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Mass Notification System testing and modeling in large, reverberant spaces

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ABSTRACT

Several large, high-bay spaces with Mass Notification Systems (MNS) were tested for speech intelligibility using the Common Intelligibility Scale (CIS). The rooms had predominately hard finishes and long reverberation times, and did not meet the CIS criteria for the project. The rooms served a variety of functions, including equipment maintenance and assembly areas. EASE software was used to model the rooms and investigate how the CIS rating could be increased through the application of acoustical treatment and changes to the MNS sound system. Consideration was given to whether the CIS criteria could be relaxed to 0.7 as required by NFPA 72 instead of the 0.8 required by the project specifications. The EASE software was used again to create auralizations of different CIS levels to demonstrate the difference in intelligibility between 0.7 and 0.8. The auralizations proved to be an effective tool that helped the users make an informed decision on the MNS requirements.

1. INTRODUCTION

The Department of Defense Unified Facilities Criteria on the design, operation, and maintenance of Mass Notification Systems describes mass notification as “the capability to provide information and instructions to people, in a building, area, site, or Installation using intelligible voice communications including visible signals, text, and graphics, and possibly including other tactile or other communication methods. This capability is intended for the protection of life by indicating the existence of an emergency situation and instructing people of the necessary and appropriate response and action”.[1]

The key difference between a traditional fire alarm system and a Mass Notification System is that the Mass Notification System provides information and instructions in addition to alerting that there is danger. In order to be effective, the system needs to be intelligible, not just audible. An annex to the 2007 edition of the NFPA 72 National Fire Alarm Code[2] provides guidance on the design, installation, and testing of Mass Notification Systems, including requirements for speech intelligibility.

The NFPA 72 annex uses the Common Intelligibility Scale (CIS) to evaluate speech intelligibility. This metric is a modified version of Speech Transmission Index (STI) and is designed to be easily converted to other measures, including Articulation Index (AI), Speech Intelligibility Index (SII), and Percentage Articulation Loss of Consonants (%Al_{cons}). The same

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test method is used to measure both CIS and STI, and the two measures are related by the following mathematical equation.[3]

$$CIS = 1 + \log(STI) \ . \qquad (1)$$

This paper describes a case study where multiple large, reverberant rooms had Mass Notification Systems installed, and the systems did not meet the CIS criteria for the project. The rooms were tested and modeled to determine what methods could be implemented to bring the systems up to conformance. The project requirements were also evaluated to determine whether they could be relaxed for these low-occupancy rooms.

2. PROJECT CONDITIONS AND CRITERIA

A. Room Descriptions

Two room types are included in this case study: a "Maintenance Bay" and an "Assembly/Storage" room. Both room types have tall ceilings and predominantly sound-reflecting surfaces, such as concrete, steel deck, and glass. The Maintenance Bay is approximately 862,000 ft^3 (24,410 m^3) and the Assembly/Storage room is approximately 615,000 ft^3 (17,415 m^3) in total volume. The Maintenance Bay consists of a larger and smaller bay connected together, and the Assembly/Storage room is subdivided into smaller sections with wire-mesh partitions that are acoustically transparent. Both room types have relatively low occupancy relative to their size.

