SLS Ignition Overpressure-Sound Suppression System Performance Evaluated Against Historical Configurations

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During the start-up of a number of launch vehicles that include Solid Rocket Motors (SRM), the ignition transient and acoustic environments are mitigated by the implementation of a water spray system located immediately below the SRM Nozzle Exit Plane (NEP). For NASA's Space Launch System (SLS), this water system is referred to as the Ignition Overpressure Protection and Sound Suppression (IOP/SS) system. The SLS Induced Environments (IE) technical discipline conducted a comprehensive evaluation of the design and as-tested performance of the IOP/SS water that will operate underneath both Boosters during the Artemis I launch. As part of this evaluation, flow rates and imagery from a number of integrated launch pad / mobile launcher IOP/SS flow tests were studied. Additional insight was leveraged from the Space Shuttle heritage Sound Suppression Water System (SSWS) that includes data and imagery from a number of Flight Readiness Firings (FRF) and water flow tests. Lastly, the IE study included a qualitive comparison of the Space Shuttle and SLS systems to the equivalent water flow systems for Titan and Atlas V and determined that the NASA water flow systems are substantially different than those supporting other launch vehicles.

I. Introduction

Over the course of SLS development, a great deal of work has been performed to design and test the Ignition Overpressure Protection and Sound Suppression (IOP/SS) system to appropriately mitigate acoustic energy generated by the SLS vehicle during the final moments of the launch countdown and during the liftoff event itself, while also understanding and limiting the risk that such a system might pose to the vehicle itself. As a complex system of systems, the addition of one system to mitigate a risk may inadvertently create additional risk, and so any mitigation must be evaluated from an overall system of systems risk perspective, not just the perspective of the specific risk it is intended to mitigate. As part of this effort, experience from the Space Transportation System (STS, or Space Shuttle) was leveraged by taking into account the Space Shuttle heritage Sound Suppression Water System (SSWS) which brought 135 successful launches over the course of 30 years. Numerous STS SSWS water flow tests and on-pad engine firings, known as FRFs, also offered insights into the water sound suppression system and its interactions with the vehicle and pad. All these insights are particularly relevant given the obvious system similarities to the SLS architecture. That number is brought to 136 with the inclusion of the Ares I-X launch from the Constellation Program. However, despite extensive program history, it was surprisingly difficult to find details on all of the heritage water flow tests and FRFs. Those were surely documented, but in the transition from written to electronic documentation, finding those records was a significant challenge, and eventually boiled down to finding the right engineer that knew the right engineer that

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knew the right engineer who had a stack of video recordings and hand-written notes and memory of the testing. Had this been required in another 10 or 20 years, this effort would have been an even greater challenge, as those that were present in the late 1970s and early to mid-1980s move from graybeard to retirement, and from retirement to the rest that awaits us all. There is information, and in some cases, video recordings available across the internet, on the NASA website and on video platforms, but details about dates, objectives, configuration, and the events themselves is not always reliable, especially on outside video platforms. Some detective work was required. As a result of that effort and with the 30-years-from-now engineer in mind, the authors of this paper wanted to put in one location a description of testing performed for the SLS system and to provide some scope and details on the STS testing that was found during this process.

It is worth noting that other launch vehicles aside from STS were evaluated for the purposes of this effort. This included commercial launch vehicles currently or previously produced and flown in the United States, as well as developed and flown by foreign governments and entities. Several of these are analogous to the SLS configuration in either flow rate, nozzle configuration, and/or proximity to the engines and booster Nozzle Exit Planes (NEPs). In many cases, these details are either outright provided by the manufacturers of those vehicles in media presentations, press releases, and public relations videos, and as a result in the public domain. In other cases, details can be surmised or estimated based on what is available (e.g. the size of a booster or nozzle is known, and so the separation between that booster NEP and the water system can be estimated based on photography, or the total system flow rate is known and the number of water nozzles can be counted, so the flow rate/nozzle can be calculated). For the purposes of the release of this paper, these other vehicles are not named or discussed here.

II. Space Launch System Overview

NASA's SLS vehicle is the workhorse to propel Artemis missions to the Moon and beyond. The SLS Vehicle is comprised of multiple Elements that provide the propulsive power to launch the Orion space capsule far beyond low Earth orbit. There are two Solid Rocket Boosters (SRBs) on either side of the central portion of the vehicle. These Boosters are similar in design to the Boosters that flew on the Space Shuttle program. However, the Space Shuttle-era Solid Rocket Boosters only included four segments filled with solid propellant, while the SLS version of the SRBs has a fifth segment added to the middle of the stack. The attach points are also modified to connect to the Core Stage (CS) of the SLS Vehicle instead of attaching to the External Tank in the Space Shuttle configuration. The Core Stage of the SLS Vehicle is based on the Space Shuttle External Tank but is elongated along with a number of smaller design updates. It has a liquid hydrogen tank and a liquid oxygen tank that provide propellant for four RS-25 engines located at the base of the SLS Core Stage. Above the SLS Core Stage is the Interim Cyrogenic Propulsion Stage (ICPS) that provides the second stage propulsion through a liquid hydrogen tank and a liquid oxygen tank that feed a single RL-10 engine. Above the ICPS is the European Space Agency's European Service Module (ESM) and the Orion crew module. Atop the entire stack is the Launch Abort System (LAS) which provides an escape mechanism for the Orion crew capsule in the event of an abort condition. The LAS is jettisoned partway through the launch ascent process.

Fig. 1 Artemis I at Pad 39-B

III. Mobile Launcher IOP/SS Overview

The Mobile Launcher (ML) is a crucial component of the launch of an SLS Vehicle. The ML provides a number of critical functions to support launch: providing a platform for vehicle assembly, allowing crew and support personnel ingress/egress to the Orion Crew Module, forming the base and connection points for vehicle support and stabilization, and supplying power, gases, and cryogenic fluids to fuel and operate the SLS Vehicle. The ML also provides inert purge gases to prevent accumulation of hazardous gases that are produced by boiling cryogenic fluids. Another critical function of the ML is to provide the IOP/SS system water to a number of different locations in order to allow the SLS Vehicle to safely launch. The launch induces environments that are quite austere and must be accounted for in order to prevent damage to the SLS Vehicle as it lifts off and clears the ML Tower. The SLS is assembled vertically on the ML within the Vehicle Assembly Building (VAB) at the Kennedy Space Center Complex 39, and is rolled to Pad 39-B for launch via the crawler-transporter. Aside from the ML, which was built for the cancelled Ares I and modified for the SLS Block 1 configuration, all of these ground systems were built for the Apollo program, modified for the STS program, and again modified for the needs of the Artemis program. Pad 39-B provides several functions for the vehicle pertinent to mitigation of ignition and liftoff environments. A large water deluge system, which is fed by a water tower adjacent to the pad, is connected to a valve complex that feeds various systems on the pad. The water tower is filled by means of pumps, but flow to the ML is driven entirely by gravity head pressure. Details of the systems relevant to this topic are discussed below. The ML also provides a platform to gather imagery for pre-launch and launch activities, also discussed below.

