K4.25 THREATENED AND ENDANGERED SPECIES

K4.25.1 Overview of Marine Mammal Acoustics

This appendix contains additional information on applicable noise concepts and methodologies used in development of Section 3.25 and Section 4.25, Threatened and Endangered Species. These noise concepts are applicable to non-federally listed marine mammals, and are also referenced in Section 4.23, Wildlife Values. This appendix focuses on the properties of underwater noise, which are relevant to understanding the effects of noise produced by construction and operations activities on the underwater marine environment in the Environmental Impact Statement (EIS) analysis area. This document does not provide a detailed calculation of acoustical thresholds of specific project components, but where possible, provides surrogate noise levels from similar equipment, vessels, etc., that may be used during construction and operations of the project. It also does not provide a detailed assessment of estimated numbers of marine mammal incidental take through acoustic harassment. This detailed information would be analyzed further in a Marine Mammal Protection Act (MMPA) authorization request to the US Fish and Wildlife Service (USFWS) and National Marine Fisheries Service (NMFS).

K4.25.1.1 Underwater Noise Descriptors

Noise received at and below the sea surface has the potential to negatively impact marine mammals. The noise descriptors used in this report and for underwater acoustics in general, include the following:

- Sound pressure level (SPL), which represents the sound pressure of a sound relative to a reference pressure; it is measured in decibels (dB) referenced to one microPascal (μPa).
- Sound exposure level (SEL), which is the total energy of an event accumulated over a specified duration; therefore, the SEL accounts for both the noise level and duration of an event. SEL can be used to represent a range of different types of noise sources and is expressed in dB with a reference pressure of 1 μPa^2s. Variations of SEL include:
  - Single-strike sound exposure level (SEL_{ss}), which is the total energy of a single occurrence of an impulsive noise source.
  - The cumulative sound exposure level 24-hour cumulative SEL (SEL_{24h}), which is the total energy over a 24-hour period.
- Peak level, which is the maximum instantaneous noise level for an event. A peak level is typically used to represent impulsive noise sources and is expressed in dB with a reference pressure of 1 μPa.

Underwater sound propagation depends on several factors, including sound speed gradients in water, depth, temperature, salinity, and seafloor composition. In addition, characteristics of the sound source, such as frequency, source level, type of sound, and depth of the source, would also affect propagation. For ease in estimating distances to NMFS acoustic thresholds, simple transmission loss (TL) can be calculated using the logarithmic spreading loss with the formula:

$$TL = B * log10(R)$$

TL is transmission loss, B is logarithmic loss, and R is radius

The three common spreading models are cylindrical spreading for shallow water, or 10 $_{log}$(R); spherical spreading for deeper water, or 20 $_{log}$(R); and practical spreading, or 15 $_{log}$(R) (NMFS 2018a).

K4.25.1.2 Applicable Noise Criteria

Through the Endangered Species Act (ESA) and the MMPA, the NMFS and USFWS have defined levels of harassment for marine mammals. Level A harassment is defined as "…any act of pursuit, torment, or annoyance which has the potential to injure a marine mammal or marine mammal stock in the wild." Level B harassment is defined as "…any act of pursuit, torment, or annoyance which has the potential to disturb a marine mammal or marine mammal stock in the wild by causing disruption of behavioral patterns, including, but not limited to, migration, breathing, nursing, breeding, feeding, or sheltering" (16 United States Code [USC] Section 1361 et seq.).

For Level A, NMFS (2018b) provides guidelines for assessing the onset of temporary and permanent threshold shifts from anthropogenic sound. Under these guidelines, marine mammals are separated into five functional hearing groups; source types are separated into impulsive (e.g., seismic, impact pile-driving) and non-impulsive (e.g., vibratory pile-driving, vessels); and require analyses of the distance to the peak received SPL; L_{pk}, and SEL_{24h} (NMFS 2018b).

Noise exposure criteria have been established by NMFS for identifying underwater noise levels capable of causing Level A harassment (potential injury) of certain marine mammals, including otariid pinnipeds (i.e., sea lions) (NMFS 2018b). Sea otter-specific criteria have not been determined by USFWS; however, because of their biological similarities, USFWS assumes that noise criteria developed by NMFS for injury for otariid pinnipeds are suitable surrogates for sea otter impacts (USFWS 2019).

The current Level B harassment (potential disturbance) threshold for assessing behavioral disturbance for impulsive sound is 160 decibels, referenced to one microPascal (dB re 1 μPa) root mean square (rms) for impulsive, and 120 dB re 1 μPa rms for non-impulsive sound for all marine mammals (NMFS 2018b). USFWS considers Level B harassment for both impulsive and non-impulsive sound to be 160 dB re 1 μPa rms.

Table K4.25-1 provides a summary of the disturbance guidelines. For purposes of this appendix, all underwater SPLs are reported as dB re 1 μPa and all airborne SPLs are reported as dB re 20 μPa.

Table K4.25-1: Summary of NMFS Acoustic Thresholds

Marine Mammals	Injury (Level A) Threshold		Disturbance (Level B) Threshold	
	Impulsive	Non-Impulsive	Impulsive	Non-Impulsive
Low-Frequency Cetaceans (blue, fin, and humpback whales)	219 dB L_{pk} 183 dB SEL	199 dB SEL	160 dB rms	120 dB rms
Mid-Frequency Cetaceans (beluga and sperm whales)	230 dB L_{pk} 185 dB SEL	198 dB SEL	160 dB rms	120 dB rms
High-Frequency Cetaceans (Dall's and harbor porpoise)	202 dB L_{pk} 155 dB SEL	173 dB SEL	160 dB rms	120 dB rms
Phocid Pinnipeds (harbor seal)	218 dB L_{pk} 185 dB SEL	201 dB SEL	160 dB rms	120 dB rms
Otariid Pinnipeds (Steller sea lion)	232 dB L_{pk} 203 dB SEL	219 dB SEL	160 dB rms	120 dB rms
Sea Otters	190 dB rms	180 dB rms	160 dB rms	160 dB rms

Notes:
dB = decibels
L_{pk} = peak sound pressure
rms = root mean square
SEL = sound exposure level

K4.25.1.3 Description of Sound Sources

The acoustic characteristics of each of the activities proposed under all alternatives are described in the following section and summarized in Table K4.25-2. Not all sources of noise would result in Level A or Level B acoustic harassment, but are presented for reference. The noise sources that may be detected underwater associated with construction would comprise:

- Vessel operations (including anchor handling)
- Aircraft overflights
- Causeway construction
- Pile-driving (impact and vibratory)
- Caisson placement/excavation for wharf and causeway
- Dredging

Table K4.25-2: Summary of Noise Sources for Each Activity

Activity	Sound Pressure Levels (dB re 1 μPa)	Frequency	Reference
General vessel operations and dynamic positioning	145 to 200 dB rms at 1 m	10 Hz to 1,500 Hz	Richardson et al. 1995a; Blackwell and Greene 2003; Ireland et al. 2016
General aircraft operations	100 to 124 dB rms at 1 m	<500 Hz	Richardson et al. 1995a
Rock laying for causeway	Less than dredging: 136 to 141 dB rms at 12 to 19 m	<500 Hz	Nedwell and Edwards 2004; URS 2007
Impact pile-driving (12 96-inch pipe pile)	185 to 220 dB peak at 10 m 160 to 195 SEL at 10 m 170 to 205 rms at 10 m	<100 to 1,500 Hz	Illingworth & Rodkin 2007
Vibratory pile-driving (12 72-inch pipe and sheet pile)	165 to 195 dB peak at 10 m 150 to 180 dB SEL at 10 m 150 to 180 dB rms at 10 m	<100 to 2,500 Hz	Illingworth & Rodkin 2007
Caisson fill placement (dumping of dredge material onto barge)	108.6 dB peak at 150 m	<1,000 Hz	Dickerson et al. 2001
Backhoe dredging	178.4 dB rms at 1 m	<1,000 Hz	Dickerson et al. 2001; URS 2007

Notes:
μPa = microPascal
dB = decibels
Hz = Hertz
m = meter
rms = root mean square
SEL = sound exposure level

The majority of underwater vessel sound energy is restricted to frequencies below 100 to 200 Hertz (Hz), but broadband sounds may include acoustic energy at frequencies as high as 1 kiloHertz (kHz). The underwater SPLs of vessels depend on size and speed, but typically range from 145 to 175 dB re 1 μPa-m rms (Richardson et al. 1995a). Underwater sound levels from pile-driving vary with the size and type of piles, as well as the size and type of hammer. Impact pile-driving is generally below 4 kHz, with peak sound pressure levels ranging from 185 to 220 dB re 1 μPa at 10 meters; vibratory pile-driving generally has energy up to 10 kHz, but produces lower peak levels ranging from 165 to 195 dB re 1 μPa at 10 meters (Illingworth and Rodkin 2007). Underwater noise from aircraft (e.g., helicopter and fixed-wing) is greatest directly below the aircraft, with energy generally below 500 Hz, and ranging 100 to 124 dB re 1 μPa-m rms. Airborne sound levels associated with construction equipment generally range from 75 to 85 dB re 20 μPa at 15 m, with pile-driving producing higher sound levels between 95 to 105 dB re 20 μPa at 15 m.

Dredging Operations

During installation of the natural gas pipeline, several methods may be used during trenching/dredging activities in Cook Inlet, which are described in Section 4.22, Wetlands and Other Waters/Special Aquatic Sites. Table K4.25-3 details various types of equipment that may be used during installation of the natural gas pipeline through Cook Inlet. Table K4.25-3 lists the sound at the energy source and the distance from the noise source where marine mammals may experience Level B disturbance (120 dB).

Table K4.25-3: Underwater Noise Impacts from Various Dredging Technologies

Equipment Type	Sound Energy at Source (dB re 1μPa rms @ 1 m)	Distance to Level B 120 dB Disturbance Threshold (based on spherical spreading model)	Data Source
Cutter suction dredge	167 to 178	735 to 2,605 feet	Greene 1987; Reine et al. 2012b, 2014a
Trailing hopper suction dredge	161 to 171	377 to 1,165 feet	Reine et al. 2014b
Clamshell/bucket dredge (scoop)	146	66 feet	Dickerson et al. 2001, Reine et al. 2012a, 2014a
Winching in/out	149	350 feet	Dickerson et al. 2001

Notes:
μPa = microPascal
dB = decibels
m = meter
rms = root mean square

There are additional technologies that may be used for pipeline installation that are not detailed in Table K4.25-3, above. One method employs the use of a marine support vessel that is capable of pulling a plow along the pipeline route. Although the specifics of the vessel and the plow are unknown, the recent Quintillion Subsea Operations request for authorization to take marine mammals incidental to conducting subsea cable-laying and maintenance activities provides a potentially analogous noise analysis (82 Federal Register [FR] 22099). It was determined that the distance to the Level B harassment threshold for continuous noise when the *Ile de Brehat* was pulling a sea plow was 3.32 miles. Although the specifics of the vessel and plowing technology that may be used for the project are unknown, the distance to the Level B harassment threshold would likely extend several miles in every direction from project equipment.

The second method involves either pulling a jet sled along the top of a pipeline after it has been installed or flying a jetting remotely operated vehicle along the pipeline route before or after laying the pipe. High-pressure water jets liquefy the soil, and air lift or eductor pumps remove it from under the pipeline. The specific underwater noise levels generated from this technology would be explored in detail later in the permitting process if this technology was to be used.

Vessel Operations

Vessels are major contributors to the overall acoustic environment (Richardson et al. 1995a), particularly in Alaska (Huntington et al. 2015). The characteristics of sounds produced by vessels are a product of several variables pertaining to the specifications of the vessel, including the number and type of engines, propeller shape and size, and the mechanical condition of these components (USFWS 2019). In a 2012 Cook Inlet Vessel Traffic Study Report (Eley 2012), patterns of activities were described for vessels over 300 gross tons operating during 2010. Results showed that there were 480 port calls or transits through Cook Inlet, with 80 percent of the transits made by 15 ships for the purpose of crude oil and product transport, packaged commodity shipments, and passenger/vehicle carriage. This class of vessel is characterized with source levels of 160 to 200 dB re 1 μPa rms at 1 meter in the 6- to 500-Hz range (Richardson et al. 1995a).

Position keeping in Cook Inlet is a challenge due to strong currents; therefore, some vessels use dynamic positioning with bow thrusters when anchoring is not possible. Ireland et al. (2016) measured source levels from 148.5 dB re 1 μPa rms at 1 meter at 2,000 Hz to 174.5 dB re 1 μPa rms at 1 meter at 10 Hz with 100 percent of all four thrusters.

Blackwell and Greene (2003) recorded underwater noise produced by both large and small vessels near the Port of Anchorage. The *Leo* tugboat produced the highest broadband levels of 149 dB re 1 μPa at a distance of approximately 100 meters, while the docked cargo freight ship, *Northern Lights*, produced the lowest broadband levels of 126 dB re 1 μPa rms at 100 to 400 meters. Ship noise was generally below 1 kHz. Manipulation of anchors for the installation of the natural gas pipeline would involve vessel operations that are likely to be louder than normal transit.

Aircraft Operations

Helicopters and fixed-wing aircraft generate noise from their engines, airframe, and propellers. Noise from aircraft overflights is anticipated to be a major source of airborne sounds for sea otters during project construction. Aircraft operations at the Amakdedori port would be associated with construction of the port access road to the south ferry terminal. There would be an increase in ambient noise around the port during construction due to regular aircraft flights involving take-offs and landings over Kamishak Bay. Once construction of the port access road is complete, the amount of aircraft landing at Amakdedori port would be anticipated to be greatly reduced and restricted to emergencies only. The dominant tones for both types of aircraft (helicopters and fixed-wing) generally are less than 500 Hz (Richardson et al. 1995a). Richardson et al. (1995a) reported that received sound levels in water from aircraft flying at an altitude of 152 meters were 109 dB re 1 μPa rms for a Bell 212 helicopter, 101 dB re 1 μPa rms for a small fixed-wing aircraft, 107 dB re 1 μPa rms for a twin otter, and 124 dB re 1 μPa rms for a Orion P-3 (a four-engine turboprop aircraft).

Penetration of aircraft noise into the water is greatest directly below the aircraft; at angles greater than 13 degrees from vertical, much of the sound is reflected and does not penetrate (Richardson et al. 1995a). Duration of underwater sound from passing aircraft is much shorter in water than air. For example, a helicopter passing at an altitude of 152 meters, audible in air for 4 minutes, may be detectable underwater for 38 seconds at a 3-meter depth, and 11 seconds at an 18-meter depth (Richardson et al. 1995a).

Pile-Driving

Impulsive underwater sound generated by construction activities has the potential to harass marine mammals where it exceeds 160 dB re 1 μPa rms. Impulsive noise sources proposed for the construction phase of the project include pile-driving using an impact hammer. Pile-driving would be necessary for construction of the Pile-Supported Dock Variant at the Amakdedori port under Alternative 1 and the Diamond Point port under Alternative 2—North Road and Ferry with Downstream Dams. Levels of underwater sounds produced during pile-driving are dependent on the size and composition of the pile, the substrate into which the pile is driven, bathymetry, physical and chemical characteristics of the surrounding waters, and pile installation method (impact versus vibratory hammer) (Denes et al. 2016).

