Affordable Electro-Magnetic Interference (EMI) Testing on Large Space Vehicles

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ABSTRACT

Objective: Perform System-Level EMI testing of the Orion Exploration Flight Test-1 (EFT-1) spacecraft in situ in the Kennedy Space Center's Neil Armstrong Operations & Checkout (O&C) Facility in 6 days.

The only way to execute the system-level EMI testing and meet this schedule challenge was to perform the EMI testing in situ in the Final Assembly & System Test (FAST) Cell in a reverberant mode, not the direct illumination mode originally planned. This required the unplanned construction of a Faraday Cage around the vehicle and FAST Cell structure.

The presence of massive steel platforms created many challenges to developing an efficient screen room to contain the RF energy and yield an effective reverberant chamber.

An initial effectiveness test showed marginal performance, but improvements implemented afterward resulted in the final test performing surprisingly well!

The paper will explain the design, the challenges, and the changes that made the difference in performance!

Key Words: Orion, Human Space Flight, Spacecraft Production and Test, System Environmental Test, EMI, Electromagnetic Interference, Faraday Cage, Reverberant Mode Test

BACKGROUND

Orion is the Multi-Purpose Crew Vehicle planned to be the National Aeronautics and Space Administration's (NASA) deep space exploration spacecraft, destined to take astronauts beyond the International Space Station, beyond the Moon to the Earth-Moon L2 LaGrange point, and eventually to Mars. This spacecraft is composed of a Crew Module (CM), a Service Module (SM), a Spacecraft Adapter (SA), and three jettisonable fairings. The spacecraft is topped by a Launch Abort System (LAS) intended to pull the Crew Module away to safety in the event of a launch vehicle anomaly.

The Orion Exploration Flight Test-1 (EFT-1) was a development first-build spacecraft supported by NASA as a Lockheed Martin-owned and operated project. As a developmental spacecraft it was decided that system environmental tests would be minimal, accepting component-level environmental testing as mitigation to keep program costs to a minimum. System environmental tests were limited to a vibration test on the Crew Module, powered operations for a minimum of 200 hours for operational confidence, and limited EMI/EMC (ElectroMagnetic Interference / ElectroMagnetic Compatibility) testing to meet requirements for range safety. This paper explores the facility built to support the limited EMI/EMC test.

ElectroMagnetic Interference testing is also referred to as Radiated Susceptibility testing. This test exposes the spacecraft to the tracking radars and communications signals (non-ionizing radiation) that barrage the spacecraft throughout its mission, and includes strong signals that are not necessarily associated with the project.

ElectroMagnetic Compatibility testing is also referred to as Self-Compatibility testing. This test verifies the various systems on the spacecraft do not interfere with each other. This testing is not the focus of this paper.

Without a dedicated test facility to perform the EMI testing it was originally decided to perform the test in the direct illumination mode without a special chamber. This meant the broadcast frequencies simulating the threats to the Orion spacecraft would be openly broadcast and could interfere with other systems sensitive to those frequencies. A special request specifying the frequencies and powers for this test was filed, and NASA approved performing this test in this manner. The planned test duration was three weeks.

However, schedule pressure reduced the available test window such that Direct Illumination was no longer a viable option due to the number of test runs required to exercise all of the combinations of frequencies, locations, and polarizations that direct illumination testing requires. Testing in the reverberant mode became the only option to meet the reduced schedule, but this required the construction of a test facility to contain and reflect the radiated signals to all parts of the spacecraft at once, without having to reposition the antennas and incur additional test runs.

FACILITY

The Orion EFT-1 spacecraft was assembled and tested in NASA's Operations & Checkout (O&C) facility at the Kennedy Space Center. This is the historic facility in which the Apollo spacecraft underwent final integration and test. The O&C Highbay and associated office areas have been contracted to Lockheed Martin as an Industrial Operation Zone (IOZ), allowing Lockheed Martin to perform the assembly, integration, and test work under Lockheed Martin policies and procedures, eliminating the risk of slightly different NASA policies and procedures confusing the engineers and resulting in out-of-policy work being performed. The IOZ was completely refurbished by Lockheed Martin and the State of Florida to now be a state-of-the-art integration facility, and was the topic of a paper titled “Affordable Final Assembly and Test Facilities for the Orion Program at Kennedy Space Center Operations and Checkout Building” and submitted by John Stalder and Ron DaSilva in 2011 at the 26th Aerospace Testing Seminar.

The Final Assembly and System Test (FAST) Cell resides against the north wall at the east end of the IOZ. This station was developed to stack Orion’s CM on the SM and perform final system-level testing. (Historically, this is also the same location the Apollo Command Module was stacked on its Service Module.) The FAST Cell provides access to the Orion spacecraft on three levels to support mating, testing and final assembling operations. See Figures 1 and 2.

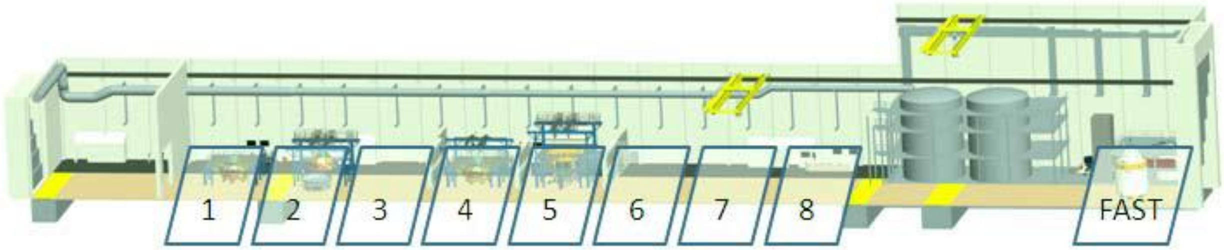


Figure 1: FAST Cell Location is at the East End in the IOZ

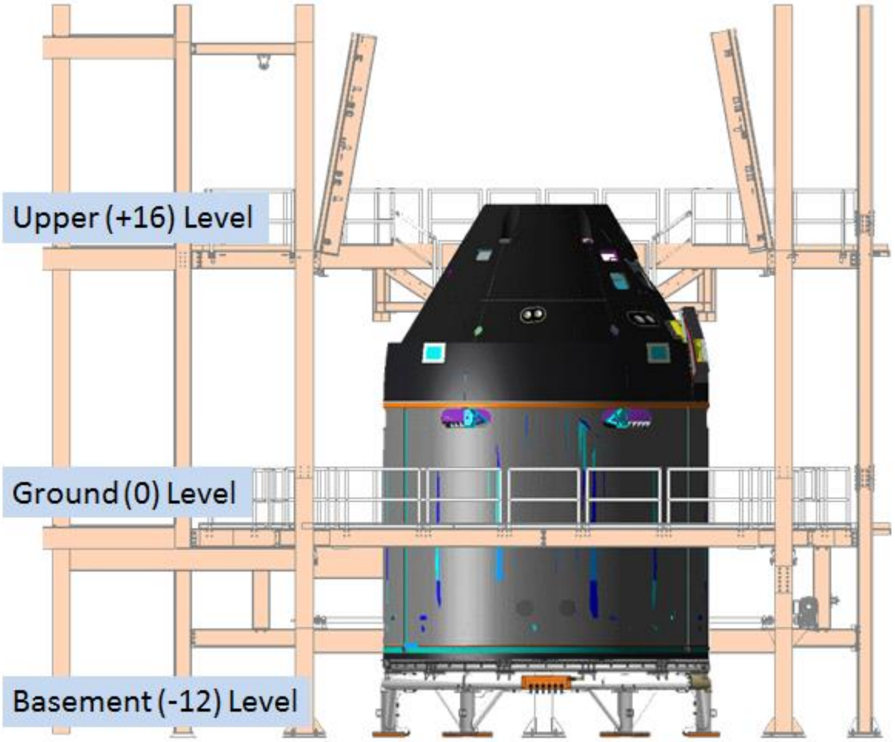


Figure 2: FAST Cell’s Three Levels

The FAST Cell was not intended to support EMI testing – this was a system-level test that was originally planned to be performed at NASA's Plum Brook Station for the Orion Qualification Test Vehicle. With the cancellation of the Constellation Program and the continuation of the Orion project as the Multi-Purpose Crew Vehicle, the EFT-1 vehicle's simplified test program brought the EMI test back to the O&C for this first vehicle. This is why direct illumination open-air testing was originally pursued for EFT-1 – it required no special facility. However, nearby EGSE had to be protected, so a temporary RF shield would be constructed around the racks. See Figure 3.

