An Overview of the A-3 Subscale Diffuser Test Project

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Introduction

- The Subscale Diffuser Test (SDT) Project comprised a series of tests of a subscale model of SSC's A-3 Test Stand diffuser.
- SDT was conducted at NASA's Stennis Space Center (SSC) Apr 2007 - Jan 2008
- Purpose of SDT was to mitigate design risk for the A-3 diffuser.
- Initial scope of the SDT project successfully completed in Jan 2008
- Follow-on A-3 risk mitigation testing being planned/considered
- This presentation presents an overview of the SDT project.

A-3 Test Stand

A-3 Test Stand:

- Under construction at SSC, activation is scheduled to begin in the latter part of 2009.
- Will perform simulated altitude (100,000 feet, 0.16 psia) testing of J-2X engine
- 300-foot tall, steel support structure
- LOX and LH2 propellant capabilities
- Altitude simulation will be accomplished by means of a test chamber-diffuser combination.

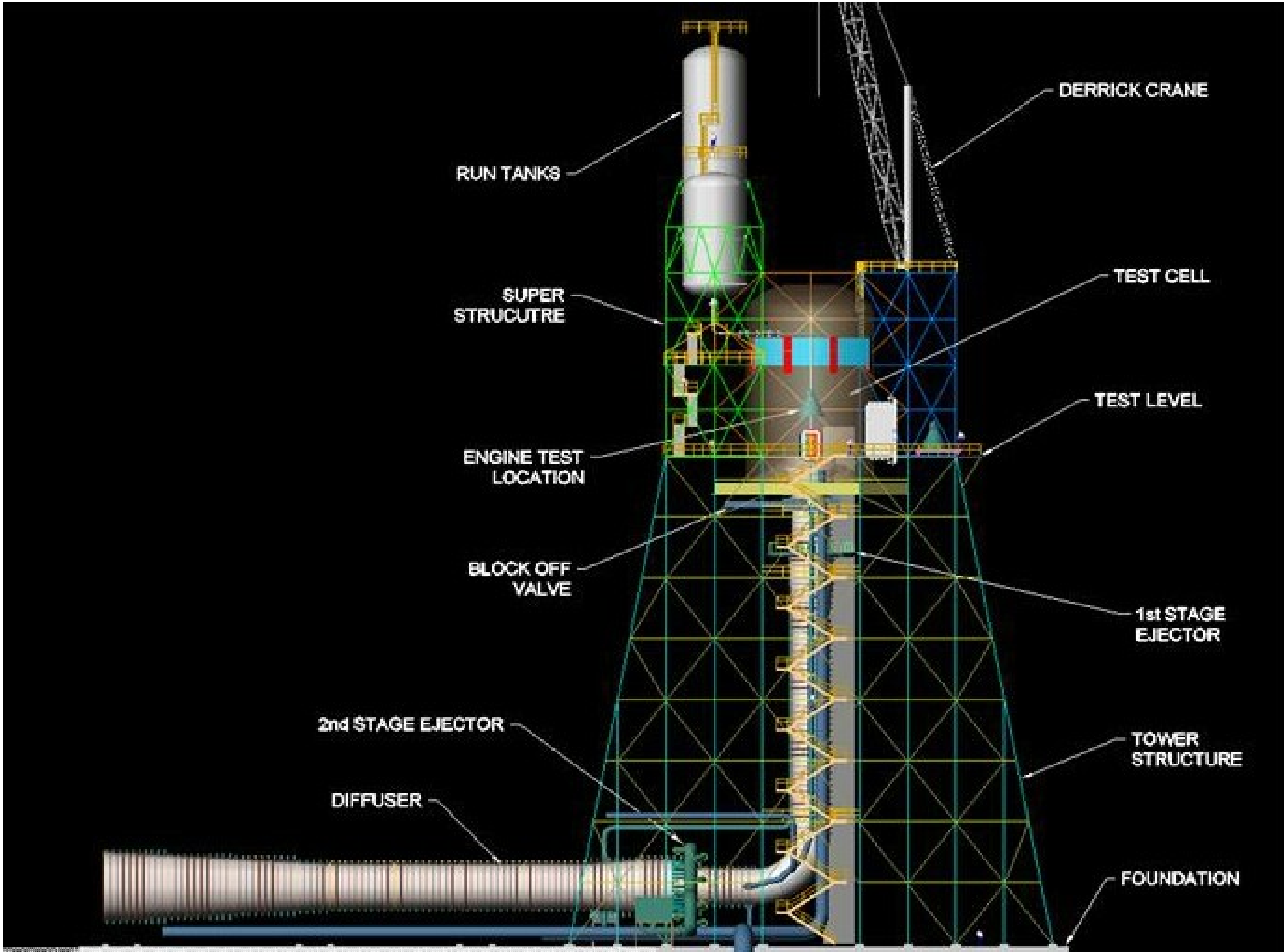
Diffuser:

- 360-foot long
- Carbon steel segments, approx 12 feet diameter.
- Each segment of the diffuser has dedicated cooling water piping
- Cooling water fed by SSC's existing High Pressure Industrial Water pumping system
- Pump-down of the test chamber will be accomplished by means of the diffuser's two annular steam ejectors.
- Testing in both gimbaled and non-gimbaled orientations

Steam:

- Diffuser steam ejectors driven by superheated steam
- Dedicated chemical steam generation system
- 27 isopropyl alcohol/LOX chemical steam generators
- Steam mass flow rate of 4,800 lbm/sec.

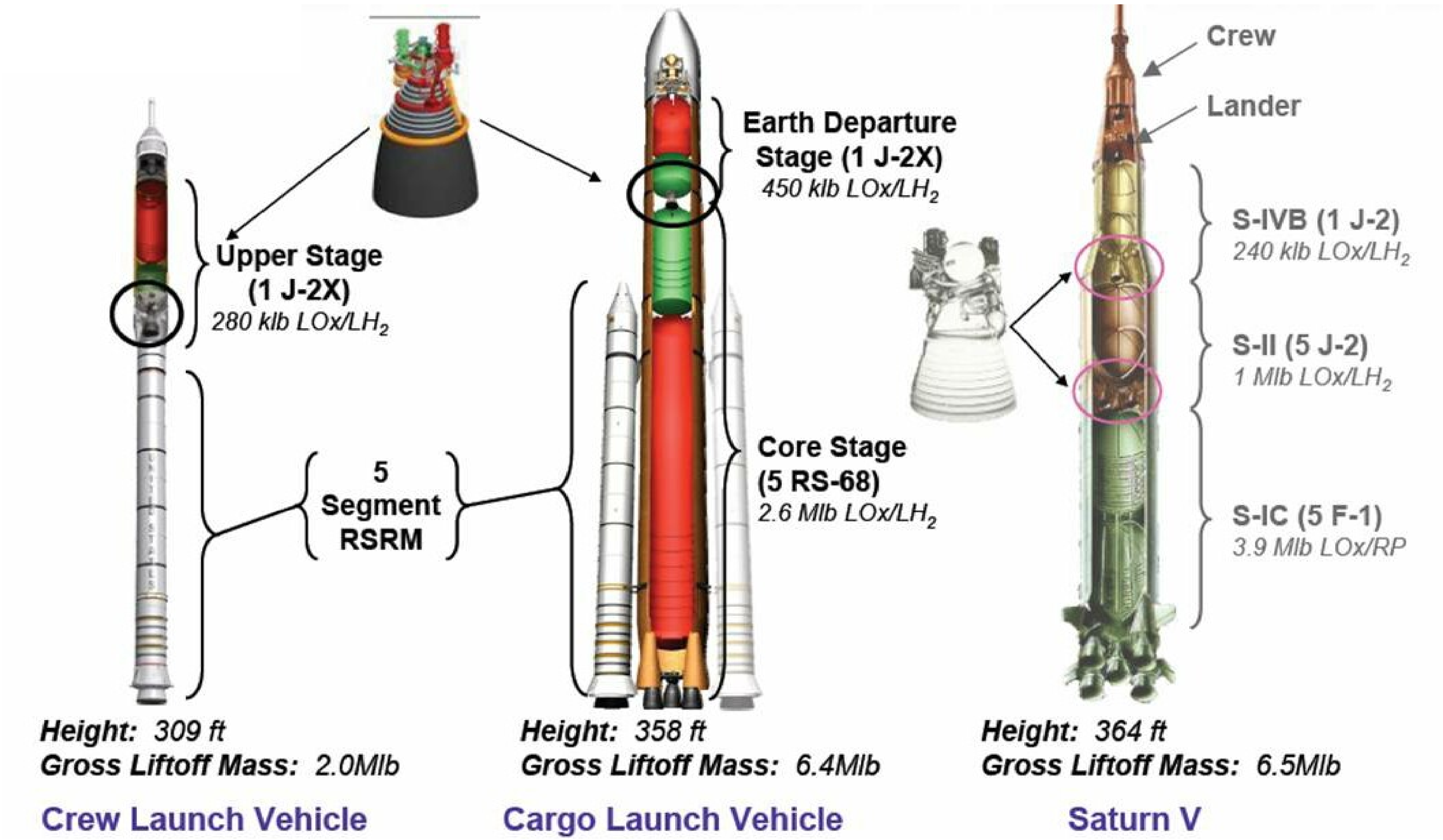
A-3 Test Stand



J-2X and the Constellation Program Mission Architecture

- NASA’s Constellation Program will result in replacement of the Space Shuttle and in the resumption of human missions to the Moon.
- Constellation Mission Architecture includes two new launch vehicles:
  - ARES I for human launch capability, i.e., Crew Exploration Vehicle
  - ARES V for heavy cargo lift capability
- J-2X engine will act as main propulsion element for
  - ARES I’s upper stage
  - Earth Departure Stage, placed in LEO by ARES V for lunar missions