Both impact and vibratory pile installation produce underwater sounds of frequencies predominantly lower than 2.5 kHz, with the highest intensity of pressure spectral density at or below 1 kHz (Denes et al. 2016). Source levels of underwater sounds produced by impact pile-driving tend to be higher than for vibratory pile-driving; however, both methods of installation can generate underwater sound levels capable of causing behavioral disturbance or hearing threshold shift in marine mammals, and both methods may be used in Cook Inlet.

Illingworth and Rodkin (2007) compiled measured near-source (i.e., 10 meters) SPL data from impact pile-driving for pile sizes ranging in diameter from 12 to 96 inches (Table K4.25-2). Vibratory pile-driving generally results in lower source sound levels, but the behavioral harassment threshold for NMFS species is 120 dB re 1 μPa rms for non-impulsive sounds, resulting in a larger area of potential disturbance. Illingworth and Rodkin (2007) also compiled measured near-source (i.e., 10 meters) SPL data from vibratory driving for pile sizes ranging in diameter from 12 to 72 inches; because the in-water construction details are not fully developed, a range of sound is provided in Table K4.25-2.

Rock Laying

Measurements of underwater noise during rock placement have shown that the rock placement itself is not distinguishable from the vessel noise (Nedwell and Edwards 2004); rock placement vessels are similar to dredging vessels. URS (2007) measured underwater sound levels from clamshell dredging at the Port of Anchorage and reported broadband levels of 136 to 141 dB re 1 μPa rms at 12 to 19 meters.

Caisson Placement

Caisson installation requires leveling the footprint on the seabed prior to caisson placement, which may require 0.6 to 0.9 meter of excavation to level the seabed. Footprint preparation would make use of an extended reach excavator mounted on a barge to minimize the extent of the disturbed area. Once the footprint is prepared, the caisson is floated into place with a tugboat at high tide and then seated into place with the falling tide, or is slowly lowered by pumping water into it. Once each caisson is set in place, it would be filled with material sourced from preparing the caisson base or from project quarries. Information on the underwater noise from placement of fill directly into the caisson is not available, but Dickerson et al. (2001) measured a sound level of 108.6 dB re 1 μPa peak at 150 meters associated with dumping of fill material into an empty barge in Cook Inlet. URS (2007) measured underwater sound levels from clamshell dredging at the Port of Anchorage, and reported broadband levels of 136 to 141 dB re 1 μPa rms at 12 to 19 meters. Dickerson et al. (2001) report higher levels for bucket dredging of 178.4 dB re 1 μPa rms at 1 meter.

K4.25.1.4 Effects of Noise on Affected Marine Mammals

Marine mammals use hearing and sound transmission to perform vital life functions. The introduction of sound from project-related activities to their environment could be disrupting to those behaviors. Sound (hearing and vocalization/echolocation) serves four primary functions for marine mammals, including: 1) providing information about their environment; 2) communication; 3) prey detection; and 4) predator detection. The distances to which noise associated with the project activities are audible depend on source levels, frequency, ambient noise levels, the propagation characteristics of the environment, and sensitivity of the receptor (marine mammal) (Richardson et al. 1995a).

The effects of sound from industrial activities (including project-related activities, depending on the alternative or variant) on marine mammals could include one or more of the following: tolerance, masking of natural sounds, behavioral disturbance, and temporary or permanent hearing impairment or non-auditory physical effects (Richardson et al. 1995a). In assessing potential effects of noise, Richardson et al. (1995a) has suggested four criteria for defining zones of influence. These zones are described below from greatest influence to least:

> ***Zone of hearing loss, discomfort, or injury—***the area where the received sound level is potentially high enough to cause discomfort or tissue damage to auditory or other systems. This includes temporary threshold shifts (TTSs) (e.g., temporary loss in hearing) or permanent threshold shifts (PTS) (e.g., loss in hearing at specific frequencies or deafness). Non-auditory physiological effects or injuries that theoretically might occur in marine mammals exposed to strong underwater sound include stress, neurological effects, bubble formation, resonance effects, and other types of organ or tissue damage.

> ***Zone of masking—***the area where noise may interfere with detection of other sounds, including communication calls, prey sounds, or other environmental sounds.

> ***Zone of responsiveness—***the area where the animal reacts behaviorally or physiologically. The behavioral responses of marine mammals to sound is dependent on a number of factors, including: 1) acoustic characteristics of the noise source of interest; 2) physical and behavioral state of animals at time of exposure; 3) ambient acoustic and ecological characteristics of the environment; and 4) context of the sound (e.g., whether a sound is similar to that of a predator) (Richardson et al. 1995a; Southall et al. 2007). However, temporary behavioral effects are often simply evidence that an animal has heard a sound, and may not indicate lasting consequence for exposed individuals (Southall et al. 2007).

> ***Zone of audibility—***the area where the marine mammal might hear the noise. Marine mammals as a group have functional hearing ranges of 10 Hz to 180 kHz, with best thresholds near 40 dB (Kastak et al. 2005; Ketten 1998; Southall et al. 2007). These data show reasonably consistent patterns of hearing sensitivity in each of three groups: small odontocetes (e.g., harbor porpoise and Dall's porpoise), medium-sized odontocetes (e.g., beluga whales and killer whales), and pinnipeds (e.g., harbor seal and Steller sea lion). There are no applicable assessment criteria (Table K4.25-1) for the zone of audibility due to difficulties in human ability to determine the audibility of a particular noise for a particular species.

Due to relatively low sound levels, the short period of time that louder activities would occur over the life of the project, and the implementation of mitigation and monitoring measures, it is unlikely there would be any temporary or especially permanent hearing impairment, or non-auditory physical effects on marine mammals. Additionally, most of Cook Inlet is a poor acoustic environment because of its shallow depth, soft bottom, and high background noise from currents and glacial silt, which greatly reduces the distance sound travels (Blackwell and Greene 2003). This means that underwater sound does not travel as fast, or is masked because of interference with the sound's ability to propagate.

The effects of sound on marine mammals are highly variable, and can generally be categorized as follows (adapted from Richardson et al. 1995a):

- The sound may be too weak to be heard at the location of the animal (i.e., lower than the prevailing ambient sound level), the hearing threshold of the animal at relevant frequencies, or both.

- The sound may be audible but not strong enough to elicit any overt behavioral response (i.e., the mammal may tolerate it) either without or with some deleterious effects (e.g., masking, stress).
- The sound may elicit behavioral reactions of variable conspicuousness and variable relevance to the well-being of the animal; these can range from subtle effects on respiration or other behaviors (detectable only by statistical analysis) to active avoidance reactions.
- On repeated exposure, animals may exhibit diminishing responsiveness (habituation/sensitization) or disturbance effects may persist; the latter is most likely with sounds that are highly variable in characteristics, unpredictable in occurrence, and associated with situations that the animal may perceive as a threat.
- Any human-made sound that is strong enough to be heard has the potential to reduce (i.e., mask) the ability of marine mammals to hear natural sounds at similar frequencies, including calls from conspecifics, echolocation sounds of odontocetes, and environmental sounds due to wave action or (at high latitudes) ice movement. Marine mammal calls and other sounds are often audible during the intervals between pulses, but mild to moderate masking may occur during that time because of reverberation.

Very strong sounds have the potential to cause temporary or permanent reduction in hearing sensitivity, or other physical or physiological effects. Received sound levels must far exceed the animal's hearing threshold for any TTS to occur. Received levels must be even higher for a risk of permanent hearing impairment.

K4.25.1.5 Hearing Abilities of Affected Marine Mammals

The hearing abilities of marine mammals are functions of the following (Au et al. 2000; Richardson et al. 1995a):

- Absolute hearing threshold at the frequency in question (the level of sound barely audible in the absence of ambient noise). The "best frequency" is the frequency with the lowest absolute threshold.
- Critical ratio (the signal-to-noise ratio required to detect a sound at a specific frequency in the presence of background noise around that frequency).
- The ability to determine sound direction at the frequencies under consideration.
- The ability to discriminate among sounds of different frequencies and intensities.

Marine mammals rely heavily on the use of underwater sounds to communicate and to gain information about their surroundings. Experiments and monitoring studies also show that marine mammals hear and may react to many types of human-made sounds (Richardson et al. 1995a; Gordon et al. 2004; Nowacek et al. 2007; Tyack 2008).

Baleen Whales (Mysticetes)

The hearing abilities of baleen whales (humpback, fin, and gray whales) have not been studied directly given the difficulties in working with such large animals. Behavioral and anatomical evidence indicates that they hear well at frequencies below 1 kHz (Ketten 2000; Richardson et al. 1995a). Frankel (2005) noted that gray whales reacted to a 21 to 25 kHz signal from whale-finding sonar. Some baleen whales react to pinger sounds up to 28 kHz, but not to pingers or sonars emitting sounds at 36 kHz or above (Watkins 1986). In addition, baleen whales produce sounds at frequencies up to 8 kHz; and for humpback whales, with components up to >24 kHz (Au et al. 2006). The anatomy of the baleen whale inner ear seems to be well adapted for detection of low-frequency sounds (Ketten 1992a, b, 1994, 2000; Parks et al. 2007). Although humpback and minke whales may have some auditory sensitivity to frequencies above 22 kHz, for baleen whales as a group, the functional hearing range is thought to be about 7 Hz to 22 kHz, or possibly 35 kHz; baleen whales are said to constitute the "low-frequency" hearing group (NMFS 2016; Southall et al. 2007). The absolute sound levels that they can detect below 1 kHz are probably limited by increasing levels of natural ambient noise at decreasing frequencies (Clark and Ellison 2004). Ambient noise levels are higher at low frequencies than at middle frequencies. At frequencies below 1 kHz, natural ambient levels tend to increase with decreasing frequency.

The hearing systems of baleen whales are undoubtedly more sensitive to low-frequency sounds than the ears of the small-toothed whales that have been studied directly (MacGillivray et al. 2014). Therefore, baleen whales are likely to hear vessel sounds farther away than small-toothed whales; at closer distances, vessel sounds may seem more prominent to baleen than to toothed whales. However, baleen whales have commonly been seen in the distances where sounds from vessels would be detectable, and often show no overt reaction to those sounds. Behavioral responses by baleen whales to various anthropogenic sounds, including sounds produced by vessel thrusters used for anchor handling during construction of the natural gas pipeline and general vessel traffic associated with the project, have been documented; however, received levels of sounds necessary to elicit behavioral reactions are typically well above the minimum levels that the whales are assumed to detect.

Toothed Whales (Odontecetes)

Toothed whales (beluga whales and porpoise species) often show tolerance to vessel activity; however, they may react at long distances if they are confined by ice, shallow water, or were previously harassed by vessels (Richardson et al. 1995a). Toothed-whale responses to vessel activity also vary depending on the activity of the whale. Many species of dolphins tolerate or even approach vessels in the area and often ride the bow and stern waves (this reduces the energy cost of travel); however, dolphins have also been observed avoiding vessels. Other species of toothed whales that have avoided vessels include river dolphins, harbor porpoise, and sperm whales. Foote et al. (2004) found increases in the duration of killer whale calls from 1977 to 2003, when vessel traffic in Puget Sound increased dramatically, particularly whale-watching boats.

Average hearing thresholds for captive beluga whales have been measured at 65 and 120.6 dB re 1 μPa at frequencies of 8 kHz and 125 Hz, respectively (Awbrey et al. 1988). Castellote et al. (2014) measured their peak sensitivity at between 45 and 80 kHz. Masked hearing thresholds were measured at approximately 120 dB re 1 μPa for a captive beluga whale at three frequencies between 1.2 and 2.4 kHz (Finneran et al. 2002). Beluga whales do have some limited hearing ability down to approximately 35 Hz, where their hearing threshold is about 140 dB re 1 μPa (Richardson et al. 1995a). Thresholds for pulsed sounds would be higher, depending on the specific durations and other characteristics of the pulses (Johnson 1991).

Seals and Sea Lions (Pinnipeds)

Underwater audiograms have been determined for several species of phocid seals (true seals), monachid seals (monk seals), otariids (eared seals), and the walrus (reviewed in Cunningham and Reichmuth 2016; Kastak and Schusterman 1998, 1999; Kastelein et al. 2002, 2005, 2009; Reichmuth et al. 2013; Richardson et al. 1995a; Sills et al. 2014, 2017). The functional hearing range for phocid seals in water is generally considered to extend from 50 Hz to 86 kHz (NMFS 2016; Southall et al. 2007), although a harbor seal, spotted seal, and California sea lion were shown to detect frequencies up to 180 kHz (Cunningham and Reichmuth 2016). However, some species, especially the otariids, have a narrower auditory range (60 Hz to 39 kHz; NMFS 2016). In comparison with odontocetes, pinnipeds tend to have lower hearing frequencies, lower high-frequency cut-offs, better auditory sensitivity at low frequencies, and poorer sensitivity at frequencies of best hearing.

At least some of the phocid seals have better sensitivity at low frequencies (equal to or less than 1 kHz) than odontocetes. Below 30 to 50 kHz, the hearing thresholds of most species tested are essentially flat down to approximately 1 kHz, and range between 60 and 85 dB re 1 µPa. Measurements for harbor seals indicate that below 1 kHz, their thresholds under quiet background conditions deteriorate gradually with decreasing frequency to approximately 75 dB re 1 µPa at 125 Hz (Kastelein et al. 2009). Recent measurements of underwater hearing for spotted seals (*Phoca largha*) showed a peak sensitivity of approximately 51 to 53 dB re 1 µPa at 25.6 kHz, with the best hearing range at approximately 0.6 to 11 kHz, and good auditory sensitivity extending seven octaves (Sills et al. 2014).

For the otariid seals, the high frequency cut-off is lower than for phocids, and sensitivity at low frequencies (below 1 kHz) rolls off faster, resulting in an overall narrower bandwidth of best sensitivity (NMFS 2016).

Sea Otter (Mustelid)

In-air vocalizations of sea otters have most of their energy concentrated at 3 to 5 kHz (McShane et al. 1995; Thomson and Richardson 1995). Sea otter vocalizations are considered to be most suitable for short-range communication among individuals (McShane et al. 1995). However, Ghoul and Reichmuth (2012) noted that the in-air "screams" of sea otters are loud signals (source level up to 113 dB re 20 µPa) that may be used over larger distances; screams have dominant frequencies of 4 to 8 kHz. Controlled sound exposure trials on southern sea otters (Enhydra lutris *nereis*) indicate that hearing ability spans frequencies between 125 Hz and 38 kHz, with best sensitivity between 1.2 and 27 kHz (Ghoul and Reichmuth 2014). Aerial and underwater audiograms for a captive adult male southern sea otter in the presence of ambient noise suggest the sea otter's hearing was less sensitive to high-frequency (greater than 22 kHz) and low-frequency (less than 2 kHz) sounds than terrestrial mustelids (USFWS 2019). Underwater, sea otter hearing is most sensitive at 8 to 16 kHz; however, their hearing is not specialized to detect sounds in background noise (Ghoul and Reichmuth 2016).

