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Controlling Underwater Noise from Offshore Gravel Islands During Production Activities

MMS Noise Project #538

Jesse Spence

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Prepared for:
Joseph Mullin
Minerals Management Service
Technology Assessment and Research Branch
381 Elden Street, Mail Stop 4021
Herndon, VA 20170-4817

Prepared by:
NOISE CONTROL ENGINEERING, Inc.
799 Middlesex Turnpike
Billerica, MA 01821
978-670-5339
978-667-7047 (fax)
nonoise@noise-control.com
http://www.noise-control.com

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Disclaimer

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NCE would like to thank BP and Greeneridge Sciences Inc. for voluntarily providing NCE with measured underwater noise data near Northstar Island. NCE would like to acknowledge BP for providing the funding to Greeneridge for the collection of this data. NCE would also like to thank everyone at Greeneridge for their assistance and comments regarding on the underwater data, and notes on the general conditions at Northstar.

0.0 EXECUTIVE SUMMARY

Noise Control Engineering (NCE) has performed a study investigating methods for reducing the underwater radiated noise resulting from oil and gas production operations on gravel islands. The purpose of this study is to develop noise control treatments that can reduce the underwater radiated noise from future gravel islands as compared with current designs. This study was performed for and funded by the US Minerals Management Service (MMS). This study was carried out with the cooperation and assistance of BP and Greeneridge Sciences, Inc.

Northstar Island, operated by BP Exploration (Alaska) Inc. (BP), was used as the primary case study to uncover the pertinent mechanisms of underwater noise radiation from gravel islands. Airborne noise and structural vibration data were collected by NCE on and around machinery items located on Northstar that are rated at 50 HP and higher. In addition, NCE was provided with underwater noise data measured at 400m North of Northstar Island during a time period shortly preceding NCE's site visit (data measured by Greeneridge Sciences, Inc.). The airborne noise, vibration, and underwater noise data were studied in an effort to identify primary sources of underwater radiated noise on Northstar and the dominant noise paths. This information was used to make general recommendations for the construction of future gravel islands, with the specific intention of reducing the underwater radiated noise generated during production activities relative to those measured at Northstar. This study does not include noise created by non-island sources such as boats that may be operating near the island during production activities. In addition, noise resulting from construction and drilling activities have been specifically excluded from this study. It is noted that some of these sources have been shown to create higher underwater noise levels than those seen during gravel island "production only" activities.

Analysis of the available underwater noise data showed that virtually all detectable underwater noise caused by man-made sources occurs at frequencies below 250 Hz. Tones at 30 and 60 Hz were present in all analyzed data sets, indicating that they are a result of machinery that is virtually always running (in some form) such as power generation equipment. Many other tones were detectable in the various underwater noise measurements; however, all other tones were seemingly intermittent; i.e. they were seen in some underwater measurements and not in others. The sources of these tones were most likely caused by intermittent machinery operating on Northstar and / or machinery operating under varying loads. Other explanations related to sea conditions such as varying background levels and shallow water propagation effects may also be responsible for some of the variation seen in the underwater measurements.

In studying the various potential noise paths from machinery items on Northstar to the surrounding water, it was found that two are dominant. The first is the Primary Structureborne Noise path, where noise is radiated into the water from the gravel itself due to vibrations created by machinery excitation. It was found that this is a viable path largely due to the fact that the gravel is compacted and acts as a solid, at least at low frequencies (i.e. below 250 Hz). Sources on Northstar identified as being responsible for noise radiated through this path include the SOLAR Turbines, HP and LP Compressors, Water Injection Pump Skid, Air Compressors (2nd Level SPM), AHUs, and the Flare Blower, with possible minor contributions from the Oil Shipping Pumps and Water Booster Pumps. These sources are all rated at 800 HP and above, with the exception of the Flare Blower. Other sources located on the pad or not measured by NCE may also create detectable underwater radiated noise.

The second dominant path is the direct radiation from sea connected systems. It is noted that the actual influence of this path could not be determined from the available data; however, this path certainly holds the potential for significant underwater noise and should be considered when designing future gravel islands. Other noise paths were found not to be feasible or to have secondary influences, at best.

In the design of future gravel islands, source treatments for noise transmitted over the Primary Structureborne Noise path include providing additional module structural stiffness at and near machinery foundations (relative to what is seen on Northstar) and resiliently mounting equipment with high-to-medium power ratings (i.e. above 500 HP). It has been estimated that the use of these treatments could reduce noise levels from 5-30 dB, depending on the exact design and configuration of the modules. The larger of these attenuation values is expected at frequencies near 60 Hz and above. In addition, all equipment items should be properly mounted within a module. While tone detectability is based on the background noise levels at any given time, implementation of these treatments should help to bring the underwater radiated noise levels closer to the background in the Beaufort Sea, and possibly below background in some cases.

Treatments for sea connected pumps include the use of cofferdams for pump intake and outlet connections. It is shown that a cofferdam can be designed to act as an acoustic muffler, providing significant transmission losses at low frequencies (on the order of 20-30 dB). Flexible connections and pulsation dampers can be used to further reduce noise from these sources; however, the performance of these treatments will depend on the specific usage and setup. In addition, all pumps should be located inside of modules; the use of submerged pumps on the perimeter of the gravel island should be avoided. While it is not possible to provide estimations of underwater noise reduction from these systems relative to Northstar, the treatment recommendations outlined in this report can be used to create systems with low underwater radiated noise.

Lastly, it has been found that the noise radiated by the pipeline itself may cause detectable underwater noise levels at some distances. However, this finding is fairly uncertain as the transmission loss of sound through the sea floor is not known (the pipeline is located approximately 9 feet below the sea floor). It is recommended that noise transmission from this source/path be investigated further. As a precautionary measure, flex connections and/or pulsation dampers located at any pumps directly connected to the pipeline can be used to reduce noise from this source.

1.0 INTRODUCTION

Noise Control Engineering (NCE) has been contracted by the Minerals Management Service (MMS) to study methods for reducing underwater noise from gravel islands during production activities. Underwater noise in the Beaufort Sea has been a topic of discussion among many groups and individuals, including local Eskimo communities that engage in subsistence hunting of the Bowhead whale. One particular concern for underwater noise generation is that created by gravel islands where oil and gas production activities take place. It is important to note that this report does not in any way assess or make assumptions regarding the impacts of noise from any man-made structure on the Bowhead whale or any other mammal.

The goal of this study is to recommend noise control treatments to help reduce the underwater radiated noise from future gravel islands relative to existing designs[1]. In performing this task, NCE has attempted to identify specific sources that exist on gravel islands that will create detectable underwater noise and to describe the noise paths from these sources to the water. Using this information, specific noise control recommendations can be made for each source and noise path. To study the mechanisms of noise generation from gravel islands, airborne noise, structural vibration, and underwater noise measurements were collected on and near Northstar, a gravel island located approximately 9 km due North of Pt. Storkerson, AK in the Beaufort Sea, operated by BP Exploration (Alaska) Inc. (BP). Northstar was used as the primary source of information for this study since no models currently exist for underwater noise transmission from gravel islands. The selection of Northstar Island for use in this study was made by MMS.

This report focuses on noise created during production activities, i.e. the act of continuous extraction or injection of oil, gas, or other products from the ground, including full or partial separation of these products. This may include re-injection of gas or water for disposal, maintaining pressure or storage. It is noted that this report does not discuss noise created on gravel islands during drilling operations, island construction or repair, or noise created by boats, helicopters, or any other means of transportation to and from the island. While some of these sources have been shown to create noise levels similar to or significantly higher than those created by Northstar alone during production activities [1, 2], investigations into controlling noise from these sources are outside the scope of this project. It is also noted that drilling and construction (i.e. maintenance) activities may normally occur during production of oil and gas; however, these activities are outside of the scope of this project.

This report is divided into eight sections. Section 2 provides background information on Northstar and outlines underwater noise data that existed prior to the efforts described herein. Section 3 describes the general approach taken by NCE to identify sources of noise and develop appropriate noise control techniques for a gravel island, as well as descriptions of the methods used for collecting airborne noise, vibration and underwater

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[1] While there are very few gravel islands currently located in the Beaufort Sea, it is the belief of the Minerals Management Service that more gravel islands will be built in the future.

noise data. Section 4 provides an analysis of the underwater noise data taken in 2005 and presents conclusions about the overall characteristics of the underwater measurements. Section 5 discusses the various potential noise paths and the probability of each path playing a significant role on Northstar and other gravel islands. Section 6 discusses the efforts to identify major noise sources, and Section 7 describes methods for controlling noise from those sources. Section 8 gives a summary and final conclusions.

In addition, Appendix A provides guidance for reducing the airborne noise levels in various locations on Northstar. This discussion can also be used for noise considerations on future gravel islands. Appendix B provides design guidance for implementation of flexible connections on equipment.

2.0 BACKGROUND

2.1 NORTHSTAR OVERVIEW

The following is a general description of Northstar and its construction. For the purposes of this study, Northstar is considered to be a typical gravel island, and it is assumed that future gravel islands will be based on its design[2].

2.1.1 Modules and Equipment

Northstar Island itself is made up of approximately 1.6 million metric tons of sand and gravel and is located in an area with an approximate water depth of 12 meters. The island's perimeter is surrounded by a "sheet pile wall" which is used to help prevent erosion and provides protection from local wildlife and weather. The dimensions of the island inside the wall are approximately 603' x 421'. The majority of production and drilling equipment are located inside the wall, and the gravel inside of the wall is approximately 16 feet above sea level. Approximately 75 feet of gravel exists between the wall and the water, and there is a gradual slope down to the water outside of the wall.

The majority of equipment items on Northstar are housed inside large equipment modules. Separate living, recreation, and storage spaces also exist on the island, and are similar in construction to the equipment modules. It is important to note that the gravel making up the island is compacted, and much of it is frozen year round[3]. The island is constructed in such a way that this compacted/frozen gravel can support the very large loads of the equipment modules, which typically have weights on the order of thousands of tons.

There are four modules that contain most of the equipment used during production: South Process Module (SPM), North Process Module (NPM), Pump House, and Compressor Module. Some additional equipment is located in the Warehouse, Utility Module, and on the "pad" (i.e. outside of any module). Most of these modules are several stories tall, and contain equipment of various kinds on all levels. Some equipment items that operate during production activities are used for habitability related services.

The modules are all designed to be supported by I-beam pillars, as seen in Figures 2.1a and b. The bottom of each pillar is welded to a 1.75" thick plate. This plate rests on a separate 1.75" thick steel plate that is connected to a concrete "footer". Structures surround this friction connection that limit slippage in order to avoid catastrophic movement. The tops of the concrete footers are flush with the top of the gravel surface.

The primary structures making up the modules themselves are steel beams. This can be seen in Figures 2.2a and b, which are pictures of the Compressor and South Process Modules. The beams are of various sizes and shapes, including W36x230 I-beams, C12x30 C-channels, 12"x12" Rectangular tubing, and smaller sized stiffeners. The

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[2] Note that this does not imply that specific equipment items (make, model, RPM, etc.) or detailed module layouts found on Northstar will be copied in the design future gravel islands. Details on the pertinent similarities are given in Section 7.

[3] Frozen gravel refers to the fact that the water in the spaces between gravel (or sand) particles is frozen.

general spacing between the large I-beams that make up each deck is typically on the order of 18'.

Some areas of the modules are covered with steel plating. This includes some outside surfaces (as seen in Figures 2.2 a and b) and some floor surfaces. Floor surfaces without plating use a steel grating for foot traffic. This is typical of the upper levels of the process modules and around the various turbines. The undersides of the modules are insulated in most locations.

Figure 2.1a: Module Pillar Base

Figure 2.1b: Module Pillar

Figure 2.2a: Compressor Module

Figure 2.2b: South Process Module

Some stationary equipment items such as the Load Banks and Refrigeration Plant are located on the pad at the perimeter of the island (inside the sheet pile wall, outside of any module). These items are typically raised above the gravel on wood supporting structures. Figure 2.3 shows the Load Banks on their wood supports. The supports for the Refrigeration Plant are smaller palettes than those used for the Load Banks.

Power is currently provided to the island by three SOLAR power turbines, two of which are generally running at any given time[4]. This has been the case for several years. Prior to 2002 power was provided by several diesel generators. This study focuses on the current arrangement where power turbines provide island power.

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[4] Data has been provided by BP that indicates there are times where only one SOLAR turbine is operating. It is plausible to assume that there is a time when all three SOLAR turbines run simultaneously.

Figure 2.3: Load Bank and Supports

2.1.2 Pipelines and Sea Connected Systems

Several direct connections to the sea exist for some Northstar equipment items. Oil and gas pipelines run from Northstar to the shore, and pumps draw water from and return water to the sea. Figures 2.4 and 2.5 are diagrams of how these systems are typically arranged. It is seen that, by design, the pipeline has no direct contact the sea. For the majority of its length the pipeline is buried 9 feet below the seabed. Both gas and oil pipelines run between the island and the shore. All pipelines are steel, 10.75” in diameter, 0.594” thick.

The seawater intake cofferdam seen in Figure 2.4 is used by systems such as the Utility Water Pump located in the Warehouse. It is seen that there is a direct connection to the sea through a 36” pipe. In addition, sewage and potable water piping are directly connected to the sea as indicated in Figure 2.5.

Lastly, it is noted that the Alternate Seawater Intake Pump is submerged in the water at the edge of Northstar Island. This is the only equipment item on Northstar that is located outside of the sheet pile wall (as indicated by the information available to NCE).

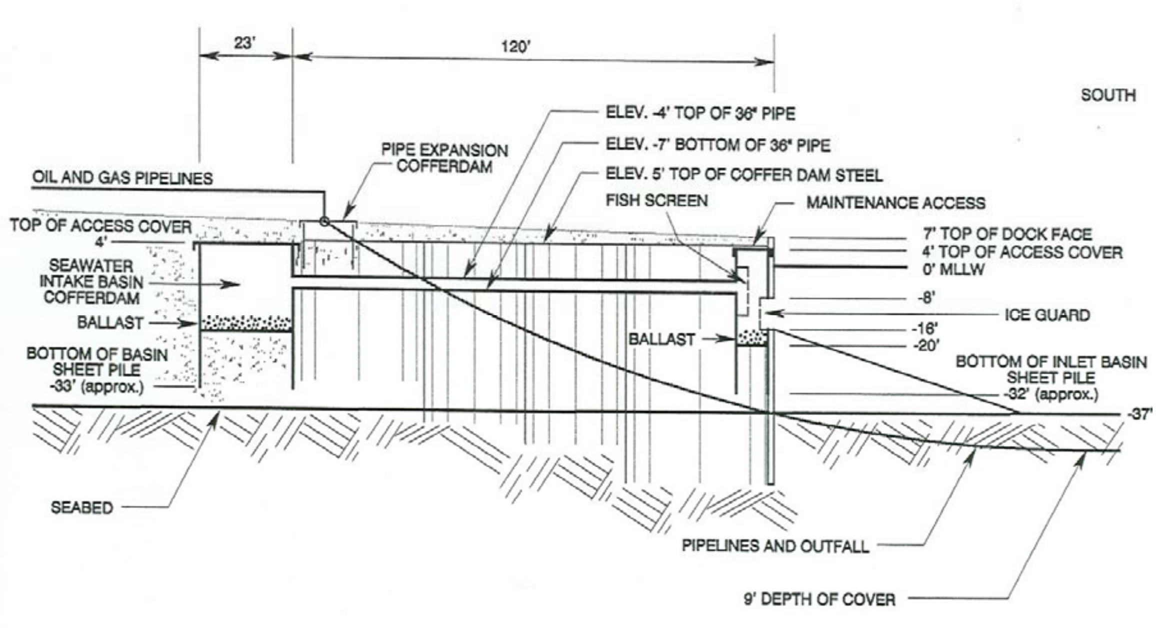

Figure 2.4: Pipeline and Seawater Intake Connections to the Sea

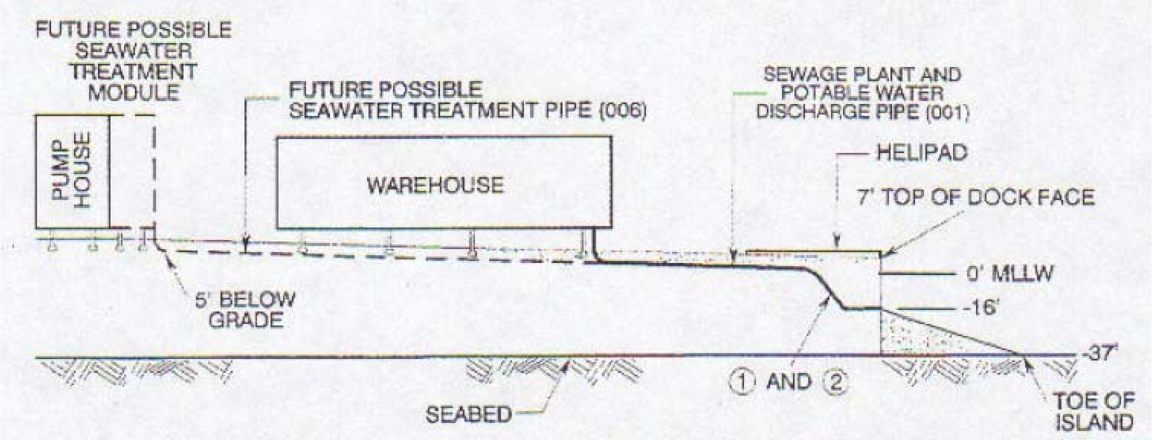

Figure 2.5: Sewage and Potable Water Discharge Connections to the Sea

2.2 EXISTING UNDERWATER NOISE DATA

Only a handful of published studies exist that look at underwater radiated noise created by gravel island drilling and/or production operations, and essentially all of those have been created by Greeneridge Sciences, Inc (with LGL Ltd., Environmental Research Associates / LGL Alaska Research Associates, Inc.). Of those, two are of particular interest with regards to the current study of underwater noise from gravel islands during production activities: References [2, 3]. These reports delve into the measurement of underwater noise from various sources related to Northstar Island, including not only the island itself but also support vessels and aircraft.

Underwater noise data is provided in many forms in these reports; however, there are only a few graphs of particular importance to this study. Figure 4.7 from Reference [2] shows measured underwater spectrum levels during "the quietest 1-minute periods in 2001 and 2002," taken from a cabled hydrophone located approximately 430 meters North of the island[5]. Figure 5 from Reference [3] shows underwater spectrum levels taken on February 28 and March 1, 2002 during production and drilling at a location 2 km north of the island, measured on consecutive days. Note that these measurements were performed when the ocean had an ice cover. Hydrophones were inserted into the water through a hole drilled in the ice. These measurements have been reprinted as Figures 2.6 and 2.7 of this report using the original data provided by Greeneridge.

Figure 4.9 of Reference [2] also shows measured underwater noise spectrum levels over six days in August – September 2002, presented in percentiles (i.e. broken out into amount of time the noise is at or below a given level). This data was taken via a cabled hydrophone and has been filtered to specifically exclude times when boats were known to be in the area. The "minimum" levels presented in this graph can be assumed to be a result of any noise generating items that were always running during this time period, plus background noise. The other percentiles seen in this graph are of less use for this study because the actual sound events are not well defined – i.e. it is not clear if the recorded levels are a result of production, drilling, repairs etc. This data has been reprinted as Figure 2.8 in this report[6].

These graphs comprise the majority of published underwater noise spectrum data measured near Northstar (or any gravel island) during production operations. It should be noted that Figure 4.8 in Reference [2] also shows underwater spectrum levels measured during production operations in 2002. However, it has recently been confirmed that these data were contaminated by sources other than Northstar and therefore are not reliable for the purposes of this report[7].

Figure 2 of Reference [5] shows several measurements made in February 1997 of underwater levels 2-5 km from activities on Tern Island, a gravel island in the Beaufort Sea. The measurements shown in this figure were taken far enough from the island (where noise was being generated) to effectively show the background noise levels in the area (i.e. no sounds were detectable from Tern Island in these data). This data is reprinted as Figure 2.9 in this report. The purpose of showing Figure 2.9 here is to give an idea of the possible background noise levels in the Beaufort Sea area, providing an indication of the lowest measurable noise levels.

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[5] It is noted that during the 2001 measurement, power was provided to the island via diesel generators. In 2002, power was provided via SOLAR turbine generators.

[6] Note the rolloff in Figures 2.6 and 2.8 above 900 Hz is due to intentional filtering.

[7] The source of contamination was found to be an inverter on the support boat where the hydrophones and recording equipment were located [4].

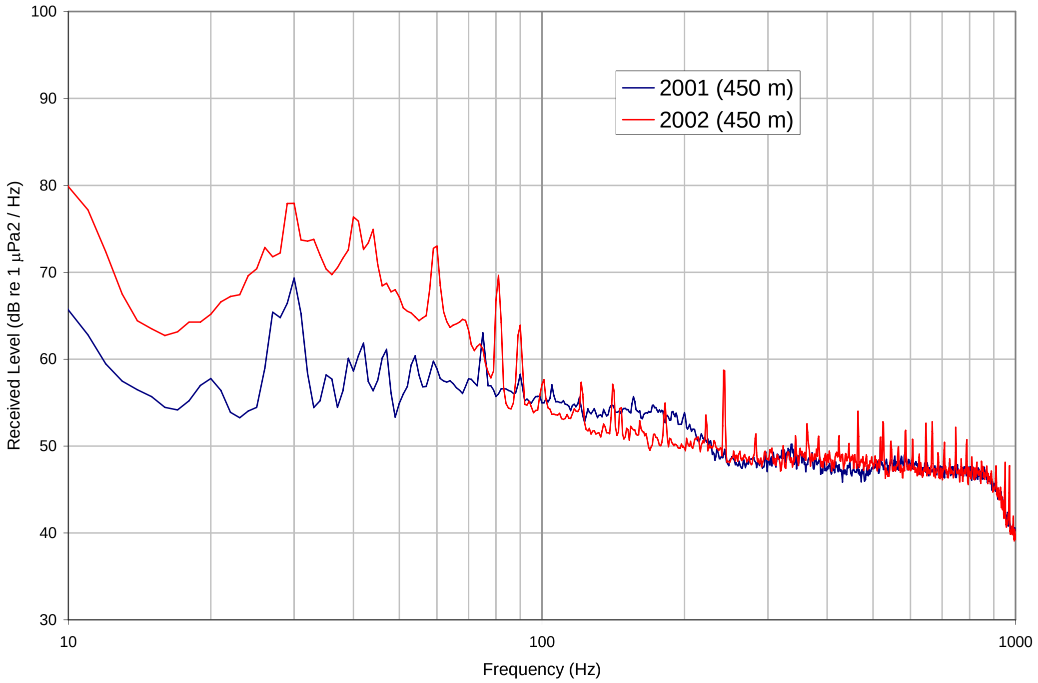

Figure 2.6: Underwater Noise Measurement 430m North of Northstar Island in Fall 2001 and 2002 during "quiet" period. Reprinted from [2]

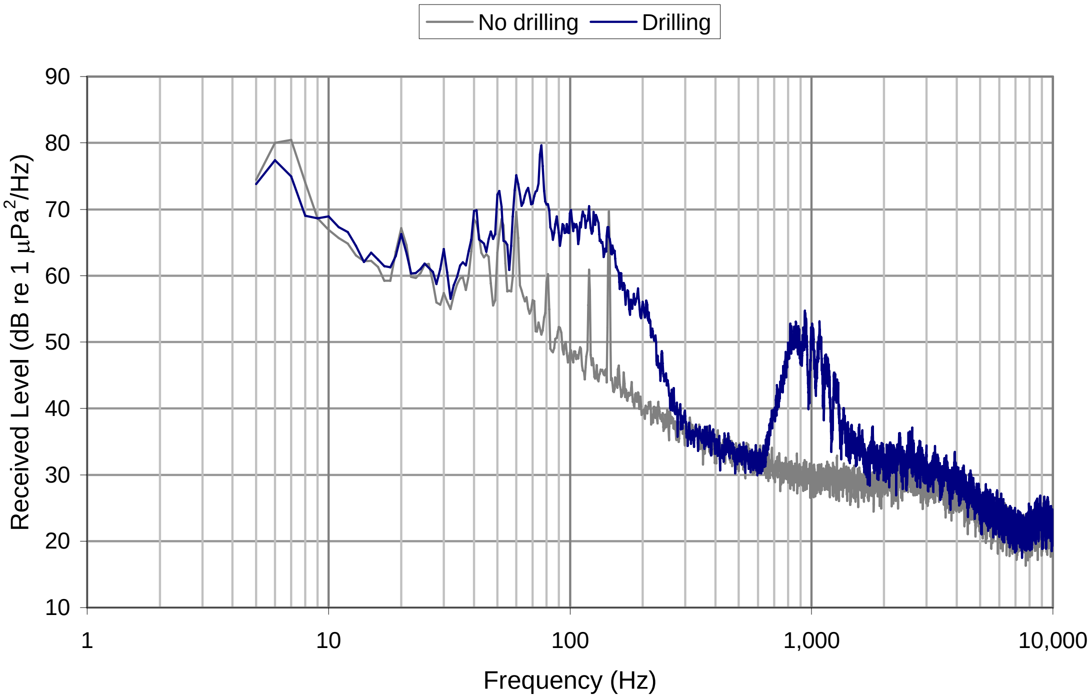

Figure 2.7: Under-ice Noise Measurement 2 km North of Northstar Island, Measured Winter 2002. Reprinted from [3].

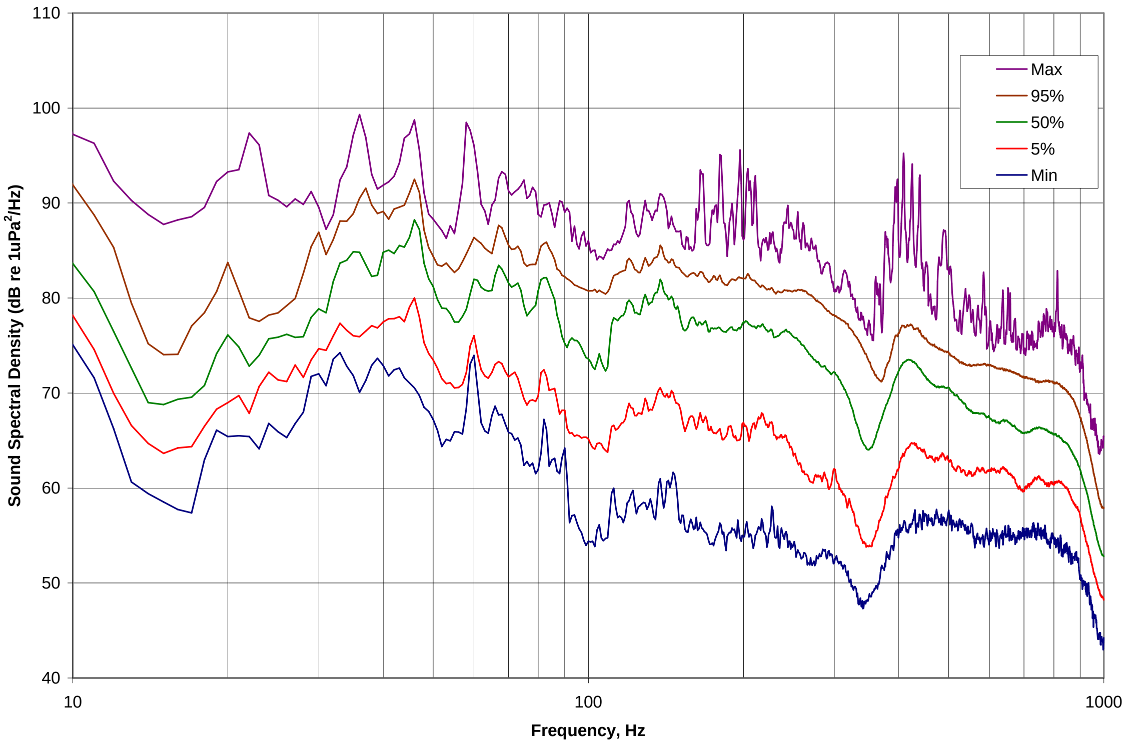

Figure 2.8: Underwater Noise Measurements 420 m North of Northstar Island, Percentile Levels over Six Days in Fall 2002. Boat Noise Excluded. Reprinted from [2].