Constellation Architecture



J-2X Engine

- Design by Pratt and Whitney Rocketdyne (PWR) under NASA contract
- Enhancement of J-2 engine, which propelled the Saturn S-II and S-IVB stages
- LH2/LOX, gas generator cycle engine
- Significant features and performance improvements over the J-2:
  - Higher combustion chamber pressure (1,337 psia)
  - Increased density injector
  - Greater nozzle extension ratio (92:1)
  - Turbine exhaust gas injection
  - Upgraded turbomachinery and gas generator
  - Increased maximum thrust capability (294,000 lbf)
  - Greater specific impulse (448 seconds)

- Development and certification testing objectives for J-2X altitude testing at A-3:
  - Demonstration in near-vacuum conditions of start and restart capability
  - Demonstration of engine performance
  - Characterization of nozzle extension response

J-2X Engine

SDT Test Project Definition

- Initiated and funded by Marshall Space Flight Center's (MSFC) J-2X Project Office

- Risk is due to lack of analysis techniques and empirical data to support design of the integrated diffuser system.

- Three A-3 diffuser performance issues recognized:
  - Is diffuser design adequate to pump down test chamber pressure to required levels?
  - What will the diffuser wall heating rates be? (Impacts design of diffuser, cooling water system, and steam system)
  - What will pressure loss in the diffuser elbow be? (Excessive pressure loss can cause internal choking, engine unstarting.)

- Approach selected to address these issues :
  - Test subscale model of A-3 diffuser/test chamber at SSC E Test Complex
  - Both hot-fire and diffuser-only testing
  - Injection of steam into steam ejectors
  - Use of small rocket in test chamber to simulate J-2X
  - No need to cool subscale diffuser – short (< 12 sec.) hot fires adequate

SDT Project Test Series

No.	Test Series	Description
1.	2nd Stage Steam Ejector Tests	• Steam flow into 2nd Stage Steam Ejector • Measure ability of 2nd Stage Steam Ejector to pump down Test Chamber at various steam drive pressures • Varied GN_2 flow into the Test Chamber test-to-test to determine secondary flow pumping performance.
2.	1st and 2nd Steam Ejector Combination Tests	• Steam flow into both 1st and 2nd Stage Steam Ejectors • Measure ability of 1st and 2nd Stage Steam Ejector combination to pump down Test Chamber at various steam drive pressure combinations • Varied GN_2 flow into the Test Chamber test-to-test to determine secondary flow pumping performance.
3.	J-2X Simulator Hot Fire Tests	• Steam flow into both 1st and 2nd Stage Steam Ejectors • Constant drive pressure on each Steam Ejector • Measure Test Chamber pressure for various rates of secondary GN_2 flow • Firing of engine at both 80% and 100% power levels • Measurement of diffuser heating profiles • Measurement of diffuser pressure profiles

SDT Project Test Objectives

Objective	Test Requirement	Addressed by Test Series:
Verify Performance of 2^{nd} Stage Steam Ejector	Produce "standard" Ejector performance curve for various secondary flow rates for the 2^{nd} Stage Ejector (Ejector suction pressure vs. ejector steam drive total pressure)	2^{nd} Stage Steam Ejector Tests
Verify Performance of combined 1^{st} Stage and 2^{nd} Stage Steam Ejectors	Produce "standard" ejector performance curve for various secondary flow rates for the 1^{st} Stage Ejector (Ejector suction pressure vs. ejector steam drive total pressure)	Combined 1^{st} & 2^{nd} Stage Steam Ejector Tests
Verify Rocket Diffuser performance when operating in conjunction with the 1^{st} and 2^{nd} Stage Steam Ejectors	• Determine Rocket Diffuser characteristics and operating margins. • Produce rocket diffuser performance curves (Test Chamber pressure vs. secondary flow rate) for both 80% and 100% rocket power levels	J-2X Simulator Hot Fire Tests
Determine Diffuser heat transfer rates	Determine maximum heating rates under hot fire • at plume impingement areas • at downstream locations, esp. in elbow	J-2X Simulator Hot Fire Tests
Determine Diffuser pressure profiles	Determine pressure profile along the Diffuser path, particularly in the 90 deg. elbow, under hot fire	J-2X Simulator Hot Fire Tests