Thresholds have been developed for other marine mammals. Above these thresholds, exposure is likely to cause behavioral disturbance and injury; however, species-specific criteria for preventing harmful exposures to sound have not been identified for sea otters (USFWS 2019).

K4.25.1.6 Potential Effects of Project-Induced Noise on Marine Mammals

Vessel noise can contribute substantially to a low-frequency ambient noise environment already filled with natural sounds. Vessel noise from the project could affect marine animals along the underwater portion of the natural gas pipeline corridor. Houghton et al. (2015) proposed that vessel speed is the most important predictor of received noise levels, with low vessel speeds (such as those expected during the proposed activity) resulting in lower sound levels. Sounds produced by large vessels generally dominate ambient noise at frequencies from 20 to 300 Hz (Richardson et al. 1995a). However, some energy is also produced at higher frequencies (Hermannsen et al. 2014). The following sections detail studies addressing the potential effects of vessel sounds on marine mammals, or lack thereof.

Tolerance

Numerous studies have shown that underwater sounds from industry activities are often readily detectable in the water at distances of many kilometers. As described below, numerous studies have also shown that marine mammals at distances more than a few kilometers away often show no apparent response to industry activities of various types (Harris et al. 2001; Moulton et al. 2005). This is often true even in cases when the sounds must be readily audible to the animals based on measured received levels and the hearing sensitivity of that mammal group. Although various baleen whales, toothed whales, and (less frequently) pinnipeds have been shown to react behaviorally to underwater sound such as airgun pulses under some conditions, at other times mammals of all three types have shown no overt reactions (Stone and Tasker 2006). In general, pinnipeds and small odontocetes seem to be more tolerant of exposure to some types of underwater sound than are baleen whales.

Masking

Masking is the obscuring of sounds of interest by interfering sounds, which can affect a marine mammal's ability to communicate, detect prey, or avoid predation or other hazards. Through masking, ship noise can reduce the effective communication distance of a marine mammal if the frequency of the sound source is close to that used by the animal, and if the sound is present for a significant fraction of time (Cholewiak et al. 2018; Clark et al. 2009; Dunlop 2016; Erbe et al. 2016; Gervaise et al. 2012; Hatch et al. 2012; Jensen et al. 2009; Jones et al. 2017; Rice et al. 2014; Richardson et al. 1995a). In addition to the frequency and duration of the masking sound, the strength, temporal pattern, and location of the introduced sound also play a role in the extent of the masking (Branstetter et al. 2013, 2016; Finneran and Branstetter 2013; Sills et al. 2017). Branstetter et al. (2013) reported that time-domain metrics are also important in describing and predicting masking. To compensate for increased ambient noise in the presence of elevated noise levels from shipping, some cetaceans are known to increase the source levels of their calls, shift their peak frequencies, or otherwise change their vocal behavior (Azzara et al. 2013; Bittencourt et al. 2016; Castellote et al. 2012; Dahlheim and Castellote 2016; Gospić and Picciulin 2016; Gridley et al. 2016; Heiler et al. 2016; Luís et al. 2014; Martins et al. 2016; Melcón et al. 2012; O'Brien et al. 2016; Papale et al. 2015; Parks et al. 2011, 2016a,b; Sairanen 2014; Tenessen and Parks 2016; Tyack and Janik 2013).

Using acoustic propagation and simulation modeling, Clark et al. (2009) estimated lost communication space from vessel traffic for fin, humpback, and North Atlantic right whales in the northwestern Atlantic Ocean. They found that because of higher call source levels and the frequency range of calls falling outside of the range of strongest ship sounds, fin and humpback whales are likely to experience much less of a reduction in communication space than North Atlantic right whales. Because right whale call frequencies are more centered on the strongest frequencies produced by large ships and their call source levels are typically lower, they may experience nearly complete loss of communication space when a large ship is within 4 kilometers of that whale. However, the sound source levels of the ship used by Clark et al. (2009) were much higher than those expected to be produced by the smaller and slower-moving vessels used during pipe-laying activities.

Auditory studies on pinnipeds indicate that they can hear underwater sound signals of interest in environments with relatively high background noise levels, a possible adaption to the noisy nearshore environment they inhabit (Southall et al. 2000). Southall et al. (2000) found that northern elephant seals, harbor seals, and California sea lions lack specializations for detecting low-frequency tonal sounds in background noise; but rather, were more specialized for hearing broadband noises associated with schooling prey.

Disturbance Reactions

Baleen whales are thought to be more sensitive to sound at low frequencies than toothed whales (e.g., MacGillivray et al. 2014). Reactions of gray and humpback whales to vessels have been studied, and there is limited information available about the reactions of right whales and rorquals (fin, blue, and minke whales). Reactions of humpback whales to boats are variable, ranging from approach to avoidance (Payne 1978; Salden 1993). Baker et al. (1982, 1983) and Baker and Herman (1989) found humpbacks often move away when vessels are within several kilometers. Humpbacks seem less likely to overtly react when actively feeding than when resting or engaged in other activities (Krieger and Wing 1984, 1986). Increased levels of ship noise have been shown to affect foraging (Blair et al. 2016) and singing behavior by humpback whales (Tsujii et al. 2018). Fin whale sightings in the western Mediterranean were negatively correlated with the number of vessels in the area (Campana et al. 2015). Minke whales and gray seals have shown slight displacement in response to construction-related vessel traffic (Anderwald et al. 2013).

Southall et al. (2007) reviewed a number of papers describing the responses of marine mammals to non-pulsed sound. In general, little or no response was observed in animals exposed at received levels from 90 to 120 dB re 1 μPa rms. Probability of avoidance and other behavioral effects increased when received levels were 120 to 160 dB re 1 μPa rms. Some of the relevant studies are summarized below.

Baker et al. (1982) reported some avoidance by humpback whales to vessel noise when received levels were 110 to 120 dB re 1 μPa rms, and clear avoidance at 120 to 140 dB re 1 μPa rms (sound measurements were not provided by Baker, but were based on measurements of identical vessels by Miles and Malme 1983).

Malme et al. (1986) observed the behavior of feeding gray whales during four experimental playbacks of drilling sounds (50 to 315 Hz; 21 minutes overall duration and 10 percent duty cycle; source levels 156 to 162 dB re 1 μPa-m). In two cases for received levels of 100 to 110 dB re 1 μPa, no behavioral reaction was observed. Avoidance behavior was observed in two cases where received levels were 110 to 120 dB re 1 μPa rms. Richardson et al. (1990) performed 12 playback experiments in which bowhead whales in the Alaskan Arctic were exposed to drilling sounds. Whales generally did not respond to exposures in the 100 to 130 dB re 1 μPa rms range, although there was some indication of behavioral changes in several instances.

Frankel and Clark (1998) conducted playback experiments with wintering humpback whales using a single speaker producing a low-frequency “M-sequence” (sine wave with multiple-phase reversals) signals in the 60 to 90 Hz band with output of 172 dB re 1 μPa rms. For 11 playbacks, exposures were between 120 and 130 dB re 1 μPa, and included sufficient information regarding individual responses. During eight of the trials, there were no measurable differences in tracks or bearings relative to control conditions; on three occasions, whales either moved slightly away from (n = 1) or toward (n = 2) the playback speaker during exposure. The presence of the source vessel itself had a greater effect than did the M-sequence playback.

Nowacek et al. (2004) used controlled exposures to demonstrate behavioral reactions of northern right whales to various non-pulse sounds. Playback stimuli included ship noise, social sounds of conspecifics, and a complex, 18-minute “alert” sound consisting of repetitions of three different artificial signals. Ten whales were tagged with calibrated instruments that measured received sound characteristics and concurrent animal movements in three dimensions. Five out of six exposed whales reacted strongly to alert signals at measured received levels between 130 and 150 dB re 1 μPa rms (i.e., ceased foraging and swam rapidly to the surface). Two of these individuals were not exposed to ship noise, and the other four were exposed to both stimuli; these whales reacted mildly to conspecific signals. Seven whales, including the four exposed to the alert stimulus, had no measurable response to either ship sounds or actual vessel noise.

A negative correlation between the presence of some cetacean species and the number of vessels in an area has been demonstrated by several studies (Campana et al. 2015; Culloch et al. 2016; Oakley et al. 2017). Based on modeling, Halliday et al. (2017) suggested that shipping noise can be audible more than 100 kilometers away, and could affect the behavior of a marine mammal at a distance of 52 kilometers in the case of tankers.

Temporary Threshold Shift

TTS is the mildest form of hearing impairment that can occur during exposure to a strong sound (NMFS 2016). While experiencing TTS, the hearing threshold rises, and a sound must be stronger to be heard. It is a temporary phenomenon, and (especially when mild) is not considered to represent physical damage or “injury” (Le Prell 2012; Southall et al. 2007). Rather, the onset of TTS has been considered an indicator that, if the animal is exposed to higher levels of that sound, physical damage is ultimately a possibility. However, research has shown that sound exposure can cause cochlear neural degeneration, even when threshold shifts and hair cell damage are reversible (Kujawa and Liberman 2009; Liberman 2016). These findings have raised some doubts as to whether TTS should continue to be considered a non-injuring effect (Tougaard et al. 2015, 2016; Weilgart 2014).

The magnitude of TTS depends on the level and duration of sound exposure, and to some degree on frequency, among other considerations (Richardson et al. 1995a; Southall et al. 2007). For sound exposures at or somewhat above the TTS threshold, hearing sensitivity recovers rapidly after exposure to the sound ends. Extensive studies on terrestrial mammal hearing in air show that TTS can last from minutes or hours to days (in cases of strong TTS). More limited data from odontocetes and pinnipeds show similar patterns (Finneran and Schlundt 2010; Mooney et al. 2009a, b).

There are no data, direct or indirect, on levels or properties of sound that are required to induce TTS in any baleen whale. The frequencies to which mysticetes are most sensitive are assumed to be lower than those that odontocetes are most sensitive to; natural background noise levels at those low frequencies tend to be higher. As a result, auditory thresholds of baleen whales in their frequency band of best hearing are believed to be higher (i.e., less sensitive) than are those of odontocetes at their best frequencies (Clark and Ellison 2004). From this, Southall et al. (2007) suspected that received levels causing TTS onset may also be higher in mysticetes. However, Wood et al. (2012) suggested that the received levels that cause hearing impairment in baleen whales may be lower.

In pinnipeds, initial evidence from exposures to non-pulses suggested that some pinnipeds (harbor seals in particular) incur TTS at somewhat lower received levels than most small odontocetes exposed for similar durations do (Kastak et al. 1999, 2005, 2008; Ketten et al. 2001). Kastak et al. (2005) reported that the amount of threshold shift increased with increasing SEL in a California sea lion and harbor seal. They noted that, for non-impulse sound, doubling the exposure duration from 25 to 50 minutes (i.e., a +3 dB change in SEL) had a greater effect on TTS than an increase of 15 dB (95 versus 80 dB) in exposure level. Mean threshold shifts ranged from 2.9 to 12.2 dB, with full recovery in 24 hours (Kastak et al. 2005). Kastak et al. (2005) suggested that, for non-impulse sound, SELs resulting in TTS onset in three species of pinnipeds may range from 183 to 206 dB re 1 $\mu Pa^2 \cdot s$, depending on the absolute hearing sensitivity.

Permanent Threshold Shift

When PTS occurs, there is physical damage to the sound receptors in the ear. In some cases, there can be total or partial deafness; whereas in other cases, the animal has an impaired ability to hear sounds in specific frequency ranges (NMFS 2016). Physical damage to a mammal’s hearing apparatus can occur if it is exposed to sound impulses that have very high peak pressures, especially if they have very short rise times (i.e., the interval required for sound pressure to increase from the baseline pressure to peak pressure).

K4.25.1.7 Potential Impacts of Noise on Food Sources

Zooplankton

Zooplankton is a food source for several marine mammal species, as well as a food source for fish that are then prey for marine mammals. Popper and Hastings (2009a, b) reviewed information on the effects of pile-driving, and concluded that there are no substantive data on whether the high sound levels from pile-driving or any human-made sound would have physiological effects on invertebrates. Any such effects would be limited to the area close (1 to 5 meters) to the sound source and is unlikely to cause population effects due to the relatively small area affected at any one time, and the reproductive strategy of most zooplankton species (short generation, high fecundity, and very high natural mortality).

No adverse impact on zooplankton populations would be expected to occur from project activities, due in part to large reproductive capacities and naturally high levels of predation and mortality of these populations. Any mortalities or impacts that might occur would be expected to be negligible compared to the naturally occurring high reproductive and mortality rates. Impacts from sound energy generated by vessels and dredging would be expected to have even less impact, because these activities produce much lower sound energy levels.

Benthos

Limited research has been conducted on the effects of noise on invertebrates (Hawkins and Popper 2012). Christian et al. (2003) concluded that there were no obvious effects from seismic signals on crab behavior, and no significant effects on the health of adult crabs. Pearson et al. (1994) had previously found no effects of seismic signals on crab larvae for exposures as close as 1 meter from a seismic array, or for mean sound pressure as high as 231 dB. Pearson et al. (1994) did not observe any statistically significant effects on Dungeness crab (*Cancer magister*) larvae shot as close as 1 meter from a 231-dB source. Invertebrates such as mussels, clams, and crabs do not have auditory systems or swim bladders that could be affected by sound pressure. Squid and other cephalopod species have statocysts that resemble the otolith organs of fish that may allow them to detect sounds (Budelmann 1992). Some species of invertebrates have shown temporary behavioral changes in the presence of increased sound levels. Fewtrell and McCauley (2012) reported increases in alarm behaviors in wild-caught captive reef squid (*Sepioteuthis australis*) exposed to seismic airguns at noise levels between 156 and 161 dB. Additionally, captive crustaceans have changed behaviors when exposed to simulated sounds consistent with those emitted during seismic exploration and pile-driving activities (Tidau and Briffa 2016). In general, there is little knowledge regarding effects of sound in marine invertebrates or how invertebrates are affected by high noise levels (Hawkins and Popper 2012). A review of literature pertaining to effects of seismic surveys on fish and invertebrates (Carroll et al. 2017) noted that there is a wide disparity between results obtained in field and laboratory settings. Some of the reviewed studies indicate the potential for noise-induced physiological and behavioral changes in a number of invertebrates. However, changes were observed only when animals were housed in enclosed tanks, and many were exposed to prolonged bouts of continuous, pure tones.

No adverse impacts on benthic populations would be expected, due in part to large reproductive capacities and naturally high levels of predation and mortality of these populations. Any mortalities or impacts that might occur because of construction and operations are negligible compared to the naturally occurring high reproductive and mortality rates.

Fish

Fish are the primary prey species for marine mammals in Cook Inlet and Iliamna Lake. In general, fish perceive underwater sounds in the frequency range of 50 to 2,000 Hz, with peak sensitivities below 800 Hz (Popper et al. 2005). However, fish are sensitive to underwater impulsive sounds due to swimbladder resonance. As the pressure wave passes through a fish, the swimbladder is rapidly squeezed as the high-pressure wave, and then under-pressure component of the wave, which passes through the fish. The swimbladder may repeatedly expand and contract at the high SPLs, creating pressure on the internal organs surrounding the swimbladder.