A. Pad 39-B IOP/SS System

The Pad 39-B portion of the IOP/SS water flow system consists of a single large water tower and large diameter pipes that go through a valve complex before entering the ML via three large risers. The water flow system is split into two major components that direct water towards the various water nozzles on the ML and Pad 39-B. The first leg is referred to as the Ignition Overpressure Protection (IOP) water, which directs water towards the ring of IOP nozzles that direct flow underneath the four RS-25 engines and the Left-Hand (LH) and Right-Hand (RH) Boosters. The IOP portion of the pad water system also directs water to the nozzles on top of the Flame Deflector, with the water spraying down the Flame Deflector towards the North side of Pad 39-B. The IOP portion of the Pad 39-B IOP/SS water system is split into three legs that each include a valve (IOP Valve), and then those three legs reconnect before traveling into the ML. The three redundant valves ensure that IOP water is available even if one of the valves fails. The other major leg of the IOP/SS water system is the sound suppression water flow. Similarly to the IOP water, the sound suppression water is split into three legs in the Pad valve complex, with an Sound Suppression (SS) Main Valve on each of those three legs. Additionally, there is an SS Bypass leg that provides a smaller diameter flow that goes around the SS Main Valves. Given the tremendous amount of water that is required to flow through the SS portion of the IOP/SS system shortly after Booster ignition, the SS system is required to provide this initial flow via the SS Bypass valves. This allows the

Fig. 2 ML at Pad 39-B. Note the water tower to the northeast of the pad surface, with the valve complex just west of the base.

large-scale nozzles, called Rainbirds, to begin flowing water at a sub-peak flow rate. This initial sub-peak flow allows the system to more rapidly increase to the peak flow rate once the SS Main valves are opened just prior to liftoff. The timing of opening of each valve leg is determined to balance required flow rates to different areas of the ML to appropriately mitigate liftoff environments within the total capabilities of the system.

B. Ignition Overpressure Mitigation

The first major function of the IOP/SS water system is to dampen the ignition overpressure (also IOP) event. The Booster IOP represents the low-frequency response of compressed ambient air and plume gas as the plume is accelerated into the trench below. Rapid compression leads to a relatively large amplitude transient pressure wave that travels up the vehicle, where the amplitude is partly governed by the rise rate of the Booster chamber pressure. The portion of the large compression wave exiting the top of the exhaust hole moving up the vehicle is termed IOP, which is mitigated by a pre-launch water system, so called because it activates prior to liftoff. The Ignition Overpressure Protection water nozzles form a ring around the Blast Hole (or Exhaust Hole or Flame Duct) located in the center of the ML Zero Deck (top level of the ML main structure, which forms the base platform for the ML Tower). Two Booster plumes and four RS-25 engine plumes are directed downward through the center of the Blast Hole towards the Flame Deflector and Flame Trench, which directs the plumes down and out towards the north portion of Pad 39-B. There are six Ignition Overpressure Protection water nozzles that direct water under each of the two Boosters. The RH Booster is located on the East side of the SLS Vehicle and the LH Booster is located on the West side of the SLS Vehicle. There are a number of smaller IOP nozzles located in two rows on either side of the RS-25 engines; one row is on the north side of the Blast Hole facing south and the other row is on the south side of the Blast Hole facing north. Collectively, these Ignition Overpressure Protection nozzles suppress the IOP event(s) to a manageable level. Also, part of the Ignition Overpressure Protection portion of the IOP/SS water system are the water nozzles located on the top of the Flame Deflector. They serve a role in dampening the IOP and acoustic environments but also help protect the Flame Deflector from the multiple impinging plumes during liftoff.

C. Sound Suppression

The second major function of the IOP/SS water is related to sound suppression of the acoustic environment following Booster ignition during liftoff. The acoustic levels from the SRB are sufficiently large to damage critical portions of the SLS Vehicle during liftoff if they are not dampened out by the IOP/SS water system. The acoustic environment is particularly problematic to SLS hardware shortly after liftoff when the SRB plumes are able to impinge on the ML Zero Deck and send acoustic waves back up to the SLS Vehicle. The hard, metallic flat surface of the Zero Deck is particularly efficient at acoustic reflections. This acoustic reflection issue is exacerbated if there are cross-winds that cause the SLS Vehicle to drift in the timeframe between Booster Ignition and Tower Clear, causing additional plume impingement on the deck of the ML. The SS portion of the IOP/SS water comes from five massive water nozzles located on the Mobile Launcher Zero Deck that are called Rainbirds (RB). There is a Rainbird located at the southwest (SW) corner, northwest (NW) corner, north center (NC), northeast (NE) corner, and southeast (SE) corner. Collectively, these five Rainbirds discharge an incredible amount of water across the ML Zero Deck. The airborne water droplets and the accumulated water on the ML Zero Deck work in conjunction to help suppress the acoustic reflections that otherwise would pose a significant hazard to the launching SLS Vehicle. The design of these rainbirds is not dissimilar to the rainbirds that may be found in a home irrigation system, albeit at a significantly different scale.

NASA Marshall Space Flight Center (MSFC) performed the SLS Scale Model Acoustic Test (SMAT) with a 5% subscale SLS Vehicle, Pad, and ML with representative Rainbird nozzles in order to verify the required Rainbird flow rates. The total Rainbird flow rate is defined at several instances at Booster ignition and during the liftoff phase. This assures there is sufficient SS water present to suppress the acoustic environment, preventing damage to critical components of the SLS Vehicle. The overall goal of the water flow tests described in this paper is to verify that the ML is able to provide the required amount of water to the right locations during a launch of the SLS Vehicle.

Fig. 3 Sound Suppression Rainbirds for Integrated System Validation and Verification-14, Test Event 4-1.

D. Hydrogen Burn-Off Igniters

The start-up of the four RS-25 engines involves a small amount of lead hydrogen that exits the engine nozzle before the start-up is complete. This hydrogen gas has the potential to accumulate in sufficient quantities that a subsequent ignition could lead to a combustion event sufficient to produce a damaging shockwave. This hydrogen gas must be ignited and burned off before it is able to accumulate in sufficient quantities. This ignition process is accomplished by the Hydrogen Burn Off Igniters (HBOIs). Several of these HBOIs are directed at the exit plane of each of the RS-25 Core Stage engines, which quickly ignite the lead hydrogen gas emitted during RS-25 start-up. In the event of an on-pad shutdown, these HBOIs are also crucial for igniting the hydrogen gas that lags the shutdown of an RS-25 engine. There are also several exhaust ducts on the base of the SLS Vehicle that emit pulses of hydrogen gas. These are the Core Auxiliary Power Unit (CAPU) exhaust ducts. There are several HBOIs directed at these CAPU exhaust ducts in order to provide a similar function of igniting the hydrogen gas before it is able to accumulate in a potentially dangerous quantity. The IOP/SS water is sprayed in close proximity to these HBOIs. As such, much care is given to assure that the IOP/SS water is able to perform its functions without directly impinging on the HBOIs or their spray of burning particles. This is one of the constraints for the IOP/SS water, both in terms of total water flow rate, placement and relative valve opening timing.

E. Mobile Launcher Zero Deck Imagery

Another critical function of the ML is to provide imagery assets in order to view the SLS Vehicle during cryogenic propellant loading and during liftoff, when a number of events are occurring in close succession. The standard-speed video cameras are called Operational Televisions (OTV) and there are also a number of high-speed film cameras that capture liftoff events with a high dynamic range. Additionally, there are several high-speed digital cameras on the 30 ft level of the ML Tower that look down at the ML Zero Deck. The imagery assets located on the Zero Deck are critical to resolve liftoff related events, as well as capturing events that would occur during an on-pad shutdown of the RS-25 engines. The five Rainbirds throw significant amounts of water over and across the ML Zero Deck, which poses a visual obstacle for the operation of imagery assets. Direct impingement of the Rainbird water on the imagery assets removes their ability to resolve the launch events in their field of view. Additionally, Rainbird water can sometimes be thrown over an imagery asset without direct impingement, but still precludes resolution of the intended field of view in the timeframe of interest. While potentially losing the imagery assets during a launch does not necessarily preclude a successful mission, these imagery assets are critical to understand the multi-layered launch dynamics which inform resolution of potential hazards to the vehicles. There are a number of events and potential hazards that need to be properly captured during an SLS launch in order to inform potential design and/or operation changes for subsequent missions in order to ensure a safe and successful launch of NASA's astronaut crew on Artemis missions. And in the off-nominal event of an on-pad shutdown, the imagery assets are required to verify successful shutdown of the RS-25 engines and to identify potential hazards existing on the SLS Vehicle and ML. Thus, the Rainbird water throw is limited by its impact on critical ML Zero Deck imagery assets in a similar manner to the considerations for their effect on HBOI efficacy.