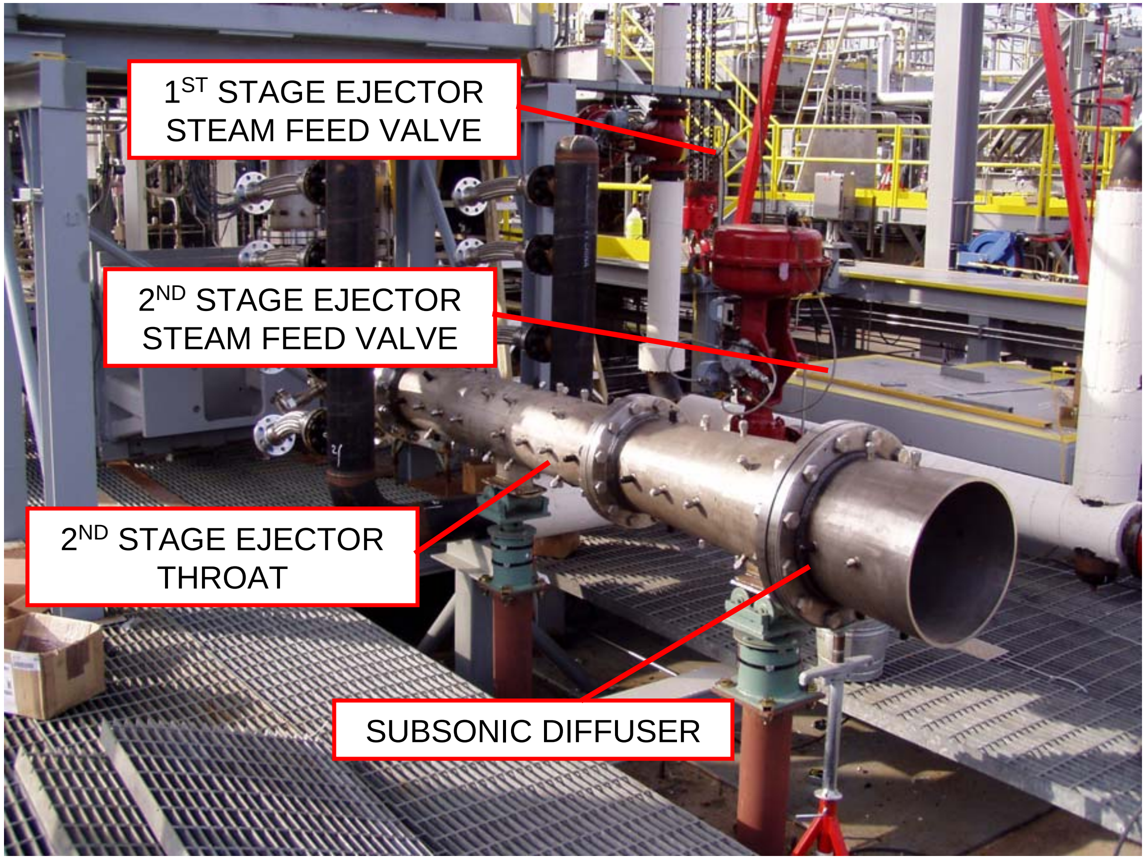
Minimum Measurements

Parameter	HS/ LS	Instrument	Comment
Test Chamber Pressure	LS	Pressure Transducer	
GN_2 Secondary Flow Drive Pressure	LS	Pressure Transducer	Used to calculate GN_2 flow rate
1st and 2nd Stage Steam Ejector Drive Pressures	LS	Pressure Transducers	
Diffuser Pressure (at various points along Diffuser)	HS	Pressure Transducers	Used for pressure profile along the diffuser path, particularly in the 90 deg. elbow
Rocket Diffuser Pressure (at various points, inside Test Chamber)	HS	Pressure Transducers	Assessment of rocket diffuser performance
Diffuser Temperature (at various points along Diffuser)	HS	Type K Co-axial Thermocouples	Heat flux measurements, particularly in plume impingement areas and compression corners
Diffuser Temperature (downstream of 2nd Stage Steam Ejector)	HS	Type K Co-axial Thermocouples	Determine flow characteristics along diffuser wall, evaluate necessity of active cooling

