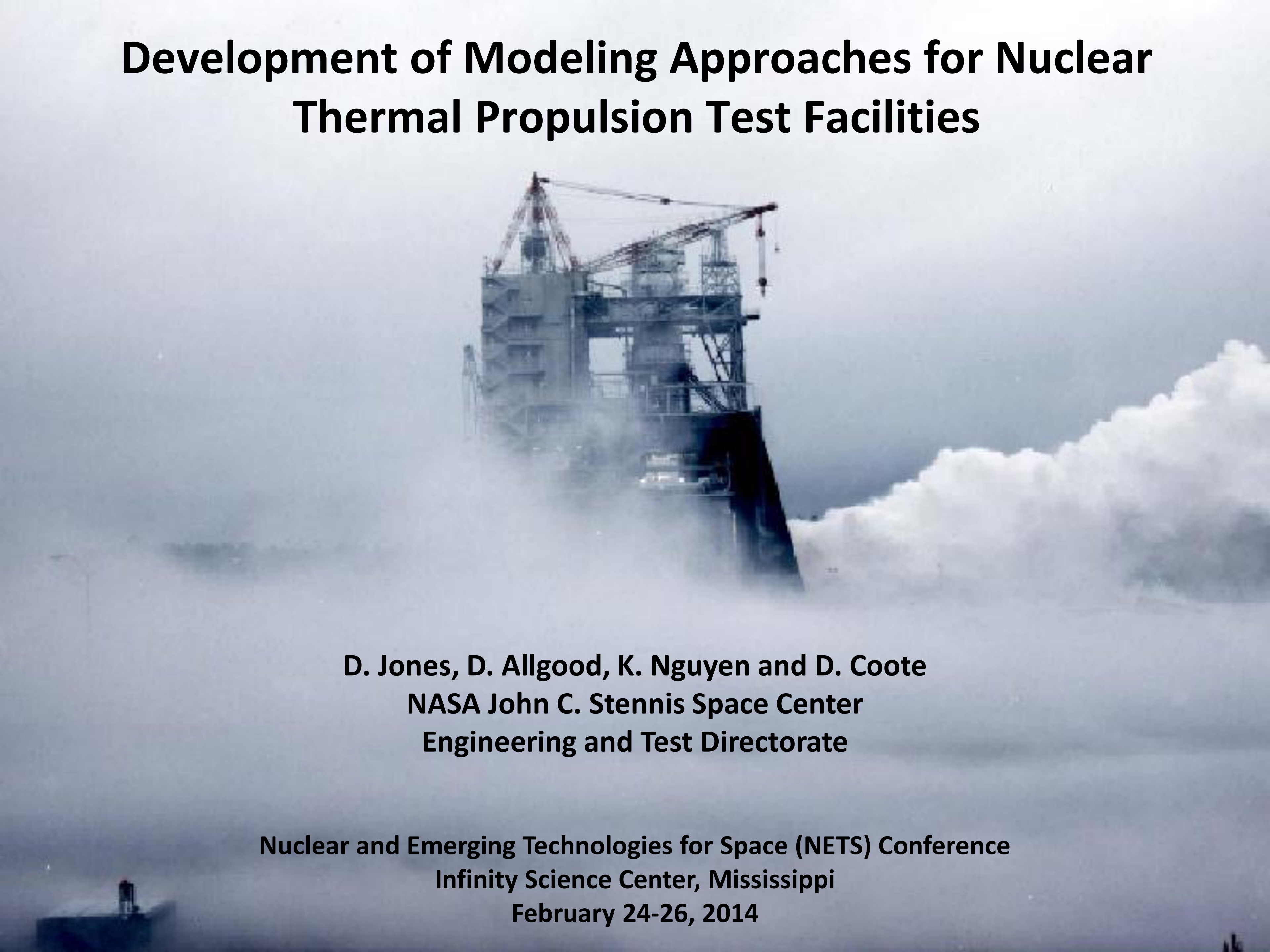
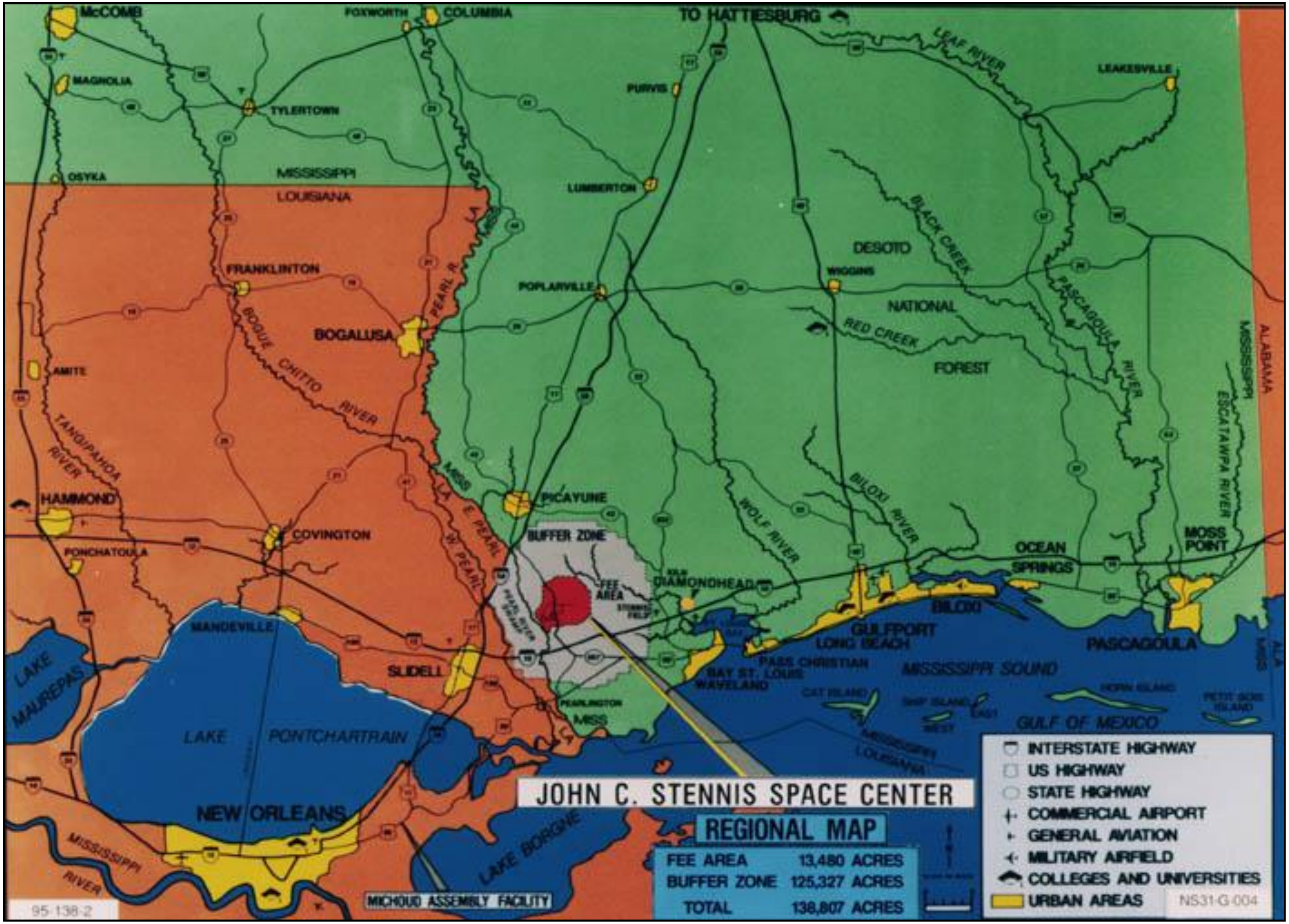
Development of Modeling Approaches for Nuclear Thermal Propulsion Test Facilities