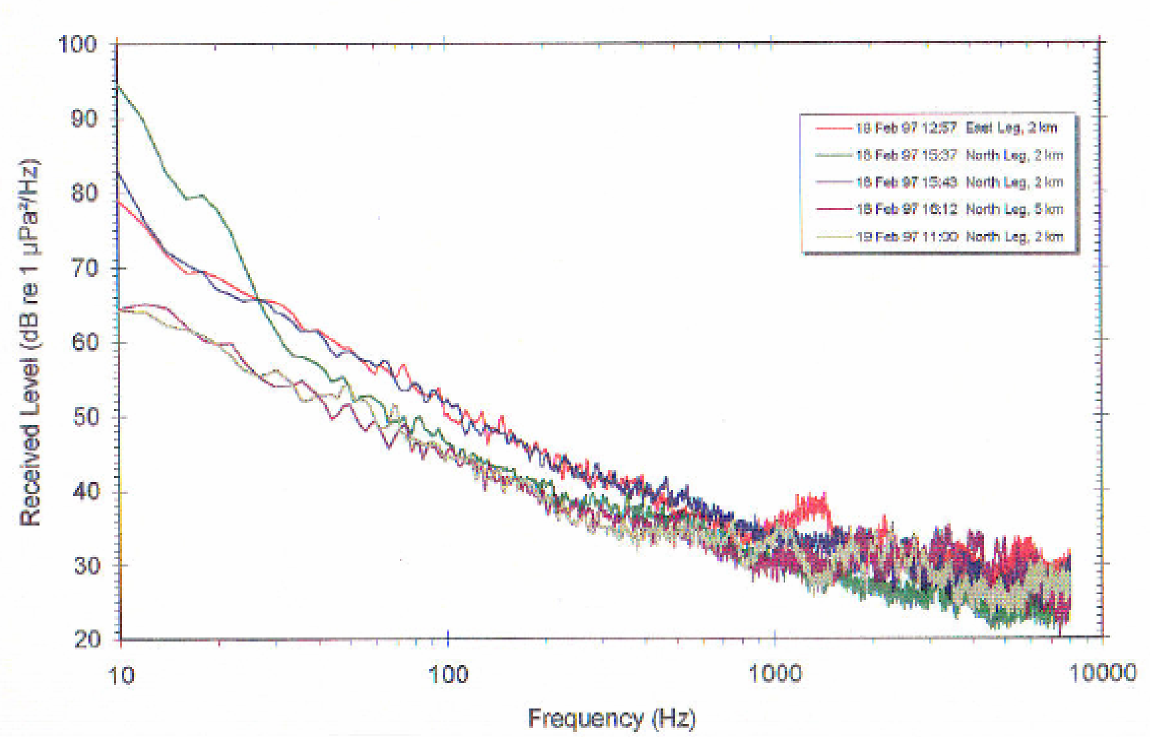

Figure 2.9: Under-ice Noise Measurement Showing Approximate Background Levels in Beaufort Sea. Reprinted from [5].

2.3 ANALYSIS OF EXISTING DATA

2.3.1 Background Noise vs. Northstar Noise

By comparing the levels in Figure 2.9 to those seen in Figures 2.6 through 2.8, it is clear that much of the presented data is essentially the background noise of the Beaufort Sea (i.e. not attributable to Northstar). Figure 2.10 compares the "No Drilling" underwater noise data in Figure 2.7 to the estimated background level derived from Figure 2.9[8]. A similar curve can be constructed for the data in Figure 2.6, however it appears that the background levels are higher than those shown in Figure 2.9. It is important to note that the background underwater level will be strongly dependent on specific sea state conditions [6, 7]. The measurements in Figure 2.6 were taken in open water conditions (compared with the ice covered measurements of Figure 2.9), and are therefore susceptible to higher levels of background noise.

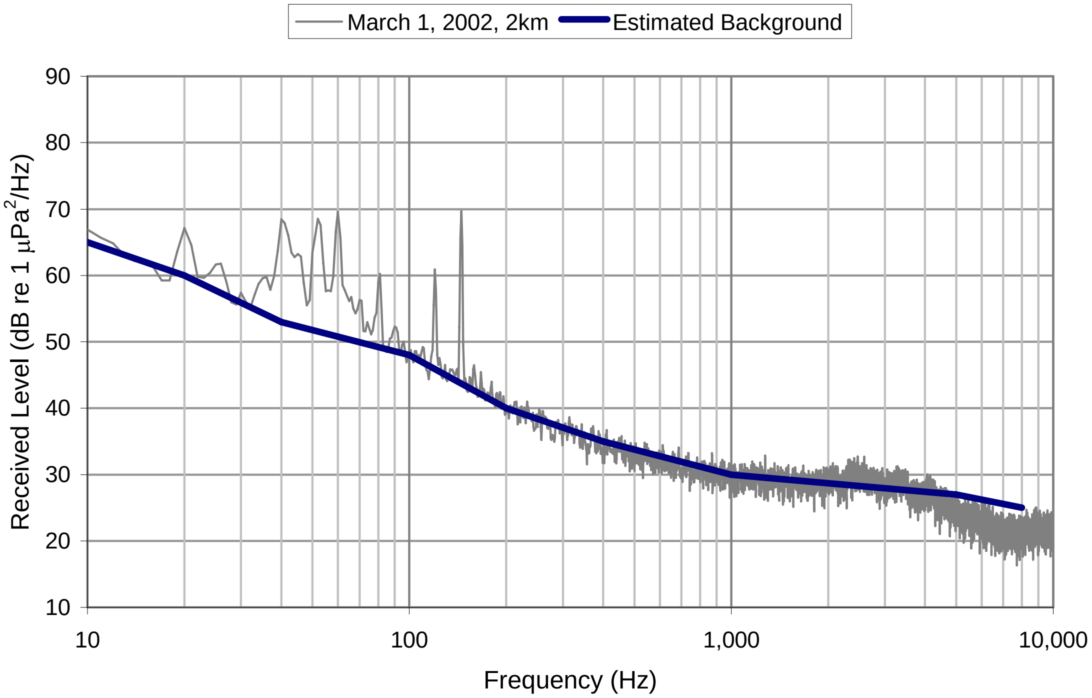

Figure 2.10: Comparison of Measured Underwater Noise Levels to Estimated Background Levels for 2 km Measured Data

Inspection of Figures 2.6 and 2.7 with reference to the probable background levels indicated in Figure 2.10 shows that there is very little noise above background for most of the frequency range, and much of this noise is focused below 200 Hz[9].

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[8] In creating the "Estimated Background" level of Figure 2.10, the average of all curves in Figure 2.9 above 100 Hz was used. Below this frequency, the lowest levels were used, as it is clear that the background is low for the Figure 2.7 measurement at these frequencies. It is also clear from Figure 2.9 that low frequency background noise levels have the largest variability as compared with high frequencies.

[9] Some tones are seen above 200 Hz in the 2002 data of Figure 2.6 where they are not seen in Figure 2.10 / 2.7. The exact reason for this is not known; however, based on additional information seen in Section 4, it is presumed that sources other than the Northstar may account for the additional high frequency information in Figure 2.6.

The data also shows that the noise levels above background are typically sharp spikes, indicating the presence of individual tones. It is typical for machinery such as diesel engines, turbines, pumps, compressors, etc, to produce individual tones both as airborne noise and structural vibration, particularly in the low frequency region. Measured spectrum levels of foot vibration and airborne noise consistently show this fact (See Sections 5 and 6, and measured data spreadsheets accompanying this report). In addition, several of the tones seen in the underwater noise data are identical to those commonly seen in power generation noise and vibration (i.e. 30, 60 and 90 Hz). This is a strong indicator that the underwater noise measured during Northstar production activities is a result of its operating machinery.

Furthermore, it is possible to infer that these tones are coming from Northstar Island when the following factors are considered:

1. Noise from other sources (such as boats) is often significantly higher than the levels seen in Figures 2.1 and 2.5. In addition, the fact that several tones exist in the "minimum" levels seen in Figure 2.8 indicates that these noises are ever present, a phenomenon not typical of boat related activities.

2. Underwater noise readings taken at various distances (during approximately the same time period) indicate that overall and third octave band levels decrease with increasing distance from Northstar [2, 3]. This is a strong indicator that Northstar Island is in fact the source of these tones as sound spreads and decreases as it moves further from its source[10].

In summary, the underwater noise data presented here indicates that there are some detectable tones at various distances from Northstar, generally at frequencies below 200 Hz. These tones are most likely a result of operating machinery on Northstar Island. However, identification of the specific machinery items causing the recorded levels cannot be determined from the underwater data alone.

2.3.2 Frequency and Amplitude Analysis

2.3.2.1 Tonal Frequencies

Figure 2.11 shows a summary of the spectra measured in 2002 when power was provided to Northstar by the SOLAR generators; it is a combination of Figures 2.6, 2.7, and the "minimum" values in Figure 2.8. It is important to note that the varying broadband levels are likely due to differing sea states and/or recording conditions.

By comparing the data in this figure, the tones that are seen can be grouped into two categories:

- Tones that are present in all measurements.

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[10] Rates of spreading indicated in [2, 3] often vary depending on different factors. However, some decrease of sound with increasing distance is almost always observed, indicating the Northstar is the source of these sounds.

- Tones that are present in some measurements and not in others or seem to vary slightly in frequency.

Note that these classifications are independent of actual tone amplitude.

Examples of tones that are clearly present in all data are at 30, 60, and 90 Hz. It is fair to say that these tones are a result of machinery items that were always or almost always operating at a constant speed, such as from power generation equipment. Tones that have similar but not identical frequencies in all graphs are those tones near 33, 40, 44, 70, 81, 120, and 145 Hz. This shift in frequency can be the result of several things, including machinery that operates at different RPMs, varying load conditions, or simply one equipment item was operating in one data set and a different one was operating in another.

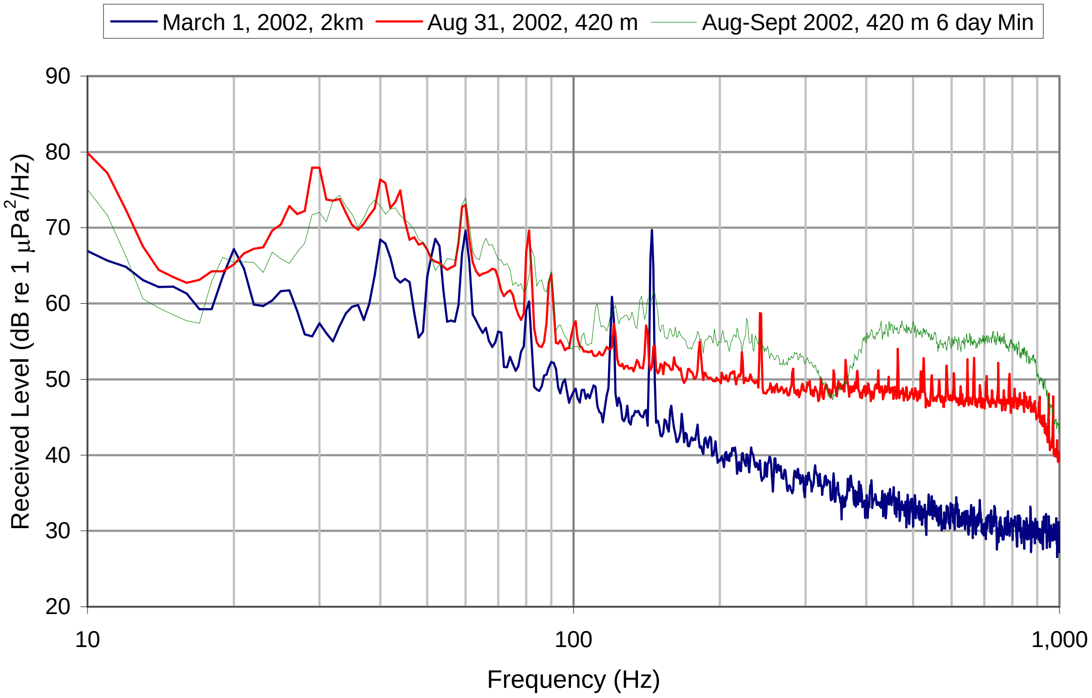

Figure 2.11: Comparison of Measured Underwater Noise Level Spectra for 2002

Lastly, certain tones are seen in some curves and are completely missing in others. For example, there is a strong tone at 52 Hz in the March 1, 2002 data that is missing from the other data sets. Similarly, the tone at 101 Hz in the March 1st and August 31st data is absent in the 6 day minimum data, the 112 Hz tone in the March 1st and 6 day minimum is not present in the August 31st data, and several tones above 200 Hz in the August 31st data do not appear in either of the other two curves.

Possible explanations for these differences are:

- Varying background levels – i.e. the background level is too high in one curve as compared to the next to be able to see a particular tone.
- Differences in distance between the measurements result in spreading losses that make some tones undetectable.
- Varying sea conditions create different sound propagation mechanisms, such as ice-covered seas vs. open seas.
- The presence or lack of tones may be due to spatial and temporal variations associated with propagation in shallow water. Normal mode propagation and temperature gradients may exist in the water surrounding Northstar that make it generally difficult to consistently measure the amplitude of radiated noise [10].
- Some equipment is operated intermittently or at varying loads.
- Some noise sources are not related to Northstar Island.

2.3.2.2 Amplitude Analysis

In analyzing Figure 2.11 it is possible to compare the amplitudes of each tone to attempt to glean additional information regarding the nature of the noise. However, this extraction can be misleading, particularly based on the available data curves. For example, it is possible to attempt to look at the sound from one position to another to get a sense of the appropriate spreading losses. One issue with combining this approach with the data sets in Figure 2.11 is that the measurements at different locations occurred at times separated by many months. To attempt to overcome this, it would make sense to use those frequencies that appear to be due to power generation, i.e. 30, 60, and 90 Hz, as it is more likely that the source levels (i.e. the noise and/or vibration levels of the SOLAR turbines) will remain more or less constant through time.

If the levels at these three frequencies are compared between the March 1st and Aug 31st measurements (2 km and 420 m), it is seen that the differences in levels are 21, 4, and 12 dB, respectively. This is quite a large range, and the variation can be due to anything from different machinery operating conditions to varying shallow water propagation effects. As a result of this data alone, little can be said regarding the spreading losses in the region of Northstar Island.

In general, noise propagation underwater is complex, with many factors being superimposed to create the actual sound field, especially at low frequencies where shallow water is known to have high temporal and spatial variability [8, 10]. Attempts have been made in [2, 3, 8] and elsewhere to characterize the spreading of sound from various sources in the Beaufort Sea, which have resulted in a wide range of spreading loss factors. Because of these issues, it is not practical to attempt to backwards calculate the underwater source level at Northstar from the measured far field underwater sound pressure levels[11]. The implication for the purposes of this report is to say that, to a large extent, the absolute amplitudes of the noise and vibration tones created by machinery on

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[11] The practical application of this information would be to say that machine X produces a certain level in the water at the Northstar due to some path, and as a result of a defined spreading loss calculation would then produce the underwater level seen at the measurement location.

Northstar Island will be less useful than the specific frequencies of these tones when attempting to identify which sources are most significant[12].

One final note regarding the levels of underwater noise is that it has been shown that noise propagation in shallow water tends to attenuate high frequencies more than low frequencies. Reference [10] makes the delineation between "high" and "low" at about 400 Hz. This statement appears to be at least partially confirmed by the measured data in Figures 2.6 through 2.8 where the majority of the non-background data is below 200 Hz.

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[12] However, it should be possible to compare the relative amplitudes of different tones as long as they are close in frequency. For example, if a machinery item creates two "source" tones at 30 and 35 Hz, and the 35 Hz tone is 20 dB less than the 30 Hz tone, it is reasonable to say that the 30 Hz tone will produce a more prominent underwater noise tone (assuming the path from the source to water is viable). The difference in level between these tones in the water may not be 20 dB due to varying propagation effects, but it is reasonable to assume that the difference will not be vastly different from the difference at the source (i.e. 0-10 dB). If the tones were at 30 and 60 (or 100) Hz, the difference in the water could be significantly different than at the source.

3.0 NORTHSTAR NOISE AND VIBRATION SURVEYS

3.1 APPROACH FOR IDENTIFYING NOISE SOURCES, PATHS, AND CONTROLLING NOISE

In order to effectively reduce underwater radiated noise levels from gravel islands, it is necessary to identify the "noise paths" taken from the source(s) to the water[13]. Identification of noise paths is critical in the selection of treatments as their effectiveness varies for different noise paths. Secondary to this, it is important to identify the most significant sources of measurable underwater noise. Once the noise paths and machinery items have been identified, noise control treatments can be chosen that will be most effective in reducing underwater noise from gravel islands.

In order to accomplish the tasks described above, NCE proposed to survey the noise and vibration created by machinery items on Northstar. NCE's intention was to measure the following:

- Foot vibration levels of machinery items rated at 50 Hp or more[14].
- Vibration levels of the structures supporting these equipment items.
- Airborne noise levels near these equipment items.
- Airborne noise levels at various locations around the perimeter of the island.

These measurements were to be carried out while Northstar was operating under production conditions[15]. Details of this effort are given in Section 3.2.

In addition, underwater noise measurements were carried out by Greeneridge Sciences, Inc., during a similar timeframe as NCE's airborne noise and vibration study. These efforts were performed directly for BP and were not originally related to this project. It was agreed between all parties involved that NCE would have access to the underwater noise data measured closest to the island (approximately 400m north of the island). Details of the collection and analysis of underwater noise data is provided in Section 3.3.

The purpose of collecting the above data was to compare the narrowband spectra (~1Hz frequency spacing) of the airborne noise and vibration data to the measured underwater noise data. Given the caveats regarding possible amplitude analysis of the underwater noise data described in Section 2.3, identification of individual sources was to be performed primarily by matching specific tones in the airborne/vibration data with those seen in the underwater noise. Relative amplitude analyses could also performed on the airborne/vibration data to determine major sources. Noise path identification could be performed using the available noise and vibration data as well as by making comparisons

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[13] The term "noise" is used here to mean an oscillatory disturbance, whether it is airborne noise or structural vibration.

[14] The "foot" of a machinery item is a generic term used to describe the attachment location to the supporting structure. For example, many equipment items on the Northstar are attached to skids, or "sub-bases". These skids are in turn attached, typically via bolts, to the floor of the module where it is located. This attachment point is considered the "foot".

[15] It is noted here that a more direct method of determining what sources cause specific levels of noise, such as cycling specific equipment items while underwater noise data was recorded, was deemed to be not feasible by all parties involved.

of the specific physical/acoustical noise path phenomena to specific Northstar machinery and module arrangements.

3.2 NCE SURVEY OF AIRBORNE NOISE AND STRUCTURAL VIBRATION

All airborne noise and vibration testing was performed by NCE on October 6 and 7, 2005, on Northstar Island. Data was acquired using a Larson Davis 2900 and 3000+ handheld signal analyzers. All data was processed into third octave bands (TOB) between 5 - 20,000 Hz, as well as in "narrowbands" between 0-1250 Hz and 0-20,000 Hz. TOB integration time was set to 1 second, and all TOB filters satisfy the requirements of ANSI S1.11-1986 and IEC 61260-1994. Ten seconds of data were captured and averaged for each TOB measurement.

Hanning time weighting windows were used for all narrowband analyses. 800 frequency bins (“lines”) were used for each narrowband analysis, yielding frequency resolutions of 1.56 Hz and 25 Hz per band for the 0-1250 Hz and 0-20,000 Hz analyses, respectively. 25 seconds of data were captured and averaged for the 1250 Hz measurements, and 10 seconds for the 20,000 Hz measurements. These analysis parameters yield time-bandwidth products of 39 and 250, respectively.

All processing was performed by the analyzer in real time. No time data was recorded during this survey.

3.2.1 Vibration Measurements

Vibration measurements were taken using one channel of a PCB Model 356B21 Tri-axial Accelerometer. The measurement direction was always normal to the measurement surface, typically being the vertical direction. It is noted that the amplitude response of the accelerometer is calibrated to be within -0/+1 dB up to 10,000 Hz. The response above this frequency is not guaranteed to be accurate, however amplitude variations are generally gradual relative to typical spikes created by machinery (i.e. amplitude readings above 10,000 Hz are not accurate, but tone detection is possible).

Vibration measurements were taken at the "foot" (i.e. connection point to the main structure) of major machinery items, generally being rated at 50 HP or more. Typically, four locations were measured for each equipment item; fewer positions were measured for smaller items or where access was limited.

Equipment used during production activities was tested. This equipment was located in the South Process Module (SPM), North Process Module (NPM), Pump House, Compressor Module, Warehouse, Utility Module, and outside on the pad. The tested equipment items includes the following:

- SOLAR Gas Turbine Generator A and C
- Oil Shipping Pump A and B (P1130)
- Crude Booster Pump A and B (HS1080)
- Water Injection Pump Skid (HS3160B)
- Water Booster Pump A and B (P3040A and B)

- Ventilation fans on Level 1, north side of North Process Module (2 fans)
- HP Compressors (x2 -- LM 2500 drive)
- LP Compressor
- Utility Water Pump (Warehouse, sea connected)
- Water Injection Pump (Utility Module)
- Load Bank (located outside near Compressor Module)
- Refrigeration Plant (located outside on southeast corner of island)
- Air Compressors (2nd Level, SPM)
- Heat Media Circulation Pump (P4710A)
- Glycol Pump (2nd Level, SPM)
- AHU 5055A + B (SPM, 2nd and 3rd Levels)
- Seal Blower 4770A + B (SPM, 3rd Level)
- Flare Blower 4840 (Compressor Module, 2nd Level)

It is noted that the majority of these equipment items are driven with electric motors (SOLAR and Compressor turbines being obvious exceptions). Other large equipment items used in production were not measured because they operate infrequently[16]. These include

- Lube Oil Standby Pump (GTP 2325)
- Hydrocyclone Booster Pump (P6100)
- Well Cleanup Injection Pump (P6150)
- Firewater Intake Pump (P-S3 2101)
- Slop Oil Pumps (P4830)

Some equipment items were not readily accessible and could not be measured, such as large fans associated with the power and compressor turbines. Equipment items that operate durring drilling operations were not measured as this is outside of the scope of this project. Drilling was not taking place at the time of this survey.

In addition to direct equipment vibration measurements, vibration levels were taken at other structural locations mostly consisting of readings on the pillars supporting the SPM, NPM, Pump House, Compressor Module, and Utility Module. These measurements were performed at the base of the pillars (i.e. lowest horizontal plate) and on the horizontal plate located approximately 5 feet vertically from the base (as seen in Figures 2.1a and b). Additional measurements were taken at the following locations:

- Pipe connected to submerged Alternate Seawater Intake Pump
- Sheet Pile Wall near Compressor Module
- Vertical structural support on level 1 and 2 extending above Compressor Module pillar. This pillar was located one pillar south of the module's northwest corner

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[16] NCE was informed by BP employees that these items operate a few times a year. It is not known if any of these items were running during any of the underwater measurements presented in this report.

3.2.2 Airborne Noise Measurements

Airborne noise levels were measured using a Larson Davis Model 2560 with a 1/2" random incidence microphone and a Larson Davis Model PRM902 preamplifier. This setup is accurate to within +0.5/-2dB up to 10,000 Hz. Above this frequency the response rolls off smoothly at about 9 dB per octave.

Airborne noise measurements were made at approximately 1 meter from all equipment items listed in Section 3.2.1 that are on Level 1 of the SPM, NPM, Compressor Module, and Pump House. For those equipment items that are large (more than several meters in dimension) several measurements were made at various locations around the perimeter of the unit/skid. In addition, measurements were made around the perimeter of the island inside of the sheet pile wall. Figure 3.1 is a diagram of these measurement locations.

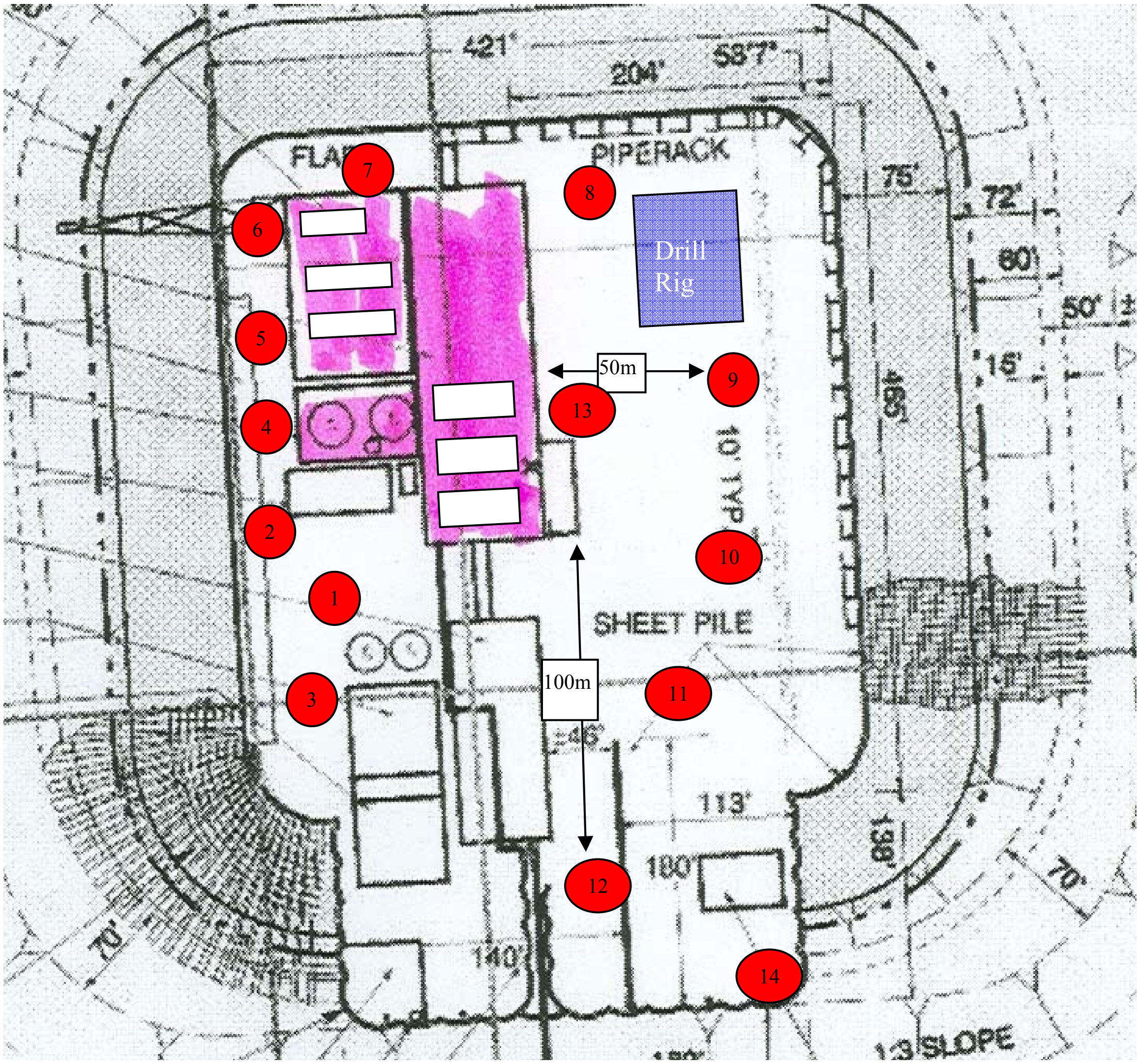

Figure 3.1: Airborne Noise Measurement Locations Outside of Modules

3.3 UNDERWATER NOISE SURVEY - 2005

Underwater noise was measured by Greeneridge Sciences, Inc. from August 30, 2005 through October 3, 2005. Measurements provided to NCE were of two types: Directional Autonomous Seafloor Acoustic Recorder (DASAR) recordings and measurements from a boat (i.e. hydrophones deployed over the side). The techniques used for these measurement types are assumed to be similar to what is described in [2]. The total water depth for all recordings was between 12 and 13 meters.

The DASAR data provided to NCE was from “DASAR NB”, which was located 410 m North of Northstar. Continuous time data was sampled at 1000 Hz, 16 bits for the entire measurement period (1 channel). The DASAR hydrophone was located on a stand 10-20 cm above the sea floor [11]. A low pass filter was applied to this data prior to digitizing at approximately 400 Hz to prevent aliasing errors.

Two boat-based recordings were provided. The first was recorded on August 30 at approximately 16:24 local time and lasted for 3 min 6.204s. The second was recorded on October 3 at approximately 14:38 local time and lasted for 3 min 3.504s. Both recordings were sampled at 48 kHz, 16 bits, and were measured approximately 400m north of the island. Two channels were provided for each recording, corresponding to hydrophones at 5 meter and 10 meter depths.

It is noted that the August 30 boat-based measurement was taken while no oil production was occurring. BP has confirmed that other activities such as gas injection, refrigeration unit testing, “LP seals 1-6 replacement,” and “drilling re-supply” were taking place [12]. The October 3 boat-based measurement was taken during “normal” production activities. It is assumed that in general the activities occurring between August 30 and October 3 were typical for production, however this has not been confirmed; it is assumed that no drilling occurred during this time.

All data was provided to NCE in “wav” file format. These files were analyzed using a script created by NCE for use with Matlab™. The wav files were imported into Matlab™ and processed into power spectra. A Hanning window was used for all sampled data sets. For each spectrum, 30 sample sets were computed and averaged. Multiple spectra were created from each wav file when possible. The data was scaled to pressure in µPa using scaling factors provided by Greeneridge.

For boat-based recordings, 32768 frequency bins were used, yielding a frequency resolution of 0.73 Hz. The entire wav file was analyzed for these recordings, yielding 4 different spectra per channel. For DASAR recordings, 512 frequency bins were used, yielding a frequency resolution of 0.98 Hz. Since each of the DASAR wav files was very long, short sections of the DASAR files were selected for analysis. It was seen that most of the DASAR recordings contained spikes in the time data. NCE was informed by Greeneridge that these spikes were the result of wave motion. As a result, the analyzed sections were selected to be those with extended periods of time where no spikes were present. Ten different spectra were created from each DASAR wav file section.

