

Ensuring Safe Exploration: Ares Launch Vehicle Integrated Vehicle Ground Vibration Testing

*M.L. Tuma, PhD and D.J. Chenevert, PhD, P.E.
Ares Flight & Integrated Test Office (FITO), Structural, Environmental, and Vibration Test (SE&VT),
Marshall Space Flight Center
Huntsville, AL 35812*

Abstract

Integrated vehicle ground vibration testing (IVGVT) will be a vital component for ensuring the safety of NASA's next generation of exploration vehicles to send human beings to the Moon and beyond. A ground vibration test (GVT) measures the fundamental dynamic characteristics of launch vehicles during various phases of flight. The Ares Flight & Integrated Test Office (FITO) will be leading the IVGVT for the Ares I crew launch vehicle at Marshall Space Flight Center (MSFC) from 2012 to 2014 using Test Stand (TS) 4550. MSFC conducted similar GVT for the Saturn V and Space Shuttle vehicles.

FITO is responsible for performing the IVGVT on the Ares I crew launch vehicle, which will lift the Orion crew exploration vehicle to low Earth orbit, and the Ares V cargo launch vehicle, which can launch the lunar lander into orbit and send the combined Orion/lander vehicles toward the Moon. Ares V consists of a six-engine core stage with two solid rocket boosters and an Earth departure stage (EDS). The same engine will power the EDS and the Ares I second stage.

For the Ares IVGVT, the current plan is to test six configurations in three unique test positions inside TS 4550. Position 1 represents the entire launch stack at liftoff (using inert first stage segments). Position 2 consists of the entire launch stack at first stage burn-out (using empty first stage segments). Four Ares I second stage test configurations will be tested in Position 3, consisting of the Upper Stage and Orion crew module in four nominal conditions: J-2X engine ignition, post Launch Abort System (LAS) jettison, critical slosh mass, and J-2X burn-out.

Because of long disuse, TS 4550 is being repaired and reactivated to conduct the Ares I IVGVT. The Shuttle-era platforms have been removed and are being replaced with mast climbers that provide ready access to the test articles and can be moved easily to support different positions within the test stand. The electrical power distribution system for TS 4550 was upgraded. Two new cranes will help move test articles at the test stand and at the Redstone Arsenal railhead where first stage segments will be received in 2011.

The Hydrodynamic Support systems (HDSs) used for Saturn and Shuttle have been disassembled and evaluated for use during IVGVT. Analyses indicate that the 45-year-old HDSs can be refurbished to support the Ares I IVGVT. An alternate concept for a pneumatic suspension system is also being explored. A decision on which suspension system configuration to use for IVGVT will be made in 2010.

In the next three years, the team will complete the updates to TS 4550, upgrade the test and data collection equipment, and finalize the configurations of the test articles to be used in the IVGVT. With NASA's GVT capabilities reestablished, the FITO team will be well positioned to perform similar work on Ares V, the largest exploration launch vehicle NASA has ever built. The GVT effort continues NASA's 50-year commitment to using testing and data analysis for safer, more reliable launch vehicles.

Introduction

Most launch and space vehicles, as well as aircraft, undergo a low-energy vibration test to measure the modal characteristics of the vehicle. This modal testing or ground vibration testing (GVT) usually

captures the natural frequencies, mode shapes, and damping of the vehicle's structure. This data is then used to correlate dynamic finite element models (FEMs) to produce test-verified dynamic FEMs for use by disciplines such as aeroelasticity, structural loads and dynamics, and guidance, navigation and control (GN&C) to analyze, and estimate vehicle responses to expected flight, and ground loads and environments. Analyses employing the test-verified FEMs are used to support the design certification review (DCR) process, ensuring that the vehicle is structurally sound and safe to fly. Current analyses show the fundamental frequencies of a fully fueled, launch-ready Ares I launch vehicle to be in the 1 to 10 Hertz (Hz) range, giving the Ares I the lowest primary bending frequency of any human-rated launch vehicle that NASA has ever flown. Therefore, understanding the flex properties of this vehicle is especially important. By measuring the response to a known excitation at the precise location of the flight control sensors a significant amount of uncertainty can be removed from the sensed data processed by GN&C algorithms allowing improved flight control system performance. Furthermore, the IVGVT data can help fine-tune models used to optimize the performance of thrust oscillation mitigation and POGO suppression devices.

Without test-calibrated IVGVT models, the model uncertainty factors (MUF) used in verification loads analysis are not updated and remain the more conservative values employed during earlier phases of the design. This can translate into flight envelope reduction and launch/payload restrictions. If model uncertainties are too large, GN&C stability requirements either cannot be met or make the design of the GN&C system more challenging. Model inaccuracies in the bending dynamics of the vehicle could create an unstable control system design, which in turn could result in loss of the mission. A GVT also supports GN&C analysis by reducing uncertainty in the flex model.

The Aerospace Corporation conducted a study of 47 launch and space vehicle test programs¹. In all but one program, the analytical models required updating prior to final vehicle deployment. The study's authors concluded that they were "not aware of a single analytical model of complex structure that has had acceptable agreement with its mode survey test data before adjustment; significant changes in loads from analytical to test-verified model."²

Failure to conduct such testing often has catastrophic consequences. The Delta III launch vehicle was destroyed on its maiden launch due to the control system responding to a 4 hertz oscillation that would have smoothed on its own without correction. Designers had relied on known Delta II vehicle responses even though the Delta III launch vehicle had a significantly different configuration, with an increased-diameter first stage fuel tank, a shorter length, two additional solid rocket motors, and a new second stage engine fueled by liquid oxygen/liquid hydrogen (LOX/LH₂). Based on the heritage Delta II system modes, the Delta III control software responded to a vehicle mode (oscillation) that did not require correction. Had the program conducted dynamic testing on the Delta III, it is likely this mode would have been understood and the control software adjusted to accommodate it.³

Similarly, the Ariane 5 was lost on its inaugural flight due to a lack of understanding of the vehicle's new engine nozzle and a decision by management not to compensate by adding additional safety margins into the vehicle's design and testing. The loss of the satellite payload resulted in the need for Arianespace to conduct a further demonstration flight with no payload before another paying customer would sign up to use the launch system.⁴

More recently, the commercially developed SpaceX Falcon 1 suffered a partial failure on its second test flight in March 2007. The launch went well until separation of the first stage. The first stage bumped the engine bell of the second stage engine as the interstage separated. A circular coning oscillation began and increased in amplitude causing the vehicle to roll. This ultimately produced a vehicle roll that caused the LOX tank to slosh due to the amplified oscillation. LOX tank slosh increased the oscillation, which would normally be compensated for by thrust vector control (TVC). The increased oscillation caused the TVC to overcompensate the correction, which in turn led to premature burnout of the second stage engine and a failure to meet mission objectives. Perhaps some modal characteristics of the Falcon 1 vehicle were not well understood if a bump could excite a mode that would persist and ultimately doom the mission. Falcon 1 is an example of the worst modal attributes coupling together (natural modes, slosh modes), leading to TVC overcompensation and perhaps failure of other systems to respond. More ground testing,

including dynamic testing, could have helped identify these modes prior to launch, ensuring better characterization and design of the structural and slosh modes and the vehicle's ability to control them.

The size of NASA launch vehicles necessitates extensive planning to ensure the vehicle and facility meet requirements not only for good test results but for the safety of those setting up and conducting the test. NASA is currently developing the next generation of launch vehicles—the Ares I crew launch vehicle and the Ares V cargo vehicle—along with the Orion crew exploration vehicle. Both Ares vehicles will require a GVT to validate analytical models to support loads and GN&C modeling.