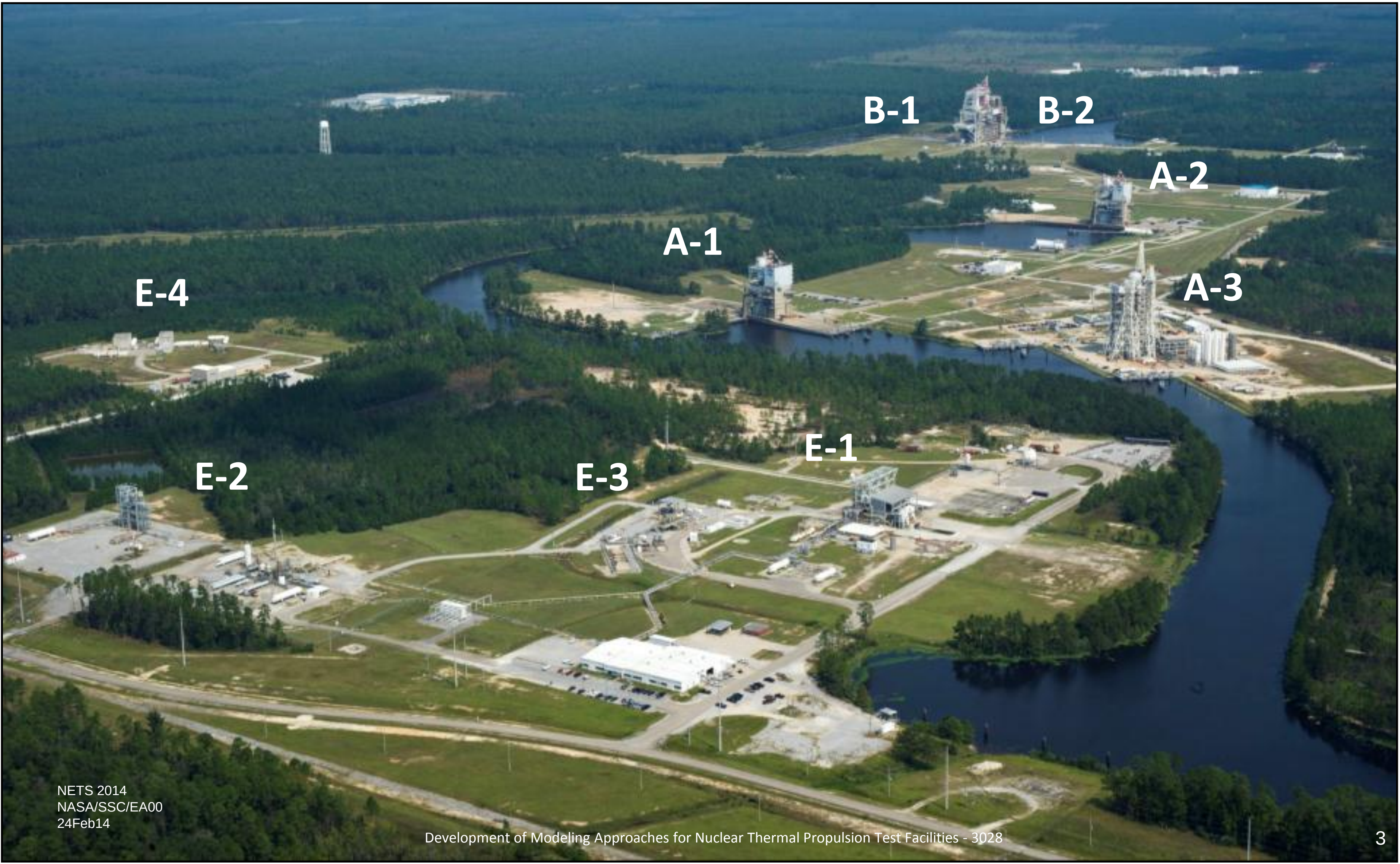
D. Jones, D. Allgood, K. Nguyen and D. Coote
NASA John C. Stennis Space Center
Engineering and Test Directorate

