

# The Development of the Acoustic Design of NASA Glenn Research Center's New Reverberant Acoustic Test Facility

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## ABSTRACT

The National Aeronautics and Space Administration (NASA) Glenn Research Center (GRC) is leading the design and build of the new world-class vibroacoustic test capabilities at the NASA GRC's Plum Brook Station in Sandusky, Ohio, USA. Benham Companies, LLC is currently constructing modal, base-shake sine and reverberant acoustic test facilities to support the future testing needs of NASA's space exploration program.

The large Reverberant Acoustic Test Facility (RATF) will be approximately 101,000 ft<sup>3</sup> in volume and capable of achieving an empty chamber acoustic overall sound pressure level (OASPL) of 163 dB. This combination of size and acoustic power is unprecedented amongst the world's known active reverberant acoustic test facilities. The key to achieving the expected acoustic test spectra for a range of many NASA space flight environments in the RATF is the knowledge gained from a series of ground acoustic tests. Data was obtained from several NASA-sponsored test programs, including testing performed at the National Research Council of Canada's acoustic test facility in Ottawa, Ontario, Canada, and at the Redstone Technical Test Center acoustic test facility in Huntsville, Alabama, USA. The majority of these tests were performed to characterize the acoustic performance of the modulators (noise generators) and representative horns that would be required to meet the desired spectra, as well as to evaluate possible supplemental gas jet noise sources. The knowledge obtained in each of these test programs enabled the design of the RATF sound generation system to confidently advance to its final acoustic design and subsequent on-going construction.

**KEY WORDS:** Reverberant acoustics, test facility, acoustic chamber, chamber volume, acoustic modulators, noise generators, horns, acoustic test spectra, spacecraft and launch vehicle acoustic testing, acoustic absorption

## INTRODUCTION

The NASA Space Environmental Test (SET) Project is tasked to develop new environmental test facilities to support NASA's developing space exploration program. The Space Power Facility (SPF) at the NASA Glenn Research Center's (GRC) Plum Brook Station in Sandusky, OH, USA is already the home of the world's largest thermal vacuum chamber (Figure 1). In order to provide one-stop testing for the suite of space environmental testing, the SPF is being augmented through the NASA SET Project Office with new reverberant acoustic

(Hughes et al. 2010), mechanical vibration (Otten, Suarez and Le 2010), and modal test (Otten, Suarez and Le 2010) facilities.

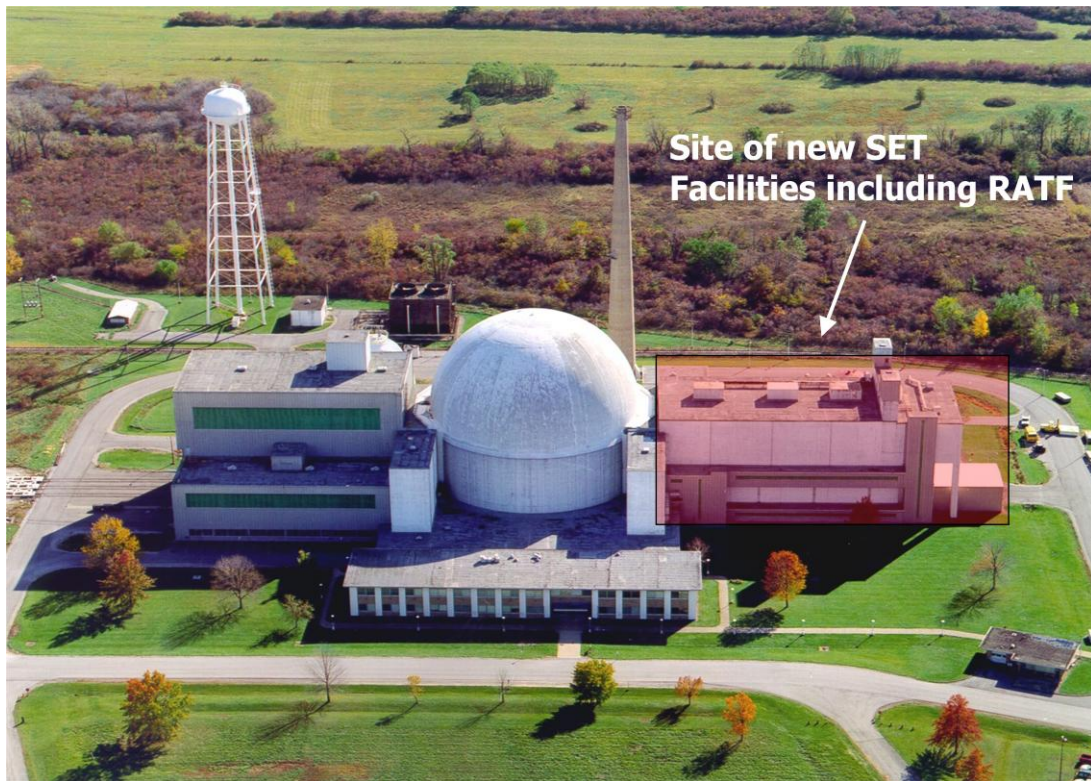


Figure 1: NASA GRC's Plum Brook Station is home of the Space Power Facility

In August 2007, Benham Companies, LLC (Benham), located in Oklahoma City, OK, USA, won the NASA prime contract to design and construct the acoustic, vibration and modal test facilities, as well as to provide the high speed data acquisition system to support these facilities. Benham contracted with Aiolos Engineering Corporation (Aiolos), located in Toronto, Ontario, Canada to provide the acoustic design of the Reverberant Acoustic Test Facility (RATF). This paper addresses the various acoustic test programs that advanced the acoustic design of the RATF.