F. Off-Nominal Operations

Given the necessity of opening the IOP/SS valves prior to Booster ignition, there are several scenarios in which the IOP/SS water flow system operates while the SLS Vehicle remains on the pad in the event of an on-pad shutdown. Once opened, all of the IOP/SS valves are unable to be closed until the Pad 39-B water tower is drained. The first scenario would be if the IOP valves are opened prior to an on-pad shutdown. This is the most benign scenario, as the IOP ring nozzles and Flame Deflector nozzles are able to drain the water tank without interfering with the SLS Vehicle while it is safed. The second scenario would be an on-pad shutdown while the IOP valves and SS Bypass valves have been opened. In this scenario, the lower flow rate would exit the five Rainbirds in addition to the IOP ring valves and Flame Deflector nozzles. This scenario is less benign, as the Rainbird flow rate is still quite high even with the SS Bypass flow rate, and this poses a potential issue with obscuring deck level imagery, impacting the SLS Vehicle, and inhibiting the performance of the HBOIs that are required to mitigate the unburned hydrogen gas that is emitted from the CAPU exhaust ducts and RS-25 engines during the safing process. The final scenario is the most problematic—an on-pad shutdown after the SS Main valves have been actuated. The high flow rates from the Rainbirds once the SS Main valves are opened results in a potential for direct impingement of the SLS Vehicle for a short period of time before the IOP/SS water has drained. The SLS program asked each impacted Element to assess the potential risks to hardware in the event of a ’vehicle deluge’ scenario, and was able to accept the risk to the Vehicle, traded against the need to open the main valves prior to T-0 to provide sufficient water for acoustic mitigation during a nominal launch while still allowing for one of three main valves on the IOP/SS system to fail to open. Part of this risk evaluation included looking at the extensive RS-25 flight history from the STS program to estimate probability of an on-pad shutdown being necessitated in the final moments of the countdown, as well as options for repair and replacement given hardware on hand for future missions. There is ongoing work to eliminate the potential for a vehicle deluge or to decrease the impacts of this type of on-pad shutdown scenario, part of which is included in the Artemis II testing discussed below.

IV. Artemis I ISVV-14 Test Series

The Artemis I Integrated System Validation and Verification (ISVV) – 14 test series was performed in 2019, and was the first integrated water flow test series for Pad 39-B and the ML built to support Artemis missions. This was a test series to verify performance of the IOP/SS system fully integrated with Pad 39-B. This would include verification and, where necessary, adjustments to the system to balance the needs of the IOP and SS water systems for flow rates and timing and the needs of necessary imagery assets and HBOI systems, as discussed above. There were several issues of concern to adjudicate and balance as part of this testing.

The ISVV-14 test series included a number of flow events to test various launch scenarios and to allow the system to undergo water balancing. Water balancing is a process in which the flow rates to individual nozzles or series of nozzles are tailored via changes to orifice plates (OP) or changes to valve opening timing. The SLS program has set flow rate requirements at various instances throughout a nominal launch process in order to safely operate the SLS Vehicle. The water balancing process allows each of those flow rates / launch timing pairs to be accomplished. Water flow balancing has been historically performed by NASA for previous programs such as Shuttle.

A. ISVV-14 TE1-1

The first flow for ISVV-14 was Test Event 1-1 (TE1-1), which was performed on July 2nd, 2019. This was the first successful test of the integrated IOP/SS system for support of the Artemis campaign. This inaugural test did not meet the majority of the flow rate requirements due to initial over-restriction of a number of orifice plates as well as the relative timing between the three sets of valves in the valve complex. An additional driving factor was that the SS Main valves were not opened until T-0 secs in this test flow. It was also clear that too much water was flowing through the Flame Deflector nozzles, which decreased the flow rates for the nozzles located higher up on the ML itself. The other complicating factor was the interference of the Rainbird water with the HBOIs and imagery assets on the ML Zero Deck.

B. ISVV-14 TE1-2

The second test flow, TE1-2, was performed on July 25th, 2019. This test included a number of system improvements such as water dams to protect the north HBOI installation, so called because they block water from the deck flowing over top of the HBOIs. The IOP ring flow was also increased by removing the orifice plates within the ring. The north center Rainbird was restricted in flow rate using an orifice plate. The four corner Rainbirds were each clocked slightly in order to throw SS water over the ML Zero Deck in more ideal locations. The most substantial change was moving the SS Main valve opening timing to pre-Booster ignition, which would create the potential for a vehicle deluge scenario that is discussed above. Overall, TE2-1 exhibited significantly improved overall performance over TE1-1 as a result of the improvements listed above.

C. ISVV-14 TE1-3

The third test flow, TE1-3, was performed on August 10th, 2019. Prior to this flow test, additional alterations were made to the IOP/SS water flow system, including improvements to the north HBOI water dam. The water flow to the Flame Deflector nozzles was restricted through addition of an orifice plate. The north center Rainbird was further restricted via a smaller orifice plate. The SS Bypass orifice plates for the three valves in the Pad Valve Complex were opened up, which allowed a higher SS Bypass flow rate in order to jump-start the ability of the system to reach peak SS flow once the SS Main valves were opened. A number of additional changes were made to IOP Main, SS Bypass, and SS Main valve opening timings in order to account for the need times for various flow rates for the respective water delivery systems. This flow test was a SS Bypass run-out test, which opened only the IOP Main Valves and the SS Bypass Valves. Thus, this test provided a confirmation of the peak flow and timing associated with the higher SS Bypass flow achieved by opening up the orifice plates in the valve complex. It also served as test for an on-pad shutdown prior to SS Main Valve opening.

D. ISVV-14 TE1-4

The fourth flow test, TE1-4, was performed on August 11th, 2019. Compared to TE1-3 the day before, there were no hardware changes to the IOP/SS system and no changes to valve opening timing for the IOP Main Valves and SS Bypass Valves. The only change for TE1-4 from TE1-3 was that the SS Main Valves were actuated and the system operated according to a nominal launch timeline. The overall results for this test were significantly improved from the first two flows (TE1-1 and TE1-2) but the overall SS flow rates were still clipping the requirement. Another potential issue was that the south HBOI installation was also observed to become overwhelmed by SS water. The impacts to the north HBOI installation were significantly improved from the initial tests, but the ML Zero Deck imagery assets were shown to be obscured at non-optimal times in regard to the nominal launch process.

E. Hurricane Dorian

Before any additional testing could occur, a hurricane threatened Florida’s Space Coast. Hurricane Dorian was predicted to significantly impact Kennedy Space Center. The decision was made to perform a ML rollback to the VAB in order to preclude excessive wind loads and potential damage to the system. The rollback was performed on August 30th, 2019. Hurricane Dorian did not cause excessive damage to critical infrastructure when the ML was safely stowed in the VAB. Shortly after post-hurricane damage assessments and repairs were enacted, the ML was able to be safely returned to Pad 39-B in order to complete the ISVV-14 testing process.

F. ISVV-14 TE2-1

The fifth flow test, TE2-1, was performed on September 13th, 2019. As with previous flows, a number of improvements had been incorporated into the system using the results of the previous test flows, TE1-3 and TE1-4. The overall flow from the Rainbirds was improving but came at the detriment of critical Zero Deck level imagery assets. Thus, the northeast Rainbird, southwest Rainbird, and southeast Rainbirds were restricted through implementation of smaller orifice plates. Additional improvements were made to the north HBOI water dams, and a set of south HBOI water dams were added as well. Lastly, final tweaks were made to the valve opening timing sequence. The TE2-1 flow served as a test of a potential 2-of-3 IOP Main Valves in order to demonstrate the ability of the system to withstand a failure to actuate one of the IOP Main Valves prior to launch.

