OSPAR CONVENTION FOR THE PROTECTION OF THE MARINE ENVIRONMENT OF THE NORTH-EAST ATLANTIC

Draft Preliminary Comprehensive Overview of the Impacts of Anthropogenic Underwater Sound in the Marine Environment

Module 5: Shipping

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1. NOISE PROFILES OF MARINE VESSELS

1. Among the many human-induced sources of low frequency sound in the marine environment, marine vessels (and particularly large commercial ships) represent numerous, widespread, and relatively loud individual sources of underwater noise, the exact characteristics of which depend on ship type, size, mode of propulsion, operational characteristics, speed, and other factors. Much of the incidental noise results from propeller cavitation, though onboard machinery and turbulence around the hull can also result in underwater noise transmitted underwater via direct or secondary paths. Various vessel elements produce different frequencies, with low frequency sound generally travelling farther due to the physical properties of sound in water.

1.1 SMALL BOATS AND SHIPS (*e.g.*, recreational craft, support and supply ships to ~80m)

2. Small boats produce relatively broad-band acoustic signatures with overall free-field source levels up to approximately 165-175 dB (re: 1µPa), although the output characteristics are highly dependant on speed and other operational characteristics (see Richardson *et al.*, 1995; Kipple and Gabriel, 2003a; 2004). Small tugs, crewboats, and supply ships typically have larger and more complex propulsion systems, often including the presence of bow-thrusters. Typical source levels for these small to mid-size vessels are generally in the 160-180 dB (re: 1µPa) range (see: Richardson *et al.*, 1995; Kipple and Gabriel, 2003a; 2004). Source spectra for small boats and ships can include tonal harmonics at the resonant vibrational frequencies of propeller blades below about 1 kHz, as well as significant energy resulting from propeller cavitation extending up to and above 10 kHz. Due to the generally higher frequency and near-shore operation of many smaller boats and ships, these sources are generally regarding as having potential environmental impacts (from noise) relatively nearby. Small boats and ships may thus be less of a concern with regard to overall increases in marine ambient noise, although they can dominate some coastal acoustic environment, particularly partially-enclosed bays, harbours and/or estuaries (*e.g.*, Kipple and Gabriel, 2003b).

1.2 LARGE VESSELS (*e.g.*, container/cargo ships, supertankers, cruise liners)

3. A significant human contribution to overall ambient noise at low frequencies is thought to be generated by the growing use of the ocean for international shipping. Commercial ships, which are increasing in both number and size, are producing ever-greater amounts of underwater noise as an incidental by-product of operation (see: Southall, 2005; U.S.G., 2008). Large commercial vessels produce relatively loud and predominately low frequency sounds. Although the exact characteristics of these depend on vessel type, size, and operational mode, the strongest energy tends to be below several hundred Hz with source levels generally in the 180-190 dB (re: 1µPa) range (see: Richardson *et al.*, 1995; Arvenson and Vendittis, 2000; Kipple, 2002; Heitmeyer *et al*., 2004; Kipple and Gabriel, 2004). Most of the acoustic field surrounding large vessels is the result of propeller cavitation (when air spaces created by the motion of propellers collapse), causing ships at their service speed to emit low-frequency tonal sounds at multiples of propeller blade rate (shaft speed in revs/second x number of propeller blades). Smaller, but potentially significant, amounts of radiated noise can arise from on-board machinery and flow noise (Richardson *et al.*, 1995). Heitmeyer *et al*. (2004) obtained recent measurements on individual commercial vessels indicating that acoustic source levels are not necessarily a function of speed for modern diesel vessels and that there are significant depth and aspect-dependences of radiated vessel sound fields as a function of

shadowing and the Lloyd mirror effect near the surface of the water. Source (propeller) depth is also important in terms of long-range propagation, which is a potentially significant historical factor in terms of ambient noise trends due to shipping, as propeller depths have increased with increasing vessel size.

