE WEIGHT OF EVIDENCE APPROACH TO DETERMINING THE RISK TO MARINE MAMMALS FROM TIDAL TURBINE BLADE STRIKE. A CONSERVATIVE APPROACH WAS TAKEN AT EACH STEP WHEN HIGH LEVELS OF UNCERTAINTY AROUND INPUT DATA OR ANALYSES WERE IDENTIFIED.

Key Step	Approach
Species Definition	SRKW data were examined to choose the optimum size and configuration of animal to provide the greatest potential momentum transfer (and therefore potential harm) from a blade strike.
Scenario Development	Scenarios were developed for the most severe potential strike of a SRKW, consisting of a large male SRKW (weighing ~4000 kg), inspecting the tidal turbine out of curiosity, and placing its rostrum between the blades.
Properties for Engineering Analysis	The geometry, mass, material properties, and speed characteristics of the tidal turbines were characterized, calculating the force a tidal turbine blade could impart to a marine mammal.
Biological Property Analysis	The biomechanical properties of the marine mammal tissue were defined from computerized tomography (CT) scans to understand the morphology of the animals' head. Biomechanics of skin and underlying tissues were determined from the scientific literature, from surrogates including synthetic rubbers, and from laboratory testing of SRKW tissue. The biomechanical information was used to determine how these tissues might resist mechanical damage by spreading force across the region of impact.
Combining Engineering and Biomechanical Analyses	The engineering and biological analyses were brought together to estimate the potential effects of an encounter between a marine mammal and a tidal turbine blade.
Seeking Real-World Verification	Published results of blunt force head trauma were examined to seek appropriate analogues to effects of a tidal turbine blade on the head region of a marine mammal. Experienced marine veterinarians were interviewed for results of injury to marine mammals.

III. ENGINEERING ANALYSIS.

The initial case examined was the encounter between an adult SRKW and an open-centred ducted turbine manufactured by OpenHydro. Sandia National Laboratories (SNL) developed a finite element model to examine the interaction.

A. Methods

1) Turbine Material Properties: OpenHydro provided specifications on the open-centre ducted turbine. The device modelled is planned for deployment in Puget Sound, Washington State, USA by the Snohomish Public Utility District. The ducted turbine is 6 m in diameter, with a rotor blade diameter of 4.8 m (Fig. 3). Based on communications with OpenHydro, the blade material properties could be adequately estimated using a stiff plastic or composite material; an elastic modulus of 7 kPa was chosen.

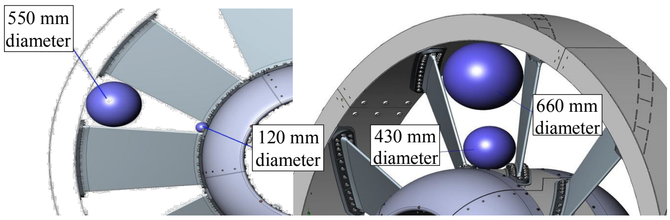

Fig. 3 Drawings of the OpenHydro turbine blade assembly, as specified by OpenHydro, showing spacing of blade edges (left) and the spacing between blades (right). The details of the design were used in the engineering analysis.

2) Blade Impact Scenarios: A killer whale was created in the finite element model from field data for an adult male SRKW ([6]). The scenario involved placing the SRKW rostrum as far into the ducted turbine as possible, with the blade acting on top of the whale's head (Fig. 4). This scenario provide the most conservative case, causing the greatest absorption by the tissue due to impact (greatest momentum transfer), and the probability of the most acute injury among the mixed sizes of the SRKW population, that includes smaller females and juveniles. This scenario considered only the movement of the blade; later iterations will include forward movement by the whale, which should cause less force to be absorbed by the whale. Based on tidal speed and the location of impact along the blades, a probability distribution of potential blade impact speeds was generated (Fig. 5).

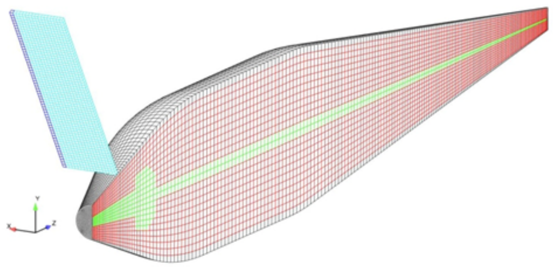

Fig. 4 Finite element analysis model setup of whale (in red and green) and single blunt edge turbine blade (in blue).

