INTEGRATED VEHICLE GROUND VIBRATION TESTING OF MANNED SPACECRAFT: HISTORICAL PRECEDENT

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ABSTRACT

NASA is developing a new human space flight launch system. The Constellation Program launch vehicles will carry crew and cargo to the International Space Station and onward for the future exploration of the Moon and Mars. The Ares I control system and structural design depend on complex computer models of the vehicle structural dynamics. An Integrated Vehicle Ground Vibration Test (IVGVT) will validate the efficacy of these computer models. The IVGVT will reduce the technical risk of unexpected conditions that could place the crew in jeopardy. The NASA Marshall Space Flight Center (MSFC) Ares Project Office Flight and Integrated Test Office (FITO) commissioned a study to determine how historical programs validated the structural dynamics of an integrated flight vehicle. The study examined the historical record and also sought out members of the engineering community who recall the development of historic manned launch vehicles. These records and interviews provided insight into the best practices and lessons learned from these historic development programs. Timelines of the development programs were created to trace programs from development through test preparation, test operations, and test data reduction efforts. They also demonstrate how the historical tests fit within their overall vehicle development programs. Finally, the study quantifies approximate staffing levels during past development programs. FITO has used the results of this study to evaluate the IVGVT schedule and workforce in light of the precedents.

INTRODUCTION

In the history of U.S. human space flight, only four development programs have had the goal of placing a human in Earth's orbit or beyond: Mercury, Gemini, Apollo, and Space Transportation System (STS or Space Shuttle). Mercury and Gemini were fast-paced development programs with only experimental data collection and flight experience as their technical goals. These programs used existing non-human rated launch vehicles to carry the manned spacecraft into orbit. Mercury and Gemini were principally stepping-stones along the way to developing a viable space transportation system infrastructure as epitomized in Apollo. As the development processes of Mercury and Gemini were so radically different from those of Apollo, STS, and Constellation, the precedents they offer regarding development schedules and workforce usage (labor loading) are limited. The present study also briefly reviewed the development processes for the NASA X-33 (VentureStar prototype), the NASA X-43A (HyperX), and Scaled Composites' SpaceShipOne projects. Their development processes were also radically different from that of Constellation Program. The X-33 and X-43A projects were principally

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experimental in nature and did not follow the NASA human flight vehicle development process. The SpaceShipOne project was a private enterprise. Its development process was unlike that of NASA. As a result, the contemporary development processes were not applicable to the Ares I IVGVT. With these factors in mind, the focus of this study became the Apollo and STS eras.

The engineers, technicians, and managers who will conduct the IVGVT developed the preliminary workforce budgets and test schedules; however, in the past 30 years very few structural dynamicists have had opportunities to participate in large-scale dynamic tests encompassing years of pre-test preparation and using integrated launch vehicles. To bolster confidence in the IVGVT schedule and budget estimates, NASA initiated an examination of the historical record and interviews of Subject Matter Experts (SMEs) to provide an independent look at the estimates.

STUDY METHODOLOGY

Saturn launch vehicles were conceived as Juno launch vehicles in 1958. Their designs were not finalized until 1968. The Space Shuttle can trace its roots back to the 1969 Presidential Space Task Group recommendations. The Space Shuttle program was still incorporating design changes at the time of the first launch in 1981. Both of these projects employed hundreds of thousands of engineers, technicians, and managers. The development process included an untold number of tests, experiments, and trade studies. Documentation of launch vehicle designs generated thousands of technical memoranda and reports. Many of these documents have been lost in the past 30 to 50 years. Most of the surviving documents deal with technical issues. Also, very few documents were written at the time of the Apollo and STS programs documenting how tests were conceptualized, planned, and executed.

Hundreds of government- and contractor-generated technical memoranda, reports, and articles were reviewed. The reference section of this paper includes the most significant documents. The most illuminating sources of information in determining how the various test activities fit together (such as design milestones, fabrication completion dates, and test conduction dates) appear in References 7, 8 and 9. Reference 11 provides a synopsis of the overall Apollo program and lends insight into the managerial and engineering environment in which the Saturn V ground vibration test was conducted. Unfortunately, Reference 11 does not provide significant details about the Saturn V ground vibration test. These references were used to create composite timelines of the Apollo and STS ground vibration tests. They enabled NASA management to evaluate the IVGVT schedule against successful historical ground vibration tests similar in scope to verify reasonableness of the proposed schedule.

While the timelines provide a view of the duration of a particular activity during the historic tests, they do not provide insight into how much effort was required to meet the project milestones. For example, the Saturn V ground vibration test had a total test time of approximately seven months; however, this does not tell us how many work hours were needed to run the test. Because very little documented information existed on workforce needs, it was necessary to seek out SMEs familiar with Apollo and STS ground vibration tests. Two inherent problems limited the usefulness of data from SMEs: first, their knowledge is restricted to subject areas where they had direct involvement; second, their knowledge is generally unverifiable. Interviewing a sufficiently large pool of SMEs can minimize these issues, but in the case of both the Apollo and STS programs, this was not possible. Three SMEs were interviewed: Mr. Bob Ryan, Mr. Bohdan Bejmuk, and Mr. Ron Tepool.

SATURN TESTS

APOLLO PROGRAM TEST ARCHITECTURE

The Juno launch vehicle program (later renamed Apollo) was planned with small intermediate goals along the path to creation of the C-5 heavy launch vehicle (or the Nova direct ascent launch vehicle, if orbital rendezvous proved problematic). This was based on German Army at Peenemünde successes in developing the V-2 rocket and successes in developing the Redstone rocket for the U.S.

Army Ordnance Guided Missile Center.[11] Development of the C-5 launch vehicle used a building block approach. A smaller launch vehicle, the C-1, was used to evaluate concepts and prove functionality of each stage before trying to prove the next concept or stage. Block upgrades were used as part of the development process. (A block upgrade is a series of lessons learned and incorporated as one to minimize design cycles and manufacturing retooling.) A medium launch vehicle, the C-2, was also designed to test upper-stage and payload concepts. Near the end of the conceptual design phase of the Juno program, the program was renamed Apollo, the C-1 became the Saturn I, the C-2 became the Saturn IB, and the C-5 became the Saturn V. Figure 1 illustrates the building block approach to the Apollo development program.

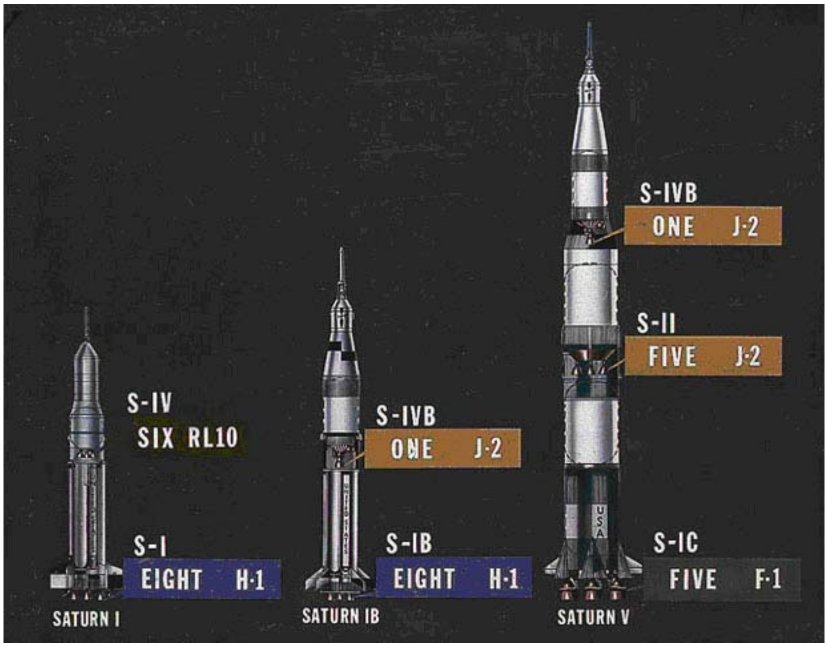


Figure 1. Apollo Building Block Development Approach

This concept of building on past successes and proven concepts extended throughout the Apollo program. As illustrated in Figure 2, the Apollo Structural Dynamics Design process built from fundamental structural dynamics knowledge acquired from legacy launch vehicles such as the V-2, Redstone, and Titan rockets. The development approach progressed to scale model testing, which then allowed the creation of mathematical models. The mathematical models were validated by testing a full-scale launch vehicle. Finally, launch vehicle operation was tested in an unmanned flight. This process repeated as each development phase was successfully completed.

The Apollo program began with development of the Saturn I launch vehicle. A timeline of Saturn I development appears as Figure 3. Note that the Saturn I Block I test article (SA-D1) was the actual vehicle that flew as SA-1. The Saturn I Block II test articles were dedicated to the test and were not used as flight inventory stages. The SA-1 ground vibration test setup shown in Figure 5 depicts a Saturn I ground vibration test configuration. Observations include:

- Design and fabrication of Saturn I Block II test articles were not begun until results of Saturn I Block I ground vibration test were available.
- There was at least a six-month gap between Saturn I Block II ground vibration tests and launching the corresponding flight vehicle. This time allowed analysis of test results and the completion of any necessary field modifications.