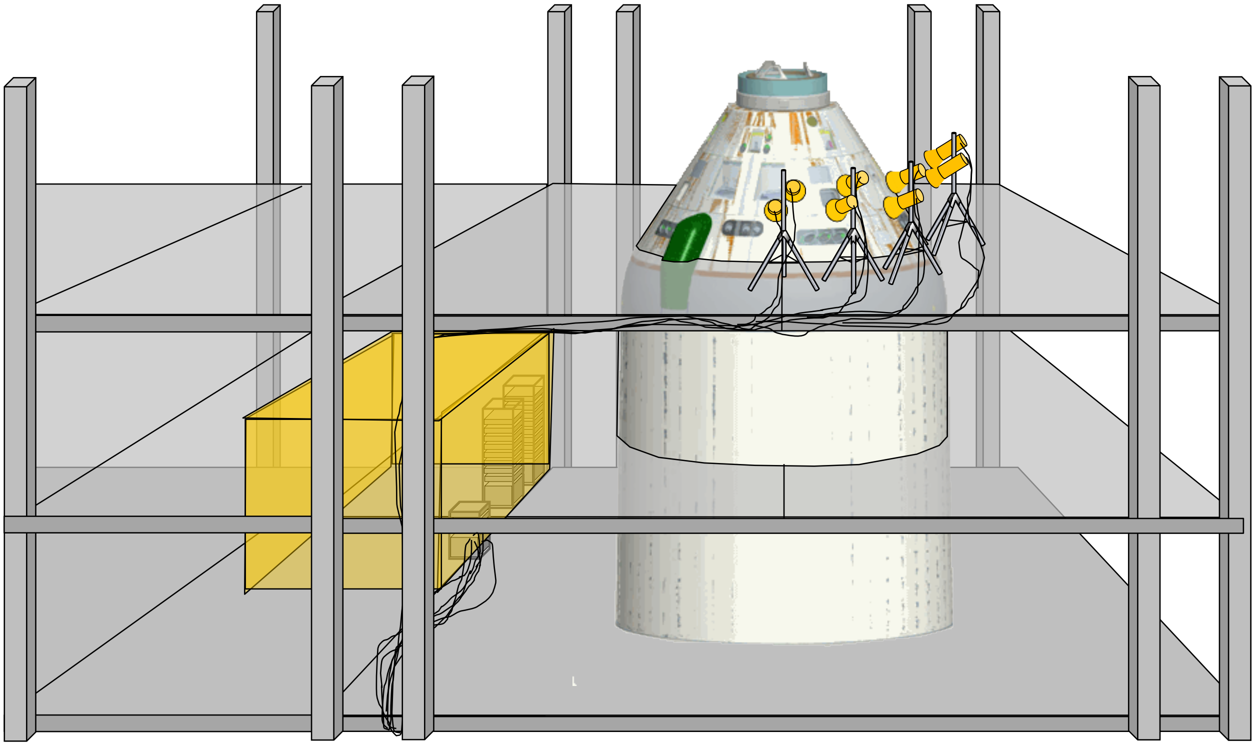


Figure 3: EMI Direct Illumination Open Air Concept

Enter the schedule compression. How do we execute a 3-week test in 6 days? We had to modify the plan to go with building a reverberant chamber. We call it the EMI Screen Room.

Rather than explain the lengthy process we went through to create the EMI Screen Room around the structure you see above, this paper will outline the design challenges and obstacles that need to be resolved to build a large EMI Screen Room in a not-so-perfect location. But before we go there, let's review the final product.

THE AS-BUILT EMI SCREEN ROOM

The FAST Cell was transformed from a relatively clean structure shown in Figure 4 to the Reverberant EMI Screen Room shown in Figure 5 in about four months with a small crew of usually 3 technicians.

Figure 4: FAST Cell Just After Structural Completion

Figure 5: EMI Screen Room Ready for Effectiveness Test

The chamber shown above is configured to perform the initial Effectiveness Test, with boxes of "lossy foam" placed in the center of the chamber as an energy sink. This test would reveal whether the chamber behaves as a reverberant chamber should, and be capable of yielding a successful test with the spacecraft scheduled for a couple of months later. There were items not completed, such as all of the stitching of the cable trays and socking the intruding air pipes, but we hoped simple workarounds would not impact the results enough to harm the test.

Details of the test preparation and conduct are provided later in this paper, but to summarize the results, at the end of the test the outcome did not meet expectations. Hoping for a reported Quality-factor (Q or QF) of 4,000 or better, the evaluated Q was only a couple of hundred rather than a couple of thousand. (Q is an indicator of how effective the chamber is at reflecting and moving the energy without dissipating it.) See Figure 6. If we couldn't fix the Screen Room to improve the reverberant characteristics, and, as a result, raise the Q, the test would have to be performed with direct illumination method and require significantly more schedule.

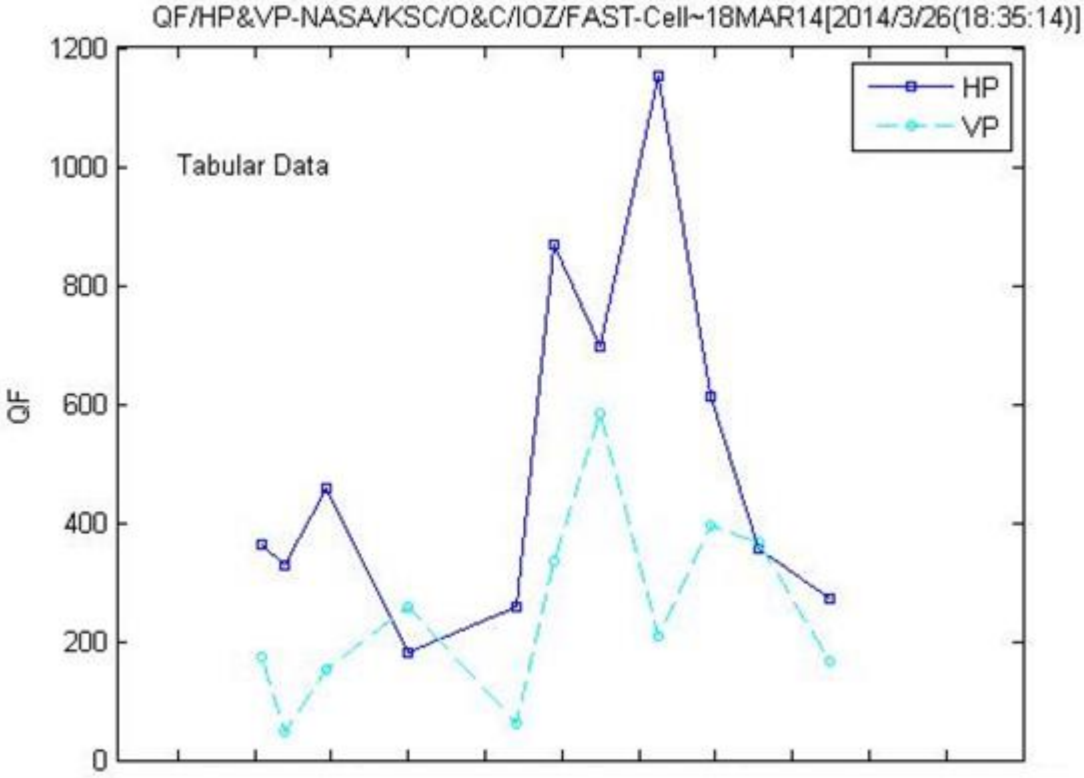


Figure 6: Effectiveness Test Quality Factor Results

Determined to improve the results for the actual test, we used the next few months to finish make some changes. Based on the weakness in the vertical polarization we assessed the columns supporting the 16'-level platform played a larger role in absorbing RF energy than expected. And the overall weakness of the results suggest the platforms were a significant energy sink and more diligence needed to be performed in "taking them out" of the picture.

Three months later it was time to run the actual test. Figure 7 shows the chamber with the spacecraft in it, just before the run began.

Figure 7: Final EMI Screen Room Configuration

The one item visibly different from Figure 5 to Figure 6 is the closest column (which is the southeastern column) moved from inside the screen room in Figure 5 to outside the screen room in Figure 7. Other changes will be discussed later.

The results of the final EMI/EMC test were drastically improved from the effectivity test and successful! This allowed us to certify the spacecraft for launch.

The remainder of this paper will explain what we did, and what you need to consider if you elect to create your own in situ EMI Screen Room.

CONSIDERATIONS

There are basic decisions that need to be made that can significantly affect the design and cost of an EMI Screen Room, and work that should be performed to improve the likelihood of building a successful EMI Screen Room. Please, learn from our lessons learned!

DECISION 1: WHAT CONCEPT DOES YOUR BUDGET SUPPORT?

The concepts to be addressed are for an inexpensive EMI Screen Room based on the size of your test article. A dedicated facility can easily be in the millions of dollars. A purchased free-standing RF Fabric room can be in the $100k-500k range. In this case $50,000 was our material budget, which put the RF Fabric room out of our reach.

The Orion EFT-1 spacecraft is one of the largest spacecraft ever flown on an expendable launch vehicle. EFT-1 is 18 feet in diameter and 26 feet tall. The EMI Screen Room size needed for an article this size should be at least 28 feet wide by 28 feet deep by 31 feet tall (allowing 5 feet clearance all around the vehicle for reverberant reflections). A freestanding structure this size would require significant engineering and would block the highbay transfer aisle, making crane operations impossible. Freestanding was also not an option for Orion EFT-1 because we had a requirement to test in situ to eliminate schedule impacts of moving the vehicle and EGSE/MGSE. The room size dictated by the FAST Cell structure was to be approximately 30 feet wide, 30 feet deep, and 36 feet high; adequate for our purposes. Using the FAST Cell structure to give our Screen Room support seemed the best concept to pursue.

DECISION 2: WHAT MATERIALS WILL YOU USE?

Our EMI specialists showed us photos of small free-standing EMI Screen Rooms they built for small (2 ft cube-sized) test articles. Second, to build a screen room large enough to fit around this spacecraft we needed to make use of the support the FAST Cell structure could give.

For the budget, a Faraday Cage made primarily of copper screen was the appropriate direction to go. Building on the concept of the free-standing screen room we settled on a concept of wood-frame panels covered in copper screen. While wood is not ideal for a clean room environment, it was affordable, easy to work, and manageable for FOD (foreign object debris) control. The FAST Cell structure could support the panels, and the screen would be wrapped in a way to allow the panels to be screwed together to make tight seams.

DECISION 3: TO MAKE DRAWINGS, OR TO NOT MAKE DRAWINGS?

The best way to know if the concept selection stands a chance of being fabricated and stays in budget is to have it put into a drawing. This is especially important if the EMI Screen Room is to be built around a multi-level structure such as the KSC O&C's FAST Cell.

Our drawings raised the question of stability for the upper level screens that had to free-stand on the platform. This resulted in the addition of a 2"x4" support wall to provide extra stability. While rope stays were planned to ensure the walls would not fall in to the center, the structure was so stable the stays were not employed except at one location.