Material Properties for SRKW: Tissue data collected from SRKW were not available at the time of the initial engineering analysis. In lieu of SKRW-specific tissue data, the SRKW was modelled with tissue made entirely of blubber, using data from Cuvier's beaked whale blubber ([7]). The head structure of the whale was derived from data collected on a variety of other small whales ([8]). Material properties for bone originated from a study on North Atlantic right whale (NARW) ([9]). Although the NARW is much larger than a SRKW and has a more massive mandibular, in the absence of other data, this analysis assumed that the SRKW mandibles have similar biomechanical properties to those of right whales. This assumption is considered to be appropriate as SRKWs are thought to have sturdy mandibles, based on the animals' use of their rostrums to batter prey animals, competitors, and conspecifics ([10]).

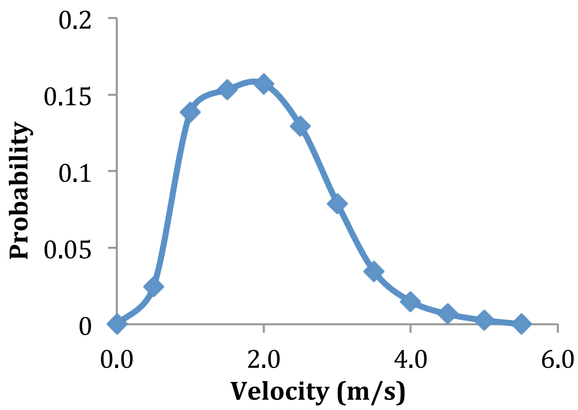

Fig. 5 Probability distribution for velocity at the location of impact between the whale and blade.

3) Analysis with Finite Element Model: The whale and turbine blade model was reduced in complexity by using a symmetry plane. The turbine rotor was represented by a single blunt edge blade that is constrained to move in one direction (Fig. 4). The OpenHydro duct prevents a potential encounter between the animal and the blade tip. The model considered blade impact speeds of 1-5 m/s (Fig. 5), which mimics the likely speed of the OpenHydro turbine in Puget Sound tidal currents. In each simulation, the blade was constrained so that its edges can translate, but not rotate.

B. Results

The model provided the impact forces at different blade speeds (Fig. 6). Due to element distortion inherent in the model, the simulations with the standard blade could not run to completion for speeds greater than 3 m/s. This is a computational artefact as large shear deformations caused an element nearest the impact to invert; this does not however imply tissue damage.

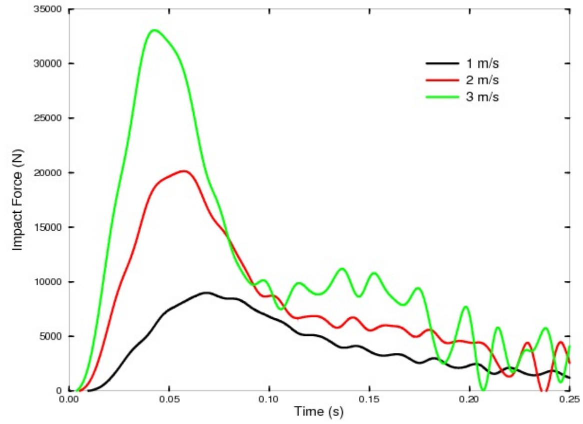

Fig. 6 Impact force as a function of time for different blade speeds

Maximum stress and strain for the model runs showed a linear relationship; these data were extrapolated linearly to determine the values at blade speeds of 5 m/s. For the median speed of the blade of 3 m/s, the maximum stresses (pressure) for turbine blade strike on the head of an adult male SRKW was approximately 2.35 MPa, with a strain (tissue elongation) of 73%. For the maximum speed of 5 m/s and using a linear extrapolation from the lower impact speeds, the maximum stress was determined to be 3.75 MPa.

IV. Biological Assessment of Consequences of Impact

The scarcity of biomechanical data for compression deformation and puncture of the SRKW's skin led PNNL researchers to seek surrogate materials to estimate the likely outcome of a turbine blade strike. The potential consequences of a tidal turbine blade strike on the head of the SRKW was estimated using properties of these similar materials, by examining of the consequences of other blunt force trauma on other animals, and through anecdotal information of injury and death to marine mammals from marine veterinarians.

