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SPACE SHUTTLE NOISE SUPPRESSION CONCEPTS
FOR THE EASTERN TEST RANGE

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ABSTRACT

During the early lift-off period of Space Shuttle vehicle (SSV) launch, i.e., the first 10 seconds of flight, the Shuttle's propulsion system's main engines (SSME's) and solid rocket boosters (SRB's) generate intense acoustic pressure fields. This intense pressure field excites various Shuttle structures, components, avionics, and sensitive payload hardware. SSV system elements, of course, must be designed and qualified to withstand the lift-off, ascent, and reentry acoustic environments. In order to minimize the Shuttle's lift-off acoustic design environments, a noise suppression model test program was initiated to examine techniques to reduce the Shuttle noise environments via modifications to the launch facility. This approach has been shown to be advantageous from the standpoint of mission operations, simplicity, payload capability, and particularly from the ecomonic aspect for the reusable orbiter. Particular emphasis has been given herein to the orbiter payload bay environments. This paper discusses the potential noise suppression techniques utilized in this recent test series. These techniques are the candidates for use with the full-scale Shuttle system during launch from Launch Complex 39 (LC 39) at Kennedy Space Center, the Eastern Test Range for NASA.

INTRODUCTION

The sound suppression test program for the Space Shuttle vehicle was developed as an extension of the baseline effort to define the vehicle's acoustic environments resulting from operations at the launch pad complex (LC 39) at Kennedy Space Center, Florida. These baseline environments, measured from a series of model tests at the Acoustic Model Test Facility (AMTF) were noted to exceed the environmental design criteria for certain portions of the vehicle. The main exceedances were noted for the payload bay on the orbiter, which is scheduled to be the "workhorse" in a reusable mode over many missions. To reduce these payload bay environmental exceedances, two general actions could be taken. First, the orbiter or payload bay could be modified to reduce the internal payload bay acoustic environments induced by the exhaust flow. Second, the severe environments could be attacked and suppressed at the source. One candidate "fix" is a major structural design modification to the orbiter. This, of course, imposes costly weight penalties on the orbiter that would have to be "paid for" on each and every mission. Another "fix" would be to impose payload modifications. But reducing the severe environmental conditions in this manner would require using shrouds or encapsulations around the payload or critical element resulting in impacts in terms of size, weight, shape, complexity, etc. On the other hand, if the noise levels for the payload bay could be alleviated or suppressed by a modification of the launch facility itself, the savings would be significant. MSFC proposed such modifications, to be determined from the results of scaled model tests.

The environments were to be suppressed by a "one time" fix to the launch facility, providing some means of reducing the vehicle environments with a ground based structural or operational change to meet the Shuttle vehicle's acoustic design criteria. This approach was accepted and tests began in August,1975.

The constraints on a ground based solution were less critical and less costly than a modification to the vehicle or to each payload. Thus, an optimum candidate was to be found with minimal impact in terms of design and fabrication or on operational plans as well as preflight preparation and postflight refurbishment. Simplicity and economic utilization are strong guidelines in the joint JSC/KSC/MSFC efforts in determining the best suppression mode for application to the launch complex and vehicle missions associated with the Kennedy Space Center launches.

Few cases of similar programs and goals were found in the literature. Whatever limited study attempts were found, in most cases, were not directly applicable to the Shuttle system because of various constraints associated with the geometry of the full-scale hardware, refurbishment requirements, overall scope, etc. Because of specific geometric variations in the vehicle/launch facility designs, extrapolation of a given suppression mode to another launch configuration may not be totally successful because of the influence of the related geometries on the induced environments. Experimental data, no doubt, support this judgment in cases other than those studied in this program.

BASIC OBJECTIVES AND TEST PHILOSOPHY

The basic objectives of this experimental effort included (1) the definition of the acoustic environment of the Shuttle vehicle and adjacent ground plane for both the "on-pad" and "lift-off" conditions and (2) the definition of realistic noise suppression techniques and required modification to the launch facility that could in any way reduce the engines' acoustic power generation capability associated with the supersonic flows. After obtaining the baseline test data, the necessity of reducing the vehicle environment became apparent, and a significant portion of the tests have involved attempts to provide several candidate techniques to suppress the Shuttle's engine exhaust generated noise. Several "candidate" suppression techniques were chosen in these model hot test firings to best meet current design criteria with minimal impact on the facility design and operations. The final suppression mode for LC 39 will be selected from these candidates. This selection will be based on the specific suppression characteristics that best meet the currently imposed design criteria and on compatibility with the launch facility design, fabrication, and operations during launch, as well as on the need for refurbishment.

In a research and development program of this type where major overall goals and application of results are usually achieved in a timely manner, the initial effort generally involves the determination of all the measurable parameters influencing the phenomenon of primary concern, in this case acoustics. However, because of the stringent schedule demands and need for almost immediate design plans, no effort could be expended in measuring internal flow temperatures, velocities, and turbulence as affected by the injection of water or other similar suppression approaches. It is mandatory, for the complete understanding of the sound generation and suppression phenomena, that such flow relatable quantities be measured for the more direct determination of how to control the resultant acoustic fields. The approach herein has necessarily omitted this important intermediate step in an attempt to meet existing schedules and program implementation.

Nineteen model firings were conducted in the initial test phase to define the baseline vehicle environments, including two configurations of the mobile launcher (ML). Figure 1 shows the orbiter model used in this test series with pressure transducers flush mounted on the external model surface. There were 40 acoustic measurements on the 6.4% SSV model, 5 were located on the SRB, 7 on the ET, and 28 on the orbiter. Figure 2 shows the orbiter model and many of the transducers on the top surface. Figure 3 shows the orbiter's under-surface measurement locations. The orbiter aft heat shield has three measurements and the external payload bay has eight measurements distributed over the sides and top.

A typical 6.4% model test firing at AMTF is delineated in figure 4 showing the sequence of events. The SSME's are ignited first, as is done in most cases, for a period of 3 to 5 seconds and then the SRB motors are ignited and burn for more than 9 seconds. A sufficient period for acquiring data for the SSV case (SRB's and SSME's) is maintained. The SSME's are then cut off or terminated while the SRB's continue firing dry for a short period in order to establish the environments for the baseline or dry condition. The sound suppression device, the "horseshoe" water injector in this case, is then activated. For this case the water flow rate was increased from zero to a steady state value of $w_w/w_p = 1.7$. The reduced environments for this flow ratio can clearly be seen. This can be compared with the baseline environments for definition of the sound suppression for each case.