G. ISVV-14 TE2-2

The sixth flow test, TE2-2, was performed on September 14th, 2019. Compared to the TE2-1 test from the day before, there were no changes made to the IOP/SS system or valve timing, other than opening all three of the IOP Main Valves. This test simulated a nominal launch environment. This test demonstrated a significantly improved performance of the integrated IOP/SS system in regard to flow rates, HBOI interactions and ML Zero Deck imagery asset interaction.

H. ISVV-14 TE4-1

The seventh and final flow test, TE4-1, was performed on October 12th, 2019. This was a repeat of the IOP/SS configuration and valve opening timing that was demonstrated in TE2-2. Models for the expected performance of the IOP/SS system for Artemis I were able to utilize flow data from both TE2-2 and TE4-1. The only addition to TE4-1 was the inclusion of HBOI activation on both the south and north HBOI locations. This test allowed the team to observe the as-installed spray patterns of the HBOIs and to accurately characterize the influence of the IOP/SS water on these two HBOI locations. The TE4-1 test was able to successfully demonstrate HBOI operation in a nominal launch environment.

Fig. 4 ISVV-14 TE4-1.

I. ISVV-14 Follow-On Efforts

The overall ISVV-14 test program was a success in order to prepare the ML for the eventual Artemis I launch of the SLS rocket. There were two lingering issues associated with the IOP/SS system. The first was related to the potential for a vehicle deluge if an on-pad shutdown was required after the SS Main Valves were actuated. The second was a clip to the minimum total Rainbird flow requirement. The requirement clip was waived for the first, uncrewed launch of SLS but plans were enacted to improve the IOP/SS system in the interlude between Artemis I and Artemis II. The ongoing Artemis II ISVV-2 test series is the implementation of that plan. Additional work is being done in order to prevent and/or mitigate the hazards associated with a vehicle deluge scenario.

V. Ignition Overpressure Protection Water Assessments

An area of particular interest in the ISVV-14 water flow test series was the interaction of the IOP water underneath the RH Booster and LH Booster. These IOP nozzles each emit a fan of water that overlaps with the other IOP nozzle sprays only a short distance underneath the Booster NEP. A potential hazard was noted with this configuration, related to the potential spray of water entering the Booster nozzle cavity volumes prior to Booster ignition. The expanding hot gases from the developing Booster plume could interact with the water inside the Booster nozzle, causing the potential for non-axisymmetric, damaging loads. The original concern was if the as-welded Booster IOP water nozzles and associated maximum flow rates would result in sustained geysers into the Booster nozzle volumes. The results of ISVV-14 indicated that there were no sustained geysers that would enter the Booster nozzle volumes. However, the IOP water sprays from the various Booster IOP water nozzles could result in temporal splashes of water that enter the Booster nozzle volumes before falling back into the main water spray. Most of the splashing that made it high enough to meet or exceed the Booster NEP was outside the circumference of the Booster nozzles, closer to the outer wall of the ML Blast Hole surrounding each Booster. The Booster IOP nozzles themselves were not aimed up into the Booster nozzle volumes, but the interactions between adjacent water sprays and even adjacent IOP nozzles created the observed upward splash behavior.

A. Ignition Overpressure Protection Water Splashes

A substantial effort was made to characterize the splashes that could enter the Booster nozzle volumes. It should be noted that all ISVV-14 tests did not incorporate the integrated SLS Vehicle, requiring imagery analysis to digitally place a representative Booster nozzle in the correct position. This process was further complicated by the locations of the ML Zero Deck cameras. There were a number of imagery assets looking down and in towards the IOP water under the RH and LH Booster locations, but there were no views available for the in-plane component. Note that the post-Artemis I IOP/SS water testing series, ISVV-2, included 4 haunch located imagery assets that were able to address this issue. NASA investigated a number of measurement techniques to capture the quantity of water splashes in the Booster nozzle volume. However, none of these techniques were feasible to implement given the sheer size of the ML Blast Hole and the SS water deluge coming from all sides with the five Rainbirds that operate simultaneous to the IOP ring water spray. An additional idea was broached to include a representative mock-up of a Booster nozzle with additional sensors inside the nozzle volume. However, this system would pose a potential foreign object debris (FOD) hazard and was considered to interfere with the overall goals. Thus, the splash characterization was limited to imagery-only.

Another complicating factor for characterizing these IOP water sprays was that the water sprays that went high enough to enter the Booster nozzle volumes were diffuse sprays, as opposed to geysers or cohesive 'ligaments' of water. Thus, the imagery of these splashes had to differentiate between the spray inside the Booster nozzle volume and the spray that was located lower but still in the same field of view for a given imagery asset. The best option to address this was to create synchronized videos from multiple angles that included a digitally added Booster nozzle in order to determine which splashes were in the critical volume.

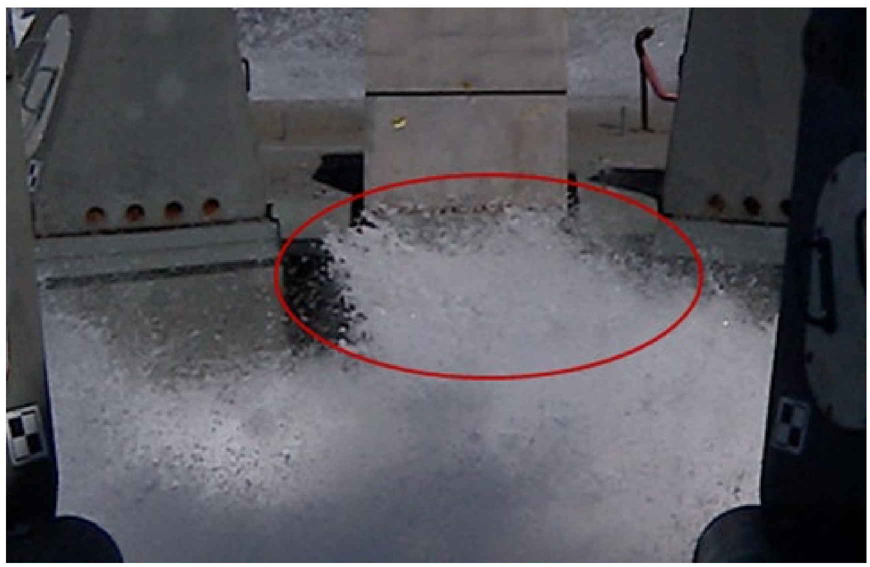

Fig. 5 Ignition Overpressure Protection Water Splash in ISVV-14

B. Ignition Overpressure Protection Splash Volumetric Assessments

Additional imagery work was done to define the volumes associated with the splashes that could enter the Booster nozzle volumes. These volumes were then correlated to the geometry within a Booster nozzle so that the analysis teams could assess the impact of the water volume in those specific locations. Another item of interest was the proximity of the splashes to the inside edges of the Booster nozzles. One factor that was not able to be included in either the ISVV-14 and ISVV-2 test series is the influence of entrainment from the four RS-25 engines that are started prior to Booster ignition.

VI. Leveraging SLS and Historical Tests to Establish and Strengthen Flight Rationale

The flight operation of the SLS IOP/SS is a complex mix of geometric, fluid, and acoustic interactions. Prior to the moment of Booster ignition at T-0, the water for the IOP rings begins flowing and interacting with each other and the surrounding pad, and in some cases, vehicle geometry. At approximately T-6 seconds, the RS-25s begin to ignite, adding multi-phase flow and significant gradients to what was water sheets, sprays, and mists, as well as significant entrainment of surrounding air. Finally, at T-0, the SRBs ignite in an event that is short lived in real time, but defined by events that are predictably spaced and heavily influenced by shock passage and plume development in discrete partitions of a fraction of a second. Many tests and simulations were executed to quantify the performance of the system of systems, but each was only a partial model. The only practicable test to observe the full system of systems interactions, performance, and behavior, was the Artemis I launch itself, because it requires water flowing from the IOP/SS system, with the vehicle in place, with RS-25s firing in the runup to launch, and the SRB ignition itself. To develop flight rationale and quantify the risk of having the first all-up test of the IOP/SS system on the first launch of SLS, all of the available partial models were utilized to fill in the evaluation space.