The Saturn and Space Shuttle programs both performed subscale model dynamic tests in addition to their full-scale tests. Saturn used a $1/10^{\text{th}}$ scale model. Shuttle used a $1/4$ scale model. Ares I analysts have determined that Ares I will not require a subscale model due to its simple in-line configuration and payload and because NASA now uses faster, more accurate computational tools. While useful in developing designs for the earlier projects, modern tools allow Ares I to omit the cost and time required to perform subscale model testing.

Planning for the Ares I/Orion IVGVT has been ongoing since the inception of the Constellation Program. This planning draws heavily on the historic data archived in NASA libraries for Saturn V and Space Shuttle dynamic testing in the dynamic test stand at Marshall Space Flight Center (MSFC). The Ares I vehicle's shape is significantly different from Saturn V and Shuttle. The Ares I crew launch vehicle has a large-diameter upper stage (approximately 18 feet) and a small-diameter first stage (approximately 12 feet). The IVGVT has already conducted two Subject Matter Expert (SME) reviews to obtain the evaluation and lessons learned from experts from both the Saturn and Shuttle GVT projects. The availability of historic records and professional authorities with hands-on GVT experience has been a tremendous aid in IVGVT planning. A third subject matter expert (SME) review is planned prior to the Ares I Critical Design Review (CDR).

While not an objective of dynamic testing per se, the dynamic test conducted in TS 4550 provides an additional benefit to the space flight program, as it is usually where launch vehicles are fully stacked for the first time. Both the Saturn V and Space Shuttle vehicles were first stacked in TS 4550, allowing engineers to verify hardware fits and tolerances and also to test out stacking procedures prior to them being employed for flight vehicle launch preparations at KSC. It will be the same with Ares I. To prepare for the initial stacking of the upper stage, the IVGVT team will receive an Upper Stage Pathfinder test article. The Pathfinder will be used to dry run a number of activities related to transportation, ground support equipment (GSE), special test equipment (STE), stacking, various procedures, interfaces, and fit-up in the Second Stage Test Position #3 in Test Stand 4550.

I. Saturn V Testing

NASA planned and executed a GVT during the Saturn V program, called Dynamic Vehicle Test (DVT). The test was performed on a full-scale test article to determine the structural dynamic characteristics for flight control system design and to verify the vehicle's structural integrity. The test article was built to flight article specifications. Deviations from these specifications were built in to ensure that the overall dynamic response of the vehicle was not changed.⁵

The Saturn V vehicle consisted of three booster stages, the instrument unit (IU) and the payload. Fully fueled, the vehicle weighed approximately six million pounds, was 365 feet tall, and was 33 feet in diameter at the base. For the Saturn V DVT, de-ionized dichromate water was used to simulate the propellants, liquid oxygen (LOX) and RP-1, in the first stage as well as the simulant for LOX in the second and third stages. Due to the difficulties of adequately simulating liquid hydrogen (LH₂), the LH₂ tanks were left empty in the second and third stages for lateral testing and were weight-simulated with water for longitudinal and roll testing.⁶

Test Stand 4550 (TS 4550) was built at MSFC during 1962-1964 to perform dynamic testing for the Saturn program. Due to the very large size of the Saturn V vehicle, TS 4550 is 360 feet high. The 200-ton stiff-leg crane on top of the building adds 64 feet to the overall height. Platforms capable of folding back and away from the test article were built at TS 4550's 15 levels, [levels are 24 feet apart vertically],

providing access to the vehicle.⁷ The vehicle was handled in the stand by derrick cranes installed on the roof and about halfway up the exterior of the stand.⁸

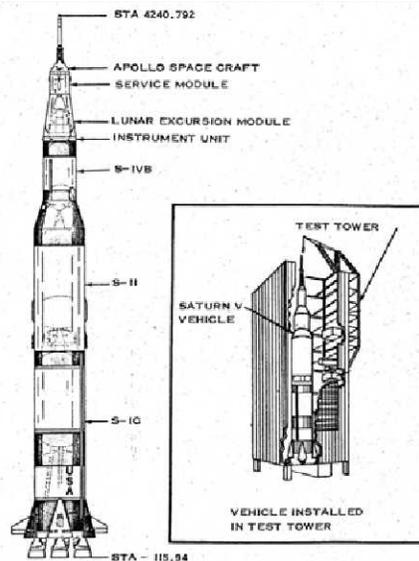
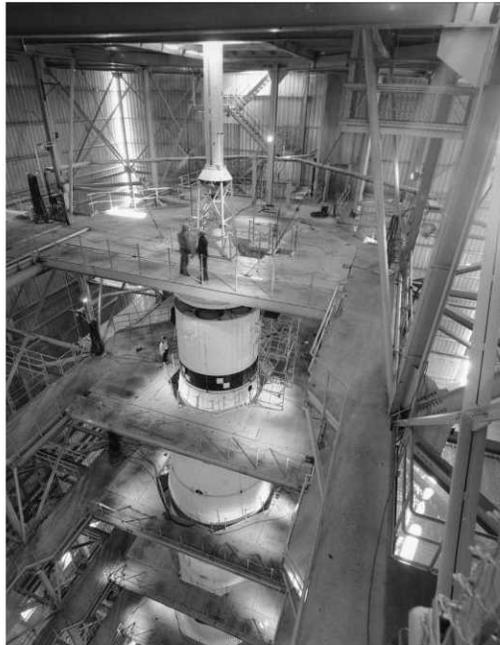


Figure 1 - Saturn V test article and installed in TS 4550

The suspension system required to simulate free flight was a particular challenge. Suspending the vehicle by cables would not work, as the cables resonate at frequencies similar to that of the vehicle which might have complicated or invalidated test results.

NASA developed a state-of-the-art suspension system to simulate the free-free boundary conditions of flight. The hydrodynamic support system or HDS consists of oil bearings and vertical gas springs for lateral and roll stability (Figure 2). Oil under pressure was pumped between flat contacting surfaces to provide a near-frictionless support. This system transmits the heavy vehicle load directly to the ground, enabling the support mass to be relatively small.⁹ The HDS units were so effective that the entire six-

million-pound vehicle could be excited in its low frequency suspension modes by two people pushing the fins on the first stage, deflecting the vehicle as much as two inches.¹⁰

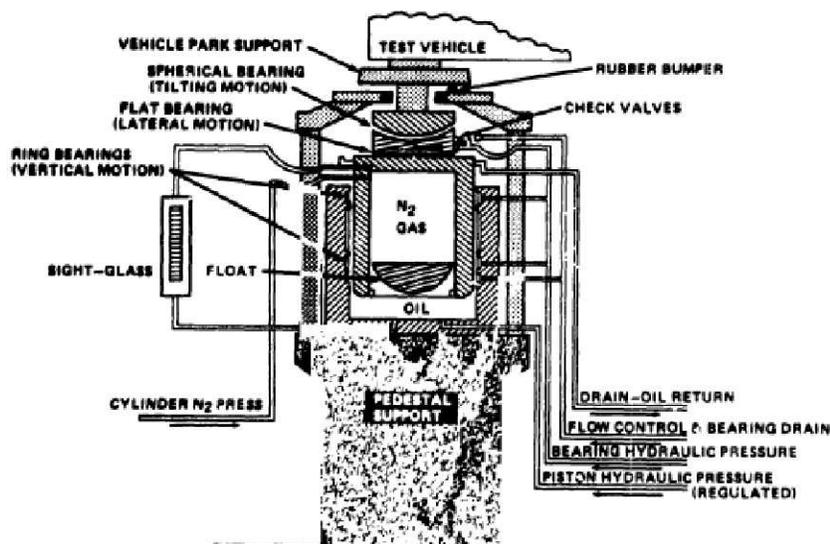


Figure 2 - Hydrodynamic Support (HDS)