Popper et al. (2005), in a review of 40 years of studies concerning the use of underwater sound to deter salmonids from hazardous areas at hydroelectric dams and other facilities, concluded that salmonids were able to respond to low-frequency sound, and to react to sound sources in close proximity of the source. They speculated that the reason that underwater sound had no effect on salmonids at distances greater than a few feet is because they react to water particle motion/acceleration, not sound pressures. Detectable particle motion is produced very short distances from a sound source, although sound pressure waves travel farther.

Hastings and Popper (2005) reviewed all pertinent peer-reviewed and unpublished papers on noise exposure of fish through early 2005. They proposed the use of SEL to replace peak SPL in pile-driving criteria. This report identified interim thresholds based on SEL or sound energy. The interim thresholds for injury were based on exposure to a single pile-driving pulse. The report also indicates that there was insufficient evidence to make any findings regarding behavioral effects associated with these types of sounds. Interim thresholds were identified for pile-driving consisting of a single-strike peak SPL and a single strike SEL for onset of physical injury. A peak pressure criterion was retained to function in concert with the SEL value for protecting fishes from potentially damaging aspects of acoustic impact stimuli. The available scientific evidence suggested that a single-strike SPL of 208 dB and a single-strike SEL of 187 dB were appropriate thresholds for the onset of physical injury to fishes.

Following the Hasting and Popper (2005) paper, NMFS developed their version of the dual criteria that included the single-strike peak SPL of 208 dB, but addressed the accumulation of multiple strikes through accumulation of sound energy by setting a criterion of 187 dB SEL. The accumulated SEL is calculated using an equal energy hypothesis that combines the SEL of a single strike to 10 times the 10-based logarithm of the number of pile strikes.

Fish have been shown to react when engine and propeller sounds exceed a certain level (Olsen et al. 1983; Ona 1988; Ona and Godo 1990). Avoidance reactions have been observed in fish (e.g., cod and herring) when vessel sound levels were 110 to 130 dB re 1 μPa rms (Olsen 1979; Ona and Godo 1990; Ona and Toresen 1988). Vessel sound source levels in the audible range for fish are typically 150 to 170 dB re 1 μPa/Hz (Richardson et al. 1995a). Several studies that assessed noise impacts on cod, crab, and schooling fish found little or no injury to adults, larvae, or eggs when exposed to impulsive noise sources exceeding 220 dB. The continuous noise levels from ship thrusters, which are generally below 180 dB, do not create enough pressure to cause tissue or organ injury (82 FR 22099).

Several caged fish studies of the effects of pile-driving have been conducted, and most have involved salmonids. Ruggerone et al. (2008) exposed caged juvenile coho salmon (93 to 135 millimeters) at two distance ranges (near 1.8 to 6.7 meters, and distant 15 meters) to 0.5-meter steel piles driven with a vibratory hammer. Sound pressure levels reached 208 dB re 1 μPa peak, 194 dB re 1 μPa rms, and 179 dB re 1 μPa^{2}s SEL, leading to a cumulative SEL of approximately 207 dB re 1 μPa^{2}s during the 4.3-hour period. All observed behavioral responses of salmon to pile strikes were subtle; avoidance response was not apparent among fish. No gross external or internal injuries associated with pile-driving sounds were observed. The fish readily consumed hatchery food on the first day of feeding (day 5) after exposure. The study suggests that coho salmon were not significantly affected by cumulative exposure to the pile-driving sounds.

Hart Crowser, Inc. et al. (2009) similarly exposed caged juvenile (86 to 124 millimeters, 10 to 16 grams) coho salmon to sheet pile-driving in Cook Inlet using vibratory and impact hammers. Sound pressures measured during the acoustic monitoring were relatively low, ranging from 177 to 195 dB re 1 μPa peak, and cumulative SEL sound pressures ranging from 179.2 to 190.6 dB re 1 $\mu Pa^2 s$. No measured peak pressures exceeded the interim criterion of 206 dB. Six of the 13 tests slightly exceeded the SEL criterion of 187 dB for fish over 2 grams. No short-term or long-term mortalities of juvenile hatchery coho salmon were observed in exposed or reference fish, and no short- or long-term behavioral abnormalities were observed in fish exposed to pile-driving sound pressures or in the reference fish during post-exposure observations.

Ensonification from the activities should have no more than a negligible effect on marine mammal food sources because:

- No studies have demonstrated that noise affects the life stages, condition, or amount of food resources (e.g., fish, invertebrates, eggs) composing habitats used by marine mammals, except when exposed to sound levels a few meters from the source, or in a few very isolated cases.
- Where fish or invertebrates responded to noise, the effects were temporary and of short duration (Popper et al. 2005). Consequently, disturbance to fish species would be short-term, and fish would return to their pre-disturbance behavior once the activity ceases. Therefore, project activities (construction of the port, lightering locations, and natural gas pipeline in Cook Inlet) would have little, if any, impact on marine mammals feeding in the area where work is planned.
- The project activity area covers a small percentage of the potentially available habitat used by marine mammals in Cook Inlet, which allows marine mammals to move away from any project area–specific program sounds to feed, rest, migrate, or conduct other elements of their life history.

Therefore, the activities included in the project area are not expected to have any permanent habitat-related effects that could cause significant or long-term consequences for individual marine mammals or their populations because operations would be limited in duration, location, timing, and intensity.

K4.25.1.8 Acoustic Analysis

Per the ESA and the MMPA, applicants are required to evaluate the number of marine mammals potentially exposed to sound levels exceeding the thresholds from Table K4.25-2. This method requires an estimated density of marine mammals (animals per square kilometer), the area of ensonification (square kilometers), which is determined by calculating the distance from the source to the threshold, and duration in a 24-hour period of the activity. Once project-specific details are finalized, details such as pile type and size, size of hammer and number of strikes per pile to install, number of piles per day, and duration of the pile strike would be used to calculate the approximate number of potential marine mammal exposures. Calculated distances to agency thresholds are also used to establish mitigation and monitoring zones. ESA and MMPA consultation with the USFWS and NMFS would define potential estimates of marine mammal take, and provide avoidance and minimization measures to reduce and eliminate take where feasible.

K4.27 SPILL RISK

A REVIEW OF RECENT TAILINGS DAM FAILURES, DAM FAILURE MODELS, AND THEIR RELEVANCE TO THE APPLICANT'S PROPOSED BULK TSF DESIGN

Numerous public comments were received on the Draft Environmental Impact Statement (DEIS) requesting analysis of a full tailings dam failure to be included in the Environmental Impact Statement (EIS). Commenters cited historic tailings dam failures at various locales around the world, particularly recent tailings dam failures in British Columbia (Mount Polley 2014) and Brazil (Fundão 2015; Feijão 2019), and expressed concern that similar failures could occur at the Pebble mine. Commenters were specifically concerned about the potential for adverse impacts to downstream ecosystems, as have occurred from historic failures.

Many commenters cited results from recent tailings dam failure models produced by the US Environmental Protection Agency (EPA) in the Bristol Bay Watershed Assessment (EPA 2014) and by the Nature Conservancy (Lynker 2019), which were based on a hypothetical mine at the site of the Pebble mine. These models predicted extensive downstream inundation with high volumes of tailings and fluid released in the event of catastrophic dam failures. These models were intended to model failures from the Applicant's mine, but did not take into account details of the design of the bulk Tailings Storage Facility (TSF), including the use of thickened tailings, water removal plans, dry closure design, and other features described below. Rather, the models assumed the release occurred from a water-inundated TSF, and based their release volume results on historic failure data that are not relevant to the proposed Pebble mine.

Commenters expressed concern over failures at both the bulk TSF and the pyritic TSF. Most comments, however, were focused on the bulk TSF, as it is the largest facility, and would exist in perpetuity. The pyritic TSF would exist only during and shortly after active mine operations, and would then be removed, with pyritic tailings pumped into the open pit for permanent subaqueous storage. The EPA and Lynker failure models also focused on the bulk TSF that would exist in perpetuity. Therefore, this review on tailings dam failure and hypothetical modeling relevance with respect to the mine is focused on the bulk TSF.

K4.27.1 Purpose

This review is intended to: 1) review commonalities of historic TSFs that have experienced failure; 2) provide details on the design of the proposed bulk TSF in comparison with historic TSFs that experienced failure; 3) provide a review of recent tailings dam failures that have occurred since 2014, in context of how those facilities compare with the proposed bulk TSF; and 4) review the tailings dam failure models put forth by EPA and Lynker to note how they are or are not relevant to the Applicant's proposed project.

K4.27.1.1 Historic Tailings Dam Failures

There is a history of catastrophic tailings dam failures around the globe. Some of these failures have been devastating, causing loss of life, adverse impacts to downstream environments, and property damage. The most damaging dam failures involve a large release of fluid, and tailings that are mobilized with the fluid or entrained in the fluid.

Most significant historic tailings dam failures have some commonalities: 1) most large failures were from traditional "lagoon" type TSFs that typically had much of their surface inundated with water; 2) most of the stored tailings were discharged into the TSF as conventional or water-rich slurries; and 3) most of the dams that have failed historically were raised by upstream dam construction methods.

Water-inundated Tailings Storage Facilities

Many types of mine tailings are categorized as potentially acid generating (PAG). These tailings contain significant amounts of sulfur, which, when exposed to oxygen, can produce sulfuric acid. Sulfuric acid can be harmful to the environment. PAG tailings have therefore been traditionally stored in subaqueous conditions, in TSFs that are under a constant water cover, often referred to as tailings "lakes" or "lagoons." This constant water cover cuts off the oxygen supply to tailings, and thereby reduces or eliminates the ability of the tailings to generate acid, thereby protecting downstream environments.

The presence of a full water cover on top of a TSF, however, increases the potential severity of a tailings release. When large amounts of water are present during a dam failure, the tailings are subject to "erosion," wherein the water which flows out of the TSF erodes or mobilizes solid tailings particles as it flows; and/or to "static liquefaction," wherein the tailings mass liquefies because of the high content of water contained in the tailings. The mobilized tailings can be carried, or entrained, by the flowing water, and the flow becomes a slurry of water and tailings. A water-rich release can entrain significant amounts of tailings, such that many historic releases drained large amounts of the stored tailings, which flowed out of the TSFs as slurries.

Some tailings are not PAG, and do not require subaqueous storage. These tailings can be stored under comparatively dry conditions. (The extreme case of this is the storage of "filtered" or "dry stack" tailings.) The absence of a water cover over the tailings reduces the probability of a tailings dam failure, and reduces the potential severity of a release. In the event of a dam failure, without a large amount of water present to mobilize the tailings, fewer tailings would be entrained and able to flow out of the facility, such that tailings release volumes and travel distances would be limited.

The Applicant's mine site design includes two TSFs. The pyritic TSF would be a water-inundated "lagoon" type TSF required to store the PAG/pyritic tailings subaqueously during operations. These tailings would be relocated from the pyritic TSF shortly after the close of mining and placed in the open pit for perpetual subaqueous storage.

The other TSF would be the bulk TSF. Bulk tailings would not require subaqueous storage, so the bulk TSF would not have a full water cover, but would have only a small supernatant pond during operations. At the end of operations, the bulk TSF would be put into "dry" closure, with no supernatant pond, and would remain as a landform in perpetuity. See "Applicant's Bulk TSF Design" below.

Tailings Slurries

Historic mines have generally disposed of tailings into TSFs by adding water to the tailings to create tailings "slurries" that can be pumped through pipelines into a TSF for storage. Tailings slurries typically contain 65 to 80 percent water, and the remainder tailings solids. Because of these high water contents, tailings slurries have low viscosity; or low resistance to flow. Such fluid slurries held in TSFs are generally poorly consolidated and are therefore more susceptible to erosion, static liquefaction, and liquid flow in the event of a dam breach. Tailings slurries can exhibit fluid behavior and readily flow like water (MEND 2017). Most historic failures have occurred from TSFs that accept and store tailings slurries.

The Applicant would not be using tailings slurries, but would use "thickened" tailings, which have a lower water content than slurries. Thickened tailings cannot flow as easily as slurry tailings because there is less water to mobilize them. See "Applicant's Bulk TSF Design" below.

Upstream Dams versus Downstream and Centerline Dams

Tailings dams, often called embankments, may be constructed and sequentially raised by various methods, including upstream, downstream, or centerline methods (as well as modifications of these methods). Upstream dams are the most common, and are sequentially raised by placement of fill on top of stored tailings in the upstream direction. Downstream dams are raised in the downstream direction by placing fill on top of the dam crest and downstream slope of the previous raise. Centerline construction is a method in which a dam is raised by concurrently placing fill on top of the dam crest; the upstream slope, including portions of the tailings beach; and the downstream slope of the previous raise. Centerline dam raises are built mostly on top of fill material from the previous raise, and partly on top of tailings adjacent to the dam.

Upstream dams are generally considered less stable than downstream or centerline dams because the dam raises are built on top of tailings. When these tailings are fluid-saturated, they can be especially weak and susceptible to static liquefaction and liquid flow in the event of a dam breach. Upstream dams require the least amount of fill material to construct, and are the least expensive type of dam. Most historic failures have been from dams built by upstream construction methods.

The Applicant would construct the bulk TSF embankments by downstream and centerline methods, not the upstream method. The main embankment would be raised by the centerline method, and the south embankment would be raised by the downstream method. See “Applicant’s Bulk TSF Design” below.

K4.27.1.2 The Industry Call for Water Reduction in Tailings Storage Facilities

There is widespread awareness across the mining industry that excess fluid stored with tailings increases the risk of tailings releases. In particular, since the 2014 Mount Polley dam failure, there has been a call within the mining industry to reduce the amount of water held on top of TSFs and within the tailings (interstitial, or pore water) to promote stability of the stored tailings. Best available technology (BAT) principles suggested following the Mount Polley dam failure (Morgenstern et al. 2015) include eliminating or minimizing surface water in TSFs and promoting unsaturated conditions in tailings through drainage provisions.

When a flood of surface water spills from a TSF, the water erodes, or entrains, the tailings beneath, so that the release becomes a slurry of tailings-rich fluid. This flood of tailings slurry can mobilize very high volumes of solid tailings. When there is no water cover or supernatant pond present on top of the tailings, it eliminates the chance of a flood of a large volume of water, and also reduces the ability of the stored tailings to be mobilized out of the TSF.

Providing drainage in the TSF allows excess pore fluid to drain out of the tailings, so that less water is held in the pore space, and tailings remain less saturated. Less-saturated tailings are less susceptible to static liquefaction, and would therefore not be able to mobilize and flow as easily in the event of a dam breach. Therefore, promoting unsaturated conditions in the tailings through drainage provisions reduces the chances of a major release of tailings.