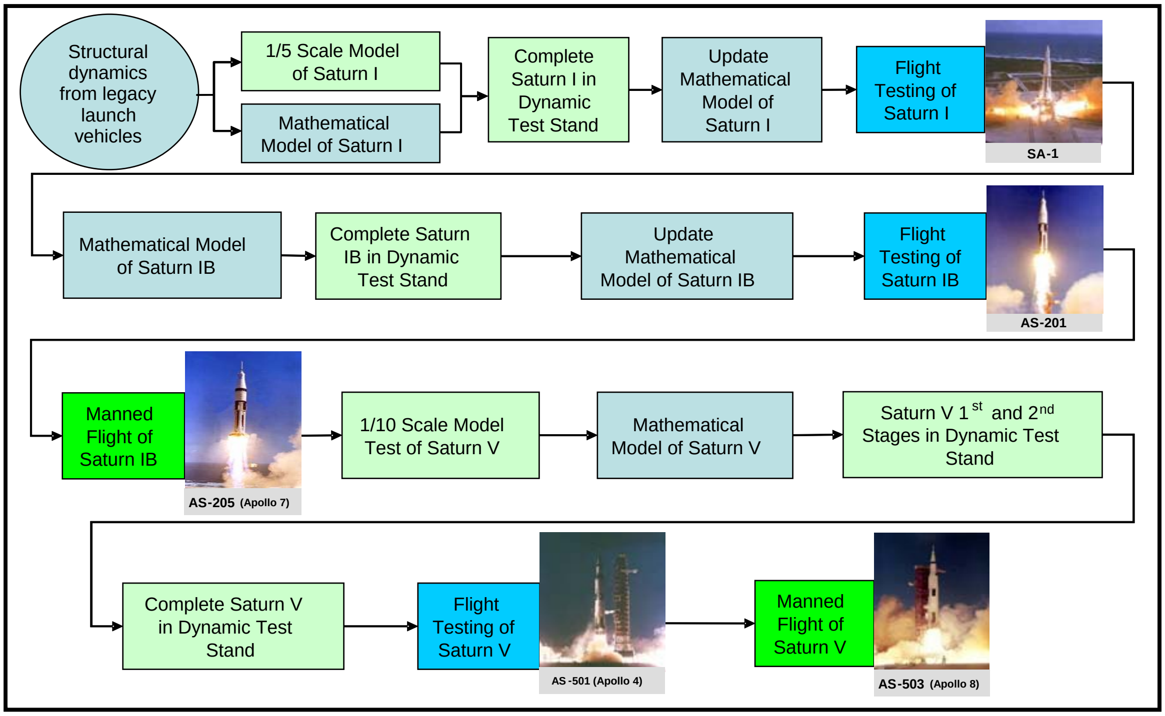


Figure 2. Apollo Structural Dynamics Development Process

A timeline of the Saturn IB development is shown in Figure 4. The SA-202 ground vibration test setup shown in Figure 6 is typical of Saturn IB ground vibration test configurations (note the plywood Lunar Exploration Module (LEM]) test article at the base of the Dynamic Test Stand). Observations regarding the Saturn IB ground vibration tests progression include:

- Design of Saturn IB Block I test articles was concurrent with the Saturn I Block II ground vibration tests, as the Saturn IB stages were an upgrade of the proven Saturn I designs.
- Fabrication of the Saturn IB Block I test articles did not begin until Saturn I Block II ground vibration tests were complete to allow incorporation of the test data into the design upgrade.
- There was a one-year gap between the SA-203 ground vibration test and the AS-201 test flight. The AS-201 test flight gave the first opportunity to use the test data. There was a 19-month gap between the SA-203 ground vibration test and the AS-203 flight in July 1966. (While the flight numbers for the Saturn IB used the AS- prefix, the corresponding dynamic tests used the SA-prefix.)
- As the Saturn IB Block I flight vehicle design changed, test articles were modified to match it, and the vehicle was retested. The same test articles were used for all Saturn IB Block II tests, with payload changes as the primary difference between the tests.
- A gap of nearly six-months between the end of Saturn IB ground vibration tests and the first flight test allowed for review of test data.

Experience gained from Saturn I and IB projects benefited the design of the Saturn V vehicle. Figure 7 shows concurrent engineering of the Saturn V upgraded stages and the preceding Saturn I and Saturn IB stages. Design and fabrication times for Saturn V upgrades were much longer than those of Saturn I or Saturn IB (five and one half years versus two and one half years, respectively). Figure 7 also shows that Saturn V Engineering Design Review (equivalent to the Ares I Design Certification Review [DCR]) occurred during the conduct of the ground vibration test. The Saturn V Design Review Board (equivalent to the Ares I Flight Readiness Review) occurred only seven months after completion of the Saturn V Ground Vibration Test. Finally, the test program was declared complete only one month after the final test series. This compressed project schedule was the result of a one-year delay between the AS-500D Configuration III test and the Configuration I and Configuration II tests. The Configuration III test