Although FRFs have been executed on similar launch vehicles (including, notably, the STS), such a firing comes at significant risk and often requires modifications (e.g., re-directed water or a shorter duration engine firing) which limit their usefulness for such a study. Additionally, an FRF would not provide the final event in the IOP-vehicle system timeline, which is Booster firing itself. With the cost of using two Boosters aside, the launch pad configuration at Pad 39-B is not designed to withstand the significant plume heating, loads, and acoustics that the SRBs would generate for the ~120 seconds they will fire. It is instead designed to withstand those environments during the liftoff event, which lasts only for several seconds as the vehicle rises away from the pad. Although full scale firings of the SRBs are executed, they are performed in a horizontal position, with no direct impingement from the plume on any surface. As a measure of the severity of these environments, the sand aft of the booster during such firings turns into glass.

Computational fluid dynamics (CFD) was certainly utilized to qualitatively understand the environment. However, because of the multiphase, multispecies flow characteristics of the water (of varying density with respect to air mixing), RS-25s, SRB plumes, and complex geometry in short spaces of time, CFD has limited usefulness in this area. There have been significant advances in the capabilities of various codes over the course of the SLS program, but it is still a phase of flight which necessitates significant grounding of those computation results to test.

Ultimately, many assessments were performed and tests leveraged in order to develop flight rationale. A tool called the 7-elements of flight rationale was utilized in order to quantify the risk and objectively develop rationale to move into first flight without an all-up test. This is an engineering tool that assesses the strength of seven different criteria: solid technical understanding, condition relative to experience base, bounding case established, self-limiting aspects, margins understood, assessment based on data/test/analysis, and interactions with other elements/conditions. The total assessment undertaken was able to strengthen the condition relative to experience base, self-limiting aspects, assessments based on data/testing/analysis, and interactions with other elements/conditions. This assessment included tests performed by the Artemis Program, described in the SLS Primary Data Sources Review, and tests performed by other launch vehicle programs, described in the Historical Data Sources Review.

A. SLS Primary Data Sources Review

Aside from CFD and other computational analyses, four main tests were utilized to partially model and understand the IOP/SS-vehicle system of systems interactions and performance. The initial IOP/SS system water flow rate requirements were based on the maximum expected capability of the IOP/SS system. The SMAT program operated with equivalent water flow rates and used to develop the initial acoustic environment specifications. The remaining three were the ISVV-14 test already discussed in detail above, the Core Stage Green Run, and the SRB Flight Support Booster (FSB) 1 test. These three are referred to as primary data sources for SLS because they are tests performed using SLS hardware in a manner consistent with the SLS launch configuration. Variations from that configuration are due to limitations of the test to include the total system, either because it was not practicable or was not the main purpose of the test. For example, the ISVV-14 test series was intended to exactly replicate the flow system and conditions used during launch, but lacks the launch vehicle, and so is only a partial model. As already discussed, ISVV-14 was performed between July 2nd and October 12th, 2019, including real time and high-speed video captured from 28 different cameras, and were useful for characterizing the IOP/SS system performance itself.

The FSB-1 test was performed on September 3rd, 2020 at Northrop Grumman Innovations Systems in Promontory, Utah. A horizonal test stand was utilized with a full scale SLS SRB. This test stand has been utilized for STS, Constellation, SLS, and commercial programs to test large scale solid rocket motors. For SLS, demonstration, qualification, and flight support boosters have been fired, the latter series of which was intended to test various technologies or conditions that may be needed for a better understanding of the system in its current or future form. FSB-1 in particular included a secondary test objective to measure response of the Booster in the event of water being present inside the nozzle during firing. This test was intended to be a bounding case, and provided useful imagery and loads data to quantify system capability and to understand the physical phenomenon. This test provided insight to the performance of the Booster with respect to proximity to water, but was a partial model because it was performed in the horizontal orientation, without the ML and Pad, IOP/SS system, and the Core Stage.

Fig. 6 FSB-1 Booster.

The Core Stage Green Run was intended to test out and prove the performance of a fully integrated and tanked SLS Core Stage with full duration firing of the RS-25 engines. This included several throttle levels as well as gimbal profiles. This test was performed at the Stennis Space Center in the B-2 test stand. This test stand was built for the Apollo program, and was again utilized for the STS Main Propulsion Test Article (MPTA) testing, and most recently was used for the Artemis I Core Stage Green Run Campaign. After several wet dress rehearsals, two hot fires were conducted. The first, performed on January 16th, 2021 was aborted early. The second was fully successful and ran for approximately 8 minutes, on March 18th 2021. The B-2 test stand did include a sound suppression system, but the requirements for that system are very different from those on the ML at Pad 39-B during an SLS launch. In some ways, the environment experienced by the B-2 test stand is more severe, because it features a full duration burn of the four RS-25s. The duct is approximately twice the diameter as the ML exhaust hole, the water nozzles are smaller and more plentiful, and direct water straight out, though total flow rate is consistent. The biggest differences are that the NEP separation is much greater, and it lacks the SLS Boosters. This test was leveraged for the purposes of IOP/SS evaluation because, although the sound suppression system at the B-2 test stand is a different configuration from the ML (i.e., different nozzle orientations, different distance from the RS-25s, different plume hole, and different flow rates), it does provide an opportunity to observe the SLS Core Stage configuration with RS-25 plumes in proximity to a large flow rate water system. The differences in flow system and lack of Boosters makes this a partial model. This test showed two things of interest: 1.) the RS-25s do, as expected, behave as ejectors and very quickly entrain and remove water spraying above an access platform that is roughly similarly located to where the Booster NEPs are (prior to reaching full engine power level) and 2.)

Fig. 7 B-2 Test Stand Sound Suppression System.

visibility through the HBOI particles and RS-25 plumes can be expected to be sufficiently clear to observe Booster IOP rings and the NEP from the haunch cameras on the ML. This test also provided the ability to measure entrainment velocities of water droplets and HBOI particles, both manually and particle trace algorithms developed by NASA MSFC for plume soil interaction. The entrainment was clearly noticeable, and extended beyond the boundaries of the test stand in the area of the NEPs. One other observation is that the plume-induced entrainment, in addition to the large downward dynamic pressure force opposing upward splashes of the sound suppression system, increases Weber number leading to further breakup of coarse water droplets into a finer mist.

Fig. 8 Core Stage Green Run with sound suppression system active prior to ignition (above), and shortly after RS-25 startup where water is fully entrained (below).

B. Historical Data Sources Review

As discussed in the introduction of this paper, a number of launch vehicles across the Space Force portfolio (both current and retired) were evaluated, but will not be discussed in any detail in this paper. However, use of water for ignition overpressure mitigation and sound suppression has been common in the launch vehicle industry for many decades and has proven to be effective with no safety-of-flight incident observed as a result of its use. There are also several launch vehicles that could be considered analogous for the purposes of IOP/SS system evaluation. These are vehicles that fly with a liquid core and a number of solid rocket motors, with core engine and booster NEPs in close proximity to each other and to suppression system water. Some of these vehicles feature smaller boosters than what are used by SLS, but there are vehicles with boosters on the same order of magnitude. Some of these feature larger distances between the NEP, but are on the same order of magnitude, and some of these also feature flow rates that are consistent with the SLS system.

Two systems were heavily leveraged, both because of availability of detailed data, and because of analogous configuration: STS and Ares I-X. STS flew 135 total missions, all of which were successful from the perspective of launch and liftoff acoustic mitigation. Ares I-X could be considered a 136th flight, because although it lacked RS-25s and a second booster, it did utilize a first stage derived from the STS SRB, and did launch from an STS mobile launch pad (MLP), with the STS SSWS left unmodified.

