December 21, 2007

MEMORANDUM

TO: Suzanne Theiss, California Department of Transportation
Paul Wagner, Washington Department of Transportation

FROM: Thomas Carlson, Mardi Hastings, Arthur N. Popper

SUBJECT: Update on Recommendations for Revised Interim Sound Exposure Criteria for Fish during Pile Driving Activities

This memorandum updates the results of a meeting that took place July 19-20, 2007, in Arlington, VA. Attending were the three authors of this memo. David Buehler of Jones & Stokes served as facilitator. The purpose of the meeting was: to review previous interim sound exposure criteria for fish; to examine the earlier criteria in light of new and emerging data; and to make recommendations for revisions of the interim criteria for pile driving based on new information. In addition, this memo provides comments on the NOAA memo "Rationale for Use of 187 dB Sound Exposure Level for Pile Driving Impact Threshold," dated 4-30-07.

The recommendations we propose here are based on the most recent scientific data for potential impacts of transient sound on fish with swim bladders.[1] We also emphasize that the criteria we recommend are *interim* and that we anticipate, and expect, that these criteria will be replaced by newer criteria based on data in future studies.

Ideally we want to define interim sound exposure criteria as representing the received signal level that defines the *onset* of effects, rather than using data representing effects at some point past their onset; however, data for the onset of effects in fishes are not available in the literature. Moreover, instead of proposing one set of criteria, peak sound pressure level (SPL) and cumulative sound exposure level (SEL), we propose criteria for each of *three different effects on fish*:

1) Hearing loss due to temporary threshold shift (TTS);
2) Damage to auditory tissues (generally sensory hair cells of the ear); and
3) Damage to non-auditory tissues.

[1] The data on fish without swim bladders are insufficient to serve as a basis for recommendations. However, based on observations in the literature that fish without swim bladders may less likely be affected by sounds because they do not have an internal compliant air bubble that oscillates in response to acoustic pressure, it may tentatively be predicted that such species would less likely be affected than fish with swim bladders.

At the same time, we also recognize that the biology of individual fish species as well as the physiological state of individual fish may alter the nature and sequence of effects. Based on the available scientific literature, vulnerability to non-auditory tissue damage increases as the mass of the fish decreases. Therefore, non-auditory tissue damage criteria are different depending on the mass of the fish. Table 1 summarizes our recommendations.

Table 1: Recommended *interim sound exposure criteria for fish* based on the most recent data for signal levels that result in observed effects on fish having swim bladders that were not fully equilibrated to ambient pressure.[2] The non-auditory tissue damage criteria are based on additional analyses (Hastings 2007) of acoustic data reported by Govoni et al. (2003) and Popper et al. (2007). The TTS criteria are primarily based on Popper et al. (2005) for exposure to seismic airguns. Auditory tissue damage criteria are primarily based on Song et al. (submitted) and additional analysis (Hastings 2007) of the sound exposure data reported by Popper et al. (2007). Note, when there was variation in data, the values given below are the minimum level resulting in any effect. Cumulative SEL is calculated based on Hastings and Popper (2005) where [CUMULATIVE SEL = 10 log (# pile strikes) + single strike SEL].

		Peak	Cumulative SEL	Application Notes
Non-auditory tissue damage	Mass of fish <0.5g	Not Relevant	183 dB	Based on results of previous research (Yelverton et al. 1975; Stuhmiller et al. 1996), the relationship between SEL and fish body mass will most likely be linear on a log-log scale. Therefore for body mass between 0.5 and 200 grams: $$\text{Cumulative SEL} = 186.47 + 11.53 \cdot \log_{10}(\text{mass})$$ Extrapolations below 0.5 g and above 200 g are conservative based on available data.
	Mass of fish >200g	Not Relevant	>213 dB	
Auditory tissue damage (hair cells)	Hearing generalist[3]	>206 dB	>213 dB	Accumulation of SEL should not be reinitiated if cumulative SEL >213 dB.
	Hearing generalist	>206 dB	>189 dB	After an 18-hour period of non-exposure, accumulation of SEL to the values given here should be reinitiated.
	Hearing specialist	>205 dB	>185 dB	
TTS	Hearing generalist	207 dB	185 dB	After an 18-hour period of non-exposure, accumulation of SEL should be reinitiated.
	Hearing specialist	205 dB	183 dB	

