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A STEAM INERTING SYSTEM FOR HYDROGEN DISPOSAL FOR THE VANDENBERG SHUTTLE

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ABSTRACT

The Space Shuttle main engines (SSMEs) lead gaseous hydrogen (GH_2), run fuel rich, and lag GH_2 at shutdown during an SSME abort or flight readiness firing (FRF). At the Kennedy Space Center (KSC), the SSME plumes exhaust into an open trench that is vented and consequently considered safe. At Vandenberg Space Launch Complex Six (SLC-6), the plumes exhaust into a closed duct. There is a concern that the confined hydrogen could ignite, produce an accelerated deflagration or detonation, and damage the launch vehicle.

This paper surveys the two-year feasibility and development test program completed in December 1987 to solve this problem and to design a hydrogen disposal system (HDS) for SLC-6. It was necessary that the solution lend itself to evaluation and verification by subscale testing because of the cost and risk of full-scale experiments with the shuttle or associated flight hardware.

In December 1986, after screening concepts that attempt to burn excess GH_2 and open-duct designs that vent GH_2, the Air Force selected a novel steam inerting design for development. This concept superheats available sound suppression water to flash to steam at the duct entrance. Testing, analysis, and design during 1987 showed that the steam inerting system (SIS) solves the problem and meets other flight-critical system requirements. The SIS design is complete and available for installation at SLC-6 to support shuttle or derivative vehicles. Without the SIS, the Vandenberg Air Force Base (VAFB) facility might be unusable by hydrogen-fueled space launch systems.

INTRODUCTION

This paper concerns a postulated threat to the Space Shuttle vehicle (SSV) from unburned hydrogen at SLC-6 at VAFB (figure 1). The SSMEs lead GH_2, run fuel rich, and lag GH_2 at shutdown during an SSME abort or FRF. At KSC, the SSME plumes exhaust through the mobile launch platform (MLP) into an open trench that is vented and consequently considered safe. At VAFB, the SSME plumes exhaust through the launch mount (LM) into a closed duct (figure 2).

In November 1984, the National Aeronautics and Space Administration (NASA) raised the concern that unburned confined hydrogen might ignite, producing an accelerated deflagration or detonation, and damage the launch vehicle. In September 1985, the Air Force formed a team to develop a solution, make necessary facility modifications, and verify effectiveness in time to support a May 1986 FRF and subsequent shuttle launch at Vandenberg. Program participants are listed in figure 3. This paper surveys the

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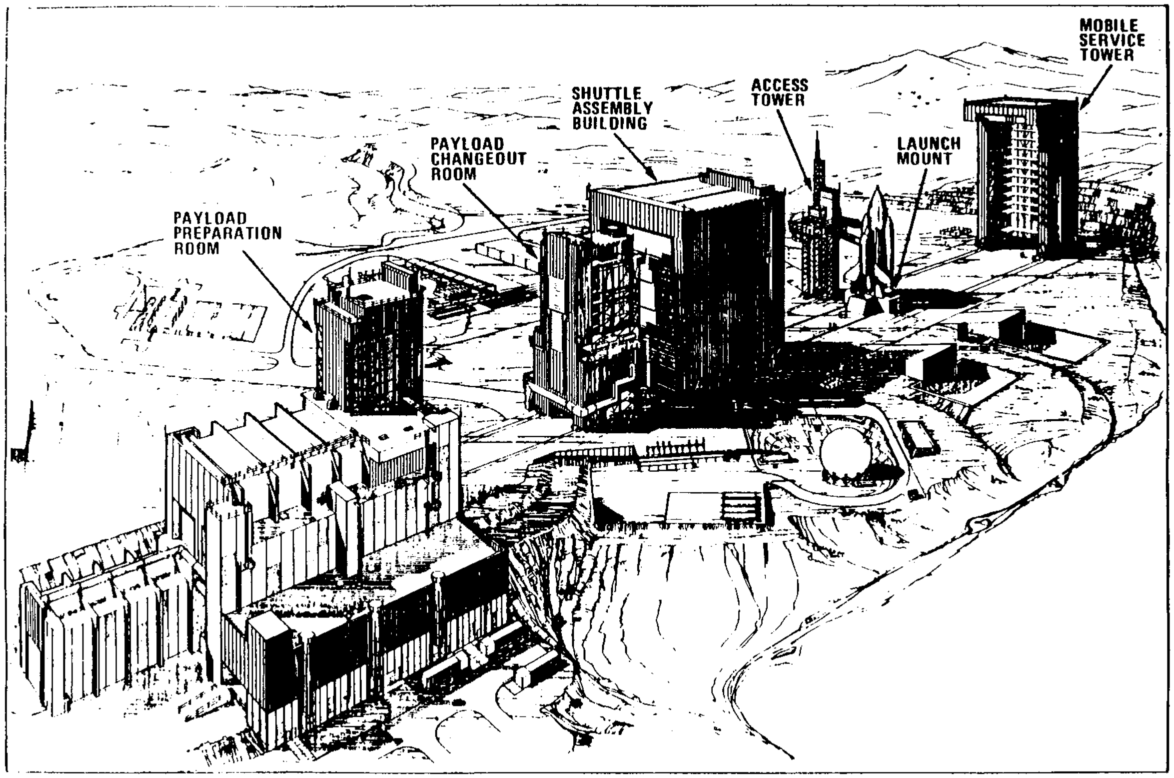


Fig. 1 Space Launch Complex Six at Vandenberg

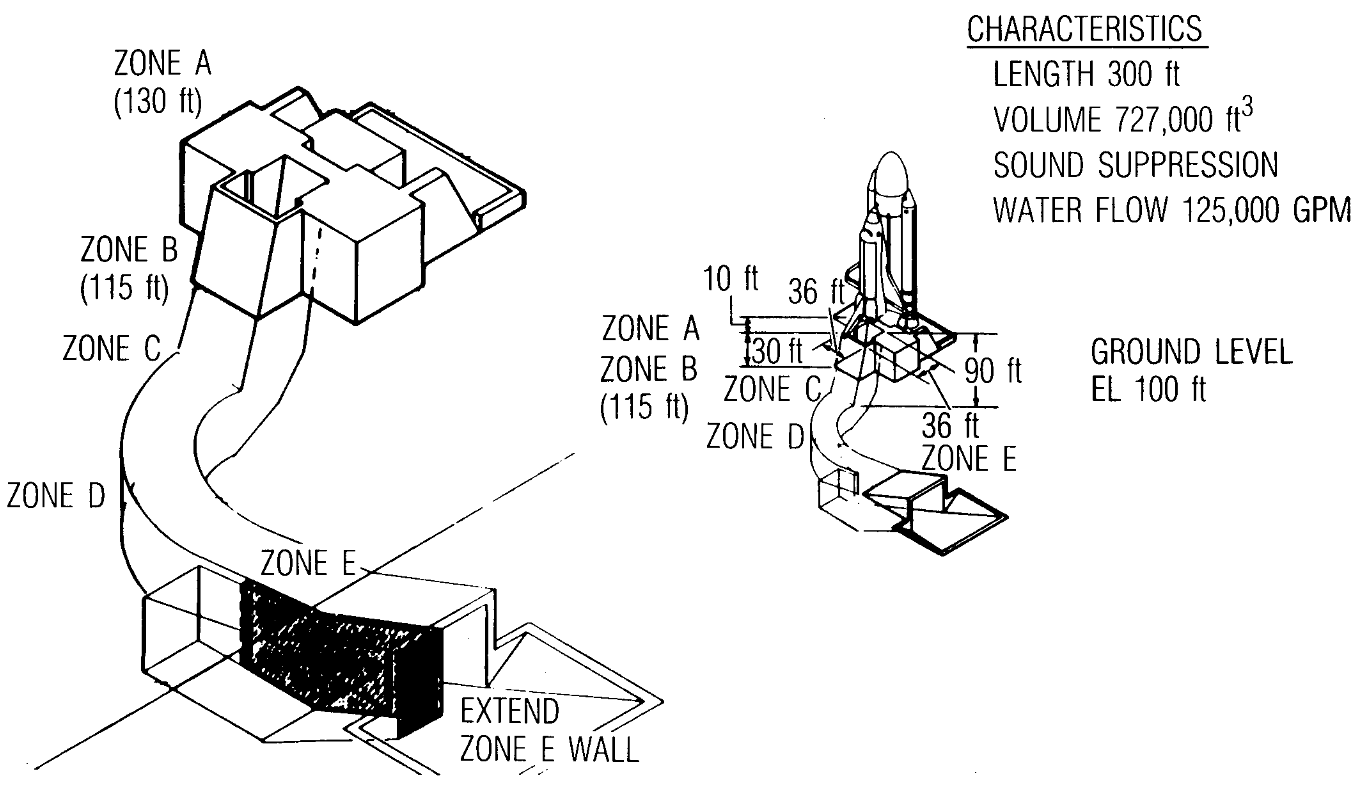


Fig. 2 SSME Duct at Vandenberg

Organization	Scope of Work
United States Air Force	Program Management
Aerospace Corporation	Program and Technical Support 1/20 Scale Cold Testing Instrumentation Development
Martin Marietta Corporation	
Vandenberg	Integrating Contractor for HDS Concept Selection
Denver	Technical Support and 1/7 Scale Testing
Shuttle Processing Contractor	Integrating Contractor for SIS Development Program
Astron Engineering	Steam Inerting Concept Technical Support, 1/100 Scale Testing Nozzle and Header Design
Wyle Labs	1/20 Scale Hot Testing Nozzle and Header Testing
S. Levy Corporation	Technical Support Scaling
Lockheed Missiles and Space Company	
Sunnyvale and Palo Alto	Technical Support Instrumentation Development
Santa Cruz	6.4% Transient Testing
Huntsville	MSFC Support
Eagle Engineering	Technical Support
Cermak Peterka Peterson	Wind Effects Testing Technical Support
Grumman	Instrumentation
Sverdrup Corporation	Architecture and Engineering
Perkin Elmer	Instrumentation Development
Jaycor	Computational Fluid Dynamics
NASA	
JSC	Program Management Support
KSC	Technical Support
MSFC	6.4% Scale Induced Environment Testing
Ames	Computer Support
Rockwell	
Downey and Vendenberg	Technical and Testing Support
Huntsville	MSFC Testing