The model, geometrically scaled at 6.4% of full scale, is shown in figure 5 for the on-pad case. The facility, deflectors, and trench are also built to the 6.4% scale. Figure 6 illustrates the SRB over the exhaust flow holes in the ML for the on-pad case. The structural members protruding into the holes are used to support the SRB through four support columns at the SRB aft skirt/ML interface.

The current baseline ML design includes large holes in the ML deck for the SRB exhaust flow passage onto the deflector and flow trenches. A ML design considered earlier involved much smaller holes in an attempt to reduce the on-pad environments.

The vehicle trajectory effects were simulated. Model tests were conducted at various vehicle altitudes with the appropriate vehicle drift variations totally simulating the vehicle's three-dimensional movement relative to the launch facility at LC 39. Two general drift conditions were considered in the model test program; nominal and worst-case drifts were simulated in separate tests to describe the environmental variations from lift-off to full-scale altitudes of almost 300 feet.

One of the major concerns in these tests was the simulation of the exhaust impingement on the top of the ML, since the vehicle drift is highly pronounced even just after lift-off. The early impingement of the supersonic exhaust flow on the non-optimized "flat-plate" portion of the launch facility induced higher vehicle environments and consequently the need became apparent for suppressing the acoustic energy reaching the vehicle during this portion of flight. Several alternate modes were proposed and tested in order to provide various trafe-offs, if necessary, in the facility/vehicle design and/or operational constraints, or simply to allow an effective economical weighting of each suppression approach.

The degree of sound suppression necessary for the Shuttle to meet the internal design criteria for the payload bay is dependent on several factors. The permissible OASPL for the internal payload bay is 145 dB with a prescribed spectrum. The necessary suppression is then derived from the external environments (measured in the baseline test series) and the appropriate transmission loss, i.e., the acoustic energy loss through the orbiter payload bay structure, and the internal noise reduction. It appears that at this time only the external environments are available. No transmission loss data from experimental efforts have been acquired.

SCALING CONSIDERATIONS

As is well known, the Space Shuttle system consists of two solid rocket motors and three (high chamber pressure) liquid propellant rocket engines. Any scale model contemplated for acoustic testing would generally be required to have both propulsion systems scaled by the same relationship. Different scaled values between the two systems would greatly complicate the testing and possibly restrict the usefulness of the results, especially for those test conditions where the interaction between the two systems is considered to be significant. Consequently, for Shuttle acoustic model testing, careful selection of compatibly scaled solid rocket motors and liquid engines had to be made.

Acoustic model testing is based upon the principle of dynamic similarity. This principle states that two systems are dynamically similar if they are geometrically scaled and if the time average values of temperature, velocity and density are the same at identical locations. Consequently, this implies that temperature, velocity, and density are preserved in dynamically similar systems. This points out then that the mean squared sound pressure (or total energy) is the same at similar points or scaled locations in dynamically similar systems. This is shown below as

$$p^2 = \int_o^\infty Gm\ (fm)\ dfm = \int_o^\infty Gp\ (fp)\ df_p$$

where G(F) is the mean squared pressure per unit bandwidth (PSD)

The complete derivation of the scaling relationship and subsequent dimensional analysis is beyond the intended scope of the material being presented, however, this brief analysis reveals that time and length quantities scale directly with a characteristic length. Because the velocities are preserved in a dynamically scaled system, the frequency must be inversely proportional to this characteristic length, such as

$$f \propto \frac{1}{L\,o}$$

By employing the use of the dimensionless frequency or Strouhal number which is widely used in many forms of dynamic analysis, this is perhaps more clearly seen. The Strouhal number is given as: $S = f\,L/v_o$, where L is the characteristic length, v_o is the characteristic velocity, and f is the frequency. Dynamic similarity states that S(model) = S(prototype) or:

$$S_p = S_m = \frac{f_p L_p}{v_p} = \frac{f_m L_m}{v_m}$$

Because velocities are preserved in dynamically similar systems,

$$\frac{f_m}{f_p} = \frac{L\ p}{L\ p}$$

If the exit nozzle diameter is selected as the characteristic length in both systems, then $L\ p/L\ m$ becomes the "scale factor" of the experiment, i.e., $f_m = (S.F.)f_p$. This states, therefore, that the frequencies generated by the model are equal to the product of scale factor times the full scale frequencies. This is the procedure used to scale the acoustic data presented herein. In summary, between the model and full scale, the mean squared sound pressures are identical at geometrically similar locations and the frequencies scale inversely with the characteristic length (or scale factor).

It has been stated that pressures, densities, velocities, and temperatures are identical in dynamically similar systems. This is not the case for the thrust of the engines and other derived quantities which are of second order, such as areas. For example, thrust is given as

$$T = \frac{mv}{g}$$

$$\text{Where } m = \rho A v$$

In the above equations m is the flow rate, v is the velocity, ρ is the density, and A is the area of the nozzle exit. The thrust ratio between full scale and model becomes

$$\frac{T_p}{T_m} = \frac{A_p}{A_m} = \frac{(D_p)^2}{(D_m)}$$

The ratio D_p/D_m is the scale factor, therefore, the thrust requirement between full scale and model is

$$\frac{T_p}{T_m} = (S.F.)^2$$

The thrust of the model then should be equal to the full scale thrust divided by the scale factor squared. Areas and flow rates between full scale and model would scale in the same manner.

The first consideration in any acoustic model test program is the selection of compatible engines. This, of course, defines the scale factor of the experiment. This selection is, as always, dependent upon the availability of hardware, development required, time schedules involved, and cost.

