Executive Summary

The draft Final Report in its original form has received various comments and recommendations from colleagues and program sponsors since its completion on September 11, 2001. Except the very few comments which may have based on some concept inapplicable to the problem considered, most suggestions are accepted and proven to be helpful in eradicating numerous typographical and transcribing errors, as well as clarifying several important statements in the report. Among sponsors' specific recommendations are the additions of an Executive Summary and also statements for each section indicating the need for the subject research towards reducing the environmental impact of the space-launch and other flight operations. Brief statements in small-italics font are thus added at the beginning of most sub-sections, where expositions of analyses and examples detailed in the text may appear to be lengthy and confusing to a non-specialist. Summary statements are not added, however, to each of the five main sections, since the significance of the collective research to marine impact study have already been high-lighted by the head of each main section. Together with an Executive Summary written for the less technically-oriented readers, it is concurred that these brief statements or descriptions may help reaching a wider circle of audience.

Recent analysis by Cheng and Lee has shown that disturbances from acoustic sources produced by interaction of a surface wave train with an incident sonic boom wave will attenuate in deep water at a rate much lower (slower) than those predicted by Sawyers' theory for a flat (non-wavy) ocean, and will accordingly overwhelm the latter at large depth. Experimental and theoretical research on underwater impact from sonic booms are performed to ascertain the significant influence of wavy ocean surface on sonic boom's penetration power, and to determine, through application of the validated model to aircraft and space-launch examples, if predicted signal intensity and characteristics at depth belong to the ranges and types that may allow meaningful impact assessment in marine mammal study.

To ascertain the important difference in underwater sonic boom response between wavy and non-wavy surfaces and the cylindrical-spreading rule underlying deep-water attenuation rate in the Cheng-Lee theory, laboratory experiment was set up to record over-pressure in a small, 3-meter long, water-filled tank during overflight of a supersonic projectile. Microphone driven wave makers were used to generate trains of surface gravity waves; sensor arrays utilizing Kistler piezotrons with electronics and computer-interface support were employed to record wave-form at different depth levels; the laboratory set-up and procedures are detailed in Sec. 4 and Attachment II. A number of obstacles in measurement encountered, including the effect of the muzzle blast, persistent anomalous signals, and the non-uniformity in the surface wave train, were overcome and resolved. In spite of limitations in the laboratory set-up, the significant wavy-surface effects on underwater response to sonic boom, and the cylindrical-spreading rule are well confirmed in accord to the theory; in addition, the extensively collected wave-forms reveals wave-packet behavior and their dependence on surface wave length and surface wave slope, which are again in agreement with the theory.

Having validated the surface-wave interaction model, the method was applied to determine over-pressure wave-forms underwater for generic examples of aircraft supersonic over-flight at different depth levels, Mach numbers, surface wave numbers, and conditions corresponding to surface wave trains propagating in directions oblique to the flight track. The method was similarly applied to an example of rocket space launch, using the Focus-Boom type sea-level signature (recorded during a Titan IV ascent) as an input, assuming two distinctly different surface-wave numbers. These examples, discussed in detail in Sec.3.6-3.8 and 3.10, broadly indicate that infra-sound of frequency 10-40 Hz originated from the transmitted sonic boom can reach down to 50-500 meters below sea surface at sound pressure level of 100-130 dB (re 1 μPa), corresponding to 0.002-0.209 pound per square foot depending on specific depth levels. Infrasound at these sound pressure levels is common in records of baleen whale calls and can be expected to be audible or perceived by these marine mammals. Another noticeable feature of the predicted waveforms is the frequency down-shift in the tonal pitch that reduces towards the end of the signal, which is also commonly found with the individual pulse in call records. Unlike the repetitive short pulses in the records, however, the duration of the underwater wave packet produced by a sonic boom will be rather long, according to results of the study. At one km below the surface, or deeper, this duration can be 3-5 seconds for an aircraft supersonic flight and will be 20-40 seconds in the case of a rocket space launch. (The 20-40 seconds in the latter case presents an area underwater affected by the sound pulse extending over a distance 7-14 km horizontally.) Understanding submarine animals' response to infrasound of this nature must therefore be central to the next phase of studies on impact to marine mammals.

Furthermore, results at the 50 m depth examined indicate that the wavy-surface interaction effects on amplitude and wave-form may not be altogether ignored even at locations not far from the surface; therefore, analysis of wave field near the surface may yield vital data to help assessing potential harassment at the physiological level to a broader class of marine animals. Presence of the sea floor must be an important consideration in analyses for the shallow coastal water where the sonic boom impact is expected to be the most severe. A shallow-water model with a flat (non-wavy) surface under an incident N-wave is adopted to investigate its response to sonic booms; cases with rigid and elastic bottom surfaces are both analyzed. Whereas, in the presence of a rigid bottom, the over-pressure is expected to increase by an amount as large as the surface value in the case of a very shallow depth, calculations show that the sea-floor effect will remain small until the channel depth becomes as small as a half of the sea-level sonic-boom signature length. For a sea-floor with sediment properties resulting in a very low (slow) compressive-wave speed, examples studied confirm the existence of sonic-boom excited sediment-boundary waves.

Two unresolved discrepancies remain in current prediction methods of sonic booms above the water; they will significantly affect the reliability of underwater impact analyses. The first is the failure in predicting the surface signatures of Focus-Boom type from space-launch operations (except for the peak over-pressure). Extensive studies with current sonic boom codes as well as a CFD Euler program confirm the culprit to be the inadequate provision of near-field data corresponding to a lack of accurate description of the rocket plume shape. Resolving the latter is thus one of the specific tasks in future study. The second discrepancy is concerned with the propagation code break-down when and where a "super-boom" occurs. The latter can occur near the ground or sea level where the ambient sound speed becomes the same as, and higher than, the horizontal propagation speed of the incident sonic boom wave field. This type of wave field has been known to yield wave intensity much stronger than the typical sonic-boom strength elsewhere, and is thus called the Super-Boom. A CFD program based on the nonlinear Tricomi equation governing this type of wave problem was used to test its adequacy as a program amendment to the standard method and to study super-boom's wave intensification power. Applications to examples with incident waves of the Focus-Boom (Titan IV) type and the N-wave type confirm super-boom's intensification power for both types, and reveal also the feasibility for a new, linear approach to the problem as well as important features unrecognized by standard propagation methods.