Lateral support of the vehicle was provided by two sets of lateral stabilizing springs. These springs were located as close to the mean nodal points as possible to minimize their impact on the overall bending modes of the vehicle. An upper stabilizing system of 16 springs was attached tangentially to provide roll restraint and keep the vehicle centered.¹¹

The excitation consisted of a thruster system with a four-inch single amplitude linear stroke with 20,000 pounds of output. It was eventually determined that the four-inch stroke was not required and that a 0.5-inch stroke would suffice. The initial requirement was based on an excitation of sufficient amplitude at the sensor point to accurately determine mode shapes with available instrumentation. However, due to improvements in instrumentation sensitivity and less-than-expected modal damping, the lower stroke option would have been adequate.¹²

Instrumentation consisted of accelerometers, rate gyros, pressure sensors and strain gages. A typical test used 120 sensors feeding directly to the Data Acquisition System (DAS). The DAS automatically controlled the frequency sweeps and frequency increment changes. To record or check data, the DAS used three cycles at 900 data points per second from all the sensors simultaneously.

The DVT tested three configurations of the Saturn V. Configuration I consisted of the S-IC first stage, S-II second stage, S-IV third stage, instrument unit (IU), Command/Service Module (CSM) and Launch Escape System (LES). Configuration II included the S-II second stage, S-IV third stage, IU, CSM and LES. Configuration III included the S-IVB-D third stage, IU, CSM, and LES. All configurations tested both the liftoff and burn-out conditions of the fuel tanks.

Dynamic testing was conducted on the Saturn V test vehicle between October 1966 and August 1967. A series of tests was performed, including force linearity, ring-out damping and ring mode. The force linearity test excited the vehicle at three different force levels at each resonant frequency to determine nonlinear characteristics of the vehicle. The first four flexible mode resonant frequencies and measurement of the logarithmic decay of response to determine sensor damping when force was suddenly removed was measured by the ring-out damping test. The ring mode test was an incremental frequency sweep to determine the IU ring mode activity.¹³

The mathematical model developed during pre-test analysis was verified by the dynamic test and used to analyze the flight vehicle and account for mass and stiffness differences. Generally, the correlations between test results and this model were very good. A major difference, however, was found at the flight

gyro cold plate in the IU. The control gyro was located on the upper half of this plate, which had a higher slope than the lower half. This made the analytical flight control parameters marginal. This finding resulted in relocating the control gyro to the lower half of the plate where it correlated well with analytical predictions.¹⁴

The following table summarizes the major findings and likely consequence found during the Saturn V DVT.¹⁵

Table 1. Dynamic vehicle testing helped identify several critical issues during Apollo that could have resulted in loss of mission or crew.

Problems Discovered	Hardware Impacted	Consequences if Not Discovered
Design deficiency in the SPS tank supports. Unexpectedly high local resonant coupling was detected between the SPS and its bulkhead support.	The upper support bracket for the SPS tanks was redesigned to eliminate a strong tank cantilever mode.	Hardware failure resulting in loss of mission and possible crew loss.
High LOX and fuel dynamic tank bottom pressures. These pressures were under-predicted by a factor of 2. The significance of these pressures was not understood until after pogo occurred on AS-502.	The higher tank pressures contributed to the S-IC pogo accumulator hardware design.	Potential loss of vehicle and crew due to pogo.
High 18 Hz S-IC Crossbeam mode gains. DTV data showed that an accumulator should not be used on the inboard engine.	Elimination of a planned inboard engine accumulator.	Potential loss of vehicle and crew due to pogo between the 18 Hz accumulator mode and the 18 Hz crossbeam mode.
Local rotation of the flight gyro support plate. Vehicle dynamic shears and moments deformed the support plate. The math model under-predicted this deformation by 135%.	The gyros were relocated to the bottom of the support plate where the local rotation was much less. This required wire harnesses of new length. The flight control filter network was redesigned.	Flight control instability resulting in loss of vehicle.

II. Space Shuttle Testing

NASA authorized the development and manufacturing of the National Space Transportation System, commonly called the Space Shuttle, in 1972. The Space Shuttle launch vehicle consists of the orbiter, a winged vehicle capable re-entry and controlled landing as a reusable craft. At launch, the orbiter is mated to an external tank (ET) that supplies the LOX/LH₂ propellant to the orbiter's three main engines. Two reusable solid rocket boosters (SRBs) provide additional power at launch. The launch assembly is 184 feet tall and 122 feet long with a wing span of 78 feet. The launch vehicle weighs 4.5 million pounds at liftoff (weight may vary depending on payload). On the re-entry runway, the orbiter is 57 feet tall from the landing gear to the top of the vertical stabilizer. The STS can lift a payload of 35,000 pounds to orbit. The orbiter can carry a crew of up to seven.

The Space Shuttle is the first reusable space vehicle and as such represented new challenges to design and analysis due to the coupled interaction of the four-body configuration (orbiter, solid rocket boosters and external tank) with many joints and local load paths. Viscoelastic effects added complexity due to the

solid rocket boosters (SRBs) and their unsymmetrical stiffness and mass effects on the orbiter. A vigorous dynamic test program was planned that included not only the ¼-scale model, but also a horizontal GVT (HGVT) performed on the orbiter by itself and a mated vertical GVT (MVGVT) performed on the four-body vehicle to validate the mathematical models.

The MVGVT was performed between the summers of 1978 and 1979 at MSFC in TS 4550. The vehicle test configuration required modifications to the test stand and the HDSs used for Saturn V testing (Figures 3 and 4). TS 4550 was designed to test vehicles larger than the Saturn V, specifically a vehicle with a 50-foot diameter and about the same height as Saturn V; however the interior of the stand required modifications to accommodate Shuttle dynamic testing.¹⁶ Three columns and all horizontal and vertical connectors to them were removed. Five new columns were added and the derrick crane was relocated. The door was widened to allow the orbiter to be emplaced in one piece.

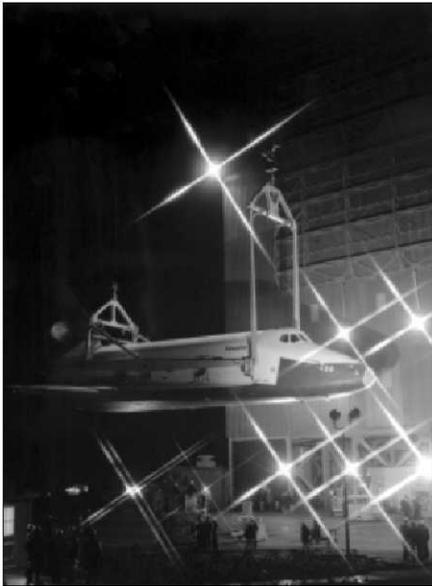


Figure 3 - Orbiter Prepared for Lift into TS 4550



Figure 4 - Orbiter Lifted into TS 4550

The Saturn-era HDSs were used to provide the simulated free-free boundary condition representing free flight. To save cost, adapter frames were developed for the Saturn-era HDS. These adapter frames required removing the SRB nozzles, as the weight of these components was compensated by the adapter frames.