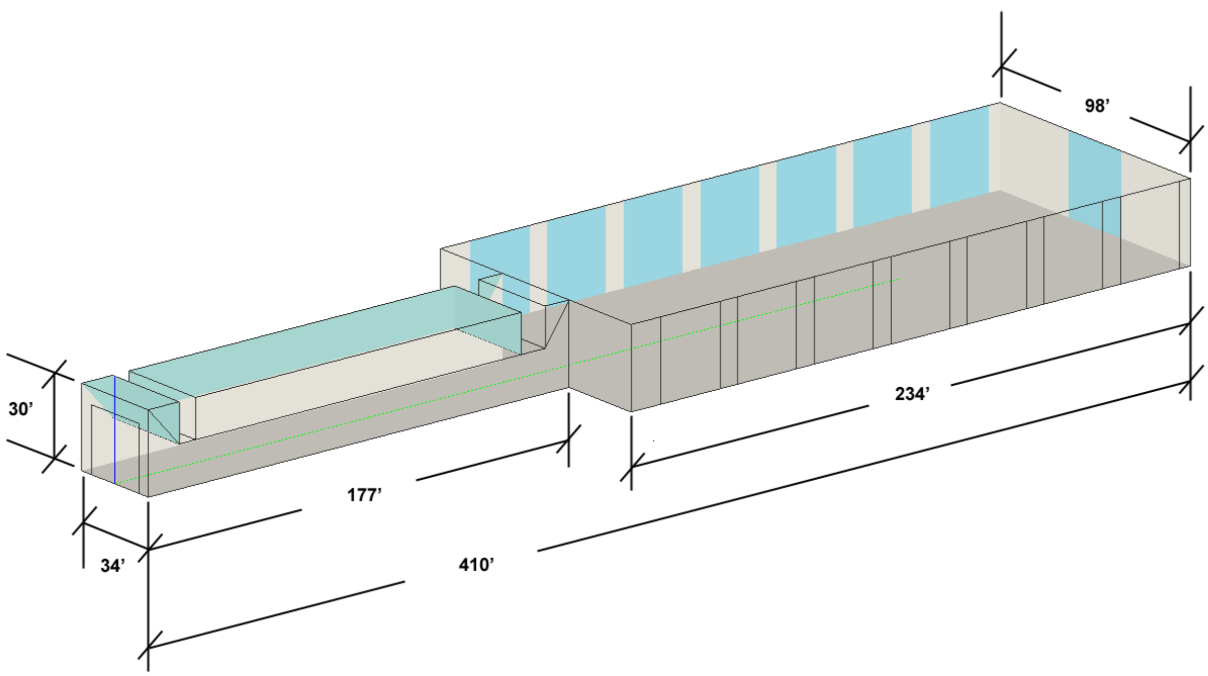

Figure 1: Maintenance Bay Model Isometric View

B. Project Criteria

The specifications for this project required that the Mass Notification Systems in these rooms achieve a CIS rating of 0.8 or higher. For comparison, the NFPA 72 National Fire Alarm Code requires only CIS 0.7. Subjectively, a CIS 0.7 rating is considered marginally intelligible. A paper presented to the National Fire Protection Association Congress in May 2001, describes the subjective evaluation of the minimum criteria and why it is acceptable, "a CIS of 0.70 is far from perfect intelligibility. It corresponds to about 80% word intelligibility, and about 95% sentence intelligibility, which has been shown to be slightly higher than what is required to reliably and accurately transmit an emergency message. The same level of intelligibility for a sound system used for non-emergency purposes would often be considered barely acceptable".[4] Given the low occupancy and the usage of the rooms in this case study, we suggested that the users re-consider the strict project criteria of 0.8, as described later in this paper.

B. Existing Conditions

When we began work on this project, these new buildings were almost complete, and the Mass Notification Systems had already been designed, installed, and tested. Most rooms in the buildings had smaller volumes and lay-in acoustical tile ceilings, and they met the CIS 0.8 requirement. However, the large Maintenance Bays and Assembly/Storage rooms were much more reverberant and did not meet the project specifications. In the Maintenance Bay we measured an average CIS of 0.58, and in the Assembly/Storage room we measured average CIS readings of 0.58 and 0.62 in different sections. Both room types had an array of suspended ceiling loudspeakers spaced about 7 meters apart and about 7 meters above the floor. A few sections of the Assembly/Storage room also had a few horn speakers added to the lower walls in a failed attempt to improve the CIS rating.

The testing and subsequent modeling showed that the primary reason for the low CIS scores was excessive reverberation. The background noise in the rooms was sufficiently low relative to the voice announcements. Speaker coverage was adequate and the speech was audible throughout the rooms. The ceiling loudspeakers had sufficient fidelity to reproduce the voice announcements, and these same loudspeakers were used in other rooms that did meet the CIS 0.8 criteria. The reverberation time in the rooms was not measured, but the computer modeling estimated it was in excess of 3 seconds in the mid frequencies in both room types.