A. Whale Head Morphology

A CT scan for the head of an adult female SRKW weighing approximately 5,300 kg, was used to investigate potential consequences of the blade strike. Data from the CT scans were used to delineate each layer of tissue, demonstrating that the whale head consists of approximately 50 mm of skin and fibroelastic material, overlying approximately 200 mm of connective tissue. A thick blubber layer underlies the dermal layers, with the bone of the mandible and upper jaw beneath (

Fig. 7).

Based on the CT scan data, the depth of penetration of the whale's head into the OpenHydro turbine may be less than considered in the finite element model. Less penetration into the turbine assembly would result in less potential force from the strike as the impact would occur further from the whale's centre of mass. However, the region of potential strike on the whale's rostrum has a thinner layer of soft tissue to absorb the force, potentially resulting in more severe consequences.

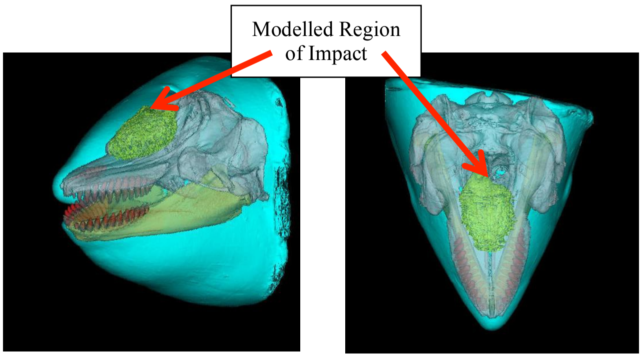

Fig. 7 CT scan-based images of the head of an adult female SRKW from the side (left) and from top view (right). The teeth are shown in red, bone in light colour, and the various soft tissues in other colours. The region of impact used for modelling purposes is indicated.

Based on these findings, the forces modelled and potential effects of the blade strike on the SRKW must be viewed as conservative. The engineering analysis used a whale made entirely of blubber. Biomechanical information on the high-density skin and fibro-elastic layer allowed for a more realistic area of tissue over which the force of a blade strike would be distributed.

B. Biomechanical Data and Surrogate Tissues

The primary function of skin is to protect the animal from mechanical injury. SRKWs use their heads to batter other marine animals, indicating that the skin layer is relatively tough and resilient; an effort was made to examine the scientific literature to identify a material with known properties that might be used as a surrogate for whale skin in engineering models.

Natural and synthetic rubber exhibits many similar biomechanical properties to those of SRKW skin, although the rubber appears to be somewhat more fragile. Examination of these surrogate materials did not provide quantifiable biomechanical measurements for input to the engineering analyses; however the attributes of the surrogate tissues further reinforced the outcome of the engineering model as a conservative estimate of the potential harm to a SRKW from a tidal blade strike.

Human skin was also considered as a surrogate for SRKW skin; human skin has been found to behave as a nonhomogeneous, anisotropic, nonlinear viscoelastic material ([11]). Human and SRKW skin are similarly structured with an epidermis, dermis, hypodermis, and a fourth layer connecting the skin to underlying tissue.

The engineering analysis estimated that at a pressure of 2.35 MPa generated by a turbine speed of 3 m/s, the SRKW blubber would be elongated by about 73%; this same level of stress would elongate human skin by about 60%. At the highest turbine speed considered (5m/s) the blubber would elongate approximately 134%, at a pressure estimated to be 3.75 MPa.

Biomechanical properties of other tissues have been measured, suggesting that natural rubber can act as a reasonable surrogate ([12]). Based on the elastic properties of rubber, whale blubber stressed within the range of the engineering analysis should elongate without deformation. It seems highly likely that consideration of the epidermal and dermal layers of whale skin, in addition to the hypodermis (blubber), would result in values for strain lower than those predicted for blubber alone and would produce stress levels lower than are likely to damage SRKW skin. The blade strike stress and strain levels would likely be within the elastic region.

C. Tissue Analysis

After the first engineering analysis was completed, opportunity presented to test two samples of SRKW tissue from stranded animals. Tests were performed to gain additional insight into the biomechanical properties of the skin and blubber.

1) Methods:

Tissue Samples: Tissue from the two stranded animals was obtained with the cooperation of the Northwest Marine Mammal Stranding Network. A juvenile female (L112) was found on the Pacific coast (Long Beach, WA) on February 11, 2011. The animal was 3 years old and 3.7 m in length. The tissue sample was approximately 20 cm long (anterior to posterior) by 15 cm (dorsal to ventral) with an average 3.5 mm skin thickness and 31.5 mm partial blubber layer. The whale was necropsied during February of 2011 and the tissue sample frozen until the week of January 21, 2013 when test sections were incrementally thawed for testing.