Interfaces between the ET-SRB and the ET-orbiter (Figure 5) were of prime importance and were heavily instrumented. The ET also required extra instrumentation to adequately characterize the dynamics of the tank, sidewalls, bulkhead, and sump areas. The MVGVT used 320 channels of accelerometers, 30 channels of strain gauges, 40 channels of force transducers, 10 channels of pressure transducers, and 9 channels of rate gyros.¹⁷



Figure 5 – Space Shuttle Orbiter, External Tank, and Solid Rocket Boosters in TS 4550

The MVGVT shakers were [either rigid mounted or suspended] 150 foot-pound shakers as well as 1,000 foot-pound electrodynamic units. The suspended shakers were free pendulums with a maximum frequency of 0.5 hertz.¹⁸

During MVGVT, sinusoidal excitation was applied to the vehicle by driving shakers located to excite and isolate all significant symmetrical and asymmetrical vibration modes. The transverse excitation range was 1.5 to 30.0 hertz; the longitudinal excitation range was 1.5 to 50.0 hertz.

A new data system, the Shuttle Modal Test and Analysis System (SMTAS), was designed and used. The SMTAS was a digital system capable of maintaining modal excitation control, acquiring modal response data and processing, and displaying real-time data. Off-line, the SMTAS could perform data transformation, math model matrix loading, mode shape, frequency, generalized mass, damping, calculations and modal orthogonality checks.¹⁹ The SMTAS provided control for 24 shaker channels, but was capable of driving 38 shakers.²⁰

The vehicle was tested in five configurations during the MVGVT, two for the four-body vehicle and three for the two-body vehicle (Figure 6). The four-body vehicle consisted of the orbiter, two solid rocket boosters (SRBs) and the external tank (ET). This was tested at lift-off and pre-SRB separation (burn-out) vehicle configurations. The two-body vehicle consisted of the orbiter and ET. This was tested at start of boost, mid-boost and end of boost vehicle configurations.

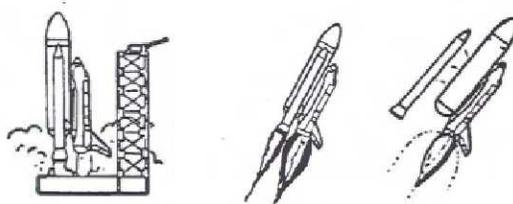


Figure 6 - Shuttle MVGVT Test Configurations

Major MVGVT test results identified local resonances in the SRB rate gyros. These resonances corrupted sensor signals. If they had occurred during flight, they would have caused the possible loss of the sensor or vehicle. Anomalies were also observed in the orbiter side-mounted rate gyros.

Overall, structural damping data ranged from 0.1 percent to greater than 10 percent. Average modal damping was between 1 and 3 percent. If not corrected, this signal content due to local effects (to the SRB RGA) would likely have cause the loss of the first Shuttle mission. Anomalies also were observed in the orbiter side-mounted rate gyros. This damping data was invaluable in the flight certification stability margins.²¹

Table 2 summarizes the major findings and likely consequences found during the Space Shuttle MGVGT.²²

Table 2. With its much different configuration, the Space Shuttle experienced new issues that were identified during mated vehicle ground vibration testing.

Problems Discovered	Hardware Impacted	Consequences if Not Discovered
SRB-mounted rate gyros exhibited abnormally high transfer functions. The rate gyros mounted on the forward SRB ring frames resonated at local frequencies and high gains that were critical to flight controls.	Structural redesign was required to stiffen the SRB ring frame, which raised the local resonant frequencies and reduced the gain.	Flight control instability and possible loss of vehicle.
Axial Space Shuttle Main Engine (SSME) frequencies and mode shapes did not correlate with pre-test analysis. A half shell dynamic math model using symmetry was used in pre-test analysis.	A new three dimensional asymmetric math model of the SSME engines and thrust structure was required. No hardware changes necessary.	Pogo stability analyses would have been suspect.
Test rate gyro values showed greater response variations than analysis. Response variations between the Rate Gyro Assemblies (RGAs) were much larger than those used in the analytical studies in determining the Redundancy Management (RM) trip levels.	RM software trip levels and cycle counter levels were increased. The fault isolation routine was modified to inhibit kicking out RGAs and ACCs after first sensor failure.	Flight control instability and possible loss of vehicle.

The Space Shuttle was the first crewed NASA spacecraft to fly humans on its inaugural launch. Results of the dynamic testing during the MGVGT were critical to the decision to launch the vehicle without first performing unmanned flight tests. Clearly the verification of vehicle mathematical models was vital to the successful first flight and the eventual assessment to declare the Shuttle ready for crewed flight. Without this test data to verify the models, confidence to launch humans on the first flight of the vehicle would have been greatly reduced.

III. Ground Vibration Testing in the 21st Century

In 2005, NASA began work on the Constellation Program to return humans to the Moon and build a permanent outpost there as a stepping stone to exploring Mars. The Ares Projects are responsible for developing, building and testing the Ares I and Ares V launch vehicles for the Constellation Program.

The Ares I crew launch vehicle was designed to lift the Orion crew exploration vehicle to low Earth orbit. Ares I is an in-line, two-stage vehicle. Ares I is 325 feet tall, weighs approximately two million pounds at launch, and is capable of lifting 56,500 pounds into low Earth orbit. Ares I has two missions:

carry up to four crew members (or cargo) to the International Space Station or to low Earth orbit for rendezvous with Ares V for missions to the Moon. The first stage is a five-segment solid rocket booster based on the heritage Space Shuttle design, and, like the Shuttle SRBs, is reusable. The second, or upper, stage is powered by the J-2X engine, based on the Saturn second- and third-stage J-2 engine. The Orion crew module sits atop the second stage.

The Ares V cargo launch vehicle will be a heavy-lift vehicle designed to launch cargo and rendezvous with Ares I in Earth orbit. The core stage will be powered by six RS-68 LOX/LH₂ engines. Two 5.5-segment SRBs like the first stage of Ares I also will provide launch power. The second stage, or Earth departure stage (EDS), will be powered by the same J-2X engine used for the Ares I upper stage. The Altair lunar lander is the nominal payload.

Ares V's mission is to lift Altair and other cargo aboard the Earth departure stage (EDS) to low-Earth orbit where it will rendezvous with the Orion crew module prior to its journey to the moon. Ares V will be 381 feet tall, weigh 8.1 million pounds at launch, and be capable of lifting about 414,000 pounds into low Earth orbit and 156,700 pounds to lunar orbit.

Plans to perform the Ares I Integrated Vehicle GVT (IVGVT) began in early 2006. The models correlated from IVGVT data will support the Orion 2 Design Certification Review (DCR) in January 2015. The DCR supports the first crewed launch of the Ares I/Orion vehicle planned for March 2015. The state of the Constellation Program is now in doubt, as the President has requested a budget that cancels the program. Nevertheless, a great deal of work has been accomplished, and improvements to GVT infrastructure would be needed to support any future vehicles. Until a final decision is made, the Ares IVGVT team is proceeding with plans to complete modifications associated with Constellation, with the understanding that their work could be changed to support another launch vehicle system. The most recent IVGVT schedule is depicted in Figure 7, below.

Because of its mothballed state since Shuttle-era MGVGT, Test Stand 4550 was inspected and necessary structural repairs are being made to bring it up to safety and IVGVT facility requirements. The 200-ton capacity derrick crane on the roof of TS 4550 underwent inspection and load testing. Upgrades and repairs to the 200-ton capacity roof derrick crane include installation of a new motor and controls and crane cable blocks/boom sheeves. In March 2008, the crane was used to remove the roof panels and lower the door for the first time since the MGVGT. The Shuttle-era platforms and special test equipment (STE) were removed and additional equipment is being installed to meet current safety codes and future operational needs (Figure 9).