3. COMPUTER MODELING

A. EASE Analysis

The EASE acoustical analysis software was used to investigate numerous methods for improving the CIS ratings in these two room types. The rooms were first modeled in their existing configuration, including the surface finishes and the loudspeaker types and locations. EASE loudspeaker data was not available for these loudspeakers, so data from another manufacturer was used with very similar size, directivity, and sensitivity. Absorption coefficients for the surfaces were adjusted somewhat to calibrate the model so that the results agreed with the CIS ratings measured in the existing rooms.

The EASE software is not able to calculate the CIS rating directly. It does calculate Rapid Speech Transmission Index (RaSTI), which could be converted simply to CIS using Equation 1 above. However, our research indicated that EASE does not calculate RaSTI directly either. EASE actually calculates $\%Al_{cons}$ and converts it to RaSTI using an empirical formula. Rather than make a double conversion and risk introducing more error, EASE was used to calculate $\%Al_{cons}$ for each configuration and convert it directly to CIS using the graph shown in Figure 3 of the Steeneken paper, "The Measurement of Speech Intelligibility".[3] Based on this graph, CIS of 0.8 equals $\%Al_{cons}$ of 6% and CIS of 0.7 equals $\%Al_{cons}$ of 12%.

If EASE is equipped with the AURA module, it is possible to create an impulse response for a listener location and calculate STI directly from that. During the course of the modeling, a few locations were also analyzed using AURA and the results compared closely with the %Al_{cons} calculated with the standard EASE statistical methods.

B. Maintenance Bay

After calibrating the EASE model for the baseline existing configuration, various combinations of acoustical treatments and loudspeaker changes were analyzed with the goal of achieving CIS 0.7. Figure 2 shows the results from EASE of several of these configurations. Options for treatment were somewhat limited since the building was nearly complete and the Mass Notification System was installed. For a project still in the design phase, other acoustical treatments or loudspeaker designs could be considered.

Option 1: The ceiling loudspeakers were replaced with directional horn loudspeakers. Surface finishes were not changed. The ceiling loudspeakers could not be suspended lower and closer to the occupants because clearance had to be maintained for two cranes in the room. Mounting horn loudspeakers on the lower walls brought the sound sources closer to the receivers, which is usually beneficial in very reverberant rooms. Using more loudspeakers, closer to the listeners, and at a lower power level can provide better speech intelligibility without exciting the entire room. In this case, the CIS rating was improved for small areas near the horns, but they could not cover the middle of the room effectively, so the average rating did not change significantly. Result: CIS 0.55.