Scale model high chamber pressure (3000 psi) liquid engines were not available for this program and the cost and time required to develop such an engine were prohibitive. Selection of equivalent liquid rocket engines thus began. Fortunately, during the early Saturn engine development work, several model liquid rocket engines of different scales were fabricated by MSFC (J-2's and RL-10's) and this hardware was available for use provided a compatibly scaled solid rocket motor could be found. A search of existing inventories of solid propellant motors of the Army, Air Force, and Navy revealed that an acceptable motor was currently in use. This motor was the "Tomahawk" built by Thiokol and originally used as a high altitude sounding rocket. There is an ample supply of these motors available and it is still in production.

The Tomahawk motor, along with existing liquid engines simulating the SSME's, established the scale of the Shuttle acoustic model test program at 6.4%, or a scale factor of 15.6. As in any test program, compromises have to be made, however, those made in the development of this program are not considered significant, perhaps on the order of 5% to 10%, and are well within the realm of acceptable engineering design tolerances in terms of repeatability of results, accuracy of instrumentation systems, and statistical uncertainty in data processing.

SUPPRESSION APPROACHES

The sound suppression modes considered in this study were potential candidates for use at LC 39 at Kennedy Space Center. The general guidelines for the preliminary design phase included significant environmental reductions in conjunction with the many factors which promote acceptable launch facility installation and minimal operational constraints with minor refurbishments, if any. The suppression mode selected must be simple, such that its complexity does not jeopardize its success or otherwise indirectly compromise the vehicle or mission objectives. The associated hardware must allow for necessary prelaunch and launch operations without excessive constraints. Refurbishment requirements for any suppression related hardware must be minimal in terms of manpower, time and cost, because of the stringent flight turnaround readiness requirements.

Approaches to reduce the payload region environments generally included the use of several concepts. Barriers or shields were used to block the direct line-of-sight between the source and receiver (e.g., portions of the exhaust flow and the payload bay region) and water was injected to add mass to the exhaust. Adding mass is a means of attempting to reduce the turbulent flow velocities in a constant momentum flow system. Also, flow screens were used to break up the flow into smaller "portions" attempting to reduce the amplitude of the lower frequency acoustic energy in a mode similar to that used in aircraft engine noise suppression.

The relative vehicle/launch facility geometrical relationships have also been studied, especially in regard to minimizing the flow impingement on the top of the mobile launcher platform surface after vehicle lift-off and subsequent drift. For the off-pad case, deflectors were used to prevent the flow from impinging on the launch facility in a "flat plate" manner which would tend to induce higher acoustic environments. Thus, a technique for reducing the inherent vehicle drift also was investigated and recommendations are forthcoming. A model firing has been made to evaluate the effectiveness of reducing the vehicle drift and subsequent exhaust impingement through positive control of the vehicle also allowing other schemes of sound reduction to supplement the reductions gained by keeping the SRB exhaust flow in the holes in the ML.

As a specific example of the barrier or shielding technique, the use of exhaust flow trench covers was considered. This portion of the study was similar to that utilized in the Titan noise suppression program. If the vehicle exhaust were directed into a closed-channel type configuration, as shown in figure 7, the vehicle environments could be significantly reduced, depending on the exact dimensions and geometry. In the case at LC 39, however, the trench cover scheme is not suitable for several reasons. First, the existing ML design requires the rather large opening for the passage of the exhaust through the mobile launcher. Such large openings, however, provide a direct line-of-sight between the orbiter and a large portion of the exhaust flow. This situation exists in this case whether or not the exhaust trenches are covered. Second, the trench dimensions are quite large and the loads on a 55-foot-wide unsupported cover are significant and result in problems in design and fabrication. Third, the refurbishment requirements and operational interferences of trench covers are not considered totally acceptable to the vehicle launch facility operational goals at LC 39. Figure 7 illustrates only one of the cover configurations used in these tests. Other covers used in this test series also blocked the vertical open area between the bottom of the ML and the top of the exhaust trench. Other covers were designed like "venetian blinds" or slats with variable degrees of closure as an alternate to the solid plate covers.

Other barriers considered in cold flow model tests included a solid divider between the SSME and SRB exhaust flows from the top of the deflector to the bottom of the ML. This would prevent the SRB noise contributions from radiating through the large opening for the SSME exhaust flow through the ML. Because of potential flow impingement problems, this particular scheme was not pursued in the 6.4% hot flow model test.

Solid barriers show certain related structural problems of loading, physical interferences, etc. However, barriers composed of sheets or sprays of water could be used to some degree where solid walls are prohibitive. Several schemes using water barriers were proposed and some tested but other types of suppression approaches have generally proved more effective.

Another barrier considered in this study involved the partial closure of the SSME exhaust flow hole in the mobile launcher. Because of the divergent cant angles of the SSME's, the degree of closure had to be limited in order to maintain the clearance between the exhaust flow and vertical side surfaces of the SSME hole through the ML. The limited closure allowed for engine gimballing and exhaust spread (approximately 13°) but did not prove to be sufficient to provide any appreciable reduction of the vehicle environments for the on-pad (pre-lift-off) case.

Another barrier-type mode was designed by KSC and was tested but did not include solid or structural barriers. The "trench grid" shown in figure 8 was a crossed-pipe water injection system over the SSME exhaust flow trench. It was suggested that a fine spray of water over the entire trench region might provide some reduction in the environment as a "barrier" in addition to the added mass effect to reduce the exhaust velocities. A water pipe across the bottom of the ML base is also shown in figure 8 and is designated as a "spray bar." Its contribution can be described much as the trench grid except that the injection is in a near vertical plane.

The "nozzle injection" device, used in solid motor model tests under the sponsorship of the Navy, was tested here with the SSME's but did not favorably fit into the facility requirements and operational flexibilities at LC 39. Water could be injected, as shown in figure 9, into the immediate exhaust flow area near the nozzle exit plane.

One of the basic approaches utilized in the SSME tests was the "water ring" shown in figure 10. The water ring was a peripheral pipe around the SSME exhaust flow hole in the ML, flush with the deck surface. The water injection was very near the SSME nozzle exit plane in an attempt to efficiently mix water with the exhaust flow at the earliest possible time after the exhaust emergence from the engine.