2. TRENDS IN MARINE AMBIENT NOISE

4. Multiple studies estimate that there has been an approximate doubling (3 decibel (dB) increase) of background noise per decade in some ocean areas, particularly off the west coast of North America (Andrew *et al.*, 2002; Cato and McCauley, 2002; McDonald *et al.*, 2006; Andrew *et al.*, in press; see Fig. 1 below). Over this period, commercial shipping density increased dramatically and is the most probable source of the increase, given that natural sound sources would be unlikely to change so dramatically over such a relatively short time. Additionally, many other studies have characterized the relative contributions of shipping to the total low frequency noise in highly-trafficked and less-trafficked coastal and open-ocean areas. These studies indicate that ships are the dominant source of low frequency noise in many, if not most, highly-trafficked coastal zones in the northern hemisphere. These areas are also heavily used by marine animals that depend on sound, many of which use the same low frequency bands that are being affected by incidental noise from commercial shipping (Cato, 1976; Ross, 1976; Worley and Walker, 1982; Zakarauskas, 1986; Bachman *et al*., 1996; Zakarauskas *et al*., 1990; Curtis *et al.*, 1999; Andrew *et al*., 2002, in press; Cato and McCauley, 2002; Heitmeyer *et al*., 2004; McDonald *et al*. 2006; Hatch *et al*., 2008). Empirical measurements prior to the advent of human noise contributions to the ocean are lacking and sufficient longitudinal measurements in all but a few areas are absent. This limits our understanding of precisely whether and how ocean ambient noise is increasing as a function of shipping or other human activities (*e.g.*, NRC 2000; 2003). However, the studies referenced above (and others) have resulted in a general conclusion that ocean ambient noise in some parts of the ocean, particularly heavily-industrialized areas, appears to be increasing within the low frequency band as a function of commercial shipping in many industrialized ocean areas (above, and Southall, 2005; Wright, in press).

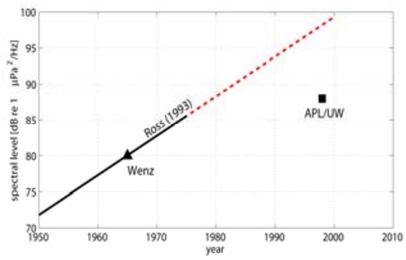

Figure 1. Ambient noise measurements in the 100-200 Hz band measured off California in the 1950's (Ross, 1976) and APL/UW noise measurements in the late 1990's (Andrew *et al*., 2002).

3. EFFECTS OF SHIPPING NOISE ON MARINE MAMMALS

5. The production, perception, and processing of sound is critical for various life functions (including communication, foraging, navigation, and predator-avoidance) for most, if not all, marine mammals. Marine mammals use sound as a primary means for underwater communication and sensing (*e.g.*, Wartzok & Ketten, 1999). Specifically, the toothed whales

have developed sophisticated biosonar capabilities to feed and navigate (see Au, 1993), the large baleen whales have developed long-range communication systems using sound in reproductive and social interaction (*e.g.*, Clark, 1990; Edds-Walton, 1997), and the pinnipeds make and listen to sounds for critical communicative functions (Schusterman, 1981; Schusterman *et al*., 2000).

6. It is also evident that noise may interfere with these critical biological functions in various ways, inducing: alteration of behavior; reduction of communication ranges for social interactions, foraging, and predator avoidance; temporary or permanent compromise of the auditory or other systems; and/or, in extreme cases, habitat avoidance or even death (*e.g.*, Richardson *et al*., 1995; NRC 2003, 2005; Clark and Ellison, 2004; Nowacek *et al*., 2007; Southall *et al*., 2007). Noise may also affect behavior of animals and can also affect physiological functions and cause more generalized stress. Additionally, the impacts of noise may be additive or synergistic to those of other human stressors (*e.g.*, Evans 2002). With regard to the incidental noise generated by large vessels (*i.e.*, commercial shipping), the general low frequency band overlaps the frequencies generally produced by some marine animals, primarily large whales, seals and sea lions, and fish (see Fig. 2 below).