The RATF will be a unique acoustic test facility due to its combination of very large chamber test volume and extremely high acoustic sound levels. The world's larger reverberant test chambers typically have a volume of  $\sim 50,000$  to  $76,000 \text{ ft}^3$ , and can produce an empty chamber overall sound pressure level (OASPL) of approximately 152 to 157 dB. However the RATF has a volume of approximately  $101,000 \text{ ft}^3$  and has been designed to produce an empty chamber test level of 163 dB OASPL. Amongst the world's active known reverberant acoustic chambers it is recognized that the Lockheed Martin test facility located in Sunnyvale, CA, USA is larger in volume at  $189,200 \text{ ft}^3$  than RATF, however that test facility produces an empty chamber level of approximately 156.5 dB OASPL, which is at least 6 dB less than the predicted capability of RATF. The RATF's combination of size and acoustic power was necessary to meet NASA's requirements to test the next generation of large space exploration vehicles whose acoustic environments have been predicted to be 163 dB OASPL or even higher.

## RATF REQUIREMENTS

The key requirements for the RATF acoustic design were as follows:

- The RATF shall be physically as large as possible within the given space limitations of SPF.
- The RATF's test chamber shall be properly sized to acoustically test four space vehicle configurations, encompassing an 18-ft diameter test article, and a 47-ft tall test article.
- The RATF's test chamber shall physically allow a 32.8-ft diameter test article weighing up to 120,000 pounds.
- The RATF shall generate the empty chamber acoustic test spectra shown in Figure 2, for continuous test duration of 10 minutes. These eight (8) "C" spectra represent a wide range of current and future NASA missions, including five (5) spectra with a 163 dB OASPL.
- The RATF shall include an independent, multi-channel digital acoustic control system capable of controlling the noise sources to the sound pressure levels (SPL) and spectra shown in Figure 2, within specified tolerances ( $\pm 5$ dB below the 50 Hz one-third octave bands (OTOB),  $\pm 3$ dB covering 50 Hz-2000 Hz OTOB's,  $\pm 5$ dB above 2000 Hz OTOB's,  $\pm 1.5$ dB on OASPL).

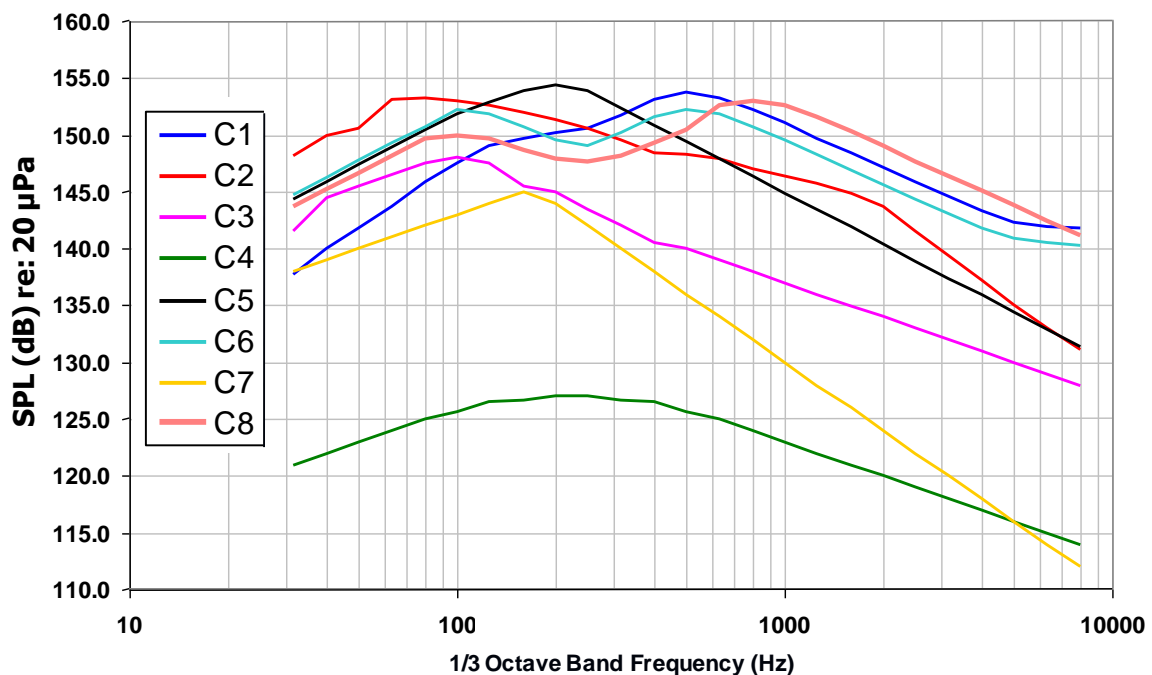


Figure 2: Acoustic test spectra requirements for RATF

## RATF CHAMBER SIZING AND INITIAL ACOUSTIC MODULATOR SELECTION

The physical size of the RATF was determined from the maximum available space within the SPF, along with following guidelines on proper room ratios and good acoustic test practices. Benham and Aiolos ultimately designed a reverberant acoustic test chamber with the follow-

ing dimensions: 47.5-ft long x 37.5-ft wide x 57-ft high. After accounting for the main chamber door jamb structure the resulting chamber volume is 101,189 ft<sup>3</sup>.