After preliminary tests of the water ring configuration, it was found that the water flow rates required pipe diameters larger than could easily be implemented without interference with vehicle launch preparation. An alternative to this water ring problem was the "horseshoe" injection device which was situated on the ground plane at LC 39 and consequently did not interfere with the vehicle preparation as the ML deck-mounted water ring did. The horseshoe, shown in figure 11, utilizes a pipe on the edge of each side of the exhaust flow trench and a connecting pipe across the trench along the crest of the exhaust deflector. The configuration is thus "horseshoe"-shaped and injects water from the deflector crest and side pipes along the trench walls.

The horseshoe configuration was also used with the SRB exhaust, again injecting water from the trench sides and from the deflector crest into the SRB exhaust flow below the ML. This configuration is shown in figure 12. The curved pipe over the trench is arched to avoid flow impingement and is not used to inject water.

Figure 13 shows the model facility with the vehicle at a full-scale altitude of about 280 feet, which occurs between 5 and 6 seconds after lift-off. The vehicle is placed at the proper test elevation as indicated and the launch facility is moved to simulate the proper vehicle drift relative to the facility at that time in flight. The exhausts then flow into the ML exhaust flow holes or onto the ML deck where impingement occurs. Exhaust impingement, as noted previously, is influential in increasing the vehicle environments during lift-off. As previously stated, one mode of reducing the environments during launch is to restrict the degree of vehicle drift and, therefore, the degree of impingement of the SRB exhaust on the ML deck. If the vehicle drift is significant and cannot be controlled, other means of suppression are available. Figure 14 shows a model sound suppression device for the post-lift-off period during which the SRB exhaust leaves the hole area in the ML. The "top ring" water injection device is situated about 25 feet above the ML deck (full scale) and injects water into the exhaust impingement area on the deck. There are potential problems anticipated for this configuration including facility operations and refurbishment difficulties. KSC is now studying trade-offs for this lift-off suppression technique.

Another post-lift-off sound suppression device has also been tested. KSC proposed the "geyser" configuration shown in operation in figure 15. Water is piped up through the ML and out the top of the ML deck. A "diffuser cap" was installed at the pipe end, almost flush with the ML deck, and holes in the cap were to advantageously distribute the water for optimum exhaust flow mixing. A modification to this design has been proposed and results are not available at the time of the paper presentation to indicate the "modified geyser" results.

DISCUSSION OF PRELIMINARY RESULTS

A time history showing the overall sound pressure level in dB for the lower payload area as a function of time is presented in figure 16. These time traces are "constructed" from data from various tests for the simulated flight times shown. The SSME's are operating approximately 3.5 seconds before SRB ignition. As can be seen, for the payload bay the acoustic environment generated by the SSME's is the dominating environment, approximately 8 dB over the SRB environment, for the on-pad case. As the Shuttle lifts off the mobile launcher, the SSME noise contributions decrease rapidly, while the noise environment generated by the SRB's has a somewhat gradual increase in OASPL. This increase is approximately 2 to 3 dB at the highest elevation tested. This increase in environment for the SRB is due to increased impingement of the SRB exhaust flow as a result of the inherent drift of the Shuttle. This effect of drift on the OASPL will be discussed more fully.

The SSME's were utilized as a common source to study many various modes of sound suppression. The simplicity and low cost for these firings, as compared to the SRB model, directed the use of the SSME cluster as the "workhorse" for this suppression study effort. The water ring injection device shown in figure 10 was tested at various flow rates and with two sizes of holes in the discharge pipe and with two hole patterns for the water spray configuration for this specific water ring design. No advantages were noted from these hole size and pattern changes. Figure 17 illustrates the acoustic spectra for the "SSME's-only" firing for the on-pad condition comparing a dry baseline with water ring flow ratios ranging from about 1 to almost 7 (w_w/w_p = 1 to 7). The baseline case OASPL was 158.9 dB, and the water ring injection shows an OASPL of 149.0 dB for the higher flow rates (w_w/w_p = up to 6.9), a reduction in OASPL of almost 10 dB and about 15 dB in the 100 Hz one-third octave band.

Figure 18 presents a comparison of the "suppressed environments" obtained with various noise suppression techniques utilized during the test series. These results are shown for the "SSME's-only" configuration for the lower payload bay area. The baseline configuration, i.e., dry with unmodified ML, is shown as the solid line and it can be compared directly with the various noise suppression techniques indicated. As can be seen, the more elaborate concepts, or those used in combinations, exhibited the larger amounts of suppression. For example, the water ring (w_w/w_p = 5.8) with spray bar and trench grid combination (w_w/w_p = 4.1) indicates a large amount of suppression throughout the total frequency range presented. The OASPL decreased about 10 dB and the one-third octave SPL values decreased about 12 dB to 16 dB in the critical range of 30 Hz to 125 Hz. Of all the conditions tested to date in the SSME's-only configuration, this combination achieved the greatest amount of suppression. The total water requirement with the set of conditions is $w_w/w_p = 9.9$, i.e., approximately 243,000 gallons per minute. The water nozzle injection technique (see figure 9) is comparable to those configurations listed within the shaded area. Specifically, the configurations indicated by the shaded band are (1) full length exhaust trench cover (no ramp) see figure 7, (2) trench grid alone, $w_w/w_p = 2.84$, (3) spray bar alone, $w_w/w_p = 2.3$, and (4) combined spray bar and trench grid, $w_w/w_p = 3.86$, see figure 8.

The information in figure 19 was derived from all the tests utilizing (1) the horseshoe water injection device shown in figure 11, (2) the two separate portions of the horseshoe device herein noted as the "crest pipe" which lies across the SRB deflector crest and the side pipes which include the two parallel pipes of the horseshoe configuration, (3) the water ring, and (4) the tests involving the combination of the above suppression modes with the spray bar and trench grid. The suppression results from the horseshoe/crest pipe/side pipe water injectors were not as effective as the other modes noted in figure 19. The 4 dB reduction in the OASPL at a horseshoe water flow ratio of about 9 to 1 (w_w/w_p) is not significant in relation to that obtained by the water ring or combination test schemes where 11 and 13 dB, respectively, were noted for a 9 to 1 water flow rate. The data obtained for the ring/bar/grid combination were generally in the water flow ratios of $w_w/w_p = 7$ to 10. The suppression for the low flow range is estimated.