Another technology that aims to reduce the amount of water held in TSFs is the use of “thickened tailings.” Tailings have long been transported into TSFs via pipelines in the form of “tailings slurries,” which typically contain 65 to 80 percent water, and the remainder tailings solids. Thickened tailings, in contrast, have only 40 to 50 percent water. The use of thickened tailings rather than tailings slurries introduces significantly less water into a TSF.

The Mount Polley Independent Expert Engineering Investigation and Review Panel (IEEIRP) also stated that placing tailings in mined-out open pits is the most direct way to reduce the number of TSFs subject to failure (Morgenstern et al. 2015). The Applicant has proposed this for pyritic TSF.

This was also considered for the bulk TSF as part of the National Environmental Policy Act (NEPA) Alternatives Analysis (Appendix B), but was ruled out as not practicable for the Pebble Project.

The Mount Polley IEEIRP also stated that "surface storage using filtered tailings technology is a prime candidate for BAT" (Morgenstern, et al. 2015). This alternative of filtered tailings (also called dry stack tailings) was also put forth for consideration as part of the NEPA Alternatives Analysis process (Appendix B). However, dry stack/filtered tailings were considered not practicable for the Pebble Project.

The BAT objective of reducing water in the tailings could also be achieved by compacting tailings to drive out excess fluid from the pore spaces between the tailings particles, and reduce the ability of tailings to flow in the event of a dam failure. Luino and De Graff (2012) conclude that tailings that are deposited as a slurry and not able to drain their excess fluid will tend to maintain a state of saturation under their self weight. This would result in limited additional consolidation over time and the continuation of a lower tailings density. Tailings can be mechanically compacted, which is generally not feasible for slurry or thickened tailings, but is routinely performed on dry stack tailings. Compaction of tailings is considered not practical for the bulk TSF.

K4.27.2 Applicant's Bulk Tailings Storage Facility Design

The Applicant has proposed a design for the bulk TSF that would minimize surface water storage above the tailings and promote unsaturated, or dryer, conditions in the bulk tailings through drainage provisions. The Applicant would also use thickened tailings, which would reduce the amount of fluid that is actually introduced into the TSF to start with.

The Applicant's bulk TSF design is different than that of most other historic and current TSFs. The proposed design is especially distinct when compared to most historic mines that have experience large failures. Some of these differences are:

1. Separate tailings streams and TSFs for the bulk tailings and pyritic tailings. This is in contrast to mines with one TSF for all the tailings combined, which often have a full water cover.
2. Bulk TSF main embankment starter dams fully founded directly on bedrock and not on soil. This is in contrast to mines with TSF embankments built on top of soil, or, in some cases, on top of saturated tailings, that provide weaker embankment foundations than bedrock.
3. Centerline and downstream embankment construction above the starter dam, versus upstream dam construction above the starter dam, to provide increased stability of the embankments. This is in contrast to mines with upstream construction raises over the stored tailings, which are inherently less stable than centerline raise embankments.
4. Discharge of thickened tailings to the bulk TSF at 55 percent solids content by weight, versus slurry tailings disposal of 20 to 30 percent solids, such that the stored tailings would contain a third to a half of the water that a conventional slurry would contain. This is in contrast to mines that use slurried tailings that would contain two to three times the amount of water than thickened tailings would contain.
5. Bulk TSF design based on flow-through seepage out of the main embankment to control the water in the tailings, such that the water level in the tailings (the phreatic surface) would be lowered near the main embankment, in order to improve the embankment stability. This is in contrast to mines that have higher water levels (phreatic surfaces) near the embankments, and therefore lower embankment stability.

6. Minimal supernatant pond size on the bulk TSF tailings surface. Surface water from the TSF would be continually removed and pumped to the main water management pond (main WMP), which would be sized sufficiently to always receive and store excess surface water from the TSF. This would reduce the amount of water in the TSF so that it can operate as a TSF, and not as a water storage reservoir, and to eliminate the risk of overtopping. This is in contrast to mines with large TSF supernatant ponds or full water covers and no means of storing this water elsewhere, such that the TSFs need to be operated as water storage reservoirs, which they may not be designed to do.
7. Bulk TSF would be put into “dry closure,” the tailings would be contoured and ultimately converted into a permanent landform with no water ponded on the surface. This is in contrast to mines with permanent water covers over the TSFs.

K4.27.2.1 Separate Bulk and Pyritic Tailings Storage Facilities

Most hard rock mining operations have tailings with some level of a pyritic/PAG component, so that subaqueous storage of tailings is required to reduce the potential for ARD. There is added expense in separating PAG tailings from non-PAG tailings, so most mines keep all the tailings together and store them in one TSF with a water cover.

The Applicant’s design is distinct from most mine sites, in that it would separate bulk tailings from pyritic/PAG tailings. This design would serve to minimize the volume of tailings that require subaqueous storage.

Based on extensive analysis of rock samples from the site, 88 percent of tailings would be bulk tailings. Bulk tailings are chemically distinct from pyritic/PAG tailings, in that they do not have a significant PAG component, and therefore do not require subaqueous storage. (Although because the process of tailings separation is inherently imperfect, the bulk tailings would likely have a small PAG component.)

The remaining 12 percent of tailings would be PAG/pyritic tailings, which would require perpetual subaqueous storage to reduce the potential for acid rock drainage (ARD). Pyritic tailings would be stored in a separate full water cover-type TSF during operations, and then relocated to the open pit soon after the close of mining operations. The open pit would be allowed to fill with water during closure/post-closure, which would maintain the pyritic tailings in subaqueous storage in perpetuity.

K4.27.2.2 Embankment Foundations on Bedrock, not on Overburden

The bulk TSF main embankment starter dam would be constructed directly on top of bedrock, and not on soil/overburden, as advocated by Morgenstern (2018). A bedrock foundation would provide the dam with greater stability than that of a soil foundation, especially a soil profile with loose, unconsolidated materials that may not be detected during geotechnical investigations. See Section 4.15, Geohazards and Seismic Conditions, for further details on the embankment foundation.

K4.27.2.3 Centerline and Downstream Dams versus Upstream Dams

Most historic mine failures have been from upstream dams, which are known to be less stable than downstream or centerline dams. Rico et. al. (2007a) estimated that 76 percent of global TSF failures involved upstream dams. Many of the upstream dams failed because of overtopping and/or weak soils, or saturated tailings under the dams and the upstream raises.

It is noted that the Mount Polley Perimeter Dam, which was a centerline dam, failed in 2014 as discussed below. The main reason for the failure was found by the IEEIRP (Morgenstern et al. 2015) to be a relatively weak soil layer under the dam that had not been properly studied during investigations and designs. This deficiency was exacerbated by a downstream slope that was constructed steeper than the original design requirement, and by occasional water cover over the TSF surface (Morgenstern et al. 2015; BCMOE 2015). The fact that the dam was of centerline construction was not cited as a contributory factor to the failure.

K4.27.2.4 Tailings Viscosity: Use of Thickened Tailings versus Slurry Tailings

A technology that aims to reduce the amount of water held in TSFs is that of thickened tailings. Tailings have long been transported into TSFs via pipelines in the form of slurries, which typically contain 65 to 80 percent water, with the remainder being tailings solids. These slurries have low viscosity, or low resistance to flow. Such fluid slurries held in TSFs are generally unconsolidated and remain saturated for several years (Luino and De Graaf 2012). As a result, these slurry-deposited tailings can be more susceptible to static liquefaction and liquid flow in the event of a dam breach.

The Applicant would thicken the tailings to 55 percent solids (by weight). The use of thickened tailings rather than slurried tailings introduces less water into the TSF initially, and maintains a smaller supernatant pond on the surface of the TSF, both in accordance with the BAT water reduction objectives advocated by the Mount Polley IEEIRP (Morgenstern et al., 2015) and as described by MEND (2017). Therefore, the bulk TSF would contain reduced water levels compared to TSFs which store slurried tailings.

Because thickened tailings have a lower water content, they are more viscous, and therefore are more resistant to flow compared to a slurry. In the event of a tailings dam failure, the more viscous tailings are not able to flow readily and cannot travel as far as a slurry. With respect to the mobilization and flow ability of thickened tailings, MEND (2017) states "[F]ailure, if it occurs, would likely be local slumping and consequences would be restricted to the local area (or the distance equivalent to roughly 20 times the dam height), unless the material slumps into a water body." MEND cautions that this estimate of the tailings flow distance is included for comparison purposes only, which is appropriate at this point of the Pebble Project development. This would predict that a full failure of the bulk TSF main embankment would result in a tailings release that could flow for a distance of about 2.2 miles (not accounting for surface topography or other structures in the path of the flow).

The strength of deposited tailings is also controlled by the density of the tailings. MEND (2017) describes that thickened tailings are somewhat more dense than slurried tailings in the upper 5 to 10 meters (16 to 33 feet) of the tailings deposit; however, due to self-weight consolidation, thickened and slurry tailings deposits often achieve a similar final density at depth. This would apply if the slurried tailings can drain excess fluid and thereby consolidate and densify.

There is currently a limited history of successful thickened tailings operations at large mines in cold regions. The thickened tailings are planned to be discharged at 55 percent solids content at Pebble. This should be achievable based on existing project histories, where solids content goals were greater than 60 percent and mostly were not achieved, but 55 percent was achieved in the process of striving for more than 60 percent.

The MEND (2017) conclusions provide the most up-to-date and comprehensive reporting on the current state of tailings technology, with much of its emphasis on cold regions. A MEND conclusion on thickened tailings is as follows: "[H]istorically, this is the least common facility type in Canada. Based on our research, consistency of tailings product over time and lack of ability to achieve steep tailings slopes are a main concern with high density thickened/paste tailings."

The MEND reference to "Canada" is relevant to the Pebble site because of the climate similarities with Alaska. The comment on "ability to achieve steep tailings slopes" is not as relevant because Pebble's thickened tailings would be stored behind a fully sized dam, and not deposited as a cone with a minimal dam as at some mines. The comment on "consistency of tailings product over time" could be an uncertainty at Pebble, although the 55 percent solids slurry at Pebble would be easier to achieve than the higher percentages targeted by other mines with thickened tailings operations.

K4.27.2.5 Minimizing Surface Water in the Tailings Storage Facility, and "Promoting Unsaturated Conditions" in Tailings

Because the bulk TSF does not require a water cover, its design is distinct from that of many historic TSFs. During operations, thickened tailings would be pumped into the bulk TSF, and would contain 45 percent water content/55 percent solids by weight. The Applicant's design includes reducing the amount of water that remains stored in the bulk TSF by minimizing the size of the supernatant pond in accordance with the BAT principles for tailings dams advocated by the Mount Polley IEEIRP (Morgenstern et al. 2015). Excess supernatant water has been cited as one of the causes of the Mount Polley tailings dam failure (BCMOE 2015). Excess surface water from the supernatant pond would be continually pumped to the main WMP, which has been sized to continually accommodate this excess water from the bulk TSF.

The "flow-through" design of the main embankment and use of underdrains would encourage excess fluid to drain out of the tailings in order to maintain a reduced phreatic surface. However, tailings below the phreatic surface would remain saturated throughout operations. Figure K4.15-3 shows the predicted phreatic surface during operations and early closure (see additional discussion of seepage modeling, which predicts the phreatic surface, under "Drainage Provisions," below).

Grain Size Segregation of Tailings

Wet tailings, in the form of thickened tailings at 55 percent solids content by weight, would be added to the upper surface of the TSF by way of spigots around the TSF perimeter. Water would percolate, or seep, downward through the tailings. The Applicant's design relies on gravitational segregation of tailings, in that coarser tailing particles would fall out and deposit closer to the spigots around the perimeter, while finer tailings would flow downslope and deposit closer towards the center of the TSF, away from the embankments.

Per the design, drainage would be facilitated through the coarser tailings closest to the main embankment, so that the phreatic surface would be lower alongside the main embankment. The tailings deposited along the south dam perimeter and hillside perimeters would optimize the filling of air space in the TSF, and would control the surface pond location in combination with pumping of the excess surface water to the main WMP.

There is uncertainty, however, regarding the ability of thickened tailings to segregate into coarse and fine particles. It is uncertain if coarser tailings would actually deposit closer to the main embankment; and if so, that the phreatic surface would actually be as low as assumed. Tailings below the phreatic surface would be saturated. These conditions could be confirmed by means of geotechnical investigations during the first 2 years of TSF operations, and then accounted for in the design of the first centerline raise and subsequent centerline raises.

Permeable Flow-Through Main Embankment

The main embankment is designed as a "flow-through" structure with engineered filter zones that are designed to allow fluid to drain through the embankment, while reducing the potential for piping and internal erosion of tailings and fine fill particles through the embankment. The design is intended to promote unsaturated conditions in the coarse tailings deposited near the embankment and reduce porewater pressures in the embankment fill materials.

Modeling results suggest that based on this design, the phreatic surface adjacent to the main embankment would be lowered (although uncertainty remains as to what the actual phreatic surface depths would be). Large, continuous, engineered filter zones in the embankment would be designed to promote internal drainage and reduce the phreatic surface, which would enhance stability.

Based on the Applicant design of the bulk TSF, the only standing water above the tailings in the TSF would be a relatively small supernatant pond near the center of the TSF, away from the main and south dams. Tailings “beaches” would surround the pond and would not be inundated with water (see Figure 2-66). The uppermost tailings of the beaches, based on the design, would be relatively well-drained; that is, not fluid-saturated. The maintenance of a minimal supernatant pond and lack of surface water cover over the tailings would be critical to the success of the TSF design.

Drainage Provisions

The bulk TSF would include basin and embankment underdrains to help maintain a reduced phreatic surface in both the tailings and in the embankment. Underdrains would be used in natural tributary drainages beneath the TSF, and an aggregate drain at a topographic low point beneath the main embankment to provide a preferential seepage path from the tailings to downstream of the embankment toe. Additional underdrains running parallel to the main embankment would allow for drainage of seepage collected along the embankment.

Water would then be able to seep downward beneath the TSF and be collected in the seepage collection system, reducing the amount of fluid held in the TSF. Drainage provisions would be intended to promote unsaturated conditions, but the phreatic surface could remain higher throughout mine operations, as discussed above. Piezometers would be used in the TSF to monitor the phreatic surface levels. Adequate drainage would be critical to the success of the bulk TSF design. If required to achieve drainage goals, alternative drainage-enhancing features would be considered, such as vertical or horizontal drains (PLP 2019-RFI 130; described in Chapter 5, Mitigation).

As described above, the only standing water above the tailings in the TSF would be a relatively small supernatant pond near the center of the TSF, away from the main and south embankments. Tailings beaches would surround the pond and would not be inundated with water (see Figure 2-66). The uppermost tailings of the beaches, based on the design, would be coarser, and therefore would drain better so they would not be saturated. The flow-through concept would allow water to percolate downward through the tailings. Deeper tailings would be fluid-saturated, below the phreatic surface. See Figure K4.15-3 for a cross-section of the estimated phreatic surface.