A neonate male SKRW was found dead on the shoreline in the inland waters of the Pacific (Dungeness Spit, Strait of Juan de Fuca, WA) on January 7, 2013. The calf was approximately 2.1 m in length. The whale was necropsied on January 8, 2013, then frozen until incrementally thawed starting February 11, 2013. The calf tissue was in better condition than the adult tissue at the time of testing.

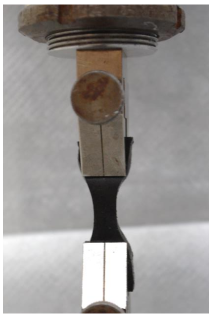

Fig. 8 Sample of SRKW tissue loaded into MTS Synergie 100.

Specimens: Samples approximately 5cm wide were excised from each of the adult and calf tissue. Subsamples of skin and blubber were tested using an MTS Synergie 100 using a 500 N load cell in tension and compression (Fig. 8 *Sample of SRKW tissue loaded into MTS Synergie 100.*). Specimens were tested at different strain rates to determine if the tissues were sensitive to strain rate.

2) Results:

Skin and blubber samples belonging to the juvenile and calf were anisotropic, displaying different material properties along different axes. Values derived for the modulus of elasticity or stiffness of the tissue using a strain rate of 1 m/s can be seen in Table 2; the literature value for Cuvier's Beaked Whale is also shown for comparison.

Tissues from both animals showed wide variability; methods for using these data to best inform the finite element model are still under consideration at this time.

TABLE 2
VALUES DERIVED FROM SRKW TISSUE STIFFNESS TESTING IN TENSION.

Animal	**Tissue Orientation**	**Mean Stiffness (MPa)**	**Standard Deviation (MPa)**	**Number of samples**
Cuvier's Beaked Whale		1.8		
SRKW Juvenile	0°	3.70	3.26	8
	90°	11.80	9.96	8
SRKW Neonate	0°	1.48	0.51	8
	45°	2.59	0.86	8
	90°	1.13	0.56	9

D. Consequence of Turbine Blade Impact on Whale Tissue

The engineering analysis provided results that might be considered a "worst case" for damage to the blubber layer of the whale. The overlying skin and fibroelastic layers of whale tissue will act as a membrane to distribute force over a larger area, resulting in less damage to the underlying tissues than is predicted for the "all blubber" whale.

Based on the potential for blubber to elongate like rubber, it appears that, for the conditions modelled, the underlying tissues might be expected to suffer little damage, perhaps akin to bruising.

Potential for damage to the mandible of the SRKW was considered; the closest surrogate found was that of a mandible of a North Atlantic right whale damaged by collision with a ship. Campbell-Malone ([9]) estimated that the trabecular right whale mandible bone might fracture at compressive pressures over 17.95 MPa. The SRKW mandible is almost certainly less massive than that of right whale. The highest pressure predicted for the OpenHydro turbine (3.75 MPa) is 20% of the pressure that is expected to affect the right whale mandible. Qualitatively it appears that the pressures may not affect the SRKW mandible.

E. Blunt Force Head Trauma

The potential for blunt force trauma as an agent of harm to the SRKW from a head strike was considered. Additional information was sought from research and monitoring results of head trauma to other species of mammals. Initial literature searches were focused on marine mammal head trauma, with most results describing consequences of collisions between ships and marine mammals, as well as effects of underwater explosions. However, few studies incorporate information on the forces that resulted in head trauma, which prevents direct comparison beyond the specific event or collision incident, and provides limited insight for the tidal blade strike scenario. One notable exception is the work by Tsukrov et al. ([13]); this study developed a three-dimensional finite element mesh model to predict the mechanical behaviour of a NARW mandibular bone under strain, combined with the potential forces exerted by a whale–ship collision. This information provides insight into how a similar approach could be used to develop mechanical models of the SRKW skull and brain. The vast majority of studies on blunt force trauma are reported for rodents, pigs and horses; little direct insight into the SRKW turbine blade strike scenario can be gleaned. The results of the literature search are available online through the *Tethys* knowledge management system on environmental effects of marine energy development (http://mhk.pnnl.gov/wiki/index.php/Orca_Strike_Analysis).