4.0 COMBINED UNDERWATER DATA ANALYSIS

Due to the large amount of collected and analyzed data, the full data set is not repeated here. Excel files with all collected data for vibration and noise are provided as a supplement to this report. Only those data that are directly applicable to the presented discussion are shown within the report. As such, pertinent airborne noise and vibration data will be presented in Section 5, as needed. Underwater noise data is presented in this section along with analysis and comparisons to data from previous years. Indications of overall characteristics and pertinent frequencies/frequency ranges are given.

4.1 BOAT BASED MEASUREMENTS – 2005

Figures 4.1, 4.2, and 4.3 show the analyzed wav files of the boat-based recordings described in Section 3.3. These graphs show all four power spectra for both channels, from 0-20,000 Hz. As discussed in Section 2, it is expected that noise created by Northstar Island (or any gravel island) during production activities would be tonal in nature as a result of operating machinery. It is clear from these figures that there is essentially no measured noise for much of the frequency spectrum; what is seen here is estimated to be largely background noise (see Section 2.3.1).

In the October 3 measurements, some real data (i.e. spikes possibly due to machinery sources) appear to occur at frequencies below 2000 Hz. The same can be said for the August 30 measurements below 500 Hz. Figure 4.4 shows a close-up of the frequency range between 0 and 2000 Hz for the October 3, 10m hydrophone measurement. A closer look at this data shows that the "spikes" in the frequency range of 800-2000 Hz are actually somewhat broadband in nature, and do not exist for some spectra. It is noted that the difference in time between consecutive spectra is about 45 seconds for a given wav file. This means that whatever was creating the elevated noise levels at these higher frequencies came and went over the course of 45 seconds to 3 minutes. It is suggested that these elevated levels are actually a result of weather conditions or other artifacts of the measurement technique rather than actual noise produced by Northstar[17].

By analyzing the rest of the data in a similar fashion, it is seen that the only non-sea condition (i.e. "real") data is below 150 Hz for the August 30 measurements and below 250 Hz for the October 3 measurements (with the exception of a single tone at 606 Hz). The analyzed power spectra for these ranges are presented in Figures 4.5 and 4.6. It is seen that for the August 30 measurements, the Channel 1 (i.e. 5m hydrophone) has background levels that appear to be higher than any tone seen in Channel 2, and thus any real information is masked. Channel 2 (i.e. 10m hydrophone) shows some broad tones at approximately 20, 40, 60, 80, and 100 Hz, as well as a broad peak near 7 Hz. The October 3 measurements show good correlation between both the 5 and 10m hydrophones, with sharp peaks occurring at approximately 30, 51, 60, 82, 121, and 242 Hz (a tone at 606 Hz was also seen in the data, although not shown here).

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[17] NCE was informed by Greeneridge that the measurements made on October 3, 2005 were performed while the water was in the process of freezing ("apple sauce") [13]. As a result there is an "odd 'shhhhhhh' sound that permeates that recording." This may be the source of these broadband peaks.

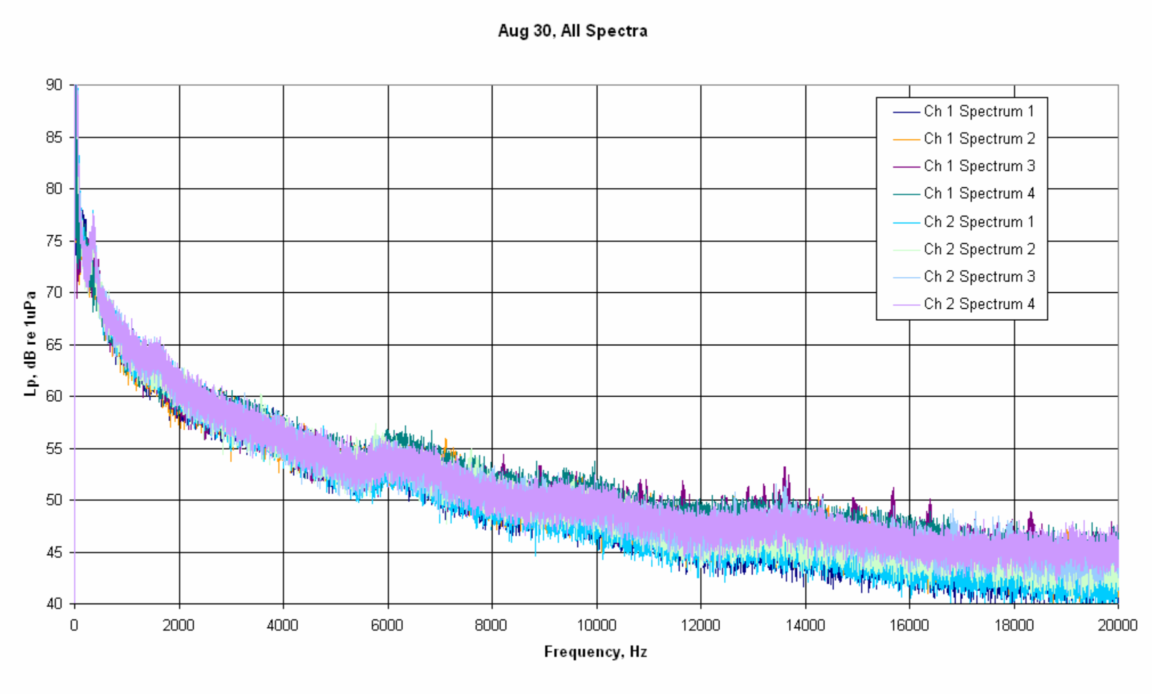

Figure 4.1: August 30 Boat-Based Measurement, Full Bandwidth, All Spectra
(Channel 1 is 5m hydrophone, Channel 2 is 10 m hydrophone)

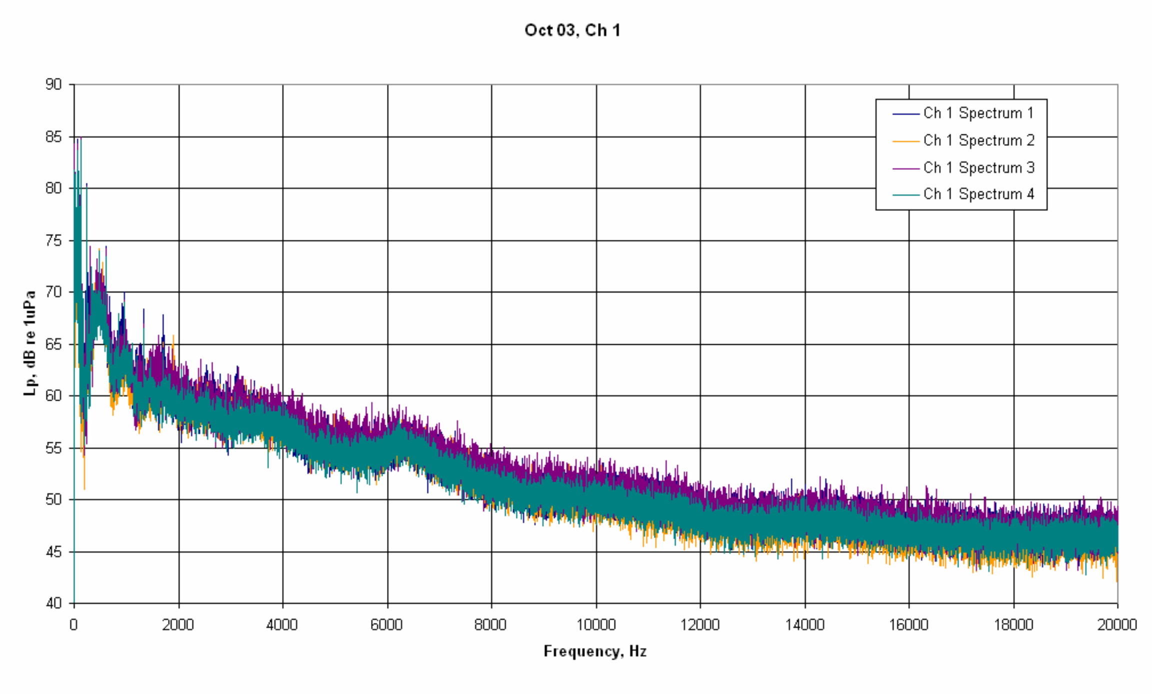

Figure 4.2: October 3 Boat-Based Measurement, Full Bandwidth, Channel 1 (10m Hydrophone)

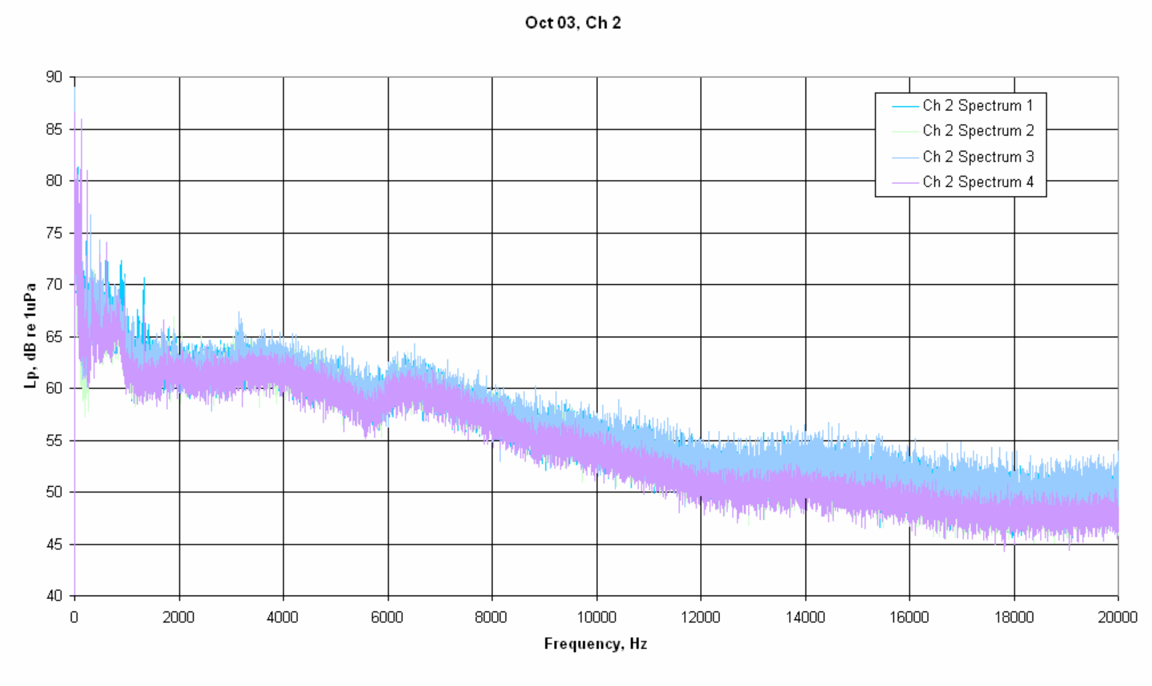

Figure 4.3: October 3 Boat-Based Measurement, Full Bandwidth, Channel 2 (5m Hydrophone)

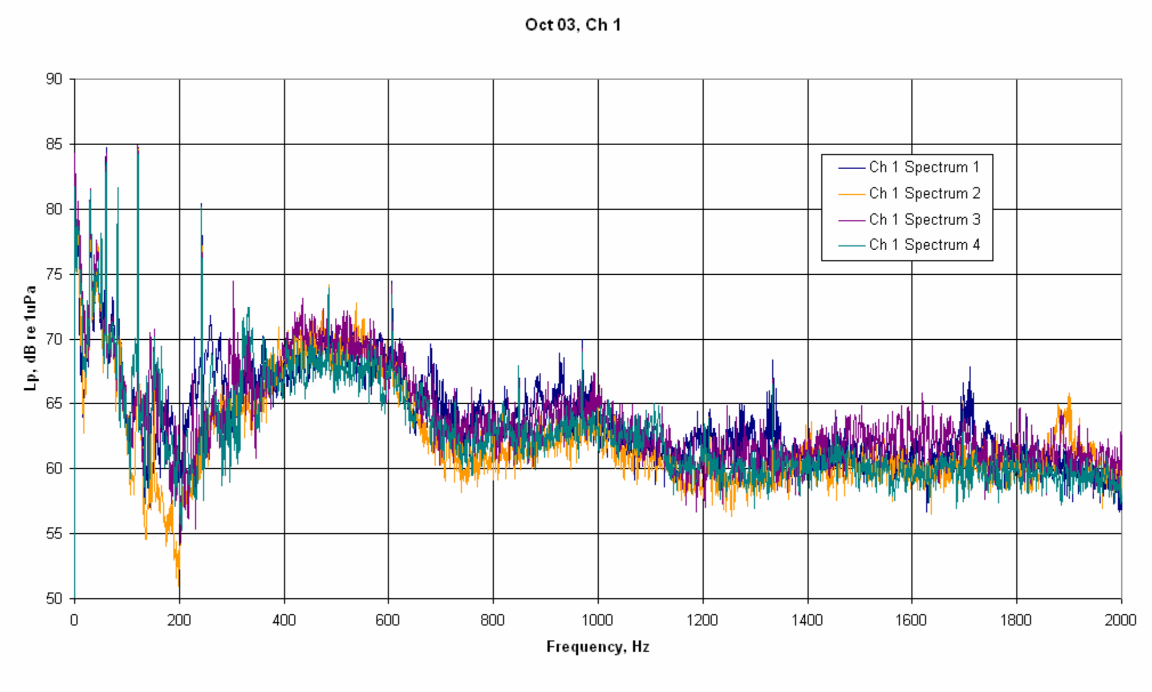

Figure 4.4: October 3 Boat-Based Measurement, 0-2000 Hz, Channel 1 (10m Hydrophone)

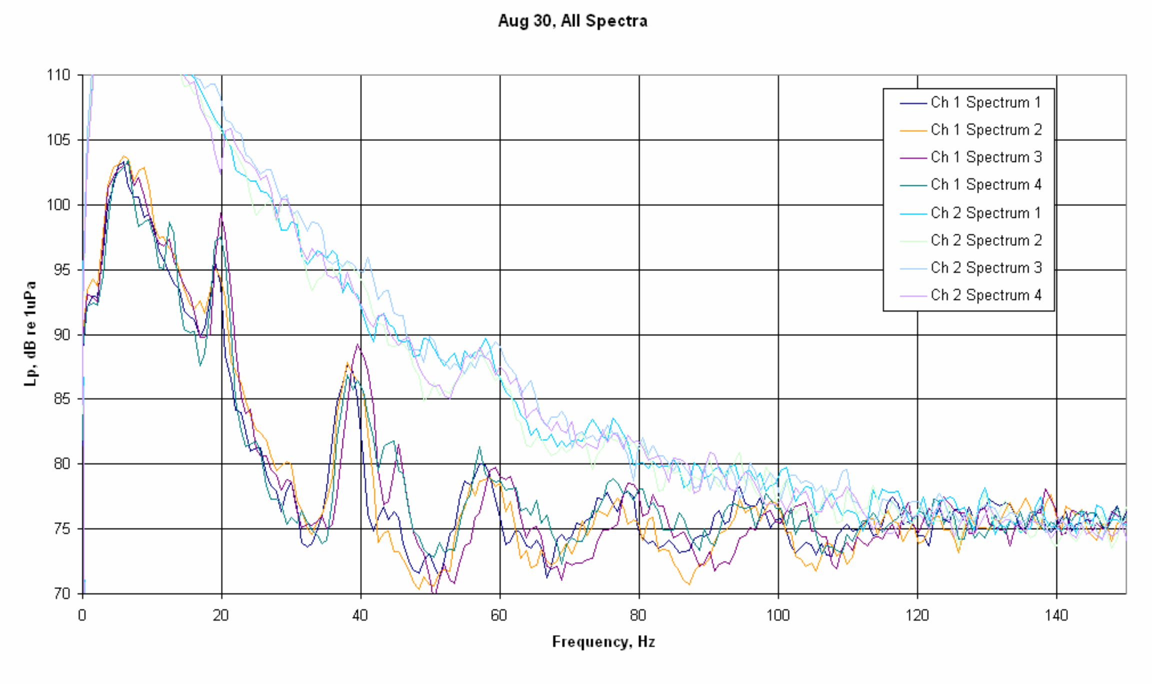

Figure 4.5: August 30 Boat-Based Measurement, 0-150 Hz

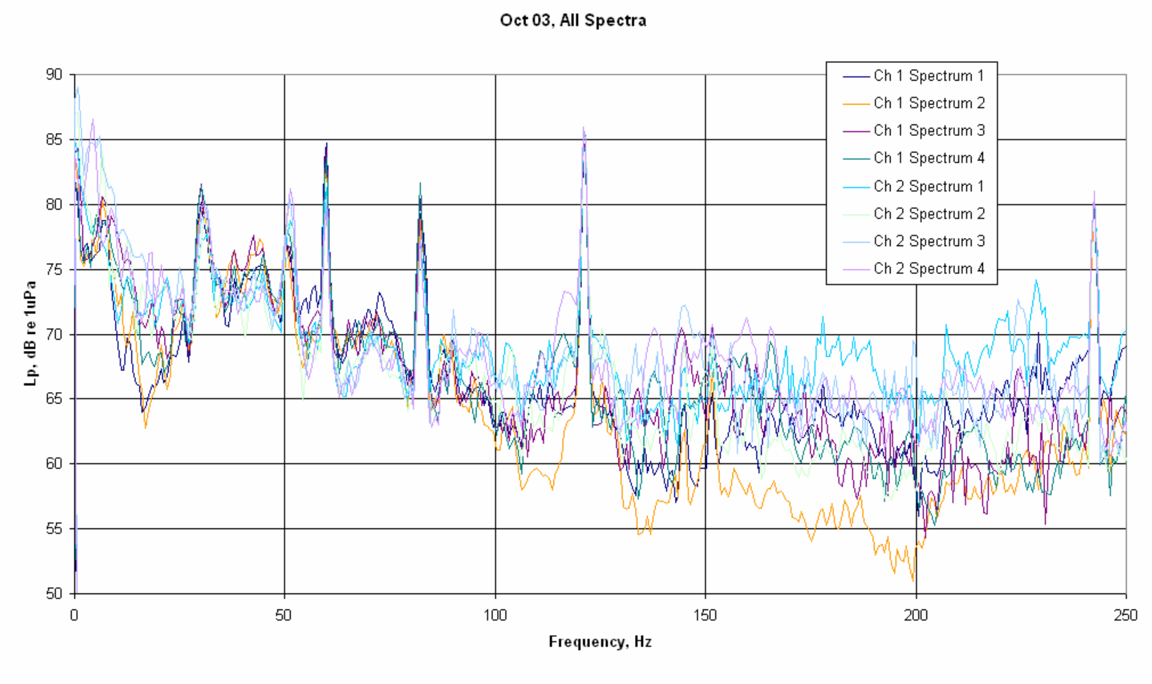

Figure 4.6: October 3 Boat-Based Measurement, 0-400 Hz

Comparison of the tones from the two boat based recordings indicates a gross dissimilarity in the data. It is noted again that the operations occurring during these two measurements were not the same; no oil production was occurring during the August 30 measurement, however other activities that are not typical of production were occurring.

In addition, the noise peaks seen in the August 30 data at 20, 40, 60, 80 and 100 Hz are more broad than would be expected coming from a machinery item operating at a constant RPM. In addition, it is seen that the specific frequency of any single peak (near the primary frequencies of 20 Hz, 40 Hz, etc.) is different for consecutive spectra, again indicating a change in the sound characteristic from one minute (or 45 seconds) to the next. Because of this, it is suggested that the data may be the result of one or more equipment items operating at a variable RPM. At a minimum, this data does not reflect production operations as measured during NCE's site visit. For this reason the boat-based data from August 30 will be ignored for the rest of this analysis.

4.2 DASAR MEASUREMENTS – 2005

As suggested in Section 3.3, it is impractical to analyze all the data measured by the DASAR NB. Sections of time data were selected from the DASAR wav files that did not contain spurious data spikes and that appeared to be "steady state", i.e. no major variations in overall amplitude with time. While it has been assumed that production activities were occurring during the chosen time sections, there is no guarantee that this is the case.

An example of the power spectra calculated from a selection of DASAR data is given in Figure 4.7. These (consecutive) spectra are for a time period covering approximately 5 minutes. As noted in Section 3.3, the roll-off above 400 Hz is due to the anti-aliasing filter applied to the analog signal at the DASAR.

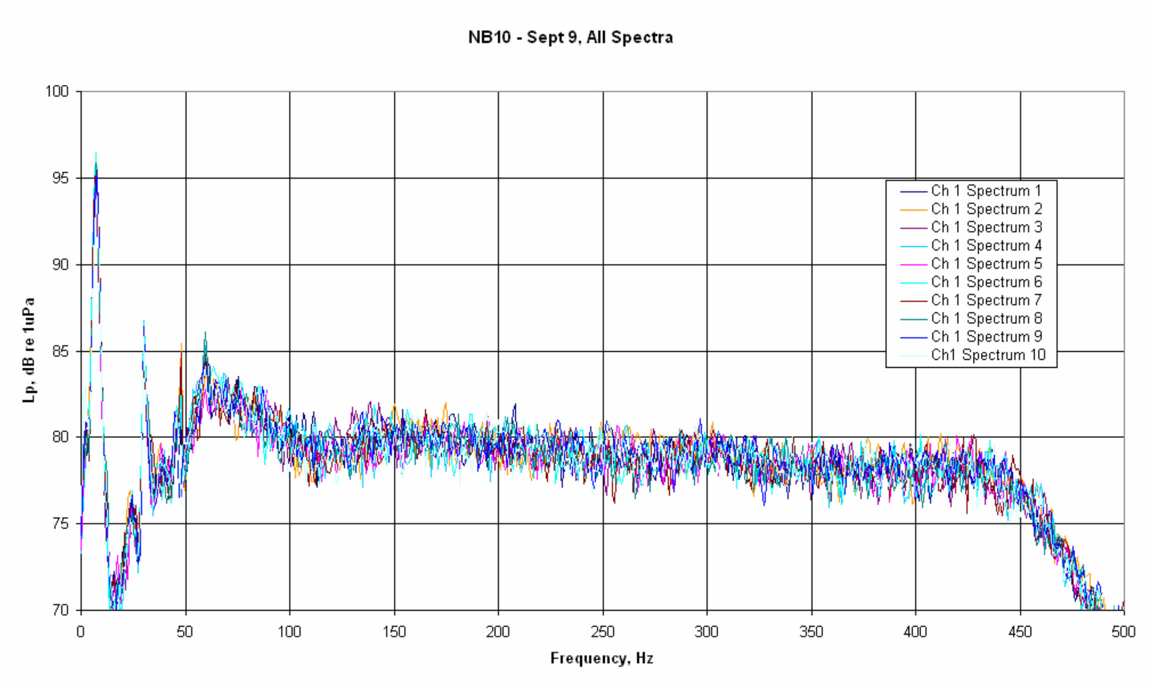

Figure 4.7: September 9 DASAR Measurement

Similar to the boat based measurements, the majority of the data appears to be background. No noise spikes are seen above 60 Hz. Figure 4.8 shows the power spectra from 0-100 Hz of several DASAR measurements taken on different days. It is noted each of the spectrum curves shown in Figure 4.8 are the result of a linear average of the dB values for all 10 spectra in a given measurement (i.e. average over several minutes on a given day). This was done to reduce some of the randomness of the data at locations where no strong tone exists and to make the graph easier to read. It should also be noted that the broadband levels at high frequencies differ from day to day due to varying sea conditions.

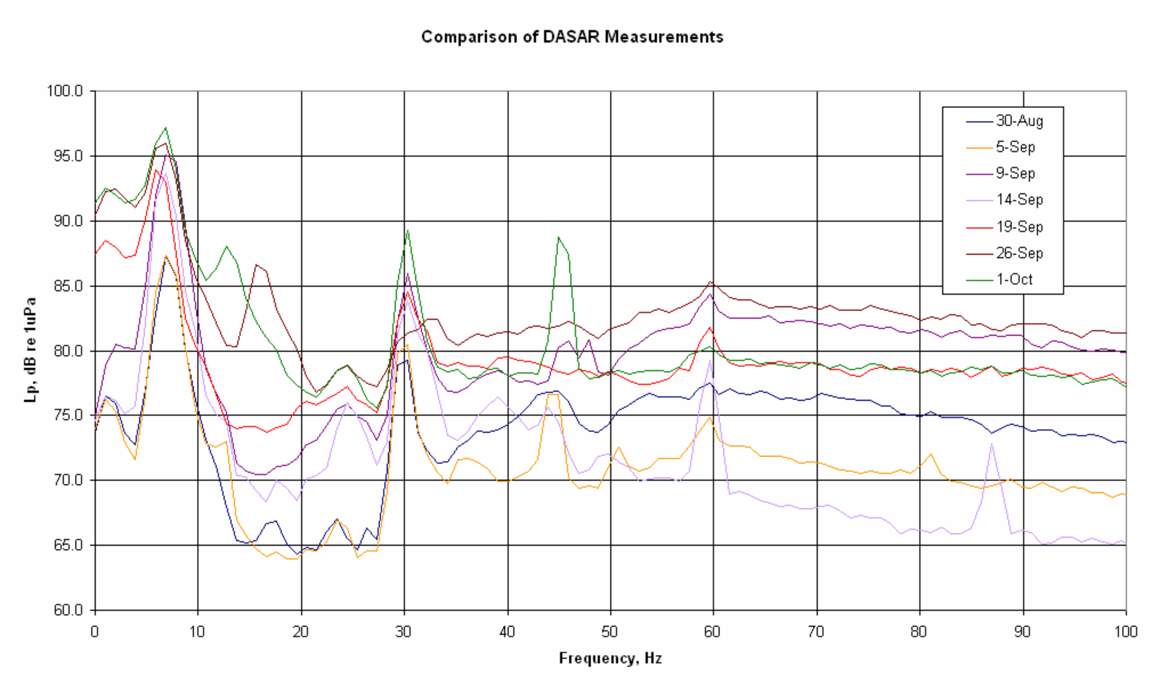

Figure 4.8: Comparison of Various DASAR Measurements

Analysis of Figure 4.8 shows that consistent noise spikes exist at 30 and 60 Hz. Spikes near 45 Hz appear on some days and not others, and the spike near 24 Hz appears to change frequencies slightly in two of the spectra, although it is always present in some form. Spikes at several other frequencies occur in only one to two spectra. It is noted however that some tones may be masked by high background noise for some spectra.

4.3 UNDERWATER NOISE SUMMARY

4.3.1 Tones

It has been shown that tones in the underwater noise data, which are indicative of rotating or reciprocating machinery, are generally seen at frequencies below 250 Hz, and are mostly seen below 100 Hz. Several tones appear to be present in almost all data, while others appear to come and go depending on the day. Table 4.1 summarizes the tones seen in all available underwater noise data, including data from years prior to 2005. All measurements were taken between 400 and 450 meters north of the island, except as noted. Note that the data from the August 30, 2005 boat-based measurements are not included here for reasons noted in Section 4.1.

Table 4.3 – Primary Underwater Tone List

Frequency, Hz	Boat-Based Measurement, Oct. 3, 2005	DASAR Measurements, 2005	Boat-Based Measurement March 1, 2002 (2 km)	Cabled Hydrophone Measurement Aug 31, 2002	Cabled Hydrophone, Min 6 Days, Aug-Sept 2002
~7		✓	N/A	N/A	N/A
13		✓ **			
16		✓ **			
20			✓		
24		✓ *			
26			✓		
30	✓	✓	✓	✓	✓
33					✓
39					✓
40			✓	✓	
44				✓	
45		✓ *			
46			✓		
48		✓ **			
51	✓				
52			✓		
60	✓	✓	✓	✓	✓
66					✓
81		✓ **	✓	✓	
82	✓				✓
87		✓ **			
90				✓	✓
101				✓	
112					✓
120			✓		
121	✓				
122					✓
124				✓	
138					✓
142				✓	
145			✓		
147				✓	✓
184				✓	
242	✓			✓	
606	✓				

*Occurs in several DASAR spectra, but not all
** Occurs in 1-2 of the analyzed DASAR spectra

The only tones that are seen in all spectra are at 30, and 60 Hz (marked in Orange). All other tones are seen in some measurements and not others. As suggested in previous sections, masking due to high background noise or other propagation effects may cover up some tones that actually exist (but are not detectable) where Table 4.3 suggests they do not. In addition, an argument can be made to say that tones that are within 1 Hz of each other are actually from the same equipment, just running at slightly different speeds. These include tones at or near 51 and 121 Hz.

Obviously, many differences exist with regards to frequency content between the various measurements. The constant 30 and 60 Hz tones that are seen in all measurements are most likely a result of sources that are always or almost always on. Similarly, it can be said that the intermittent tones, including tones with similar frequencies, may be the result of equipment that operates on a regular basis but not all the time. In addition, it is possible that this equipment is run under varying loads, modifying the amplitudes of the pertinent tones.

It is noted that tones above 100 Hz measured in the 2005 boat-based measurements do not appear at all in the 2005 DASAR measurements analyzed by NCE. An exact reason for this can not be stated based on the available data alone.