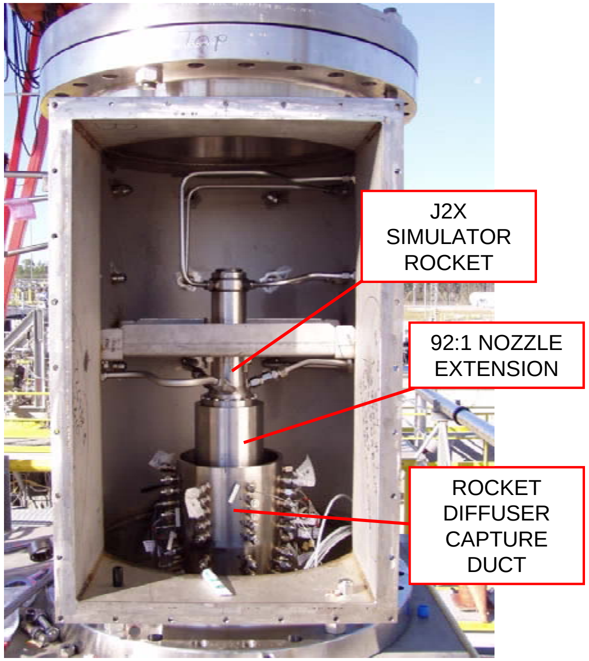
SDT Test Article

- Designed by Jacobs Technology Incorporated (JTI) under a NASA contract.
- Design based on extensive JTI knowledge/experience with altitude testing at AEDC
- SD is a 5.783% model of the fullscale A-3 diffuser design.
- SD includes:
  - L-shaped diffuser
  - two annular steam ejectors
  - no active cooling system
- Test Chamber:
  - encloses engine during hot fire test
  - secondary GN_2 flow through the test chamber and into the diffuser by means of a ring purge device at the top of the chamber
  - variable GN_2 flow rate