There are several key differences that limit the analogy however. Proximity from the water to the RS-25s, and RS-25s to the booster NEPs is different. SLS uses four RS-25s at the base of the Core vectored straight down, where RS-25 and booster NEPs are nearly in line with the engines. STS used three RS-25s, vectored slightly to the side at the aft end of the Space Shuttle orbiter, which was hung off the side of the external tank. The Space Shuttle engines were positioned well away from the engine exhaust hole, Boosters, and SSWS, whereas SLS engines were in very close proximity

Fig. 9 STS and Ares I-X Sound Suppression Water Systems as Analogy for SLS.

to the IOP/SS water system. Additionally, the MLP plume exhaust holes are split into three separate holes (one for each booster and one for the RS-25s), whereas SLS has one hole for all Boosters and engines. Furthermore, the nozzle configuration within the SRB exhaust holes is different in design from the SLS configuration, which results in less water sheet-to-water sheet and water sheet-to-geometry interactions for STS (i.e., for flights subsequent to STS-1, the water was distributed in two spray layers beneath each booster NEP, whereas for SLS the water flow was combined into a single spray layer). As a result, data collected from the 136 flights from the MLP is also only a partial model.

The SSWS has many similarities to the SLS IOP/SS system. It utilizes the same water tower and valve complex, though the SS leg did not feature the by-pass valve system and only used main valves. The water flowed from the valve complex to the pad via the same risers up to the MLP, at which point it was distributed to IOP water nozzles in each of the three exhaust holes. Rainbirds for sound suppression were activated at liftoff to mitigate acoustics during liftoff that reflected off of the MLP deck as the vehicle drifted to the north The rainbird design used for SLS has its heritage in the SSWS rainbird head design. The flame deflector for STS was two-sided instead of the one-sided deflector of SLS, where RS-25 plume was deflected primarily to the south of Pads 39-A and B, and booster plume deflected primarily to the north. As with the SLS IOP/SS system, the SSWS also put water inside the trench, fed from nozzles at the crest of the flame trench.

Fig. 10 STS at Pad 39.

One additional difference with the STS concept of operations and resulting MLP design is with respect to the booster plume exhaust holes. For SLS, the primary vector for all nozzles is straight down, which means that as SLS lifts off, it primarily lifts straight up, with any drift experienced primarily by winds that may drive it slightly across the deck. STS always drifted to the north because the RS-25s were canted slightly towards the south. To prevent significant plume impingement on the MLP during the earliest part of liftoff, the booster exhaust holes were rectangular, extending towards the north. As the vehicle drifted to the north, the plumes were kept primarily in these exhaust holes as a result. For SLS, because the motion is straight up, the Booster nozzle exhaust hole is relatively confined, and so all of IOP mitigation can be provided by the water sheets from the IOP ring (both mitigating the strength of the IOP as the plume develops downward, and mitigating the reflected energy on its way back out of the exhaust hole). For STS, subsequent to STS-1, IOP mitigation in the exhaust hole directly under the booster (referred to as the primary hole) was provided by an IOP ring of different design, but this left the northern portion of the exhaust hole (referred to as the secondary hole) open for returning IOP to impact the vehicle uninterrupted. Water bags were hung in a row to fill the remaining portion following STS-1. These

Fig. 11 Water bags or troughs in STS-2+ Booster Exhaust Holes.

water bags, which were essentially like hammocks, were filled with water, and absorbed the energy of the returning IOP wave, and then were destroyed during the liftoff event. No such waterbags are utilized for SLS, because water sheets themselves are able to serve that roll.

Of note, significant changes were made to the MLP portion of the SSWS after STS-1. That first mission had water in the trench, both as a spray from the sides of the trench and the crest of the flame diverter, water in the RS-25 hole, and rainbird water on the deck, but no water inside the SRB holes. During STS-1, significant loads were measured on the vehicle during ignition, attributed to booster IOP. To mitigate this for future flights, water from the flame trench side pipe was redirected to new overpressure piping installed on the MLP, leaving only flame diverter crest water in the trench. As with the IOP/SS system for SLS in the ML, the SSWS piping was integral to the design of the MLP, and to rapidly accommodate this change without designing and building entirely new MLPs, the additional piping was installed largely externally. Nozzles on the flame trench side were capped to allow additional water pressure to feed the new J-pipes connecting to the new overpressure piping. Water was fed up the northeastern and northwestern corners of the respective booster holes to a manifold on the Zero Deck that then split to an outer loop directly to the south along the eastern and western edges of the exhaust holes respectively on one leg, and towards the center of the ML and then back along to the south on the inner sides of each exhaust hole. Th outer loop terminated at the orbiter tail service masts (TSMs) and provided addition RS-25 exhaust hole water directed towards the middle of the hole

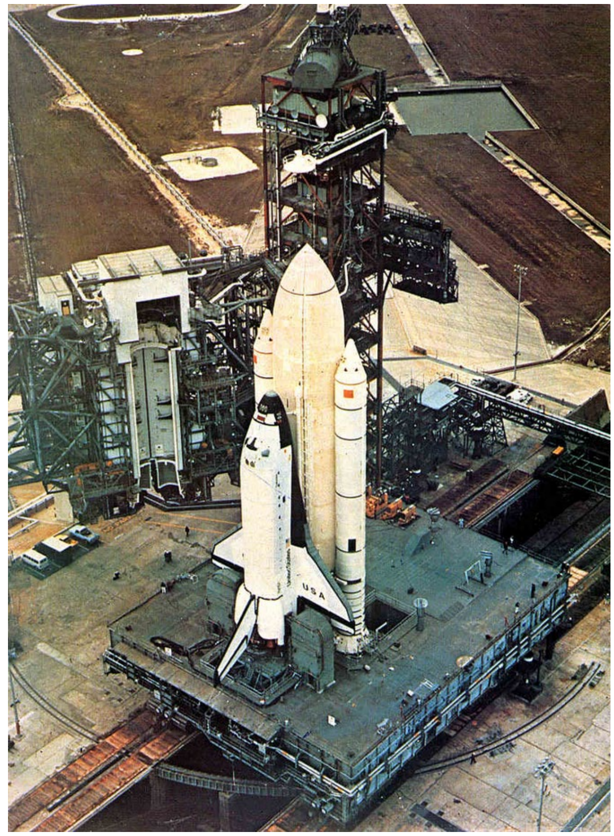

Fig. 12 STS-1 on final rollout to the pad. Note the booster plume exhaust holes do not have any IOP piping.