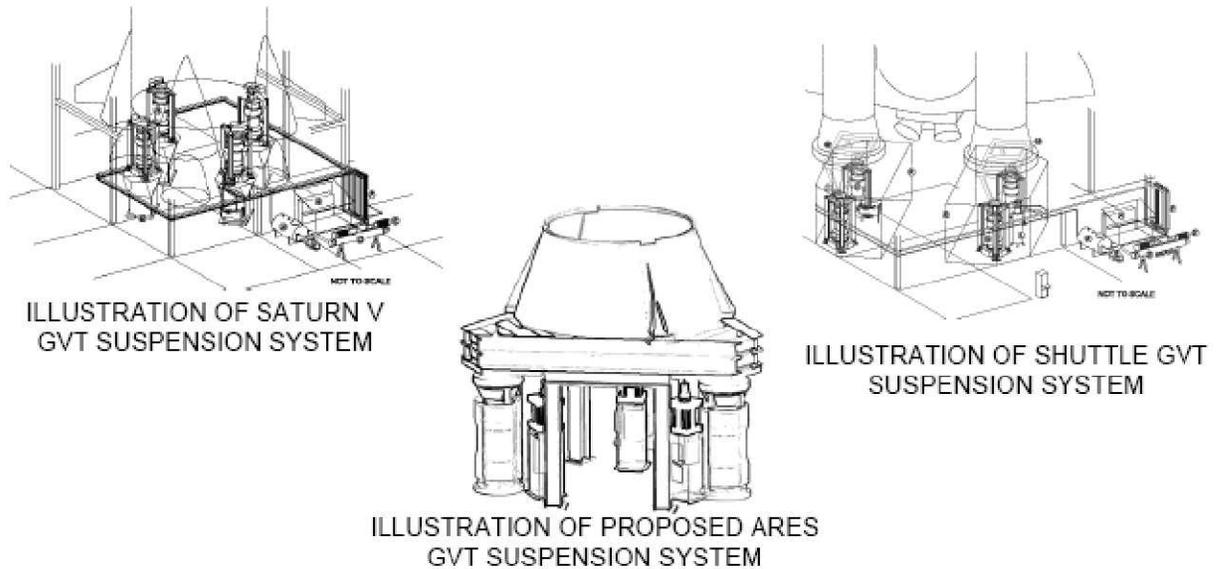


Figure 9. Since the 1960s, Test Stand 4550's HDSs have been adapted to support a variety of vehicles and test positions.

Mast climbers will be used to access the vehicle instead of platforms. IVGVT is using modified, commercially available, industrial mast climbers instead of building numerous fixed individual test article access platforms. The mast climbers allow almost unlimited vertical and circumferential access to the test article from the First Stage Aft Skirt to the top of the Orion LAS. Mast climbers (Figure 10) will provide ready access to the test articles and can be moved easily to support different test positions within the test stand.

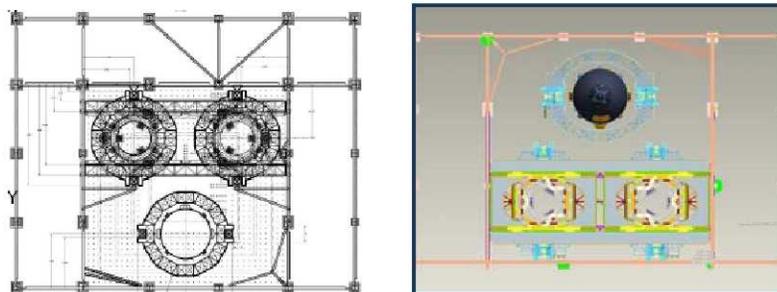




Figure 10. Test positions and mast climber concepts and the final product for TS 4550.

The upper stage IVGVT test article is scheduled to be shipped to Redstone/MSFC by NASA barge (Figure 12), from Michoud Assembly Facility (MAF) [near New Orleans, LA] and move on a transporter to TS 4550. Prior to receiving the IVGVT upper stage test article, the IVGVT team would receive an upper stage pathfinder test article (Figure 11) via NASA barge. The pathfinder would be used to dry-run a number of activities related to transportation, GSE, STE, stacking, various procedures, interfaces, and fit-up in the upper stage test position #3 in Test Stand 4550.

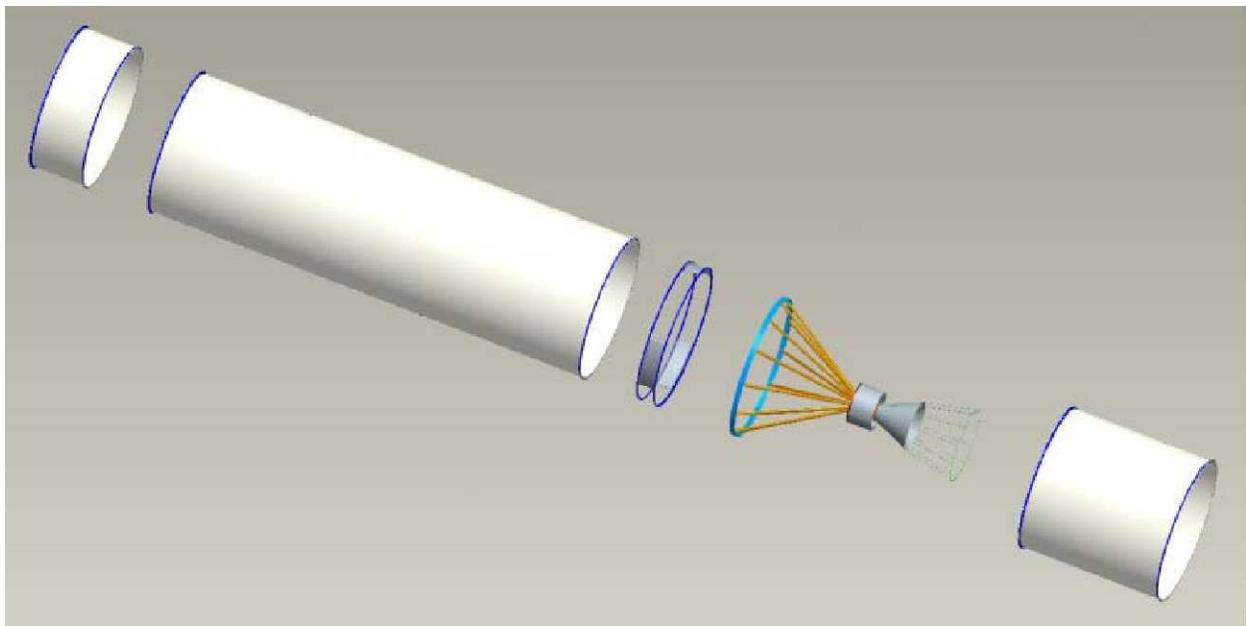


Figure 11. Expanded view of Upper Stage Pathfinder Test Article (PTA)



Figure 12. NASA will use the Space Shuttle's external tank barge to deliver the upper stage IVGVT unit.

The Orion IVGVT test article is slated to be shipped via the "Super Guppy" cargo aircraft to the Redstone Arsenal airfield and moved by convoy to TS 4550 (Figure 13). Some Orion hardware would travel to TS 4550 from Glenn Research Center's Plum Brook facility in Ohio and some from the manufacturing vendor.



Figure 13. The Super Guppy was first developed to transport vehicle components of the Apollo Program.

Ground support equipment (GSE) is an important aspect of IVGVT. GSE is needed to unload test article hardware at the entry point to MSFC; transport it to TS 4550 from the entry point; and stack, destack, and relocate hardware in the three test positions in TS 4550 (Figure 10). Two new cranes have been procured: a jack/gantry crane and a mobile crane to aid in moving the test articles both at the test stand and at the new Redstone Arsenal/MSFC railhead where first stage segments will be received. The IVGVT first stage test article segments will arrive from ATK in Utah in two train shipments consisting of five railcars each (one solid rocket motor (SRM) segment per railcar) and will be moved by convoy to TS 4550 from the MSFC/Redstone railhead using the Kneel Down Transporter (KDT) vehicle for FS segments (Figure 14).