A seepage analysis was conducted of the bulk TSF based on a two-dimensional (2D) model (SEEP/W) that predicted seepage rates for use in the site-wide water balance model (Section 4.16, Surface Water Hydrology). The analysis provides information on the behavior of the phreatic surface in the TSF. During operations, the phreatic surface would vary based on the tailings discharge spigot locations around the TSF perimeter. The seepage model also shows that the phreatic surface would be expected to decline in early closure after the tailings discharge ceases (PLP 2019-RFI 006b, 008h, 130). Details of the seepage model assumptions, input parameters, material layout, boundary conditions, and results are provided in Appendix K4.15. Figure 10 in RFI 109e also shows the predicted phreatic surface in the bulk TSF based on additional 3D groundwater modeling (see Section 4.17, Groundwater Hydrology).

There are several examples of centerline dams worldwide that are directly comparable in design, height, and seepage rate to the bulk TSF main embankment, and are operating successfully. The Constancia Mine tailings dam in Peru, owned by Hudbay Minerals, is a zoned rockfill dam with a vertical clay core, and is greater than 328 feet high. The Highland Valley Mine H-H tailings dam in British Columbia, owned by Teck Resources, is an earthfill dam with a low-permeability vertical core, with random fill and tailings placed upstream, and variable waste fill on the downstream side, and is 318 feet high. The Yankee Doodle tailings dam at Continental Mine in Montana, owned by Montana Resources, is built of rockfill and is 750 feet high with alluvial soils placed over the upstream slope as a filter between the tailings and rockfill to reduce the potential of tailings piping through the embankment. These three dams have similar configurations and materials as planned for the bulk TSF main embankment, but only the Yankee Doodle Dam can be considered to be a flow-through embankment. The Constancia and Highland Valley H-H dams are not flow-through dams because of the presence of the vertical cores. The engineered filter zone in the bulk TSF, consisting of graded sands and gravels, is expected to be more effective than these low-permeability core examples in lowering the phreatic surface within the embankment and promoting stability. The Constancia and Highland Valley H-H dams are lower (the Yankee Doodle dam is higher) than the planned bulk TSF main embankment. These dams are still being raised.

The Applicant has provided eight other examples of dams that reportedly have similarities to the planned bulk TSF main embankment. Three of these dams are described as “Modified Centerline” dams, or hybrids of centerline and upstream or downstream construction with rockfill raises. These dams are somewhat comparable to the planned bulk TSF main embankment configuration. The other five dams are described as being raised using cyclone sand instead of rock fill, which means that the dams are not comparable to the planned bulk TSF embankment. Also see Section 4.15, Geohazards and Seismic Conditions, for more discussion of flow-through dam design.

At the current conceptual level of bulk TSF design, there is uncertainty regarding the ability of the tailings to drain sufficiently. It is uncertain whether the thickened tailings at 55 percent solids would segregate enough, with coarse tailings forming the tailings beach near the spigots, and finer tailings in the middle of the impoundment, to promote reduction of the phreatic surface near the main embankment (AECOM 2019n). Although the design is intended to promote unsaturated conditions, most of the tailings may remain saturated throughout operations, and potentially into post-closure. See Figure K4.15-3 for a cross section of the estimated phreatic surface.

Future tailings geotechnical investigations by field explorations, field and laboratory testing, and seepage, stability, and liquefaction analyses have been committed to by the Applicant in RFI 008h, and are described in Chapter 5, Mitigation. Additional analysis would further the understanding of tailings deposition behavior and help address this concern. See Section 4.15 and Appendix K4.15, Geohazards and Seismic Conditions, for additional details.

Success of the bulk TSF design would depend on the continued maintenance of low phreatic surfaces in the TSF, especially near the main embankment. Appropriate mitigation and monitoring plans would be critical to ensure compliance with the design. Requirements on details such as phreatic surface elevations in the TSF would be developed as part of the Operations, Maintenance, and Surveillance (OMS) manual.

After active mine operations cease, the bulk TSF would be closed by grading its surface so that all drainage would be directed off the TSF. This is known as dry closure. The tailings surface would be covered with soil and/or rock, and possibly a geomembrane liner that would act as a water barrier. This would prevent water from ponding on the TSF surface. The liner would reduce water infiltration into the tailings, thereby continuing to promote unsaturated conditions in closure.

K4.27.2.6 Very High Capacity Water Storage in Main WMP

The Applicant has designed the mine site layout specifically to allow for very high capacity water storage, with the goal of maintaining minimal fluid on the tailings surface. Any excess fluid that may begin to collect in the supernatant pond would be pumped to the main WMP, which is the key component of the TSF water management plan.

The very high capacity of the main WMP is one element that makes the mine layout unique with respect to other mine layouts. The main WMP is designed to manage surplus contact water from the mine site under the full range of climate conditions, including prolonged wet and dry periods. The average volume of planned contact water stored in the main WMP is approximately 1,470 million cubic feet (ft^3), with maximum storage of approximately 2,440 million ft^3. Storage capacity of the main WMP would also include storage of the required inflow design flood (IDF) (equal to the Probable Maximum Flood), and additional freeboard for safety (Knight Piésold 2018q). The very high capacity allows for storage of excess contact water from the bulk TSF in the main WMP, to maintain a minimal supernatant pond in the bulk TSF.

If the bulk TSF seepage control system cannot keep up with the surface water draining through the TSF, the phreatic surface could start to rise in the tailings. In this case, the excess surface water in the supernatant pond could be pumped to the main WMP. Likewise, if there were extreme precipitation events, to the extent that the water level began to rise in the TSF and the supernatant pond started to increase in size, that excess fluid could be pumped to the main WMP, and there would be adequate warning and time to do this safely without any risk to the stability of the main embankment.

Additionally, the bulk TSF itself has extra supernatant pond freeboard built into the design to temporarily hold the IDF, etc., if needed (see Section 4.15, Geohazards and Seismic Conditions).

K4.27.2.7 Dry Closure and Post-Closure

The bulk TSF closure plan would include a dry surface cover with precipitation drained off so that the TSF would ultimately become a dry landform. This is in contrast to mines with permanent water covers over the TSFs through to post-closure that would require long-term treatment of excess surface water and seepage, and would require continued stability assessments of the embankments as long as they are retaining water on the TSF surface.

The stability benefits of a dry closure are summarized by Cobb (2019b) as follows: "At the end of the operating life the risk is immediately reduced if the operational pond can be removed, resulting in a "dry" closure. After that, the risk is dependent on the nature of the design and the post-closure maintenance requirements." The bulk TSF post-closure maintenance requirements would be developed as part of the closure design and post-closure objectives.

K4.27.2.8 Failure Modes and Effects Analysis Risk Assessment

In October of 2018, the US Army Corps of Engineers (USACE) hosted an EIS-Phase Failure Modes and Effects Analysis (FMEA) workshop to assess the likelihood of failures and the severity of potential environmental impacts from the major embankments in the bulk TSF, pyritic TSF, and main WMP, and to determine appropriate release scenarios for impacts analysis in the EIS. The FMEA workshop was preceded by the development of a draft list of potential failure modes that was updated as an initial part of the workshop.

Participants at the FMEA workshop used the available information on the Applicant's design to assess the likelihood of various dam failure scenarios (potential failure modes), including a full tailings dam breach. The FMEA participants considered the design (as described above) and determined that the probability of a large-scale release of tailings was extremely low. See

Section 4.27, Spill Risk, and the EIS-Phase FMEA Report (AECOM 2018l) for full details on the FMEA risk assessment process.

K4.27.3 Examples of Four Recent Dam Failures

Numerous comments were received on recent tailings dam failures in British Columbia (Mount Polley in 2014) and Brazil (Fundão in 2015; Feijão in 2019). Note that the names Fundão and Feijão are used in this Technical Memorandum versus the media-used names of Samarco and Brumadinho, respectively, for two reasons: consistency with the independent review panel names in the failure review reports; and Fundão and Feijão are the mine names (like Mount Polley is a mine name) versus Samarco, which is the mine owner company name; and Brumadinho, which is the name of the nearest town to the mine.

Commenters expressed concern that similar failures could occur at the Pebble mine. These three tailings failures are reviewed here, along with a recent tailings dam failure in Australia (Cadia in 2018), for purposes of addressing the largest global tailings dam failures in the last 6 years. This section reviews these four recent tailings dam failures in the context of the similarities and differences between these facilities and the bulk TSF.

K4.27.3.1 Mount Polley Failure, British Columbia, Canada 2014

The Mount Polley mine near Quesnel Lake, British Columbia, Canada, had a failure of their TSF Perimeter Dam on August 4, 2014. A variety of factors led up to the dam failure, as outlined in the Chief Inspector of Mines report (BCMOE 2015) and the IEEIRP report (Morgenstern et al. 2015). Morgenstern (2018) provides recommendations for future TSF designs partly based on information from the Mount Polley TSF failure.

There was a change in dam design and construction to a steeper outer slope than engineers had originally designed; there was a deep clay layer beneath the foundation whose extent was underestimated and whose weakness was not sufficiently considered in the design; there was a history of water management that resulted in an occasional full water cover over the TSF; and there was a lack of regulatory oversight and enforcement to correct these inadequacies (Morgenstern et al. 2015).

At the time of the release, approximately 10 million cubic meters (m^3) of surface water were covering the TSF that should not have been present, per the water management plan. When the dam failed, this additional water eroded and entrained significant amounts of tailings. The total volume of the release was 17 million m^3 of water (surface water + interstitial water held within the tailings) plus 8 million m^3 of tailings solids (Morgenstern et al. 2015). The flood of fluid and tailings flowed down Hazeltine Creek and into Quesnel Lake.

The total release has been estimated to account for approximately 30 to 36 percent of the total volume of the TSF. This release estimate is based on information provided in the Chief Inspector of Mines report (BCMOE 2015) and other public data sources. Had the excess surface water not been present in the TSF, fewer tailings would have been entrained in the release, and the amount of released tailings and fluid would have been much lower.

The mine is in a remote area with no communities directly downstream of the dam. There were no human fatalities from the failure and ensuing flood.

The overall environmental impact was considered limited. Portions of Hazeltine Creek were damaged from erosion. Water quality downstream of the Mount Polley release was reduced for approximately 6 months, after which time the water quality returned to baseline (Nikl et al. 2016). Spilled tailings were recovered as was practicable from Hazeltine Creek, and the damaged channel was reconstructed. Salmon in the Quesnel Lake watershed downstream of the Mount

Polley release returned to spawn in high numbers in 2018, 4 years after the spill (Williams Lake Tribune 2018).

The failed Mount Polley Perimeter Dam had been constructed and raised by the centerline method. Tailings were deposited into the TSF as a conventional slurry. Excess water on the surface of the tailings eroded, entrained, and mobilized a significant amount of tailings, thereby increasing the volume of released tailings.

Comparison of the Mount Polley Perimeter Dam with the proposed bulk TSF main embankment on the Pebble Project is only in the method of dam construction; namely, the centerline method. This was not cited by either Morgenstern (2015) or the British Columbia Ministry of the Environment (BCMOE) (2015) as a contributary factor to the Mount Polley failure. Otherwise, the bulk TSF main embankment is planned to differ from the Mount Polley Dam in three main ways: 1) the bulk TSF embankment would be founded on bedrock without risk of overlying a weak soil layer; 2) tailings discharge into the bulk TSF would be with thickened tailings, not slurried tailings, thereby reducing the water volume in the bulk TSF; and 3) the supernatant pond on the bulk TSF surface would be kept small by pumping to the main WMP.

The first of these three differences is the application of fundamental soil mechanics and prudent geotechnical engineering that is already proposed, and would be further addressed in the bulk TSF main embankment starter dam and raise final designs and stability analyses. The second and third factors are direct applications of the IEEIRP, and advocacy for BAT by reducing the volume of water in a TSF, which are part of the proposed bulk TSF operations plan.

K4.27.3.2 Fundão Failure, Minas Gerais, Brazil 2015

The Fundão dam at the Germano iron ore mine near Bento Rodrigues, Minas Gerais, Brazil, experienced a failure on November 5, 2015. The owner of the mine is Samarco Mariana Mining (joint venture of Vale and BHP Billiton). The failure is often referred to as the "Samarco" dam failure, but it is referred to here as the Fundão dam failure, consistent with the Fundão Tailings Dam Review Panel report (Morgenstern et al. 2016) terminology. Morgenstern (2018) provides recommendations for future TSF designs partly based on information from the Fundão failure.

Tailings became liquefied and flowed out of the dam, with a total release of up to 60 million m^3. The flood of fluid and tailings flowed into the towns of Bento Rodrigues and Paracatu de Baixo, causing 19 fatalities and displacing hundreds more. The plume of tailings traveled down the Doce River, entering the Atlantic Ocean approximately 400 miles away 2 weeks later.

Two types of tailings of different grain sizes had been delivered to the TSF as fluid slurries. Much of the tailings were loose and fluid-saturated, and therefore susceptible to liquefaction. The approximately 100-meter (328-foot)-high dam was constructed and raised by upstream methods on top of previously deposited weak and saturated tailings, several hundred feet upgradient of the original tailings starter dam (Morgenstern et al. 2016).

The Fundão TSF had a multi-year history of design, construction, and operations changes that triggered liquefaction of the deeper tailings. These included: "(1) damage to the original Starter Dam that resulted in increased saturation; (2) deposition of slimes [finer grained tailings] in areas where this was not intended [which reduced drainage]; and (3) structural problems with a concrete conduit that caused the dam to be raised over the slimes" (Morgenstern et al. 2016). Ongoing drainage problems continued in the years prior to failure. A series of three small earthquakes occurred about 90 minutes prior to the dam failure, and "this additional movement is likely to have accelerated the failure process that was already well advanced" (Morgenstern et al. 2016). This failure could not be compared to potential failures at a properly designed, constructed, operated, and regulated facility.

There is no relevant comparison between the Fundão dam and the proposed bulk TSF main embankment on the Pebble Project. The bulk TSF main embankment is planned to differ from the Fundão dam in five main ways: 1) the bulk TSF embankment would be founded on bedrock and not on weak and saturated tailings; 2) the bulk TSF main embankment would be built by centerline and not upstream construction methods; 3) discharge into the bulk TSF would be by thickened rather than slurried tailings, thereby reducing the water volume in the bulk TSF; 4) the TSF would also employ a flow-through seepage control by means of the embankment and underdrains; and 5) the supernatant pond on the bulk TSF surface would be maintained at a small volume by continually pumping the surface water to the main WMP.

The first two differences are the application of fundamental soil mechanics, and prudent geotechnical engineering that is already proposed and would be further addressed in the bulk TSF main embankment starter dam and raise final designs and stability analyses. The remaining differences are direct applications of the Mount Polley IEEIRP advocacy for reducing the volume of water in a TSF that are part of the proposed bulk TSF operations plan.