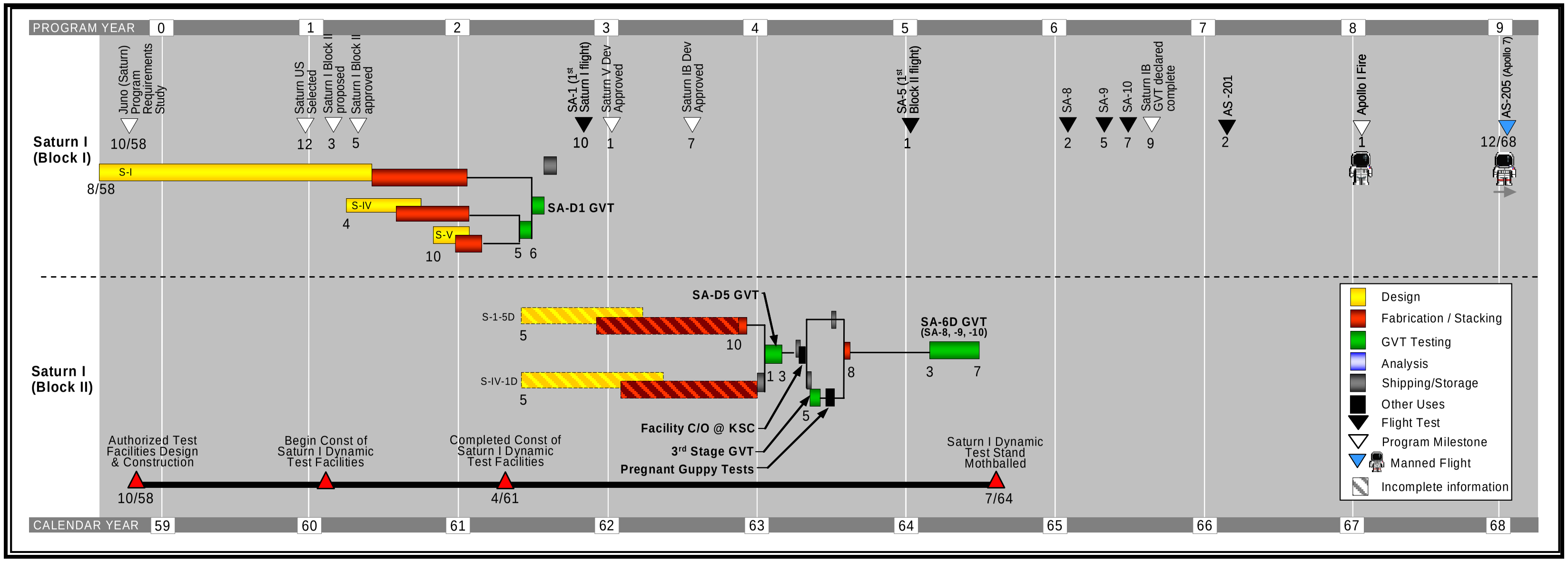


Figure 3. Saturn I Timeline

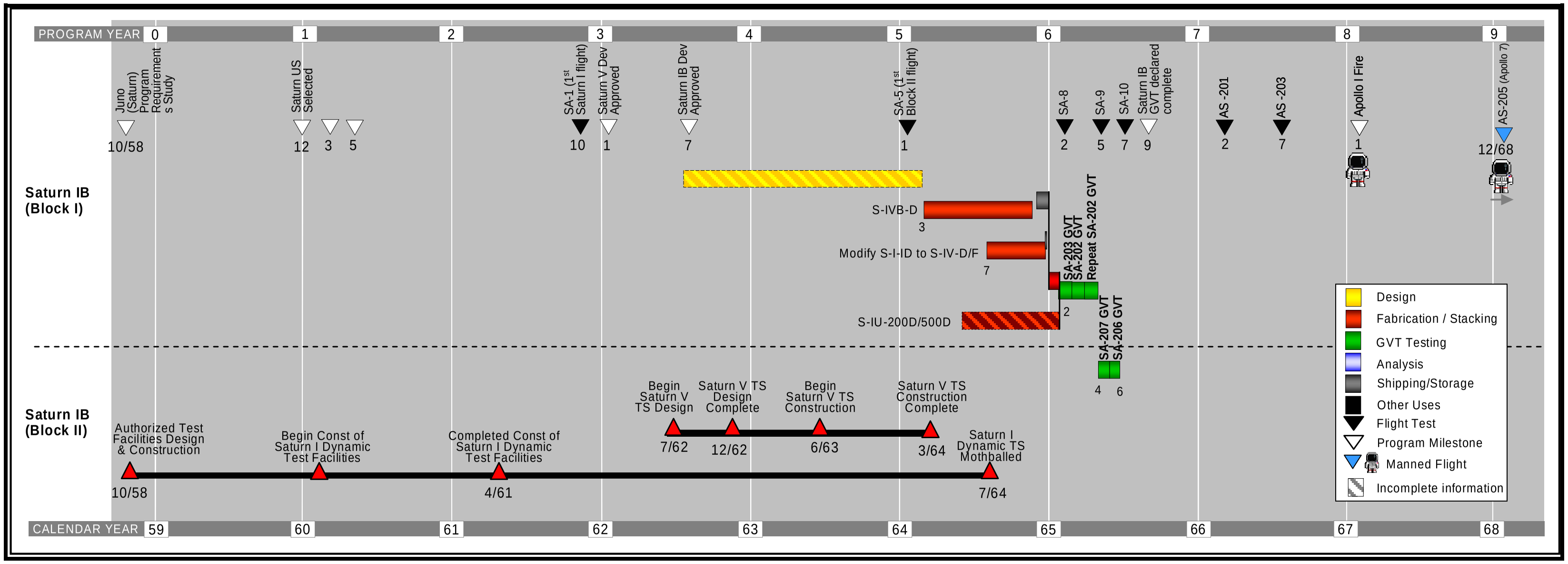


Figure 4. Saturn IB Timeline

Figure 5. Saturn I in Dynamic Test Stand

Figure 6. Saturn IB in Dynamic Test Stand

consisted of the S-IVB stage and the Apollo payload. The Configuration II test added the S-II stage. The Configuration I test added the S-IC stage, resulting in a complete vehicle.

Unavailability of the S-II test article delayed the AS-500D Configuration I and Configuration II tests. At various times, four different S-II stages were designated for the AS-500D ground vibration test. Figure 8 shows the design, fabrication, and use activities of these S-II stages. Design of all four of these test articles began in September 1961. The test article designs were frozen during the third quarter of 1964. The S-II-S (structural test article) was the first test article to be fabricated. The others were to be sequenced subsequently through manufacturing, with the S-II-D (dynamic test article) being either the third or fourth production stage.

During fabrication of the initial S-II stages, the Apollo program experienced significant difficulties with welding of the common bulkhead between the S-II hydrogen and oxygen tanks. The fabrication delays became so acute that program managers canceled the S-II-D stage and designated the S-II-S as its replacement. Seven months later, during a hydrostatic pressure test of the stage's ultimate load limit, the S-II-S ruptured, destroying the test article. Program managers then decided to reuse the S-II-T (static fire test article) in AS-500D. During a helium pressure test at the Mississippi Test Facility to isolate chronic hydrogen leaks, the S-II-T ruptured, destroying the test article. Program managers then decided to reuse the S-II-F (facilities checkout test article) in AS-500D.[7] At the time of the decision, the S-II-F was at Kennedy Space Center for the Facility Checkout Tests (AS-500F). This conflict resulted in adding a one-year hold to the AS-500D schedule between the Configuration III and Configuration I tests

To provide data to the structural dynamicists so that they could begin correlation of actual vehicle behavior to mathematic models, program managers decided to conduct the Configuration III (S-IVB-D and payload) test as scheduled and to add to the test plan an element-level ground vibration test to validate the S-IC stage design. Together, these two tests allowed analysts to complete the majority of the test-to-mathematical-model correlation work without waiting for delivery of the S-II test article. As the Configuration I and Configuration II tests of the integrated vehicle did not reveal significant anomalies, analysts could compress the correlation effort schedule as described above. Figure 9 shows the complete Saturn V test article (AS-500D) in the Saturn V Dynamic Test Stand.