Penetrations required by cable trays required some creative design in the wood panels to ensure we could assemble the wall around the trays. The CAD drawings were critical in shaping the panels around the cable trays, and in three cases split the panels into upper and lower sections.

DECISION 4: SHOULD YOU MAKE FACILITY MODIFICATIONS?

In a word: yes. Unless it was designed from the start to support the EMI/EMC test, it is highly likely something will need to be changed. In this case we had three specific mods to make: 1) extend the southeast column up 12 feet, 2) add power all around the FAST Cell for the amplifiers, and 3) strip paint. The first two required drawings and approvals. The last just required approval.

Contrary to requests, the southeast column of the FAST Cell was cut off at the height of the 16'-level platform. However, in order to support the front corner of the screen room, we required the column be extended to match the height of the southwest column. This was approved and provided a mounting point to support what became the Front Curtain. See the drawing snapshot in Figure 8.

The FAST Cell structure had been painted per the design requirements for a clean room facility. However, in order to "take the structure out" of the EMI Screen Room we were driven to strip the paint from several locations in order to make direct contact with the copper screen (details will be provided later). Make certain the program understands the necessity of this and allows it if any of the structure will be inside of the Screen Room.

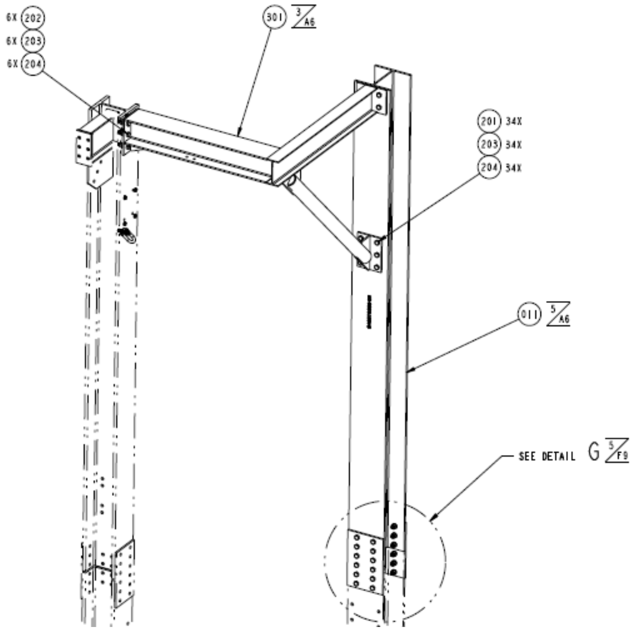


Figure 8: FAST Cell Southeast Column Extension Drawing

As the power distribution was not involved in the actual EMI Screen Room design, it is not going to be further discussed. However, it, too, was necessary to support the EMI/EMC test and was a cause for drawings and modifications around the FAST Cell.

CHALLENGES

Now that the fundamental decisions have been made, there are a myriad of challenges to consider and overcome to have a successful reverberant EMI Screen Room. Again, please, learn from our lessons learned!

Before we start we need to provide you with a few more details on our screen room build.

The EMI Screen Room outline was partially dictated by the platform structure – where could we drill holes for the C-channel without going through the box beams or angle iron webbing? We also had to consider allowing room on the platforms for the EGSE racks, and avoid the moving parts such as the lower platform that raises to various working heights around the spacecraft, and the upper platforms that flip back to allow the vehicle to be craned in and out of the FAST Cell. As a result of these considerations we defined the outline as shown in red in Figure 9.

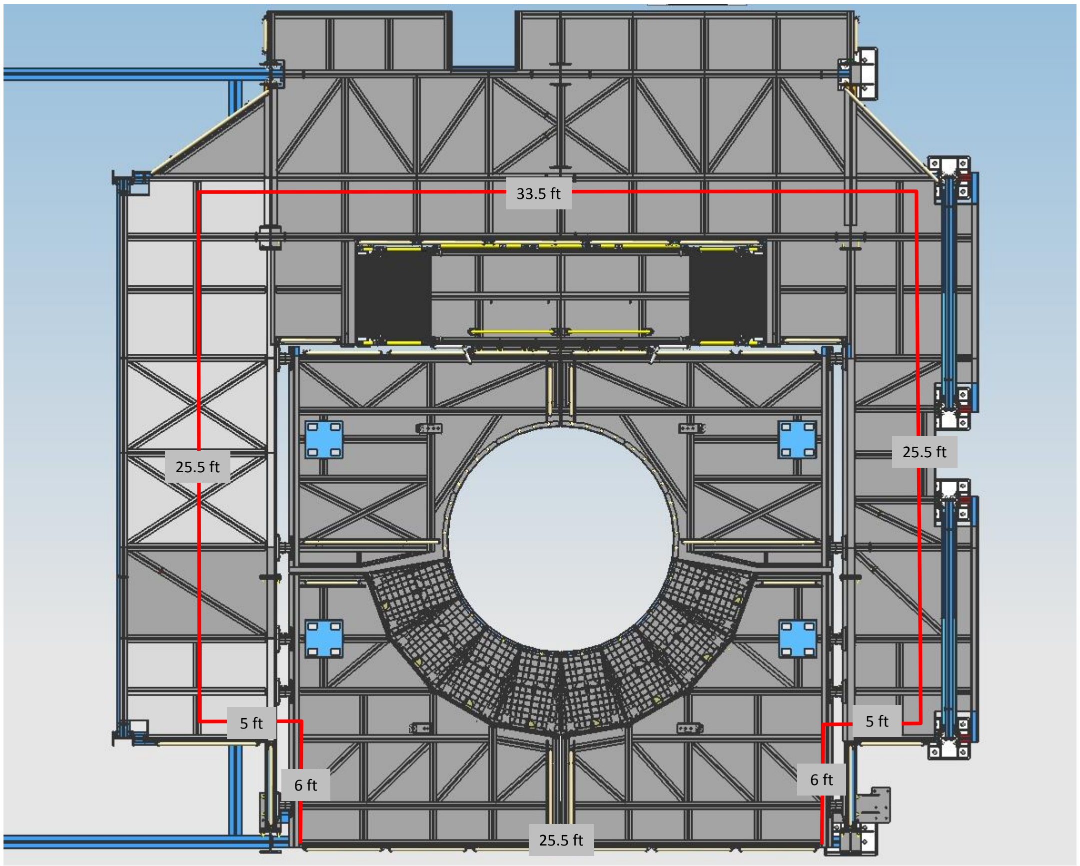


Figure 9: FAST Cell Wall Outline (Red)

The vertical screen outline was defined as shown in Figure 10 with the orange outline. Beginning at the top, the screen on the upper 16’-level platform stood 10 ft above the platform, with the screen wrapping around the outer edge of the platform, connecting to the lower wall panels. The lower wall panels were 14 ft tall, standing between the 0’-level and 16’-level platforms. The screen at the bottom of the 14 ft-tall panels ran across the platform to the center, at which point the screen dropped down and wrapped the lower 8 ft of the Orion Service Module.

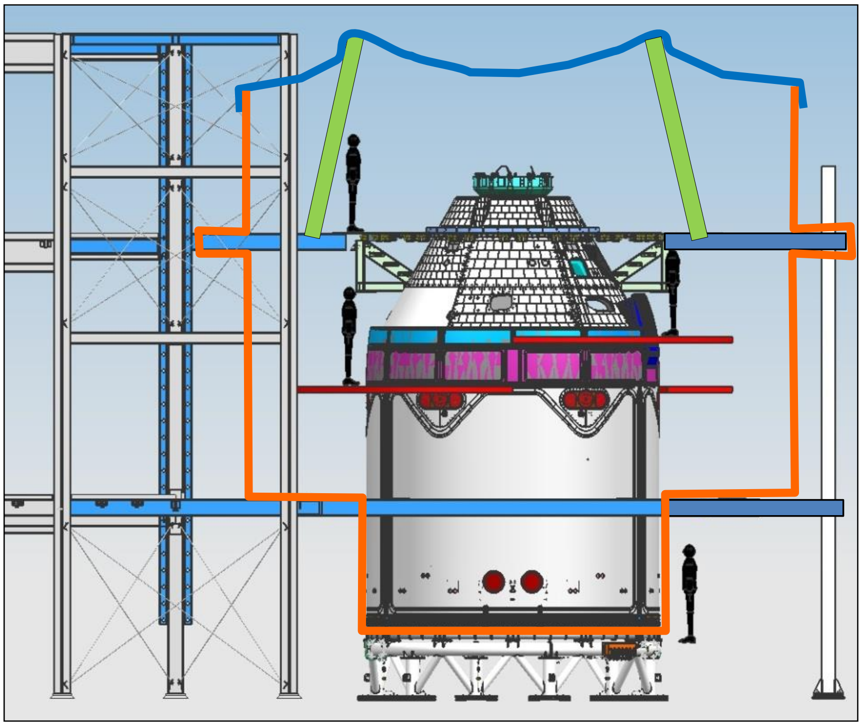


Figure 10: Screen Wrap Platforms to Protect EGSE

Also depicted at the top of Figure 10 in blue is the Screen Room roof. We will briefly discuss each of these – the walls, the platforms, the bottom of the spacecraft and the roof – and the challenges they presented in completing the EMI Screen Room.

On to the challenges!

CHALLENGE 1: Protect the EGSE

While this was obvious and one of the easiest issues to conquer, it must be stated that the Electrical Ground Support Equipment (EGSE) must be protected from the EMI RF energy. This equipment is critical to power and support the spacecraft under test and may be susceptible to the RF energy being used to test the spacecraft. Every effort must be made to ensure the EGSE is not compromised. Had we proceeded with a Direct Illumination test (no Faraday Cage) we would have built a screen room around the EGSE to ensure the RF signals would not reach the EGSE. For a Reverberant test, the simplest approach is to ensure the EGSE is on the outside of the Faraday Cage.