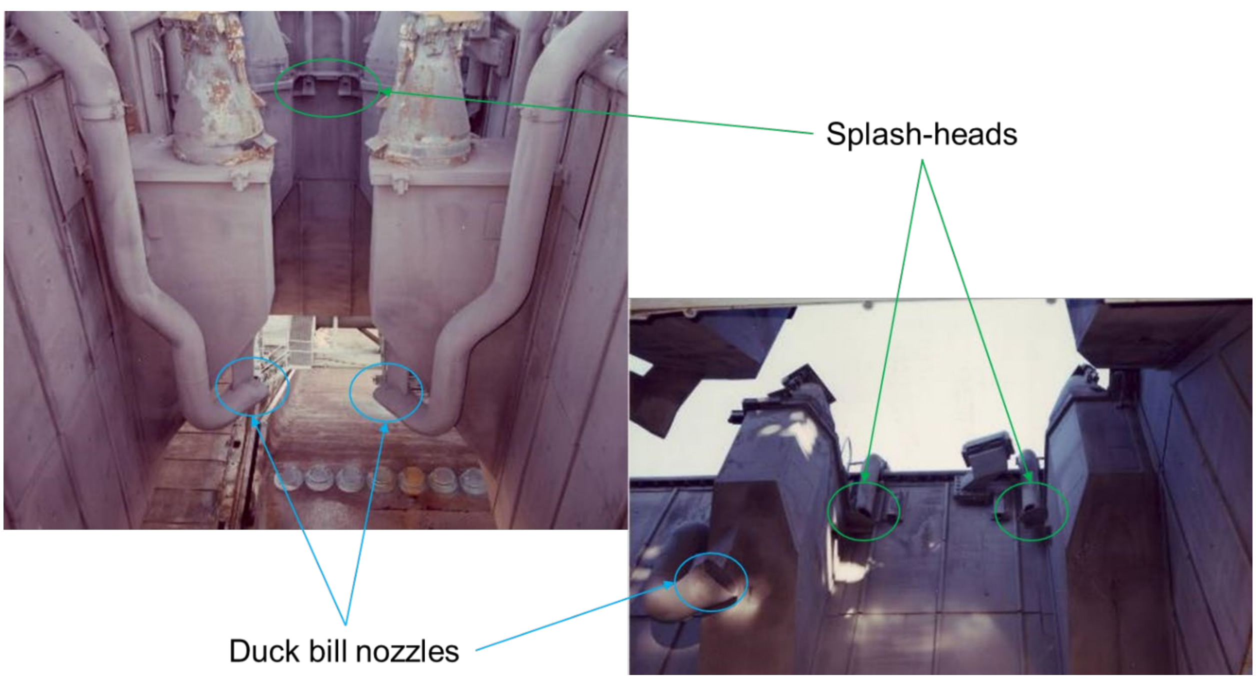

Fig. 13 STS-2+ Booster Exhaust Hole IOP Nozzles.

from each TSM. The outer loop terminated on the southern side of each booster hole and fed two small downcomers that directed water towards the north. Each leg of the Zero Deck piping fed three downcomers on the east and on the west side. The first duct was a large diameter downcomer that fed a nozzle similar in design to those used for SLS, and which was sometimes referred to as a duck bill nozzle. Those were directed generally towards the south. These two pipes accounted for about 50% of the water fed into the booster holes, and terminated several feet from the booster NEP. The remaining four downcomers were smaller than the duck bill downcomers, but larger than the terminating downcomers, and directed water generally towards the opposite corner, at the same elevation as the terminating downcomers. This distance has the same approximate distance from the booster NEP. The volume of water from these six nozzles in relatively close proximity to the NEP is on the same order of magnitude as that used per hole for SLS. These six nozzles vary from SLS in that, rather than a nozzle, they utilize a splash plate (or splash head) angled downward, so that water from the downcomer impinges on the splash plate, and is directed out in a fan, with water deflected between the angle of the splash head and straight out. There tends to be an oscillatory, pseudo-random nature to the net downward angle of these water sheets observed in video from water flow tests that means that the water is directed somewhere between upward and downward along the angle of the splash head rather than a steady-state fan. The sheets are also the cleanest and most consistent in the middle of the splash heads, and oscillate the most up and down along the outer edges. One of the most amazing parts of this effort is that these modifications were designed, performed, and tested in time for stacking of STS-2 in the VAB, rollout to the pad, processing at the pad, and launch on November 12th, 1981, exactly seven months after the launch of STS-1 on April 12th, 1981. This system remained unmodified for the remainder of STS, being used for 135 missions (including Ares I-X), for a total of 269 boosters, without SSWS-related launch issues.

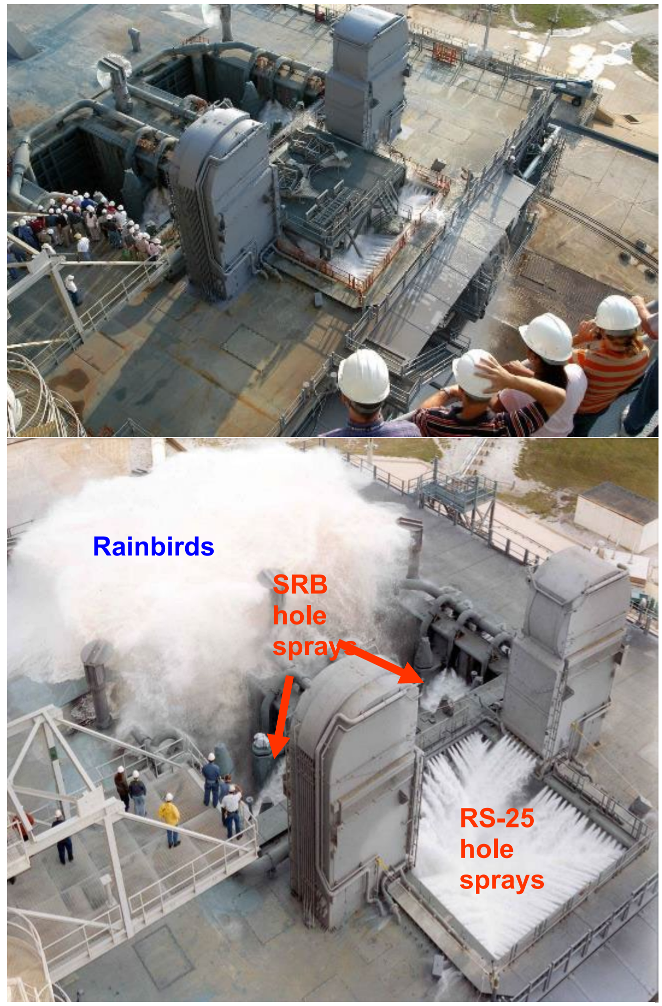

Fig. 14 SSWS Tests. Note the Booster IOP piping and spray, and also note the engine access platform in place during test (above).

Aside from the booster exhaust hole IOP outer leg termination at the TSMs, the RS-25 exhaust hole remained unchanged throughout, and was fed by a ring embedded in the MLP around the exhaust hole. Nozzles oriented around hole are canted downwards and provide approximately the same amount of water as is provided to each booster hole. Flow rate is on the same order of magnitude as that used for SLS.

Also note, the total crest water flow rate for STS is on the same order of magnitude as that for SLS. SLS directs all the water to one side of the flame deflector, with all six plumes deflected towards the same side. STS is different in that the water is split to go both directions. The RS-25 side of the flame deflector used about half the flow rate as the booster side of the deflector to the north.

The only modifications known to the system after the STS-2 modifications were maintenance and end of life replacement, and use as-is for Ares I-X.

The best opportunity to observe the booster IOP system in-work is during one of several water flow tests, in line with the ISVV-14 testing discussed here for SLS. When the Space Shuttle vehicle was stacked on the pad, the view inside the booster holes was almost completely obscured. However, with the exception of the first water flow test, in which Enterprise was stacked with a tank and two boosters during the water flow, all other tests were performed without a stacked vehicle, providing unobstructed views. The downside however is that several of these tests were also performed with some of the maintenance platforms in place, which resulted in some obstructions, or else additional water-hardware interactions that do not exist in the launch position. For evaluation of SLS water flow systems, a total of six tests were identified for the SSWS. Note, the names provided below are based on the best available information, which in some cases was the labeling on video cassette tapes.

1) STS Wet Dress Rehearsal (WDR) – 18 July 1979: Limited utility because, although this provided interesting footage, Enterprise was stacked and obscured the booster holes, and also the configuration was the STS-1 configuration and not the STS-2+ configuration, which was the most SLS-like
2) Water Flow Test after MLP Booster IOP Modifications (presumed) – Prior to 12 November 1981
3) SSW (presumably standing for Sound Suppression Water) Test 1 and 2 - 7 – 11 December 1990
4) SSW Test – 18 October 2001
5) Main Valve Replacement Validation – 7 May 2004: Booster hole was unobstructed, but the RS-25 engine platform was in place in the RS-25 hole, and obscured the view of the RS-25 water ring. Note, this test was performed after the replacement of the six main system valves in the valve complex. These had not been replaced since the beginning of the STS program and had reached end of service life.
6) Ares I-X Sound Suppression Deluge Test – 6 April 2009: Some limited utility because test stands/fixtures in the SRB holes are close to the main flow heads, which caused splashing not observed in other tests.