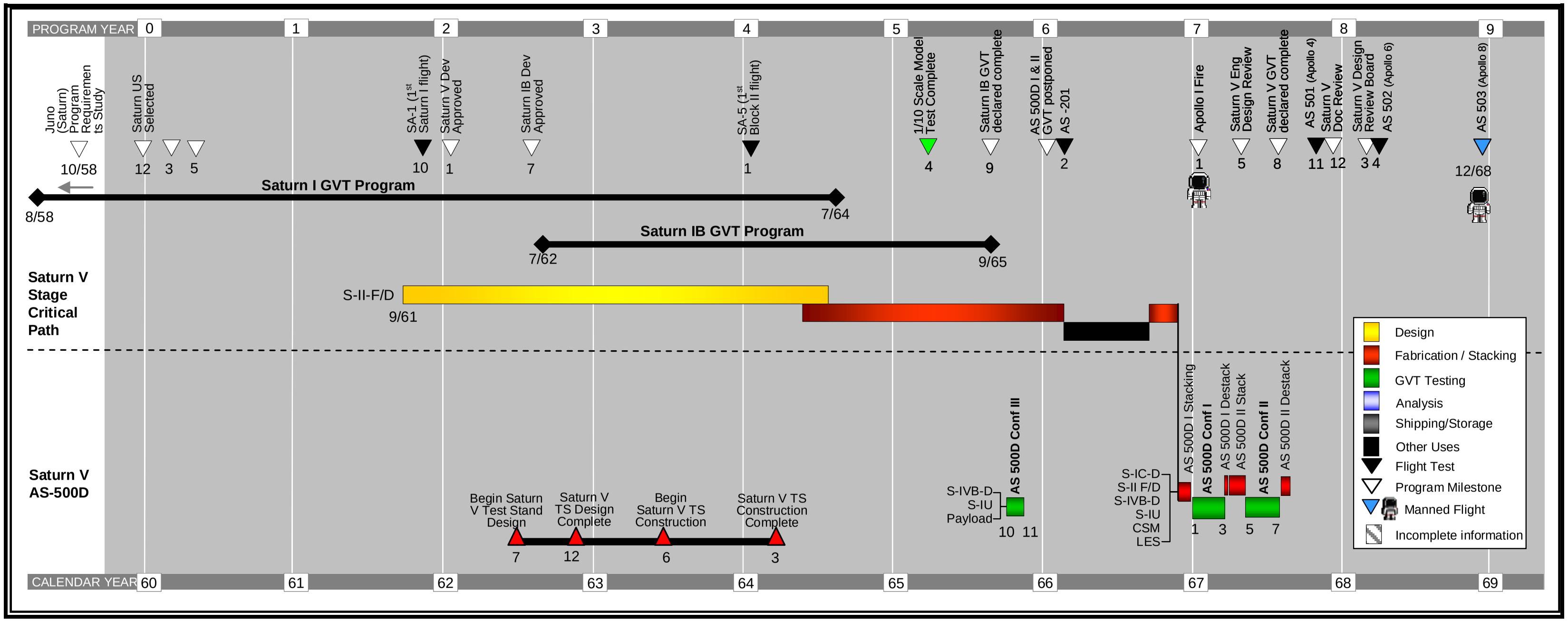


Figure 7. Saturn V Timeline

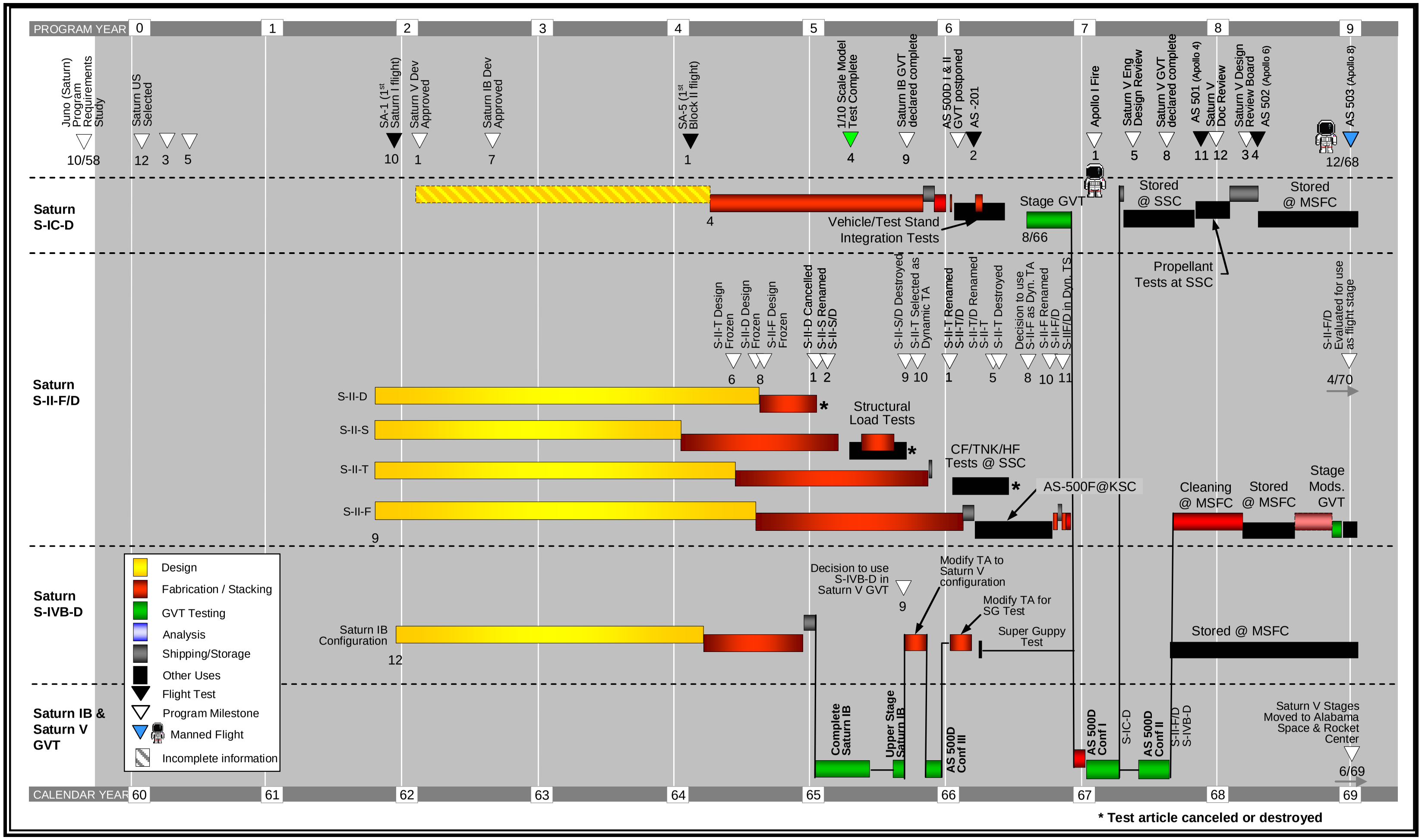


Figure 8. Saturn V Stage Production Timeline

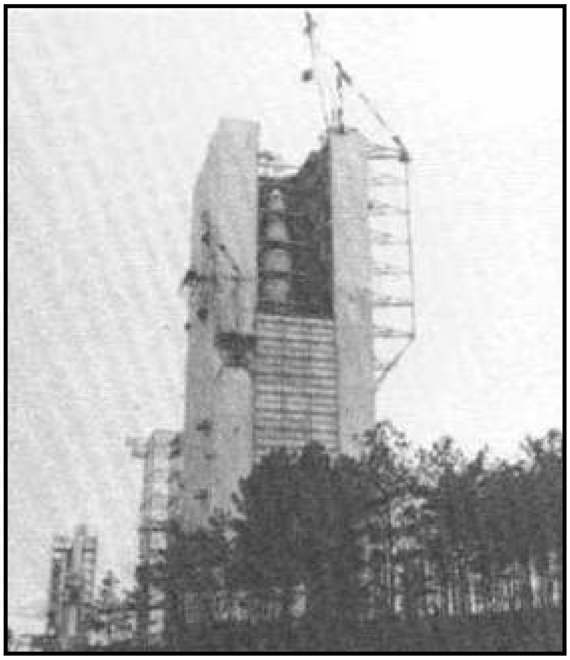


Figure 9. AS-500D in Saturn V Dynamic Test Stand

Upon completion of AS-500D, Apollo program managers considered the Saturn V Ground Vibration Test Program a success. The test met all test objectives and supported the Saturn V Engineering Design Review and Saturn V Design Review Board despite the delays in delivery of the S-II test article. The test effort resulted in some minor changes to the vehicle.[5] Although the analysis of AS-500D correlated longitudinal data only through 10 Hertz, test data were acquired through 30 Hertz. This additional data proved valuable to the program later, when a test flight demonstrated unanticipated pogo instability (longitudinal vibrational instability). A second look at the test data revealed a corresponding instability at 18 Hertz that confirmed the post-flight analysis.

The fidelity of the LEM test article did not accurately reflect the flight vehicle's asymmetrical stiffness. Although the original test plan called for a test article taken from flight inventory, schedule and budget constraints necessitated use of a lumped mass simulator with a plywood structure. This change resulted in test data that did not reflect coupled pitch/longitudinal instability. This instability resulted in control anomalies during the AS-502 (Apollo 6) flight and prompted subsequent design changes.

SATURN V TEST WORKFORCE

While knowledge of the duration of a historical test program is useful in developing new test programs, it does not accurately reflect the amount of effort expended in a given time period. Labor loading (workforce allocation) is a critical planning variable of any program. As mentioned above, very little information regarding the conceptualization, planning, and execution of historical ground vibration tests has been preserved. To augment the paucity of program management information, it was necessary to seek out and interview SMEs. This section will summarize information that was collected from historical documents and estimates by SMEs.

Volume I of Reference 1 states that initially, 23 engineers and technicians were involved in the test conduct, but the number required dropped to 15 with gains in experience. Volume II of Reference 1 mentions that the mathematical modeling (analysis) took 65 man-months over a 13-month period and an additional 9 man-months over a 5-month period. Reference 1 does not describe the levels of effort that went into these composite man-months (e.g., 24 hours per day or 8 hours per day). Neither does it include information on how many man-months it took to do the post-test analysis (i.e., model correlation).

The only senior engineer or manager from the Apollo era interviewed as an SME was Robert S. Ryan. Mr. Ryan estimates that there were 50-100 people working on AS-500D at any one time, but he cannot recall specifics as to work breakdown between the analysts, test operations, and technical support. Mr. Ryan estimates with confidence that test operations and stacking operations (configuration breaks) were conducted 24 hours per day, 7 days per week.

As shown in the timelines included in this paper, Configuration III took 22 days to complete, Configuration I took 69 days, and Configuration II took 78 days. The post-test analysis of Configuration II took 14 days to complete. The following assumptions were used to evaluate the AS-500D workforce data:

- 24-hour, 7-day operations occurred during the actual test.
- Configuration III (the first AS-500D test) required 23 engineers and technicians.
- Configurations I and II required 15 engineers and technicians.
- All pre-test analysis occurred in 1963 and 1964.
- Test conduct was continuous.

The AS-500D pre-test analysis took 74 man-months (6.17 man-years) and the test conduct took 8,133 man-days (32.5 man-years). No information was available regarding the amount of effort expended in designing and fabricating the Special Test Equipment. Additionally, as the majority of the model correlation work used data from the Configuration III and S-IC element tests, there was effectively no post-test analysis time after completion of Configuration II.

SPACE TRANSPORTATION SYSTEM TESTS

STS PROGRAM ARCHITECTURE

In September 1969, 18 months after NASA declared the Saturn V flight-worthy, the Presidential Space Task Group recommended development of a new space transportation capability to supplement or replace the Saturn launch vehicles. Over the next two years, the concept of a reusable orbital shuttle system was developed. Commitment to the Space Transportation System (STS) occurred in early 1972.

During the initial STS program scheduling and budgeting process, program managers assumed that structural dynamic testing of full-scale STS elements was not necessary. They assumed that mathematical modeling in conjunction with scale-model testing would provide sufficient data to validate the structural dynamics and guidance, navigation, and control system. P.J. Grimes of The Boeing Company documented this position in a two-volume contractor report.[1, 2]

The concept of omitting dynamic testing of large space structures was in direct opposition to the experiences of Marshall Space Flight Center (MSFC) structural dynamicists. In 1972, Henry C. Dyer of the MSFC Astronautics Laboratory presented a proposal to STS program managers. The proposal argued that both full-scale element tests and integrated ground vibration tests were necessary. Structural dynamicists argued that the Apollo and Skylab programs had shown that analysis alone and analysis in conjunction with scale model testing had “consistently failed to predict significant local effects, dynamic coupling mechanism, interface characteristics, and propellant/structural coupling.”[5] Mr. Dyer included in the presentation numerous examples of Apollo and Skylab design problems not identified by analysis or subscale testing but by the ground vibration tests. In the end, program managers rejected this position. According to another SME, Robert S. Ryan, rejecting the proposal was not based on a technical matter but on an evaluation of schedule and budget impacts that the test would have on the STS program.