We did this by ensuring the platform that had to be encased already had copper screen laid on the floor (Figure 11) and stitched together before the EGSE was brought in. Setting the EGSE on top of the screen on the platform ensured it is physically outside of the Faraday Cage (Figure 12). Whether the seams in the screen are adequately sealed is another topic.

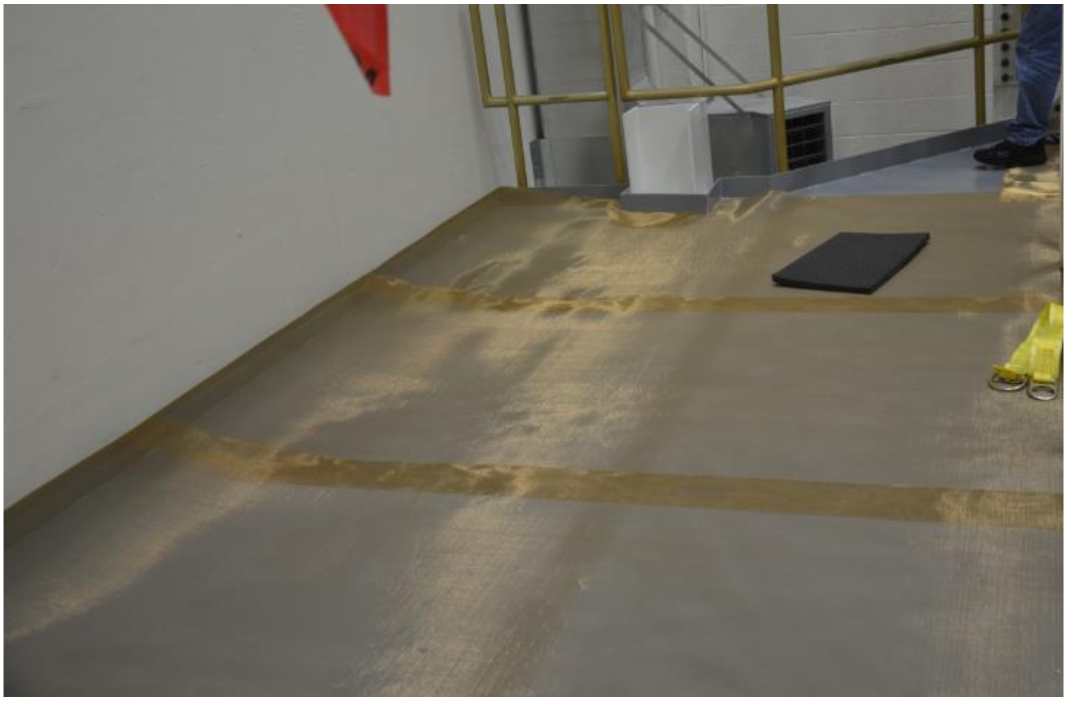


Figure 11: Screen-Wrapped Platform – from Above

Figure 12: EGSE Brought in After Screen was Laid Down and Stitched

CHALLENGE 2: Building the Panels

In order to stay within budget, we decided to make the panels with wood frames panels long enough to fit between the platforms on the 0-level (about 14 ft high), and to stand up 10 ft tall on the +16-level. 1”x4” boards were selected to keep the weight down, and a backer board spine (1”x6” for 10-ft panels and 2”x6” for 14-ft panels) was added to provide stiffness. Readily available material from the local hardware store could only be found in 12-ft lengths. In order to make the 14 ft panels the vertical boards had to be pieced together. We found that a simple spline 3-ft long provided adequate strength when glued and fastened with screws. See Figure 13.

CHALLENGE 3: Joining the Panels

The backer board spine (1”x6” for 10-ft panels and 2”x6” for 14-ft panels) added to provide stiffness also provided a surface to screw adjacent panels together. See Figure 14. Joining the panels in this fashion securely pinched the screen together at the backer board spine, making the panels appear to be a continuous metal wall for the Faraday Cage. Screws every 10-12 inches secured the panels together and eliminated the need to sew the screen together at every panel interface.

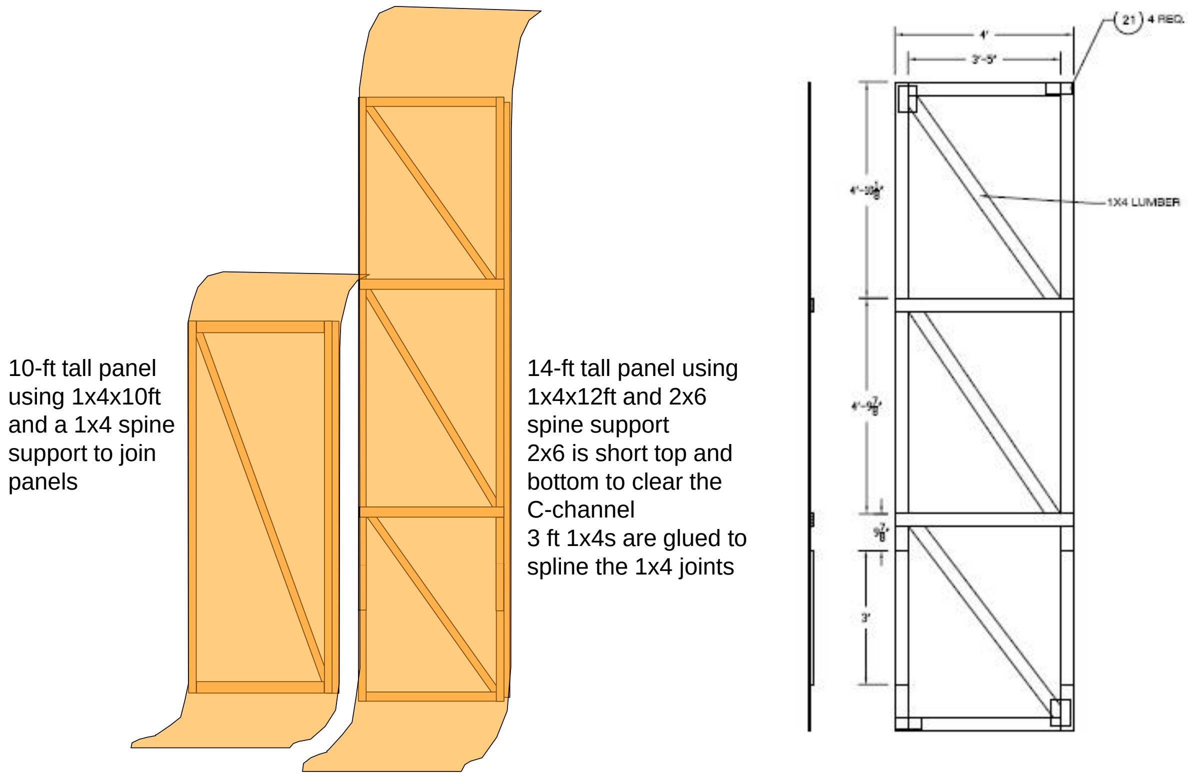


Figure 13: 10’ and 14’ Panel Concept, and 14’ Panel Drawing, Side and Front Views

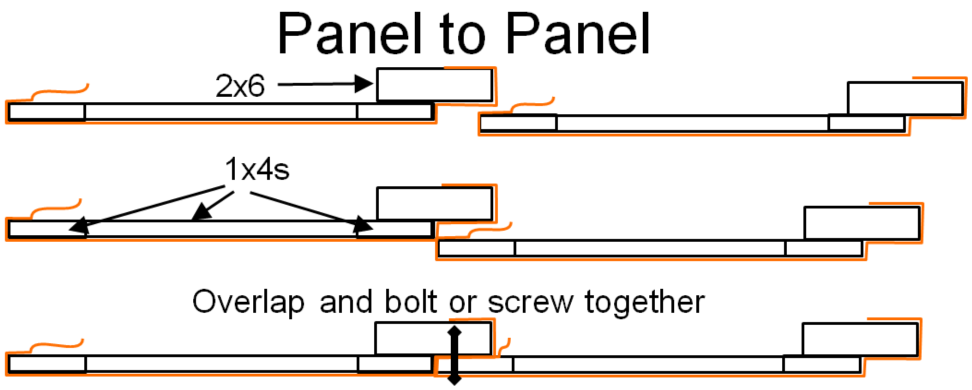
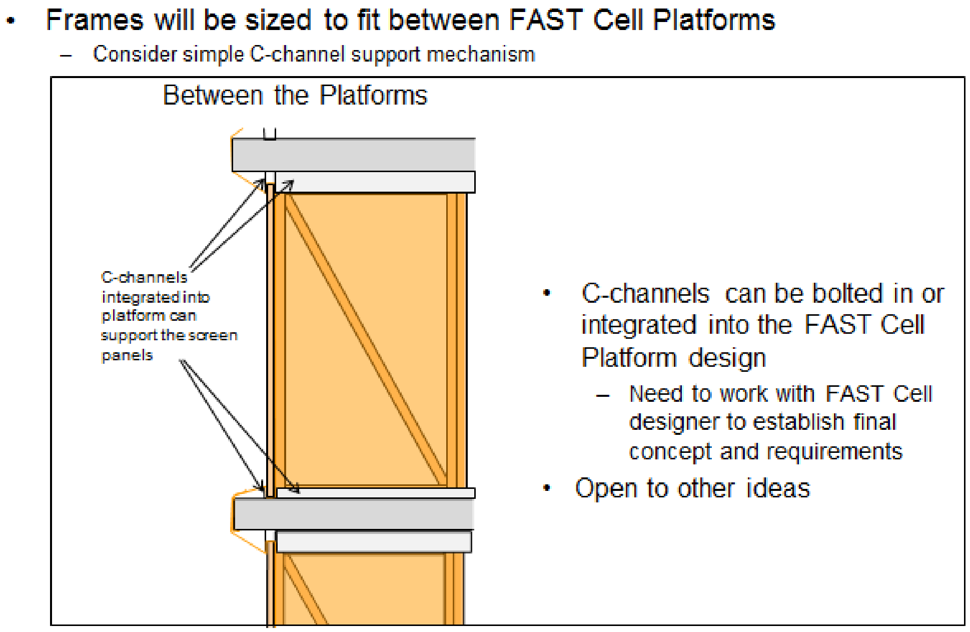


Figure 14: Panel to Panel Overlap, Top View

CHALLENGE 4: Connecting Walls and Floors/Ceilings

Between the 0-level and +16-level, a means of holding the panels in place and preventing them from falling in on the spacecraft was required. C-channel rails were identified as the solution for this. Similar to home window screens, the C-channel needed to be a deep pocket at the top, allowing the panel to be inserted, raised up then the bottom dropped into the lower C-channel. When the panel is seated in the lower channel, enough is still in the upper pocket to prevent the panel from tipping over. See Figure 15 for the initial design concept.