The next design issue was to determine the number and type of acoustic modulators or noise generators that would be needed to create the enormous sound power necessary to sustain the high SPL in this large chamber volume. Prior to the “C” acoustic spectra requirements becoming effective in September 2008, six other spectra were originally required including three spectra whose characteristics and SPL were very similar to the C2 spectra. As seen in Figure 2, C2 is particularly challenging due to its very high SPL at frequencies below 100 Hz. This need led Benham and Aiolos to initially select the TEAM Corporation (TEAM) modulators known as the MK-VI (Figure 3) and MK-VII, and propose using horns with three different cut-off frequencies (25, 35 and 50 Hz) for the RATF design. The TEAM modulators, although not widely utilized within the reverberant acoustic industry, are especially effective at the low frequencies (at or below the 125 Hz OTOB) with a rated modulator acoustic power of 150 kW (kilowatts) and 200 kW, respectively.

Although the TEAM modulators have been in service for over 50 years, there was not much acoustic characterization data available on them. To obtain characterization data, and to qualify and mitigate any associated risk, Aiolos, jointly with staff at the National Research Council of Canada (NRC) designed and conducted a test program at the Ottawa NRC reverberant acoustic test facility.

#### **INITIAL NRC TESTING, PART 1 (AIOLOS):**

- Date: December 2007 to January 2008
- Location: Reverberant acoustic chamber at the NRC, Ottawa, Ontario, Canada. NRC's chamber is 32-ft L x 22.6-ft W x 26.3-ft H, with a volume of ~ 19,000 ft<sup>3</sup>.
- Objectives: a) Validate the acoustic performance and obtain operating parameters of the TEAM modulators, b) Obtain acoustic test data to benchmark RATF's acoustic predictions.
- Equipment: a) MK-VI and MK-VII modulators, b) 25 Hz and 100 Hz horns
- Findings: a) MK-VI and MK-VII modulators achieved the published acoustic power, b) No major impact of modulator supply pressure on acoustic performance was observed, c) Two modulators operating simultaneously on two horns, result in the same acoustic output as the acoustic sum of two modulators operating individually, d) Results for two modulators operating on one horn via a Y-adaptor produced less than the expected doubling, e) Both modulator's output varied linearly with input gain, f) The modulator's bias setting (a measure of the force required to hold the modulator valve closed) requires further exploration to optimize its effect on noise generation, g) Two modulator shaft failures occurred.
- Go-forward plan: a) The TEAM modulator's performance, especially at low frequencies, showed promise for meeting the RATF requirements, b) Need for additional understanding of affect of bias, c) Need to instrument the modulator shaft to understand modulator failure that was then believed to be due to assembly workmanship.