Figure 14. The Kneel-Down Transporter (KDT) is an essential part of the logistical hardware needed to transport IVGVT inert SRM Segments through Marshall Space Flight Center.

For Ares I testing, the plan is to fill five first stage SRM segments with inert solid propellant. Five other first stage SRM segments will be “empty” and built to represent SRM segments at the first stage burnout condition. Due to their size, two FS aft skirts will be shipped to Redstone Arsenal (RSA) railhead from KSC by rail. First stage forward structures would be shipped to RSA directly from the vendor. The unloading gantry procured for the railhead has arrived at MSFC (Figure 15).

The GSE also will stage the hardware outside TS 4550 and at other MSFC locations and after completing the test, the organizations supplying the hardware for the test would be responsible for its disposition after IVGVT. GSE is generally being provided to IVGVT from the Ares I Elements and the Orion Project. Hundreds of GSE items are required for IVGVT.



Figure 15. A variety of cranes will be used to move IVGVT hardware from transportation facilities to Test Stand 4550.

The design for a new electrical power distribution system and modifications for TS 4550 has been developed and released. Work on these modifications began in the fall of 2008 and was completed in the fall of 2009. TS 4550 elevator repairs and updates are scheduled to be complete by mid-2010.

The first phase of developing the test requirements for the IVGVT was completed in January 2008, establishing at the assembly level, the level of test hardware fidelity desired for the IVGVT. Subsequent phases have solicited and compiled IVGVT stakeholder requirements and analytical evaluation of these requirements, with IVGVT models exercised under various IVGVT test boundary and excitation conditions have been underway to develop the IVGVT test requirements. STE design for the full stack test positions is in the final design phase while second stage STE design is in the preliminary design phase.

The HDS units used for Saturn and Shuttle were disassembled and evaluated for use during IVGVT. Four HDS units have been refurbished and are undergoing functional testing. Three HDS units are needed to accomplish the Ares I IVGVT with the fourth being kept as a spare. A modular hydraulic powerpack unit was designed, and a contract was awarded to build the first of three such units, one unit for each of the three HDS. One HDS modular hydraulic powerpack unit (Figure 16) was delivered and is being used in HDS functional check-out and load testing. In parallel with the HDS evaluation, a pneumatic or hybrid system is being explored to offer more efficient test operations (Figure 17). A decision on what elements of the hydraulic, pneumatic, or hybrid suspension system to use for IVGVT will be made in May 2010.



Figure 16. One of the major components of the HDS power unit at the vendor, prior to shipping to MSFC.

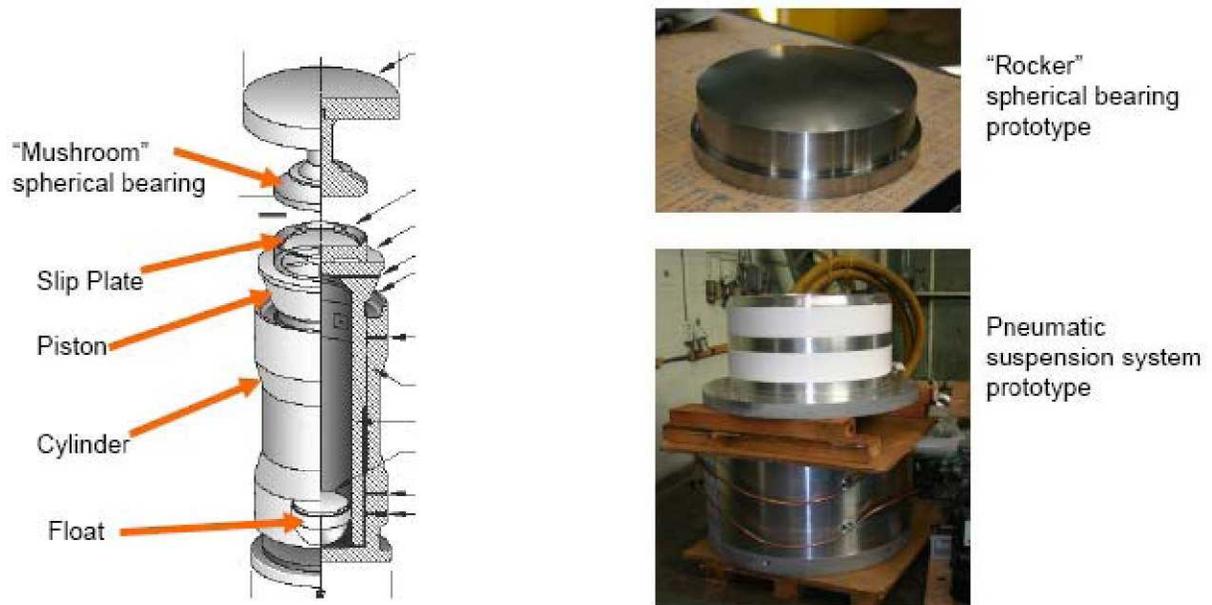


Figure 17 – While both hydrodynamic and pneumatic alternatives are being explored for the HDS, a hybrid system is also being considered.

Hydraulic shakers will be used to excite the vehicle at locations to be determined by pre-test analysis. The IVGVT team anticipates that the majority of shaker locations will be near the base of the vehicle. Testing will include both random and sinusoidal excitation. Random excitation will be used to acquire the

primary modal data, while sine sweeps will be used to characterize nonlinear behavior and to acquire transfer functions to validate GN&C models.

IVGVT test article instrumentation will consist primarily of tri-axial accelerometers. At this time in test planning and analysis, the exact quantity and locations for IVGVT test article instrumentation have not been specified, though a preliminary instrumentation plan is under development. Some facility instrumentation will be required to fill, drain, pressurize, and vent the US tanks. The facility instrumentation and control list is under development.

The current plan is that the Ares I IVGVT will test six configurations (Figure 18) representative of select points in the Ares flight trajectory in the three test positions in TS 4550. TS 4550 test position 1 (TP#1) consists of the entire launch stack at liftoff representing gross liftoff weight (GLOW) or total launch stack mass at $t = 0$ using inert FS segments and propellant simulants throughout the vehicle. Test position 2 (TP #2) consists of the entire launch stack representing FS burnout (using empty FS segments) just before FS and US stage separation. Test position 3 (TP #3) consists of the Ares I Upper Stage with the Orion vehicle. TP #3 will be used to test four second stage flight configurations after FS separation. These are, nominally, J-2X ignition, post Launch Abort System (LAS) jettison, critical slosh mass and J-2X shutdown, or Main Engine Cut-Off (MECO). GN&C transfer function measurements will be made during all test configurations.