K4.27.3.3 Feijão Failure, Minas Gerais, Brazil 2019

On January 25, 2019, there was a failure of dam B-1 at the Córreigo de Feijão iron ore mine near the town of Brumadinho, in the state of Minas Gerais, Brazil. Official information on this failure was not available during the DEIS preparations and the comment period. Official information on the failure only became available in December 2019, with the release of the Report of the Expert Panel on the Technical Causes of the Failure of Feijão Dam (Robertson et al. 2019):

> This dam failure is unique in that there are high quality video images of the event that provide insight into the failure mechanism. …The videos clearly show a slope failure within the dam starting from the crest and extending to an area just above the First Raising (the Starter Dam). The dam crest dropped and the area above the toe region bulged outwards before the surface of the dam broke apart. The failure extended across much of the face of the dam and collapse of the slope was complete in less than 10 seconds, with 9.7 million cubic meters (Mm^3) of material (representing approximately 75 percent (%) of the stored tailings) flowing out of the dam in less than 5 minutes (min).

It is noted that slope failure of the B-1 dam released 9.7 million m^3 of wet tailings, which calculates to 75 percent of the total tailings that were stored in the TSF. This ratio of tailings release is almost double and quadruple the flow ratios that were derived from historic data, and used in the two flow models described below. The failure resulted in a catastrophic mudflow that traveled rapidly downstream, resulting in 270 fatalities. A 75-mile length of the Paraopeba River was contaminated. Toxic levels of lead and chromium were measured in the first 12 downstream miles.

The B-1 dam that failed was constructed using the upstream method, in which dam raises are constructed on top of weak underlying tailings, and had a relatively steep upstream slope. Tailings had been deposited in the TSF as slurry. No tailings had been deposited in the facility since 2016, but the phreatic surface did not drop significantly after tailings deposition ended.

Tailings were dominantly non-PAG, like those of the Applicant's bulk tailings, and did not require subaqueous cover. Therefore, there was no full water cover over the tailings, but the phreatic surface was quite high, so that most tailings were fluid-saturated.

The dam was monitored and reportedly showed no signs of deformation or change prior to failure (Robertson et al. 2019). Installed drainage provisions were insufficient, and drainage was impeded, particularly through the toe of the dam, resulting in a high phreatic surface. Seepage from the dam was observed periodically. The dam failed in the middle of the wet season, so precipitation also contributed to the high phreatic surface.

The tailings were not able to drain properly, and were predominantly loose and saturated, and therefore highly susceptible to liquefaction and flow. The Report of the Expert Panel states that "[W]ater management within the tailings impoundment…at times allowed ponded water to get close to the crest of the dam, resulting in the deposition of weak tailings near the crest"; and that the tailings were heavy and brittle due to their high iron content, to the extent that "significant parts of the dam were under very high loading due to the steepness of the dam, the heavy weight of the tailings, and the high internal water level" (Robertson et al. 2019). The failure "was the result of flow (static) liquefaction within the materials of the dam" (Robertson et al. 2019).

There is no relevant comparison between the Feijão dam and the proposed bulk TSF main embankment of the Pebble Project. The bulk TSF main embankment is planned to differ from the Feijão dam in five main ways: 1) the bulk TSF embankment would be founded on bedrock and not on weak and saturated tailings; 2) the bulk TSF main embankment would be built by centerline and not upstream construction methods; 3) discharge into the bulk TSF would be by thickened and not slurry tailings, thereby reducing the water volume in the bulk TSF; 4) the TSF would also employ a flow-through seepage control by means of the embankment and underdrains; and 5) the supernatant pond on the bulk TSF surface would be maintained at a small volume by continually pumping the surface water to the main WMP.

The first two differences are the application of fundamental soil mechanics, and prudent geotechnical engineering that is already proposed, and would be further addressed in the bulk TSF main embankment starter dam and raise final designs and stability analyses. The remaining differences are direct applications of the Mount Polley IEEIRP, and advocacy for BAT by reducing the volume of water in a TSF that are part of the proposed bulk TSF operations plan.

K4.27.3.4 Cadia Failure, New South Wales, Australia 2018

The first three failures reviewed above were cited in comments on the DEIS, because they were large-scale releases involving significant impacts, including loss of life and environmental impacts. Here a recent failure from another TSF is addressed, which is somewhat distinct from the preceding three facilities. Note that official information on this failure was not available during the DEIS preparations. Official information on the failure became available in April 2019 with the release of the Independent Technical Review Board (ITRB) report (Jefferies et al. 2019).

The Newcrest Cadia copper mine near Orange, New South Wales, Australia, stores tailings in two TSFs behind dams that were raised by upstream construction methods, with the upper dam that contains the Northern TSF (NTSF) directly upgradient of the lower dam that contains a lower TSF. Tailings are dominantly non-PAG, similar to the Applicant's bulk tailings, and do not require subaqueous cover. Therefore, the tailings facilities are not water-inundated. Tailings are delivered as a slurry. The TSF at Cadia is more analogous to the Applicant's bulk TSF in that the tailings are not under a water cover, and there is just a small supernatant pond.

On March 9, 2018, there was an embankment failure at the NTSF. The ITRB report described that in the failure, the downstream slope of the NTSF slumped, so that tailings containment was lost (Jefferies et al. 2019). The failure resulted in a relatively viscous flow of tailings, because there was no ponded surface water involved, but tailings were saturated. Very few tailings were mobilized, because there was no excess fluid to entrain them. The small amount of tailings released from the TSF was captured in the lower TSF. There was no release of tailings or fluid outside of mine facilities; therefore, there were no resulting environmental impacts. The worksite was evacuated prior to the failure, and there were no injuries or loss of life (Jefferies et al. 2019).

The failed NTSF dam was constructed initially by downstream methods and was later raised by upstream methods. Tailings were delivered as a conventional slurry. The stored tailings were saturated and loose, so that they were susceptible to liquefaction if triggered (Jefferies et al. 2019).

The failure was concluded to have resulted from foundation instability, likely due to a weak, low-density volcanic unit in the vicinity of the slump. “Other factors contributing are the local height of the dam, the prevailing phreatic conditions, and the additional excavation at the toe of the structure” (Jefferies et al. 2019). The resulting deformation of the dam consisted of slow initial movement for many months prior to failure “as the failing mass adjusted to changing states of equilibrium” followed by “relatively sudden losses of resistance and/or increases in loading to create conditions to accelerate movements to the distances ultimately achieved” (Jefferies et al. 2019). Two small seismic events in the days preceding (4.3 magnitude) do not appear to have contributed to the liquefaction (Jefferies et al. 2019).

Construction work was under way before, and up to the time of failure, for purposes of improving the already marginal stability of the NTSF dam. This construction increased the potential for the outward movement of the embankment, and was a contributory factor in triggering movement of the dam that led to the mobilization of the tailings by static liquefaction.

The only relevant comparison between the Cadia dam and the proposed bulk TSF main embankment on the Pebble Project is the Cadia effort to maintain a minimal surface water pond. The bulk TSF main embankment is planned to be different from the Cadia dam in four main ways: 1) the bulk TSF embankment would be founded on bedrock and not on weak and saturated tailings; 2) the bulk TSF main embankment would be built by centerline and not upstream construction methods; 3) discharge into the bulk TSF would be by thickened, rather than slurry tailings, thereby reducing the water volume in the bulk TSF; and 4) the TSF would also employ a flow-through seepage control by means of the embankment and underdrains.

The first two differences are the application of fundamental soil mechanics, and prudent geotechnical engineering that is already proposed, and would be further addressed in the bulk TSF main embankment starter dam and raise final designs and stability analyses. The last two differences are direct applications of the Mount Polley IEEIRP, and advocacy for BAT by reducing the volume of water in a TSF that are part of the proposed bulk TSF operations plan.

K4.27.4 Tailings Dam Failure Modeling

Although the probability of a catastrophic tailings failure of the bulk TSF main embankment is very remote (see Section 4.27, Spill Risk), there is public concern regarding the installation of any new TSFs, especially when there are human populations and/or fragile ecosystems downstream of the facilities.

Scientists and engineers have sought to learn more about these potential dangers and how to avoid them through modeling correlated with previous failure study findings. Tailings dam failure modeling can demonstrate potential impacts to downstream environments with reasonable accuracy if the modeling is performed using site-specific information versus hypothetical or assumed information. Modeling efforts vary greatly in their quality and usefulness.

For example, models can be very useful in predicting the potential outcomes of tailings releases when they include site-specific information such as TSF site and downstream topography; geologic, seismic, geotechnical, and hydrologic data; tailings rheology (branch of physics that deals with flow of solid and liquid materials), moisture content, and density; and TSF design, construction, and operations and management plans. On the other hand, models that do not include these specifics and assume values for them cannot predict to reasonable accuracy the failure outcomes such as volume of release, downstream impacts, and extent of inundation.

Two models were developed in the last 6 years in efforts to model a catastrophic tailings dam failure of a hypothetical TSF at the proposed Pebble mine. These models were developed by the EPA (2014) and Lynker Technologies, LLC (Lynker 2019).

The models are not relevant to the bulk TSF main embankment because the model assumptions are based on historic failures from water-inundated TSFs, most of which stored conventional tailings slurries and not thickened tailings. The models therefore assumed a high volume of water involved in the release, which erodes, entrains, and/or mobilizes tailings, leading to a larger release of both fluid and solid tailings. However, the Applicant's design would have only a small supernatant pond, and not a full water cover. Without a full water cover, bulk TSF tailings would not be triggered to experience static liquefaction and flow.

Therefore, the modeled releases and resulting impacts are an overestimation of a reasonable bulk TSF failure scenario.

Below is a review of the EPA and Lynker models, indicating where they are and are not relevant for an environmental review of the project.

K4.27.4.1 EPA Model

The EPA (2014) model/series of models was put forth in 2014 as part of the EPA Bristol Bay Watershed Assessment (EPA 2014), which was an assessment of potential mining impacts on salmon ecosystems of Bristol Bay. This model was rather general, because it was based on a hypothetical mine with several assumptions made, and the modeling used an earlier, but now obsolete, mining plan (Wardrop 2011) that was developed several years prior to the Applicant outlining its current mining plan.

It is noted that the EPA model was developed before the Mount Polley, Fundão, Cadia, and Feijão failures occurred, and therefore EPA did not have the results and lessons learned from these failures to use as case histories for its modeling.

The EPA evaluated three hypothetical Pebble mine scenarios (Pebble 0.25, Pebble 2.0 and Pebble 6.5). Each scenario represents a different mine size based on different stages of potential mining of the total deposit. These scenarios were based on processing 0.25, 2.0, and 6.5 billion tons of ore in 20, 25, and 78 years, respectively. For comparison purposes, the current Pebble Project is based on mining 1.44 billion tons of ore over 20 years, so its size fits between the Pebble 0.25 and 2.0 scenarios.

EPA describes the scenarios as follows:

> The three mine size scenarios evaluated in the assessment represent realistic, plausible descriptions of potential mine development phases, consistent with current engineering practice and precedent. The scenarios are not mine plans: they are not based on a specific mine permit application and are not intended to be the detailed plans by which the components of a mine would be designed. However, the scenarios are based on preliminary mine details put forth in Northern Dynasty Minerals' Preliminary Assessment of the Pebble Mine (Wardrop 2011), as well as information from scientific and industry literature for mines around the world …. Thus, the mine scenarios reflect the general activities and processes typically associated with the kind of large-scale porphyry copper mine development likely to be proposed once a specific mine application is developed.

Each EPA scenario had its largest tailings dam sited on approximately the same footprint as the currently proposed bulk TSF main embankment. At the time, the available Pebble reports had suggested that this dam could be up to 209 meters (686 feet) high. The EPA evaluated two potential failures of this dam: one with the dam 92 meters (302 feet) high, which corresponds to the full height of the Pebble 0.25 scenario; the other with the dam at its full height of 685 feet for both the Pebble 2.0 and Pebble 6.5 scenarios. The modeling assumed that bulk and pyritic tailings would be combined into one or more TSFs, which was the proposed plan at the time, rather than a separate bulk TSF and pyritic TSF, as is the current plan.

In a summary table of the scenario assessments, EPA outlines these assumptions:

> All water collection and treatment at site works properly, and wastewater is treated to meet state and national standards before release; however, some leachate from waste rock and TSFs is not captured. …Excess water stored in TSF 1 is released over the spillway. …Stormwater falling onto TSFs would be stored in the tailings impoundments and used in the process water cycle. …Prior to active mining, but after the starter dam was built for TSF 1, site water would be diverted to TSF 1 to allow sufficient water for process plant startup. During mine operation, groundwater and precipitation would be pumped from the mine pit to prevent flooding of the mine workings. …Water would be needed for the flotation mill, to operate the TSF, and to maintain concentrated slurry in the product pipeline. …For example, much of the water used to pump the tailings slurry from the mill to a TSF becomes available when the tailings solids settle, and excess overlying water is pumped back to the mill. …[At closure] the tailings pond would be drawn down to prevent flooding and to maintain stability, but a pond of sufficient depth would be retained to keep the PAG tailings hydrated and minimize oxidation.

These assumptions show that the model input included slurried tailings, not thickened tailings discharge, and an assumed bulk TSF operation with a full water cover versus a planned small pond by pumping surface water to the main WMP. The assumption of a large water cover in the bulk TSF skewed the model results because a larger water volume would mobilize more tailings in the event of a dam breach, and therefore cause a larger tailing release than could occur. A larger volume of tailings would be released as a result of a dam breach if the TSF contained slurry tailings and a large surface pond, as was planned at the time of the modeling, than if the TSF contained thickened tailings and a small pond.

Following a discussion on tailings dam failure probabilities based on historic failure reviews, the EPA correctly stated:

> The historical frequencies of tailings dam failures presented above may be interpreted as an upper bound on the failure probability of a modern tailings dam.…improvements in the understanding of dam behavior, dam design, construction techniques, construction quality control, dam monitoring, and dam safety assessment would be expected to reduce the probability of failure for dams designed, constructed, and operating using more modern or advanced engineering techniques.

Similarly, dam breach and tailings release model analysis methods have advanced in recent years (McPhail 2015; Martin et. al. 2019) as described below.

In its modeling, the EPA used a combined bulk and pyritic tailings bulk density of 53 percent solids and 47 percent water by volume. This equates to a water content of approximately 33 percent water by weight. This water content is within the 20 to 35 percent range for deposited tailings that were discharged as a slurry, but high for deposited tailings that are discharged as thickened tailings.

EPA (2014) used the USACE Hydrologic Engineering Center's River Analysis System (HECRAS) to model the hydrologic characteristics of the dam failures. This tool requires the selection of one of two failure initiation mechanisms: overtopping the dam; or piping (internal erosion) in the embankment. Overtopping was selected, but piping was used for sensitivity analyses. Results were similar. The study first modeled the hydrologic conditions (e.g., water discharges, depths, and velocities) in the stream channel and floodplain during and immediately following dam failure, and then used this output to estimate tailings transport and deposition along the stream network. EPA acknowledged the limitations of the model for tailings flows with high levels of sediment, because the model was developed for fluid flows with lower viscosity.

This modeling is not relevant to a failure of the bulk TSF because the model assumes that a high volume of water is stored in the TSF, making overtopping the dam more probable, and resulting in an increased volume release (both tailings and fluid). Based on the current design, overtopping is a remote possibility, because the operations plan calls for only a small surface pond, and not a full water cover (because excess water would be pumped to the main WMP). In addition, the model was developed to predict low-viscosity fluid flows versus higher-viscosity tailing flows.