4.3.2 Underwater Noise Conclusions

From the information in Section 4.3.1, it can be said that while some equipment items that cause detectable underwater noise levels appear to be on all the time or nearly all the time, others appear to be cycled over the course of several days to several weeks. As such, "normal" production activities appear to include a significant variation in equipment lineup and operation. This presents something of a complication with regards to identifying all noise contributors using the methodology assumed for this project. NCE's airborne noise and structural vibration survey took place over the course of 2 days of "normal" production activities. However, it is apparent that during production some equipment items are either run intermittently, at varying loads, varying speeds, or some combination.

It is suggested that some of the tones described thus far in the underwater data are not due to equipment on Northstar but are actually caused by external sources such as boats. NCE is aware that Greeneridge made efforts during their boat-based measurements to take data while no other sources were visible; however, Greeneridge has noted that it is possible for loud sources far away to contaminate the data. This can be the case particularly for boats operating in the area that can have source levels of 150-180 dB re 1μPa.

That being said, it is reasonable to assume that recurring tones seen at various times at specific frequencies are most likely a result of Northstar operations, as this is the most consistent factor for all measurements. Tones that appear in only one measurement are likely candidates for external sources; however this cannot be confirmed with the available information.

In any case, some tones are seen in all measurements (30 and 60 Hz), and it can be said definitively that they are the result of Northstar operations. Moving forward, it is the intention to match these tones with specific machinery items/noise paths on the Northstar and identify dominant paths for the noise. Once identified, specific noise control treatments recommendations can be made.

5.0 NOISE PATH IDENTIFICATION

This section provides analyses of the various potential noise paths, with conclusions about the feasibility and influence of each. By examining the layout and arrangement of Northstar, four noise paths are considered to be possible. They are:

1. Direct airborne to underwater transmission – Airborne noise travels from machinery components through the air directly into the ocean surrounding the island.
2. Primary structureborne noise transmission – Vibration from machinery travels through the supporting structure to the gravel. The vibrations are then carried out through the gravel to the water.
3. Secondary structureborne noise transmission – Airborne noise from machinery components impinge on local plating, thereby exciting them into vibratory motion. These vibrations then travel in a similar manner as described for the primary structureborne path, item 2 above.
4. Direct underwater radiation – sea connected equipment transmit noise directly into the water via piping open to the sea or via submerged piping vibrations.

The next four sections address these paths and the potential of each being a dominant path for Northstar and other gravel islands.

5.1 DIRECT AIRBORNE NOISE PATH

Airborne noise transmission directly into the water is a phenomenon that is often seen as a result of overhead planes, helicopters, hovercraft, or any noise producing object with a normal incidence with respect to the water [1, 2, 7]. In a classical analysis there is a limit to the angle of incidence with respect to the water plane for which noise will enter the water [14]. For a sound wave that is incident on the surface of a body of water, we can define a transmission coefficient, T, as

$$T = \frac{P^{TR}}{P^{INC}} \qquad (1)$$

where P^{TR} is the transmitted pressure wave and P^{INC} is the incident pressure wave. A plane wave traveling in air that is incident on the water will have a transmission coefficient of

$$T = \frac{2Z_{water} * \cos(\theta_i)}{Z_{water} * \cos(\theta_i) + Z_{air} * \cos(\theta_t)} \qquad (2)$$

where Z is the characteristic impedance of the medium, Z=ρc, where ρ is the density and c is the speed of sound, θ_i and θ_t are the angles of incidence and transmission, as defined in Figure 5.1.

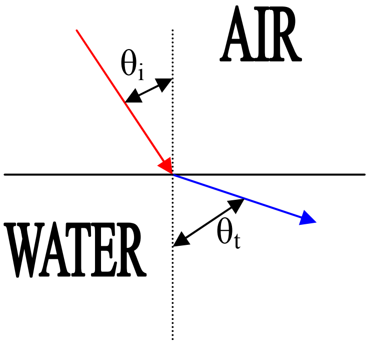

Figure 5.1: Definition of Angles of Incidence and Transmission

The angles of incidence and reflection always have the relationship (Snell's Law)

$$\frac{\sin(\theta_i)}{c_{air}} = \frac{\sin(\theta_t)}{c_{water}} \qquad (3)$$

For air and water, the speed of sound is 343 m/s and 1500 m/s, respectively. Inspection of equation (3) shows that the angle of transmission will always be greater than the angle of incidence since the speed of sound in water is greater than in air. This implies that there will be some angle of incidence smaller than 90 degrees that will produce an angle of transmission of 90 degrees. This angle is approximately equal to 13 degrees for a sound wave traveling from air to water.

Beyond this angle, sound is not transmitted to the water in the conventional sense. The waves that are transmitted to the water are called "evanescent waves" because they decay exponentially with distance, according to the formula

$$\begin{aligned} |P^{TR}| &= 2*|P^{INC}|*e^{-\alpha*x} \\ \alpha &= 2\pi f*\sqrt{(c2/c1)^2\sin^2\theta_i - 1} \end{aligned} \qquad (4)$$

where f is the frequency of the wave and x is distance. Note that this equation is for a plane wave, so for typical spherical waves there would be an extra geometrical spreading term. For the case where $\theta_i = 45$ degrees, α becomes 1.3 m^{-1} at 100 Hz. This means that after traveling a distance of approximately 77cm (in the water), the wave will have diminished in amplitude by 8 dB, not including geometrical spreading. So at any significant distance from the surface the wave is completely negligible. It is noted that this 13-degree "cone" of permissible airborne transmission to water has been verified experimentally [15].

From this analysis, it is clear that only waves that are incident on the water with angles between 0 and 13 degrees from the normal will produce any significant underwater sounds levels. Most angles of incidence from real sources on Northstar are much greater than this. For example, the top of the North Process Module is at an elevation of 109 feet above the top of the gravel, which itself is roughly 20 feet above sea level. For arguments sake, say that the top of the NPM is 130 feet above the water. The shortest horizontal distance from the NPM to the water is approximately 100 feet. This gives an angle of incidence of 38-degrees. Thus it is highly unlikely that the direct airborne to water path is actually occurring.

Similarly, it is not likely that the required angle of incidence would occur for any gravel island since, based on the construction of the Northstar, there are necessary structures between the modules and the sea – i.e. a protective wall around the island, outside of which the gravel continues outward until it meets the water. Assuming a similar arrangement would be necessary for future gravel islands, direct airborne noise should not be an issue.

An argument could be made for those conditions where waves cause the 38-degree (and higher) typical angle of incidence to appear closer to the 0 to 13 degree critical range. In this case it *may* be possible for airborne noise to create significant underwater noise. However, this path is not likely to cause significant noise, and has been similarly discounted in other studies of airborne noise to water transmission [16].

5.2 PRIMARY STRUCTUREBORNE NOISE PATH

Vibration travels well in solids such as metals. This is because there are stresses and reactions between the particles that make up the metal that will propagate any imposed disturbance. For example, oscillatory pressures exerted on one end of a metal bar are easily transmitted across the bar due to the bulk stiffness of the metal (i.e. Youngs modulus). Gravel, in the conventional sense, is made up of loose particles, and thus one may not expect any significant bulk stiffness. However, once gravel or any loose particle is sufficiently compacted it does take on a bulk stiffness that is capable of both supporting static loads and transmitting vibrations.

A common example where compaction of fine, loose particles leads to a “solid” bulk material is dirt. Dirt (i.e. soil) can very easily be separated into fine particles with little effort. However, when compacted (as is typically the case in nature), dirt can carry vibrations significant distances. Common examples of this are ground vibrations from trains and pile driven equipment.

It is apparent that the gravel making up Northstar has been compacted to a significant degree. It is capable of supporting the very large static loads of the modules, which weigh on the order of several thousand tons each. In addition, the island is capable of resisting lateral forces such as those presented from ice flows. Second to this, much of the island is frozen – i.e. the water located between gravel particles is frozen. Frozen gravel will only add to the bulk stiffness of the island, much like frozen ground (dirt) is harder than thawed ground. All of this necessarily implies that the gravel making up a gravel island is actually quite stiff, and acts as a solid as opposed to individual pieces or loose slurry. It is noted that compacted gravel has been shown by others to be capable of supporting groundborne vibration transmission [17, 18, 19, 20][18].

The implication of the above arguments is that gravel islands should be very capable of receiving vibrational energy and transmitting it to the edges of the island. The island surfaces in contact with the water would then vibrate, thereby radiating noise into the water. Although it is not expected that the vibrations are particularly large in amplitude, there is a considerable surface area of submerged gravel. Large surface areas can radiate significant noise levels even if the amplitudes of motion are small [14, 26].

As further evidence of the viability of the primary structureborne path, NCE measured the vibration on the sheet pile wall near the HP Compressors. This measurement is shown in Figure 5.2. The tones seen in this measurement can be compared with the tones seen in the foot vibration measurements of the HP Compressors, Figure 5.3. It is seen that strongest tones on the compressors do in fact show up in the sheet pile wall vibration (in addition to a secondary contribution from another source near 60 Hz). Since the sheet pile wall is only connected to the gravel and no other structure, it is apparent that the gravel has carried the vibrations from the Compressor Module pillars to the wall, thus showing the island's ability to support structureborne vibrations[19]. Further to this, Appendix G of Reference [2] discusses the high level of underwater noise that occurred during vibratory and impact driving of the sheet pile wall during the construction of Northstar. Thus, it is clear that vibrations created in the equipment modules can reach the sheet pile wall, and vibrations at the sheet pile wall can then create underwater radiated noise. As such, Primary Structureborne noise is certainly a viable noise path.

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[18] As a point of reference, it has been shown that vibrations in gravel are attenuated quickly at higher frequencies [17]. This high attenuation with frequency may be a partial reason for the lack of measurable mid- to high-frequency radiation from the gravel island.

[19] It is noted that while it is technically possible for the sheet pile wall to be excited by an airborne noise path, it is highly unlikely that this path has created the vibration levels seen. This is largely because the top of the wall is a "free end" and the sound created by the compressors at low frequencies (i.e. large wavelengths) can wrap around the wall and excite both sides. The excitation from one side will largely cancel out the excitation of the other side.

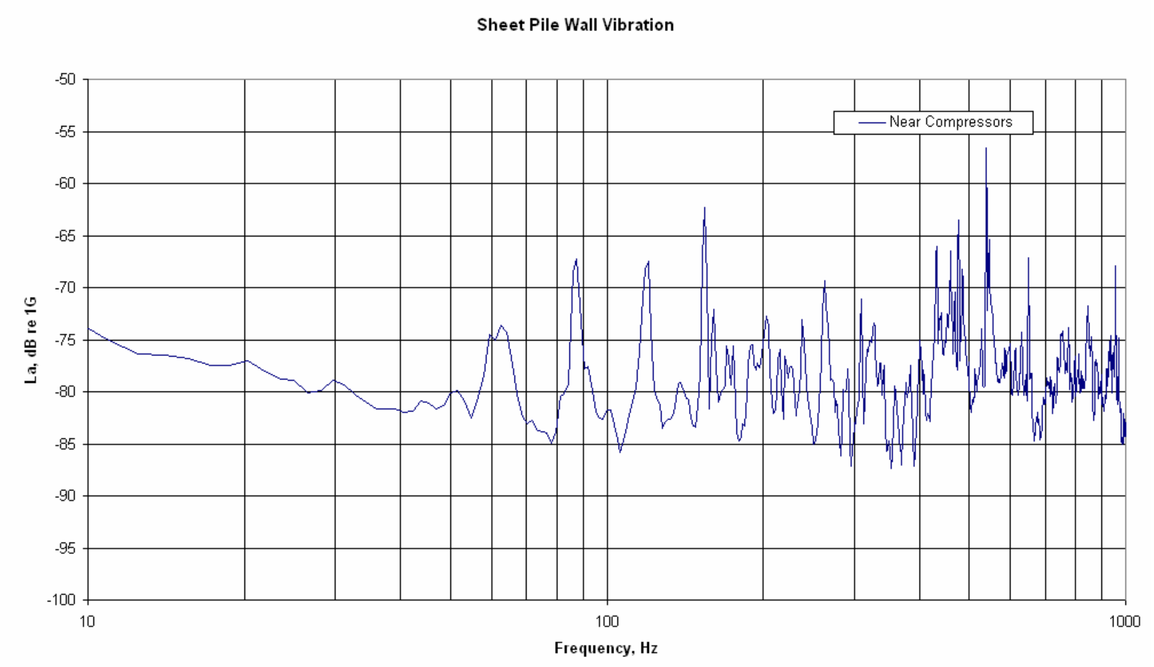

Figure 5.2: Vibration of Sheet Pile Wall Near HP Compressors

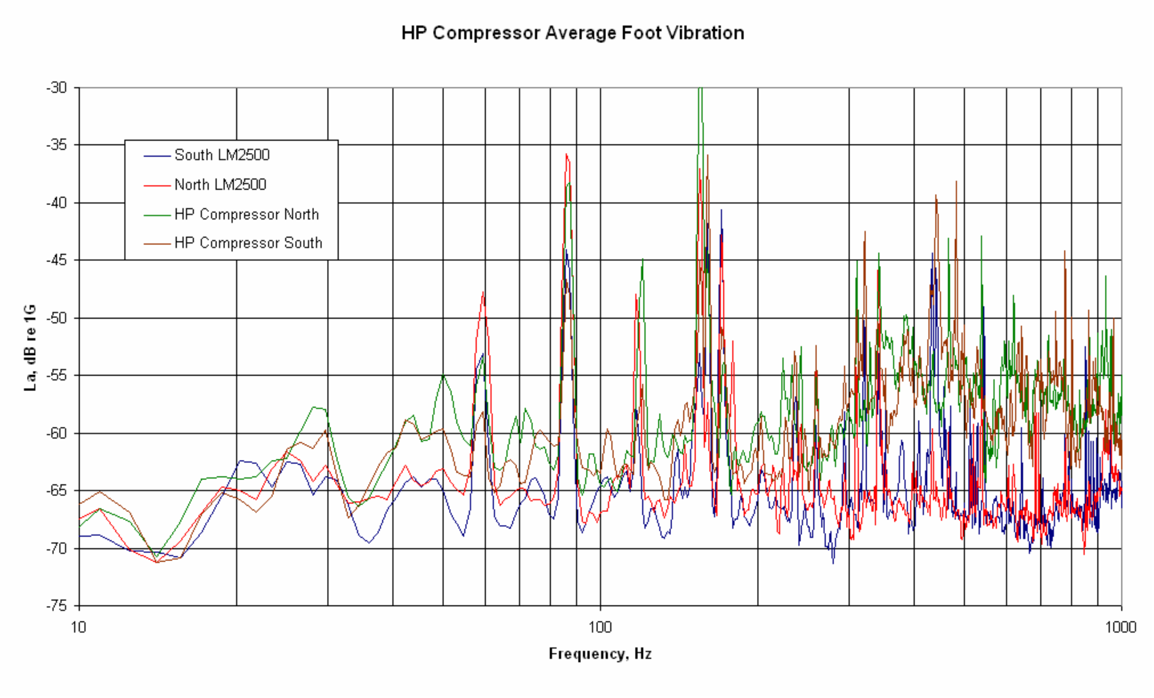

Figure 5.3: Foot Vibration of HP Compressors

5.3 SECONDARY STRUCTUREBORNE NOISE PATH

Another way of creating structural vibration is to excite it using airborne noise. For this to occur, it is generally necessary to have a large surface area for the noise to impinge upon. Therefore, this path is only really possible for those locations within a module that has plating. This includes much of the first level of the North and South Process

Modules, the Pump House, Warehouse, and Utility Module. The area around the compressors and SOLAR turbines are not enclosed and have steel grating for floors. As such, the secondary structureborne path is not a likely contributor for these sources.

Since the modules are connected to the gravel through pillars, the Secondary Structureborne Path would exist through the following sequence of events:

- Airborne noise is radiated by a machinery item.
- This noise impinges on the plating located around the machinery, thus exciting it into vibration.
- This vibration travels to the stiffeners supporting the plates, exciting them.
- The vibration travels to the pillars, the gravel, and ultimately to the sea, as in the case for Primary Structureborne Noise.

To test the influence of this path, NCE has developed transfer functions for airborne noise-to-plate vibration and from plate-to-stiffener vibration. Transfer functions are based on References [21, 22]. The resulting stiffener vibration was then compared to the source vibration measured at the feet of the machinery item creating the airborne noise.

This procedure was carried out using measured sound and vibration levels for various sources located in spaces with surrounding plates. Three example calculations are given here. The measured sound pressure levels from 0-1000 Hz for the Oil Shipping Pumps, Crude Booster Pumps (both located in the South Process Module, Level 1), and the Water Injection Pump Skid (Pump House) are presented in Figures 5.4 though 5.6. The power averaged foot vibration levels for these same sources are presented in Figures 5.7 through 5.9.

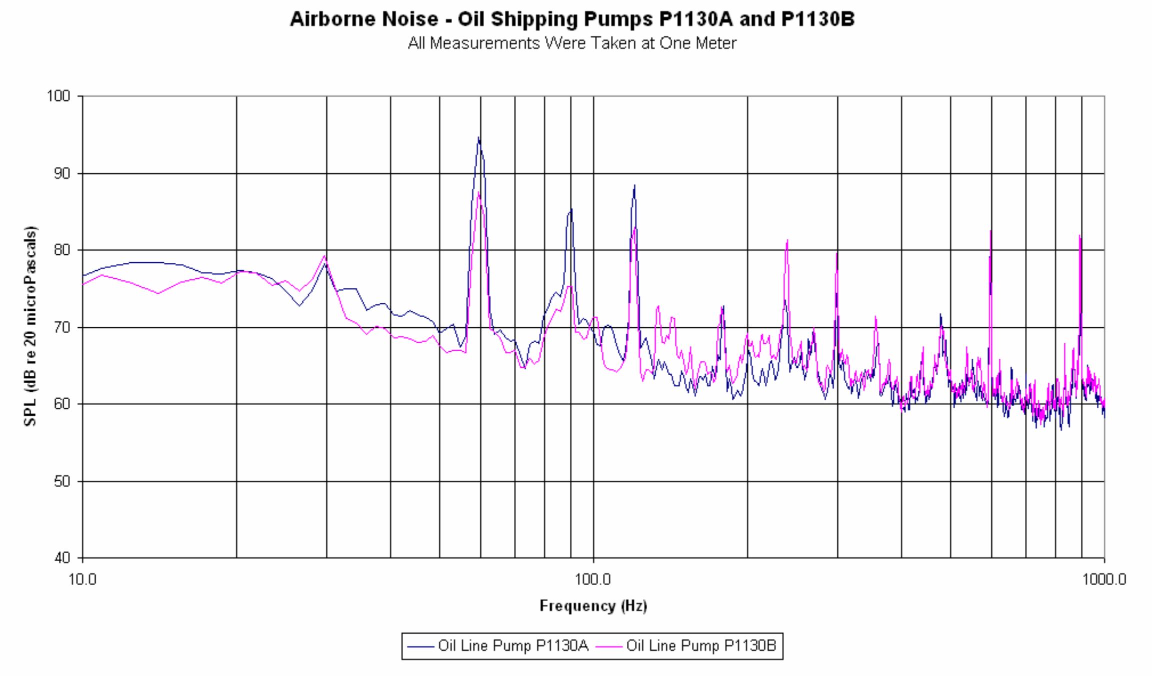

Figure 5.4: Oil Shipping Pump Airborne Noise

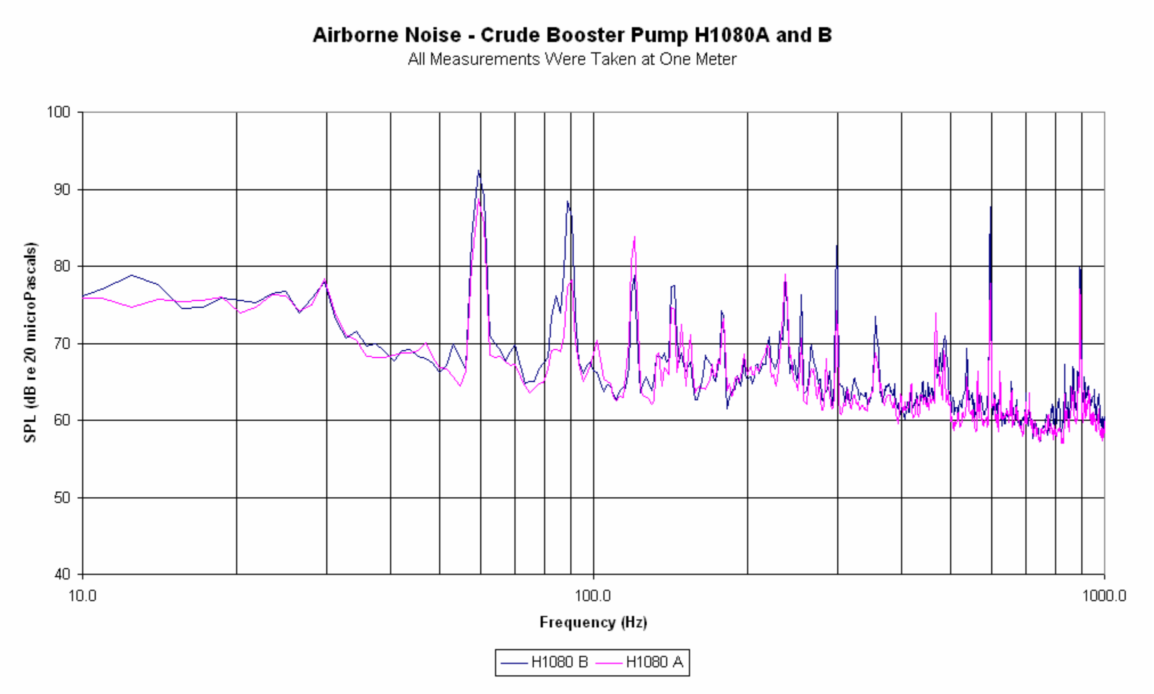

Figure 5.5: Crude Booster Pump Airborne Noise

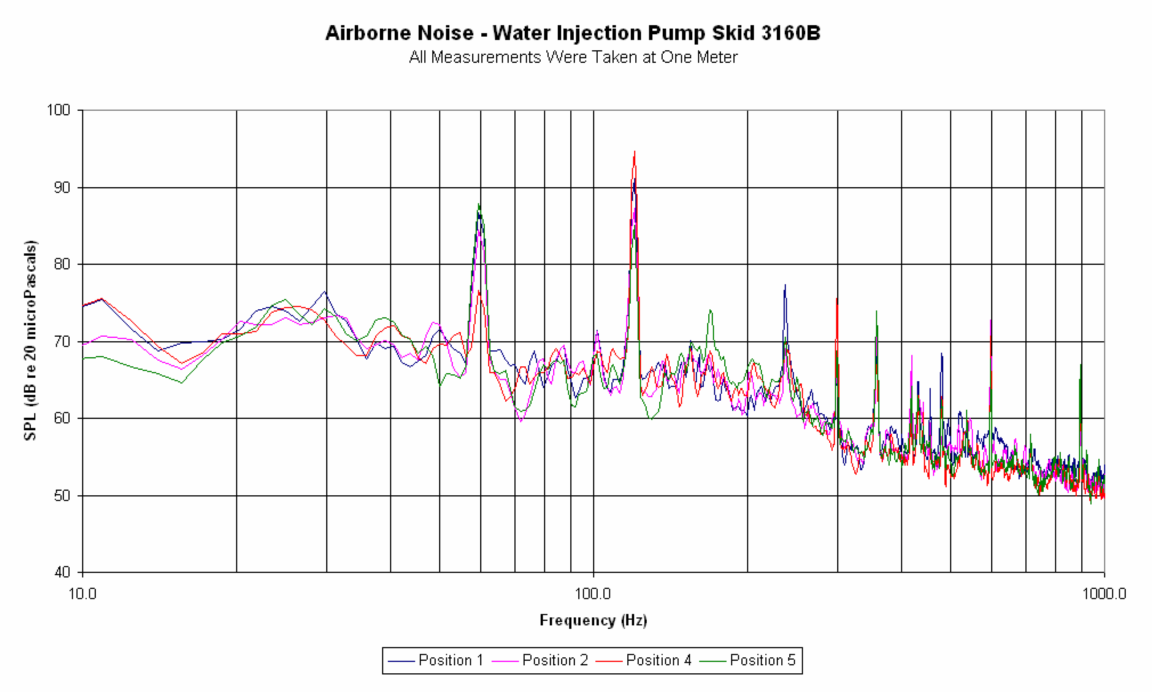

Figure 5.6: Water Injection Pump Skid Airborne Noise

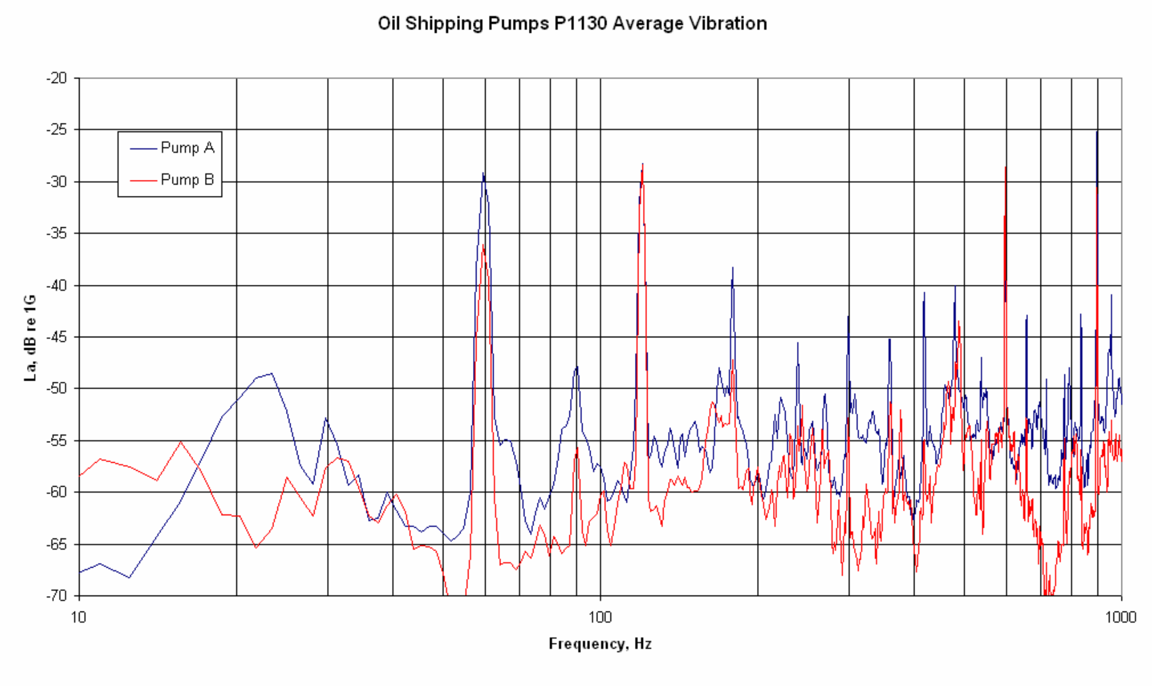

Figure 5.7: Oil Shipping Pump Average Vibration

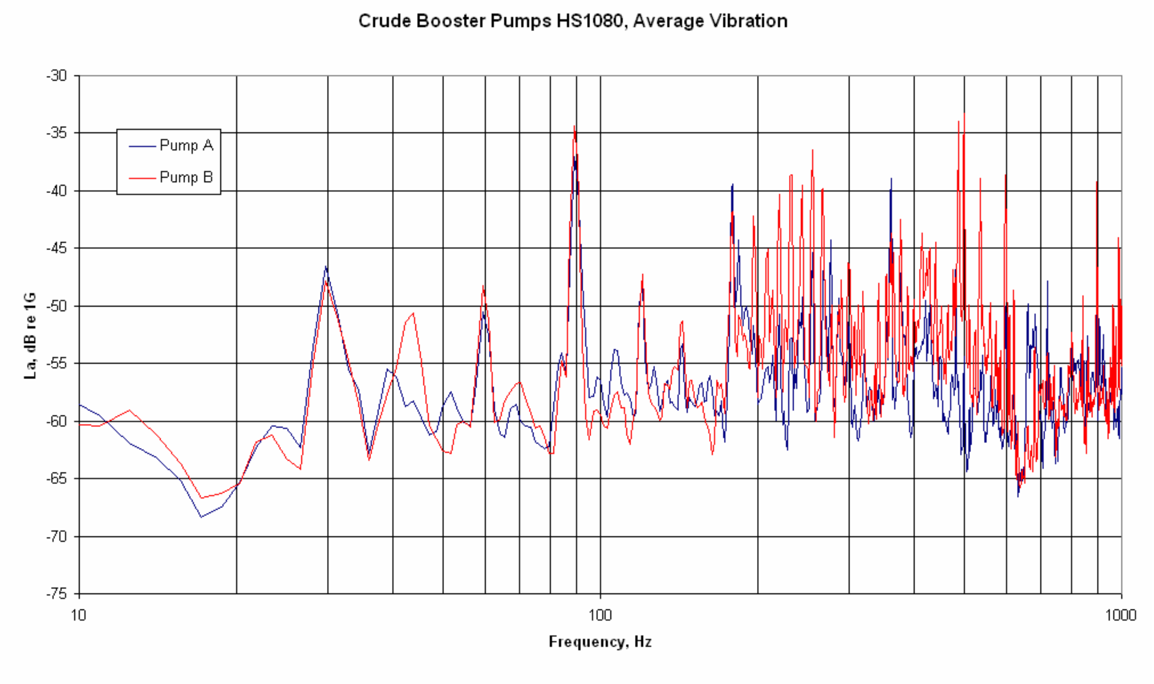

Figure 5.8: Crude Booster Pump Average Vibration

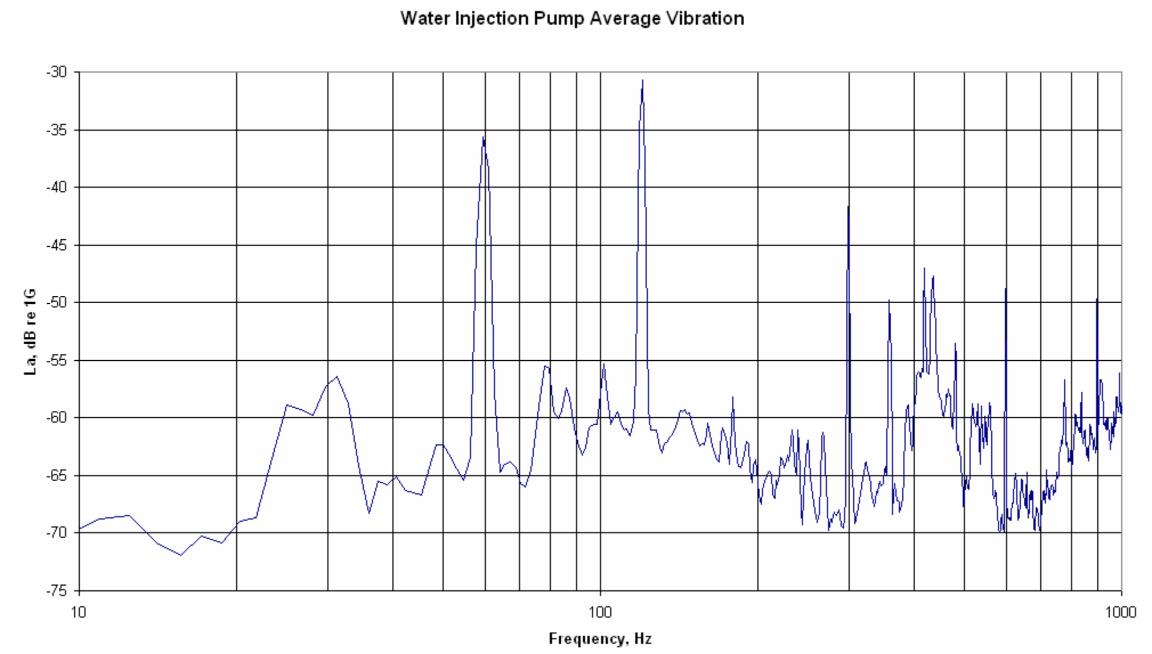

Figure 5.9: Water Injection Pump Skid Average Vibration

The maximum airborne noise amplitudes have been collected at primary tonal frequencies for each machinery item. It is assumed that the plate thickness near these pumps was approximately 3/8”[20], and the plate size between the smallest stiffeners was 3.3’ x 20’. The stiffener was assumed to be a C6x13 C-channel, with a cross sectional area of 3.8 in^2 and a moment of inertia of 17.3 in^4. A damping loss factor of 0.05 was also assumed. Given these inputs, the plate and stiffener vibration levels for each item are shown in Table 5.1. These levels are also compared to the measured foot vibration levels of each machinery item.