SDT Test Article

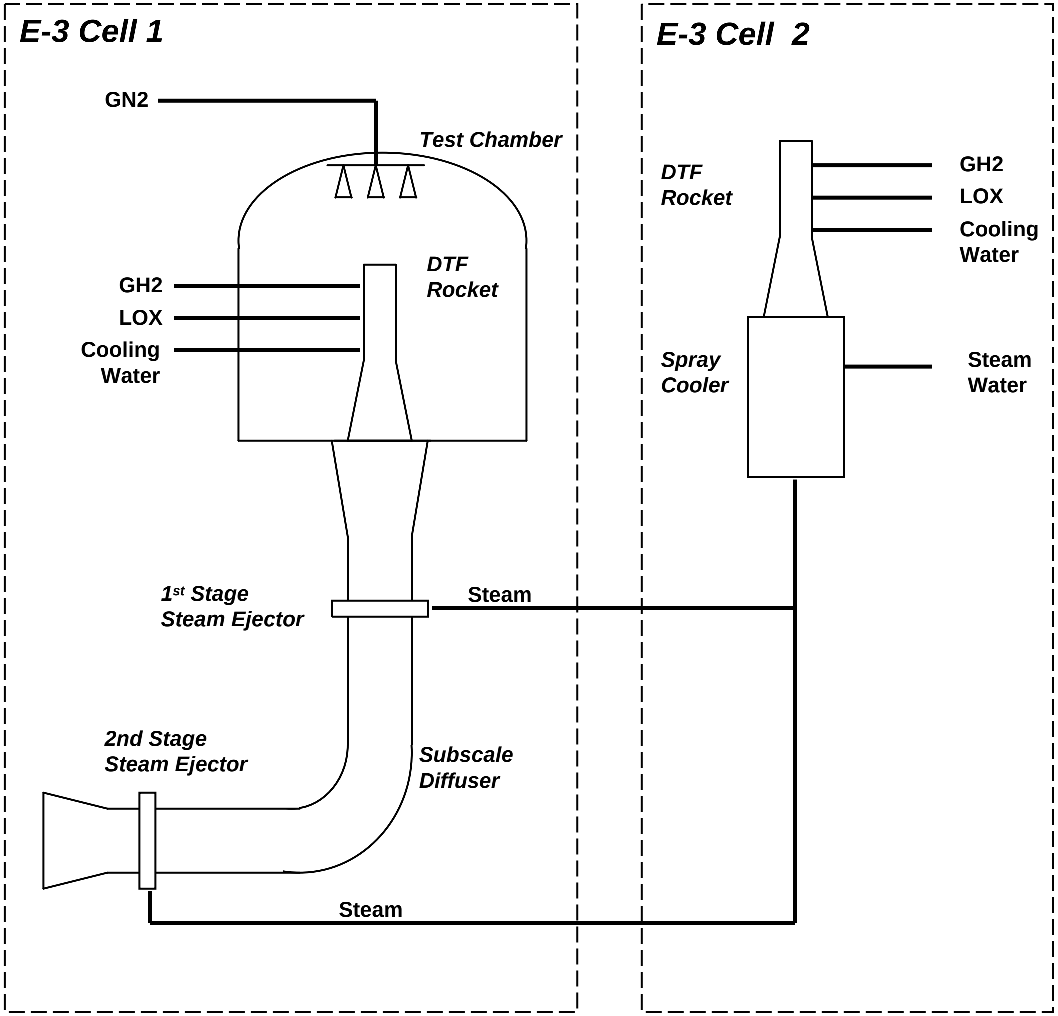


Subscale Diffuser



Test Chamber

Facility Test Configuration



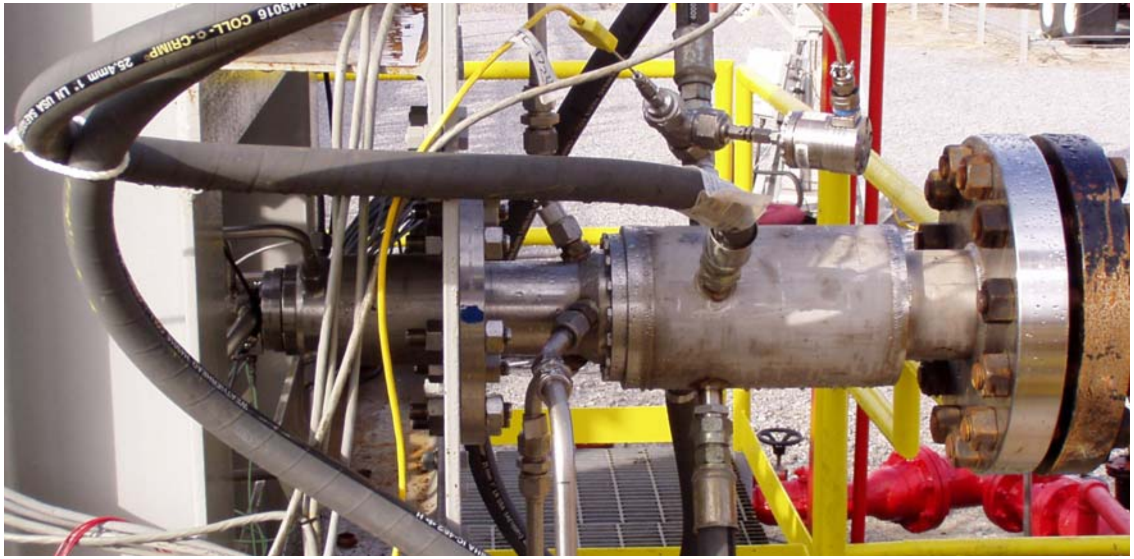
- Tests performed at SSC's E-3 Test Stand
- Test Article installed in Cell 1
- Cell 2 dedicated to steam generation to drive the diffuser steam ejectors
- Test Chamber enclosed small rocket engine to simulate J-2X firing

J-2X Simulation

- Modified “DTF” rocket engine used for J-2X simulation
- DTF features:
  - GH2/LOX-propellant
  - Water-cooled
  - ~1,000 lbf of thrust
  - modular design
    - -- injector assembly
    - -- outer sleeve
    - -- inner cylindrical copper liner/thrust chamber
- DTF history:
  - developed at MSFC in 1964 as the 1.2K Thrust Rocket Engine
  - operated by SSC at its Diagnostic Test Facility in 1992 and 1993 for plume diagnostics research
  - used at AEDC in the late 1970s
  - used at MSFC component development, plume diagnostics
- Appropriate for J-2X simulation
  - Appropriate scale
  - Simplicity and ease of reconfiguration
  - SSC’s familiarity with its operation
- SDT use:
  - 92:1 nozzle attached to DTF flange
  - Inner liner/thrust chamber redesigned for Pc = 1332 psia, equal to J-2X Pc at 100% PL
  - (A second DTF, with no-throat liner, served as the steam generator combustor.)