Fig. 3 HDS/SIS Program

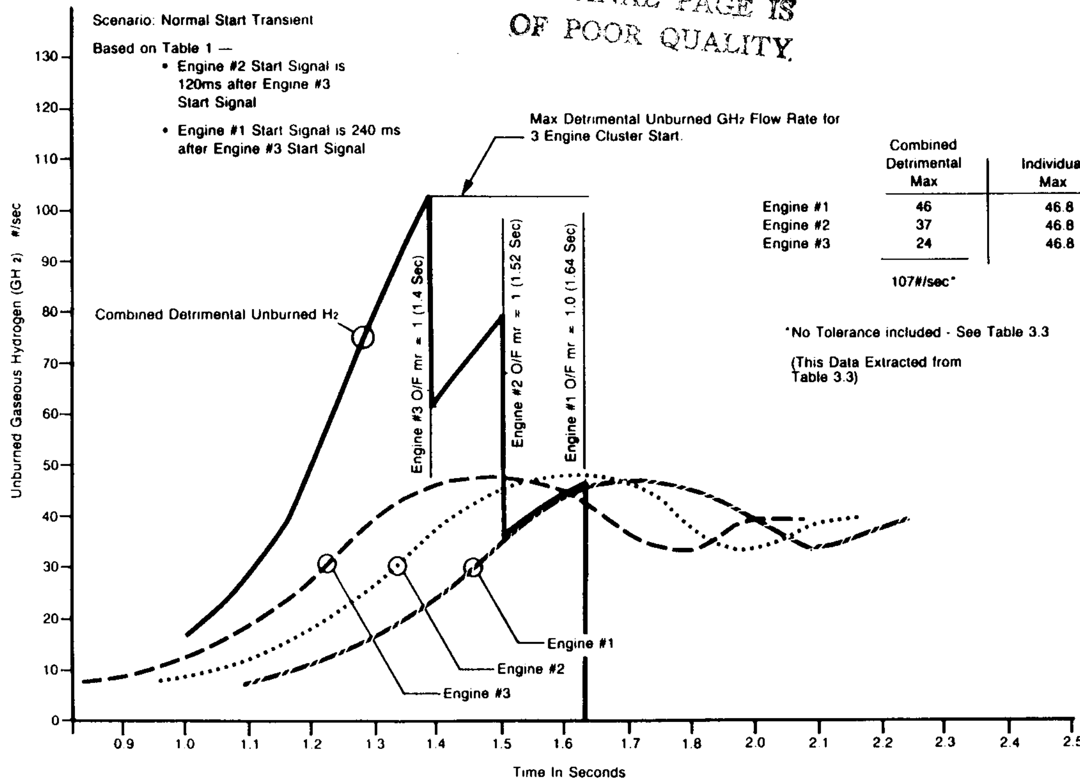


Fig. 4(a). SSME Ignition Transient

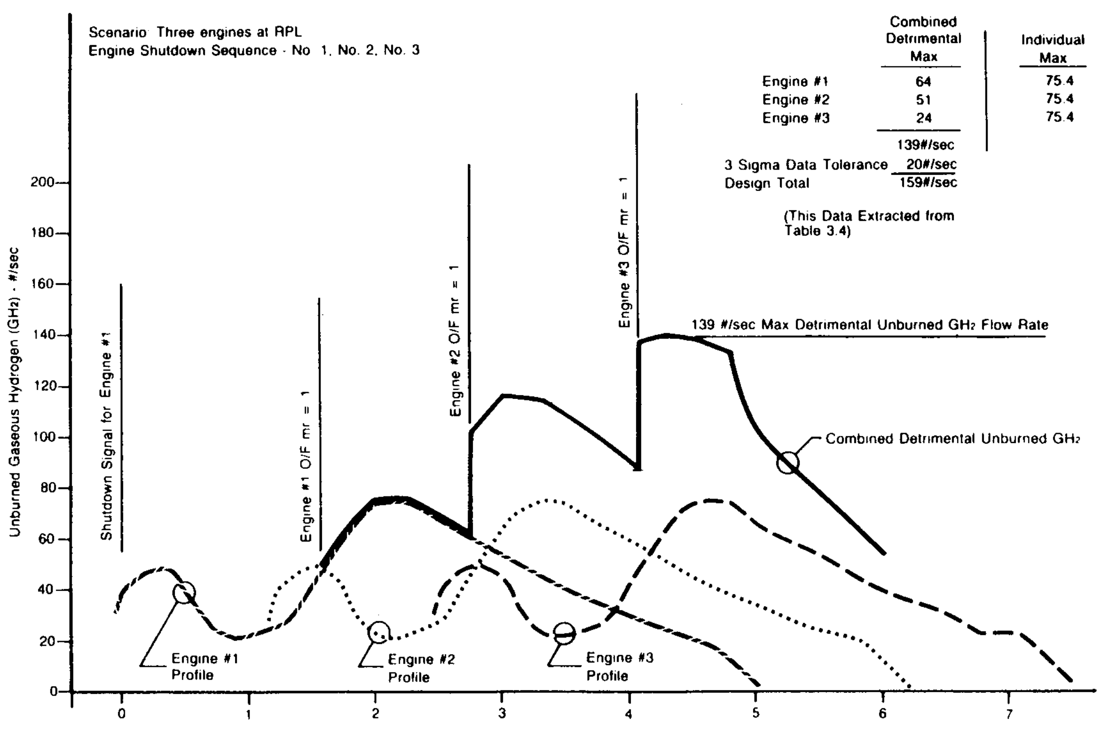


Fig. 4(b). FRF Abort Shutdown

two-year feasibility and development program completed in December 1987 to solve this problem and to design an HDS for SLC-6.

BACKGROUND

During SSME operation, combustion occurs in the chamber when the oxidizer-to-fuel ratio equals or exceeds (approximately) 1, O/F = 1 (the stoichiometric ratio is O/F = 8). Unburned hydrogen refers to the quantity of GH_2 not burned in the engine. Figure 4(a) shows unburned hydrogen time histories from a normal three-engine start to rated power level (RPL). Figure 4(b) shows an FRF shutdown from RPL. The HDS program considered these threat scenarios and other shutdown cases, including an abort during the start transient and a clustered abort that produce a high maximum rate of unburned hydrogen of 190 lb/sec (refs. 1 and 2).

The ground rule in the HDS system specification (ref. 2) is that hydrogen is detrimental only when expelled from a nonburning SSME (O/F < 1) predicated on the assumption that GH_2 from a burning engine is pyrophoric with air. This position suggests the partial summation of unburned hydrogen flows in figures 4a and 4b. A more conservative assumption is that all unburned hydrogen may be detrimental, suggesting a complete summation over the time histories. In either case, for scenarios considered, the maximum threat is an unburned hydrogen flow on the order of 160 to 200 lb/sec.

NASA supplied an estimate of 1.32 psid (as an indicator) of the maximum steady overpressure allowable at the orbiter base heat shield. This overpressure is produced by the detonation of as little as 1.0 lb of hydrogen at free space distances corresponding to locations in the Vandenberg duct.

Successful hydrogen disposal requires some combination of benign burning, inerting, or venting of excess GH_2. At KSC, radial outward firing initiators (ROFIs) mounted near the SSME nozzles provide an ignition source for unburned hydrogen during the SSME start transient. A ROFI is, in effect, a small rocket motor filled with zirconium pellets. These pellents flood the area between the SSME nozzles and the duct entrance with small (550-micron), extremely hot zirconium sparklers. During an FRF or abort shutdown at KSC, it is assumed that the SSME plumes are adequately vented as they exhaust through the MLP into an open trench and excess hydrogen continues to burn.

Between September 1985 and December 1986, the HDS team reviewed several HDS concepts for VAFB: (1) high-energy burnoff igniters (HBOIs) to burn excess hydrogen with zirconium igniters in the duct; (2) jet mixing to force burn the GH_2 at the duct entrance; (3) open duct designs to emulate the MLP at KSC; and (4) inerting, initially using carbon dioxide, but later using steam.

During 1986, it became evident that attempts to burn all excess hydrogen, whether by igniters in the duct or by forced air at the entrance, are dangerous and impossible to verify without prohibitively expensive full-scale tests. The Space Shuttle 51-L accident on 28 January 1986