- Frames will be sized to fit between FAST Cell Platforms
  - Consider simple C-channel support mechanism

Between the Platforms

- C-channels can be bolted in or integrated into the FAST Cell Platform design
  - Need to work with FAST Cell designer to establish final concept and requirements
- Open to other ideas

Figure 15: Initial Concept – C-Channels to Support Panels Between the Platforms

Screen that wrapped the platform was tucked up into the upper C-channel so the panel top pinched the screen into the C-channel, forming a strong bond between the upper screen on the panel and the platform wrap screen. Similarly, the screen on the lower floor was laid across the C-channel on the floor, and the lower screen on the panel pinched the floor screen into the C-channel.

The upper screen panels would only have a lower C-channel to sit in. To ensure they could not fall inward onto the spacecraft a support wall was planned instead, to bolt to the deck at the C-channel line and allow the upper screen panels to be attached directly to the support wall, eliminating the need for C-channel on the upper platform. So we had to ensure the screen would have adequate pressure contact with the floor screen. We pre-tucked the wall panel's tail underneath and held it with a couple of screws. For the Effectiveness Test here is where we stopped – we relied on the weight of the wall to complete the contact, and this may have been a leak point. For the final test, once the wall panels were all installed, the wall screen tail and the floor screen edges were rolled together and screwed against the wall panel. See Figure 16.

Figure 16: Screen Closeout at Bottom of Wall Panels

CHALLENGE 5: Closeout the Front

Closing out the front of the FAST Cell raised the greatest challenges and most debate. With the plan to raise the 16'-level flip platforms we were left with no structure in front to support wall panels, and 28-ft tall wall panels were out of the question, especially when we had to consider raising them with the vehicle in the FAST Cell. We settled on creating a screen "curtain" that could be raised across the opening.

The details of how to fabricate it, raise it, hold it in place, attach it to the top, sides, and bottom, spawned much discussion. The first step was to get the southeast column extended, as discussed under Decision 4, above. Otherwise we would not have had an east side support for a cable or bar to hang the screen. Would the screen hold its weight when suspended for 35 feet? Would seven sheets of screen sewed together hold together when suspended for 35 feet? When we sewed the screen for the floor we learned the screen was much more robust that we first thought. We decided the strength in the screen lay in its length and made the curtain using 7 vertical panels. A 3-inch pocket stitched into the top with a 1-ft tail provided a place to string a cable for hoisting and support and gave a surface to attach the roof, similar to the screen tail at the top of each of the wall panels. A long spreader bar was used to lift the curtain into place until the cables could be threaded through pulleys and turnbuckles, secured, and tightened.

Custom cut boards were fabricated to pinch the sides of the screen against the front of the wall panels on the lower and upper levels. This left the bottom edge of the curtain to be sewn to the front edge of the floor. This closed out the front. See Figure 17.

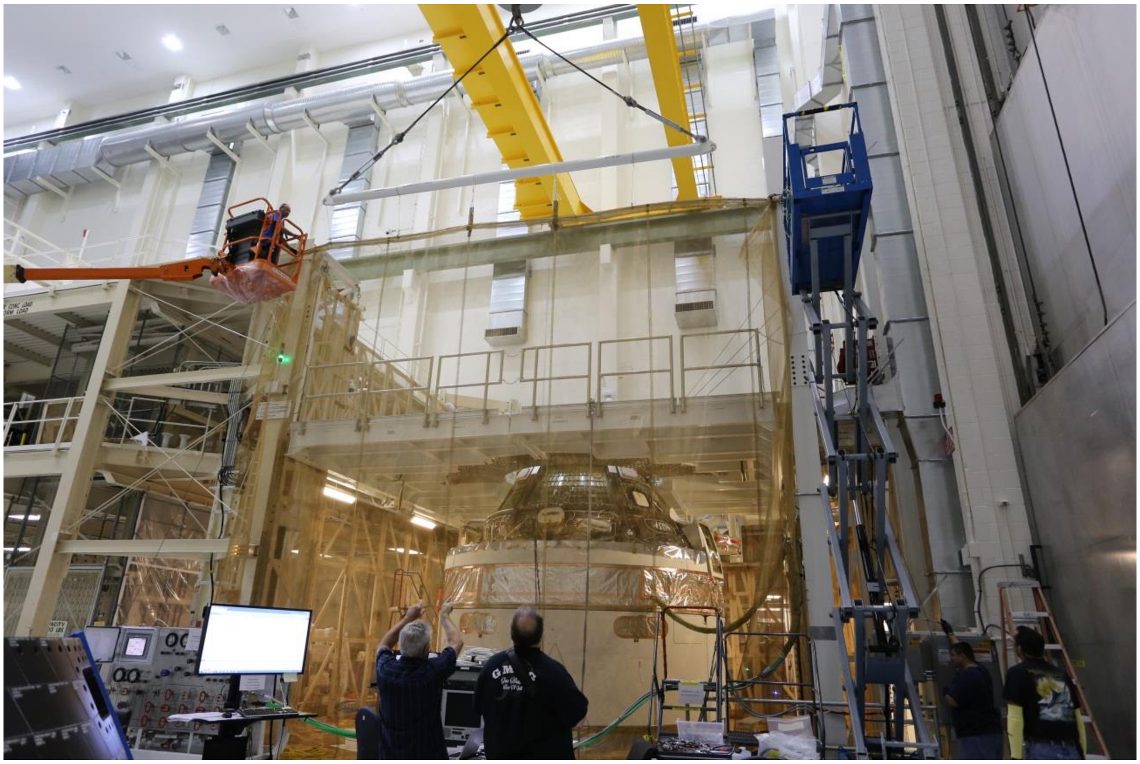


Figure 17: Front Curtain Closeout Being Craned into Place

CHALLENGE 6: Closeout the Bottom

The screen was essentially wrapped around the half of the Service Module that extended below the 0'-level platform. The SM itself was wrapped in Llumalloy (a plastic film approved for use on the Space Shuttle) to protect the surface from any marring by the screen material. The screen was bungeed around the upper flange of the stand on which the spacecraft rested. To complete the bottom portion of the Faraday Cage, it was necessary to close out the bottom of the Service Module itself, and close the contact with the screen at the stand flange.

The technicians had a brilliant scheme to accomplish this with aluminum foil. PMI cord was used to create a web across the base of the spacecraft, tying to the flange of the stand. This supported the weight of the aluminum foil allowing it to lay flat. Strip after strip was carefully laid across the PMI cord web, taped together with copper tape, and taped up to the screen edge at the base. Yes, aluminum foil is an approved material to use in your EMI Screen Room. Don't be afraid to experiment with materials. See Figure 18.

Figure 18: Service Module Bottom Closeout

CHALLENGE 7: Closeout the Top

Putting a roof on the EMI Screen Room without building a structure over the spacecraft was a challenge until we decided to follow up with several manufacturers who make RF reflective fabrics. Unfortunately, these fabrics are expensive, and a piece large enough to cover the EMI Screen Room consumed almost half of the available budget.

We ordered a large 40-ft square of fabric with a hanging loop placed in the center to lift it. Loops placed on each corner then provided tagline connections to control the fabric during lift and pull the corners out. A cable with a pulley was strung and proof loaded above the FAST Cell before the vehicle was in place. The pulley allowed us to raise the fabric up and over the spacecraft, and the tag lines pulled the corners out over the top of the upper screen walls.

Attaching the fabric to the screen walls was tabled until we had hardware in hand. But that day came and we decided to try to use a dowel around which the upper tail of the wall panel screen and edge of the roof RF fabric could be rolled. Pipe clamps applied every two feet were adequate to hold the edges tightly together. See Figure 19.

Figure 19: RF Fabric Roof in Place and Held with Pipe Clamps

CHALLENGE 8: Structural Energy Drain

The FAST Cell in which we planned to perform the EMI/EMC test is tucked in the corner of the facility. The structure itself is relatively new, built for Orion, and if it were a free-standing structure it would have been much easier to encapsulate in the Screen Room. But it was connected to adjacent structure that hails from the Apollo days – tons of steel in several thousand square feet of platforms and two 33 feet diameter, 55 feet tall altitude chambers. See Figure 20.

NASA would not allow the new structure to tie to the O&C walls. This helped in the implementation of the screen room by ensuring there is an airgap around the north, east and south sides of the structure and made it easier to wrap the platforms. However, they were allowed to tie the new structure to the Apollo-era structure. Any RF energy that entered the FAST Cell structure would “broadcast” out through the tons of steel, dissipating the RF energy in the FAST Cell.