As can be seen, the effectiveness of the suppression modes here asymptotes at flow rates where $w_w/w_p =$ about 8 to 1. In several tests the crest pipe and side pipe configurations indicated that the suppression asymptotes at lower flow ratios, i.e., at about 3 to 1 for the crest pipe and about 2 to 1 for the side pipe.

It appears that water injection from one specific physical location is effective for some limited water flow rate. After that "plateau" is reached, the additional water does not appear to be effective in further reducing the vehicle environment. The addition of water at another location with respect to the flow, however, may offer more reduction in the acoustic environment.

The "SRB's-only" on-pad noise suppression results utilizing the basic horseshoe configuration (see figure 12) are presented in figure 20. The horseshoe technique is the only suppression method attempted for the SRB on-pad condition since it was effective and met KSC design and operational requirements. As can be seen from figure 20, a significant reduction in sound pressure level is achieved with this technique. The OASPL for the mid-payload bay area decreased 10 dB with significant reductions being indicated for all frequency bands, i.e., about 7 dB to 10 dB for the 30 Hz to 125 Hz frequency band. This amount of suppression was achieved with a "small" water-to-propellant flow ratio ($w_w/w_p = 1.7$) in comparison to the water flow ratios used for the SSME's-only condition. This water flow ratio of 1.7, although seemingly small, results in a required full-scale water pumping capacity of about 262,000 gallons per minute.

Three measurements were located on the orbiter aft heat shield; one near the center, one near the base of one lower engine, and one near the outer edge adjacent to a lower engine. The top band of data in figure 21 indicates the spread in the acoustic spectra for those three measurements for the on-pad baseline (dry) case where only the SRB's were fired. The lower data band indicates the reduced environmental levels with a water flow ratio of $w_w/w_p = 1.7$ on the SRB horseshoe configuration. A reduction in the OASPL is noted at about 15 dB, whereas the one-third octave band at 100 Hz is as much as 19 dB lower for that suppression case. A recent test of the SRB horseshoe indicated that a lower water flow rate of $w_w/w_p = 0.7$ yields little suppression for any of the orbiter areas. It appears that water flow ratios (w_w/w_p) of greater than one are necessary for significant reductions.

The reductions noted for the base heat shield using the water ring and combination schemes with only the SSME's firing were generally not more than 6 dB for the OASPL. This conclusion is compatible with the relative differences between the suppression results noted for the SRB and SSME horseshoe water injectors.

After lift-off, the orbiter's payload bay external environments are dominated by the SRB contribution with the exception of the higher frequency acoustic energy (above 1000 Hz). This trend is noted in figure 16 where the SSME's contribution (OASPL) is shown to decay rapidly after several seconds into flight. Since the environments are mainly due to the SRB exhaust contribution, which is increased by the impingement of the SRB exhaust on the top of the ML, greater suppression efforts are expended on the SRB portion of the problem. Figure 22 denotes the sound suppression effects for the one-third octave band spectra for various tests attempting to reduce the off-pad or inflight environments. The unsuppressed condition is noted by the data band labeled "Baseline." One mode of reducing the environment includes the condition where the degree of SRB exhaust impingement on the ML deck is minimal. If the SRB exhaust were kept within the SRB exhaust flow hole in the ML, the continued use of the deflector and exhaust trench could be beneficial in terms of environmental reduction and more so when water is also used. The two curves in figure 22 labeled "SRB Flow in Hole" relate to the condition where the model vehicle drift was not as prescribed for nominal missions but retained the vehicle altitude with an "artificial" or devised drift which prevented SRB exhaust core from impinging on the ML deck. Water injection via the SRB horseshoe configuration could be utilized if the drift permits the exhaust to remain in the ML hole even at vehicle elevations of 300 to 400 feet. Small reductions are noted for the dry case where impingement is prevented. The addition of water at $w_w/w_p = 1.7$ resulted in a 4 dB to 5 dB reduction.

The use of the top ring water injection device (see figure 14) which sits above the ML deck and down range of the SRB exhaust flow holes in the ML, indicates a reduction of about 6 dB to 7 dB with a water flow of $w_w/w_p = 2.5$. This configuration has potential refurbishment problems because of its "above deck" structural members and has other limitations with regard to the operation plans at LC 39. To minimize the refurbishment problems and to simplify operational plans and plumbing complexities, another mode of suppressing the lift-off environments was proposed by KSC. The geyser configuration employs a pair of pipes through the ML (ending flush with the deck) injecting water vertically in a position under where the vehicle will drift and where exhaust/water mixing could occur. This configuration is shown in figure 15 with water flowing vertically and diffused somewhat by a perforated "cap" over the pipe, designed to distribute water for optimal mixing. The data from these tests are not yet available but hopefully will provide some significant suppression for the lift-off condition where the low frequency energy is dominated by the SRB contributions.

During the initial portion of this test program, the definition of the baseline Shuttle acoustic environments, a series of tests was conducted with a small SRB opening in the ML, i.e., approximately 40% of the length of the current baseline SRB opening. The results of these "reduced SRB hole" tests indicated that the inherent Shuttle drift was such that it caused very early impingement of the SRB exhaust flow, and this caused the OASPL to increase dramatically. Attempts to further reduce the baseline SRB opening were then abandoned. The remaining tests in the "baseline" series were conducted with the large (baseline) SRB opening. Tests utilizing the large and small SRB opening resulted in varying amounts of impingement at different elevations, so the data from these tests have been utilized in an attempt to determine the sensitivity of the generated noise environment (OASPL) to vehicle altitude and degree of SRB exhaust impingement. The results of this analysis are presented in figure 23. Although a limited amount of data is available, the results do show a consistent trend with increasing elevation and percentage of impingement, and the general trend is considered to be indicative of the actual conditions for the mid-payload bay area.

The percentage of SRB exhaust impingement was computed by projecting the SRB nozzle exit plane onto the top surface of the ML deck. The resulting area of the SRB nozzle exit plane was computed and plotted as a function of the OASPL that was obtained for that elevation. The OASPL value for the on-pad condition is indicated at the zero percentage impingement point. It is clearly seen that a small amount of exhaust impingement from a low vehicle elevation results in very significant increases in the OASPL. As the Shuttle altitude increases, the effects of increased impingement become less. Even at full scale altitudes of about 200 feet, the effects of impingement are still important. The data points at 100% impingement delineate how the OASPL changes solely as a function of altitude. The lowest OASPL that could be achieved at this location is the free field condition or that set of conditions without any exhaust impingement interaction with the ML and/or ground plane. This free field level has been determined through tests, measured data, to be 146 dB OASPL.