In 1973, Mr. Ryan, as the Division Chief of Structural Dynamics at the MSFC Engineering Directorate, presented a revised Mated Vertical Ground Vibration Test (MVGVT) proposal. The revision reduced the schedule and budget impacts by reducing the scope of the full-scale testing. Program managers accepted the de-scoped ground vibration test program in late 1976, and pre-test analysis commenced in 1977. No copies of this proposal are known to exist; therefore, comparing proposed schedules and budgets against actual expenditures is not possible.

In general, STS program managers replicated the Saturn vehicle structural dynamics validation process.[9] At the same time, they recognized that the configuration of the Orbiter, External Tank, and Solid Rocket Boosters was unique in the history of spaceflight and could have unforeseen dynamic couplings. Designers performed extensive mathematical modeling during the conceptual design phase of the STS program to determine if the vehicle was flyable. After selecting a flyable configuration, designers used these mathematical models to develop the various STS elements.

In 1975, program managers authorized a Quarter-Scale Model Ground Vibration Test program. This program was to provide structural dynamics data to designers early in the development process. These data would allow incorporating design changes with minimal impact to program schedules and budgets. Delivery of the scale models began in the last quarter of 1976 and continued through the first quarter of 1977. Scale model testing commenced in November 1976 and continued through March 1980. Testing of the elements and the integrated vehicle was complete in December of 1977. The testing through 1980 involved the payload testing.[6] The Quarter-Scale Model Ground Vibration Test was useful in that it identified problems with the mathematical models on which the flight vehicle designs were based. However, the development process was in the final stages when the data were distributed. For example, the scale model tests occurred after the element Critical Design Reviews, after the Horizontal Ground Vibration Test (HGVT), and concurrent with the STS Critical Design Review and the Orbiter Vehicle Approach and Landing Tests (ALT).

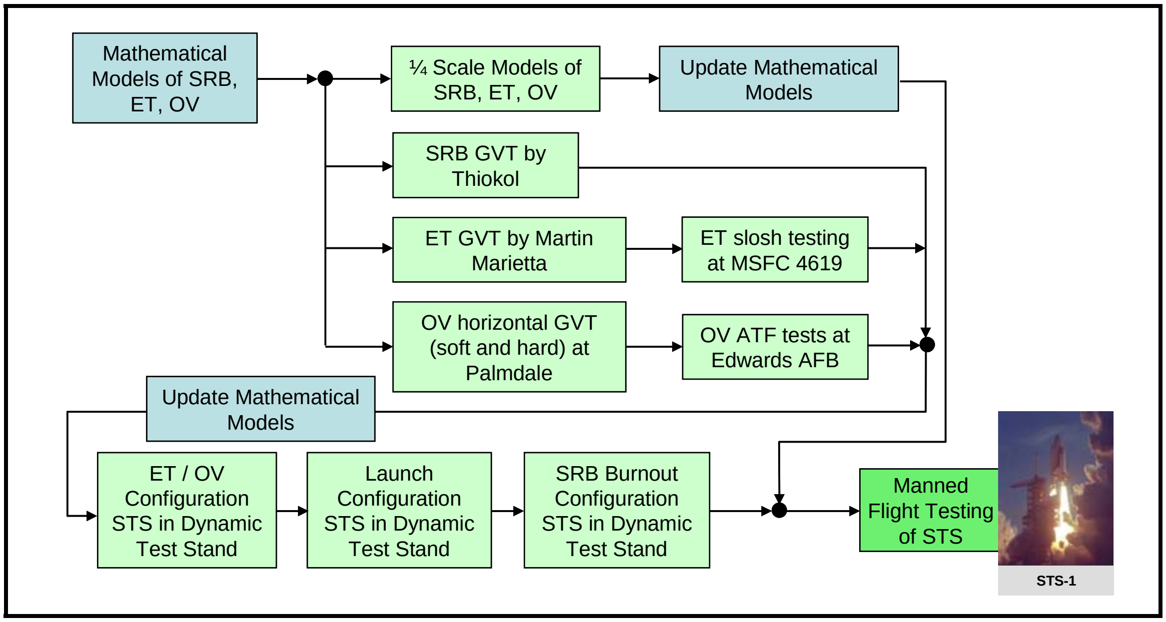
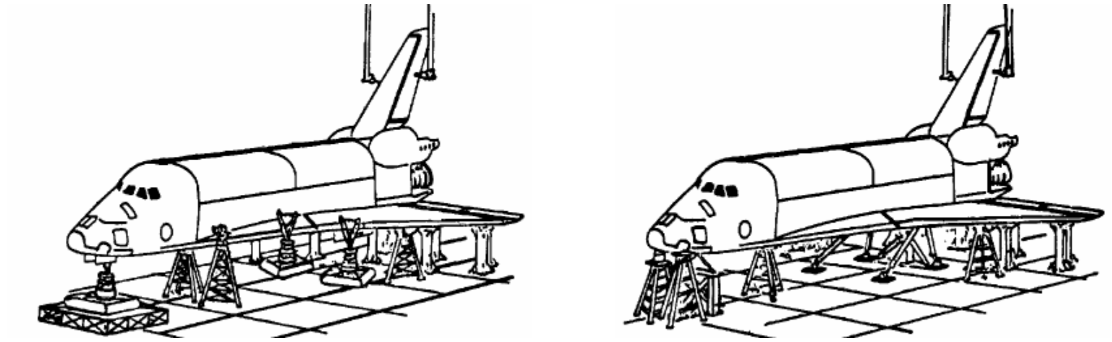


Figure 10. Space Transportation System Structural Dynamics Development Process

In parallel to the scale-model testing effort, the program elements performed ground vibration tests on their respective elements beginning in 1975. The most complex of these element tests revolved around the orbital vehicle. As the orbital vehicle had to operate both as payload and as a lifting body, it was necessary to incorporate into the test program a HGVT to validate these flight modes. The HGVT took place during the latter half of 1976. Figure 11 shows the two test configurations used during the HGVT. The first configuration used soft connections to simulate the orbiter de-orbiting and landing. This configuration used techniques common within the aircraft industry to identify aircraft modal data. The second configuration used a rigid mounted orbiter to simulate the orbiter mounted on the shuttle carrier aircraft. After completing these tests, conduct of a mated orbital vehicle/carrier HGVT validated the shuttle carrier aircraft dynamics with the orbiter attached.



Soft Connection Horizontal Ground Vibration Test Arrangement

Rigid Connection Horizontal Ground Vibration Test Arrangement

Figure 11. Space Shuttle Horizontal Ground Vibration Test Configurations

After the element tests were completed (including the ALT at Edwards Air Force Base), the program elements were transported to MSFC for integration and testing in Test Stand 4550 (formerly the Saturn V Dynamic Test Stand). Figure 12 shows the installation of the program elements in the test stand.

Solid Rocket Booster Stacking

External Tank Stacking

Integrated STS

Figure 12. Space Shuttle Elements in MSFC Test Stand 4550

The STS ground vibration test in Test Stand 4550 was designated the MVGVT. The Structural Dynamics Division of the MSFC Engineering Directorate performed the pre-test analysis, specified the test and instrumentation requirements, and performed the post-test model correlation work. Rockwell International, also the Space Shuttle Systems Integrator, ran the test program. Test operations were conducted by the MSFC Engineering Directorate Test Laboratory under the administration of Rockwell International. Figure 13 illustrates the entire STS ground vibration test program.