There was an additional test that is presumed, but no record or imagery was found for it. Given the size and significance of the changes made between STS-1 and STS-2 to the booster IOP ring and the trench water system, a test was almost certainly performed with the new system (either with or without Columbia stacked on top). Additionally, there are NASA press releases from the test conducted on 7 May 2004 that indicates it was the fourth such test performed. Assuming that the first test was 1979, the second was the presumed pre-STS-2 test, the third was the 1990 test, and the fourth was 2001, that press release would be consistent with this presumed test.

Video is available for the tests 1-5 shown above.

Another resource that was utilized was imagery and video from the STS FRFs. There was at least one FRF performed on the pad prior to the first flight of every orbiter. Challenger and Discovery both had two FRFs: the former due to issues with the first FRF necessitating a repeat, and the latter prior to Discovery's first flight and then prior to the return to flight after the Challenger launch failure on STS-51-L. Video is available from Columbia FRF and the Discovery Return to Flight FRF.

1) Columbia (OV-102) – 20 February 1981
2) Challenger (OV-099) – 18 December 1982 and 25 January 1983
3) Discovery (OV-103) – 2 June 1984 and 10 August 1988 (STS-26)
4) Atlantis (OV-104) – 12 September 1985
5) Endeavour (OV-105) – 6 April 1992

These tests were useful in that they provided imagery of the SSWS in operation with the launch vehicle in partial operation, where the RS-25s lit and ran for a short duration (dozens of seconds), in order to observe RS-25 plume interactions on the SSWS. There were limitations however, in that the FRF configuration necessitated operations changes in order to protect the vehicle and the pad, neither of which were designed specifically for prolonged on-pad firing. On the pad side, there was a finite amount of water in the water tower. It appears that to ensure that enough water is provided during the duration of the firing, some legs of the SSWS were capped, including post-launch sound suppression rainbirds, as well as water in the booster ducts. These were not significant losses because the rainbird behavior was captured by the water flow tests and not expected to be significantly impacted in performance by the plumes as the vehicle lifts off, and the booster water would be obscured by the boosters themselves. Additionally, a thermal barrier was assembled on the MLP deck between the orbiter aft end and the boosters to protect the boosters from the prolonged plume heating of the RS-25s without the benefits of ascent. These data could be used to observe RS-25 plume interaction and effects on the SSWS however.

STS launch footage was also useful. The water under the boosters was obscured by the boosters and the water bags themselves, but the RS-25 IOP water was unobstructed, and the behavior of both the RS-25s during startup and transition to full power as well as its interaction and impact on the RS-25 IOP water could be observed clearly and repeatably. Additionally, interactions and effects of the booster IOP itself could be observed in the RS-25 IOP water. Similarly, Ares I-X video was useful in providing different vantage points (from onboard cameras) that show the behavior of the RS-25 IOP water when the booster ignites, as a surrogate for entrainment effects of the RS-25s on the SLS configuration, as well as behavior with respect to booster IOP. Unfortunately (for the purposes of this study), the empty booster hole was completely covered with water bags to mitigate IOP, so there was not a clear view of the water flow system operating underneath. Behavior observed between STS launch and Ares I-X launch is consistent for the RS-25 exhaust hole IOP water. In the case of STS launch, water from the RS-25 IOP hole is initially disturbed as the engine plumes develop, but then returns to pre-startup steady state, followed by strong entrainment. Booster

IOP is observed in both STS and Ares I-X imagery, but no significant water is forced above the steady state plane during this event. In the Ares I-X footage, where the RS-25 IOP hole was uninterrupted by the RS-25 plumes, similar behavior was observed as in STS launch, and as the vehicle lifted off, water was pulled down rather than being forced up.

Finally, STS MPTA test video was useful to confirm observations from the SLS Core Stage Green Run at test stand B-2. The MPTA test series, also conducted at test stand B-2, utilized an STS external tank along with an aft end of an orbiter to house the three RS-25s and associated thrust vector control and plumbing. This was a useful link between the SLS RS-25 configuration and the STS RS-25 configuration. There are key differences in proximity between these two configurations, but the behavior observed in the MPTA video is consistent with the behavior observed in SLS Green Run, which strengthens the use of STS launch to predict Booster IOP and RS-25 startup and plume entrainment behavior for SLS.

VII. Artemis II ISVV-2 Test Series

The ongoing IOP/SS test series, ISVV-2, is intended to address the post-Artemis I work described above, including to increase the total amount of Sound Suppression water from the five Rainbirds in preparation for the Artemis II and Artemis III launches, which will carry a crew of astronauts to the Moon in support of NASA Moon to Mars campaign. As noted before, the addition of four haunch cameras will be instrumental in increasing NASA's ability to characterize the splashes able to enter the Booster nozzle volumes. This work is being done to understand the hazards associated with Booster ignition in close proximity to the IOP water sprays under the RH and LH Boosters on the ML. At the time of this paper submission, Flow 3 of this test series has been successfully executed, with Flow 4 scheduled for the coming days. The test series is expected to be completed by the time of publication, and the data will again, as in ISVV-14, be analyzed and scrutinized to determine rationale for flight for Artemis II and Artemis III.

Fig. 15 ISVV-2 Flow Event 3.

VIII. Conclusion

The data presented above, utilizing the art of partial modeling, laid the foundation for Artemis I flight rationale. These data guided a strong technical understanding of the physical phenomenon and behavior of the system. The condition relative to experience base was shown using both SLS primary tests, and also a wealth of historical data for similar systems. Bounding load cases were established, with margins understood. Strong self-limiting aspects were expected, with assessments based on data, testing, and analysis. Finally, the interactions with other elements and conditions were understood. All that remained was to fly Artemis I and scrutinize the data to ensure that the integrated IOP/SS-SLS system performed as predicted based on these data.

Artemis I launched on 16 November 2022, on a mission that proved to be nearly flawless, which, for a first launch of a new vehicle, is an impressive feat. Although the launch occurred at night, significant imagery was collected to verify the performance of the fully integrated IOP/SS system, complete with interactions with the SLS vehicle, plumes, and environments. The system behaved as predicted based on these analyses, with no negative interactions resulting with the addition of SLS hardware and plume interactions. All the while, the IOP/SS system itself performed its primary function of mitigating the liftoff environments generated by the SLS vehicle. With these data in hand, verified against Artemis I, NASA is preparing to take the next step, by sending crew on board Artemis II.

The hope of these authors is that this summary will prove useful to the engineers of today, but also for the engineers of tomorrow.

Acknowledgments

Bill Chardavoyne, David Valletta, James Ingram, and the rest of the Exploration Ground Systems Team at Kennedy Space Center have done an outstanding job designing and testing the IOP/SS system on the Mobile Launcher in support of successful Artemis missions. Their expertise and high level of effort on the ISVV-14 series, the Artemis I launch campaign, and the ongoing ISVV-2 test series is greatly appreciated by their SLS counterparts.

Beth St. Peter, Lori McDerby, Danny Osborne, Taylor Walker, and Charles Norton, along with the rest of the SLS Imagery Team have provided sustained, significant support in successfully capturing imagery data from the related tests and Artemis I. They have also performed a number of assessments to support understanding and characterization of the environments associated with IOP/SS water during Artemis missions.

Thomas Nesman, Brandon Williams, William Dziedzic, Zoe Sampson, Jerry Smith, Bill Chardavoyne, and Nick Moss were invaluable in tracking down, finding, and providing CDs, DVDs, and VHS tapes containing historic water flow and FRF testing for the STS program. All of these resources have now been digitized for future generations. Special thanks to Danny Osborne for digitizing those tapes, and for in some cases repairing tapes by removing damage and splicing the remaining tape back together.

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