As can be seen from figure 16, the overall sound pressure level time history peaks during the on-pad period for the external payload bay. The acoustic contribution from the SSME's dominates if suppression is not utilized. It is obvious that if the SSME-induced environment were radically suppressed, then the total resultant environment would be the sum of the SRB and that remaining SSME contribution. Thus, a total elimination of one contribution without some suppression of the other would still leave environments no less than that from the remaining source. Thus, the environmental contribution from each source, ideally, should be commensurate with the other, otherwise the more significantly suppressed acoustic energy cannot be realized since it will be "masked" by the other source.

Shown in figure 24 is the acoustic environment for the on-pad baseline case and that resulting from the best suppression approaches for the total SSV (SSME's and SRB's). The horseshoe used on the SRB side and the water ring/bar/grid technique on the SSME side result in the total SSV environment for the on-pad case. A reduction of 13.6 dB is noted in the composite OASPL and about a 17 dB reduction is observed for the 100 Hz one-third octave band. Also shown is the internal payload bay design criteria in spectral form with an OASPL of 145 dB. This suppression has been demonstrated via use of the noted techniques and requires only small reductions between the external and internal environments, gen rally termed "transmission loss" of the payload bay structure. It is seen that the internal criteria shown can be met with only modest transmission losses for the payload bay.

CONCLUSIONS

The various suppression modes covered herein for the KSC model launch system provide several candidates which have, indeed, demonstrated significant reductions in the engine-generated acoustic environments on the launch vehicle. At the time of this writing, no selection of a specific configuration has been made for use at KSC. Several options are available and the design and operational constraints as well as cost must be weighed to determine the best overall suppression mode(s). Decisions are to be made involving the necessary tradeoff studies and then design of full scale hardware should begin in the near future.

It is thought that the basic objectives of providing model tests for various alternatives or modes of environmental suppression for the vehicle has been successfully met. It is likewise thought that a full-scale suppression system can be developed from this model study to improve the environmental conditions, particularly for the payload bay, and that vehicle modifications are not likely needed nor will "hardening" of the payloads themselves be required.

Upon completion of this program, all model system specifications and a rather detailed synopsis of all data will be published in a form hopefully useful for other noise generation and suppression related efforts.

ACKNOWLEDGEMENTS

The authors would like to express appreciation to Mr. Bill Tolson of KSC for his valuable inputs related to facility design and operation requirements and constraints; Mr. E. Donald, test engineer for the model program at MSFC, for his long and dedicated efforts and invaluable aid in acquiring the quality data necessary from a program of this nature; Mr. J. Woo, Mr. R. Dandridge, Mr. G. Guret, Mr. B. Tidwell, Mr. M. Smith, Mrs. E. Love, and Mr. C. Corry for their valuable aid and assistance in obtaining and analyzing the vast bulk of data from this effort. Thanks is given to Mr. Frank Swalley for his overall guidance and coordination with all concerned.

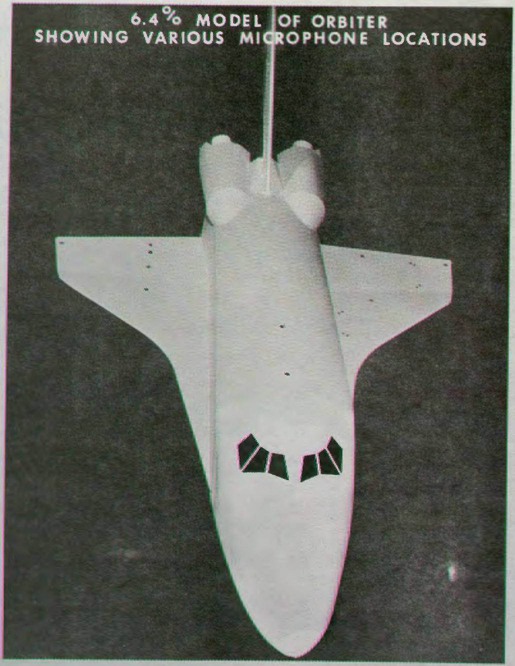
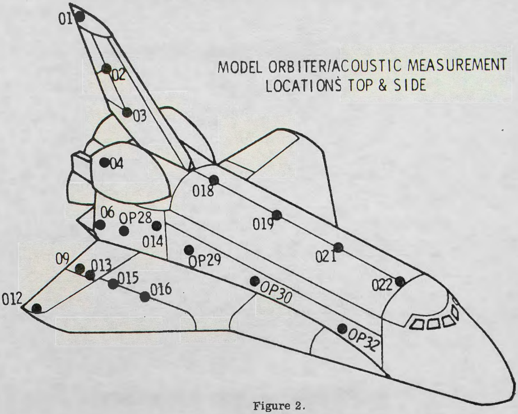


Figure 1.



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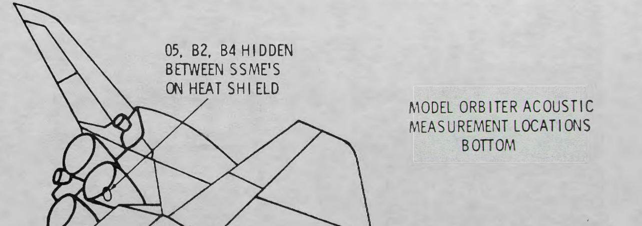
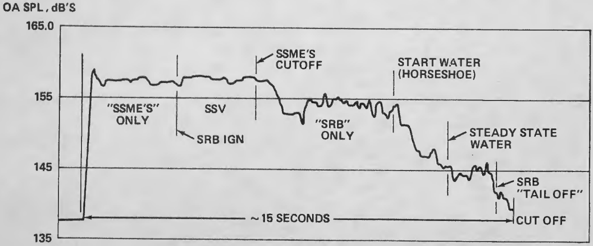


Figure 3.