Tricks to take the structure out of the EMI Screen Room include moving the walls to exclude the structure from the interior of the Screen Room, and “short circuit” the structure with the Screen Room itself, making it part of the screen room rather than a conduit or antenna out of the screen room. We implemented the former by redesigning the corner of the Screen Room to move the walls and curtain on the Southeast corner to bring them inboard of the column, taking that column out of the Screen Room, as mentioned above and visible between Figures 5 and 7.

We implemented the latter primarily by removing paint in strategic areas and compressing the screen to the bare metal. We removed the paint from under the support walls on the upper level, removed paint from the tops of the two columns still inside the Screen Room, and removed bands of paint from the top of two columns penetrating the Screen Room. See the montage in Figure 21.

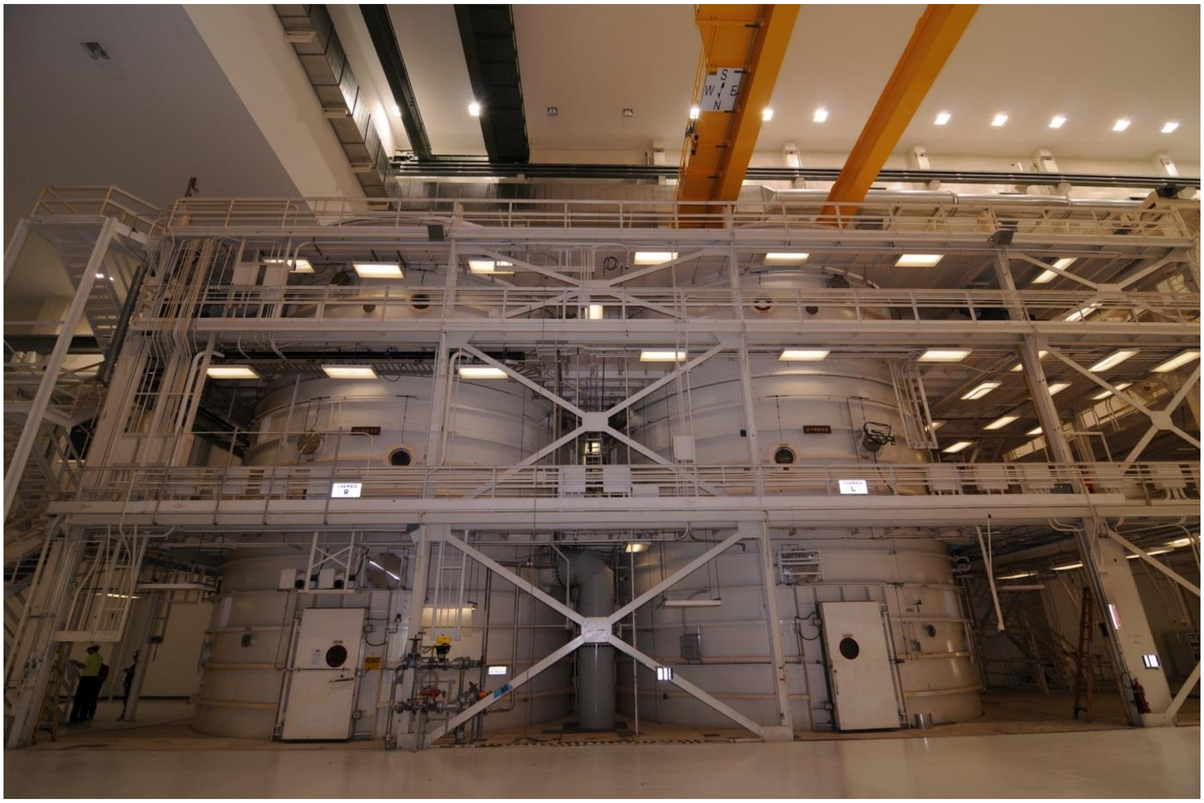


Figure 20: 50 Years of Structure Attached to the FAST Cell

CHALLENGE 9: Cable Trays, and Other Penetrations

As you might expect, there were cable trays both inside and outside of the Screen Room. For the cable trays outside of the Screen Room we were fortunate to have stretched the platform screen before the cable tray installation began. This allowed us to coordinate installing additional nuts with fender washers to punch the screen with the threaded hanger rods, and pinch the screen to the hanger's beam clamp with the fender washer, effectively sealing off the rod penetration. See Figure 22. If we did not have this opportunity, the screen would have completely enveloped the cable trays outside the Screen Room because cutting and stitching the screen around the hanger rods would have been incredibly time consuming.

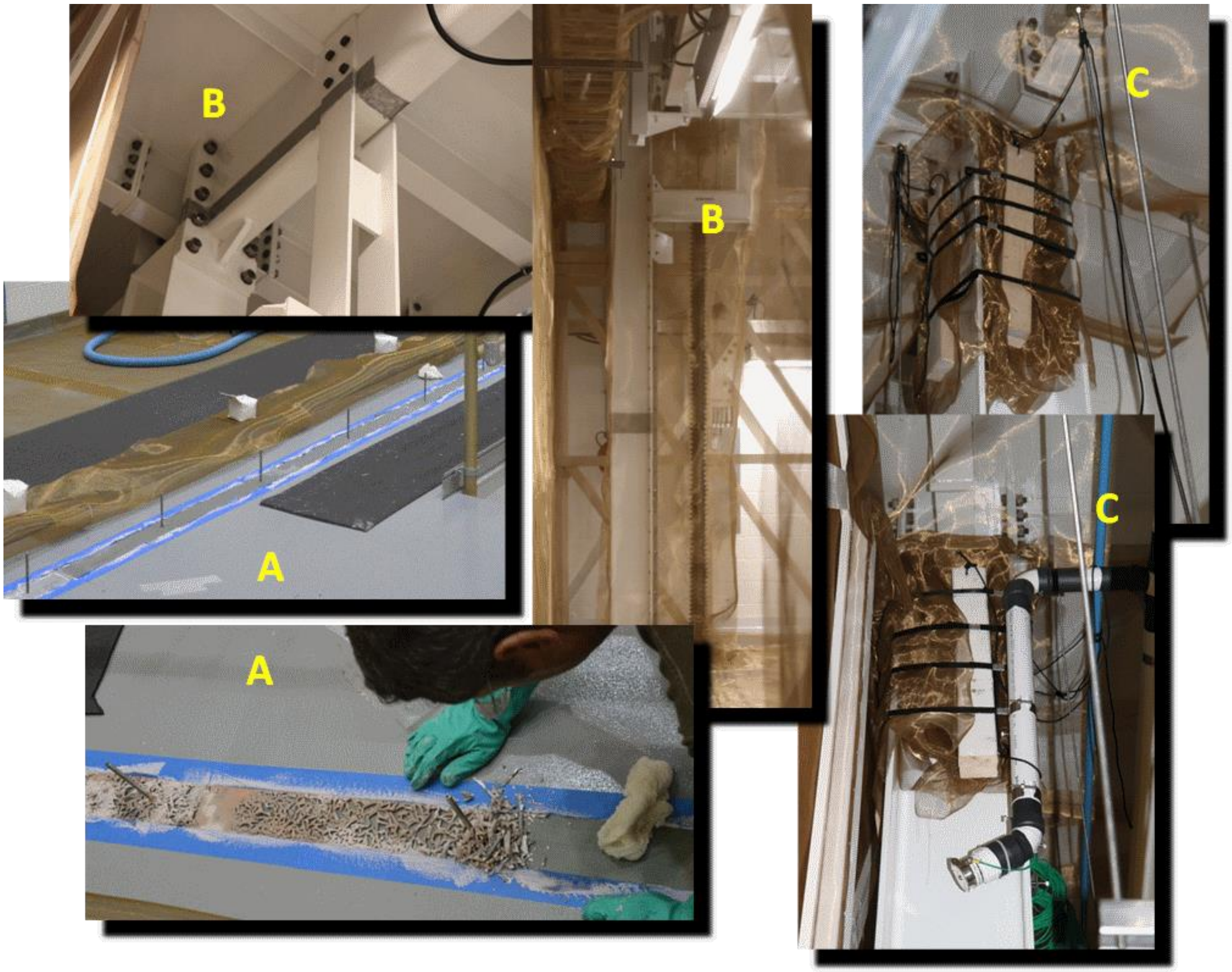


Figure 21: Taking the Structure "Out" of the EMI Screen Room

A. Stripping Paint Under Support Wall
B. Stripped Paint to Sock Column Inside Screen Room
C. Integrating North Columns into Screen Room

For the cable trays inside the Screen Room, we had a choice: either sock every cable that enters the Screen Room from its point of origin and ground to its point of connection to the spacecraft, or sock the entire cable tray and only the part of the cable that extends from the cable tray to the spacecraft. We opted for the latter solution as a more complete method of closing out the Screen Room. All cable trays were unclipped from their trapeze. Screen sheets were fed underneath the cable trays and pulled over the top of the cable tray, and cable tray clips were replaced. The sock screen was sewn to the Screen Panel screen at each penetration point. See Figure 23. This allowed cables to still be run, and the screen sealed afterward. Initially, the cable trays were only clipped closed for the Effectiveness Test; we had no cables in the cable trays. So this may have been an avenue for losing power in the early test. For the final test the cables were in place and the cable tray socks fully stitched closed. The cables coming out the end of the cable tray were bundled, packed with screen, and cinched tight. This is shown in Figure 24.