For the most part, the differences between the calculated Secondary Structureborne noise influence and the measured Primary Structureborne source vibration are quite extreme – typically 15 to 20+ dB differences are seen. The Crude Booster Pump levels are most similar at 60 Hz (3 dB difference), however the rest of the levels show an 8 dB minimum difference. From this analysis, it can be concluded that the Secondary Structureborne path is certainly not the dominant noise path. For those sources with low foot vibration levels at certain frequencies, Secondary Structureborne noise may play a supporting role; however it is not evident that the influence is strong enough to consider implementing noise control treatments[21].

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[20] It is noted that a thicker plate will give a stronger response at low frequencies. While the actual plate thickness is not known, it is believed that it is no thicker than 3/8”.

[21] In other words, a more significant reduction in underwater noise can be achieved by treating the Primary Structureborne Path before using any treatments for the Secondary Structureborne Path.

Table 5.1 – Secondary Structureborne Source Calculation

	Frequency, Hz			
	30	**60**	**90**	**120**
Oil Shipping Pump Lp, dB re 20 μPa	79	95	85	88
Plate La, dB re 1G	-58	-43	-54	-51
Stiffener La, dB re 1G	-61	-48	-59	-58
Measured Foot Vibration, dB re 1G	-53	-29	-48	-28
Difference	-8	-19	-11	-30
Crude Booster Pump Lp, dB re 20 μPa	78	92	89	84
Plate La, dB re 1G	-59	-46	-50	-55
Stiffener La, dB re 1G	-62	-51	-55	-62
Measured Foot Vibration, dB re 1G	-47	-48	-34	-47
Difference	-15	-3	-21	-15
Water Injection Pump Lp, dB re 20 μPa	-	88	-	95
Plate La, dB re 1G	-	-50	-	-44
Stiffener La, dB re 1G	-	-55	-	-51
Measured Foot Vibration, dB re 1G	-	-36	-	-31
Difference	-	-19	-	-20

5.4 DIRECT UNDERWATER RADIATION

5.4.1 Sea Connected Pumps

Any pump that has a pipe in direct contact with the sea has an obvious noise path and can radiate underwater noise. As discussed in Section 2.1, sea connected pumps on Northstar include the Utility Water Pump, sewage and potable water systems, and the Alternate Seawater Intake Pump.

Given the test methods described in Section 3, it is not possible to completely confirm whether or not these sources contribute significant underwater radiated noise levels – sound pressure levels inside of piping or near piping outlets were not measured. Generally, it is possible to infer that the tonal frequencies measured in the foot vibration would also be present in the fluidborne noise spectra (i.e. sound pressure levels in the attached piping) to some degree. The Utility Water Pump was measured for vibration and strong tones were detected, some of which were below 100 Hz. An attempt was made at measuring the vibration on the piping for the Alternate Seawater Intake Pump (which is submerged and inaccessible) to determine possible tones created by this pump, however the measured data did not indicate any particular prominent tones below 200 Hz, and was not conclusive. The sewage and potable water pumps were not measured.

Pumps used for typical ship applications have been seen to create fluidborne source levels in the fluid being pumped with amplitudes of 130 -180 dB re 1 μPa at low frequencies (<200 Hz), and possibly higher for very large pumps [23, 24]. Note that these levels are dependent on the type of pump, impeller dimensions, speeds of operation, load, etc. As a second point of reference, measurements of the noise levels in an aquarium where pumps are used to cycle 2000-3000 gallons of water per minute through several exhibits show tones at 60 and 120 Hz with levels of approximately 115 dB re

1μPa [25][22]. Higher frequency tones were also measured at lower amplitudes. These levels were measured in the middle of large exhibits, a minimum of 30 feet from any piping. Details necessary to predict the fluid source level for the sea connected sources on Northstar are not available.

It should be noted that the structural setup of the cofferdam and piping seen in Figure 2.4 can actually have an acoustical performance similar to a muffler. An estimation of the performance of such a muffler, using the cofferdam and pipe dimensions seen in Figure 2.4, is presented in Figure 5.10. This is a calculation based on an expansion muffler design where a pipe leads into a large chamber and a separate pipe leads away from the chamber [26]. It is seen that given this setup it is possible to achieve significant transmission losses at critical frequencies of interest.

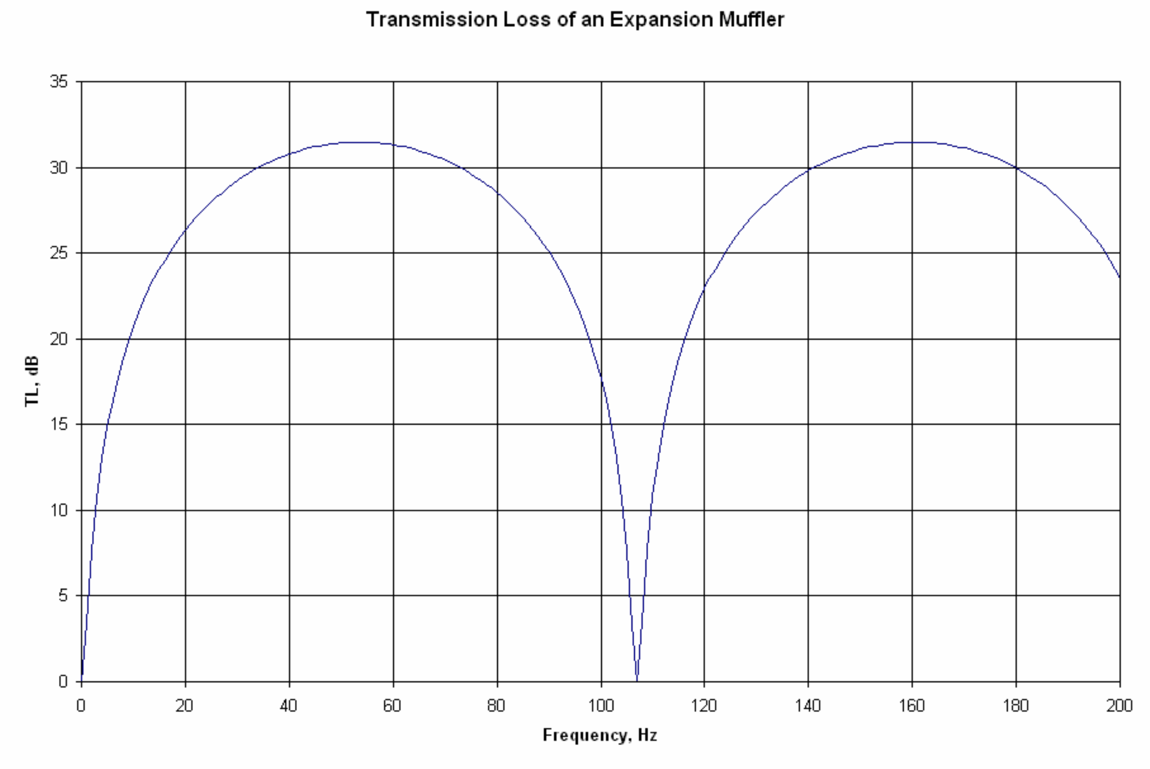

Figure 5.10: Estimation of Cofferdam TL

It is important to note that this calculation is a first order approximation based on first principles. Several factors have not been taken into account, not the least of which is the fact that the top surface of the water in the cofferdam is a “free” surface, as opposed to a hard wall. The purpose of performing this calculation is more to show the fact that this kind of arrangement has the potential to reduce noise levels produced by pumps drawing water from a cofferdam, particularly at frequencies of interest (30 Hz, 60 Hz, etc).

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[22] The levels listed in [25] are PSD with a 12 Hz bandwidth. It is noted that the underwater noise levels given in this report are PSD with 1 Hz bandwidth (for 2002 data) and Power Spectrum with bandwidths near 1 Hz (all other data). With respect to tone amplitude, these latter two analysis methods are roughly equivalent. The levels of [25] have been adjusted in this report by 10*log(BW), or approximately +11 dB, to account for the difference in analysis method.

All of this being said, this path certainly offers the potential for significant underwater radiated noise[23] and should be considered when designing future gravel islands.

5.4.2 Pipeline

Noise radiated directly by pipes into their surrounding fluid has been seen on occasion to cause noise problems, particularly in ships. In the case of underwater noise radiated by submerged piping, the path of interest is as follows:

- Fluidborne noise is created by a pump in the attached piping.
- The noise travels in the fluid through the pipe to a location where it can be radiated.
- The pressure variation of the fluid excites the pipe walls, which in turn vibrate and radiate noise into the surrounding environment.

As mentioned in Section 2.1.2, the pipe wall thickness for all pipelines leaving Northstar is 0.594”. It is estimated that the transmission loss through a pipe of this size at frequencies below 200 Hz is on the order of 40 to 70 dB [23]. Further to this, the pipe is located under 9 feet (typically) of fill (assumed to be gravel), which will add to the acoustic losses for this transmission path.

An attempt has been made to calculate the noise radiated by the pipeline. The fluidborne noise levels have been estimated based on various parameters of the Oil Shipping Pump and the approach described in [24]. Parameters required for this calculation are presented in Table 5.2. Static pressure and volume flow rate were taken from [27]. Pump RPM and the number of blades was inferred from the measured vibration data. The type of pump was estimated based on photos taken during NCE’s survey.

Table 5.2 – Source Parameters Used for Fluidborne Pipeline Noise Calculation

Parameter	Value
Static Pressure in Pipe	850 psig
Volume Flow Rate	65,000 barrels/day
Pump RPM.	3600
Number of Pump Blades.	10
Type of pump	Centrifugal

Given this input information and the fact that the Oil Shipping Pump produces vibration tones at 60 and 120 Hz, it was estimated that there are 60 and 120 Hz fluidborne tones in the pipeline at the pump with magnitudes of 175 and 174 dB re 1μPa, respectively. Assuming no losses in the fluidborne level as the sound travels away from the source, this would produce pipeline wall vibration levels of -30 and -27 dB re 1G at 60 and 120 Hz,

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[23] The findings given here indicate that the sea connected pumps may contribute to the measurable underwater radiated noise near Northstar, however the findings are not conclusive. That being said, it is possible that pumps on future gravel islands will have higher source levels than those found on Northstar, thereby creating higher underwater noise levels.

respectively [23]. For a pipe in water, this would result in a radiated sound pressure level of 127 and 128 dB re 1µPa at 1 meter at 60 and 120 Hz, respectively [28].

This is a significant level relative to the measured levels seen in Sections 2 and 4. However the losses from the pipeline being located below the sea floor have not been accounted for. Unfortunately, there is no good model to determine exactly what these losses are. A rough guess would be 20 dB, although actual values could be significantly different. Assuming the ground provides 20 dB of attenuation, and assuming cylindrical spreading (10 log(distance)), at 400 meters away the received levels at both frequencies would be on the order of 80 to 85 dB re 1µPa. Inspection of the underwater noise data provided in Sections 2 and 4 show noise amplitudes that are near or lower than this level.

Since the pipeline is on the south side of the island it may not be possible for it to be effectively detected at measurement locations on the north side. The rough calculation shown here does indicate that some significant noise levels may be radiated by the pipeline. The largest factor of uncertainty is the loss associated with the piping being located under the sea floor. This is certainly an area that would require further study in order to be able to make a more definitive conclusion. Based on this analysis alone, it is not possible to absolutely state that pipeline radiated noise is or is not a significant factor for underwater radiated noise from gravel islands.

6.0 SOURCE IDENTIFICATION

In the previous section it was found that the dominant paths of noise from Northstar to the sea are through the Primary Structureborne path and via direct radiation from sea connected systems. Both airborne noise paths (direct and Secondary Structureborne) were seen to have minor influences at best.

For sea connected pumps, it is clear which sources need to be treated. This section will attempt to determine the major sources of Primary Structureborne Noise with the purpose of limiting the potential scope of items that would require treatments.

6.1 TONE OVERVIEW

Foot vibration measurements of the equipment listed in Section 3.2 show that while some broadband level variations exist from item to item, the dominant levels are at specific frequencies (i.e. tones). Figure 6.1 is a plot of the average vibration levels measured on the foundation of the SOLAR generators, and Figure 6.2 is a similar plot showing the foot vibration of the HP Compressors (turbine and compressor ends shown separately – note this is a copy of Figure 5.3). Both plots are from 10-1000 Hz. These plots show the tonal nature of these machinery sources, and are indicative of all low frequency vibration data collected on Northstar.

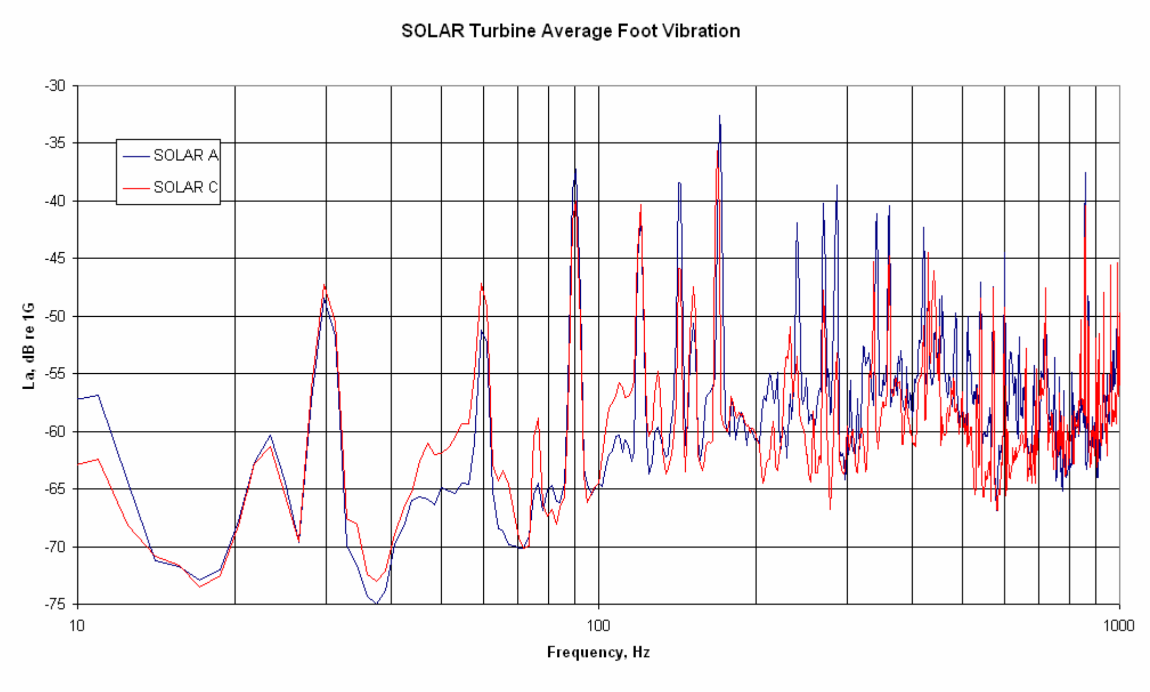

Figure 6.1: SOLAR Average Foundation Vibration

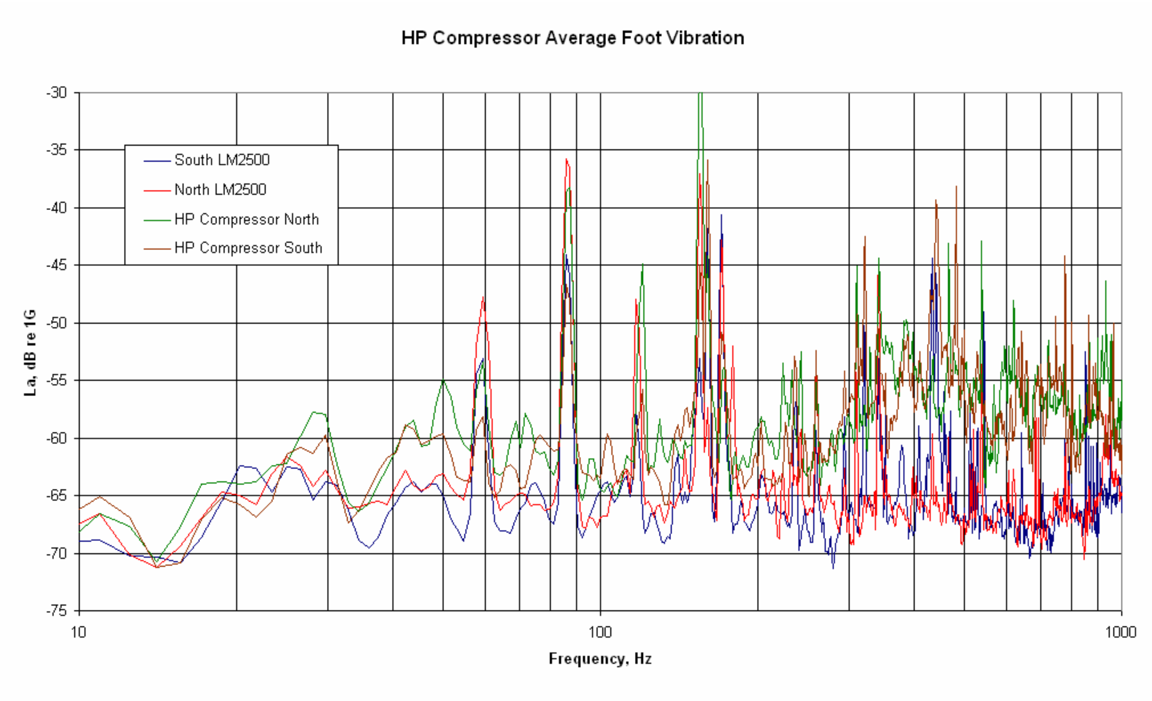

Figure 6.2: HP Compressor Average Foundation Vibration

Analysis of the SOLAR vibration shows that several strong tonal peaks exist below 200 Hz; 30, 60, 90, 120, 143, and 170 Hz are all very strong tones. Secondary tones at 11, 23, 46, 77, and 152 Hz can also be seen, but these tones are generally 10 to 15 dB lower than the next closest “strong” tone. Similar conclusions can be reached from the HP Compressor data; strong tones are seen at 60, 85, and (approximately) 120 Hz, whereas secondary tones are seen at 30 and 50 Hz.

Given the fact that several strong tones exist, it is expected that these frequencies would be most noticeable in the underwater noise readings. In fact, the tones that are seen in nearly all underwater noise readings, specifically, 30 and 60 Hz, are certainly seen as strong tones in the SOLAR data (see Section 4). Other tones that are seen occasionally in the underwater data, such as at 45 Hz, may be attributable to the 46 Hz secondary tone seen in the SOLAR vibration. That being said, this would probably occur only if the loading of the SOLARs was different than what was measured on the day the vibration data was collected[24]. This condition seems less likely than simply stating the less prominent vibration tones cause less detectable (or undetectable) underwater noise. This assumption is supported by comparing vibration measurements at the base of the pillars under the South Process Module, shown in Figure 6.3, to the SOLAR vibration. The pillar vibration measurements show relatively large tones at the prominent vibration frequencies of the SOLARs (and Oil Shipping Pumps and Crude Booster Pumps, also located near the measured pillars), particularly below 200 Hz. As such, this report will focus on primary tone creation only, as measured during NCE’s site visit.

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[24] Minor differences in analysis techniques can also produce this apparent 1 Hz shift in frequency.

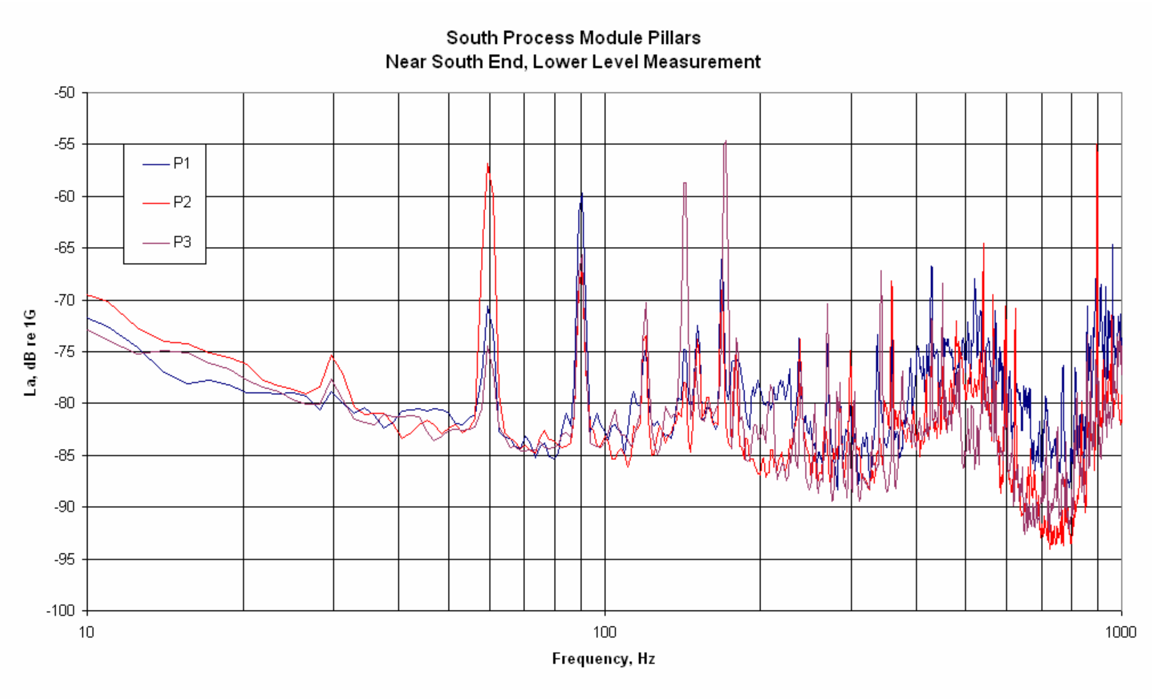

Figure 6.3: Vibration at Base of SPM Pillars

Lastly, it is noted that the HP Compressors have tones that are at 120 or 117 Hz, depending on the compressor. This is important to note that since these compressors are identical by design, they must have been operating under slightly different conditions during NCE's site visit. It would be appropriate to conclude from this fact that some machinery tones do shift in frequency within a few hertz depending on the specific day/condition. This may help to explain some of the small frequency variations seen in the underwater noise data (Sections 2 and 4).

6.2 LISTING OF VIBRATION TONES

A list of prominent tones below 200 Hz for each of the measured equipment items is given in Table 6.1. This table is broken down by location (i.e. module and level, as applicable). When selecting prominent tones, tones that are lower than 10 dB below the two adjacent tones were excluded. The average foot vibration levels for each tone are also provided. Those frequencies that exactly match or are within 1 Hz of the underwater tones listed in Table 4.3 are highlighted in red.

Inspection of Table 6.1 shows that most of the prominent machinery vibration tones below 150 Hz are seen in the underwater noise data. This is particularly true for large equipment items located on Level 1 of their respective modules. It should be noted though that some of the tones listed in Table 4.3 were not seen as being prominent in the vibration data (although most of these tones did exist in some form). This discrepancy may be due to several factors, such as the fact that not all equipment over 50 HP was able to be measured, and systems with direct piping connections to the sea may also account for some tones in Table 4.3.

Table 6.1 – Prominent Vibration Tones for Machinery (La dB re 1G)

Location	Equipment Item	Frequencies of Prominent Tones, Hz					
		Average Source Amplitude, dB re 1G					
SPM, L1	SOLAR Turbines	30	60	90	120	144	170
		-47	-50	-38	-40	-43	-34
	Oil Shipping Pumps, P1130	60	120	180			
		-32	-28	-44			
	Crude Booster Pumps, HS1080	30	39*	44*	60	90	180
		-47	-56	-51	-49	-36	-41
SPM, L2	Air Compressors	30	60	89	120	148	167
		-45	-55	-50	-50	-50	-53
	Heat Media Circulation Pump	30	60	71	90	101	126
		-58	-53	-50	-57	-53	-55
		134	150				
		-55	-53				
	Glycol Pump	60	90	120			
		-59	-50	-42			
	AHU 5055A	15	23	34	44	60	69
		-49	-54	-54	-59	-58	-58
		85	103	134			
		-58	-52	-49			
SPM, L3	AHU 5055B	134					
		-32					
	Seal Blowers 4770	60	120	179*			
		-28	-36	-22			
NPM, L1	Ventilation Fans	30	60	89	119		
		-25	-45	-40	-54		
Pump House	Water Injection Pump Skid, HS3160	60	120				
		-36	-31				
	Water Booster Pumps, P3040	50	60	120			
		-47	-34	-34			
Compressor Module, L1	HP Compressors	60	86	117*	120*	155	161
		-53	-40	-48	-45	-40	-40
		170					
		-42					
	LP Compressor	60	87	105	120	155	
		-43	-57	-50	-36	-35	
Compressor Module, L2	Flare Blower	20	33	52	60	72	77
		-50	-52	-50	-45	-46	-46
		83	108	112	116	142	154
		-47	-48	-47	-46	-47	-40
Warehouse	Utility Water Pump	60	119	145			
		-39	-41	-46			
Utility Module	Water Injection Pump	20	25	38	50	63	75
		-55	-55	-45	-45	-45	-50
		88	114	126	152		
		-43	-45	-47	-42		
Outside on Pad	Load Bank	30	40	88	120	154	175
		-52	-57	-43	-53	-56	-42
	Refrigeration Plant	30	73	120			
		-54	-54	-47			

*Indicates tone for one out of multiple units

Table 6.1 shows that most equipment items have tones at 30 or 60 Hz, or both, which are the two tones that are seen most consistently in the underwater noise measurements. As such, further efforts are needed to narrow down the probable contributors to these tones. This is addressed in the next section.