SSV MODEL TEST-TYPICAL EVENT SEQUENCE



OVERALL SPL TIME HISTORY FOR MEAS. 018
LOWER PAYLOAD BAY

Figure 4.

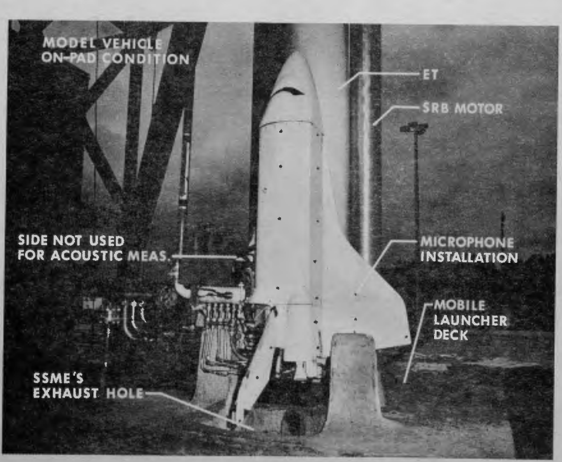
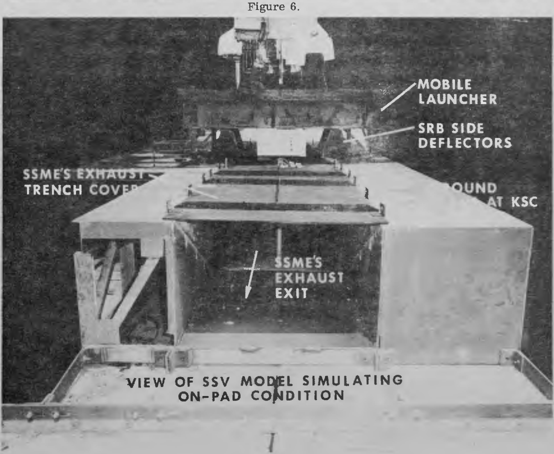


Figure 5.

Figure 6.



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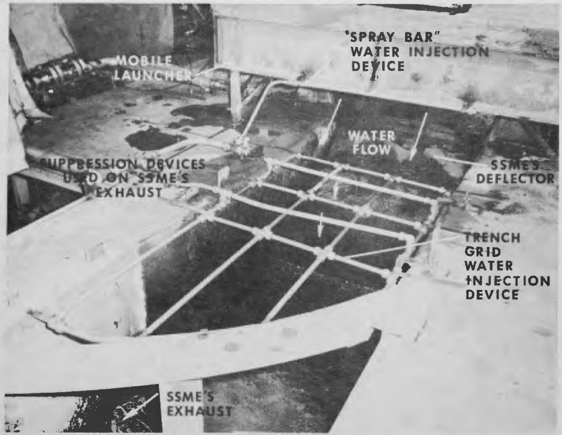

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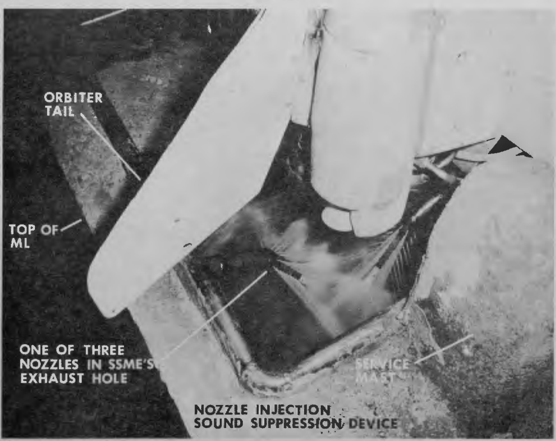

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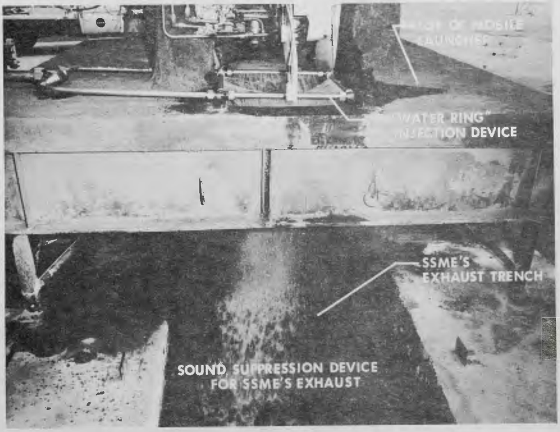

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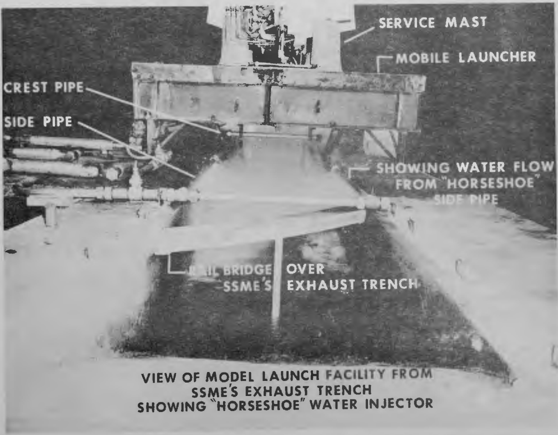


VIEW OF MODEL LAUNCH FACILITY FROM SSME'S EXHAUST TRENCH SHOWING "HORSESHOE" WATER INJECTOR

Figure 11.