[2] It should be noted that Govoni et al. (2003) placed fish at a depth of 2 feet (0.6 m), Popper et al. (2005) at a depth of approximately 1 m (~3 feet), and Popper et al. (2007) at a depth of 16.6 m (54.5 feet), and that none of these studies allowed time for the swim bladder to fully equilibrate with ambient pressure. The exact effects of changing the water depth and/or allowing full equilibration of swim bladders on the results of these studies are unknown.
[3] See Popper et al. (2003) and Hastings and Popper (2005) for definitions of terms.

Interpretation and Application of New Recommendations

Non-Auditory Tissue Damage

Examination of the scientific literature indicates that non-auditory tissue damage in fish with swim bladders does not correlate with peak sound pressure level (e.g., Yelverton et al. 1975; Teleki and Chamberlain 1978; Wiley et al. 1981; Hastings 1990, 1995; Stuhmiller et al. 1996; Govoni et al. 2003). Based on current data, the applicable metric for non-auditory tissue damage is an energy index that is indicative of mechanical work done on the tissue and does not depend on whether the pressure is positive or negative (e.g., Yelverton et al. 1975; Wiley et al. 1981; Bailey et al. 1996; Stuhmiller et al. 1996). This metric can be estimated using cumulative SEL; however, the most relevant data (Yelverton 1975; Hastings 1995; Govoni et al. 2003; Popper et al. 2007) are not reported in cumulative SEL.

Cumulative SEL for fish with estimated mass less than 0.5 grams was calculated by Hastings (2007) from graphical waveform data provided to us by Govoni (time sequence data for received pressure levels reported in Govoni et al. 2003, used with permission). This SEL recommendation is lower than previous estimates by Hastings and Popper (2005) based on Yelverton et al. (1975) primarily because tissue damage data from that study was based on gross necropsy rather than histopathology, and the calculated SEL for Govoni et al. (2003) is based only on the primary pressure wave because data were not available for the total exposure, which consisted of multiple reflections and lasted several milliseconds Yelverton et al. (1975) physically designed their experiment to eliminate reflections so that the total exposure was just the primary pressure wave.

Cumulative SEL for fish with mass greater than 200 grams was calculated from digital waveform data from the Popper et al. 2007 study provided to us by the Popper research group (time sequence data for received pressure levels in 2004 and 2005, used with permission). In this study, fish were exposed to one or two sequential low-frequency active sonar signals, each having duration of 108 seconds. The maximum sound pressure levels often exceeded 197 dB (re 1 μPa) in this signal. The cumulative SEL was calculated to be 210 dB for 108 seconds and 213 dB for 216 seconds (Hastings 2007). These signals were repeated twice, but the time between exposures was 9 minutes for the 108-s-long signal and 18 minutes for the 216-s-long signal. Since these periods of silence were long enough for some recovery to potentially occur, our recommendation is based only on the first exposure period.

Auditory Tissue Damage and Temporary Threshold Shift (TTS)

We combine auditory tissue damage and TTS for this discussion because the metrics (peak and SEL) used are the same for both. TTS or auditory tissue damage is *expected if either metric is exceeded* (Hamernik and Qiu 2001). However, TTS will occur at lower levels than auditory tissue damage (Hamernik and Qiu 2001; Popper et al. 2005; Popper et al. 2007; Song et al. submitted), so TTS and auditory tissue effects have different dual criteria. Values in the table are given for both hearing generalists and hearing specialists since the mechanism of inner ear stimulation differs depending on the relationship between a gas-filled chamber (e.g., swim bladder) and the inner ear (Popper et al. 2003). There are no data available for the onset of TTS in fish. Based on the analysis by Smith et al. (2004a) and recovery periods based on hours and days rather than minutes, the TTS data forming the basis of our recommendations appear to be asymptotic[4] TTS data.