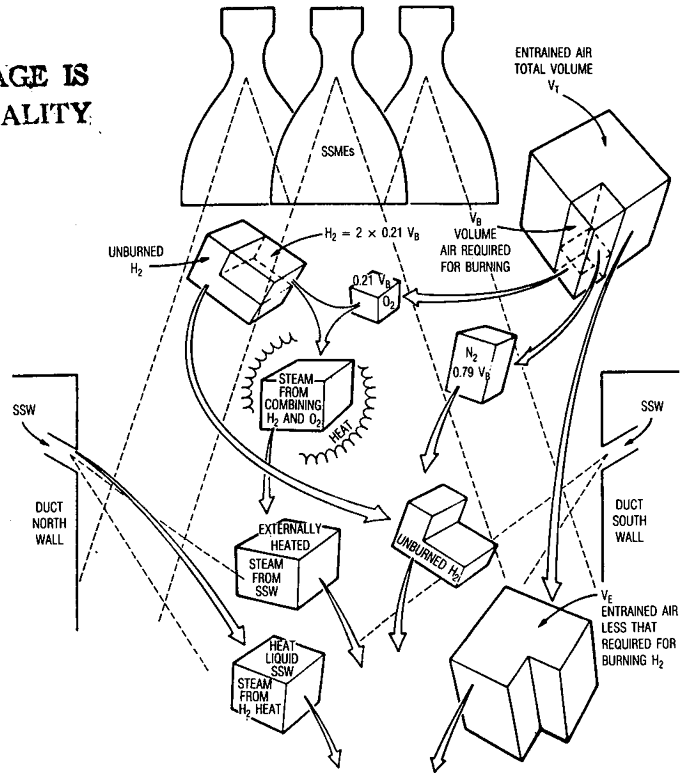


Fig. 5 Steam Sources in the Duct

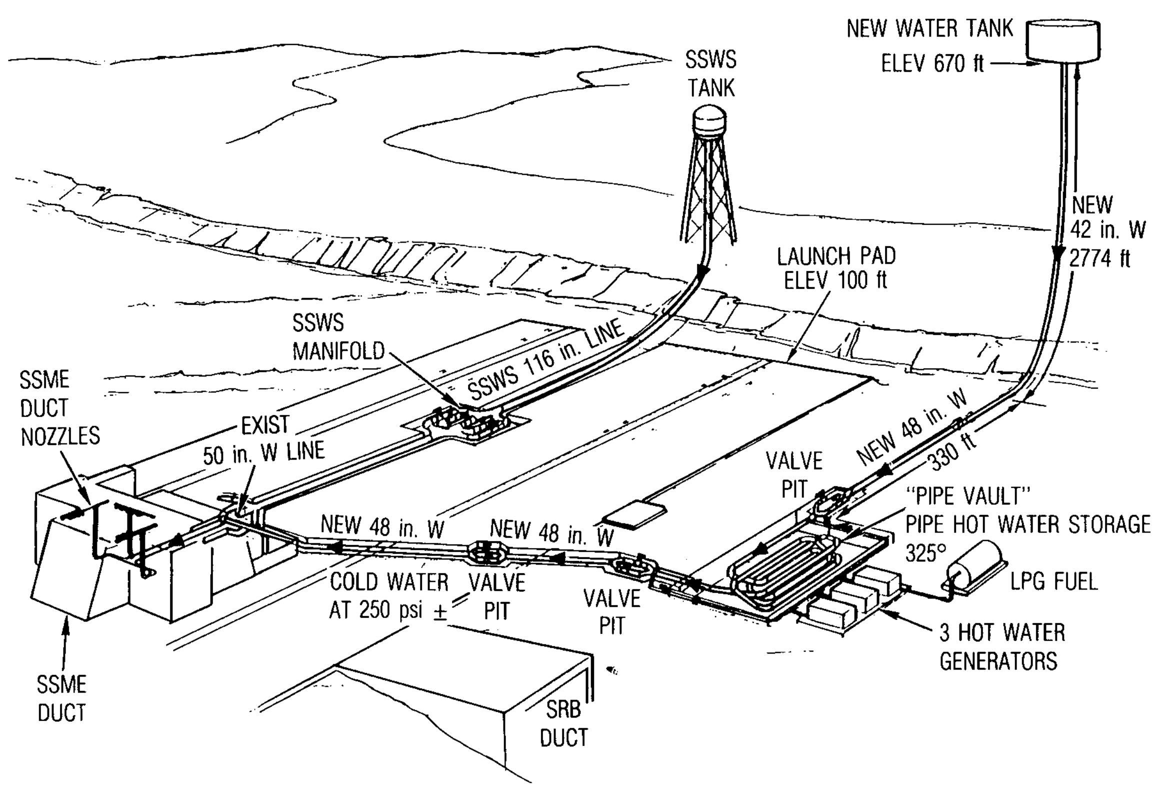


Fig. 6 Steam Inerting System/HDS Concept

suspended the imperative for a May 1986 FRF and subsequent launch at VAFB, and also intensified flight safety concerns.

Open-duct options have the advantage of resembling configurations that NASA considers safe. However, such an implementation at Vandenberg requires massive facility modifications. The open geometry also has a disadvantage with respect to analysis and evaluation by subscale testing. With the open boundary condition, controlling effects are very difficult to analyze and scale.

With inerting, the idea is to guarantee that, if combustion stops within the duct (because of a natural or induced condition), the mixture remains inert until safely vented past the duct exit. This sort of inert state should be relatively safe. Also, inert flow within a confined duct should be controlled by linear momentum and lend itself to simple geometric scaling.

After the Concept Selection Review in December 1986, the Air Force baselined the SIS for design and development for use at SLC-6 (ref. 1).

STEAM INERTING

The sound suppression water system (SSWS) at SLC-6 provides fire suppression, deluge, and sound suppression flow. The system introduces 122,000 gpm water flow at the SSME duct entrance for acoustic suppression. The steam inerting system superheats this water such that a prescribed fraction flashes to steam and inerts the duct. This approach guarantees thorough mixing of the inertant with the SSWS flow and avoids the need for a large steam generating plant. The SIS augments inerting processes caused by the SSME.

As shown in figure 5, entrained air of some total volume provides oxygen to oxidize unburned hydrogen from the SSME. A fraction of this air (containing 21 percent oxygen) combines stoichiometrically with part of the unburned GH_2 to yield steam. The remaining 79 percent is excess nitrogen, which also serves as an inertant in the duct. The exothermic combustion of the hydrogen releases large quantities of heat, causing a fraction of the SSWS flow to vaporize. This is in addition to the quantity of steam developed at the SSWS nozzles as a consequence of the flashing superheated SSWS flow. Therefore, constituents in the duct include possible residual unburned hydrogen, residual air, excess nitrogen, and steam from three sources. The SIS augments the SSME inerting process to guarantee that the duct remains benign past any station at which combustion stops.

Design Concept

The SIS does not use the as-built SSWS system for SSME flow; rather, it provides a new and separate source of superheated, pressurized water at 122,000 gpm. This design concept is illustrated in figure 6.

The design goal is 55 percent steam by volume in the duct to assure an inert condition for any hydrogen-to-air ratio (refer to requirements

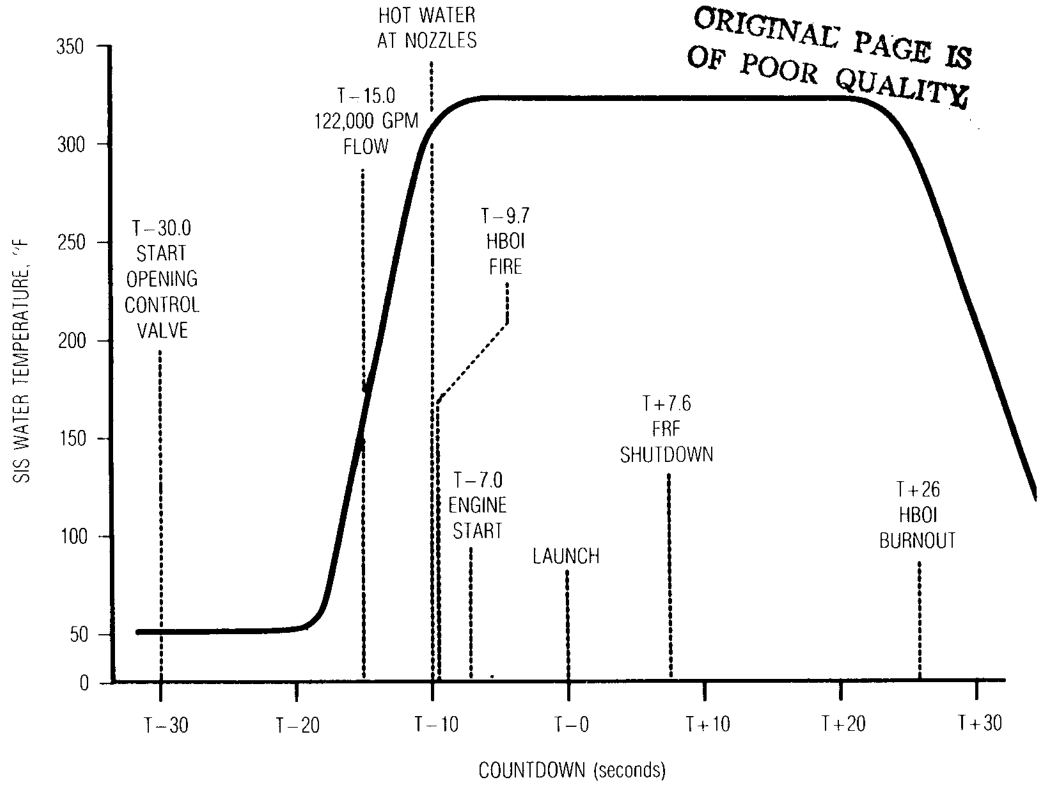


Fig. 7 SIS Operational Time Line

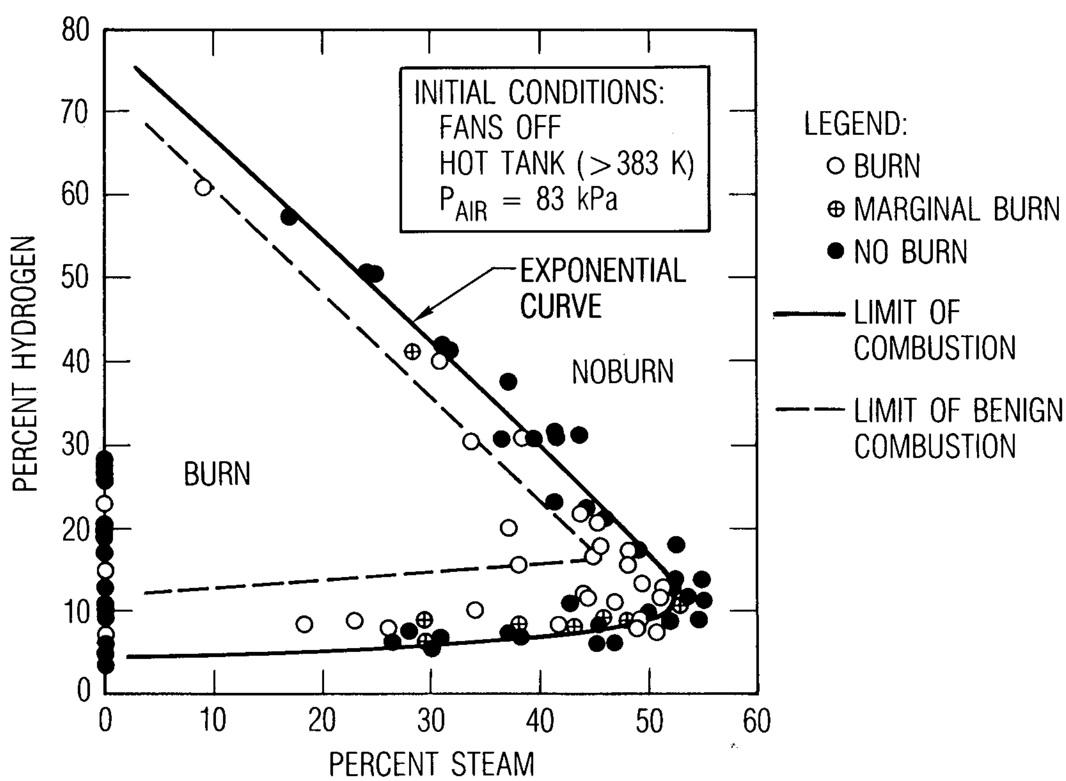


Fig. 8 Flammability Diagram

below). Analyses and tests show that this requires a header temperature of 310°F at 145 psig. There is a requirement that the SSWS not splash above the duct entrance level; in particular, it should not introduce water droplets into the SSME exit bells and past the throat prior to SSME fully developed thrust. Therefore, the SIS leads cold water to establish aspiration before the onset of steam. The SIS flow scenario is illustrated in figure 7.