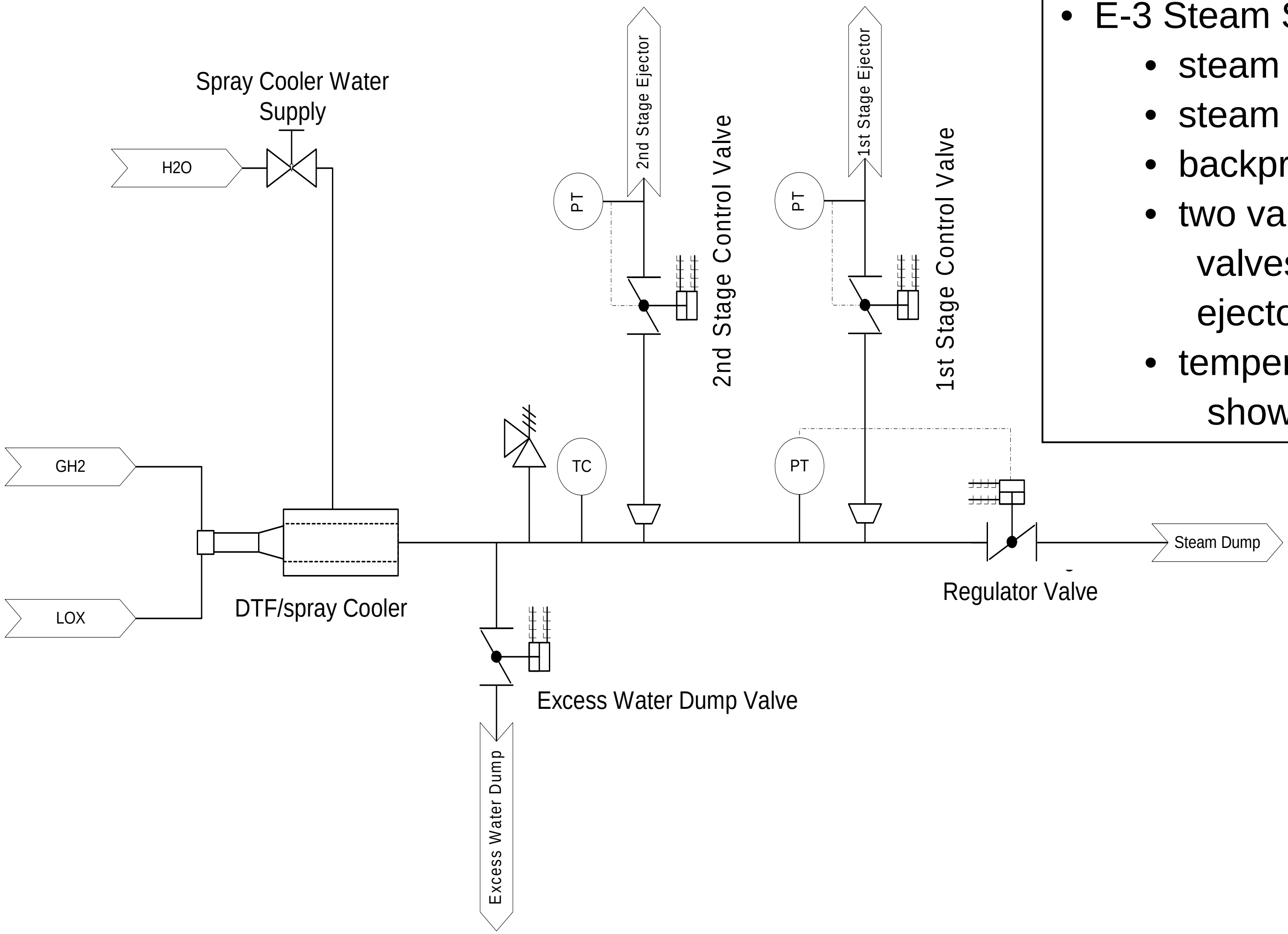
DTF Rocket Engine

SSC Steam Generator



- Commercial steam sources proved to be prohibitively expensive, oversized.
- Steam Generator designed/developed by SSC
- SSC Steam Generator comprises DTF Engine mated with Spray Cooler.
- Original DTF thrust chamber replaced with no-throat liner to act as combustor
- Spray cooler injects potable water for vaporization in the DTF plume
- Steam output:
    - ~400 psig
    - ~500 degF
    - ~20 lbm/sec

E-3 Steam System



- E-3 Steam System included:
  - steam generator
  - steam water dump valve
  - backpressure control valve
  - two variable position control valves at SD steam ejectors
  - temperature rake (not shown)