F. Input from Marine Veterinarians

In the absence of field observations to validate the outcome of the strike analysis, PNNL researchers sought input from marine veterinarians familiar with the effects of head trauma and other injuries to cetaceans and other marine mammals. The veterinarians provided professional insights into effects seen for marine mammals strandings and from observations of animals in captivity. In almost all cases, the insight gained from the veterinarians consisted of their best professional judgment and was described through anecdotes rather than through the presentation of data and conclusions.

Based on these anecdotes it appears that captive orcas tend to avoid stationary objects underwater, supporting the choice of curiosity as the only likely scenario during which an animal might encounter a turbine. The animals most likely to approach an underwater object are young; older animals are wary. Adult marine mammals examine an object but will seldom approach closely. Mothers will protect neonates from harm. The young adolescent orcas, particularly those that do not have a parent nearby, are most likely to approach an object. However, the danger from turbines underwater is likely to be small, compared to the risk to these animals from ships moving at speed with high inertia and rotating propellers ([14]).

V. Discussion

A. Weight of Evidence Approach

This analysis brings together best professional judgement on the likelihood of a SRKW encountering the turbine randomly, and an assessment of the "worst case" scenario for a curious animal examining the turbine, with an informed engineering analysis of the forces potentially imparted from a turbine blade to the head of a SRKW. The study is further informed by an analysis of the biomechanical properties of the whale skin and underlying tissues. Limited "real world" verification of the potential for harm to the animal further informed the analysis, from the scientific literature and experience-based anecdotes of marine veterinarians who care for and attend whale strandings. This string of related analyses cannot take the place of field observations of animal encounters with turbine blades, nor can it be considered to be a quantitative prediction of the risk to these animals from such an encounter. However, in the absence of deployed tidal energy systems around which such observations can be made, this analysis brings together the best judgement and estimate available. This weight of evidence approach parallels that used extensively in screening analyses for chemical contaminant body burdens in humans and animals, as well as for other emerging stressors of concern in the natural world ([15]).

B. Interpretation of Engineering and Biomechanical Analyses

The consequence of tidal turbine blade impact on SRKW tissue has been estimated from the results of the finite element modelling. The results showed the peak stresses and strains expected from impact from the open-centre turbine blade to be ~3.750 MPa for the turbine impacting the stationary body of a SRKW, with a 73% elongation of the tissue, or 2.365 MPa for the impacts with a SRKW swimming toward the turbine with a 93% elongation.

These calculated levels of stress are well below that expected to cause failure in a surrogate material such as natural rubber (10 to 30 MPa) and less than the strain expected to cause rupture of human skin (100%–300%). It is expected that if whale skin behaves similarly to these materials, whale skin tissue under the blade strike scenario will deform and (in conjunction with underlying soft tissue), absorb the force of the strike, returning to normal a short time after the pressure was removed. In much the same way that a finger pressed tightly into one's thigh might produce an indent, the skin will return to normal once the pressure is removed, the skin of the whale would be expected not to be torn by the pressures exerted by the tidal blade. With the limited biomechanical data available for marine mammals, this analysis suggests that the extent of the damage to the underlying soft tissues would be to cause some haemorrhage, resulting in the equivalent of a bruise. The SRKW that suffers this damage is expected to fully recover following such an encounter.

C. Uncertainty Analyses

This study seeks to show a weight of evidence approach with inputs from many sources, each with an inherent uncertainty. The overall uncertainty of the engineering and biomechanical analyses can best be estimated by assessing the accuracy of each piece of information that informed the analyses. The modelling techniques used are well documented and are unlikely to have introduced significant uncertainty. Table 3 qualitatively summarizes the uncertainty of each specific information source. We made a conscious choice to err on the side of conservative estimates of potential harm throughout the analyses; the overall outcome should consequently be a conservative approach to potential harm to the whale. However, the overall level of uncertainty cannot be clarified without further study.