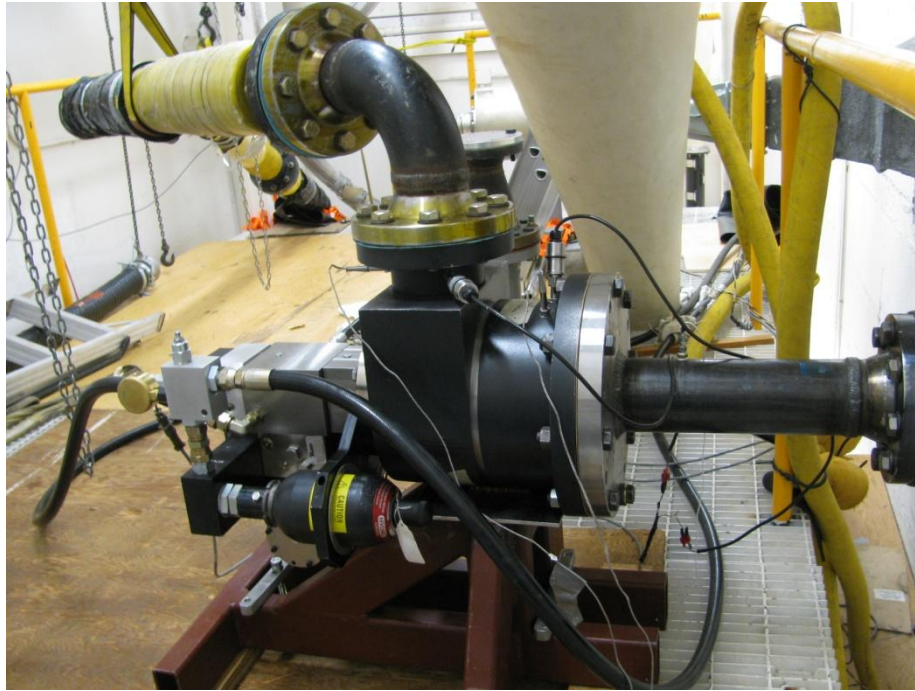


Figure 3: Testing of the TEAM MK-VI modulator at NRC

#### **INITIAL NRC TESTING, PART 2 (AIOLOS):**

- Date: April 2008
- Location: Reverberant acoustic chamber at the NRC, Ottawa, Ontario, Canada
- Objectives: a) Examine quantitative relation of bias to modulator efficiency and spectral control, b) Utilize various spectral input signal shapes for open loop testing, c) Add gas accumulator to stabilize supply gas pressure variations, d) Instrument TEAM modulator shaft with strain gauges to provide data to assess previous shaft failures.
- Equipment: a) MK-VI, MK-VII modulators, b) 25 Hz, 100 Hz and 200 Hz horns
- Findings: a) Confirmed minimal effect of gas supply pressure, b) TEAM modulators were controllable from the 25 Hz to 500 Hz OTOB, c) Optimal bias setting produced peak acoustic performance, d) Demonstrated excellent repeatability in acoustic performance, e) Performance between the 630 Hz to 800 Hz OTOB was not as controllable due to non-linear spillover and flow noise, f) Performance with the 200 Hz horn was poor due to inadequate connections and subsequent gas flow problems, and g) One additional modulator shaft failure occurred.
- Go-forward plan: a) TEAM Modulators controllability, repeatability and acoustic performance is sufficient for RATF design, especially at low to mid frequencies, b) Shaft failures of TEAM modulators pointed to reliability issues and need to reanalyze and redesign shaft.

#### **REDSTONE ARSENAL TESTING (NASA):**

Due to the TEAM modulator's shaft reliability issues, the lack of credible data from a high frequency horn (greater than 100 Hz), and continuing external questions on the controllability and acoustic performance of the TEAM modulators, NASA GRC performed its own independent test program to obtain additional acoustic test data and experience with the TEAM

modulator (Hale 2008). Since the U.S. Army's Redstone Arsenal has many years of experience with the TEAM modulator it was chosen by NASA GRC as the test site.

- Date: May 2008
- Location: Reverberant acoustic chamber at the U.S. Army Redstone Technical Test Center (RTTC) in Huntsville, AL, USA. The Redstone Arsenal chamber is 28.5-ft L x 24.3-ft W x 18.0-ft H, with a volume of ~ 12,500 ft<sup>3</sup>.
- Objectives: a) Obtain independent verification of the TEAM modulator acoustic performance (controllability, shape-ability, and repeatability), b) Collect data on two additional horn sizes (50 Hz and 167 Hz), c) Compare the response of the TEAM modulator in two facilities (RTTC and NRC), d) Compare the response of the TEAM MK-VI and the Wyle Laboratories' WAS3000 modulators at the same facility (RTTC).
- Equipment: a) MK-VI modulator, b) WAS3000 modulator, c) 50 Hz and 167 Hz horns
- Findings: a) Confirmed the NRC test findings of controllability, shape-ability and repeatability for the TEAM modulator, b) TEAM modulator performed well with the 167 Hz horn, c) Test data validated the analytical scaling procedures for using data in one chamber to predict the response in a different chamber, d) Test data re-confirmed superposition of modulators' output, e) The acoustic output of the MK-VI TEAM modulator was higher than that of the WAS3000 modulator by 6-7 dB at 25 Hz to 100 Hz OTOB; similar from 125 Hz to 1000 Hz OTOB; and higher by 2-3 dB from 1000 Hz to 8000 Hz OTOB due to non-linear spillover. Both modulators allowed the generation of shaped spectra by controlling the input signal from 50 Hz to 630 Hz.
- Go-forward plan: a) Pending a successful resolution of TEAM Modulator shaft failures, incorporate TEAM modulators into the RATF design, b) In addition to previously planned use of low frequency horns, incorporate 160 Hz horn for RATF design.

#### **PHASE 1 TESTING AT NRC (AIOLOS):**

Once the C-curve acoustic requirements (Figure 2) replaced the original acoustic requirements in September 2008 it became necessary to revisit the previous horn selection and related acoustic design, and augment the TEAM noise generators with additional high frequency sources. Additionally, test verification of the closed loop control of the TEAM modulators was planned as part of a new two-phase test program. Finally, the TEAM modulator shaft was extensively redesigned to avoid fatigue life issues and this new design and its performance needed to be test verified.

- Date: March - April 2009
- Location: Reverberant acoustic chamber at NRC, Ottawa, Ontario, Canada
- Objectives: a) Examine the acoustic performance of impinging gas jets, proposed as one alternative to the required high frequency noise sources, including their controllability, and other design features such as impinging plates and means for minimizing screech tones, b) Reconfirm TEAM modulator's acoustic performance and life reliability with new shaft design, c) Perform closed loop control of a single TEAM modulator, and d) Quantify the dynamic range of the TEAM modulator.
- Equipment: a) MK-VI and MK-VII modulators, b) 25 Hz and 160 Hz horns, c) Gas jets with various nozzle diameters, adjustable support frames, impingement plates, reflectors and chevrons