The Basis for Revised "Interim" Sound Exposure Criteria

In this recommendation we make use of several recent papers that provide additional insight into effects of sound on fish. These papers are presented in Table 2, along with the papers used by Hastings and Popper (2005, Table 4) to formulate their recommendations.

Table 2: Studies selected to serve as the basis for the recommended interim criteria in this memorandum. The papers not italicized were used by Hastings and Popper (2005), while the papers in italics are those which were published subsequent to that report or for which raw data were not available at that time.

Issue	Hearing Generalists	Hearing Specialists
Non-Auditory Tissue Damage	Yelverton et al. (1975) *Govoni et al. (2003)* *Popper et al. (2007)*	Yelverton et al. (1975) *Govoni et al. (2003)* *Popper et al. (2007)*
Auditory Tissue (hair cell) Damage	Hastings et al. (1996) *Popper et al. (2005)* *Song et al. (submitted)*[1] *Popper et al. (2007)*	Hastings (1995) *Popper et al. (2005)* *Song et al. (submitted)*[1]
Temporary Threshold Shift (TTS)	Hastings et al. (1996) *Popper et al. (2005)* *Popper et al. (2007)*	Popper and Clarke (1976) Hastings (1995) *Popper et al. (2005)*

[1] This submitted MS presents analysis of inner ear auditory tissues on the same animals exposed to sound in Popper et al. (2005).

There are four recently published papers that we found to be most important for developing recommendations for new interim sound exposure criteria for fish because effects were reported for a number of species and resulted from transient acoustic signals with characteristics similar to those generated by pile driving. These are Govoni et al. (2003), Popper et al. (2005), Popper et al. (2007), and Song et al. (submitted). Govoni et al. (2003) examined effects of blasts on non-auditory tissues of small pinfish and spot. Popper et al. (2005) examined effects of seismic airguns on hearing and damage to auditory tissue (Song et al. submitted) in broad whitefish (a salmonid), northern pike, and lake chub (a hearing specialist). Popper et al. (2007) investigated the effects of SURTASS Low Frequency Active Sonar signals on hearing and on auditory and non-auditory tissues of rainbow trout (a salmonid).

The Equal Energy Hypothesis (EEH) has been used as the basis for estimating the impact of multiple sound exposures on auditory systems. Although Hamernik et al. (1987) supported, in concept, the EEH when evaluating impacts on hearing and auditory tissues, subsequent investigations in the same laboratory revealed that the EEH by itself *does not apply to effects on hearing and auditory tissue from impulsive type sounds* (Hamernik et al. 1991, 1993, 1994; Patterson et al. 1993; Lei et al. 1994; Ahroon et al. 1993, 1996; Hamernik and Qiu 2001).

[4] Asymptotic TTS is the maximum value of TTS. When TTS is asymptotic, increasing the exposure level and/or duration will not increase the amount of TTS.

Therefore, it is *imperative* that the criteria for effects on hearing and auditory tissues of fish consist of two metrics, peak sound pressure level and cumulative sound exposure level (SEL). If either of the recommended criteria levels is exceeded, there is then potential for an effect.

Because the EEH does not generally apply to effects on hearing and auditory tissue, we reviewed, but did not include as part of the basis for our recommendations, a number of recently published studies which examined effects on hearing and auditory tissue of fish resulting from exposure to band-limited white noise (Scholik and Yan 2001, 2002; Amoser and Ladich 2003; Smith et al. 2004a, b, 2006; Wysocki and Ladich 2005).