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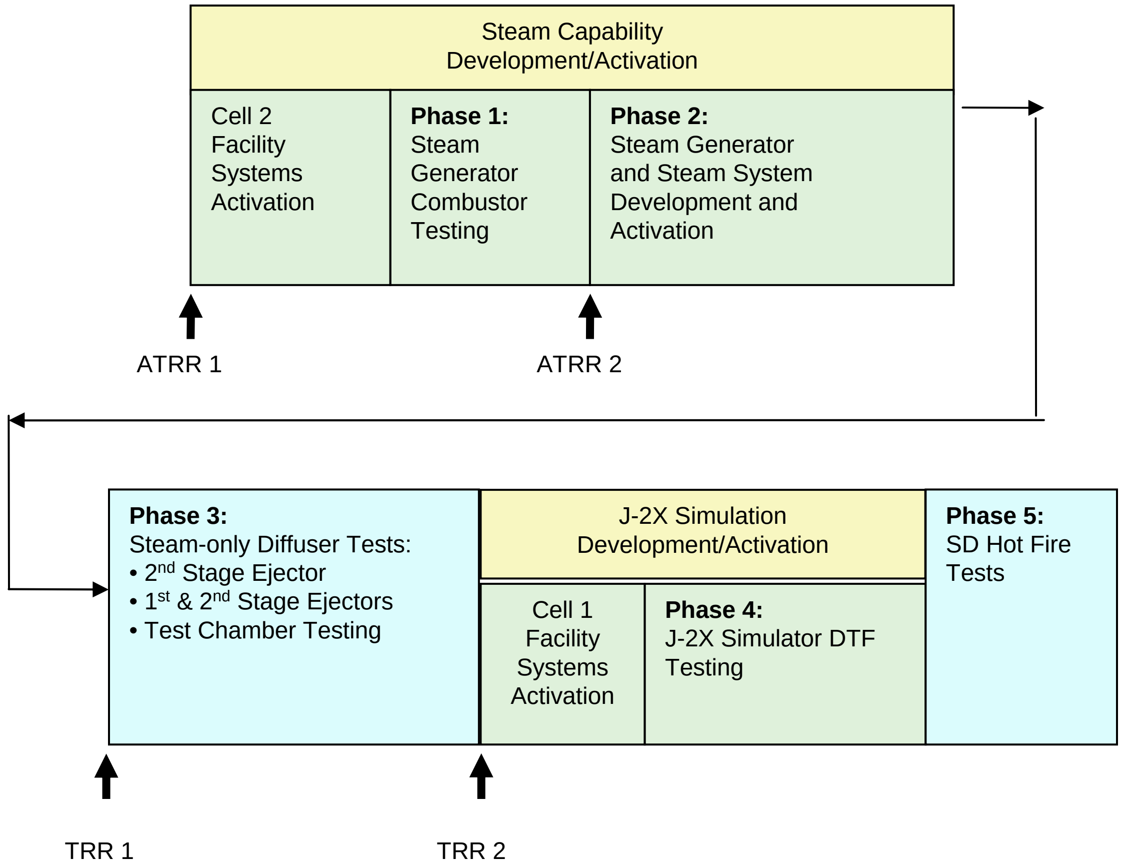
Notable Facility Modifications

- Implementation of Steam System
- Implementation of GH2 System
- Implementation of Water Systems
  - J-2X simulator cooling water
  - Steam water
  - Steam generator combustor (DTF engine) cooling water
  - Entailed conversion of systems formerly used for methane, JP, and H2O2 to potable water service
- Modification of Control System
  - Simultaneous operation of two test cells, two control consoles, two test sequencers
  - Passing of some redlines, bluelines, and other parameters between the two sequencers

Process Modifications

- Normal test project sequence of events at SSC:
    - Test system design
    - Construction
    - Activation Test Readiness Review (ATRR)
    - Facility activation
    - Test Readiness Review (TRR)
    - Testing
- SDT required modifications to the normal sequence:
    - Phased testing
    - Interleaving of test article tests, developmental tests and activation tests
    - Multiple ATRRs, TRRs



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Operations Modifications

SDT required modification of the normal test conducting procedures:

- Two test conductors
  - one to control steam generation in Cell 2
  - one to control J-2X simulator hot fire and diffuser steam valves in Cell 1
- Headset communication and coordination between test conductors
- After steam generator start, needed to wait for steam system to warm up (60 – 90 sec.) before start of J-2X simulator

Outcomes

- Original testing scope completed in Jan 2008
- Initial deliveries of thermal and pressure data delivered to the A-3 Project Office
- Analysis of other data continues.
- Original SDT test objectives were met.
- Steam generator and the entire steam system performed as required: superheated steam at required temp and press delivered to the subscale diffuser steam ejectors for up to 3 min.
- Modification of the DTF liner to raise its chamber pressure to equivalent of J-2X full power level was successful, and the rocket engine otherwise performed as required.
- Test results:
  - 2nd stage ejector suction resulted in pump-down of test chamber to better than predicted pressure level.
  - Addition of 1st stage ejector suction resulted in pump-down of test chamber to pressure level short of that required
  - The rocket diffuser reduced the test chamber pressure to below required pressure level during rocket hot-fire at 100% power level.
  - Follow-on tests with modified 1st stage ejector nozzle geometry resulted in test chamber pressure below required pressure level.

Future

- SD/E-3 test configuration is valuable as a testbed for further A-3 diffuser risk mitigation.

- Additional design and operational tests being planned or considered:
  - Rocket nozzle differential pressure
  - Soft shutdown (minimal blowback)
  - Water injection upstream of the diffuser elbow
  - GOX injection into steam system (WSTF O_2 mass fraction simulation)
  - Relationships between nozzle contours and test cell pressure excursions
  - Gimbal testing with various area ratio nozzles
  - Water deluge of exhaust exit jet (noise suppression)
  - Test without sub-sonic diffuser

- NASA/JTI plans to report further details regarding design, operation, and test results of the SDT project in the AIAA community forum.