The EPA analysis assumed that 20 percent of the tailings in the TSF would be released in the event of a dam failure. EPA considered this to be a conservative estimate in the range of historic tailings dam failures. EPA added that the ratio of tailings that would be released in the event of a dam failure could exceed 20 percent. No justifications are given on the 20 percent assumption, except that it is in the range of historic tailings dam failures, and on the comment that the release could be larger than 20 percent. There is also no discussion on the possibility that the release could be less than 20 percent, which is discussed below.

The EPA acknowledged that the range of estimated dam failure probabilities is wide, reflecting the great uncertainty concerning such failures, and then described that the most straightforward method of estimating the annual probability of a tailings dam failure is to use the historical failure rate of similar dams. Three reviews of tailings dam failures produced an average rate of approximately 1 failure per 2,000 dam-years, or 5×10^{-4} failures per dam-year, and that expected failure could occur any year in that 2,000-year window, with an average annual probability of 0.0005, or 5×10^{-4}.

The EPA then correctly argued that the record of past failures does not fully reflect current engineering, design, construction, operating, and monitoring practices, as would be used on the bulk TSF. EPA stated that some studies suggest that improved practices can reduce the failure rate by an order of magnitude or more, resulting in an estimated failure probability of failure of 1 in 250,000 per year for facilities designed, built, and operated with state-of-the-practice engineering (Category I facilities); and 1 in 2,500 per year for facilities designed, built, and operated using standard engineering practice (Category II facilities). The advantage of this approach is that it addresses current regulatory guidelines and engineering practices. The disadvantage is that it is not known if standard practice or state-of-the-practice dams would perform as expected, particularly with dam heights and subarctic conditions in these scenarios.

EPA limited the extent of the model to a 30-kilometer (19-mile) reach downgradient of the bulk TSF down the North Fork Koktuli River (NFK) valley to the confluence of the South and North Fork Koktuli rivers. It was considered that extending the simulation beyond this point would introduce error and uncertainty associated with the contribution of South Fork Koktuli River (SFK) flows. The results showed that the dam failure in all three mine scenarios would result in a flow of tailings into the NFK that would scour the valley and deposit many meters of tailings in a sediment wedge across the entire valley near the dam, with lesser quantities of tailings deposited as far as the NFK's confluence with the SFK. The tailings flow would continue down the mainstem Koktuli

River with similar effects, the extent of which was not estimated because of the model and data limitations.

K4.27.4.2 Lynker Model

The Lynker (2019) model was developed for the Nature Conservancy and Bristol Bay Regional Seafood Development Association prior to the release of the DEIS. The model used the publicly available information on the mine site and design, but did not address the planned use of BAT (Morgenstern et al. 2015) to minimize the water volume in the bulk TSF by discharging thickened versus slurried tailings, and to maintain a small supernatant pond by pumping to the main WMP versus allowing a large supernatant pond to develop.

It is noted that the Lynker model was developed after the Mount Polley and Fundão failures occurred, therefore, Lynker had access to the investigation findings of these failures as case histories. However, although the Lynker modeling was also completed after the Cadia and Feijão failures, it was prior to the release of the investigation reports of these failures; therefore, the Cadia and Feijão investigation reports were not available.

Lynker completed a model analysis of flow and deposition for a failure of the bulk TSF main embankment at approximately the same location as the Applicant's embankment. The analysis used the publicly available data from the Pebble Project. Lynker cited the following four aspects of the project to suggest that a full tailings breach was not "extremely unlikely": centerline versus downstream construction; TSF size ten times larger than TSFs of recent failures; 52 inches of annual rainfall; and seismic risks that could lead to dam failure by liquefaction.

These aspects are all controllable by application of BATs. Centerline dams are a sound technical and economic compromise between downstream and upstream dams, and can be designed to be as stable as downstream dams, especially on thickened tailings. The static Factor of Safety (FoS) for both the downstream and centerline dam alternatives would be 1.9 to 2.0 (see Section 4.15, Geohazards and Seismic Conditions).

Tailings characterization to the maximum extent possible is critical to the design of a safe TSF and assessment of tailings flow characteristics in the event of an embankment failure. However, a calculated FoS can be misleading with respect to reduction in risk because the FoS depends on the level of engineering used to develop it. Silva et al. (2008) and Altarejos-Garcia (2015) show that the level of engineering, or level of detail in the engineering, has a greater influence on the probability of failure than increasing the FoS. This is echoed by the Australia National Committee on Large Dams (ANCOLD 2012, updated 2019) guidelines as follows: "There are no "rules" for acceptable factors of safety, as they need to account for the consequences of failure and the uncertainty in material properties and subsurface conditions." Similar conclusions are outlined in the Alaska Department of Natural Resources Draft Guidelines for Cooperation with the Alaska Dam Safety Program (ADNR 2017a), and summarized by Cobb (2018, 2019b).

FoS values described for the bulk TSF main embankment are based on the current conceptual levels of design. FoS values would be refined during the advanced preliminary and detailed stages of the designs.

The dam size can be controlled, as shown by other operating tailings dams of similar heights. Rainfall can be accommodated as shown by tailings dams in similar rainfall environments in Alaska and worldwide, such as the Gibraltar and Brenda mines in British Columbia and the Continental Mine in Montana, which have centerline or modified centerline TSFs in the range of 385 to 750 feet in height. Seismic design criteria are an established science that can be used to accommodate the required design earthquake on a large dam.

Lynker developed its model using a FLO-2D software package that is a flood modeling package capable of simulating non-Newtonian flows (i.e., high-viscosity, sediment-laden flows) that characterize tailing failures. Sensitivity analyses were performed by changing parameters, including tailings release volumes and durations. The model expanded on the EPA analysis in two ways: by extending the model domain about 140 kilometers (88 miles) down the Koktuli river system to just below the confluence of the Mulchatna and Nushagak rivers, while the EPA model domain only extended 30 kilometers (19 miles) downstream; and by simulating the bulk TSF failures as a non-Newtonian flow consistent with tailings flow that would have sediment concentration with different rheology than a clear flood flow.

The release scenarios in the Lynker study are based on data from historic TSF failures compiled by Rico et al. (2007a, b) and Laurrali and Lall (2018) that date back to the 1970s. These early TSFs were mostly storing wet tailings slurries, predominantly built by upstream construction methods, and mostly under a relatively full surface water cover in traditional large “lagoon” type TSFs. Therefore, they are not applicable to the Pebble design with thickened tailings that would not be covered by water. Most historic failures were also from upstream dams, which are less stable than centerline or downstream dams. In addition, most of the failures involved dams founded on soil or tailings, instead of a bedrock foundation that is planned for the bulk TSF main embankment.

For its model, Lynker’s starting point was a calculation that 41.7 percent of the tailings would be released. This was based on an empirical formula developed by Rico (2007b) from pre-2007 failure case history studies, and is twice the 20 percent tailings release rate that EPA (2014) used in its analysis. Rico’s data are mostly based on slurry tailings retained by upstream tailings dams, versus thickened tailings retained by a centerline dam. Dam break tailings releases of 10 and 60 percent were also tested to determine their impacts to the Nushagak watershed.

The 41.7 percent tailings release volume is also excessive when compared to data discussed below, and the fact that a significantly smaller release would be expected of thickened tailings in a TSF with a small pond that would likely not have enough entrained and surface water to mobilize and sustain a large tailings flow. As described below, there are methods for calculating the breach size and release volume based on site conditions, tailings properties, and TSF operations; versus using a formula based on slurried tailings and upstream raise failure histories.

The Lynker model relied on the 11- and 24-hour breaches as most likely scenarios, and the results primarily illustrate the 24-hour breach, because it is a more conservative estimate with a lower peak flow compared with the 11-hour breach. The 11-hour breach was found to be more impactful. The Lynker modeling analysis does not seem to have addressed modes of dam failure or failure initiation mechanisms like the EPA analysis did when it selected overtopping, and also used piping for sensitivity analyses. The Lynker analysis simply selected a 41.7 percent tailings flow based on inappropriate historical data, and then performed the modeling.

The Lynker model indicated that tailings from a bulk TSF main embankment breach would travel more than 75 kilometers (47 miles) downgradient, beyond the confluence of the Mulchatna River, where most of the model simulations ended. In an expanded model domain, the results indicate that tailings under most scenarios would continue beyond the Nushagak River, more than 130 kilometers (81 miles) downgradient. The modeling showed that 50 percent of the tailings were still moving through the downstream boundary of the expanded model, and are “extremely likely” to continue to Bristol Bay. (Note that in both of the EIS tailings release models, a small amount of suspended tailings particles were modeled to extend the full length of the downstream watershed, through the Nushagak River to Bristol Bay.)

K4.27.4.3 Model Discussion

The EPA and Lynker models were developed by competent teams of scientists, and the model methods are scientifically valid and worthy of review. However, the problem with both models when used for NEPA analysis is that they do not account for the Pebble mine specifics put forth by the Applicant (as reviewed above). Instead, they are based on generic historical data for past dam failures, most of which involved TSFs that differ from the proposed bulk TSF as described above. Some of the model deficiencies and the differences between their assumptions and the planned bulk TSF are described in the following paragraphs.

Both models started with an assumed volume of tailings release based on historic tailings dam failures (Rico 2007a) without regard for the differences between the Pebble bulk TSF and the historic TSFs that failed. This is the reverse of how modeling should be performed; namely, the tailings release should be estimated as part of the modeling based on site-specific data outlined above. Then an appropriate volume of release would be determined as part of the modeling process. Larrauri and Lall (2018) outline the need to consider the potential energy associated with the released volume as opposed to the whole TSF volume.

Lynker noted that depending on the size of the TSF, Rico's formula shows that the expected tailings slurry release from a TSF failure is 35 to 45 percent of the total TSF volume. Later, Azam and Li (2010) concluded that on dam breakage, the released tailings generally amount to 20 percent of those contained in the facilities. Rico (2007b) stated the following: "The application of the described regression equation for prediction purposes needs to be treated with caution and with support of on-site measurements and observations." These cautions are supported by later case history studies by Martin et al. (2019) that show that tailings slurry released from a TSF failure could range from 1 to 100 percent of the total TSF volume.

As described above, the result of a release of thickened tailings in the event of a failure, "would likely be local slumping and consequences would be restricted to the local area (or the distance equivalent to roughly 20 times the dam height), unless the material slumps into a water body" (MEND 2017). This would predict that a full failure of the bulk TSF main embankment would result in a tailings release extending for a distance of approximately 2.2 miles from the bulk TSF main embankment.

Therefore, the use of a precise 41.7 percent as the basis for a tailings breach model analysis is inconsistent with a wide range of historic data, and the use of historic data from slurry tailings releases is misleading when applied to thickened tailings releases.

Marr (2019) reviewed the failure histories of ten TSFs, including the four failures described above. From his reviews, he developed the following characteristics of tailings dam failures:

> Failure can occur quite suddenly will little to no warning; Generally, something triggers a failure within the barrier dam or foundation which results in loss of containment of tailings; This triggers the stored tailings to liquefy; Liquefied tailings can flow very fast for long distances and present great risk to downstream people and environment; Little time to warn and evacuate people within a few km below the dam; Visual inspections may not reveal the threat of imminent failure; Most monitoring systems will not give adequate warning; These characteristics should be strongly considered in the design and operation of a tailings dam.

A key factor in Marr's findings is that tailings do not just mobilize and flow without a trigger. The trigger is typically a failure of the dam or embankment that is retaining the tailings, which then allows water, in the tailings and on the tailings surface, to mobilize and cause the tailings to liquefy and flow out of the TSF. Again, excess supernatant fluid contributed to the tailings dam failure at Mount Polley (BCMOE 2015). The bulk TSF BAT plan of water removal from the bulk TSF by means of discharging thickened tailings versus slurry tailings and minimizing the surface pond by pumping water to the main WMP would significantly reduce the risk of a large tailings flow release as a result of an embankment breach.

A more appropriate project-specific method for conducting a tailings dam breach analysis using site data and operation plans could be the McPhail (2015) approach. This is a semi-quantitative risk assessment and a probabilistic analysis performed in the following sequence: fault (or cause) analysis; event tree analysis; and probabilistic flow slide. These sequences are described below.

The fault tree analysis enables a probability to be developed from the TSF management and performance to one of five flow-slide trigger faults that were identified by reviews of historic tailings failures: embankment static instability; embankment dynamic instability; embankment overtopping; embankment piping as a result of layers in the embankment fill; and delivery pipe or buried drainage failure. In developing the fault trees, a chain of sub-faults could precipitate a trigger cause that early management intervention could eliminate before the cause can trigger a failure. In assigning probabilities to the effectiveness of management intervention, the prevailing mining economic climate must be considered, because studies show a prevalence of failures during enforced austerity (McPhail 2015; Bowker and Chambers 2015; Armstrong et al. 2019).

It is interesting that the EPA (2014) analysis addressed the trigger faults, but the Lynker (2019) analysis was silent on the trigger faults. The concept of the trigger faults, as well as dam failure scenarios, are also discussed by Martin et al. (2019).

The event tree analysis then establishes the probabilities of loss of life, environmental damage, and loss of production if a flow slide results from a dam failure. Event trees start with the top fault and proceed by assigning probabilities associated with the following questions that define progressively developing events given a top fault: does a slide occur; are people present at the failure or in the flow path; would there be a plant stoppage and production loss; and mortalities?

The flow slide analysis is then performed by applying dam break analysis methods to tailings flow studies, and recognizing the difference between a tailings dam break analysis, and a water storage dam analysis, and therefore considering the effect of the following: tailings rheology; parabolic shaped tailings failure surface versus horizontal water flow surface; topographic ground slope along the slide flow path; and flow continuity. The flow continuity would be a critical factor for the bulk TSF because thickened tailings with a limited surface water pond cannot undergo a significant flow because of the lack of water to mobilize such flow.

McPhail (2015) developed a flow slide analysis method with input parameters: flow volume released; breach width; tailings rheology defined by tailings yield stress and viscosity properties; flow profile curvature; and tailings post-liquefaction friction angle that defines the residual angle of the resultant tailings crater in the TSF. Extensive testing is required to obtain these data. Therefore, a more practical approach is to use probabilistic calculations to establish confidence limits. Historic observations show that the tailings crater can be approximated by a truncated cone. Progressive development of the crater determines the flow slide outflow hydrograph, breach width, and tailings release volume.

Observations suggest three potential modes by which the flow slide can develop after liquefaction starts. The failure mode most likely for each situation depends on the liquefied tailings characteristics, with shear strength, rheology, and available water volume being key factors.

This approach estimates the tailings release upper and lower bounds by considering the TSF geometry and depth. Past failure evaluations indicate releases of 5 to 50 percent of the total TSF volume, breach widths of 250 to 1,000 feet, and crater slopes of 0.55 to 3.3 percent, plus ranges of tailings yield stress and viscosity. Therefore, a Pebble bulk TSF with thickened tailings and small water pond should be at the low end of the tailings volume release range, possibly much less than the EPA (2014) and Lynker (2019) volumes of 20 and 41.7 percent, respectively.