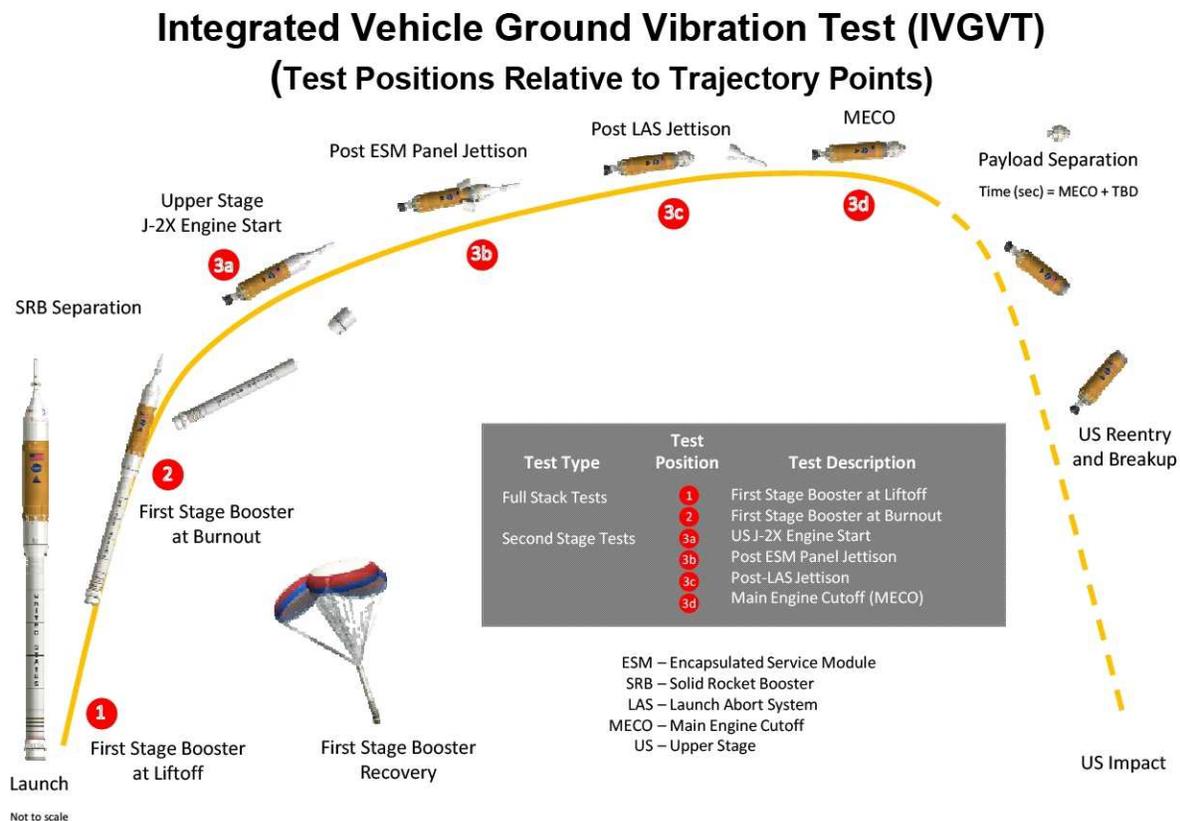


Figure 18 - IVGVT Test Configurations

The Ares IVGVT is scheduled to be conducted from late 2012 to late 2014. The IVGVT is intended to measure by test the fundamental dynamic characteristics of Ares I during various phases of operation and flight. The final measured results of the IVGVT are clearly dependent on the fidelity of vehicle hardware used during the test and appropriately simulated boundary conditions (BC). A fundamental

philosophy of structural dynamic testing is to have as few differences between the test article and the flight article as possible. For accurate testing and model correlation and acceptable levels of uncertainty, both the test and flight configurations must be known and differences understood fully.

To accurately represent the properties of the Ares I flight vehicles, the IVGVT is to be conducted on a test article built to flight-equivalent specifications. The First Stage Element Office is providing one set of empty first stage segments that will return for recertification and potential return to flight inventory at the conclusion of IVGVT. The second set of first stage segments containing inert solid propellant likely will not return to flight inventory. The FS IVGVT test article will not have a first stage flight nozzle for IVGVT but will instead use a nozzle mass simulator. The FS test article will have a refurbished aft skirt. The FS IVGVT test article will include flight-equivalent forward structures [consisting of frustum, forward skirt extension and forward skirt]. The Ares Upper Stage Element Office will provide IVGVT the first US manufactured at MAF. The Ares Upper Stage Engine (USE) Element Office will provide the US Element with a dynamic mass simulator. The Orion Project Office will provide a ground test article (GTA) to IVGVT for the Orion Service Module (SM) and Spacecraft Adapter (SA), along with a dynamic mass simulator for both the CM and LAS. The SM/SA will be a pre-production structure with tanks and removable fairing panels. The various IVGVT Ares I test articles are depicted conceptually in Figure 19.

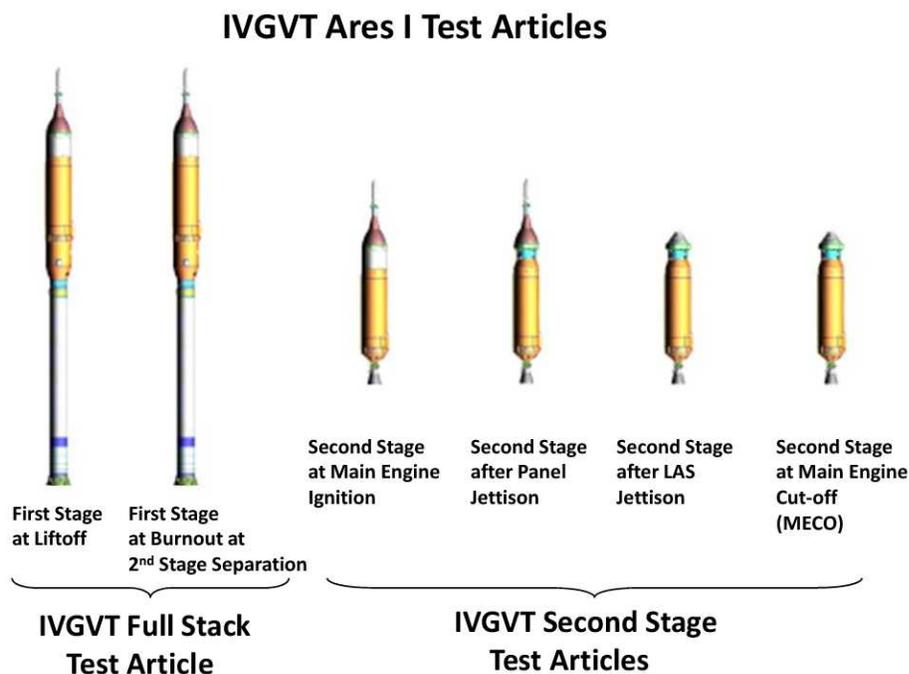


Figure 19. Ground Vibration Testing will encompass the full range of Ares I launch operations and configurations.

Mass simulators of certain components may be used for flight-quality components that are not available in the scheduled test timeframe, provided there is sufficient technical rationale to do so. As a general rule of thumb, all items weighing over 25 pounds are evaluated to determine if they have to be represented by flight-equivalent hardware or mass simulators. Items such as small boxes (<25 lbs.), cabling, small-diameter tubing, insulation, etc., are generally not represented in the IVGVT test article; however, their aggregate mass is evaluated on a case-by-case basis and either mass simulated or omitted from representation in the test article to be accounted for in the finite element models. The goal of the mass simulators is to accurately replicate the correct mass, center-of-gravity, and moments of inertia of the simulated hardware. The analysts will approve test article configuration prior to beginning a test and approve break-of-configuration before hardware removal and moving on to the next test in a series.

The primary objectives of the IVGVT will be to obtain modal data to correlate the Finite Element Models (FEMs) of the vehicle system. These FEMs are then used for the vehicle certification analyses, which support Design Certification Review, and approval to fly human-rated missions.

Test objectives pertaining to flight control objectives are to obtain:

- 1) Natural vehicle mode shapes, frequencies, generalized mass, and damping characteristics and coefficients which are used in the stability equations; and
- 2) Amplitude and phase response of the elastic vehicle and transfer functions from thruster locations to all flight control sensor locations.