The SIS design includes the use of long-burning HBOIs to augment the SSMEs as ignition sources above the duct entrance. KSC experience and White Sands Test Facility (WSTF) testing (ref. 3) indicate that zirconium sparklers are a safe and effective way to accomplish this objective.

Requirements

The SIS must inert the duct, vent unburned hydrogen safely at the exit, and not induce the following environments, which may be detrimental to the vehicle or to the facility: splash, overpressure, acoustic, or thermal.

Experiments at Sandia National Laboratories define flammability and detonation limits for hydrogen, steam, and air mixtures. Tests show that flammability limits are independent of scale; however, deflagration to detonation depends on scale. Factors promoting flame acceleration include increased size, obstacles, turns and bends, and turbulence. The requirement, therefore, is that the SIS prohibit combustion of unburned hydrogen in the duct (past the critical surface at the entrance at which combustion from the SSMEs or HBOIs stops). This allows the extrapolation of subscale test results to full scale and avoids the threat of accelerated deflagration in an environment which is, in fact, large in size and turbulent.

A flammability diagram applied to SIS testing is shown in figure 8. The figure includes combustion limits (ref. 4) and benign combustion limits (ref. 5). Then, the (derived) requirement is that the SIS maintain a state in the duct at all locations at all times corresponding to benign points in the figure. A most conservative goal is to achieve 55 percent steam with the SIS alone, because this assures a safe duct for any ratio of hydrogen to air. Failing this, a reasonable objective (with the SSME plume present and ignited at the duct entrance) is to stay beyond the limit of combustion, with additional distance to this limit as margin.

The steam inerting concept has the advantage of providing an easy way to measure system effectiveness. Experiments and analysis show that beyond the duct entrance, past a control surface at which burning has stopped, the duct is in thermal equilibrium. Liquid and gas phases are close to the same temperature such that temperature measurements yield the local concentration of steam.

FEASIBILITY AND DEVELOPMENT PROGRAM

Each test site provides a scaled flow of superheated water, the scaled hydrogen plume, and instrumentation. Feasibility and development tests flow

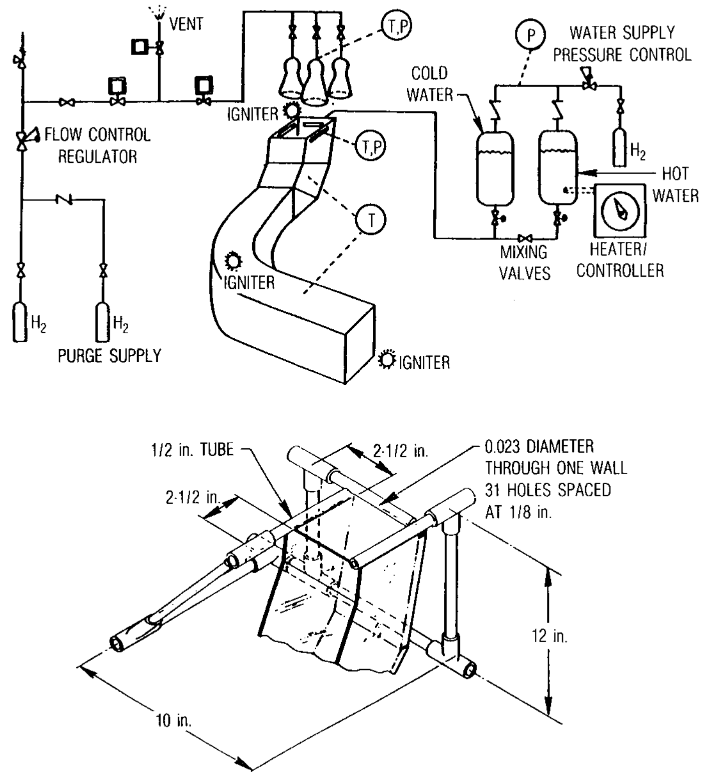


Fig. 9 Astron 1/100 Scale Test Facility

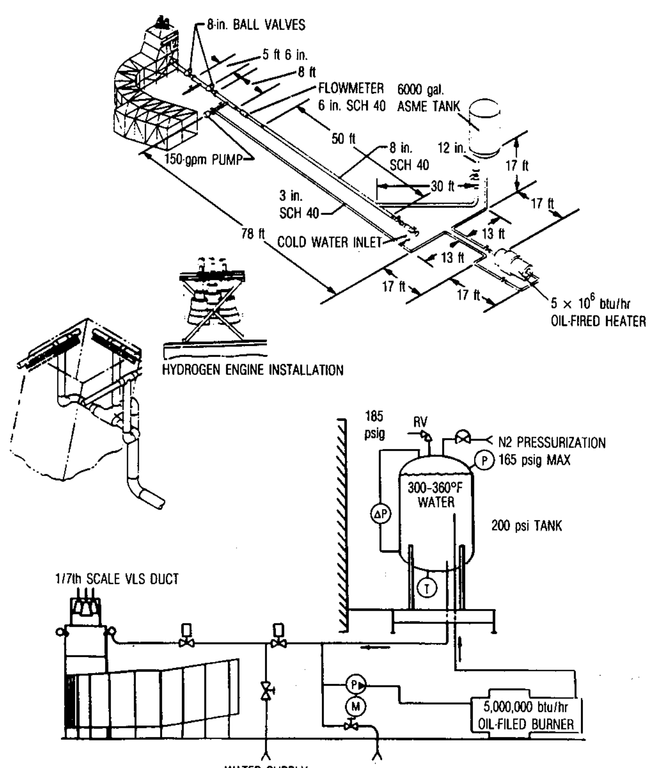


Fig. 10 MMC/EPL 1/7 Scale Test Facility

the steam header alone to trade splash back against inerting performance. This supports preliminary design of the hot water header and flashing steam nozzles. Subsequent tests use cold gas (helium) to simulate the SSME plume. Then, hot fire tests, with burning hydrogen at the duct entrance, evaluate induced effects and inerting performance. Finally, tests use spark igniters within the duct, and at the duct exit, to verify inert, as opposed to flammable, flow conditions.

The hot fire tests at each site inject a scaled, steady flow of unburned hydrogen into the model SSME duct. The flow corresponds to a maximum (design point) rate of unburned hydrogen entering the duct during a transient SSME startup, FRF, or SSME abort (figure 4). Igniting the GH_2 at the SSME nozzles emulates the function of mainstage or HBOI ignition above the duct entrance.

Astron Tests

The test configuration at Astron includes a 1/100 scale duct with viewports, three scaled SSME exit nozzles (with an igniter), a hot water supply system, and a header with tiny holes to simulate SSME steam nozzles, as shown in figure 9 (ref. 6). The water system has the capability to ramp temperature and pressure up and down or maintain constant operating conditions for a relatively long time. Typical temperature time histories, above 180° but below 212°F, suggest an inert condition in excess of 55 percent steam at points in the duct.

Astron experiments with the steam header alone show that splash above the duct entrance is very sensitive to header and nozzle design. The eventual choice is a header on the east SSME wall depressed 40 deg from the horizontal with 19 nozzles, no header on the west wall, and identical headers on the north and south walls depressed 52 deg with 18 nozzles each.

Aerospace Laboratories

The Aerospace Aerophysics Laboratory conducted cold flow tests with a 1/20 scale plexiglass model to evaluate flow and mixing effects in the VAFB SSME duct. Hydrogen flow was simulated by a helium jet emanating from a 1/20 scale aluminum SSME nozzle. Instrumentation included pitot pressure and composition sampling probes and hot wire anemometry for air flow velocities. Wool tufts and Schlieren photography supported visualization of streamlines. Aerospace also used a wet duct in which water and carbon dioxide flows operated with and without the helium jet flow.

Wyle Tests

The test configuration at Wyle resembles that at Astron but at 1/20 geometric scale with correspondingly large holes in the hot water manifolds (ref. 6). Instrumentation includes gas sampling and improved flow velocity measurements. Selected Wyle tests used a bell jar hood arrangement over the duct entrance for accurate measurement of induced aspiration.

Martin/Denver EPL Tests

As shown in figure 10, the test facility at the Engineering Propulsion Laboratory (EPL) at Martin/Denver employs a 1/7 scale steel model of the VAFB SSME duct (ref. 7). The EPL hot water manifold is a high-fidelity analog of the Vandenberg configuration at 1/7 geometric scale. The EPL manifold uses 1/7 scale steam nozzles rather than simple holes in pipe as used at Astron and Wyle. Instrumentation rakes in the duct, with locations common to Astron and Wyle, include thermocouples, pitot probes, and gas sample ports connected to collection bottles. Instrumentation at EPL included a concept developed by the Aerospace Labs: a memory tube that produces continuous gas samples at a specific point as a function of time.

The development tests at EPL established requirements for the SIS full-scale headers and nozzles. The optimum nozzle is a converging-diverging (CD) type with a full scale 16:1 exit-to-throat ratio (6:1 at 1/7 scale). The CD nozzles increase air entrainment (relieve splash) without compromising performance (inert state in the duct). Phase III tests included use of fans to evaluate wind effects on entrance splash and an air ejector to simulate effects of transient air entrainment.