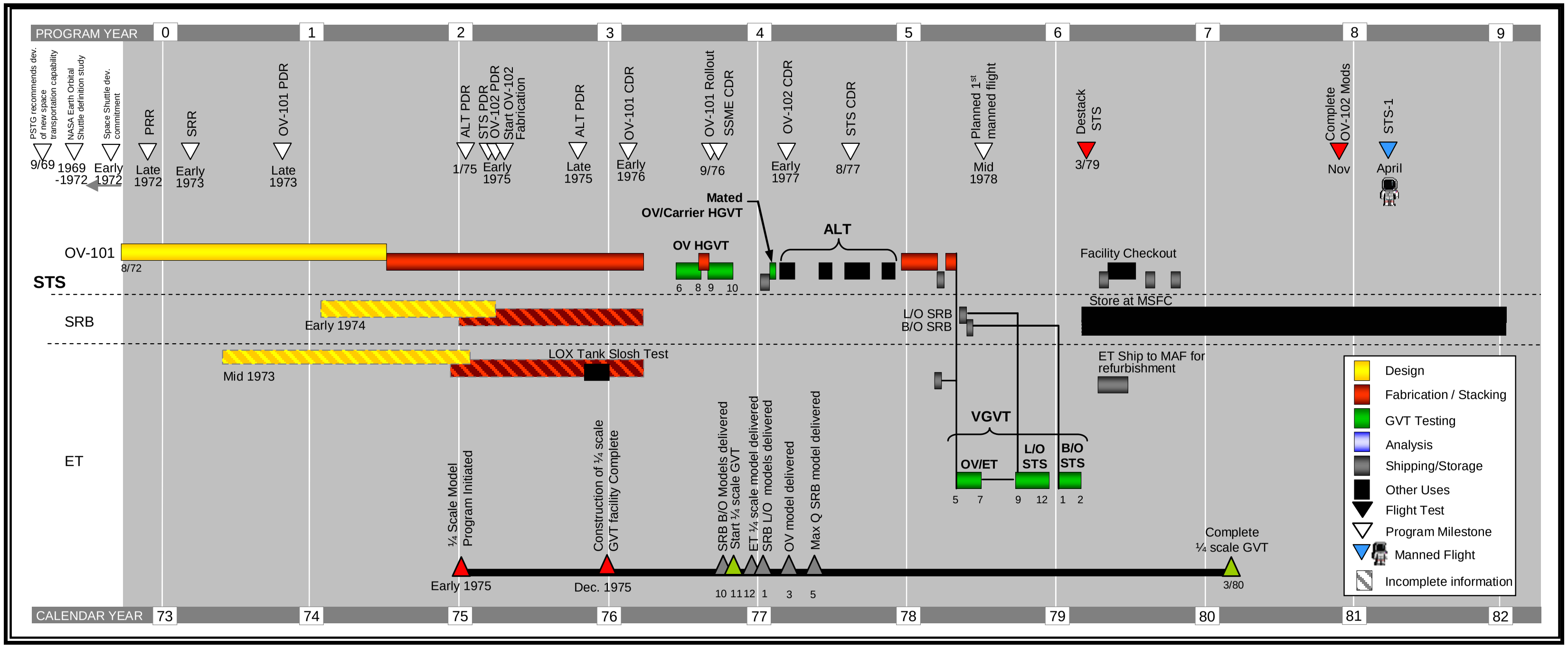


Figure 13. STS MVGVT Timeline

STS program managers considered the STS Ground Vibration Testing program a success. The HGVT met or exceeded their objectives and allowed the ALT to proceed on schedule. Despite the late program authorization for integrated ground vibration testing, the MVGVT met or exceeded its objectives. The MVGVT also identified several design issues with the STS, permitting them to be resolved before first flight.

While the Quarter-Scale Model Ground Vibration Tests were a technical success, identifying problems with mathematic models, these data were acquired significantly late in the design process (i.e., after element Critical Design Reviews and concurrent with the STS Critical Design Review). The objective of the Quarter-Scale Model Ground Vibration Tests was to provide structural dynamics data early in the development process. The designers would then have used the data to modify the vehicle designs before manufacture of production vehicles began, rather than having to rework production vehicles. Therefore, the Quarter-Scale Model Ground Vibration Tests were not an optimal use of resources and schedule. The needed data were not supplied sufficiently early in the development process.

STS TEST WORKFORCE

Information regarding the STS MVGVT was limited to two sources: the 1972 STS MVGVT Proposal by Dyer[5] and estimates of SMEs regarding actual workforce usage. Information garnered from these sources is presented here.

The 1972 STS MVGVT Proposal by Dyer[5] includes assumptions by his staff regarding test configurations needed to provide analysts data they would need to validate STS mathematical models. The most significant divergence from actual configurations used in the MVGVT is that Dyer expected use of only two solid rocket booster test articles, one empty and one filled with an inert propellant. The actual test used two test articles of each type. While the Dyer[5] presentation specifically calls out the estimated workforce needs, it does not break down the duties of each of the organizations involved. The presentation also does not break down what activities would be occurring during each year of the plan. The following assumptions were used to evaluate the proposed 1972 MVGVT workforce data:

- All Engineering Effort is for Special Test Equipment (STE) design and fabrication.
- All test requirements definition was performed in 1972 and was not included in the proposal.
- All effort in 1973 was to be test article design (including pre-test analysis).
- All effort in 1974 – 1976 was building and test article preparation (pre-test work).
- Test articles were to be delivered in 1976.
- All effort in 1977 was to be test conduct.
- All effort in 1978 was to be post-test analysis.
- Test conduct was continuous.

The 1972 Dyer Proposal included 29 man-years for Special Test Equipment design and fabrication, 180 man-years for pre-test analysis and facility preparation, 117 man-years for test conduction, and 24 man-years for post-test analysis. Building modification labor was not included in the work package estimate as it was included as a line item in the building modifications budget.

STS program managers rejected the 1972 Dyer proposal.

Documentation of actual workforce usage during the MVGVT was not available. Therefore, the actual workforce efforts during the MVGVT are based on SME estimates. MSFC Engineering Directorate Division Chief of Structural Dynamics Robert Ryan estimated that he had 10-15 people working at half-time over a 1½-year period on both the pre-test and the post-test analyses. Bohdan Bejmuk, Rockwell International (RI) MVGVT Program Manager, estimated that he had three to four mathematical model people, three force needs and shaker analysts, and one suspension system analyst working full-time on the pre-test analysis for about three months. Thus, the MSFC pre-test workforce effort was 7.5 man-years and RI's was 1.8 man-years.

The SMEs were not directly involved in the building modifications and could not speak toward the workforce effort required to perform the modifications. Likewise, the experts were not directly involved in the design and fabrication of Special Test Equipment and could not speak on that topic either.

Mr. Bejmuk noted that during test operations, he had three analysts on each shift, distributed among three shifts per day. Mr. Bejmuk also noted that he had 15-20 engineers and technicians working on this same schedule during this interval. Ron Tepool, MSFC Engineering Directorate's MVGVT Test Director, recalled that he had 50-60 people on each of his shifts and he operated two shifts per day. Mr. Tepool's people included the data acquisition system operators, data technicians, test operations personnel, instrumentation technicians, and contractors. Thus, the MSFC test operation workforce effort was 78.4 man-years and RI's was 18.9 man-years.

Selmer mentions that, "the cumulative test time for [the] three major configurations was 2,000 hours".[10] The timelines included in this paper show that the MVGVT test conduct took a total of seven months over a period of 10 months. This equates to approximately 70 hours of test time per week, or 10 hours of testing per day on a seven-day per week schedule. Assuming an equivalent amount of reset time between tests, the information from Reference 10 supports the SMEs' estimates of 24-hour per day test operations.

Subject Matter Experts Ryan and Tepool said that MSFC personnel worked only day shifts during reconfiguration efforts (de-stacking and restacking of the test articles, instrumentation of each configuration, etc.). Therefore, MSFC work effort during reconfiguration was 48 man-years. While Ryan and Tepool could not confidently recall the contract personnel population involved in reconfiguration efforts, they did note that contractors worked 24 hours per day, 7 days per week. Their best recollections as to the number of contractor personnel were that it was on the same order of magnitude of the MSFC personnel. This indicates that the reconfiguration contractors might have expended a work effort of approximately 67 man-years (100 people, 24 hours per day, and 7 days per week for 6 months). As the SMEs did not have first-hand knowledge of the labor loading of the contractors, this information is not included in the data evaluation.

As stated previously, Mr. Ryan was only able to lump his estimates of the pre-test and post-test analysis workforce needs together. The MVGVT test articles were de-stacked for the last time one month after the final test. The test articles were then disbursed for other uses within the STS program. Therefore, for the purposes of this study, it should be assumed that the MSFC analysts completed their model correlation efforts six months after the test. Mr. Bejmuk recalled that Rockwell International had four to five analysts working full-time for a month after the tests. Therefore, MSFC post-test analysis took 3.4 man-years and RI's efforts took 0.4 man-years.

Using the data introduced above, it was determined that the actual MVGVT work effort included 9.3 man-years for pre-test analysis, 145 man-years for test conduct (not including contractor reconfiguration efforts), and 3.8 man-years for post-test analysis. No information was available regarding the amount of effort expended in designing and fabricating Special Test Equipment or in modifying the building.

Estimates by the SMEs include only 9.3 man-years for pre-test analysis and 3.8 man-years for post-test analysis. It is probable that these numbers do not accurately reflect the total time spent by the STS program analysts in developing and correlating the STS mathematical models. The MVGVT was a fast-tracked program initiated late in the STS development process (late 1976). Examination of the STS timeline (Figure 13) reveals that element tests were performed prior to the MVGVT, including extensive dynamic testing of the orbital vehicle. These element tests would have provided information to the program's structural dynamists to refine and correct their mathematical models before entering into the MVGVT. The efforts expended by the elements would have reduced the amount of time required by the MVGVT analysts to formulate their mathematical model of the STS test articles. Additionally, the results of the Quarter-Scale Model Ground Vibration Test would have been available to the analysts during the MVGVT to facilitate model correlation. Together, these efforts outside the budgetary responsibility of the

MVGVT task would have drastically reduced the effort required of the MVGVT analysts to build and then correlate their mathematical models.

HISTORICAL TEST SUMMARY

Figure 14 is a timeline summarizing the IVGVT and historic ground vibration tests relative to each other. Program Year 0 is the authorization date of each program. Due to the building block approach of the Apollo program, the design and fabrication of test articles start approximately at the time of authorization. The MVGVT used test articles originally designated for other test programs; therefore, the test article design and fabrication occurred several years before the MVGVT authorization date. The Ares' IVGVT fabrication dates lag the test program authorization date for two reasons. First, the IVGVT authorization date was near the start of the Ares I project. Second, the Constellation Program is not employing a building block approach as was done in Apollo.