Figure 22: Threaded Rod Challenge – Close-Up of Fender Washer Installation (The two columns in the left image are those mitigated in the “C” images in Figure 21)

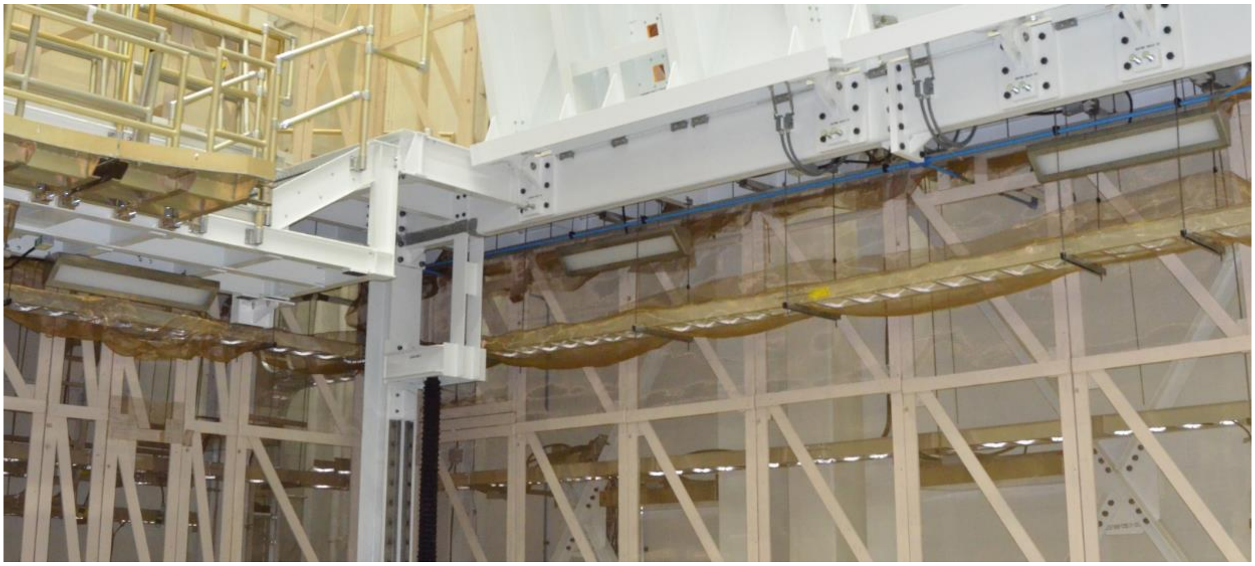


Figure 23: Socked Cable Trays (also notice Compressed Air Blue Pipe)

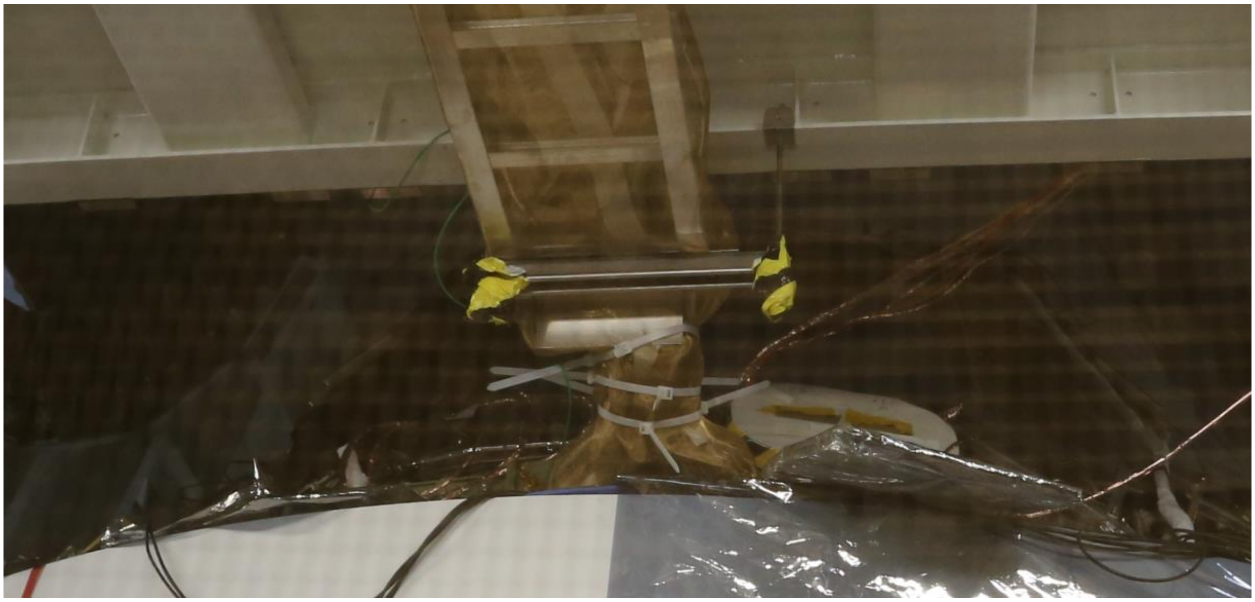


Figure 24: Socked Cables Coming Out of the Central Cable Tray

The next challenge levied by the FAST Cell utility infrastructure was the compressed air pipe. The lines, installed as blue pipe, intersected the screen wall in four locations along the east side. These penetrations were not in the Screen Room Panel drawings, and were never intended to penetrate the Screen Room. But the drawing did not carry the annotation to keep out of the Screen Room. Four wall panels required on-the-fly modifications to accommodate the pipe, rebuilding the top of the panels to notch the top crossbar. The pipe had to be sanded to bare metal on both sides of the screen, have a sock of copper screen sewn around the pipe and strapped to the pipe at the bare spots, then have the copper screen sock sewn to the wall panel screen to fully integrate the inside pipe into the screen room. The pipe can be seen above the cable tray in Figure 23, and a sample of a socked pipe is shown in Figures 25.

Figure 26: Socked and Mitigated Compressed Air Pipe Penetrations

We had winch cables to raise the upper flip platforms that had to be accommodated, since the flip platforms had to remain operational during Screen Room build and parallel spacecraft assembly and test operations. This meant providing upper wall cutouts for the winch cables to move. Once the flips platforms were in their uppermost position, safety stays were attached to allow the winch and safety lock cables to be removed. The Screen Room wall cutout could then be replaced and secured. But in all four cases the safety stays had to penetrate the RF Fabric Roof. It took a lot of time to determine where to cut the RF Fabric to allow the fabric to move without tearing (plus, as expensive as the fabric was it was difficult to get comfortable with cutting it at all!). See Figure 27.

Figure 27: Flip Platform Winch Line Access (L) and Replacing the Panel Below the Safety Stay Penetration Through the RF Fabric Roof (R)

CHALLENGE 10: Stuffing and Tucking

There were many nooks and crannies that defied smooth screen coverage. These included cutouts around columns, indents for cable trays, handrail mounts, etc. Each came with its own challenge and solution. Simply said, be prepared to wad up screen and pack it in places to help closeout screen that can’t be stitched together, and strip paint and strap wads of screen, using boards to help apply pressure. Be prepared to extend socks around penetrations. Use copper tape (with conductive adhesive) as a last resort to close out openings. See Figure 26.

Figure 26: Stuffs and Tucks and Final Socks

CHALLENGE 11: Personnel Access

The final challenge for the screen wall panels was to create a personnel access door on each level that would adequately seal the chamber. We were continuously warned by our EMI experts that this would be difficult to close out and time-consuming to open and close if frequent access is required to swap out horns. A 7’ height door was designed to overlap the wall panel boards to provide a faying surface to bond the door to the screen wall. See Figure 27. It could have been a pull-out panel, but we elected to add hinges to allow the door to swing open. During test operations the door could be sealed closed with approximately 20 screws – our techs could open or seal the door in less than 5 minutes. (They’re awesome!) We eliminated most of the entry opening/closeout cycles by cabling up all of the horns to patch panels built in to the wall panels. This allowed the horn swaps to be made from the outside of the Screen Room. See Figure 28.

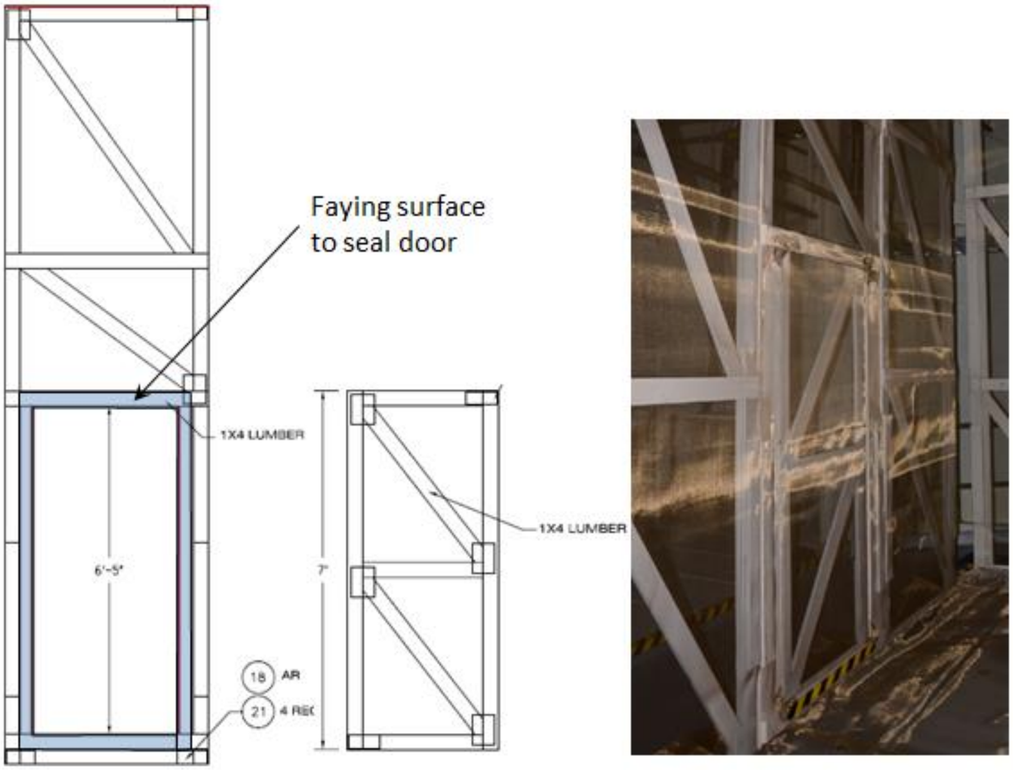


Figure 27: Personnel Access Door – 0'-Level Platform Screen Wall

Figure 28: Antenna Horn "Patch Panel" – outside (L) and inside (R)

FINAL NOTES

We have provided you with the primary issues you will face if you choose to build your own EMI Screen Room. We want to leave you with a few more items to remember to think about.