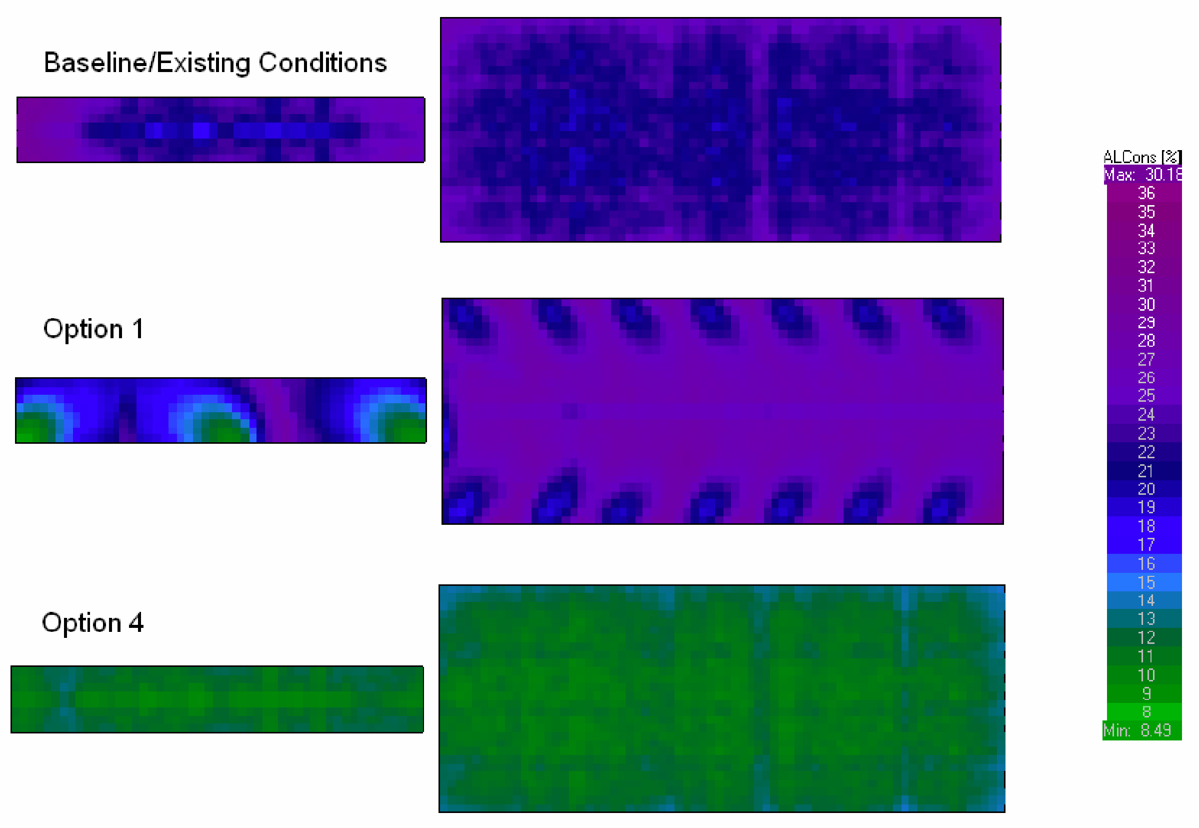

Figure 2: %Al_{cons} intelligibility mapping models for Maintenance Bay

Option 2: The ceiling loudspeakers were replaced with a total of ten column array loudspeakers which provide better control over directivity. Surface finishes were not changed.

The column arrays were located along the side walls and aimed across the short axis of the room, keeping most of the sound directed at the floor. In an assembly room with an audience or seating on the floor, this option would probably have been more effective. In this room, the concrete floor reflected the sound up into the room, and the benefit of the column arrays was mostly lost. Only a slight improvement in the averaged CIS rating was achieved. Result: CIS 0.62.

Option 3: The number of ceiling speakers was quadrupled by cutting the spacing between the ceiling loudspeakers in half in both directions. Surface finishes were not changed. The increase in speaker coverage had a negligible effect on the CIS rating because the existing coverage was already good. The problem with the room was not lack of coverage or inadequate sound level, and simply adding more loudspeakers will not overcome the adverse effects of reverberation. Result: CIS 0.57.

Option 4: The existing ceiling loudspeakers were used and acoustical treatment was added to the ceiling and walls. A total of 4,500 ft^2 (418 m^2) of treatment was added to the model, consisting of 3,750 ft^2 (348 m^2) of acoustical baffles suspended from the roof deck and 750 ft^2 (70 m^2) of 2" thick acoustical panels on the walls. Wall space was limited by large garage doors along the walls, so most of the treatment was concentrated on the ceiling. The reverberation time of the Maintenance Bay was greatly reduced, and speech intelligibility improved significantly without changing the ceiling loudspeakers. An extra benefit of the acoustical treatment is the reduction of noise buildup from the maintenance equipment and tools in the room. Result: CIS 0.71.

Option 5: The ceiling loudspeakers were replaced with the column arrays from Option 2 and the 3,750 ft^2 (348 m^2) of acoustical baffles from Option 4 were added to the roof deck. The improved directivity of the column arrays allowed for the usage of less acoustical treatment, but not enough to offset the cost difference between the ceiling loudspeakers and the column arrays. Result: CIS 0.73.