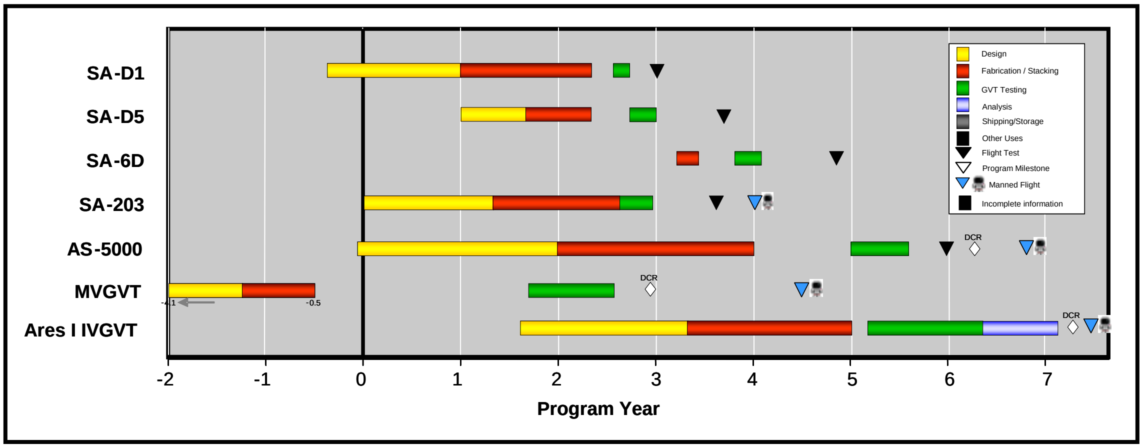


Figure 14. GVT Program Schedules Scaled Relative to Authorization Date

Workforce data shown in Figure 15 represent man-year allocations or actual expenditures for three different ground vibration test programs supporting the development of manned launch vehicles.

In References 1 and 2, P.J. Grimes recommends applying a factor of at least two when using historical data to predict workforce requirements, computational times, and flow times for new vehicle development programs. Grimes' underlying assumption was that the personnel who worked on AS-500D were highly experienced in testing integrated vehicles (Saturn I and IB), and thus they could perform faster than personnel involved in a new test program. The authors of this paper concur with Grimes' assertion that a multiplying factor should be applied when utilizing historical workforce data.

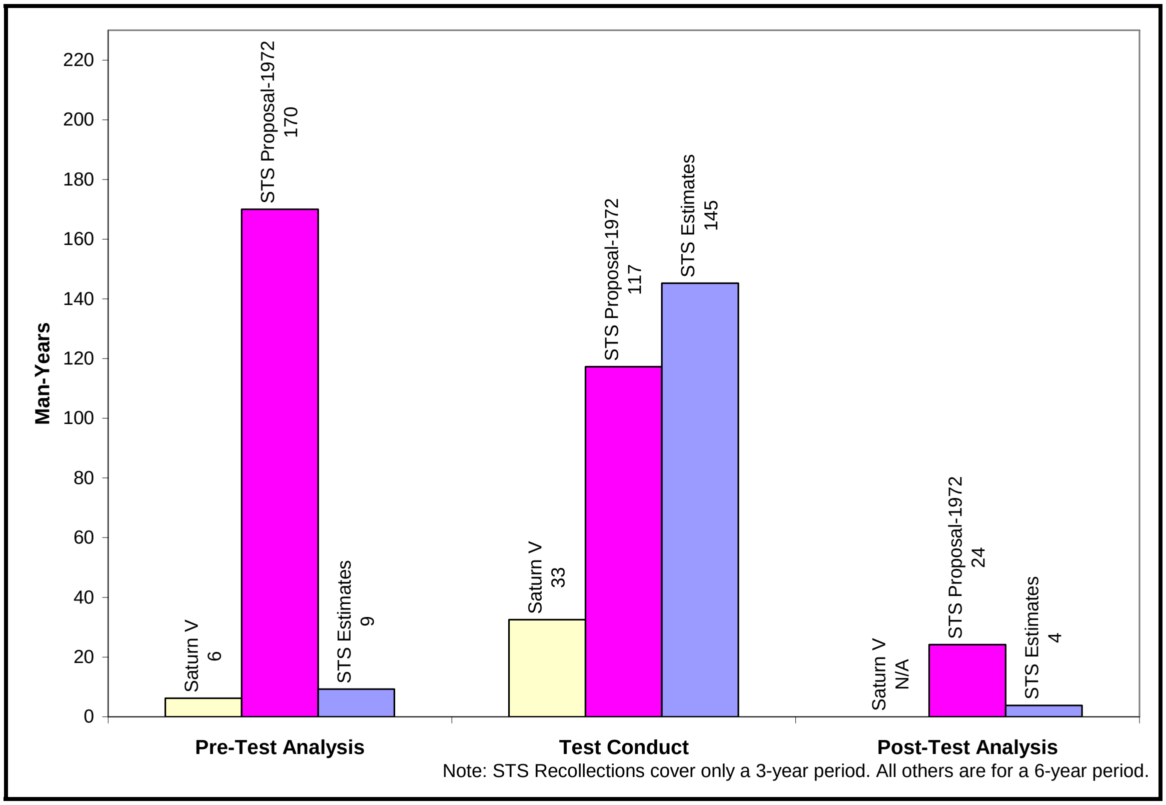


Figure 15. GVT Workforce per Activity

PRE-TEST ANALYSIS

Several underlying issues must be considered when using these historical pre-test analysis workforce effort values:

- The Saturn V portion of the Apollo program did not carry all of the development costs associated with the Saturn V stages. The development of the AS-500D test requirements was disbursed amongst other program activities.
- The mathematical models of today are more complex than those used for Saturn V and STS. Complex mathematic models require more personnel to construct and review. They also require significant coordination between test article designers and modelers to ensure that the models accurately reflect as-built test articles. Complex models also require significant coordination between modelers and test conductors to ensure that test data will be of value to the data users.
- Contemporary ground vibration test data users have increased their informational needs in proportion to increases in computational computing speed increases; therefore, it is reasonable to assume that the time required to perform test data analysis has not decreased from the Saturn and STS eras.
- Scale model test programs reduced the need for pre-test analysis during AS-500D and MVGVT, which reduced the time required to develop test requirements for the full-scale tests.

Figure 15 makes apparent that the 1972 Dyer Proposal included significantly higher workforce levels than AS-500D and MVGVT for pre-test and post-test analyses. Two factors that may have influenced this significantly higher estimate were:

- The pre-test period included design and fabrication support of both the test articles and the special test equipment by the analysts and test conductors.
- More people were allocated to model correlation effort for a longer period than what actually occurred during AS-500D and MVGVT. As was mentioned above, the cost of the MVGVT

was the basis for rejecting the 1972 Dyer Proposal. This indicates that the reduced personnel allocations for the actual MVGVT are most likely due to budget constraints.

TEST CONDUCT

Both AS-500D and MVGVT took approximately 18 months to perform the actual tests (Figures 7 and 13); however, as shown in Figure 15, the MVGVT took over four times as many personnel as AS-500D. At first, one would assume that the differences in the physical arrangement of the STS from Saturn V would be the driver for this disparity – more parts results in more handling. After reviewing the historical record, it was determined that AS-500D and MVGVT had very similar test conduct activities. These activities included:

- Stacking operations
- Configuration breaks (determined by the number of test configurations)
- Instrumentation efforts
- Tanking/de-tanking operations (number of operations and volumes transferred)

Because the physical activities associated with AS-500D and MVGVT are similar, it is reasonable to conclude that external drivers force the disparity between their test conduct workforce levels. Contemporary ground vibration test personnel must deal with significantly higher overhead labor demands than personnel from the Saturn era. Changes to the NASA safety procedures and quality control protocols since the Saturn era drive these overhead labor demand increases (e.g., personnel fall protection requirements). Similar changes between the Saturn and MVGVT eras may account for some of the increased test conduct workforce levels shown in Figure 15; however, as these test programs occurred only a decade apart, regulatory changes are unlikely to account for a significant portion of the disparity. The residual of the difference can most likely be accounted for by the highly compressed schedule of the MVGVT. This fast-track schedule resulted in much of the MVGVT specific pre-test work, e.g., development of test operational procedures, to be performed in parallel to the actual test conduct work. To minimize re-work activities, additional coordination is required between the test program's stakeholders when a test program is fast-tracked.

To account for the increased demands upon ground vibration test personnel, it is reasonable to conclude that contemporary ground vibration tests should allocate more man-hours to test conduction than are indicated in the historical precedent. Additionally, if a test program is compressed into a short time frame requiring greater than 40-hour per week schedules, the project managers should be prepared for increased labor cost associated with performing and coordinating activities progressing in parallel.