E-Field Probes are necessary equipment in a reverberant chamber. Remember to allow for a penetration for these. Also remember that battery-powered probes will have to have batteries replaced or recharged. If you have to enter the chamber to do this your personnel access is going to have to be opened and sealed more frequently. Try to get E-field probes that can operate at the same time as they are charging, and plan to extend the charge cords into the chamber. These cords also have to be socked – copper tape will work well for this. E-field probe data lines are typically fiber optic cables – these do not have to be socked. Better yet, get E-field probes that are laser-powered. The fiber optic cable is all you will have and the probe will run through the entire test without any batter charging issues.

A reverberant chamber benefits from having paddle stirrers for the lower frequencies to keep them moving around the chamber. “Stirring the Chamber” with a design such as this is supported by the “breathing” of the chamber – the facility air handlers blowing across the RF Fabric roof help it move, and an industrial fan blowing obliquely on the front curtain kept it rippling. Both of these added to the ability of the EMI Screen Room to stir the modes.

Our final test, while not as effective as a chamber built specifically for this kind of testing, was adequate for this development vehicle. The EMI Screen Room looked beautiful (see Figure 29), allowed us to test the Orion EFT-1 spacecraft in situ saving us 6-12 weeks in schedule to reposition to a distant facility, and in total cost less than $55,000 (yes, we went over budget).

NASA Health Physics swept the exterior of the chamber during testing and verified there was negligible RF leak from the chamber, assessing it was safe to be next to the chamber during RF operations. We thank them for participating in the test and for their assessment!

But the down side of the success of the chamber in preventing RF leaks is it also complicated spacecraft assembly operations as it didn’t allow the use of wireless devices for procedure tracking and headset communications.

Another downside to be aware of for this type of chamber is that FOD (Foreign Object Debris) from copper screen wire and trimmings is a significant challenge to manage. You will never eliminate it. Tacky mats and continuous vacuuming are required to keep copper wire FOD under control. Sadly copper wire cannot be picked up with magnets. Be aware!

FINAL TEST RESULTS

Our test configuration placed 2 e-field probes inside the Orion EFT-1 Crew Module and 4 probes distributed around the exterior of the Crew Module, approximately 4-5 feet from the outer mold line. We typically kept the monitors set to “Max Hold” (a setting that continuously displays the highest level recorded) so we would know the highest power seen by each probe to know if the spacecraft was seeing the level of environment required. But the best feeling we received was on one run we elected to switch to real-time display. Bob Scully was the first to recognize the behavior of the screen when he said, “Hey, look at that! It’s stirring!” We captured video of the monitor and will show that in the presentation. But a map of screenshots is presented in Figure 29. The location of the screenshot in the image suggests which channels are seeing the highest power. In the corner the channel has the highest reading, and toward the middle it shares the high readings with its adjacent neighbor channels.

Figure 29: E-Field Probes Observed the RF Energy was "Stirring"

The end result is the Q-factor for the EMI Screen Room was around where we expected, in the thousands, rather than in the hundreds we had in the Effectiveness Test. See Figure 30.

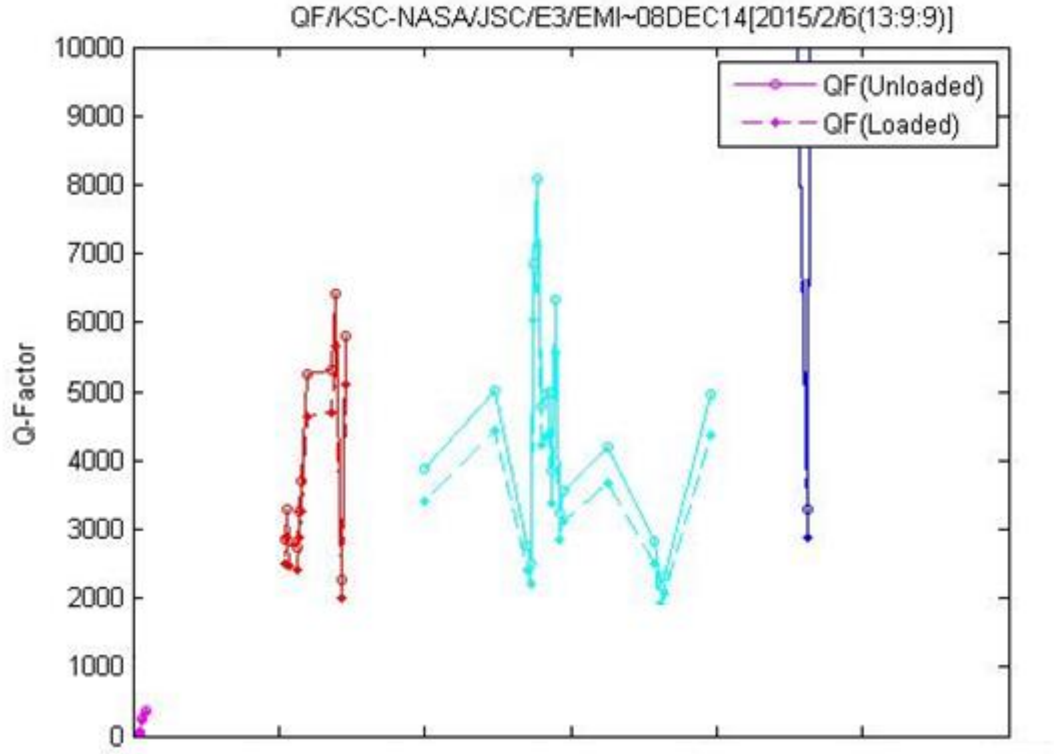


Figure 30: Final Test Quality Factor Results

SUMMARY

It is possible to design and build an affordable EMI Reverberation Chamber. (That is, inexpensive in terms of materials. This approach will require significant labor to complete.) Thoughtful planning and creative energy are required to ensure the facility can be converted to a successful EMI Screen Room. Facility modifications will likely be required, if nothing more than removing paint to get to base metal structure.

An EMI Screen Room that can use the copper screen for the roof will be far less expensive than one that requires a proprietary RF Fabric cover. Scale of the Screen room and risk to the test article are the drivers.

Certainly, the availability of a dedicated facility or a material budget of $200k-$500k to purchase a custom RF Fabric room are preferable. But we have given you the tools to work and succeed on a much lower materials budget.

REFERENCES

O&C Building Final Assembly & System Test (FAST) Tooling Stand Equipment and Utility Outfitting, Drawing OCM-0119, dated 22 May 2013

O&C Building Final Assembly & System Test (FAST) EMI Screen Installation, Drawing OCM-SKXX (No number formally assigned), dated 31 Dec 2013

IMAGE CREDITS

Figure 6: Effectiveness Test Quality Factor Results, NASA JSC
Figure 30: Final Test Quality Factor Results, NASA JSC
All other images Lockheed Martin Corporation

BIOGRAPHIES

Edward Aldridge is a Senior Staff Engineer with Lockheed Martin Space Systems Company, with over 28 years of test, systems engineering, and system architecture experience at the company. He holds a Bachelor of Science in Aerospace Engineering from the University of Southern California, and a Master of Science in Astronautical Engineering from the Air Force Institute of Technology, and is a member of Tau Beta Pi (CA **D**). He has worked on Department of Defense (DoD) satellite programs, ground processing systems, the Titan launch vehicle, and even an Army ground system. He is a retired Air Force officer with 24 years of service, the last 18 as a Reservist. Ed came to the Orion program in 2007 and is the System Environmental Test Lead within the Assembly, Test, and Launch Operations (ATLO) organization.

Bruce Curry holds a Bachelor of Science Degree from University of Nebraska in Electrical Engineering. Over the past 18 years he has been an RF Systems engineer, RF Test engineer, EMI/EMC Systems Engineer and a Certified Test Conductor (CTC) testing EMI/EMC/PIM for Lockheed Martin Space Systems (LMSSC). He is currently the Space Vehicle System Test Lead for LMSSC where he designs and executes custom on Site and in-situ EMI/EMC and Passive Intermodulation tests. He is a member of Tau Beta Pi (NE **A**) and Etta Kappa Nu Engineering societies and an iNarte Certified EMI Engineer. He is proud to have served in the US Army from 1987 to 1990.

Bob Scully is an IEEE Fellow, and holds a PhD degree in Electromagnetics. He has 30+ years in aviation electrical and electronics engineering and electromagnetic compatibility (EMC), with experience ranging from fixed wing business jets to military and commercial rotary wing aircraft to Space Shuttle and Space Station systems support. He holds a GS15 rating, and is currently the NASA Johnson Space Center (JSC) Electromagnetics Environmental Effects (E3) Group Lead Engineer. Bob is the E3 Lead for the Orion and Commercial Crew Development (CCDev) Programs, directly supports the International Space Station Program, and is the Lead for the NASA E3 Community of Practice. Bob is an Associate Editor for the IEEE Transactions on Electromagnetic Compatibility, and is currently the President of the IEEE EMC Society. He is a member of Tau Beta Pi (TX **H**) and Eta Kappa Nu, is a registered professional engineer in the state of Texas, USA, and holds certifications as an EMC Engineer from both the University of Missouri at Rolla and the International Association for Radio, Telecommunications and Electromagnetics (iNARTE).