- Findings: a) Gas jets were able to produce high sound pressure levels but generally only in the presence of intense screech tonal noise. Reduction of screech tones was possible using vortex tabs and chevrons at the nozzle exit but at the expense of significantly reduced OASPL. The expected benefit of impinging plates to amplify sound, and reflectors to reduce the screech tones were not observed (Ramakrishnan et al. 2009). Significantly more jets than originally expected, and accompanying gas flow, would be needed to satisfy RATF requirements, b) Endurance testing of the TEAM modulator demonstrated that the shaft problem was resolved through the redesign; the measured stress levels were greatly reduced and very close to the predicted levels by TEAM Corporation, c) Testing also confirmed that the shaft redesign caused no significant change in the acoustic performance, d) Closed loop control testing of the TEAM modulator with the NRC control software was successful, e) The dynamic range was found to be ~ 6-9 dB for the MK-VI and ~ 9-12 dB for the MK-VII modulators.
- Go-forward plan: a) Incorporate TEAM modulators into RATF design, b) To add robustness to the RATF design to handle future spectra, increase the number of horns types (incorporate several different horn cutoff frequencies for RATF design), c) Gas jets are not to be incorporated, but instead evaluate the proposal to incorporate the Wyle WAS5000 modulator (similar to Ling EPT-200 modulator), d) Aiolos to proceed with contract to select acoustic control system (ACS) for RATF and to demonstrate the ACS performance in the Phase 2 testing at NRC.

#### **PHASE 2 TESTING AT NRC (AIOLOS):**

- Date: October 2009
- Location: Reverberant acoustic chamber at NRC, Ottawa, Ontario, Canada
- Objectives: a) Characterize the Wyle Laboratories WAS5000 modulator's (Figure 4) acoustic performance in a similar manner as the TEAM modulator, including investigating the use of an extension spool between the WAS5000 modulator and horn, b) Demonstrate the operation of the m+p International ACS, including the simultaneous closed loop control of the three modulators (TEAM MK VI and MK VII, Wyle WAS5000).
- Equipment: a) MK-VII modulator on 25 Hz horn, b) MK VI modulator on 100 Hz horn, c) WAS5000 modulator on 250 Hz horn, d) m+p International ACS
- Findings: a) WAS5000 modulator's acoustic performance met or exceeded the expectations going into this test, b) The spool piece is not needed, c) The m+p ACS performed very well controlling three modulators simultaneously meeting the specified test tolerances, stability and ramp-up rates. Given that there were only 3 modulators and 3 horns, the ACS exceeded expectations in demonstrating compliance to a variety of acoustic spectra, including the scaled down C-curve acoustic spectral shapes.
- Go-forward plan: a) Incorporate the WAS5000 modulators on a 250 Hz horn into the RATF design, b) Incorporate the m+p ACS system into the RATF design.

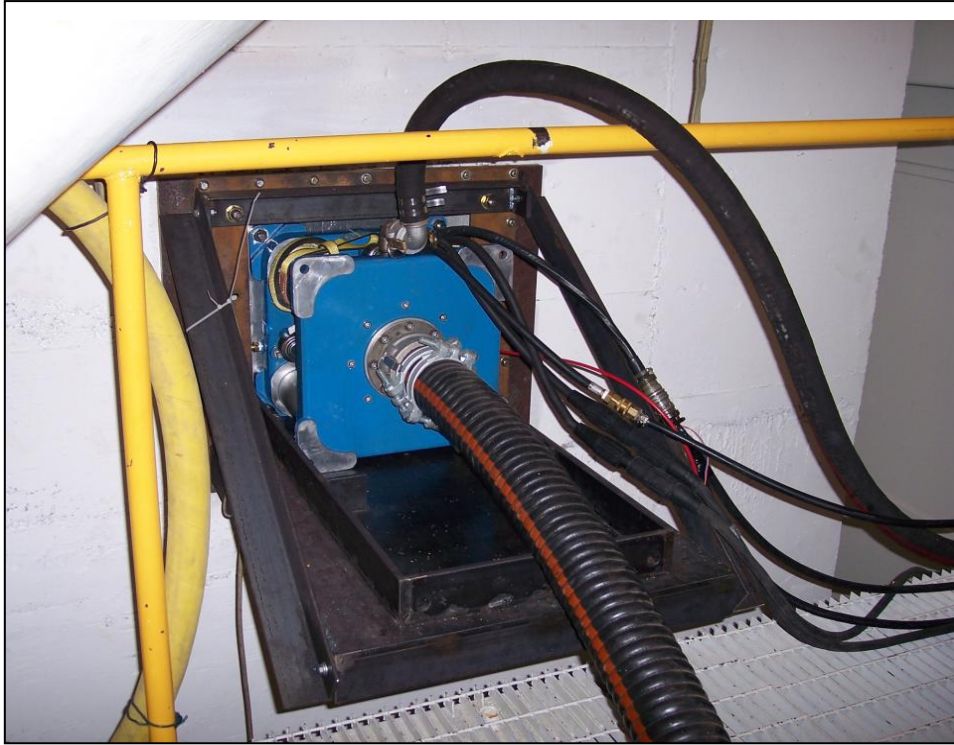


Figure 4: Testing of the Wyle WAS5000 modulator at NRC

#### **PAINT ABSORPTION TESTING AT OWENS CORNING (NASA):**

The last remaining key parameter to benchmark was the acoustic absorption of the RATF chamber. In particular, the acoustic absorption of the wall paint planned by Benham for the RATF interior surfaces is an important factor to the RATF's SPL at the mid to high frequencies (200 Hz to 3000 Hz OTOB). NASA wanted to measure this absorption (ASTM, ISO 2003) for the Benham selected paint as part of the NASA risk mitigation efforts to further establish confidence in the RATF predictions. Cambridge Collaborative Incorporated (CCI) led and performed this test for NASA.