Response to NOAA Memo (4-30-07**)**

There are several fundamental scientific flaws in the referenced memo that describes the dual metric exposure criteria being applied by NMFS. These scientific flaws include, but are not limited to, the following:

- The memo argues that the Equal Energy Hypothesis applies to effects on hearing and auditory tissue in fish based on Hamernik et al. (1987) even though Hamernik et al. cautioned that the generality of their findings was limited "because the impulse pressure-time history and the interpulse interval were not varied" in their study. So as explained above, the EEH alone does not apply to these effects when they result from impact or impulsive sounds such as those generated by pile driving or seismic airguns or blasts (Hamernik et al. 1991, 1993, 1994; Patterson et al. 1993; Lei et al. 1994; Ahroon et al. 1993, 1996; Hamernik and Qiu 2001). In addition, this has also been found to hold true in recent studies of hearing impacts for marine mammals (Mooney et al. 2006).

- The memo argues that peak SPL correlates with non-auditory tissue damage. Instead, available data indicate that the peak SPL metric does not correlate with non-auditory tissue damage, and thus it should not be used to formulate criteria for potential impacts (Yelverton et al. 1975; Teleki and Chamberlain 1978; Wiley et al. 1981; Hastings 1990, 1995; Stuhmiller et al. 1996; Govoni et al. 2003).

- The memo suggests that TTS is a physical injury to the ear. However, this is not the case. TTS is a recoverable physiological effect (e.g., Popper and Clarke 1976; Kastak et al. 1999; Scholik and Yan 2001, 2002; Finneran et al. 2002; Amoser and Ladich 2003; Smith et al. 2004a, b; Popper et al. 2005, 2007). Only damage to auditory or non-auditory tissue constitutes physical injury.

- The criteria put forth in the memo do not accommodate recovery of either TTS or tissue damage, despite recovery from sound exposure being found in numerous vertebrates, including fish (e.g., Yelverton et al. 1975; Hastings 1990, 1995; Kastak et al. 1999; Finneran et al. 2002; Popper et al. 2005).

Based on our review and analysis of the applicable recent literature as summarized in our memo, dual metric interim exposure criteria, consisting of peak and SEL, can be applied only to

TTS and damage to auditory tissue for fish with swim bladders. When considering impacts to the auditory system, separate criteria are needed for hearing generalists and hearing specialists.

According to Popper et al. (2005), full recovery from substantial TTS in both hearing specialists and generalists occurred in less than 18 hours after exposure. Therefore, a simple accumulation method that does not consider interruptions in exposure cannot be applied to sum the energy being produced during multiple hammer strikes. While Popper et al. (2005) clearly showed that there was a greater hearing loss in animals exposed to 20 airgun shots than to five, the full recovery occurred in either case in less than 18 hours, thereby negating an argument for extended accumulation when a period of quiet is imposed on a pile driving operation. This means that in application of the proposed dual criteria, it is necessary to "reset" the accumulation of SEL for TTS after any 18-hour period of non-exposure. In addition because there was no auditory tissue damage at SELs of 185 and 189 dB in hearing specialists and generalists, respectively, and full recovery of TTS occurred within 18 hours, it is necessary to reset the accumulation of SEL for auditory tissue damage to these values after any 18-hour period of non-exposure.

Summary

This memo presents recommendations for new interim sound exposure criteria for effects on non-auditory tissues and on the auditory system of fish with swim bladders based on recent findings in the scientific literature. The critical points in this memo are:

1. The revised interim sound exposure criteria;
2. The requirement that criteria be separately set for hearing generalists and hearing specialists;
3. The distinction among criteria for three different potential effects on fish;
4. The inclusion of a recovery period for auditory system effects to account for long periods of quiet in pile driving operations; and
5. The recognition of different vulnerabilities to acoustic impacts by defining non-auditory tissue damage criteria based on body mass.

The authors of this memo fully expect that these criteria will be revisited as new effects data become available for pile driving and other transient signals.

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