At the request of the client, the next process was to calculate how much acoustical treatment would be required to meet CIS ratings of 0.65, 0.70, 0.75, and 0.80, leaving the ceiling loudspeakers as installed. As expected, the relationship between the area of acoustical treatment and the CIS rating was not linear, but exponential, due to the law of diminishing returns. Adding enough treatment to the Maintenance Bay to meet CIS 0.80 would be difficult to install and very expensive. Refer to Figure 3.

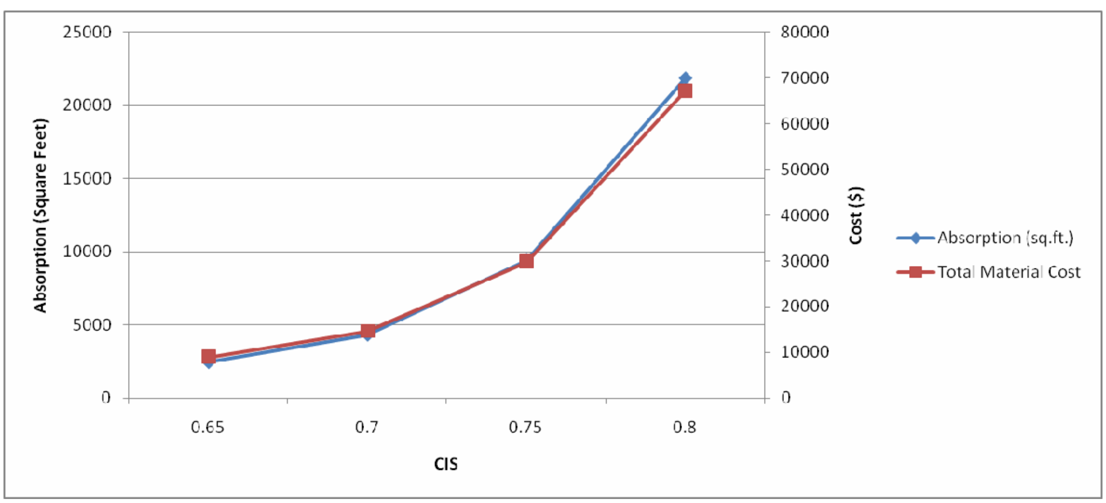

Figure 3: Amount of acoustical treatment needed and cost to achieve various CIS ratings

At some point between CIS 0.70 and 0.80, it would probably be more cost effective and practical to use a combination of acoustical treatment and a better loudspeaker configuration instead of acoustical treatment only.

C. Assembly/Storage rooms

The occupancy of these rooms varies from zero to several dozen people, depending on usage. The testing was conducted with only a few people in the room to represent the worst case scenario. The users also conducted their own tests with the room filled to the maximum expected capacity and achieved only a small improvement in the CIS rating. During the testing, some of the mesh storage lockers were filled with tarps and cardboard boxes to simulate the equipment that will be stored in the room once it is in use, and this simulated equipment was also included in the EASE model to provide an accurate amount of sound absorption in the room. Once again, the model was adjusted so that the baseline condition agreed with the CIS ratings measured in the field, and then several options for improvement were explored. Refer to Figure 4 for the results.

Option 1: The existing ceiling loudspeakers were supplemented with additional horn loudspeakers like those installed on the lower walls at one end of the large Assembly/Storage room. Surface finishes were not changed. The CIS rating went up slightly in isolated areas near the horns, but the average rating did not improve. Result: CIS 0.58.