Cermak Peterka Peterson (CPP) Wind Tunnel Tests

Wind effects testing was a major part of the SIS development work. This includes wind tunnel tests at CPP at 1/100 scale and fan tests at MMC/EPL at 1/7 scale. The subsonic wind tunnel at CPP simulates the planetary boundary layer for specific terrain, including wind magnitude, direction, and turbulent intensity (ref. 8).

Phase 1 tests modeled the VAFB terrain at 1:1200 scale. This provided boundary layer characteristics for the subsequent 1:100-scale Phase 2 experiments, which included the working model SIS from Astron testing (figure 11). In Phase 3, CPP used an indicator gas to study SIS venting effects at the duct exit.

Marshall Space Flight Center (MSFC) Testing

NASA developed the 6.4 percent shuttle test facility at MSFC to evaluate the following SSME launch-induced effects: ignition overpressure, vibro acoustic, and thermal. Following open-duct HDS testing at MSFC, the SIS development program evaluated induced environments at Marshall (ref. 9).

Lockheed Santa Cruz Testing

Lockheed's Santa Cruz Test Facility (SCTF) conducted experiments using a 6.4 percent scale model of the SSME exhaust duct, steam inerting system, and SSV. The orbiter model includes three model SSMEs that faithfully simulate transient as well as steady-state operation of the full-scale engines, including sequential start and shutdown (refs. 10 and 11).

The test program had five tasks. Tasks I through IV developed the model SSME start/shutdown transients, provided SIS steady performance data for

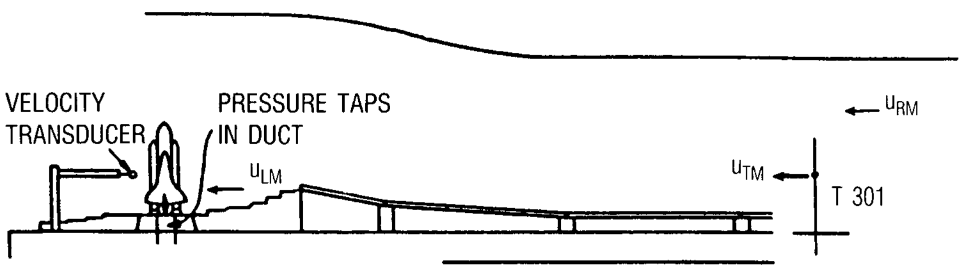
SCALING

DEFINITIONS: MODEL M/PROTOTYPE P

	SPEED	TIME	DISTANCE
GENERAL	u_M/u_P	t_M/t_P	d_M/d_P
FREE STREAM REFERENCE	u_{RM}/u_{RP}		
TOWER 301 REFERENCE	u_{TM}/u_{TP}		
LOCAL POINT	u_{LM}/u_{LP}		

SCALING RELATIONS: $(V_M/V_P)\ (t_M/t_P)\ (d_P/d_M) = \text{CONSTANT}$

$$(u_{RM}/u_{RP}) = (u_{TM}/u_{TP}) = (u_{LM}/u_{LP})$$



STATISTICS

DEFINITIONS:

DENSITY DISTRIBUTION OF SPEEDS	$f_U(u)$
DENSITY DISTRIBUTION OF PEAKS IN TIME T	$f_{UP}(u)$
MEAN SPEED	m_U
RMS SPEED	s_U
TIME INTERVAL	T
NUMBER OF UPWARD CROSSINGS PER TIME	N
MODE OF PEAK SPEEDS	m^0_{UP}

STATISTICAL RELATIONS: TURBULENT INTENSITY $= s_U/m_U$

$$m^0_{UP}/m_U = 1 + (s_U/m_U)\,[-2 \ln (1/NT)]^{1/2}$$

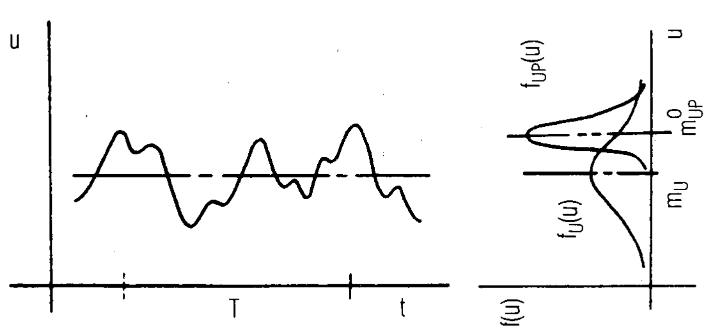


Fig. 11 Wind Tunnel Scaling and Statistics

correlation with other sites, studied transient effects on performance, and evaluated induced effects. Task V provided data to resolve issues. Task V tests included an improved SSME start simulation, improved thermocouples to deduce steam concentration, and a test with the SIS using cold water only.

RESOLUTION OF ISSUES

The Test and Analysis Program addressed concerns with SIS performance and function.* By December 1987, in the judgement of the program's Technical Advisory Committee (TAC), all concerns were answered with no outstanding issues (ref. 12). Discussion follows.

Induced Environment

This issue refers to environments induced on the facility and vehicle by the SIS; specifically pressure, acoustic, thermal, and splash.

The SIS must exert no unacceptable back pressure (induce no significant reverse flow) on the SSME during transient or steady operation. The 6.4 percent model SSME engines developed at SCTF provide an excellent emulation of the full-scale article. The model chamber pressure rise rate is tailored to 29,000 psi/sec, equivalent to the SSME rise rate of 1900 psi/sec, such that transient and steady overpressure results apply to full scale. Tests show that levels are acceptable according to Rocketdyne experience.

Results from the 6.4 percent facility at MSFC show that the SIS does not significantly increase steady-state acoustic levels on the facility or on the vehicle (ref. 9). Rockwell concluded that, from an acoustics standpoint, there are no known limitations on the use of the SIS modification at VAFB.

The SSWS, with or without the SIS, must not splash above the duct entrance for all wind conditions. Specifically, it must not introduce water into the SSME bell and past the throat prior to fully developed thrust. Wind tunnel tests with the Astron 1/100 scale SIS at CPP established worst-case winds (ref. 8). Phase 1 tests at 1:1200 scale provided boundary layer characteristics for the Vandenberg terrain for the subsequent Phase 2 (high-fidelity) 1:100-scale experiments.

Conditions in the tunnel are nearly independent of Reynolds' number, and other similarity requirements are met; therefore, speed ratios in the tunnel are equivalent to corresponding ratios at full scale for a particular wind azimuth. Figure 11 illustrates the relation between model and prototype ratios. The launch commit criteria for Vandenberg specifies peak wind speed. This, therefore, provides the criteria for wind tunnel testing. The CPP tunnel is set according to mean speed; consequently, a peak gust to mean ratio is required to set test conditions (figure 11). This ratio was measured during the 1:1200-scale test and also calculated from theory.

* Aerospace White Papers (18 Feburary 1987) and Lockheed Responses to White Papers (24 March 1987).

15 SEPT 1987					SCTF STEAM ONLY			
		MMC/EPL	MSFC STEAM ONLY		ORIGINAL H2O SYSTEM		MODIFIED H2O SYSTEM	
TEST NUMBER		#3	P216-071	P216-071	24683	24673	25104	25104
TEST DATE		APRIL 1987	30 JULY 1987	30 JULY 1987	9 JULY 1987	9 JULY 1987	14 SEPT 1987	14 SEPT 1987
TIME SLICE, SECONDS		AVERAGE	7.5 TO 7.8	9.8 TO 10.1	7.5 to 7.8	9.8 TO 10.1	6.0 TO 6.3	7.6 TO 7.9
AVG. HEADER PRES, PSIA		149	142	142	APROX 160	APROX 158	APROX 155	APROX 158
AVG. HEADER TEMP, DEG F		300	302	302	APROX 295	APROX 305	APROX 294	APROX 303
ID	LOCATION	TEMP / % STM	TEMP / % STM	TEMP / % STM	TEMP / % STM	TEMP / % STM	TEMP / % STM	TEMP / % STM
TD 7	EAST TOP ZONE D EXIT	172.60 54.83	180.94 53.08	183.18 53.76	168.83 43.30	167.93 42.41	177.38 52.61	177.98 53.33
TD 8	EAST BOT/MID ZONE D EXIT	174.20 56.86	184.63 57.55	184.58 57.49	163.10 37.87	161.35 36.32	172.27 46.87	174.63 49.46
TD 9	EAST BOTTOM ZONE D EXIT	NA	184.34 57.19	179.74 51.68	163.08 37.85	161.80 36.72	172.43 47.04	174.18 48.96
TD 4	CENTER TOP/MID ZONE D EXIT	173.50 55.97	182.91 55.43	183.46 56.10	168.20 42.68	164.60 39.23	171.87 46.44	172.47 47.09
TD 5	CENTER BOT/MID ZONE D EXIT	173.90 56.48	183.64 56.32	182.31 54.70	159.20 34.50	156.98 32.69	173.07 47.73	173.13 47.80
TD 6	CENTER BOT ZONE D EXIT	172.00 54.08	183.35 55.96	180.36 52.63	166.05 40.59	165.25 39.84	171.98 46.56	174.06 48.82
TD 1	WEST TOP ZONE D EXIT	165.40 46.42	182.83 55.33	183.64 56.32	169.43 43.91	172.70 47.33	172.18 46.77	173.19 47.87
TD 2	WEST BOT/MID ZONE D EXIT	169.10 50.60	183.63 56.31	182.94 55.46	166.60 41.12	164.40 39.05	168.48 42.96	173.80 48.53
TD 3	WEST BOTTOM ZONE D EXIT	168.30 49.67	182.18 54.55	180.68 52.77	163.73 38.43	164.20 38.87	170.18 44.68	171.93 46.51
ZONE D EXIT AVERAGE		53.11	55.75	54.77	40.03	39.16	46.85	48.71
TD 3 PRIME	WEST BOTTOM ZONE D EXIT	168.30 49.67	NA	NA	177.15 52.34	183.68 60.74	156.31 32.17	168.98 43.46
TD 4 PRIME	CENTER TOP/MID ZONE D EXIT	173.50 55.97	NA	NA	161.50 36.46	166.88 41.38	160.85 35.89	170.28 44.78
TD 9 PRIME	EAST BOTTOM ZONE D EXIT	NA	NA	NA	165.68 40.24	168.80 43.28	149.10 26.92	167.30 41.80
ZD EXIT AVG PRIME		52.82	NA	NA	43.01	48.47	31.66	43.35

Fig. 12 Steam Concentrations from SCTF Compared to MMC/EPL and MSFC

Parameter	Aston	Wyle	Santa Cruz	Martin
Scale	1/100	1/20	1/16	1/7
Phase	II	II	II	II
Test Number	1371	2A	68	45
Header Temperature, °F (Sea Level)	310	307	300	307
N/S Header Dip Angle	53/37	53/37	60/40	60/40
Nozzle Spacing	NonVLS	NonVLS	VLS	VLS
Nozzle Configuration	HIP*	HIP*	6:1 C/D	6:1 C/D
Method of Measuring	Bell Jar	Bell Jar	Anemometers	Thermocouples
Full-Scale Air Entrainment, lb/s	2380	2036	2227	2150
HIP = Hole in Pipe				

Fig. 13 Air Entrainment Rates

Worst-case wind directions at CPP are 180 deg azimuth for maximum pressure differential and 135 deg for worst observed aerosol. The puff of aerosol comes off the west wall, rises a quarter of the way to the SSME nozzles, and curves back into the center of the duct. Effects in the duct are such that the splash boundary should be the same at all scales; however, the magnitude of the splash does not geometrically scale and is probably much worse at small sizes. The next step, therefore, is to exercise these worst-case winds at the higher-fidelity MMC/EPL test facility.