Nuclear and Emerging Technologies for Space (NETS) Conference
Infinity Science Center, Mississippi
February 24-26, 2014

SSC Regional Map



SSC Test Stands



NETS 2014
NASA/SSC/EA00
24Feb14

SSC Test Capability

A-1 Test Stand
Max Thrust (Klbf)
1,500 (designed)
650 (current)
Altitude (Kft)
Ambient
Propellants
LOX/LH2

A-2 Test Stand
Max Thrust (Klbf)
1,500 (designed)
650 (current)
Altitude (Kft)
60
Propellants
LOX/LH2

B-1 Test Stand
Max Thrust (Klbf)
11,000 (designed)
750 (current)
Altitude (Kft)
Ambient
Propellants
LOX/LH2

B-2 Test Stand
Max Thrust (Klbf)
11,000 (designed)
Altitude (Kft)
Ambient
Propellants
LOX/LH2

E-2 Test Facility Cell 1
Max Thrust (Klbf)
100
Altitude (Kft)
Ambient
Propellants
LOX/LH2/RP

E-1 Test Facility Cells 1-3
Max Thrust (Klbf)
1,200
Altitude (Kft)
Ambient
Propellants
LOX/LH2/RP

A-3 Test Stand
Max Thrust (Klbf)
1,000 (designed)
300+ (altitude)
Altitude (Kft)
100 (designed)
Propellants
LOX/LH2

E-3 Test Facility Cell 1
Max Thrust (Klbf)
60
Altitude (Kft)
Ambient
Propellants
LOX/H202/JP-8

E-3 Test Facility Cell 2
Max Thrust (Klbf)
25
Altitude (Kft)
Ambient
Propellants
LOX/H202/CH4/JP-8

E-2 Test Facility Cell 2
Max Thrust (Klbf)
150
Altitude (Kft)
Ambient
Propellants
LOX/RP/H202

SSC Test Support Facilities

High Pressure Industrial Water (HPIW)

330,000 gpm (66 M gallon reservoir storage capacity)

Available Additional Support:

- Laboratories
  - Environmental
  - Gas and Material Analysis
  - Measurement Standards and Calibration
- Shops
  - Machine/Weld/Carpenter/Paint/Electrical
  - Valve/Component Cleaning/Rework
- Utilities

High Pressure Gas Facility (HPGF)

(GN, GHe, GH, Air)

Cryogenic Propellant Storage Facility

Six (6) 100,000 Gallons LOX Barges

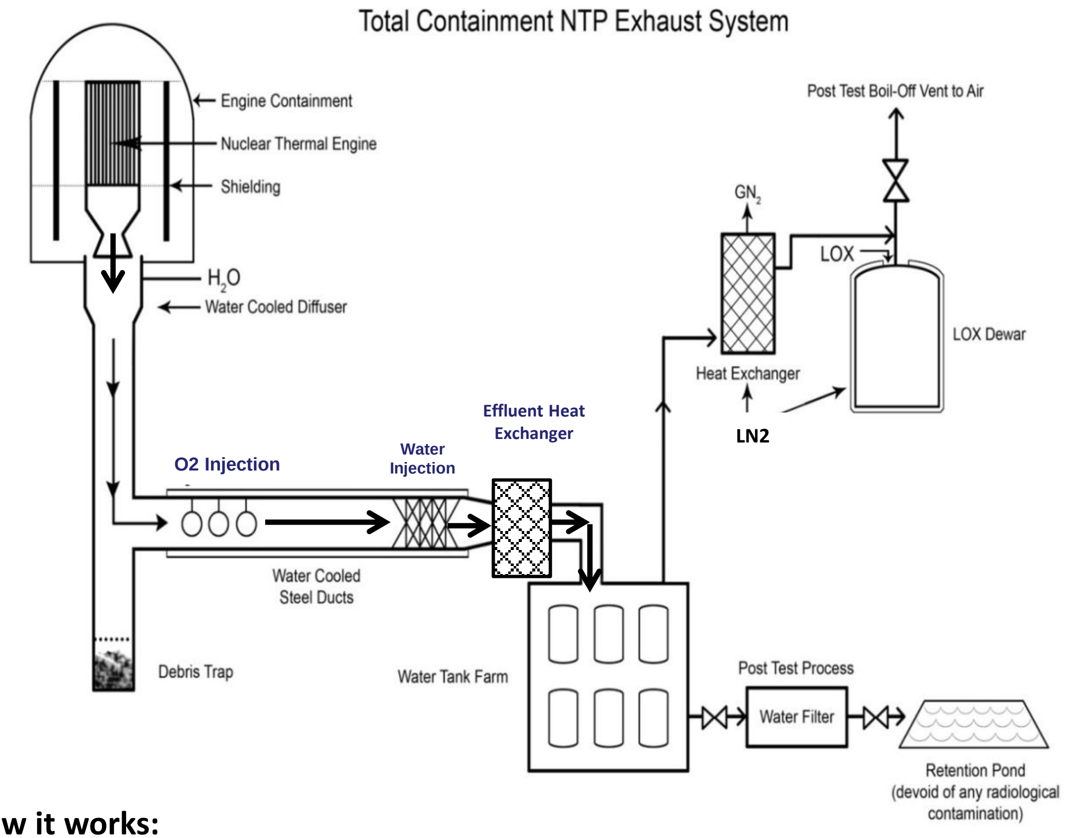
Three (3) 240,000 Gallons LH Barges

NASA/SSC's Participation in Nuclear Thermal Propulsion Technology Development

- SSC's Office of Chief Technologist has provided funding since FY05 via its Center Innovation Funding (CIF) budget to investigate two NTP engine test exhaust processing approaches.
  - Non-Nuclear NTP engine technology development (FY05,06,12).
  - Direct gas treatment (effluent scrubbing) (FY13).
  - Total exhaust containment (FY14).
    - Goal has been to investigate feasibility and identify preliminary design requirements.