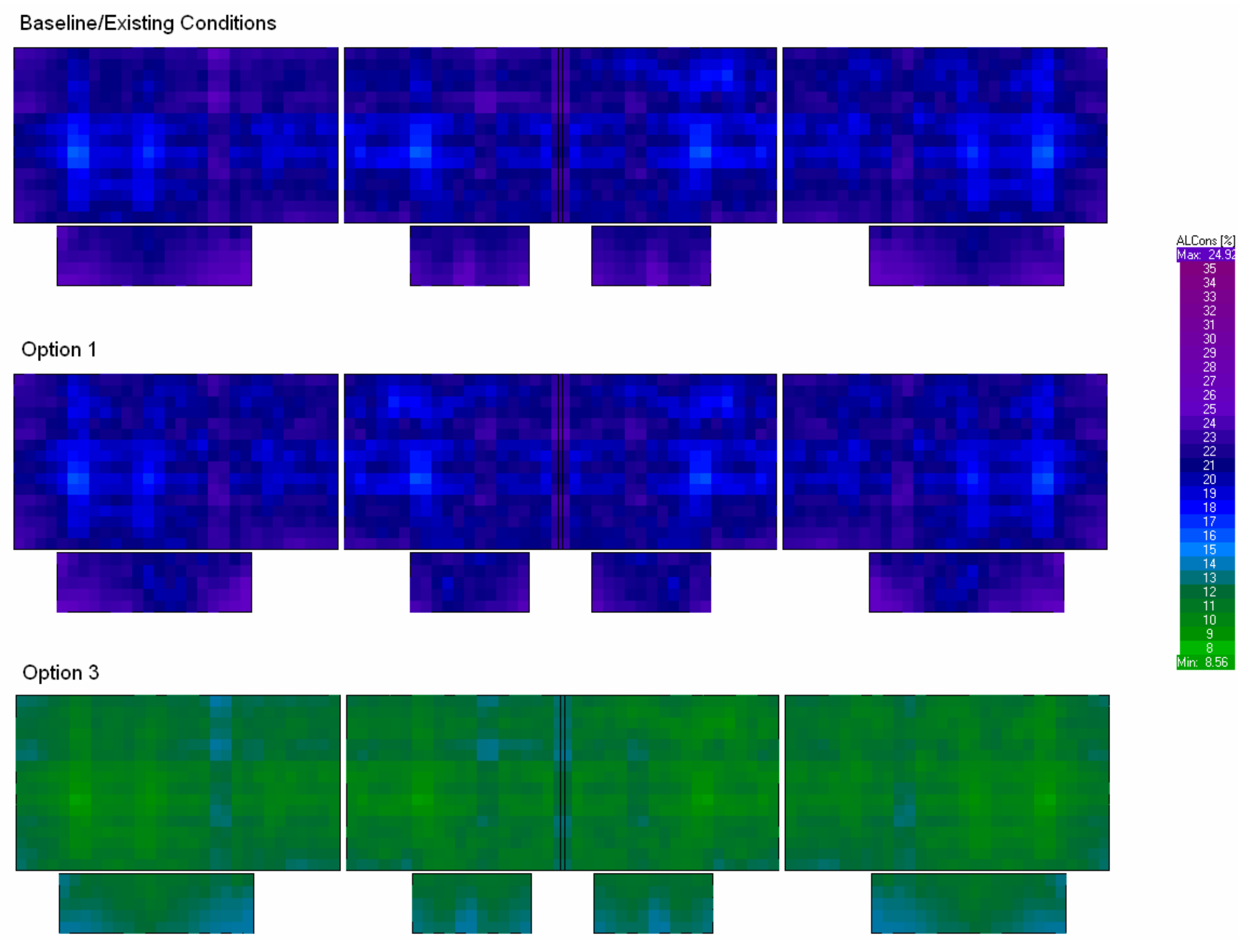

Figure 4: %Al_{cons} intelligibility mapping models for Assembly/Storage

Option 2: The existing ceiling loudspeakers were used and acoustical treatment was added in the form of baffles attached to the mesh demising partitions and 2” acoustical panels on the outside walls. A total of 5,000 ft^2 (465 m^2) of treatment was required. Result: CIS 0.70.

Option 3: The existing ceiling loudspeakers were used and acoustical treatment was added in a more evenly distributed configuration to the mesh partitions, outside walls, and ceiling. The intent was to reduce the amount of treatment needed by not concentrating it all in just a few areas. The model did not support the effectiveness of this approach, because 5,000 ft^2 (465 m^2) of treatment was still required regardless of location. Result: CIS 0.70.