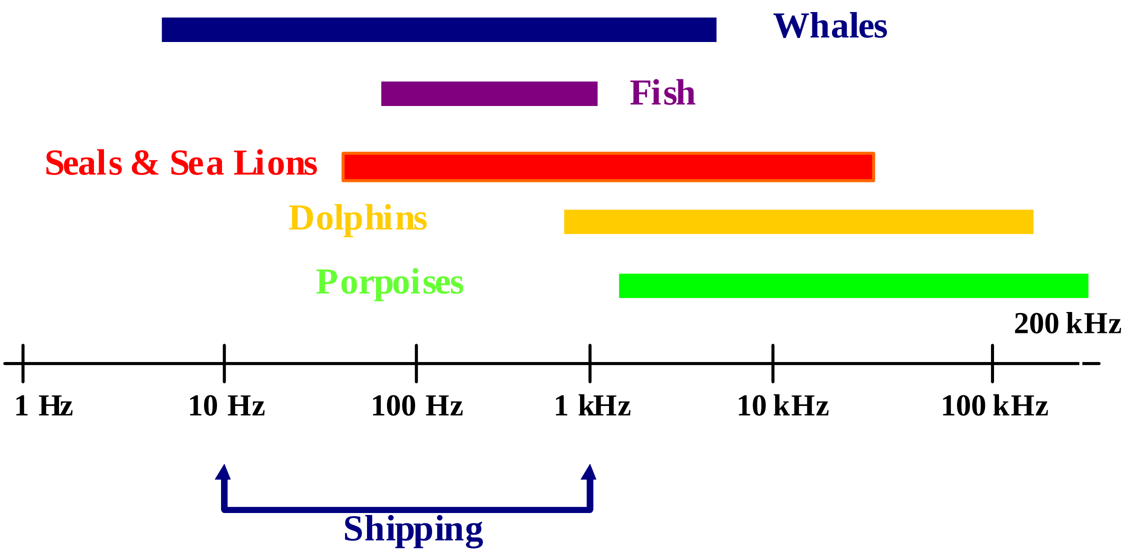

Figure 2. Typical frequency bands of sounds produced by marine mammals and fish compared with the nominal low-frequency sounds associated with commercial shipping.

3.1 BEHAVIOR

7. A considerable limitation in considering the effects of anthropogenic noise on marine mammal behavior is that most studies are observational rather than experimental. Thus, in many conditions, particularly with regards to the effects of noise from large vessels on marine mammal behavior, available data lacks appropriate controls. Given that limitation, much of the recent data on the effects of vessel activities on marine animals indicate that various dolphin and whale species exposed to close physical approaches as well as noise from different vessels may alter motor behaviors (Janik and Thompson, 1996; Nowacek *et al*., 2001; Williams *et al*., 2002; Hastie *et al*., 2003) as well as vocalization characteristics (Lesage *et al*., 1999; Au and Green, 2000; Van Parijs and Corkeron, 2001; Buckstaff, 2004; Foote *et*

al., 2004). These studies generally involve craft considerably smaller than tankers, container and dry bulk ships, and cruise liners, although some of these observations are presumably relevant to these larger sources as well (see Southall, 2005; Wright, in press). Recently, studies have been conducted involving controlled sound exposure of animals fitted with specialized tags for monitoring movements, received sound fields, and, increasingly, physiological parameters. Using such techniques, manatees have been shown to respond to approaching vessels by changing fluke rate, heading, and dive depth (Nowacek *et al*., 2004). Perhaps the most important experiment to date concerning the effects of shipping noise on marine mammal behavior involved the use of acoustic tags and controlled exposure experiments with north Atlantic right whales. Five of six individual whales responded strongly (interrupted dive pattern and swam rapidly to the surface) to the presence of an artificial alarm stimulus (series of constant frequency and frequency modulated tones and sweeps), but ignored playbacks of vessel noise (Nowacek *et al*., 2004b). Finally, measurements using a sophisticated underwater listening array demonstrated that a Cuvier's beaked whale (*Ziphius carvirostris*) reduced the production of sounds associated with foraging in response to a passing cargo ship (Soto et al., 2006).

3.2 INJURY

8. In terms of direct physical injuries to hearing structures in marine mammals, it appears from the available data that quite loud and/or sustained exposures are required to cause even temporary changes in hearing sensitivity (see Southall *et al.*, 2007). Consequently, the likelihood that a single exposure to shipping noise would be sufficient to permanently damage the hearing of marine mammals appears to be remote. However, there are some important considerations and caveats to this conclusion, including the fact that the available information on how noise can damage hearing structures is very limited in terms of the species that have been tested (all in captive settings) and the fact that long-term (chronic) noise exposure has not been sufficiently investigated with regarding to cumulative damage. Thus, there is the potential for permanent damage (injury) to hearing in marine mammals from sustained and/or repeated exposure to shipping noise over long periods, even if the available laboratory data on single exposures suggest that the ears of some species are particularly resilient to noise exposure.