Tests at EPL used large fans to induce flows representative of CPP worst-case winds. There was some splash back during the water start transient at EPL, although none as high as the SSME exit plane. A definitive test of splash effects on the engine employed a properly scaled helium purge of 3.5 ft/sec through the SSME. For worst-case winds, the purge velocity is not reversed; therefore, no steam passes the throat. And droplet trajectory analysis indicates that no large drops would reach the SSME exit plane at full scale (ref. 7).

Burning at the Duct Entrance

The specific issue here is whether or not detrimental excess hydrogen, ignited by the SSMEs or HBOIs above the duct entrance, continues to burn in a robust and global fashion down to some (defined as) critical surface within the duct.

Analysis and study by Aerospace* concludes that single-point ignition above the duct results in a fully burning (turbulent combustion) flame for SSME conditions. Maximum flame lift-off is less than eight inches (flames are inside the nozzle). Blow-off does not occur. These conclusions agree with test observations.

Inerting in Duct

It is convenient to define a critical surface at the duct entrance at which combustion stops because of a deficiency of hydrogen or air (or because of an excess of inertants from the combustion process or the SIS flashing sprays). There may also be a critical surface at (or beyond) the duct exit past which the inert mixture becomes weakly flammable. The criterion for an inert duct is that points between these surfaces correspond to benign states in the flammability diagram (figure 8).

As part of an early evaluation of SIS feasibility, Aerospace performed a control volume analysis, injecting steam plus burning hydrogen into a duct.* This study shows that the SIS should inert the duct and that the process is self-compensating: increased hydrogen or air flow increases combustion and returns the duct to an inert state. All subsequent testing confirms these conclusions.

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* Aerospace White Papers (18 Feburary 1987) and Lockheed Responses to White Papers (24 March 1987).

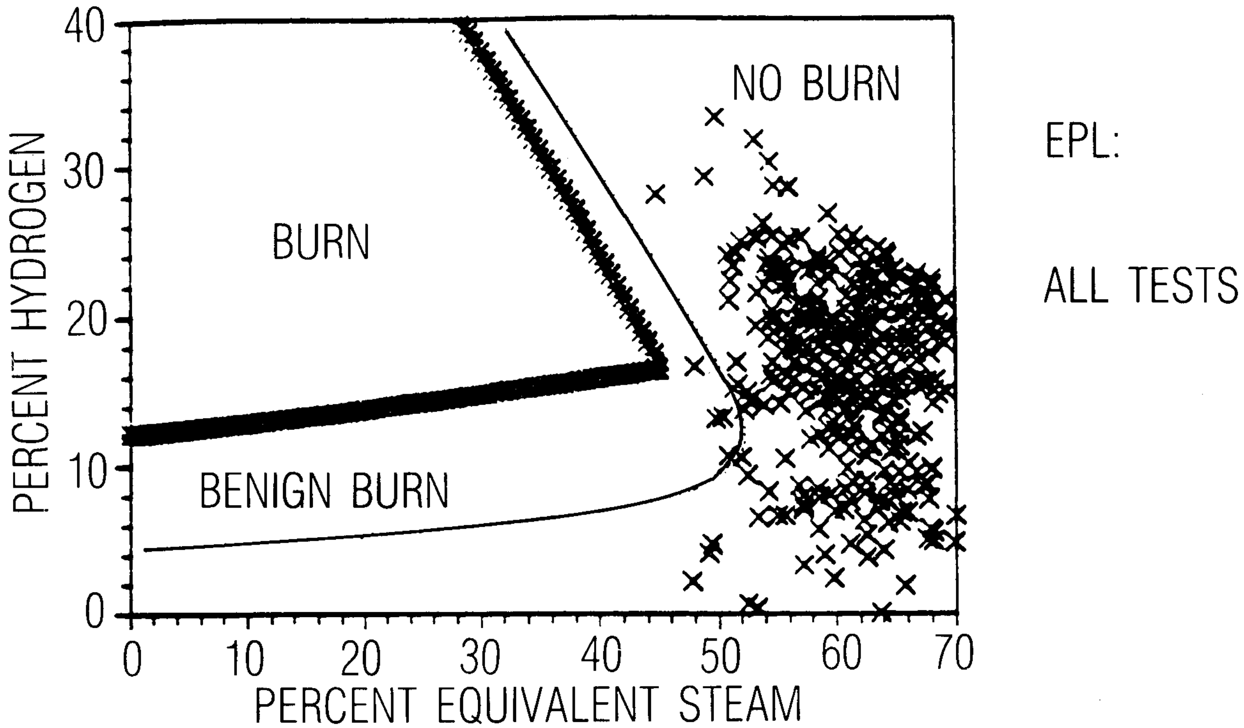

Fig. 14(a) Hydrogen vs Steam Concentrations for All EPL Tests

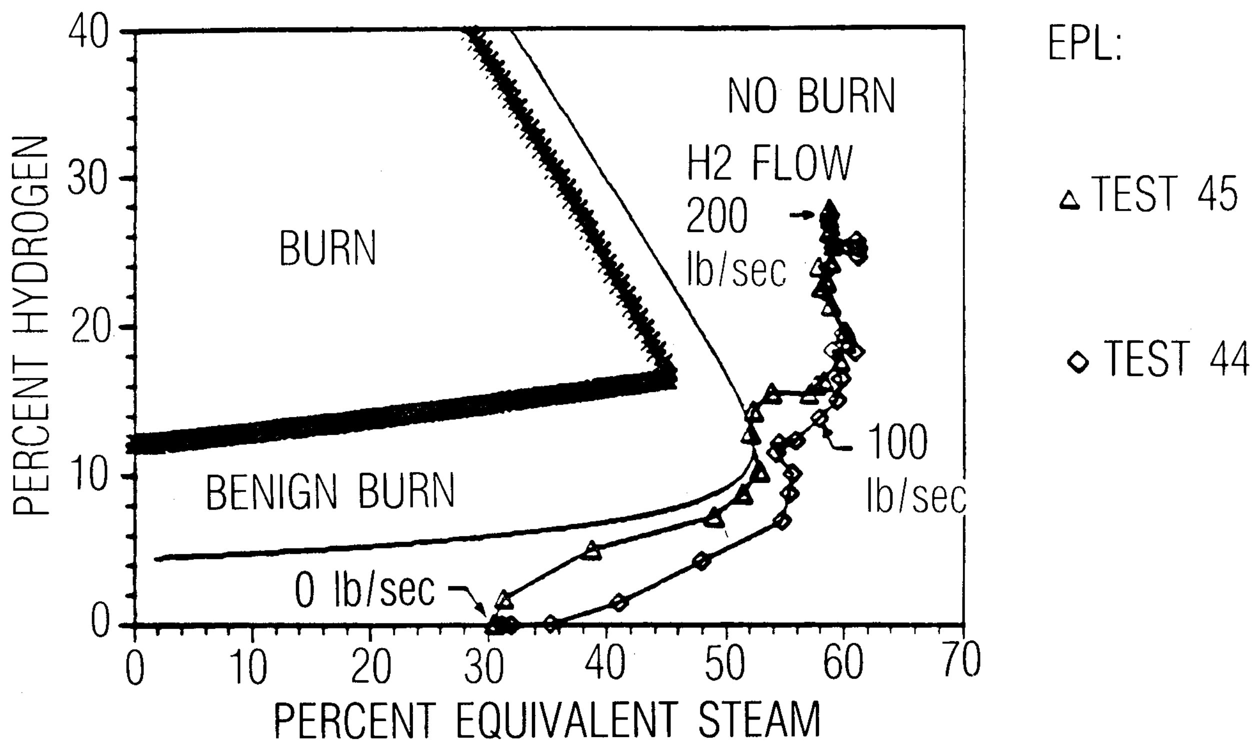

Fig. 14(b) Hydrogen vs Steam Concentrations During EPL Startup Transients

For tests with the steam header alone, figure 12 compares steam concentrations from the SCTF 6.4 percent test with data from MMC/EPL at 1/7 scale and MSFC and 6.4 percent (refs. 7, 9, and 11). Results compare well, although the SCTF values are systematically a few percent lower.

Figure 13 presents full-scale equivalent entrainment rates from steam-only tests for the four different scales and indicates excellent agreement. The MMC/EPL calculation of air entrainment is predicted on the volume fraction of steam indicated by duct thermocouples. Calculations from Wyle use a bell jar. The SCTF tests use hot wire anemometers to calculate entrainment. Agreement among these different sites and methods supports two key conclusions about conditions in the duct: geometric scaling applies, and the assumption of local thermal equilibrium is valid.