6.3 FINITE ELEMENT ANALYSIS

It is noted that the vibration levels measured on the foot of any machinery item are the result of forces being applied to the foundation by the machinery combined with the "impedance" of the machinery foundation, i.e. the ability of the foundation to move when forced. For example, equipment items such as the SOLAR turbines and HP compressors have much stiffer foundations than the Oil Shipping Pumps, and as such a given vibration level on a stiff foundation will actually be the result of a higher force as compared to the same level on a weaker foundation. To compare the actual influence of machinery items on various foundation types, it is desired to know the amplitude of the force is that is imparted to the gravel by the module pillars from each equipment item. This is directly related to the magnitude of the force at the source and the details of the surrounding structure.

In order to quantify the pillar force on the gravel, a representative Finite Element Model was created. This model was based on the construction of Northstar's South Process Module, from the Base to Level 2. Drawings showing the major stiffeners of the SPM (and other modules) were provided by BP. Level 1 of this drawing is shown in Figure 6.4 for reference.

It is noted that the Finite Element Model is only loosely based on the actual SPM for several reasons:

- Some details of structures were not known, such as the actual size and locations of small stiffeners (not shown in Figure 6.4 or other drawings). Estimations were made based on pictures and measurements taken during NCE's site visit.
- Plating was not included in order to simplify the model. It is implied in the arguments of Section 5.3 that the stiffeners carry the majority of the vibration for any given module. While some flanking may exist through the plating, it is assumed that this is a secondary effect.
- Attachments to the NPM and structures above Level 2 have not been modeled to reduce the model size.

As such, the model is intended to provide a guideline, or first approximation, for how vibration travels through a module similar to that seen on Northstar, and what kinds of forces are transferred to the gravel by various machinery items.

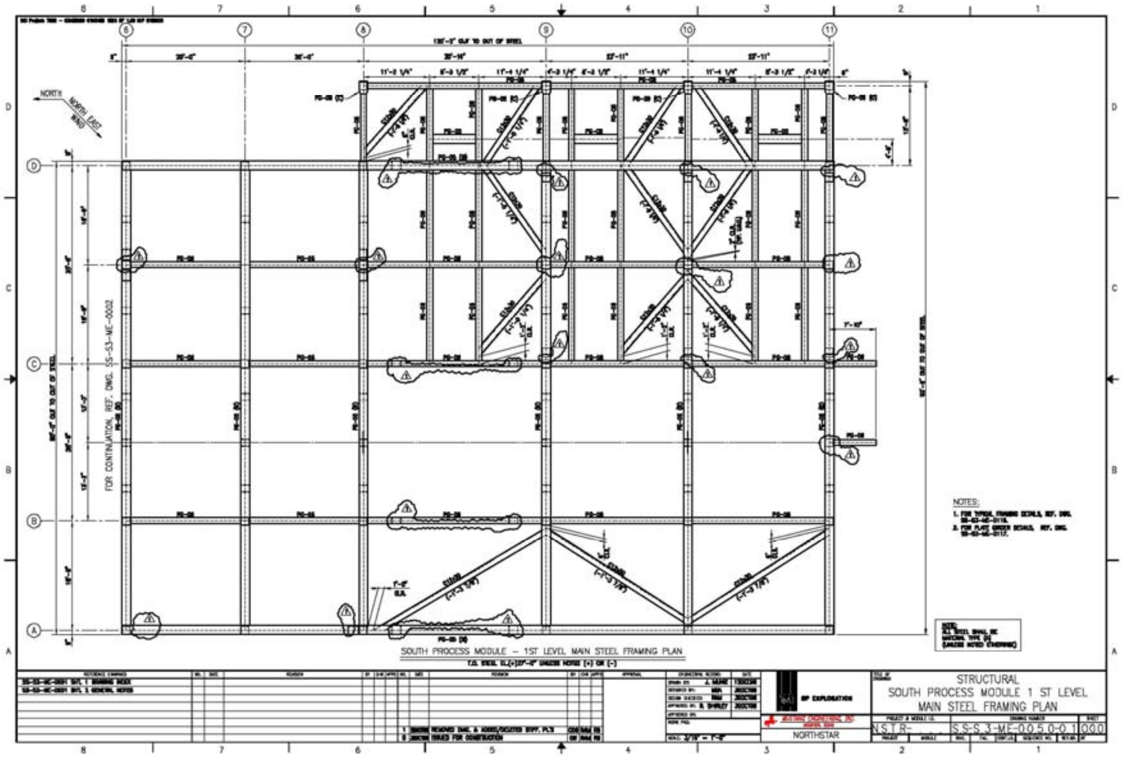

Figure 6.4: Diagram of South Process Module

Figure 6.5 shows a screen capture of the model that was created. This is a view of the southeast corner of the module, looking northwest. Table 6.2 gives a list of the beams that were used in the model and their locations. The bases of all pillars were constrained in all translational degrees of freedom. Vertical forces were applied to various locations in the model to simulate the forces from machinery items. These locations are as follows:

- "SOLAR Stiff" – North side of SOLAR C at first intersection of major stiffeners (i.e. Beam type #1) towards east side of SPM. Between locations D11 and D10, as defined in Figure 6.4. (Seen as green arrow in Figure 6.5).
- "SOLAR Weak" – North side of SOLAR C, between intersections of major stiffeners (i.e. Beam type #1), middle of SOLAR foundation (located just east of "SOLAR Stiff" location).
- "Mezzanine" – Mezzanine level above SOLAR C, on Beam type #2 midway between intersections of major stiffeners, on North/South Beam "D" as defined in Figure 6.4.
- "Oil Shipping Pump" – On small stiffener (Beam type #6) on Level 1, between locations C-10 and B-9 as defined in Figure 6.4 (approximate location of Oil Shipping Pumps).
- "2nd Level Large" – On 2nd level large stiffener (Beam type #2) on East/West location 10 between North/South locations B and C, as defined in Figure 6.4.
- "2nd Level Med" – On 2nd level medium size stiffener (Beam type #5) between locations B10 and C11, as defined in Figure 6.4.

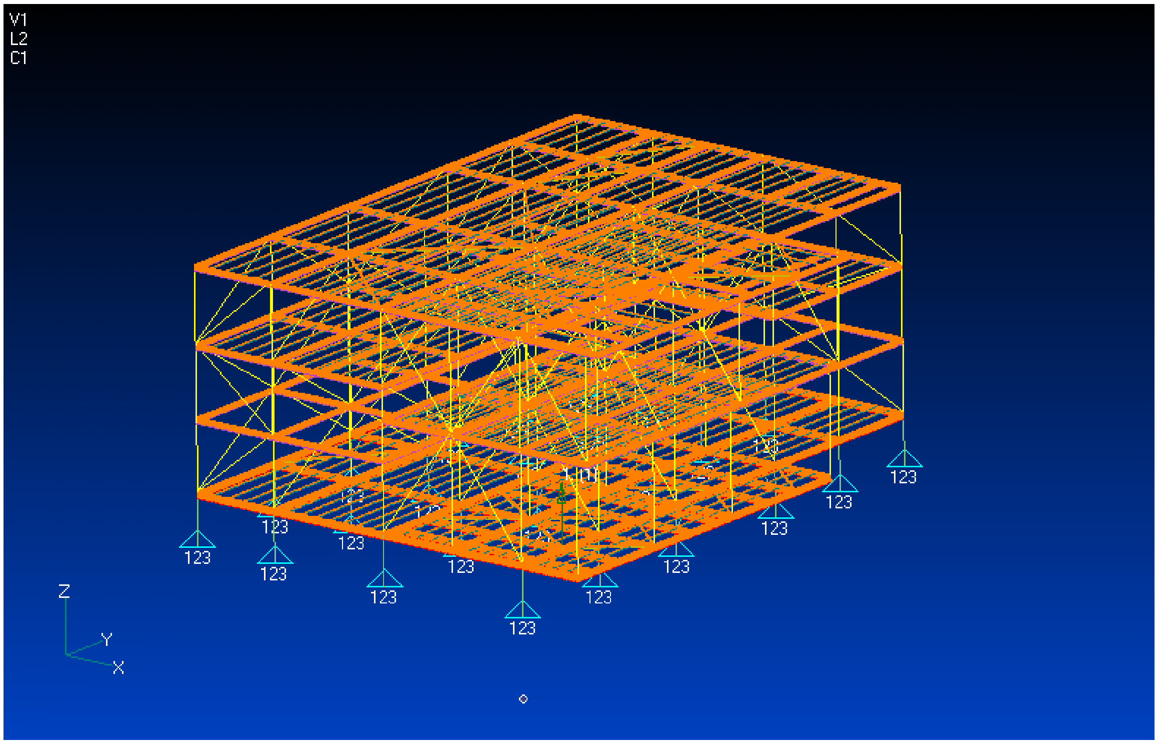

Figure 6.5: FEA Model of Process Module

Table 6.2 – Beam Sizes used in FEA Model

Beam #	Beam Size	Locations Used
1	W36x230 I-Beam	Floor, Level 1
2	W30x108 I-Beam	Floor, Higher levels
3	I-Beam, 16”x16”, 0.75” Flange thickness, 1.5” web thickness	Pillars from Level 1 to Base
4	12”x12”x5/16” Rectangular Tube	Vertical and Angled members between levels
5	C 12x30 C-Channel	Large Cross-brace members spanning larger I-Beams on all floors
6	C 6x13 C-Channel	Small stiffeners on all decks

A 1 lbf force was independently (i.e. one force at a time) input into these six locations between 10 and 100 Hz. A damping loss factor of 0.06 was used for all frequencies. The acceleration at the point of force application and the vertical reaction forces at all pillar bases were extracted from the results.

Figure 6.6 shows the accelerance (i.e. acceleration per unit force) at each location described above. Note that this is another way of describing the impedance of the structure at the source[25]. It is clearly seen that the smaller stiffeners allow higher vibration levels for the same force input.

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[25] Impedance is defined as force divided by velocity.

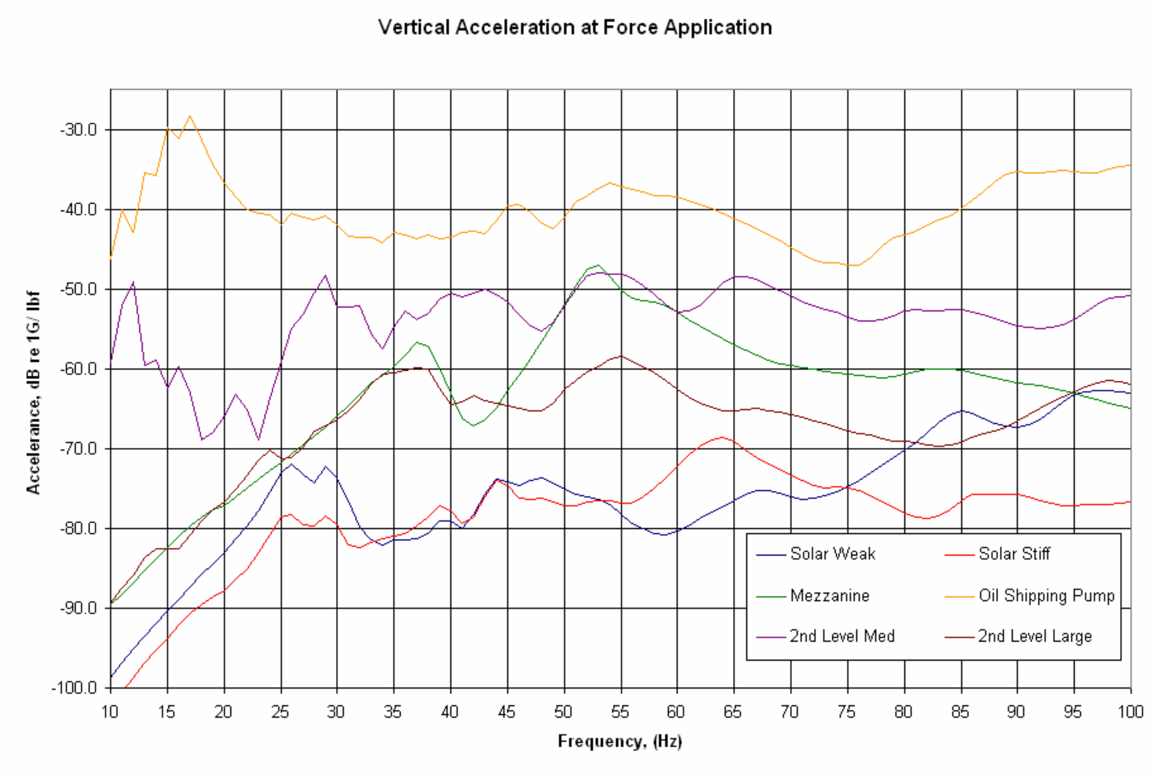

Figure 6.6: FEA Results – Accelerance

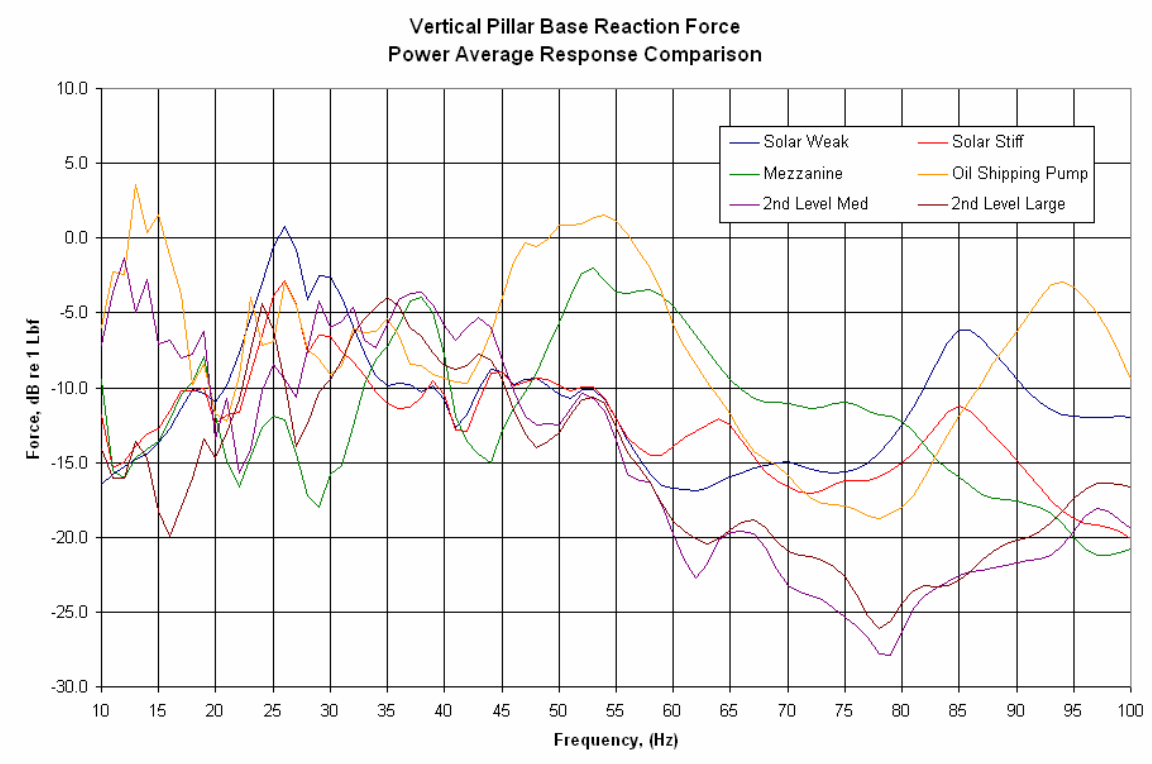

Figure 6.7: FEA Results – Reaction Forces

Figure 6.7 shows the power averaged vertical force response at the pillar bases to each input force. Figures 6.6 and 6.7 can be combined with the measured foot vibration levels to gauge the relative force at the gravel for each source by using the equation

$$L_f = L_{f,1lbf} - L_{a,1lbf} + L_{a,meas} \qquad (6.1)$$

where L_f is the computed pillar base force, $L_{f,\ 1lbf}$ is the calculated reaction force at the pillar base due to 1 lbf, $L_{a,\ 1lbf}$ is the acceleration at the point of force application in the FEA model, and $L_{a,\ meas}$ is the measured foundation acceleration. For example, for the "SOLAR Weak" source at 30 Hz, the predicted reaction force and acceleration are -2.6 dB and -73.7 dB, respectively. The actual measured acceleration level is -47 dB (from Table 6.1). Thus, the resulting pillar base force is 24 dB re 1 lbf[26]. Performing the same calculation for the Crude Booster Pumps (using the "Oil Shipping Pump" FEA location which is close by), the pillar base force is -14 dB re 1 lbf at the same frequency. This is a 38 dB difference, and is an indicator that the Crude Booster Pump is not significant at 30 Hz relative to the SOLAR Turbines.

This procedure was carried out for the majority of the measured sources. Table 6.3 shows the source locations from the FEA model that were used in Equation 6.1 for the calculation of pillar base forces from all measured sources. These locations were selected based on the approximate size of the equipment foundations and/or stiffeners located under the foundations. For sources in the SPM, most modeled locations are close to the actual source locations. For sources in other locations the results are more approximate; however the construction of the various modules is largely the same in a "big picture" sense. That being said, it should be restated that these results are only approximate, order of magnitude type levels to get a sense of the major players.

In addition, some sources were not included in this analysis (labeled as "Not Modeled" in Table 6.3). AHU 5055B was not included because it is located on the 3rd level of the SPM and the results from AHU 5055A could be considered to be similar. Similarly, the Seal blowers, Warehouse Water Pump, Utility Module Water Injection Pumps, and sources located outside of modules were not included because these locations were not modeled and/or the structure below these sources is not known. The NPM ventilation fans were not included as the foundation was found to be very weak, (giving an exaggerated foundation vibration level). It is known from measurements of the NPM pillar closest to these fans that this is not a critical source.

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[26] Note again that this is an approximate level based on the first order assumptions of the FEA model. The primary purpose in calculating this level is for comparison to other sources.

Table 6.3 – FEA Locations used for Actual Sources

Location	Equipment Item	FEA Location
SPM, L1	SOLAR Turbines	SOLAR Weak
	Oil Shipping Pumps, P1130	Oil Shipping Pump
	Crude Booster Pumps, HS1080	Oil Shipping Pump
SPM, L2	Air Compressors	2nd Level Large
	Heat Media Circulation Pump	2nd Level Large
	Glycol Pump	2nd Level Med
	AHU 5055A	2nd Level Large
SPM, L3	AHU 5055B	Not Modeled
	Seal Blowers 4770	2nd Level Med
NPM, L1	Ventilation Fans	Not Modeled
Pump House	Water Injection Pump Skid, HS3160	SOLAR Weak
	Water Booster Pumps, P3040	Oil Shipping Pump
Compressor Module, L1	HP Compressors	SOLAR Weak
	LP Compressor	SOLAR Weak
Compressor Module, L2	Flare Blower	Mezzanine
Warehouse	Utility Water Pump	Not Modeled
Utility Module	Water Injection Pump	Not Modeled
Outside on Pad	Load Bank	Not Modeled
	Refrigeration Plant	Not Modeled

Figure 6.8 shows the results of this analysis. For each source, predictions were made only for those frequencies that had prominent tones, as listed in Table 6.1. From this figure, it is seen that the SOLAR Turbines are expected to produce the highest levels at 30 Hz, followed by the Air Compressors. The Heat Media Circulation Pump and Crude Booster Pumps do not appear to be major sources at 30 Hz. At 60 Hz, the Water Injection Pump Skid, LP Compressor, SOLAR Turbines, and HP Compressors appear to be the major sources. Given the approximate nature of this prediction, it is possible but less likely that the Flare Blower, Oil Shipping Pumps, and Water Booster Pumps are also contributors at 60 Hz. Other sources do not appear to be significant at 60 Hz.

Looking at all frequencies, the major sources (of those included in this analysis) appear to be the SOLAR Turbines, HP and LP Compressors, Water Injection Pump Skid, Air Compressors, AHUs, and the Flare Blower, with possible minor contributions from the Oil Shipping Pumps and Water Booster Pumps. Note that all of these equipment items are rated at 800 HP or above, with the exception of the Flare Blower[27]. This fact is important when considering what machinery items may require treatments on future gravel islands. Further discussion is provided in Section 7.1.4.

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[27] The Flare Blower was noted at the time of the vibration survey to be mounted in a particularly weak location of the Compressor Module.

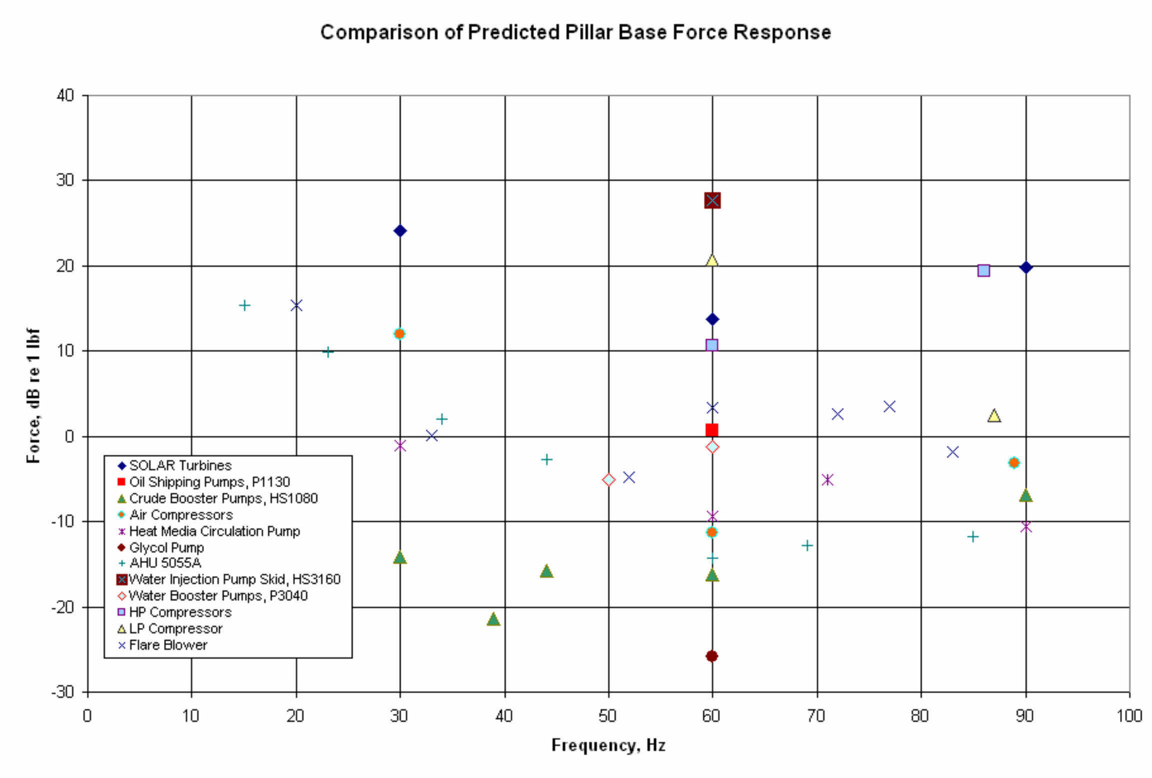

Figure 6.8: Calculated Reaction Forces Based on Measured Vibration

7.0 NOISE CONTROL RECOMMENDATIONS

The dominant noise paths and machinery items leading to measurable levels of underwater radiated noise near Northstar have been identified in the previous sections. It has been shown that low frequency noise radiation from the Primary Structureborne path and direct radiation from sea connected systems are the important issues that need to be addressed in order to reduce underwater radiated noise from gravel islands. In this section, specific noise control treatments are recommended for future gravel island designs. While these recommendations are based on the study of Northstar, they have been generalized and try to avoid specific details of Northstar construction (such as specific module layout or equipment locations). Since the recommendations given here are general, additional engineering efforts may be needed when designing new gravel islands.

It is assumed that future gravel islands will be roughly based on the design of Northstar. Important factors in this assumption include the following:

- The gravel making up the island will be compacted and will act as a bulk material at low frequencies (as described in Section 5.2)[28].
- The island will be located in "shallow" waters, i.e. waters where shallow water sound propagation effects are present[29].
- Equipment modules will be elevated above the gravel on pillars. The primary structural strength of the equipment modules will come from large beams.
- All equipment will be located such that direct airborne noise is not a viable noise path (see Section 5.1).

It is noted here that there will always be tradeoffs between the noise reduction resulting from applying a particular treatment and the impacts of that treatment on cost, weight, space, or other concerns. Within this section, approximations to the noise reductions expected from each treatment are given. Estimations of cost or other factors can not be given as they will depend on the specific gravel island design. It is assumed that the effectiveness and overall impact of each treatment will be weighed against the specific treatment costs by those who will be designing any future gravel island.

This section is separated into two parts: treatment recommendations for Primary Structureborne Noise transmission and direct underwater transmission through sea connected systems.

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[28] It is noted that gravel islands exist in locations other than the Beaufort Sea. While the requirement given in this chapter is simply for "compacted" gravel, the results given in this report with respect to the importance of the Primary Structureborne Path may not directly transfer to gravel islands in different climates due to specific gravel compositions, island designs, or installation methods. Specific studies of such structures are recommended.

[29] It is estimated that the maximum depth that is practical for any gravel island design is approximately 15 meters; shallow water propagation effects will certainly occur at this depth for low frequencies.

7.1 PRIMARY STRUCTUREBORNE TREATMENTS

As discussed in Section 5.2, the Primary Structureborne path is a dominant factor in the underwater radiated noise from gravel islands. For reference, it is restated here that this path consists of vibrations that are created at machinery attachments to the modules (at the machinery "feet") and travel through the structure (primarily through the stiffeners) to the pillar bases. From there, the vibrations are transferred to the gravel, carried to the perimeter of the island, and radiated into the water.

Two general approaches exist for reducing the noise generated along this path: source treatments and path treatments. While many treatments exist for structureborne paths as a whole, there are only a few options for gravel island structures. This is both due to the construction of the modules and the low frequencies involved. Details of the possible treatments are discussed below.

7.1.1 Structural Stiffness

7.1.1.1 Module Stiffness

It was noted in Sections 2.1 and 6.1.3 that the floors of the modules on Northstar are constructed primarily of large I-beams that are spaced approximately 18' apart from each other in a grid formation (see Figure 6.4). Between these large stiffeners are smaller stiffeners, typically oriented in one direction. Cross-bracing does exist between some large stiffener intersections. In addition, pillars are used to raise the modules off the gravel, which are also located at some of the large stiffener intersections.

Based on past experience with stiffened structures (i.e. surface ships) it is the belief of NCE that the existing spacing between large stiffeners is very large and conducive to large vibration responses, particularly at low frequencies. This can be directly evidenced by standing at the south end on the 1st Level of the SPM where significant low frequency vibration can be felt (and measured).

The effects of changing the stiffener spacing was investigated using the Finite Element Model discussed in Section 6.1.3. The model was modified as follows:

- Some small stiffeners (Beam type #6) were changed to large stiffeners (Beam type #1) on the 1st Level near the SOLAR Turbine foundations. Typically, two of the north/south oriented small stiffeners were changed between each previously existing large stiffener.
- The east/west oriented large stiffeners making the SOLAR foundations on the north side of the SOLAR C and the south side of the SOLAR B were extended to cover the full width of the module between locations A11 and C9, as defined in Figure 6.4.

The average large stiffener spacing in the modified section of the model is roughly 6 feet for north/south stiffeners and 12 feet for east/west stiffeners. The input force locations were the same as in the original analysis (beam sizes did change for some locations, including the Oil Shipping Pump location). Figure 7.1 shows the resulting accelerance at the location of force application for the SOLAR Weak and Oil Shipping Pump locations for both the original and modified designs. It is seen that the accelerance levels are significantly lower for the new model, indicating that for the same input force there will be less response from the structure. In addition, Figure 7.2 shows the average reaction forces at the pillar bases for both designs. It is seen that, for the most part, the reaction forces are lower in the modified model than in the original. This is particularly true for the peak force levels.

By inspection of these results, it is clear that increasing the overall stiffness of the module structures can reduce vibration and underwater radiated noise levels. This is particularly true at machinery foundations and the areas local to machinery items. Based on the above analysis, it is recommended that future gravel island module designs should use large stiffeners that are spaced approximately 6 feet apart, and no more than 12 feet apart. In general, shorter spacing should lead to a stiffer structure and lower radiated noise. Again, these modifications are more important near major machinery items. Locations far from major machinery do not require the module to be as highly stiffened (from a vibration perspective).

It should be noted that these recommended distances should be taken as general guidelines for future construction. The spacing best suited for any specific design will depend on the actual beam sizes that are used, the type of machinery that will be mounted to the structure, and module geometries. Similarly, it may be advantageous to add, remove, or move pillar locations to reduce the total force transmission to the gravel. It is strongly recommended that an analysis be performed (empirical, FEA, etc.) that will provide some estimate of the dynamic stiffness and force responses at the pillar bases due to machinery items[30].