TABLE 3
LEVEL OF CERTAINTY ASSOCIATED WITH EACH INPUT TO THE ENGINEERING AND BIOMECHANICAL ANALYSES

Analysis Step	Specific Input to Analysis	Accuracy/Level of Certainty of Information & Explanation
Defining the Scenario	Geometry of SRKW approach to turbine	**HIGH**-Geometry of turbine based on detailed drawings from turbine manufacturer; geometry of SRKW based on extensive measurements of SRKW. Scenario chose is "worst case for injury" approach of SRKW swimming directly into outer edge of turbine.
Modelling of Strike Forces	Speed and forces modelled for turbine, varying with tidal current speed	**HIGH**-Turbine speeds and tidal current values are well known, multiple model runs to determine forces.
	Orientation of animal with turbine blade, transfer of momentum	**MEDIUM**-Limited model runs for orientation of animal, to ensure choice of "worst case for injury" scenario. Based on engineering judgment.
	Non-linear model for materials	**MEDIUM**-Does not include model for dermal layers (modelled all-blubber whale) or non-linear model for any materials, leading to overestimate of potential harm to SRKW from turbine.
Biomechanics of orca tissues	Information on tissue thickness and properties of skin	**MEDIUM-** No direct measures for head of SRKW; information adapted from CT scans of SRKW and literature on other species. Based on professional judgment.
	Information on tissue thickness	**HIGH-** Good biomechanical property values from literature to estimate

	and properties of blubber	deformation of blubber and transfer of force to underlying tissue & bone.
	Information on tissue thickness and properties of bone	**MEDIUM-** Biomechanics of impact on bone well understood; used other species in absence of information on SRKW. Based on professional judgment.
	Information on tissue thickness and properties of melon	**LOW-** Tissue thickness from CT scan and necropsy data, biomechanical values from literature. Properties from blubber used in model because of similar biomechanical properties.
	Effects of blunt force trauma	**MEDIUM-** Good understanding and copious literature for humans and other mammals; little information for marine mammals. Some anecdotal information may be gleaned from interviews. Based on professional judgment.
Sensory response to impact	Post-trauma effects on SRKW	**LOW-** No literature on effects. Anecdotal information from interviews.

D. Next Steps

Each portion of the analysis documented here can be improved upon, yielding a more realistic outcome of an encounter between the adult male SRKW and a tidal turbine. In addition, studies that focus on other life stages of SRKW, especially juveniles and neonates, could further inform the interaction. Scenarios that allow the interaction of the whale to differ from the rostrum-first approach (dorsal fin first, ventral approach, etc.) may also yield different results. Additional health issues the animal might suffer could also be examined including delayed effects of head trauma, concussion, as well as injury or death due to infection from lacerations.

The research team is undertaking an additional modelling effort to incorporate more biomechanical information from SRKW tissue sample analysis in the encounter between the whale and the open-centre turbine. Two additional marine mammals species - harbour porpoise (*Phocoena phocoena*) and harbour seal (*Phoca vituline*) – will be incorporated into the analysis, along with two additional tidal turbine designs (a cross flow and an axial flow turbine). Working with the Northwest Stranding Network, the research team will obtain additional tissue samples as they become available, analyse CT scan data of the animals, and refine estimates of the biomechanical properties of the tissue layers of interest. The finite element models of the marine mammals will be informed by these values, while the turbine properties for the two additional turbines will be modelled to yield the potential forces affecting animals that encounter the blades.

VI. Conclusions

Combining engineering and biomechanical analyses has allowed the research team to assess the risk of a turbine blade strike to a marine mammal despite a scarcity of data. The conservative estimate of potential harm to a SRKW from an open-centered turbine deployed in Puget Sound is coupled with the knowledge that SRKWs in the region spend 97% of their time in depths less than 30 meters ([4]); the tidal turbines are planned for deployment in 55 meters of water ([2]).

This study determined that an adult male SRKW weighing approximately 4,000 kg is not likely to experience significant tissue injury from impact by an OpenHydro tidal turbine blade. Based on several assumptions, the skin and underlying soft tissues of the SRKW should absorb the force of the strike without external damage to the skin or fracturing of the mandibular bone. The paucity of available data was addressed by choosing conservative estimates whenever possible, and the "worst-case" encounter scenario was used for the modeling studies.

This study is far from definitive, but illustrates a pathway that might provide some measure of comfort for regulators and stakeholders as early deployments of tidal turbines are established in waters that support marine mammals. As a team, we are looking forward to additional studies and field data to validate and improve our analyses.

Acknowledgments

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Rich Jepsen and Kurt Metzinger (SNL) undertook the engineering analysis, based on turbine specifications supplied by OpenHydro, and tidal velocities supplied by Brian Polagye (UW-NNMREC).

Tom Carlson, Mike Watkins, and their team (PNNL) examined the physiological and biomechanical properties of SRKWs and analysed the likely effect of impacts, supporting from the engineering analysis.

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Dr. Adam Summers (University of Washington) and his laboratory team lead the tissue sample analysis.

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