- Date: February – March 2010
- Location: Small reverberant acoustic chamber at Owens Corning's Acoustic Research Center, Granville, OH. The Owens Corning chamber is 20.9-ft L x 14.7-ft W x 12.7-ft H, with a volume of ~ 3,900 ft<sup>3</sup>.
- Objectives: a) Measure the acoustic absorption of the Owens Corning chamber painted with the proposed RATF paint. b) Compare results with expectations and values used in Aiolos' SPL predictions for RATF.
- Equipment: a) Chamber coated with Benham proposed RATF paint, b) B&K (Bruel and Kjaer) sound source, c) Loudspeakers
- Findings: a) Measured test data and subsequent decay rate analysis indicates that the selected paint has absorption characteristics consistent with expectations and with predicted analytical values used by Aiolos for their RATF acoustic predictions and design.
- Go-forward plan: a) Approve the paint selected by Benham for use in RATF chamber.

## RATF's ACOUSTIC DESIGN SUMMARY:

From the beginning, Benham, Aiolos and NASA have agreed that it was important to ground the acoustic predictions of the RATF chamber with actual test data. This was especially important given the extreme SPL required for RATF, as well as the lack of available performance data for the TEAM MK-VI and MK-VII (Grewal et al. 2011) and the Wyle WAS5000 acoustic modulators. Therefore as explained in this paper, numerous and extensive test programs were completed to obtain the necessary test data to benchmark the RATF acoustic predictions. These test series have provided NASA with the confidence to proceed with the Benham and Aiolos design for RATF.

The overall layout and key properties of the RATF chamber and horn room are illustrated in Figure 5. There will be a total of 36 modulators and 36 horns to produce the acoustic power to meet the RATF requirements. The RATF design has eleven (11) MK-VII modulators distributed on the 25, 35, 50 and 80 Hz horns, twelve (12) MK-VI modulators distributed on the 100 and 160 Hz horns, and thirteen (13) WAS5000 modulators on the 250 Hz horns. In order to meet the gaseous nitrogen (GN<sub>2</sub>) flow rate needs for these 36 modulators a water-bath vaporizer capable of a GN<sub>2</sub> flow rate of 72,000 SCFM (standard cubic feet per minute) will be used in conjunction with a 6000 gallon liquid nitrogen (LN<sub>2</sub>) pusher tank and two (2) 9000 gallon LN<sub>2</sub> high pressure storage tanks.

Due to physical limitations within the SPF all the horns will be located on the shared horn room/test chamber wall. The final layout of the 36 horns is shown in Figure 6. If it ever becomes necessary to increase the number of horns/modulators, there are scarring plans which will allow for an additional seven (7) WAS5000 modulators to be installed, as well as additional horn room wall space for future expansion. The chamber walls, ceiling and foundation have been designed and built to withstand up to 166 dB OASPL.