POST-TEST ANALYSIS

As shown in Figure 15, the study was not able to determine how many people were involved in the post-test analysis of AS-500D; therefore, the evaluation of post-test analysis will be limited to information regarding the STS ground vibration test.

Figure 15 shows the Dyer estimate for post-test analysis was about six times that which was actually expended during the MVGVT. Several underlying issues may have affected the representation of the MVGVT post-test workforce data, as they did for the pre-test workforce data:

- Results of the Quarter-Scale Model Ground Vibration Test would have been available during the MVGVT post-test analysis. Availability of these data may have reduced the amount of time required to do the MVGVT post-test analysis.
- The MVGVT was a fast-paced program initiated late in the STS development process. The test articles used by the MVGVT were flight or near-flight inventory equipment (the external tank was used in STS-2; the Orbiter was used in atmospheric flight tests and was originally intended to be placed in flight inventory). These high-fidelity test articles would have dramatically reduced the efforts required of the analysts to correlate the test article mathematical model against the flight vehicle mathematical model.

- The synergy generated by the scale model data and the high fidelity of the test articles probably reduced the time required to do the MVGVT post-test analysis to the identified levels. As the 1972 Dyer Proposal includes post-test activities similar to those included in contemporary ground vibration tests, it would be prudent to assume new ground vibration test program post-test workforce needs should be approximately the same as those in the 1972 Dyer Proposal. This assumption is particularly valid if the overall vehicle development program does not include scale model ground vibration tests, or if the proposed test articles are not flight hardware.

WORKFORCE ALLOCATION TRENDS

Figure 16 shows trend lines of the workforce allocations relative to program year. The Saturn V ground vibration test program began near the start of the overall flight vehicle development program. Likewise, the proposed STS ground vibration test program was intended to start early in the program.

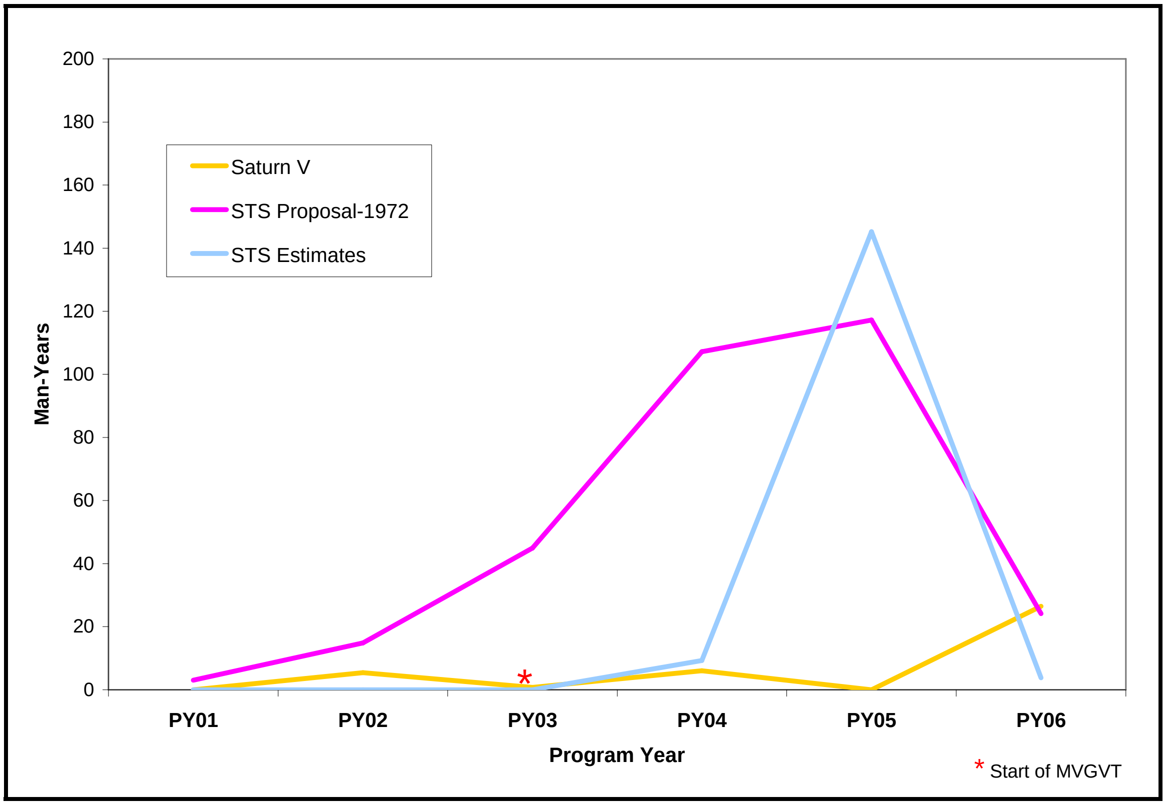


Figure 16. GVT Workforce per Program Year

AS-500D had a drop in workforce during program year three (1964). Figures 7 and 8 reveal that this drop corresponds to the year that test article designs were frozen. After freezing the test article designs, there was a reduction in analytical efforts (the work effort tracked by this trend line) during test article fabrication.

The MVGVT also reflects the pattern of workforce buildup despite the fact that the test program did not commence until late in flight vehicle development. After the test conduct phase, both the MVGVT and the Dyer Proposal trend lines show a drop of workforce requirements during the post-test analysis activity.

Because no post-test data were available for the AS-500D, the Saturn V trend line terminates at the time of the test. If the AS-500D had progressed without the one-year test delay due to the unavailability of the S-II test article, the trend line would trend downward after the test phase of the test.

CONCLUSIONS

1. Test article designs should be as close to flight vehicle designs as possible. The low-fidelity LEM used during the Saturn ground vibration tests resulted in test data that did not properly identify a coupled pitch/longitudinal instability. This instability resulted in control anomalies during the AS-502 (Apollo 6) flight and prompted subsequent design changes. Likewise, the fact that a flight inventory Orbiter and External Tank were used in the STS ground vibration test reduced the post-test correlation efforts.

2. As shown above, there were significant differences between the workforce levels of Saturn V and STS ground vibration tests. Although changes to the labor requirements existed between AS-500D and MVGVT, it is probable this disparity can be accounted for by the fact that AS-500D test personnel were highly experienced in conducting large ground vibration tests (Saturn I and Saturn IB) and the development of test requirements and procedures for the precursor test programs (including the scale model tests) reduced the AS-500D pre-test work.

3. This study can be used as a benchmark to aid in the planning of new ground vibration test programs.

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SUBJECT MATTER EXPERTS

1. Robert (Bob) S. Ryan was the Branch Chief for Dynamic Analysis in the NASA Marshall Space Flight Center (MSFC) Aeroballistic Laboratory during the Saturn I, IB, and V dynamic tests. Mr. Ryan's branch conducted the Saturn pretest analyses and model correlations as well as preparing test and instrumentation requirements. Mr. Ryan was Division Chief of Structural Dynamics at the NASA MSFC Engineering Directorate during the MVGVT. His organization developed the pretest models, the test and instrumentation requirements, and updated the models based on test results. Mr. Ryan served as co-chair of the Space Shuttle MVGVT Technical Requirements board with Mr. Don Wade of NASA Johnson Spaceflight Center. The board oversaw the test and ensured the success of the Shuttle MVGVT. During the Shuttle era Mr. Ryan was also a member of the Ascent Flight Systems Integration Group (AFSIG) and the Loads Panel. Prior to the first Shuttle flight, Mr. Ryan became co-chair of AFSIG with Mr. Enoch Jones of NASA Johnson Spaceflight Center. In 1996 Mr. Ryan retired from MSFC as Deputy Director of the Structures and Dynamics Laboratory. Mr. Ryan remains employed by NASA as a consultant.

2. Bohdan (Bo) Bejmuk was the MVGVT Program Manager for Rockwell International. Rockwell International conducted the MVGVT at MSFC and was the Space Shuttle Integration contractor. Mr. Bejumk later led The Boeing Company Space Station Integration Team and most recently served as the Vice-President of Business Development and Strategic Planning for Sea Launch System, LLC.

3. Ron Tepool was the MVGVT Test Director for MSFC's Engineering Directorate. Mr. Tepool remains employed by NASA as the Space Shuttle Main Engine (SSME) Chief Engineer.

IMAGE INDEX

1. Figure 1: NASA Technical Reports Server Image # 9801767

2. Figure 2: NASA Technical Reports Server Images # 9801803, 6636749, 6870605, 6760629, 6871798

3. Figure 5: NASA Technical Reports Server Image # 6413237

4. Figure 6: NASA Technical Reports Server Image # 6522399

5. Figure 9: *Saturn Illustrated Chronology*

6. Figure 10: NASA Technical Reports Server Image # 8111969

7. Figure 11: NASA Technical Reports Server Image #1975-2-4

8. Figure 12: NASA Technical Reports Server Images #7891971, 7992267, and 7992475