For hydrogen experiments, the state in the duct is more complex. In the neighborhood of a burning hydrogen plume, temperatures are very high -- well in excess of the boiling point of water, 212°F. During SSME mainstage, such a condition may extend well into the duct. During the ignition or shutdown transient, this condition exists near the entrance (above the critical surface at which combustion stops). The SIS must inert the duct past this surface. Tests verify this condition in that steam fractions (from temperature data) compared to hydrogen concentrations (from samples) correspond to benign points in the flammability diagram of figure 8. At a specific location, of course, the thermocouple must be robust enough to survive the plume and fast enough to track the inerting process.

The MMC/EPL tests provide additional data pertaining to steam concentrations in the duct. These include experiments to study system margin using an air ejector to augment air entrainment by factors up to 2.5 times the steady state design point level. Figure 14(a) shows that all measurement locations for all EPL tests are safe on the flammability diagram (figure 8). Figure 14(b) illustrates trajectories on the diagram during the startup transient for two EPL tests (ref. 7). The trajectories begin and remain safe. This constitutes a dynamic verification of the (statically derived) flammability boundary.

Test and analysis work at MMC/EPL answered several special performance issues: time required to fill the duct with steam, steam concentration in the region of air between the three SSME plumes, and the effects of condensation at the duct walls (ref. 7).

Scaling

The S. Levy Corporation provided scaling analysis during the SIS program. Theory and experiment, as reviewed above, show that, within the duct, inerting performance scales geometrically as required. Parameters affecting buoyancy at the duct entrance and exit are Froude scaled. Momentum scaling is used to match the 1/100 header flow to simulated winds. As noted, water sprays, droplets, and agglomerations do not scale. However, associated testing is very conservative, because effects are much more severe at small size than at large size.

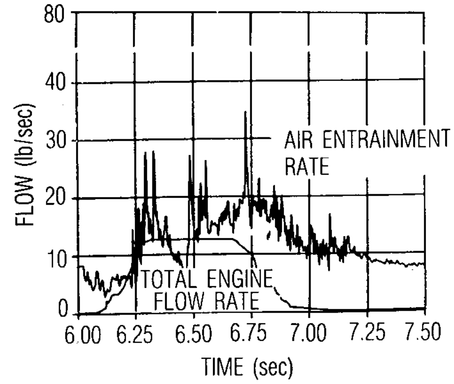

Fig. 15 Air Entrainment for SCTF 6.4% FRF Test

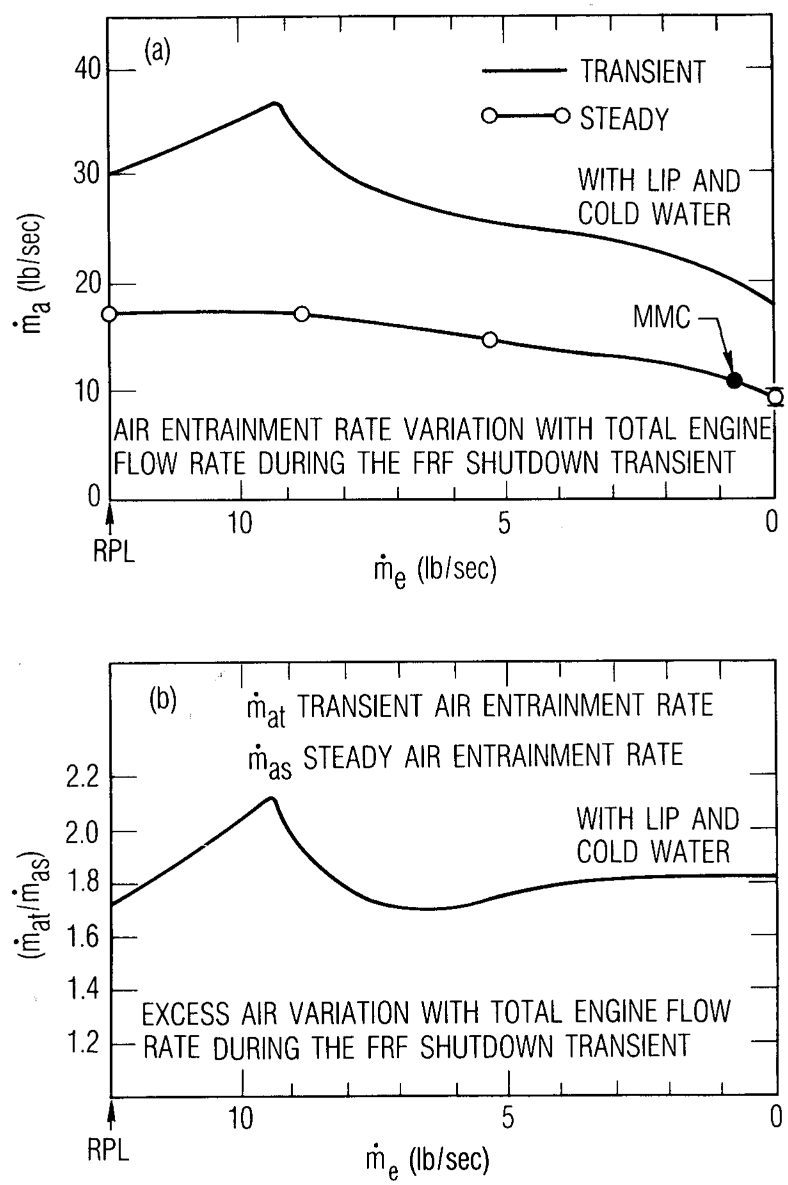

Fig. 16 Transient Compared to Steady Air Entrainment During FRF Shutdown

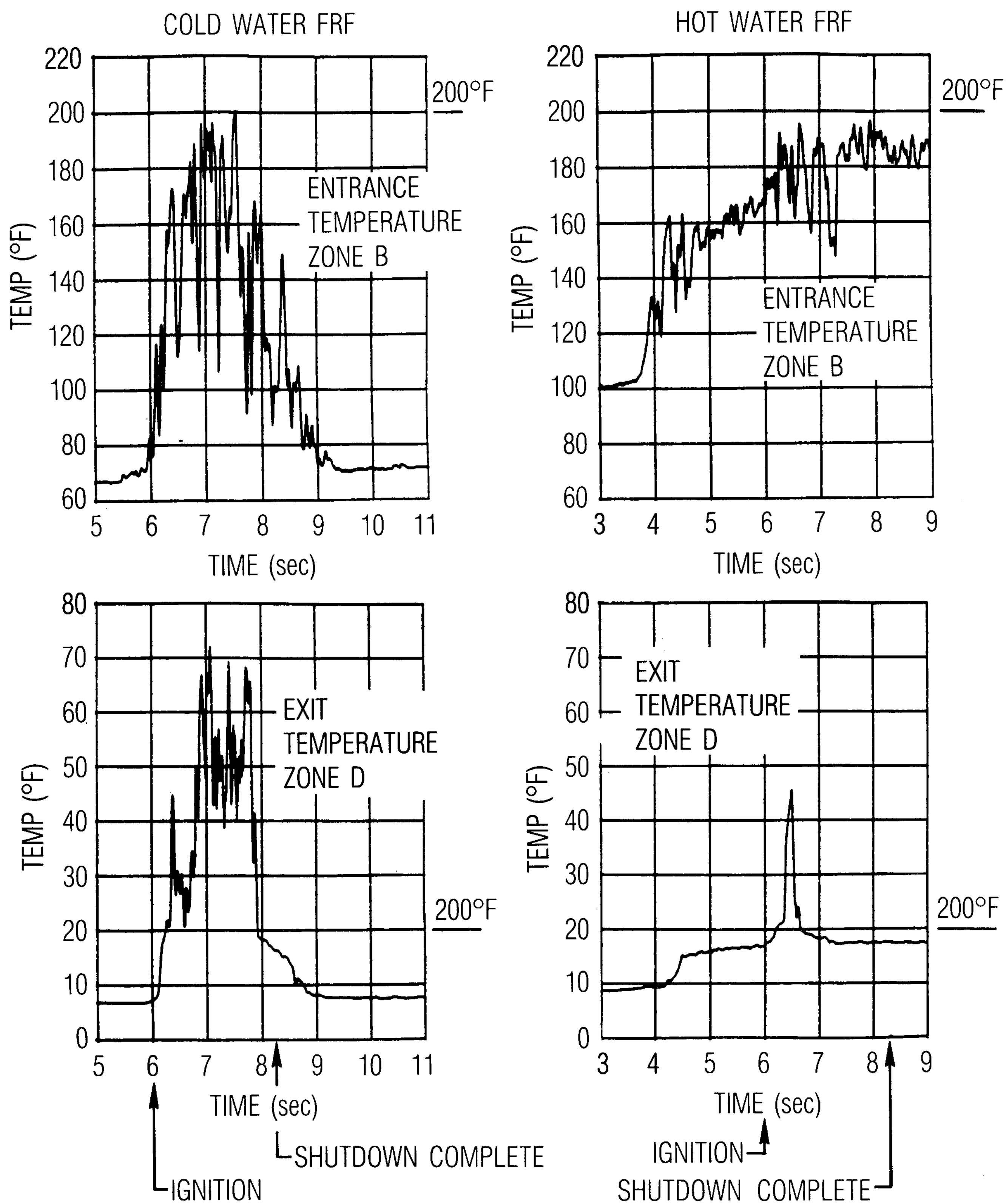

Fig. 17 Temperature in Duct During FRF With and Without Heated Water

This credibility of performance scaling is most important. It is this feature of steam inerting that supports acceptance of the SIS without a prohibitively expensive, full-scale SSME test prior to FRF.

Transient Effects

The 6.4 percent tests at SCTF satisfy a postulated need for data with SSME engines, including a transient hot fire phase. There was a question concerning whether or not steady tests at the maximum rate of unburned hydrogen (design point threat) are an adequate representation of the corresponding transient condition. The concern is that dynamic lag might significantly increase aspiration in the transient shutdown case.

The SCTF tests simulated FRF and clustered abort shutdown scenarios. Figure 15 illustrates air entrainment and total engine flow rate for a 6.4 percent FRF with SIS superheated water. For comparison, SCTF tests included an FRF run with ambient SIS water. The ratio of air entrained to engine flow rate at SSME rated power level (RPL) is approximately 2.40 for cold water as opposed to 1.35 for the baseline hot water SIS. That is, the cold water case aspirates 78 percent more air than the hot water system.