9. There are also a range of physiological effects of noise exposure on marine mammals, which may exist even if an animal that has learned to tolerate sound exposure and continues to feed or interact socially. Long-term noise exposure may induce stress responses in marine mammals, which are thought to be consistent across various species (Wright *et al.*, in press), in a manner similar to humans who live near busy highways or airports (Evans, 2001; see references in Wright *et al.*, in press).

3.3 MASKING

10. The primary concern regarding potential adverse impacts of incidental shipping noise is not related to acute exposures, but rather to the general increase in continuous background ambient noise that may result from concentrations of vessel operations and the potential masking (*i.e.*, simultaneous interference) of marine animals' communication systems. For example, masking can result in disruption of breeding in animals that use sound during mating and reproduction, and of foraging in animals that use sound to detect prey. In addition, noise can mask important acoustic environmental cues that animals use to navigate

and/or sense their surroundings, including sounds that are used to detect predators. The fact that noise masks hearing is well established for human beings (*e.g.*, Fletcher, 1940) and other animals, and it appears to be quite similar as a general phenomenon across many mammalian species (see Fay, 1986; Ward, 1997). Numerous studies have examined the impacts that masking has on a variety of species, and have considered and/or quantified the extent to which low frequency noise from shipping can dramatically reduce communication ranges for marine animals (*e.g.*, Payne and Webb, 1971; Erbe and Farmer, 1998, 2000; Southall *et al.*, 2000, 2007; Erbe 2002; Morisaka *et al.*, 2005, Nowacek *et al.*, 2007). Recent data on blue whales (*Balaenoptera musculus*) and North Atlantic right whales (*Eubalaena glacialis*) indicate that these species may be adjusting their vocalization (frequency and loudness) on both short and long timescales to compensate for masking associated with vessel noise (McDonald *et al.*, 2006; Parks *et al.*, 2007).

11. The greatest potential for masking exists for groups of marine mammals that produce and perceive sounds at the lower frequencies contained in shipping noise such as baleen whales, seals, sea lions, and fish (Fig. 2, above). The potential for masking at higher frequencies (1 – 25 kHz) exists when the vessel is in close proximity to the animal. In these close proximity circumstances other marine mammals, including many toothed cetaceans (beaked whales, sperm whales, dolphins and porpoises) may also experience masking from vessel noise. Because of the logarithmic nature of sound and what is known about hearing systems in mammals, seemingly small changes in background noise levels can result in large reductions of marine animals' communication ranges (see Fig. 3 below).

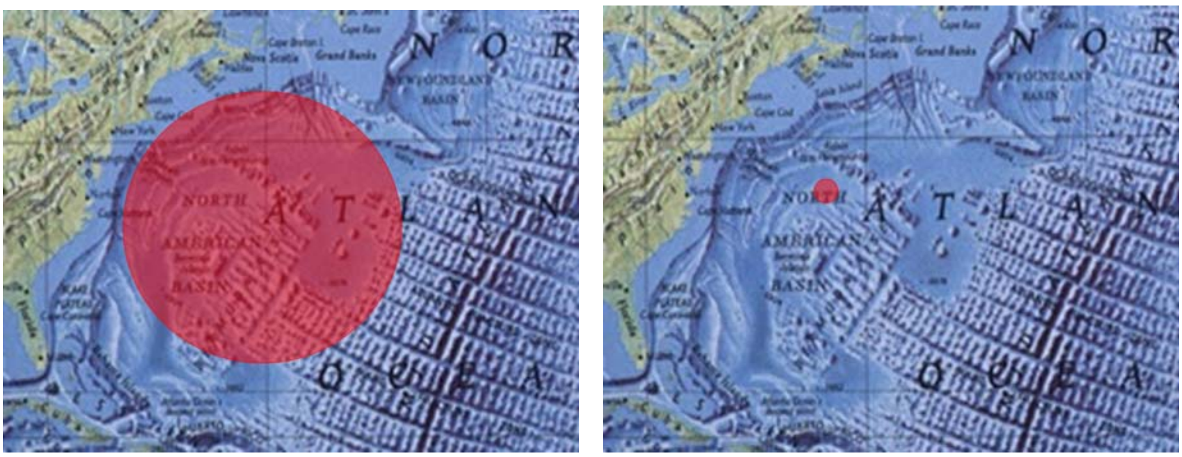

Figure 3. Expected reductions in blue whale communication ranges from the many hundreds of square miles possible prior to the advent of commercial shipping and other industrialized sounds (left) compared to the greatly reduced possible ranges for those same voices today (right). Figure courtesy of Christopher Clark, Cornell University based on historical and recent low frequency ambient noise and whale call measurements.