Some additional investigation of changes to the loudspeaker configurations showed that the amount of treatment required could probably be reduced by using more directional loudspeakers like the horns instead of the ceiling speakers. This arrangement was more effective here because the Assembly/Storage rooms were not as wide as the Maintenance Bays. This approach was not pursued in greater depth since the ceiling speakers were already installed, but it would be worth considering for new designs.

4. AURALIZATION

To help the users understand the subjective difference between the CIS 0.8 required by their project specifications and the CIS 0.7 required by NFPA 72, auralizations of several CIS ratings were created with the EASE/EARS software. The users who were in a position of authority to modify the project specifications had not heard the Mass Notification Systems in the rooms and had no frame of reference from past experience as to what CIS 0.7 sounded like compared to 0.8. The auralizations were created based on the EASE model for the Maintenance Bay using the existing ceiling loudspeakers and the varying quantities of acoustical treatment needed to achieve CIS of 0.65 to 0.80 described above.

Auralizations using both speech and music sources were created. At a presentation, each user listened to the auralizations separately on studio headphones for accurate playback. The difference between each step in the CIS rating was noticeable, and subjectively the auralizations of the baseline condition sounded close to the Mass Notification System announcements in the field. The auralizations were very well received by the users and helped persuade them that the NFPA 72 requirement of CIS 0.7 provided sufficient speech intelligibility for emergency announcements in these room types.

One difficulty was encountered when using the EARS program to create the auralizations. The large size of the rooms, long reverberation time, and high number of loudspeakers caused a memory fault in the software, and it could not process the ideal number of rays. After consulting with the software distributor, we were able to work around this problem by reducing the number of rays to about $1/10^{th}$ of the normal amount and turning on the “diffuse rain” option, which substitutes some statistically generated impulses at the end of the response in place of calculated ray traces and more accurately simulates the effect of scattering in the room. The end result still sounded realistic enough for this presentation and the software was able to complete the calculations in a reasonable amount of time.

5. SUMMARY AND CONCLUSIONS

The extensive modeling and auralizations conducted for this case study yielded several insights into the design of Mass Notification Systems in large, reverberant rooms. The EASE model demonstrated that no practical configuration of loudspeakers alone could overcome the long reverberation time and meet a CIS rating of 0.7 or more. Some amount of acoustical treatment was absolutely necessary. However, the amount of acoustical treatment required can be reduced by using more directional loudspeakers, closer to the listeners, to avoid exciting the entire volume of the room with sound. Another possibility to consider would be to use the loudspeakers for alerting only and use large LCD screens in the room to provide textual instructions instead of verbal, although this can limit the flexibility of the system for live versus pre-recorded announcements.

On this project, after accepting that a CIS rating 0.7 was sufficient for the Maintenance Bays, the users reviewed their project specifications further and concluded that a Mass Notification System was not necessary for the Maintenance Bays after all. The existing loudspeakers will remain as is, and no acoustical treatment will be added. In the Assembly/Storage rooms, the acoustical treatment will still be added to meet CIS 0.7. Material has been ordered for a mock-up, and follow-up testing will be conducted in the near future. The results will be compared to the EASE model predictions once they are available.

REFERENCES

[1]Department of Defense, "Design and O&M: Mass Notification Systems," *Unified Facilities Criteria* UFC 4-021-01, (October 2005).

[2]National Fire Protection Association, "Mass Notification Systems," Annex E in *NFPA 72: National Fire Alarm Code, 2007 Edition* (National Fire Protection Association, Quincy, Massachusetts, 2007).

[3]Herman J. M. Steeneken, "The Measurement of Speech Intelligibility," *Proceedings IoA 2001, Vol. 23, No. 8*, (Stratford-upon-Avon, UK, 2001).

[4]Kenneth Jacob, "Understanding Speech Intelligibility and the Fire Alarm Code," *National Fire Protection Agency Congress* (Anaheim, California, 2001).