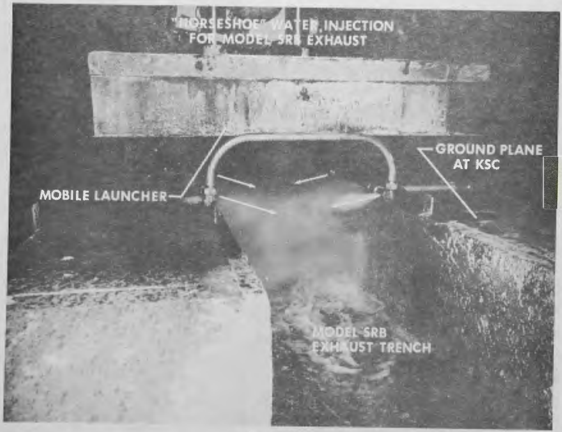
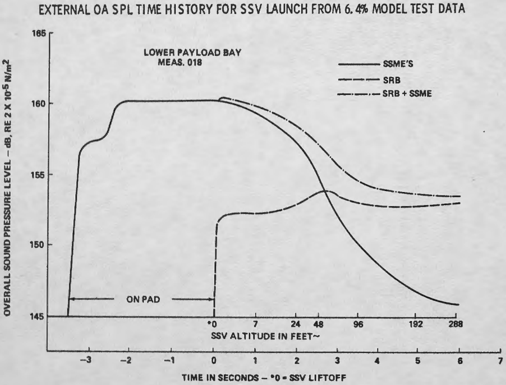


Figure 12.

Figure 13.

Figure 14.

Figure 15



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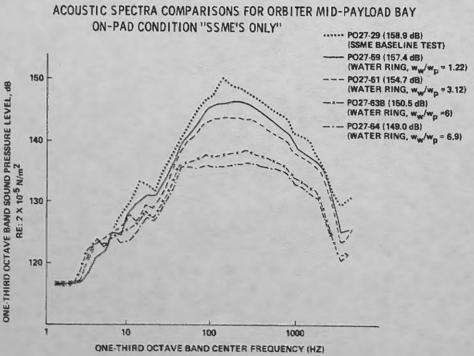

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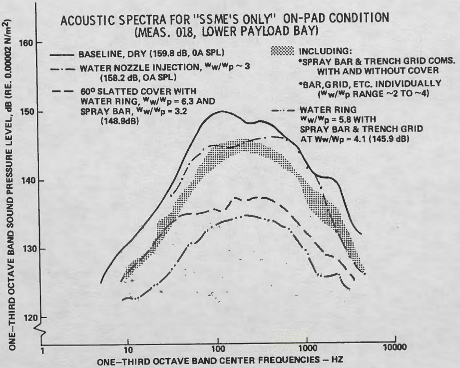

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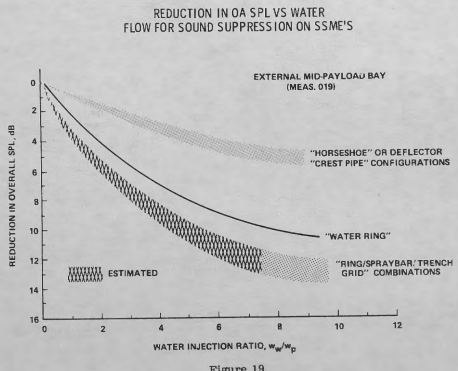

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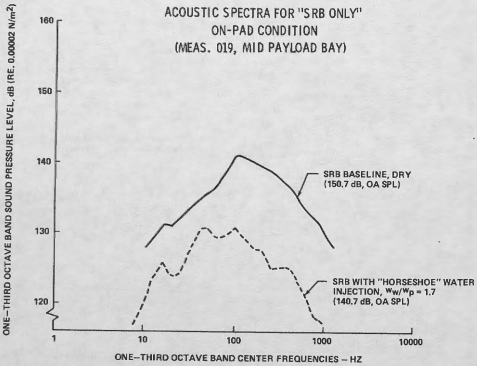

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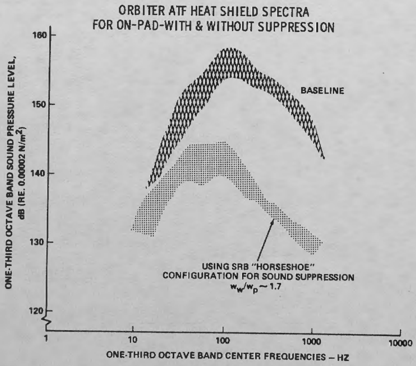

Figure 21.

ACOUSTIC SPECTRA FOR "SRB ONLY" SOUND SUPPRESSION AFTER LIFT-OFF
SSV AT 230 FT. ALTITUDE - (MEAS. 018 ON AFT PAYLOAD BAY)

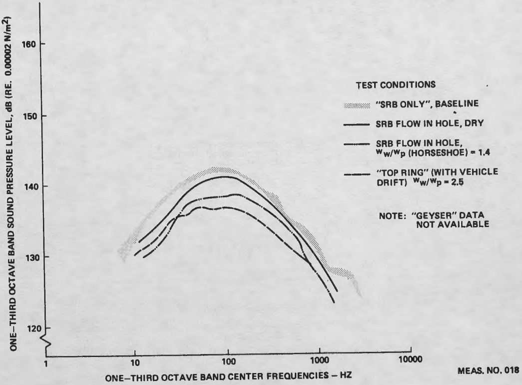

Figure 22.

ACOUSTIC ENVIRONMENTAL TRENDS GIVEN FOR VARIOUS VEHICLE
ELEVATIONS AND DEGREES OF IMPINGEMENT

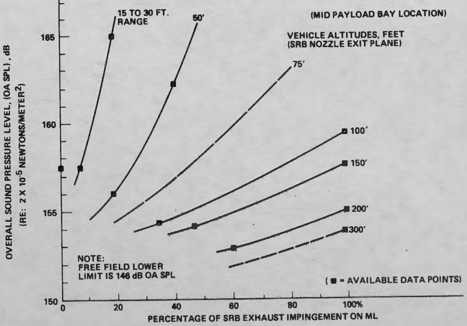

Figure 23.

COMPARISON OF SPECTRA FOR SSV BASELINE AND SUPPRESSION CASE FOR LOWER PAYLOAD BAY-ON-PAD CASE (MEAS. 018)

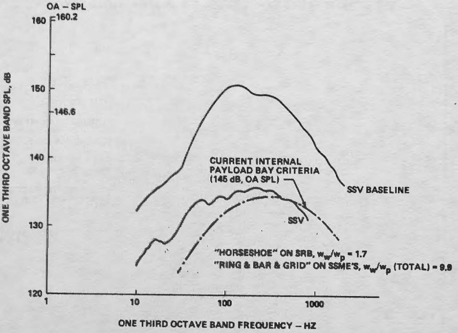

Figure 24.