The final tests at SCTF used a small lip on the SSME duct to reduce subscale splash. These experiments included increased test duration at RPL and steady operation at 72 percent and 43 percent RPL toward the end of a run to diagnose transient aspiration effects. The (final) cold water test happened to have the longest run duration; therefore, is best for this diagnosis. Figure 16 compares transient to steady aspiration for values of total engine flow rate for the cold water test. The lower sketch shows the ratio, which has a maximum value of 2.10. With a correction for hot water, this ratio is 2.10/1.78 = 1.18. Therefore, the maximum increased air entrainment because of transient lag ranged from 18 percent for hot to 110 percent for cold SSWS water.* As explained above, MMC/EPL testing shows that the SIS meets requirements and is safe for as much as 150 percent extra air (ref. 7).

Comparison of SCTF hot and cold water tests contributes insight into the steam inerting process. Figure 17 compares temperatures for the hot and cold tests at the floor of the duct entrance (zone B) and at the center of the duct exit (zone D).

With the hot water SIS, the entrance temperature near the wall advances to 180 and then to 190°F, continuing after mainstage shutdown -- indicating a continuing inert condition. The SSME plume evidently does not reach the lower wall of the duct. The exit condition is 180°F (inert) and jumps briefly to 450°F at SSME start. This suggests that the plume initially projects burning or superheated gas well into the duct. But, very quickly, the added steam from combustion inerts the entire duct. Conditions remain inert after combustion stops. This supports the key SIS operational requirement.

* Goginení, P. R.: Transient Flow Effects. Lockheed Interoffice Corresponsdence (20 Oct. 1987).

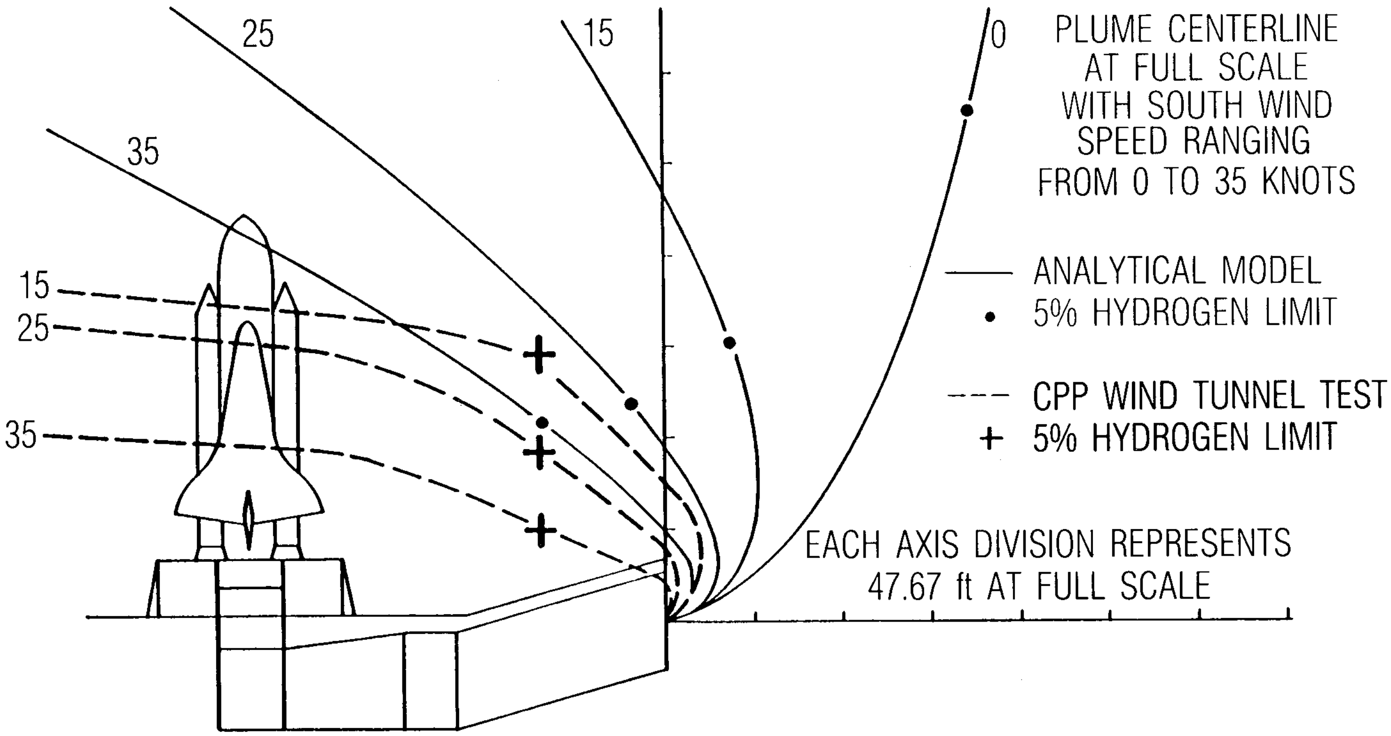

Fig. 18 Exit Plume Concentrations Test Results

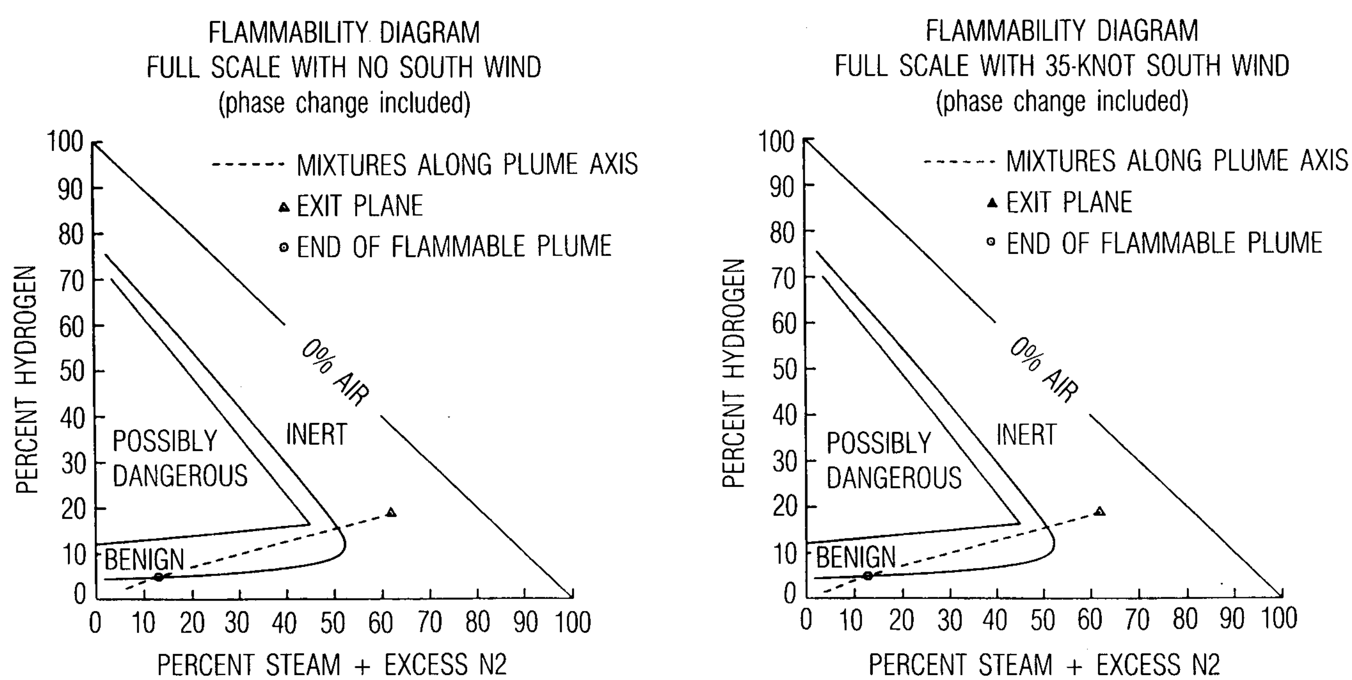

Fig. 19 Exit Plume Concentrations on Flammability Diagram

With cold water, the SSME plume quickly raises the temperature at the entrance floor to 190°F and at the exit to 550°F. For approximately 0.5 sec, just before mainstage shutdown, the cold test entrance temperature is well below 180°F. The exit temperature gradually ramps down from 180°F to ambient during this interval.

Therefore, with the hot water SIS, the duct remains inert and safe throughout the FRF. Without the SIS (with cold water), these data do not prove that the duct remains inert. Very possibly, in the cold water experiment, sufficient hydrogen has burned between the entrance and points in question such that the duct is safe. But detailed sampling over repeated runs would be required to show this, and arguments would be statistical. The SIS (with hot water) makes the duct safe with generous margin.

Purging and Venting Duct

Toward the end of the operational scenario in figure 7, the SIS must provide sufficient momentum to purge the SSME duct of hydrogen. Planetary wind tunnel tests at CPP established worst-case winds at the duct exit (ref. 8). EPL performed corresponding worst-case tests with fans at 1/7 scale (ref. 7). These experiments show that the ratio of duct exit flow to peak wind momentum is 1.33 -- indicating outflow. This verifies that wind will not enter the duct or reverse the exhaust flow.

Two requirements apply to the exhaust plume during SIS operation. There must be no possibility of a deflagration at or beyond the duct exit, and the plume must not be flammable near the shuttle vehicle for worst-case winds.

Figure 18 includes results of an Aerospace analysis of interaction of the exhaust plume with ambient air and south winds.* Corresponding state trajectories for no wind and 35 knots are shown in figure 19. The calculation includes condensation and evaporation in the plume. The trajectories remain in the benign region of the flammability diagram. Therefore, free space detonation is not possible.

The calculation in figure 18 indicates that the exit plume is not flammable (below 5 percent) near the vehicle for all wind conditions. On the same figure, data from the CPP Phase 3 tests, with an indicator gas, verify this result (ref. 8). The experimental trajectories are more depressed and differ somewhat from theory -- probably because the analysis is quasi-one-dimensional. However, in no case is there a flammable condition near the shuttle vehicle.

* Moody, D.: Effects of Wind and Scale on Plume. Aerospace Interoffice Correspondence (11 Feb. 1987).

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