4. EFFECTS OF SHIPPING NOISE ON FISH

12. Vessel noise, in addition to potentially impacting marine mammals, also overlaps frequencies within the hearing and sound production ranges utilized by many fish species (Amoser *et al.*, 2004). Masking of fish sounds by shipping noise is potentially of greatest concern for species that produce low frequency spawning sounds central to reproductive success. Over 800 species of fishes from 109 families worldwide are known to be soniferous (Kaatz, 2002), although this is likely to be a great underestimate. Of these, over 150 species are found in the northwest Atlantic (Fish and Mowbra, 1970) in areas coincident with high densities of commercial vessel traffic. Soniferous fishes include some of the most important commercial fish species, including many codfishes, drum fishes, grunts, groupers, snappers, jacks, and catfishes. However, little is known of hearing capacities in most fish species, and fish that are not acoustically active may rely heavily on their acoustic awareness within frequency bandwidths dominated by shipping noise. Continuous exposure (30 minutes) to boat noise has been shown to increase cortisol levels (stress response) in fishes (Wysocki *et al*., 2006). Hearing impairment (*i.e.*, temporary threshold shifts [TTS]), associated with long-term, continuous exposure (2 hours), and masked hearing thresholds have also been recorded for fishes exposed to noise from small boats and ferries (Scholik and Yan 2001; Vasconcelos *et al.*, 2007). Furthermore, vessels (*i.e.*, trawlers, ferries, small boats) can also alter behavior in fishes (*e.g.*, induce avoidance, alter swimming speed and direction, and alter schooling behavior), similar to marine mammals (Engås *et al.*, 1995, 1998; Sarà *et al.*, 2007). However, it is often difficult in natural conditions to understand whether behavioral responses relate to vessel's presence, operating conditions and/or their noise.

13. Laboratory experiments have used vessel engine noise to examine noise impacts to fish in controlled settings (Scholik and Yan, 2001, 2002). Fathead minnows experienced temporary threshold shift after the playback of boat engine noise at 142 underwater dB for 2 hours, whereas goldfish exhibited a threshold shift after 10 minutes of exposure to 166-170 underwater dB of white noise. In both studies, the hearing returned to normal over time, but it appears that recovery varies by the frequency and duration of exposure. The amount of hearing loss appears to relate to how loud the noise is compared to the threshold of hearing at that frequency. At frequencies where a fish is more sensitive (i.e., has a lower threshold), TTS produced by constant white noise was greater.

5. EFFECTS OF SHIPPING NOISE ON OTHER SPECIES

14. Very few studies have addressed noise impacts to marine animals other than mammals and fish. However, some marine invertebrates produce sounds, including mussels, sea urchins, white shrimp, spiny and American lobster, and perhaps squid (*e.g.*, Iversen *et al*. 1963). In addition, a broader range of marine invertebrates, including those that do not use sound to communicate with conspecifics, may be impacted by reduced auditory awareness in conditions where shipping noise dominates bandwidths with important abiotic or biotic cues.

6. MITIGATION

15. As noted above, the scientific understanding of exactly whether, when, and how shipping noise causes adverse effects on marine life (particularly regarding behavioural impacts) is currently quite limited. Thus, our appreciation of whether and how to mitigate potential impacts is similarly constrained. However, as also noted above, sufficient data exist to conclude that acoustic communication is vitally important for many marine species, these

varied functions may be negatively impacted by noise exposure (depending on conditions), and ambient noise conditions in some biologically important areas appear to be increasing over time as a function of shipping noise (*e.g.*, NRC 2000; 2003; McDonald *et al.*, 2006; Hatch *et al.*, 2008; U.S.G., 2008; Wright, in press). Given these general observations, reducing the overall noise output from marine vessels, is likely to have demonstrable positive outcomes for acoustic communication and ultimately fitness for certain marine species in certain areas. Unlike persistent forms of pollution (*e.g.*, heavy metals), noise does not linger in the marine environment after it is introduced. Thus, the application of vessel-quieting technologies and/or operational strategies, has the potential to reap immediate environmental benefits for marine life.