Structural dynamic test objectives are to obtain:

- 1) Mode shapes, frequencies, and damping to be used as the reference for test calibrated Ares I configuration models that form the basis of final verification loads and GN&C controls analysis; and
- 2) Experimental non-linear characteristics of vehicle configurations by exciting the test specimen at different force levels.

Ares V planning and early design is in work at this time, but at a very low level of effort, and is now subject to the same potential cancellation as Ares I. However, initial planning for the Ares V IVGVT has been ongoing. This planning consists primarily of facility studies and a preliminary schedule for long-range budget planning purposes.

IV. Lessons Learned and Operational Improvements in Vibration Testing

The Saturn, Space Shuttle, and other launch vehicles have demonstrated to NASA the value of early ground vibration testing. In fact, the Ares I-X flight test underwent segment and integrated vehicle modal testing in the Vehicle Assembly Building (VAB).

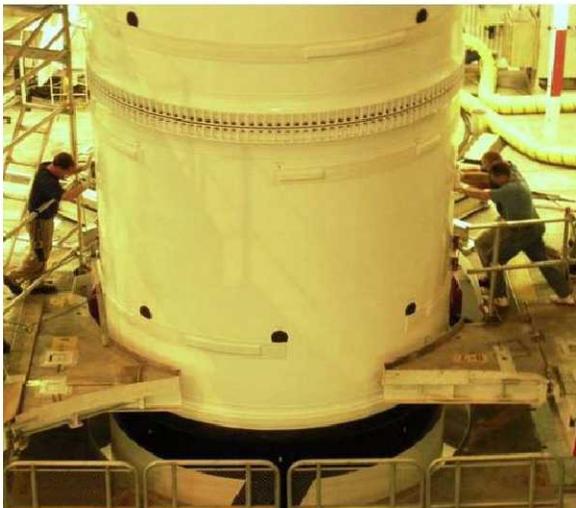


Figure 20. Ares I-X modal testing.

The Ares I-X flight test provided an opportunity to develop hardware and processes for modal testing in the VAB. In fact, some ground service equipment and the hydraulic shaker units used to excite the Ares I-X structure will be used for IVGVT. The modal testing for Ares I-X had more limited objectives than a full-scale Ares I test would have, as the flight test vehicle did not include an active, liquid upper stage. Nevertheless, the modal testing, which included shakers and people rocking the vehicle back and forth by hand (Figure 20), confirmed the first four bending modes of the rocket were within expected tolerances.

Perhaps one of the most important lessons NASA is learning in a time of limited budgets for new equipment is how to make better, more efficient use of existing special test equipment (STE) and facilities. For example, the Ares IVGVT team is using mast climbers for each test position in TS 4550, as compared with Saturn and Shuttle, which used custom “fixed platforms” at each of 15 levels. These new, moveable mass climber platforms save money, provide easier access to the test articles and allow for a more flexible facility than one using fixed platforms.

Other improvements to TS 4550 IVGVT operations include:

- Locating all three test positions in one building, unlike Saturn or Shuttle, which could only accommodate one of the test configurations at a time. This saves having to build additional new test stands, sharing the TS 4550 200-ton capacity roof crane, sharing the HDS hydraulic power units, and allows restacking for different test configurations. MSFC test engineers can share a common Test Control Room, skilled personnel, share instrumentation, data, and control systems, and keep operational costs to a minimum. The real savings from putting all the configuration footprints in the stand at one time is to minimize the destacking and restacking of the First Stage.
- Employing an air pallet system. The air pallet system will be used to move HDSs between Test Positions #1, #2, and #3. The pallets move around on a smooth floor coated with cementitious polymerized mortar. This saves having to buy several additional HDS units, each of which would cost approximately \$500,000 to manufacture.
- Using the same IVGVT Upper Stage and Orion test hardware in all three test positions rather than having to build additional test articles, again saving time and money.

Instrumentation for Ares IVGVT will be coordinated with the Ares Instrumentation Program and Command List (IP&CL), Orion IP&CL, Ares I-X developmental flight instrumentation (DFI), and the Constellation Program. This will be done to maximize common instrumentation locations for DFI, and operational flight instrumentation (OFI) across the Ares vehicles as well as other test programs and Constellation test and verification activities. In addition, IVGVT will use sensors at the flight rate gyro assembly (RGAs) locations to determine if there are spurious local effects, which were lessons learned from Saturn and Shuttle.

The IVGVT team will be using graphic user interface (GUI) screens to control each of the HDS hydraulic power units, one for each HDS. The advantage of a GUI is its use of control screens with animated icons of tanks, components, valves, instrumentation showing measured numerical values of parameters, or valve states [i.e. valve open, closed or in transition], document test configuration and setup, and digitally record raw and engineering unit data. The embedded icons actually provide configuration control for the control software by capturing the test configuration and setup info in the as-run configuration for CM. One operator can remotely control and safe [if necessary in emergencies] the systems. GUI reduces the number of operational personnel and technicians needed to conduct testing. Formerly test control rooms consisted of racks of amplifiers, filters, instrument panels, dials, gauges, and magnetic-tape or oscillograph recorders and required a large number of personnel because many operations were manual. Post-test data analysis took longer and was more tedious and much less efficient.

Conclusion

NASA has conducted dynamic tests on each of its major launch vehicles during the past 45 years. Each test has provided invaluable data to correlate and correct analytical models used to predict structural responses to differing dynamics for these vehicles. With both Saturn V and Space Shuttle, hardware changes were also required to the flight vehicles based on data obtained during GVT to ensure crew and vehicle safety.

Future efforts at IVGVT, for Ares or other launch vehicles, will undoubtedly provide similar valuable test data to support successful flight. The IVGVT will provide experimentally determined natural frequencies, mode shapes and damping. This data will be used to support GN&C and structural loads analysis by providing this test data to reduce uncertainty in the models. The value of this testing has been proven by past launch vehicle successes and failures. Performing dynamic testing on the Ares vehicles will provide confidence that the launch vehicles will be safe and successful in their missions. In addition, IVGVT will provide the following benefits for the Ares rockets:

- IVGVT data along with development flights will reduce the risk to the Orion-2 crew. IVGVT will permit anchoring the various critical math models used in certain aspects of Ares operations.
- IVGVT data will permit better understanding of the structural and GN&C margins of the spacecraft and may permit mass savings or expanded day-of-launch opportunities or fewer constraints to launch.
- Undoubtedly IVGVT will uncover some of the “unknown unknowns” so often seen in developing, launching, and flying new spacecraft vehicles and data from IVGVT may help prevent a loss of vehicle or crew.
- IVGVT also will be the first time Ares I flight-like hardware is transported, handled, rotated, mated, stacked, and integrated.
- Furthermore, handling and stacking the IVGVT launch vehicle stacks will be an opportunity to understand certain aspects of vehicle operability much better (for example, handling procedures, touch-labor time to accomplish tasks, access at interfaces, access to stage mating bolts, access to avionics boxes, access to the Interstage, GSE functionality, and many other important aspects of operability).

All of these results will provide for better vehicle safety and operations and better stewardship of national resources as NASA begins its next phase of human space exploration. In his 2011 budget request, President Barack Obama submitted a budget calling for the cancellation of Constellation and instead funding for developing commercial crew and cargo vehicles. Nevertheless, work continues to upgrade the GVT infrastructure at MSFC which will support this new budget plan for NASA and potential use of GVT infrastructure by developers of commercial crew and cargo vehicles. This work will continue, as GVT work is necessary for any new or upgraded launch vehicles the nation requires.

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