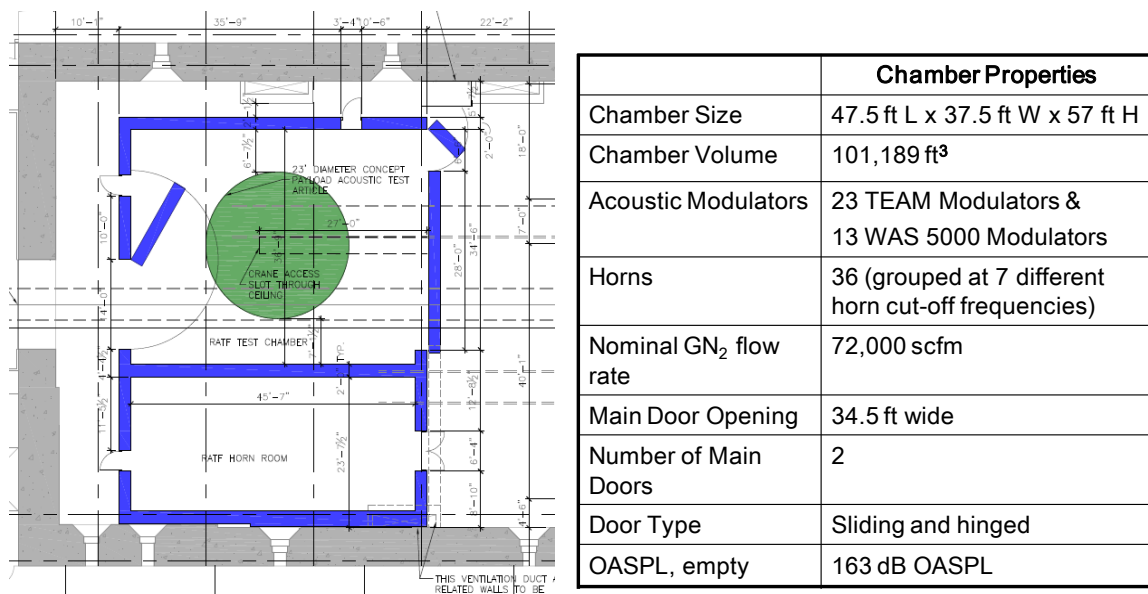


Figure 5: RATF's acoustic design and features

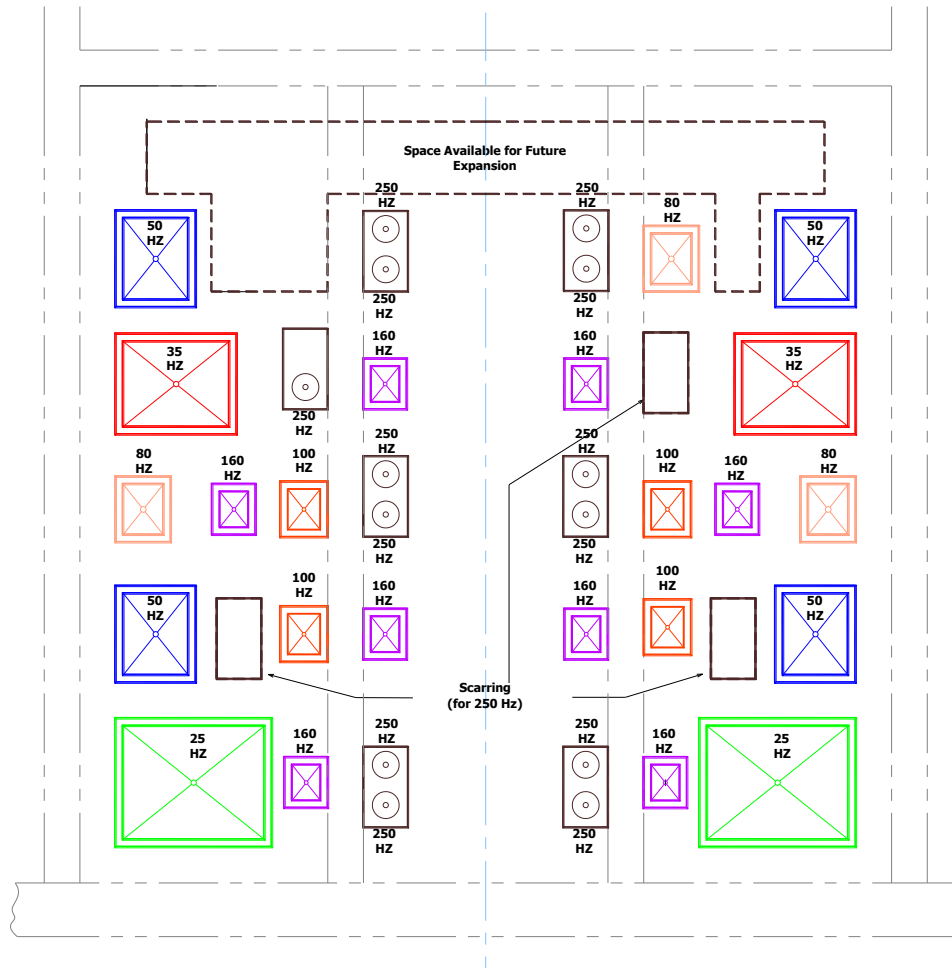


Figure 6: RATF's horn wall layout

NASA has high confidence that through the extensive series of acoustic tests summarized in this paper, the RATF will perform to its expected requirements. It is anticipated that the most difficult acoustic spectra to meet will be the C8 curve (spectra with two peaks at 100 Hz and 800 Hz), especially between 1000 to 2000 Hz. Due to its combination of very high chamber sound pressure levels and large volume, the RATF will be the world's most powerful reverberant acoustic test facility.

### RATF's CONSTRUCTION SUMMARY

Benham is scheduled to complete the construction of the RATF by late autumn 2010. Figures 7-11 shows several RATF construction photos taken in mid-autumn 2010. Following the completion of construction, there will then be a period of several months where Benham will complete their verification testing of the facility, prior to turning the RATF over to NASA. NASA then plans on performing a series of in-house integrated system tests, with an "available for customer testing" target date of the autumn of 2011.



Figure 7: Construction photo showing the installation of the final RATF horn (25 Hz)



Figure 8: Construction photo with view of the RATF chamber and horn wall taken during the installation of the main sliding door



Figure 9: Construction photo showing the RATF nitrogen generation system, including the water-bath vaporizer and the liquid nitrogen tanks and vaporizers