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[30] It is noted that Figure 7.2 does show "modified" force responses at certain frequencies that are higher than in the original design. This is due to the shifting of resonances within the system. While the overall results shown here do indicate better performance, it is possible for a structure to have a resonant response at a forcing frequency of the local machinery. This is the primary reason why an analysis is recommended.

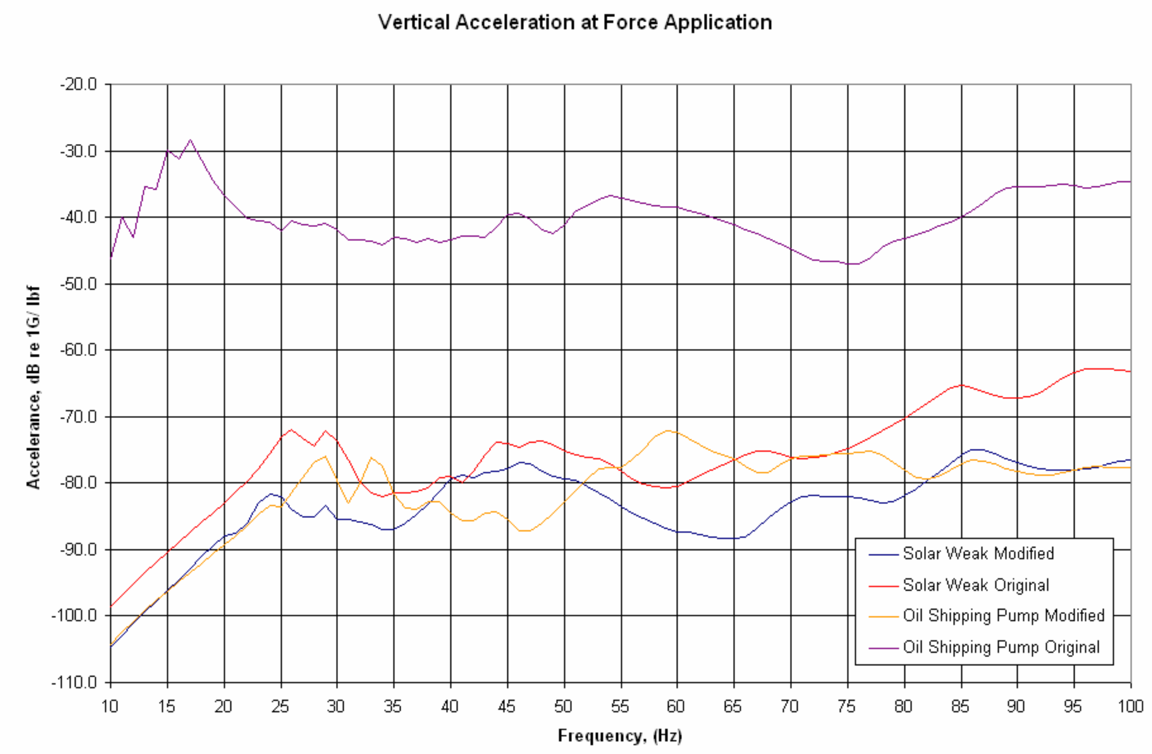

Figure 7.1: Comparison of Accelerance for Different Module Designs

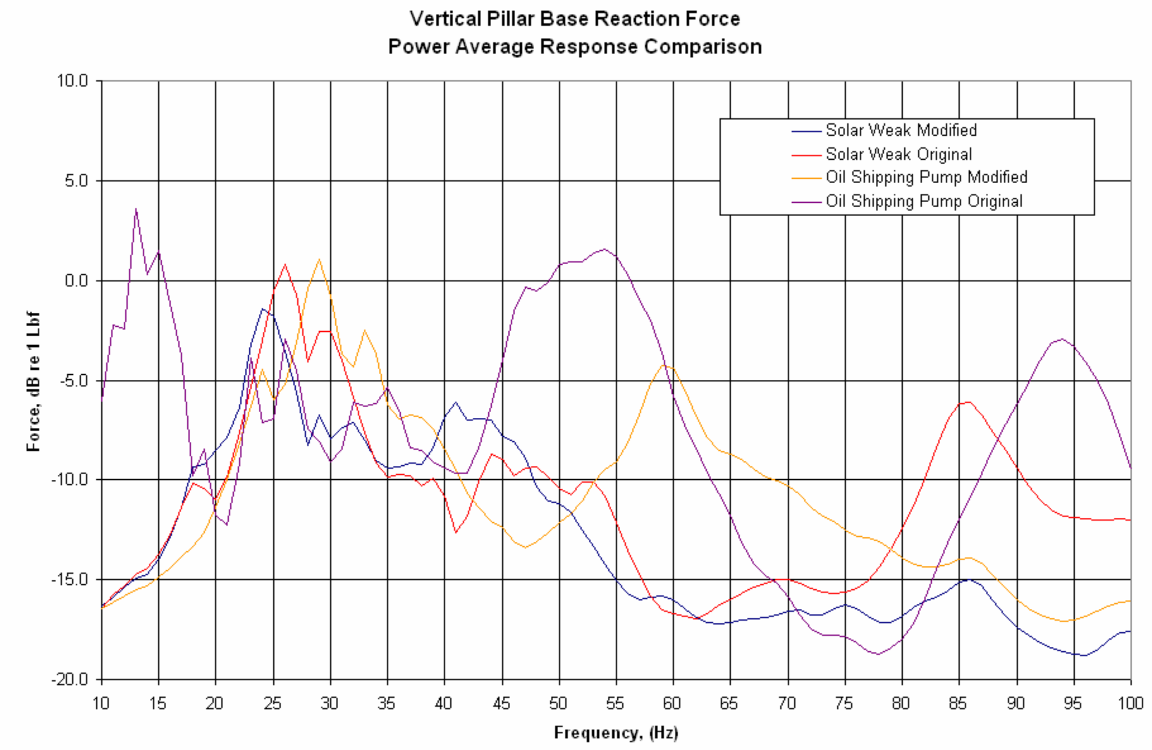

Figure 7.2: Comparison of Reaction Forces for Different Module Designs

7.1.1.2 Machinery Foundation Stiffness

In addition to the above assessment, it is noted that many of the equipment items on Northstar were mounted over relatively weak structural locations (in a vibratory sense). For example, the Oil Shipping Pumps and Crude Booster Pumps were mounted entirely over small stiffener locations, and the Air Compressors (2nd Level, SPM) were centered over a single larger beam. Although almost all machinery items had their own local foundations, these foundations were typically small and would not add significant stiffness to the structure, especially when the extended spans between large stiffeners is considered.

It is strongly recommended that foundations for all machinery items over 50 HP be located directly over medium to large sized stiffeners along at least two of the four foundation sides. Larger equipment items (based on weight and rated power) should be located on larger/stiffer foundations over larger/stiffer module supports. An example of this concept is shown in Figure 7.3.

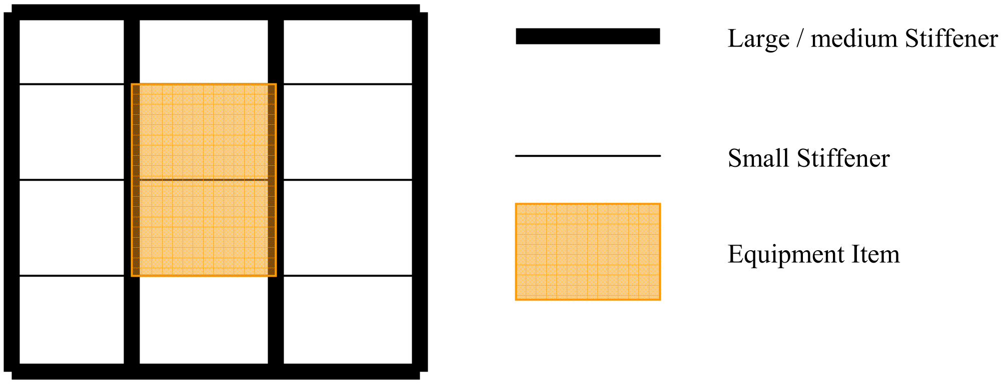

Figure 7.3: Preferred Machinery Foundation Location

7.1.1.3 Module Stiffness Summary

The total reduction in underwater radiated noise (compared to Northstar) that will be achieved by using the stiffening approaches described above will vary depending on the specific design. For small machinery items it is expected that large reductions in noise, i.e. 10 dB or more, can be achieved in some frequency ranges. For larger equipment items like the SOLARS, Figure 7.2 indicates that reductions on the order of 5 dB at 30 Hz would be gained, with higher attenuations at higher frequencies (for this specific design). More significant changes to the stiffening layout such as shorter distances between major stiffeners would most likely produce additional attenuations.

7.1.2 Resilient Mounting

Resilient mounting systems have been used in many marine and industrial applications to reduce the vibration levels that are transmitted to a supporting structure. Resilient mounts are simple, passive devices that are inserted between the machinery and its foundation. They are in effect springs that react to the motions of the mounted machinery in such a way as to reduce the transmitted accelerations / forces as compared to hard mounted machinery (i.e. machinery that is directly bolted to the supporting structure).

Figure 7.4 shows examples of typical resilient mounts. Mounts can be made of springs, elastomers (i.e. rubber), or a combination of the two. Typically, mounts made for industrial or marine applications are capable of withstanding exposure to oil or other corrosive materials. Check with the vendor regarding suitability in various environments[31].

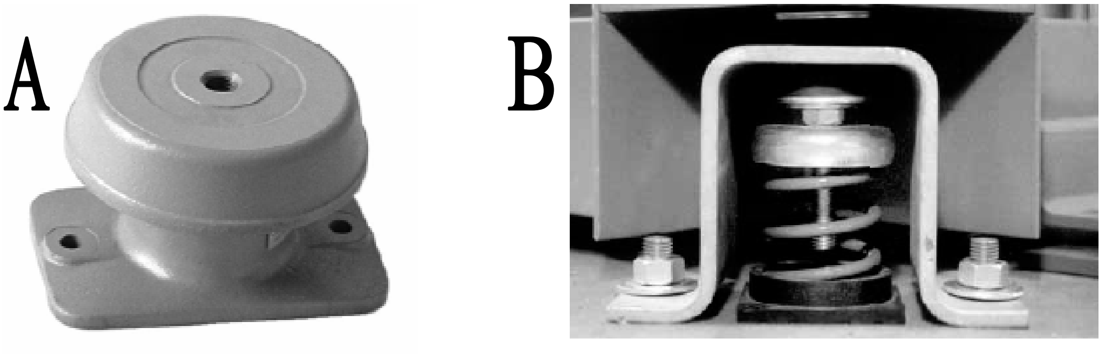

Figure 7.4: Typical Resilient Mount Types - Elastomeric (A) and Spring (B)

For any mass that is located on resilient mounts, the combined mass/mount system will have natural modes of vibration, or resonances. For a “single stage” system (i.e. a system where there is only one set of isolation mounts between the isolated item and the foundation) there are six natural “rigid body” modes. These generally correspond to translations and rotations in the three primary axes; however some coupling between modes often occurs. When a resilient mounting system is designed, it is necessary to keep the six natural rigid body modes below 1/3 to ½ of the lowest forcing frequency for the mounted item. I.e. for the SOLAR Turbines on Northstar, the lowest (major) forcing frequency is 30 Hz, so the highest of the six rigid body modes of the mounting system should be 15 Hz, 10 Hz ideally. General experience shows that this will require the first natural frequency to be approximately 3 Hz.

It is noted that it is typically easier to achieve lower rigid body frequencies with spring type mounts. This is because these mounts can be made to be softer and still have large displacement capabilities. A potential downside to spring type mounts is they generally have reduced isolation performance at mid to high frequencies; however, since

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[31] NCE has inquired about temperature suitability for elastomeric mounts and has found that most are rated to –40 to –60 degrees F.

frequencies above 200 Hz are rarely seen in the underwater noise measured near the Northstar, spring mounts are probably the preferred choice.

Single stage resilient mounting systems will typically offer vibration level reductions on the order of 5-10 dB at low frequencies, and up to 30 dB at high frequencies[32]. Mount performance is directly related to system resonance, with lower resonances resulting in higher transmission losses. Once forcing frequencies approach any of the resonances of the system, mount performance will degrade significantly and can even amplify vibration levels. For this reason it is important to design mounting systems with the lowest rigid body frequencies possible. Methods for calculating rigid body frequencies can be found in Reference [29] and can also be performed using FEA. In addition, some mount manufacturers will provide rigid body calculations.

Lastly, it is very important for the equipment foundations and module structures below resilient mounts to be very stiff in order for the mounts to be effective. This means that the general recommendations given in Section 7.1.1 should be followed even if resilient mounts are used. Resilient mounts should be located in areas of high local stiffness, such as the intersection of two large stiffeners. Subbases (i.e. structures above mounts supporting the equipment) also need to be made to have a high stiffness. Local gusseting should be used at mount locations for both the foundation and subbase.

A list of recommended resilient mount vendors is provided in Table 7.1.

Table 7.1 – Isolation Mount Vendors

Company Name	Website
Barry Controls	www.barrycontrols.com
Christie & Grey	www.christiegrey.com
Kinetics Noise Control	www.kineticsnoise.com
Lord Corporation	www.lordmpd.com
Trelleborg	www.trelleborg.com

Additional considerations and guidelines that should be followed when designing a resilient mounting system are provided in Appendix B.

7.1.3 Other Options

Two additional options for reducing the vibration path from machinery to the water are given here.

7.1.3.1 Large Scale Resilient Mounting

Instead of resiliently mounting individual equipment items, it may be possible to isolate a large area containing multiple equipment items. This can be done in several ways. The first general approach would be to design a large "raft" or sub-base upon which machinery items would be directly ("hard") mounted. The raft itself would then be resiliently mounted to the rest of the module. This approach is advantageous in that

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[32] NCE has measured transmission losses of 30 dB near 100 Hz for some well designed resilient mounting systems.

many machinery items can be isolated together, potentially eliminating the need for flexible connections between interconnected equipment. When using this approach, the raft should be designed to have sufficient stiffness such that it does not have any vibration modes near those of the total isolation system or the major forcing frequencies (i.e. RPM, blade rate, etc.) of any mounted equipment[33]. Ideally the raft will have its first natural mode at a frequency at least 3-4 times above the highest natural frequency for the mounting system; at a minimum no mode should be within 50% of the calculated rigid body modes of the system. The total weight of the raft and the mounted equipment must be taken into account when designing the mounting system[34].

As an extension of this concept, it *may* be possible to mount entire modules, or create an isolated module that only contains major machinery items. This approach certainly exploits the advantages of the raft design, as the only resilient connections that are necessary are those leaving module. However, the mass of such a module would be very large and extra care would need to be taken to design a proper mounting system that is evenly loaded. In addition, the module pillars, which currently resemble long cantilevers, would most likely need to be stiffened in the horizontal directions (or shortened if possible). It is noted that cantilevered beams are susceptible to very low natural frequencies and large responses. Cross-bracing that extends to or near the base of the pillars should be used to accomplish this. Lastly, resilient mounts often have "limit stops" and are "captive", meaning they have a limit to the allowed motion range and will not move beyond that point. This would be necessary to prevent against potential sources of disruptive excitation such as wind or seismic excitation.

7.1.3.2 Gravel Decoupling

Much of the above discussion has focused on the structureborne path through steel structures. However, it may be possible to decouple the modules from the gravel. Reference [30] shows the results of vibration testing in an area covered with dry sand. Concrete pads were placed in a large area where a trench was filled with loose sand, and the transmission loss between various positions was measured. One of the concrete slabs was excited by various impact methods and the response was measured on separate concrete pads at certain distances away. It was found that in the 63 and 125 Hz octave bands there was approximately 36 and 30 dB of attenuation for a 25 foot distance.

It may be possible to use the results of this testing to devise a method for decoupling the modules from the gravel island. A sketch of the concept is provided in Figure 7.5. The idea is that dry (non-frozen) sand is located between the concrete pillar footer and the gravel. A metal frame could be used to support the sand at the gravel interface. Given the results of [30], an approximate 10 dB reduction at low frequencies could be realized by using 8-10 feet of sand in all directions from the concrete footer (Dimension "A" in

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[33] In other words, the raft, taken as an entity floating in a vacuum, should not have natural modes of vibration near the modes calculated for the resilient mounting system assuming the raft is rigid. It should also have all modes higher than any (low frequency) forcing frequencies of mounted equipment.

[34] The only concern with this system is the potential for bearings of some non-operating machinery to go dry due to vibrations induced by adjacent operating equipment. This potential impact depends on relative vibration levels and bearing types or lubrication systems.

Figure 7.5). Naturally, in order to keep the sand dry it would need to be protected from the surroundings, possibly via sealed bags or rubber-lined plastic containers.

This idea is presented in concept form only. The data from [30], while promising, is not conclusive. Additional testing may be necessary before proceeding with such a design.

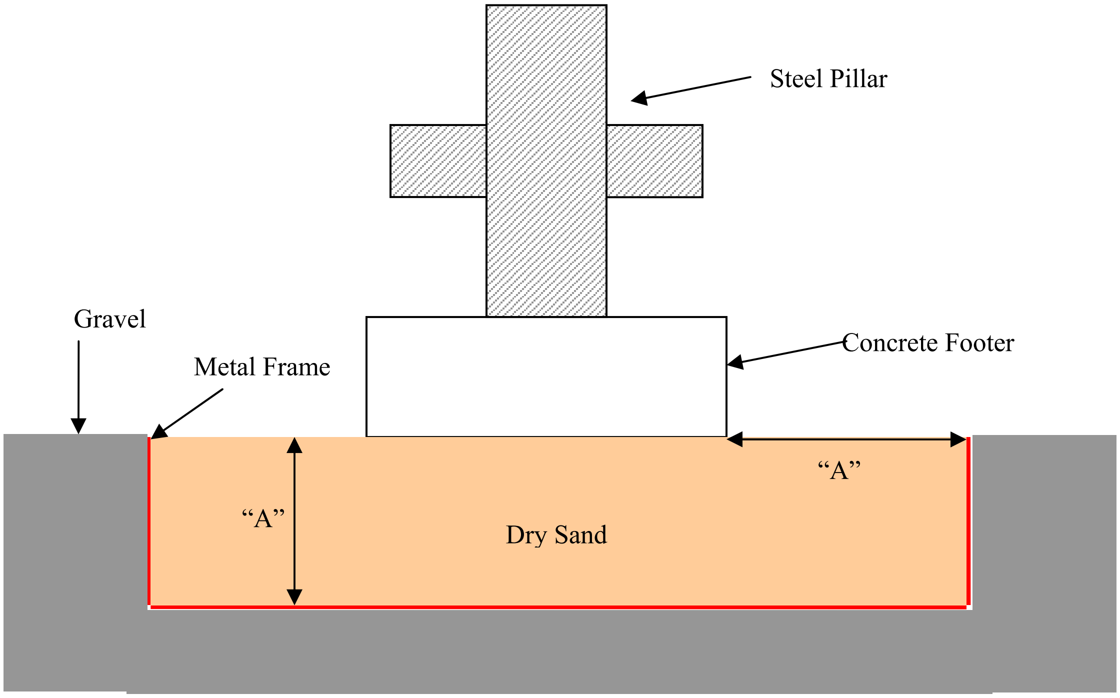

Figure 7.5: Decoupling Module Pillars from Gravel Using Loose Sand

7.1.4 Treated Equipment

The above sections have provided guidance as to potential noise control measures that can be taken to reduce the Primary Structureborne path from machinery sources. However, as seen in Section 6, not all sources require treatments. Generally, all sources will benefit from the increased stiffness module design described in Section 7.1.1. This is most clear from Figure 7.1 for the Oil Shipping Pump location. However, given the results of Section 6, it is not necessary to resiliently mount all equipment items.

For Northstar, it was found that the SOLAR Turbines, HP and LP Compressors, Water Injection Pump Skid, Air Compressors, AHUs, and the Flare Blower are major Primary Structureborne sources with possible minor contributions from the Oil Shipping Pumps and Water Booster Pumps. These equipment items are all rated at 800 HP and above with the exception of the Flare Blower[35]. If the exact equipment arrangement used on

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[35] As stated in Section 6, the Flare Blower was noted at the time of the vibration survey to be mounted in a particularly weak location of the Compressor Module. As such it should be particularly susceptible to the addition of stiffeners near its foundation.

Northstar were also used on future gravel islands, these equipment items would certainly be candidates for resilient mounting. It is noted though that this is not likely. Additionally, some equipment items were necessarily left out of the analysis in Section 6, and may also contribute significantly to underwater noise levels.

As such, the following recommendation summary is given for future gravel island designs, in order of importance:

1. Follow the guidelines given in Section 7.1.1 for the design of the modules themselves and machinery foundations. Foundation recommendations should be followed for all machinery items, particularly those greater than 50 HP.
2. Use resilient mounting systems for primary power generation units, HP/LP Compressors, and water injection pumps (or equivalent).
3. Use resilient mounting systems for all equipment over 500 HP.
4. For conservative designs, use resilient mounting systems for all equipment over 50 HP, particularly those items located on the 1st Level.

While a direct connection between the vibration produced by equipment items on the pad and underwater noise was not possible, it is likely that equipment not located in modules can cause significant underwater noise. It is recommended that all equipment be properly mounted (hard or resilient, as the case may be) inside of a module.

Lastly, it is suggested that some vendors of specific equipment items will provide units that produce lower vibration levels than others. In addition, certain pump and machinery types are preferred for similar reasons. While NCE cannot provide a list of specific vendors for low vibration equipment items, the following guidelines for machinery types can be given:

- Rotating equipment is preferred over reciprocating
- Gear type pumps typically produce higher vibration than pumps of other types. Screw pumps generally produce the lowest noise and vibration levels.

7.2 SEA CONNECTED EQUIPMENT TREATMENTS

As discussed in Section 5.4, pumps and other equipment with direct piping connections to the sea have the potential to radiate significant underwater noise levels. In addition, the submerged pipeline itself has been shown to be a potential contributor to detectable underwater radiated noise from gravel islands. Possible treatment options for these sources are discussed below.

Note that while the exact influence of these sources on Northstar could not be determined, it is important to highlight the fact that any system with a direct connection to the sea has the potential for significant underwater noise. Even if these systems do not contribute at all on Northstar, they may on future gravel islands due to the selection of equipment and specific system design. Also, keep in mind that it may be possible to use vendor data or direct measurements to evaluate the fluidborne noise contributions from these pumps on future gravel islands. This information could then be used to determine the necessity for noise control treatments.

7.2.1 Flexible Connections

Flexible pipe connections will help to reduce the in-pipe sound pressure levels by creating an "impedance mismatch" for both fluidborne and structureborne energy (i.e. vibration on a pipe) [31]. For this reason, flexible connections will help to reduce underwater radiated noise from both sea-connected equipment and equipment directly connected to the pipeline. Flexible connections should be assembled in a dogleg configuration with the use of flexible hose or double arch pieces. See Appendix B for details on designing flexible connections. Figures showing flexible connection arrangements are also given in Appendix B.

It is noted that typical flexible connections will significantly reduce high frequency underwater radiated noise; however low frequencies (i.e. below 200 Hz) may only see attenuations of 0-5 dB. This can be improved by using flexible hose lengths that are longer than in "standard" installations, and by selecting the most compliant hose possible for the given system.

In addition, it may be possible to use a pulsation damper to reduce underwater noise at low frequencies. Pulsation dampers are acoustical absorbers that are either located in-line with the pipe or in "parallel" (i.e. connected as a short, terminated branch to the pipe). Parallel dampers are "tuned" to have a resonant frequency equal to a specific frequency that is determined to be a problem (i.e. rotation rate or blade rate for a pump) and in a sense "sucks" that tone out of the fluid. In-line dampers typically use an air filled bladder that reacts to pulsations in the fluid. In-line dampers will be effective over a much greater frequency range than parallel dampers, however parallel dampers can have greater effectiveness. In addition, parallel dampers have the potential to operate at lower frequencies than in-line dampers. Specific measurements of the fluidborne noise created by a specific machinery item would ideally be performed in order to determine which method is more appropriate.

Recommended vendors of pulsation dampers are provided in Table 7.2.

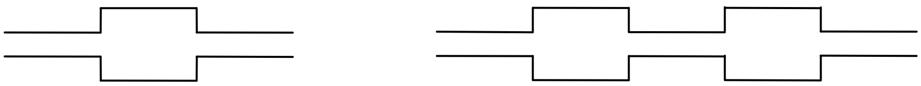
Table 7.2 – Pulsation Damper Vendors

Company Name	Website
Parallel Dampers	
Flexicraft Industries	www.flexicraft.com
In-line Dampers	
CoorsTek	www.coorstek.com
Wilkes and McLean, Ltd.	www.wilkesandmclean.com

7.2.2 Cofferdam Design

As discussed in Section 5.4.1, the cofferdam seen on Northstar can be considered to be an acoustic filter, capable of significant attenuations at low frequencies (as high as 20-30 dB). A first order approximation of the attenuation as a function of frequency is given in Figure 5.10. Given the potential for very good low frequency transmission loss performance, it is recommended that all sea connected systems draw or return water through a cofferdam. Note that the same cofferdam can be used for multiple systems, reducing the necessary footprint of this treatment.

It is recommended that the specific cofferdam design used on future gravel islands be analyzed to ensure proper attenuation performance. In addition, it may be possible to expand this idea to use multiple expansion chambers and pipes to get better response characteristics [26]. Examples of potential designs are provided in Figure 7.6.



Original Design Modification 2

Modification 1 Modification 3

Figure 7.6: Examples of Possible Extended Cofferdam Designs

7.2.3 Comments on Sea Connected System Treatments

Several options have been given to control underwater noise from sea-connected pumps. These treatments have been selected in an attempt to minimize the invasiveness of the noise control approach. Since direct measurements to determine the significance of noise from sea-connected systems were not possible, it is recommended that all of the above treatments be used (as is practical) until additional information regarding the significance of these systems is available. This will help to ensure these pumps have a minimum influence on underwater radiated noise.

It is noted that on Northstar the Alternate Seawater Intake Pump is actually submerged at the edge of the island. Again, the real contribution to underwater noise from this source is not known, however there is a great potential for significant noise generation both from pipe radiated noise and from noise radiated directly by the casing. It is strongly recommended that no pumps be located in the water surrounding the gravel island; all machinery items should be located in modules.

Lastly, as suggested in Section 7.1.4, another option would be to select pumps with low fluidborne source levels. General recommendations on "quiet" pump designs given in Section 7.1.4 apply here as well.

8.0 SUMMARY AND CONCLUSIONS

A study into methods of reducing underwater radiated noise resulting from production activities on gravel islands has been performed. The goal of this study is to develop treatments that can be used to reduce the underwater radiated noise from future gravel islands as compared with existing designs. Northstar Island, located approximately 9 km due North of Pt. Storkerson, AK in the Beaufort Sea, operated by BP Exploration (Alaska) Inc. (BP), was used as the primary case study to uncover the pertinent mechanisms of underwater noise radiation from gravel islands. This study has been limited to noise created during oil and gas production operations and does not consider noise during drilling, construction, or other non-island noise sources that may be in the area during production operations (such as boat related noise).

In performing this study, NCE collected airborne noise and structural vibration data on and near many equipment items rated at and over 50 HP. These equipment items are either used in production or normally operate during production activities. The site visit was performed in early October 2005. In addition, NCE was provided with underwater noise data collected by Greeneridge Sciences, Inc. This data was measured over several weeks prior to NCE's site visit. This data was used to identify dominant machinery sources and viable noise paths as they relate to the generation of underwater noise. Using this information, specific noise control recommendations were been made.

The underwater spectrum data measured at locations roughly 400m North of Northstar Island showed that noise from tonal sources (i.e. machinery) were generally not detectable above 250 Hz. Typically, tones were seen in the 10-100 Hz range. While many tones could be identified from the various data sets (2002 and 2005 data) only tones at 30 and 60 Hz were detectable in all measurements. Tones at other frequencies were seen in some measurements and not in others. Exact reasons for this are not known, however possible explanations include effects due to propagation in shallow water, changing background levels, and machinery that operates intermittently and/or at varying loads. The consistent presence of 30 and 60 Hz in the underwater noise data indicates that these tones are a result of operations on Northstar and are due to equipment items that are nearly always running.

It was found that the Primary Structureborne noise path, being noise radiated from the gravel itself due to vibrations created by machinery vibration, and direct underwater noise radiation from sea connected systems are the most likely paths for underwater noise generation. Direct airborne radiation was found to not be a feasible path due to physical considerations. Secondary Structureborne noise paths (i.e. vibration excited by airborne noise at machinery sources) was found to have secondary influences at best, and is most likely not important with regards to underwater radiated noise.

On Northstar, the sources that appear to cause the most significant underwater radiated noise due to the Primary Structureborne path are the SOLAR Turbines, HP and LP Compressors, Water Injection Pump Skid, Air Compressors (2^{nd} Level SPM), AHUs, and the Flare Blower, with possible minor contributions from the Oil Shipping Pumps and Water Booster Pumps. All of these sources are rated at 800 HP and more with the exception of the Flare Blower. It is noted that other sources may also be significant contributors to the Primary Structureborne path, such as items located outside of equipment modules (i.e. Load Banks and Refrigeration Plant) and sources that were not able to be measured during NCE's site visit.