16. There is a reasonably long and successful military record of quieting both surface and sub-surface vessels to reduce their acoustic signature and thus vulnerability to detection by enemy passive acoustics. Additionally, commercial applications of ship quieting technology, while more recent and less advanced, are rapidly advancing in such areas as acoustic research vessel design and environmentally-sensitive cruise ships. There are some commonalities in both of these quieting contexts, based purely on the physics of sound and constraints of vessel design. Efforts at reducing noise are most effective when incorporated into the design of ships, though retrofitting of vessels may also be successful to varying degrees. Many of these efforts center on reducing radiated noise as a function of propeller cavitation. This would likely be particularly true for any efforts to quiet large vessels, given the fact that other sources of noise (e.g., machinery or flow noise) will likely be overwhelmed by cavitation noise until considerable quieting treatments were applied (Southall et al., 2004; 2007; Wright, in press). Additionally, operational measures (e.g., routing and speed restrictions) could have positive outcomes in terms of ambient noise reduction in some areas. However, these must be carefully considered in light of potential related impacts arising from modifying traffic schemes (e.g., possibly increasing noise in specific areas, possible impacts on likelihood of vessel strikes). The relative costs and environmental benefits of either technological or operational mitigation measures related to vessel noise output are not well-known. However, the United States has recently submitted a proposal to the Marine Environment Protection Committee of the International Maritime Organization to explicitly consider this international matter and consider a global strategy to address it (U.S.G., 2008)

7. CONCLUSIONS

17. While there is clearly missing information regarding the scope and nature of the environmental impacts associated with incidental noise radiated from marine vessels, there are some simple conclusions that may be drawn. First, sound is clearly of vital biological importance to most, if not all, marine vertebrates and interference with acoustic communication may have various adverse effects. Second, marine ambient noise as a result of vessel activities may be increased on both acute and chronic time scales above natural conditions; in some areas there appears to be an increasing trend associated with increases in commercial shipping. Third, while we are uncertain as to whether we have reached critical points in terms of impacts to populations of marine animals, there is certain to be some level of adverse effect of noise introduction at some point and minimizing or reducing incidental noise would be generally environmentally beneficial. Fourth, there are existing technologies appropriate to both new design and retrofitting of various vessel classes which, as well as

carefully-considered operational measures, could minimize radiated noise; the respective costs and benefits of these measures remain somewhat uncertain.

18. Although the potential effects of noise associated with major transportation projects on land (*e.g.*, airport and highway construction) are routinely considered in planning and construction, noise impacts associated with marine transport projects (*e.g.*, port or dock construction) are rarely assessed comprehensively, if they are assessed at all. When included in environmental impact analyses, results from models used to assess underwater noise impacts for offshore commercial projects vary widely both in the quality and quantity of the information they provide for resource management. Noise impacts associated with changes in the distribution, density and/or composition of shipping traffic within coastal areas (*i.e.*, new routing measures, consolidations of lanes, local changes in operational conditions etc.) should be assessed and taken into consideration by national, regional and/or international bodies whose jurisdictions include environmental impacts associated with maritime transport, port operations and/or coastal waterways. Environmental impact analyses should incorporate empirical data, when possible, regarding local/regional ambient noise profiles and use standardized, open-source and/or peer-reviewed modeling approaches to predict changes in these profiles resulting from proposed changes in shipping.

19. More information is badly needed regarding the near and far field impacts of shipping in different marine environments. These data must take temporal variation into account. To address near-field dynamics, acoustic monitoring designed to capture the before and after impacts of changes in the contemporary distribution, density and/or composition of shipping traffic would assist both the maritime transportation industry and resource managers to more accurately assess potential impacts to species of concern in local areas. Due to the long range transmission capabilities of shipping noise, mitigation must also address shipping noise impacts experienced by populations relatively distant from highly trafficked areas. In this case, only internationally-focused initiatives addressing the number, average sound profiles and operating conditions of ships will effectively address the increasing degradation of acoustic habitat.

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