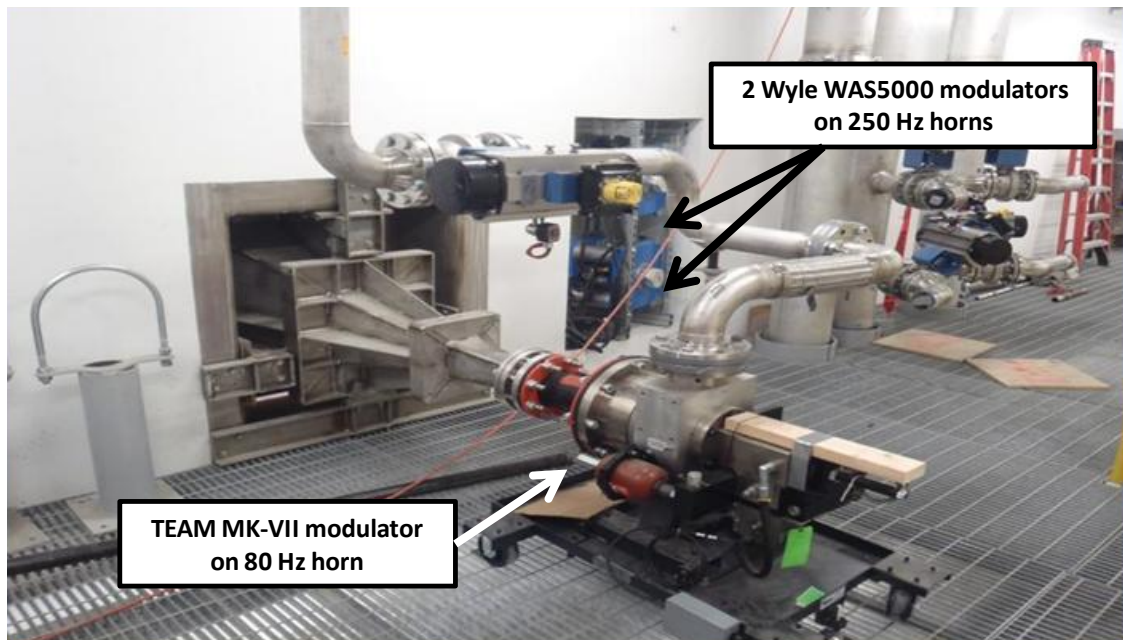


Figure 10: Construction photo of the RATF horn room (level 5) platform and modulators



Figure 11: Construction photo taken 26 November 2010 showing the interior view of the RATF chamber; also visible is the SET mechanical vibration facility (mid-left, below surface level) and the modal test floor (mid-right)

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- Wyle Laboratories: Dr. Costa Glaretas, Chito Hermoso
- m+p International: Al Proskuk, Guido Bossaert
- Cambridge Collaborative Incorporated: Dr. Jerry Manning, Dr. Patricia Manning
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- Redstone Technical Test Center: Dr. Mike Hale
- Owens Corning: Kevin Herreman, Don Hill

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## BIOGRAPHIES

William O. Hughes, a senior aerospace engineer in the Engineering Directorate, joined the staff of the National Aeronautics and Space Administration's John H. Glenn Research Center (GRC) at Lewis Field, Cleveland, OH in 1987. For over 20 years, his work at NASA GRC has focused on both the analysis and testing of space-flight hardware in the areas of structural acoustics, random vibration, and pyroshock. He develops and directs GRC's vibroacoustic environment activities, including the formulation of requirements, specifications and test plans. He is currently serving as lead for the Orion SET (Space Environmental Test) RATF (Reverberant Acoustic Test Facility) directing NASA's engineering insight/oversight of the design and build of this new acoustic test facility. In 2005, Bill received his 2nd Master's degree in Acoustics from the Pennsylvania State University. He previously earned a Masters in Mechanical Engineering from Carnegie-Mellon University in 1981, and a Bachelor of Science in Physics from the Pennsylvania State University in 1977.

Mark McNelis has been employed for twenty three years at the NASA Glenn Research Center in the Structural Systems Dynamics Branch in the Engineering Directorate. He is recognized in the aerospace industry as an expert in the definition of acoustic, vibration and shock environments and structural response of spacecraft and launch vehicles. He received his BS (1985) and MS (1987) degrees in civil engineering from Case Western Reserve University in

Cleveland, Ohio. In 2005, he also received an MS in Acoustics from the Pennsylvania State University.

Since 2007, Aron Hozman has been working for NASA and is the Vibro-acoustic Test Manager and Test Lead at the Plum Brook Station in Sandusky, Ohio. Aron has contributed to the design evaluations and test operations of the nearly-completed Mechanical Vibration Facility and the Reverberant Acoustic Test Facility. Prior to coming to NASA, Aron worked in the areas of dynamic testing and in dynamic criteria development & data analysis for 19 years at Boeing's Satellite Division in El Segundo, California. Aron was also instrumental in the design and test operations of Boeing's 68,000 cubic foot reverberant chamber, which was commissioned in 2004. Aron has a bachelor's degree from the University of Michigan in Electrical Engineering, and a Master's degree from the University of Texas at Austin in their Graduate Acoustics Program.

Anne McNelis is a NASA Glenn Research Center Aerospace Engineer with 18 years experience in analysis, prediction and testing of space flight hardware. Ms. McNelis' expertise is in the development of test levels and predictions for acoustic, random vibration, and pyroshock separation environments. Ms. McNelis' work in analyzing dynamic environments has helped determine the design and ensure mission success for various spaceflight programs and payloads including the International Space Station, Cassini, EOS-Terra, the Fluid Combustion Facility, Atlas V/MRO, Atlas V/Pluto, ARES I-X, ARES V, and Constellation/Service Module. She currently is working to mitigate the interior fairing acoustic levels for NASA's ARES V vehicle and is supporting the development of the Reverberant Acoustic Test Facility at NASA's Plum Brook Station.