Several recommendations have been provided to control noise on future gravel islands due to the Primary Structureborne path. The first is to reduce the spacing of large stiffeners (i.e. W36x230 I beams or equivalent) in the modules to 6-12 feet (as opposed to the 18 feet typical of Northstar module design). This will help to reduce the imposed accelerations at the source, resulting in lower force transmission to the gravel. In addition, changing pillar arrangements and adding cross-bracing to pillars may also assist in reducing the transmitted vibrations. The supporting structures of the modules at the equipment foundations should be stiffened to help prevent excessive vibration responses.

It has been estimated that a reduction in underwater noise levels of 5-10 dB or more are possible (relative to Northstar) by making these structural modifications, particularly at frequencies above 30 Hz. It is strongly recommended that any structural design be analyzed prior to construction to assess its adequacy with respect to low vibration and force transmission.

It is noted that all equipment used during production (and possibly other activities as well) should be located within a module. Equipment should not be located on the pad. All equipment should be secured to a module through a well designed foundation and not simply resting on the floor plating.

In addition, it has been recommended that some machinery items be resiliently mounted to help reduce the accelerations / forces that are transmitted to the module structures. For general gravel island designs, the primary electrical producing items, HP/LP Compressors, and water injection pumps (or their equivalents) should be resiliently mounted. More conservative designs may include resilient mounting of all machinery items over 500 or 50 HP. Various designs and guidance were provided for isolation mounting systems. An additional 5-30 dB of attenuation is possible between 30 and 250 Hz by using resilient mounting systems.

The combined use of these noise control approaches should significantly reduce the underwater radiated noise from Primary Structureborne paths as compared to the design of Northstar. While specific attenuations will depend on design, it is expected that noise levels should be closer if not below typical background levels measured in the Beaufort Sea, particularly at frequencies above 60 Hz.

It was not possible to determine the exact contributions to underwater noise from sea connected pumps on Northstar. However, this path has the potential to create significant underwater radiated noise for future gravel islands. On Northstar, only a few pumps are sea connected and most are relatively small; if this is also the case for future designs, treatment of these pumps should be relatively simple. It was recommended that all sea connected systems take water from or return water to one or more cofferdams. The cofferdam should be designed in such a way that it acts as an acoustic filter (i.e. muffler). This design has been shown to have the potential for very large transmission losses.

Secondary to this, piping for sea connected systems should use flexible connections and pulsation dampers which will provide additional acoustic losses. It is noted that it may be possible to avoid certain treatments of sea connected items through further study of specific fluidborne noise levels generated at the source. Pumps should not be submerged at or near the island's perimeter; all pumps should be located inside of modules.

Estimations of the noise reductions (relative to Northstar) that will result from these treatments are not possible due to their uncertain contributions. However, these guidelines outline a low noise approach to designing connected sea connected systems and should minimize any underwater noise radiation.

Lastly, it has been indicated that there is a potential for significant underwater noise radiation from the pipeline running from a gravel island to the mainland. However, this is largely based on an unknown attenuation provided by the backfill covering the pipe (located below the sea floor). Possible treatments of this path would be to use flexible connections and pulsation dampers at any pump directly connected to the pipeline. However, further study is recommended to investigate the real significance of this noise path.

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APPENDIX A –Northstar Habitability Noise

As part of NCE's data sharing agreement with BP, NCE has agreed to provide data regarding the overall noise levels on Northstar with some general recommendations for reducing habitability noise levels[36]. It is noted that NCE did not receive information from BP regarding specific locations where noise reductions are desired. All measured airborne noise data is provided in Excel spreadsheets that accompany this report. A summary of the overall dB(A) noise levels measured near equipment and on the pad are provided in Figure A.1 and Table A.1. It is seen that the noise levels are quite high in most locations, verifying the need for hearing protection when working on the pad or in the machinery modules.

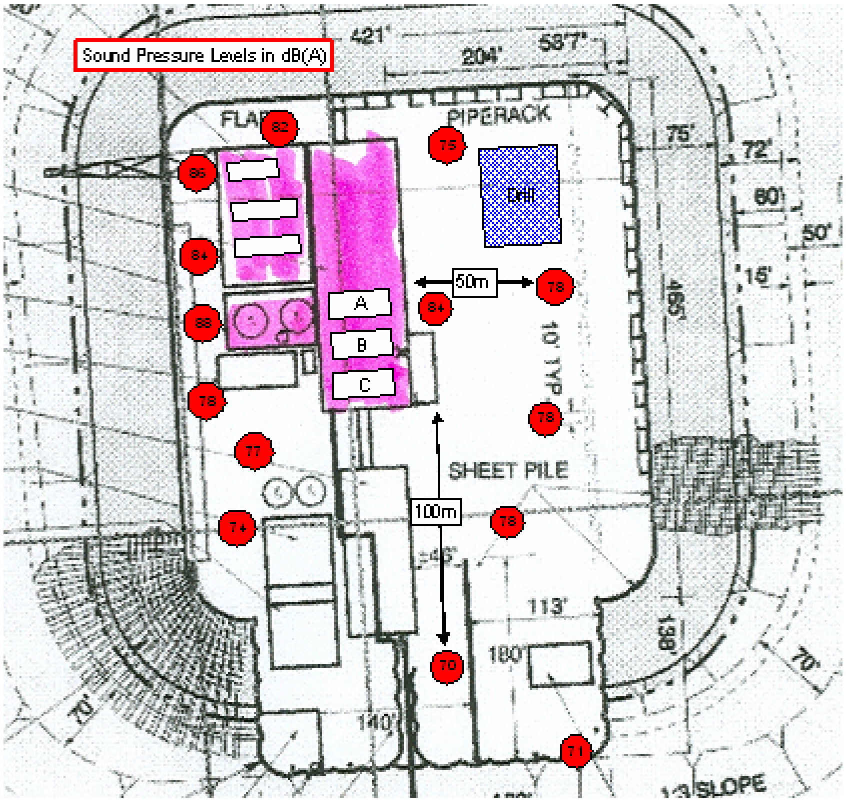

Figure A.1 – Overall dB(A) Noise Levels Measured on the Pad of Northstar

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[36] These recommendations can also be used when designing future gravel islands.

TABLE A.1 – Overall dB(A) Noise Levels Measured Near Selected Equipment

Item	Noise Level dB(A)
Oil Shipping Pump P1130A	91
Oil Shipping Pump P1130B	92
Crude Booster Pumps H1080 A and B	91
Solar A	95
Solar C	94
Fan in NW Corner of NPM	97
Water Injection Pump 3160B (Pump Module)	83
Water Booster Pumps P3040 Between A&B	82
LP Compressor	88
HP Compressor A	90
HP Compressor B	90

Noise on the Pad

The lowest noise levels on the pad are seen at the southeast corner of the island, which is furthest away from any of the machinery modules. Levels near 85 dB(A) are seen near the SOLAR Turbines and the HP/LP Compressors, all of which are exposed to the outside (i.e. these units are not enclosed in their modules).

Figures A.2 and A.3 show the A-weighted octave band levels measured at Positions 6 and 9 (i.e. near the HP/LP Compressors and SOLAR Turbines). It is seen that the contributions to the overall dB(A) levels are primarily at frequencies between 500 and 4000 Hz; 125 Hz also shows significant levels for the compressors. Based on these and other measurements taken by NCE it is believed that the primary contributors to noise on the pad are the HP/LP Compressors and SOLAR Turbines. Other machinery items located on or directly exposed to the pad do contribute to noise levels when the receiver is in close proximity (such as for the Load Banks).

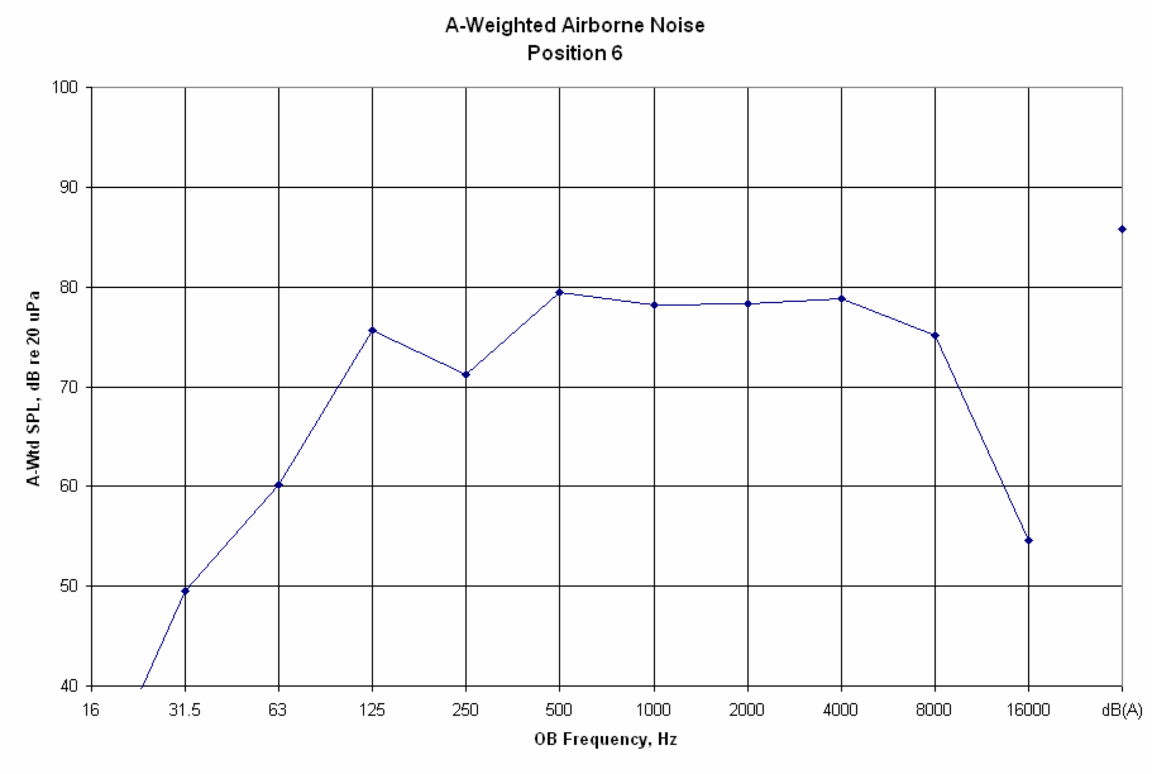

Figure A.2 – A-Weighted Noise Levels Measured near Compressors

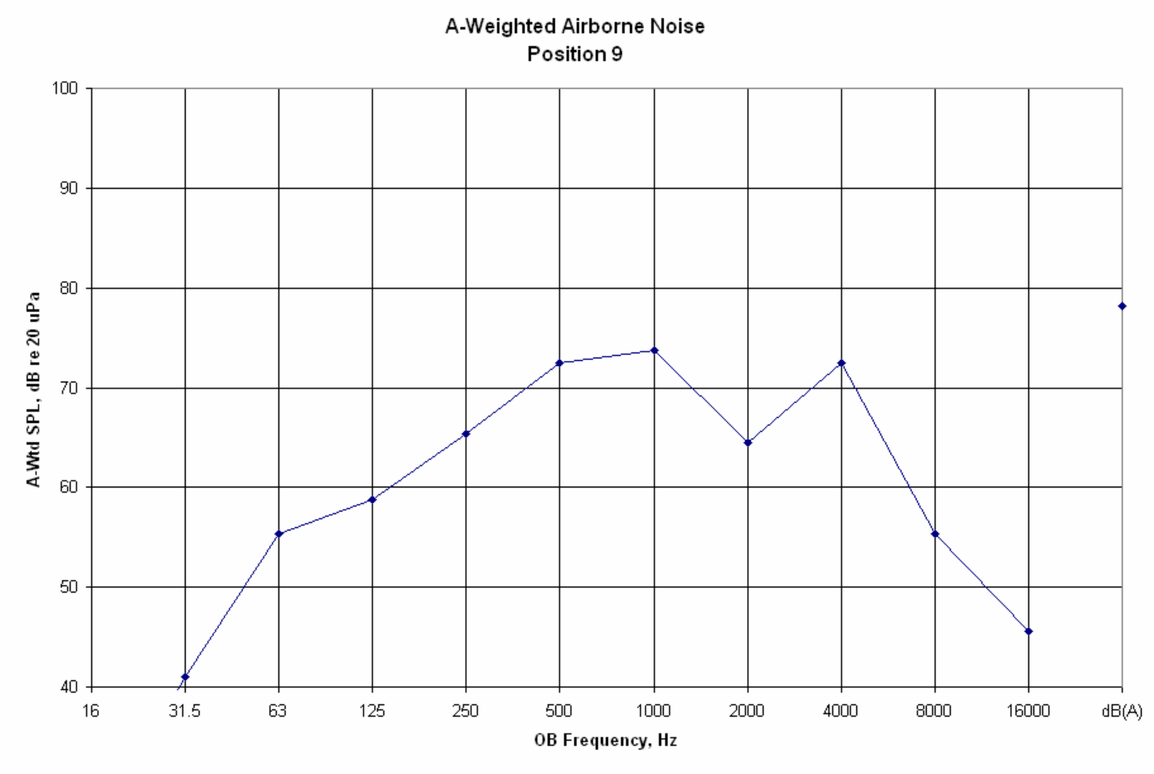

Figure A.3 – A-Weighted Noise Levels Measured Near SOLAR Turbines

In order to reduce noise levels on the pad it is recommended that the noise contributions from the primary sources, the compressors and SOLARs, be reduced. Four methods are potentially available for accomplishing this task.

1. Enclose the HP/LP Compressors and SOLAR Turbines within their respective modules.
2. Build a barrier to shield noise critical locations or locations where workers will be located for extended periods of time.
3. Build enclosures for workers at specific locations.
4. Apply cladding treatments to the exterior surfaces of the compressors and turbines themselves.

Enclosing the compressors and turbines within their modules with solid steel plating will go a long way to reducing the noise levels on the pad. Typical transmission losses of steel plating are on the order of 20 to 40 dB at 500 Hz and above. TL values may be slightly less at 125 Hz, depending on the thickness and stiffening arrangement. Further reductions can also be gained by adding 2-4" of fiberglass or mineral wool insulation to all surfaces common to the outside. Treatments can be applied either to the outside or inside of the modules as necessary. Treatments located on the module exterior should be protected from the weather, similar to what currently exists on the underside of most modules.

It is noted that the current grating used on the floor for these spaces would also need to be replaced by plating. Any holes or openings in the module will significantly degrade the performance of the enclosure. If penetrations are necessary, they should be sealed (i.e. air tight) to prevent a direct airborne path to the outside. Keep in mind that this solution will not reduce and will most likely increase the noise levels inside the modules near the compressors and turbines. This effect can be kept to a minimum by making sure that insulation is applied to the interior of the module (wherever possible) and has a minimally intrusive facing (see next section).

The barrier approach of Option 2 is potentially viable but limiting. This solution requires the identification of specific locations that will be shielded from noise. If such locations exist then a barrier may be appropriate. However, while the compressors and turbines appear to be the major sources of noise, other "local" sources such as the Load Banks would need to be considered.

A barrier is a simple solid wall structure that is used to block the noise from a specific source. Figure A.4 gives a diagram of the general approach. Barriers typically provide significant attenuation at mid to high frequencies (i.e. above 125 Hz) on the order of 10 or more dB (higher attenuations at higher frequencies). It is noted that the barrier must be significantly taller than what would be required to block the source / receiver "line of sight" due to diffraction effects re-directing the sound around the top of the barrier. As such, the barrier would need to be engineered to be tall enough (and wide enough) to provide sufficient attenuation for the specific application.

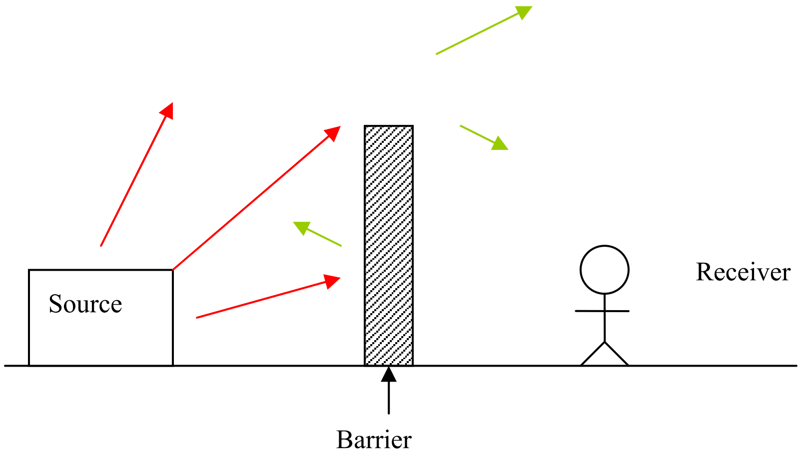

Figure A.4 – Sketch of Barrier Concept

If a barrier is not a feasible solution, it may be possible to design an enclosure specifically for workers where the noise levels would be lower than out on the pad. Again, this approach requires a specific location to be identified where noise levels will be reduced. Such an enclosure could be a fully enclosed or partially open (and potentially portable) structure, depending on the application and desired attenuation.

The fourth option is to apply cladding treatments to the compressors and turbines themselves. Such cladding would be 2-4” thick fiberglass or mineral wool, potentially with a barium sulfate “mass layer”. Cladding treatments typically provide losses of 5 to 30 dB at and above 250 Hz, with higher attenuations occurring at higher frequencies. The performance of any cladding treatment will depend on the specific material(s) used and its thickness.

It is noted that cladding treatments are a viable approach for these primary sources since the supply and exhaust air are ducted in and out, as opposed to other sources where, for example, the intake or cooling air is pulled directly from the unit’s surroundings. Cladding treatments would need to be applied to all surfaces of the compressors and turbines. This includes the undersides of the compressors and those surfaces associated with intake and exhaust including fan casings.

The above discussion has focused on the machinery items themselves; however, noise generated within the air intake and exhaust systems associated with these machinery items may also be contributing significantly to the noise on the pad. The air intake ducts associated with these sources are terminated very close to the sources themselves, and as such it is not possible to separate the intake noise from the source noise with the available data. Further study would be needed to quantify the airborne noise contribution from the intake ducts. However, general recommendations can be given to help keep noise levels low from air intakes:

- It is recommended that intake flow velocities be kept below 1000 ft/min

- No major bends should be used within 5 duct diameters of either side of the intake fans.
- It may also be desirable to use "quiet fans" or fans that produce lower airborne source levels.
- Applying acoustical lining to the inside of ducting can also help to reduce noise levels radiated by these sources.

The noise contribution from the exhausts of these large machinery items is equally difficult to separate from the noise of the machinery itself based on the available data. However, it is estimated that the contribution from the exhausts is secondary to the other sources mentioned above. The reason for this is twofold. First, the exhaust stack ends are located very far away from the machinery items they serve. As such, machinery that is close to any receivers will dominate their received noise levels. Secondly, the exhaust stacks have very large diameters and as a result will have very high directionality, particularly at high frequencies[37]. Since the exhaust stacks are directed upwards, the angle from the stack opening to any receiver is at least 135 degrees (0 degrees being normal to the duct opening), if not significantly higher. It is expected that high frequencies will be attenuated and only low frequencies will arrive at the majority of receiver locations on the pad. It has been shown that low frequencies do not control the A-weighted noise.

The combination of these factors leads to the result that the exhaust stacks are probably not a significant contributor to the noise on the pad. However, to help ensure this is the case, it may be desirable to line the exhaust ducts with absorptive insulation. This insulation would naturally need to be selected so that it could withstand the elevated temperatures inside of the exhaust duct.

Noise in the Modules

It is seen from Table A.1 that the noise levels near machinery are often very high, near 90 dB(A). As was the case with noise on the pad, for most sources the frequencies that significantly contribute to the overall dB(A) levels are at 250 Hz and above, with the occasional source having contributions at 125 Hz.

Inspection of Table A.1 shows that the highest levels measured anywhere on Northstar were near the ventilation fans on the North side of the NPM. During the time of NCE's survey, it was noted that these fans are manufactured by Hartzell Fan, Inc. It has been the experience of NCE that Hartzell fans are among the loudest and most vibroactive fans available for industrial (and ship) applications. Simply replacing these with fans of similar airflow performance from a different vendor will reduce noise levels in the NPM. American Fan Co., Greenheck, and Howden Buffalo are just some fan companies that

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[37] "Directionality" is a measure of the sound pressure level "on axis" (normal to a duct opening) relative to the sound pressure level at some angle "off axis". A "high directionality" means that more sound is being radiated on axis than off. Larger receiver angles with respect to the duct opening plane will give lower sound pressure levels than those receivers who are on axis (for the same distance).

can produce quieter fans. Most of these companies will provide noise data for their fans[38].

Similar solutions (i.e. replacement of current units with quiet units) may be possible for other sources found on Northstar, however this is often harder to do with pumps and compressors. Assuming the units will not be replaced, three options exist for noise control within the modules:

1. Build noise control enclosures around the units.
2. Apply absorptive materials to the walls and overhead of compartments containing noise sources.
3. Build a full or partial enclosure for workers.

Machinery enclosures would be built around each unit, or possibly set of units. Enclosures are typically steel and have some acoustic lining on the interior faces. Similar to Option 1 for the pad noise, enclosures typically provide a minimum 20 dB noise reduction for the frequencies of interest here. Most machinery items have some air-cooling or fan associated with the motor, and as such the enclosure would require ventilation. All air ducts attached to the enclosure should have a minimum 2” fiberglass internal lining to prevent airborne flanking paths, either through the duct and into the module or out of the outlet and onto the pad. Thicker duct walls will also help prevent flanking through the ducts. Ideally, ducting could be designed so that no supply fan would be needed. The obvious downside to building enclosures is they often require significant engineering efforts especially when the enclosed equipment is attached to piping or other large obstructions.

Applying 2-4” of acoustical absorption (fiberglass or mineral wool) to the walls and overhead of spaces with loud machinery can help to reduce noise in those spaces, particularly when there is a lack of existing exposed treatments (as is currently case with Northstar). It is assumed that any insulation that is applied to these spaces would need to have some sort of facing. Facings can significantly degrade the performance of acoustic absorption materials. The preferred facing is a 1-mil thick Mylar (which would face the interior of the space). If a more rugged facing is needed, perforated aluminum or steel sheathing can be used, however the hole diameter and total open space should be maximized (minimum 30% open area). Thick facings and/or small perforations in metal sheathing act to significantly reduce performance at high frequencies. It is expected that only a 2-4 dB reduction in noise could be expected from such an approach (assuming minimal facing effects). The reason for the small reduction is there is no control of the direct airborne noise path; adding acoustic absorption will only reduce reverberation effects.

As was the case with noise on the pad, if there are specific areas where workers need to be located (at some distance away from any significant noise source) it may be possible

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[38] It is noted that Hartzell will also provide noise data. However NCE has found this data to be very inaccurate in the past.

to design a full or partial enclosure. It may also be possible to design an enclosure that is semi or fully portable. A semi-portable enclosure would be made of steel or aluminum and the interior would be lined with acoustic insulation. It is expected that this enclosure would be partially open, although better performance could be achieved from a completely sealed enclosure. A fully portable design could be made of heavy barium sulfate sheets (with a fabric covering) and mounted to a frame on wheels. While the details of either system would need to be tailored to the specific needs of the workers, these systems should provide some significant reduction in received noise levels. It is estimated that the steel enclosure could realize a 10 dB or higher reduction. Slightly poorer performance would be expected for the portable barium sulfate sheet design.

APPENDIX B – Resilient Mounting System Design Guidelines

General Resilient Mount Guidelines

In sizing resilient mounts the total weight on the mounts should include the machinery, subbases (i.e. supporting structure above the mounts), associated fluids, and weight of piping carried by the mounts. The resilient mounts should be located equidistant from the isolated equipment's center-of-gravity (CG) in both horizontal planes. In many cases, mounts are located equidistant from the machinery's center-of-geometry. This is only acceptable if the CG coincides with the center-of-geometry. It is preferable to locate resilient mounts in the same horizontal plane as the CG. This is generally not possible, and vertical distance from mounts to the CG should be minimized.

Keep the isolation mounts to a reasonable number. It is preferable to have fewer rather than more mounts. Four is usually the minimum number of mounts. A minimum one-inch clearance envelope should be maintained around the mounted equipment to prevent the unit from striking adjacent structures, adjacent machinery or other objects during maximum deflection.

In general, resilient mounts have different static and dynamic stiffness, differing by factors of the order of 1.15 (higher for dynamic stiffness). Make sure to use the dynamic stiffness when calculating the natural frequencies of the mounting system. Lastly, make sure there are no “sound shorts”, or stiff structural connections between the resiliently mounted item and the supporting structure.

Resiliently mounted equipment should have flexible hose, exhaust, and/or cable connections in order to prevent vibration flanking paths. The preferred design for fluid systems is to incorporate two flexible hoses in 90º "dogleg" or "V" configuration. Double arch piece flexible hose, with motions that match the maximum possible excursions of the mounted equipment without over stressing the attached piping or components can also be utilized. Tie rods on flexible hose should only be used as limit stops and should be supplied with rubber grommets to prevent metal-to-metal contact. The first three pipe hangers should have resilient elements. Electrical connections should be made with generous service loops (following vendor recommended bend radius)..

Flex Connections for Piping

Synthetic reinforced flexible hose should be used wherever system requirements and regulatory bodies permit. The intent is to use as compliant a hose as possible based on system constraints. Higher-pressure systems can use metal reinforced or metal braided hose, while lower pressure systems should use softer hose.

To obtain freedom of motion in two planes, flexible hose or double arch piece flexible couplings should be installed in a right angle (a.k.a. “dogleg”) configuration (see Figures B.1a and b). For a flexible hose dogleg system, the free length (that length of hose unconstrained by clamps, fittings, nipples, spigggots, etc.) should be at least equal to 18.0 cm plus 4 hose diameters for each leg. While dogleg configurations are preferred, double arch hose are generally acceptable. Single right angle hose configurations are permissible provided they are at least equal in length to the dog leg configuration and the hose manufacturer's minimum bend ratio is not exceeded.

Figure B1a: Double Arch Hose

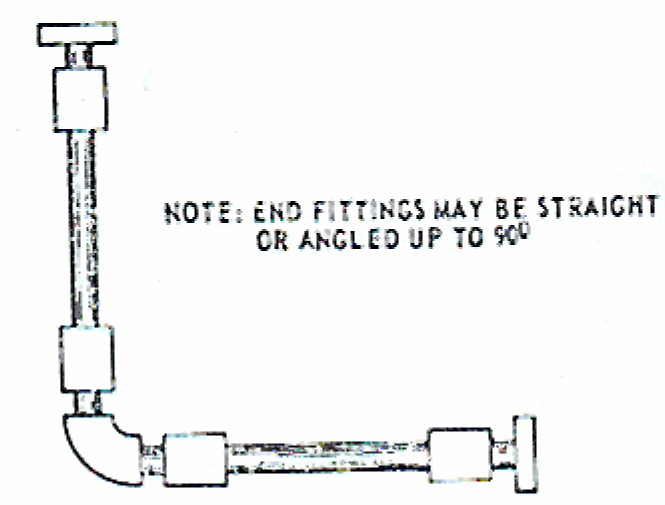

Figure B1b: Flex Hose with 90 Degree Dog Leg

Flex hose installations should have a heavy rigid pipe hanger support at the equipment end of the configuration attached to the equipment sub-base. A similar support should be attached to the opposite side of the hose and firmly attached to a structural frame. If needed, a resilient pipe support can be used at the 90 degree bend of the dogleg.

It is noted that while flexible hose/couplings are available in a wide variety of sizes (up to 12” diameter and beyond), some systems that are used on a gravel island may have piping connections with diameters that are larger than available flex hose sizes. It is noted that vibration flanking paths through piping for equipment on gravel islands are less critical than the direct vibration path of a machinery item. As such, it may be possible to avoid using flexible piping connections when absolutely necessary if the following guidelines are followed:

- Piping connected to equipment should be rigidly supported to the module at a higher level than the location of the equipment item. The support location for piping should be highly stiffened, i.e. the intersection between two large stiffeners.
- Piping should extend for some significant distance before being rigidly connected to the structure. The purpose is to provide enough flexibility in the pipe itself to allow the mounted equipment item to move somewhat freely and not be locked in place.
- Piping can be supported before the first rigid connection via resilient hangers. Hangers should be attached to moderate or large stiffeners.

Resilient Connections for Exhaust Piping

Resiliently mounted exhaust systems should be connected to their prime movers and between various parts of the system with flexible metallic bellows connections, or if water cooled, with a suitable rubber hose connection. Metallic bellows should be made with small corrugations and be extremely flexible. They should be of sufficient length to allow free motion of all resiliently mounted elements under all potential operating conditions.

Exhaust systems should be mounted resiliently to stiffeners, not to plates between stiffeners. Care should be taken to ensure that the exhaust system does not resonate and that the proper loads are placed on the mounts.