- SSC was approached by MSFC for support of its 2013/14 Nuclear Cryogenic Propulsion Stage (NCPS) Project.
  - Project goal is to demonstrate the affordability and viability of nuclear thermal rocket propulsion with an emphasis on a human rated mission to Mars in the 2033 time frame.
  - SSC is supporting MSFC efforts in the definition of affordable development and qualification strategy:
    - Task is to scope and estimate the cost to develop an NTP engine test exhaust processing facility.
      - Identify the latest technologies in radioactive effluent scrubbing.
      - Investigate total exhaust containment feasibility.

NTP Total Containment Test Facility Concept



Strategy:

- Fully contain NTP engine exhaust during burns
- Slowly drain containment vessels after test

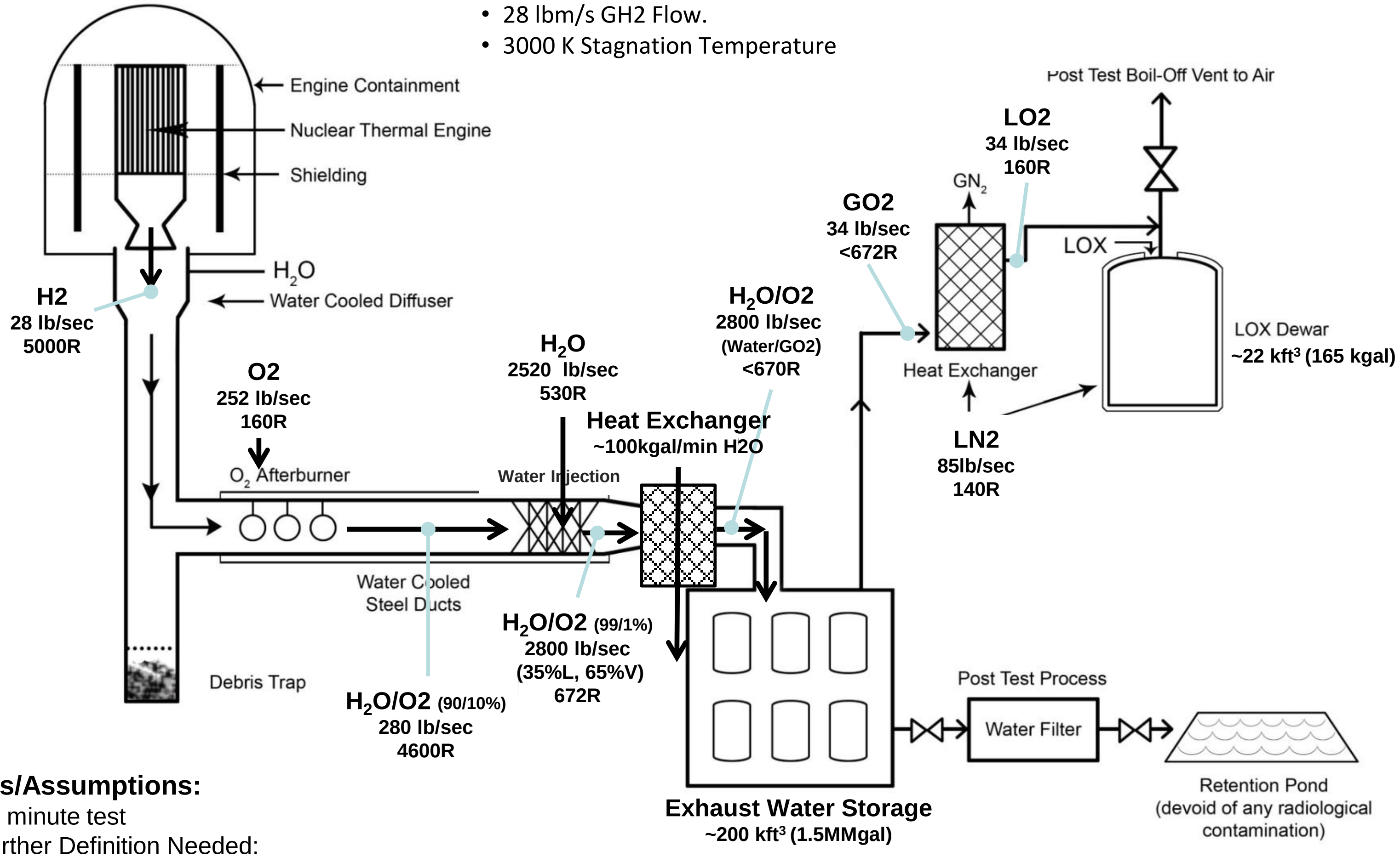
How it works:

- Hot hydrogen exhaust from the NTP engine flows through a water cooled diffuser that transitions the flow from supersonic to subsonic to enable stable burning with injected LO2
- Products include steam, excess O_2 and a small fraction of noble gases (e.g., xenon and krypton)
- Heat exchanger and water spray dissipates heat from steam/O2/noble gas mixture to lower the temperature and condense steam
- Water tank farm collects H_20 and any radioactive particulates potentially present in flow. Drainage is filtered post test.
- Heat exchanger-cools residual gases to LN2 temperatures (freezes and collects noble gases) and condenses O2.
- LOX Dewar stores LO_2, to be drained post test via boil-off

NTP Total Containment Test Facility

Preliminary System Sizing

NTP Engine Assumptions:
- 25,000 lb$_f$ thrust
- 28 lbm/s GH2 Flow.
- 3000 K Stagnation Temperature



Notes/Assumptions:
- 60 minute test
- Further Definition Needed:
  - Debris Trap
  - Water Injection/Steam Condenser Concept
  - O2/LN2 Heat Exchanger

Diffuser Sizing

Coupled Diffuser Performance and Combustion Analysis Approach:

- Find initial diffuser inlet area by assuming minimum allowable static pressure to be 2 psia.
- Use analytical methods in reference documents AEDC-TR-68-84, AEDC-TMR-85-E20, and NACA ACR No. L5D20 to determine other critical diffuser geometry parameters.
- Employ CRAFT Tech CRUNCH CFD to refine the basic design, visualize oblique shock interactions, and provide accurate predictions of test cell pressure and diffuser performance.
- Run simulation with downstream O2 combustion to determine effect of additional back pressure on the diffuser.

CFD Analysis Assumptions:

- System Back Pressure: 20 psia.
- O2 injector assumed to be annular and placed 13.6 m after the diffuser, where Mach = 0.3 in the non-combustion simulation.
- O2 injection annulus sized for equal momentum in O2 and H2 flows.
- Adiabatic pipe flow
- Used CRUNCH's finite-rate chemistry model.
- O2/GH2 ratio of 9 to minimize H2 residuals.

Combustion Analysis

O2 Injection

Task:

- Obtain amount of oxygen to combust hydrogen from NTP engine.

Approach:

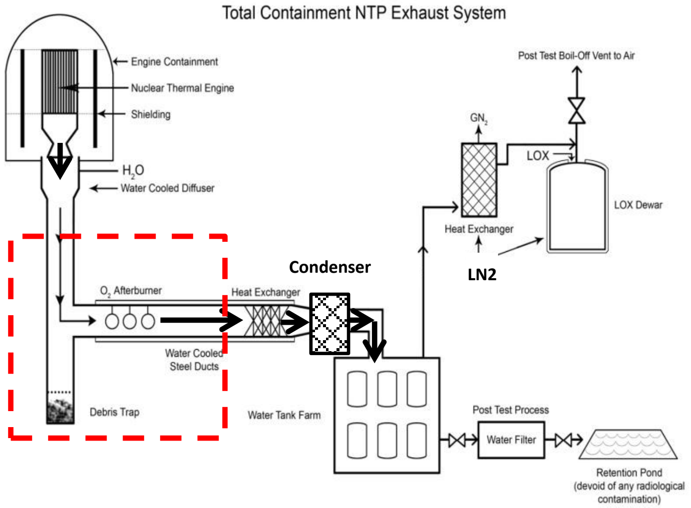
- Use MATLAB implementation of NASA's Chemical Equilibrium with Applications (CEA) method to determine adiabatic flame temperature and combustion products.

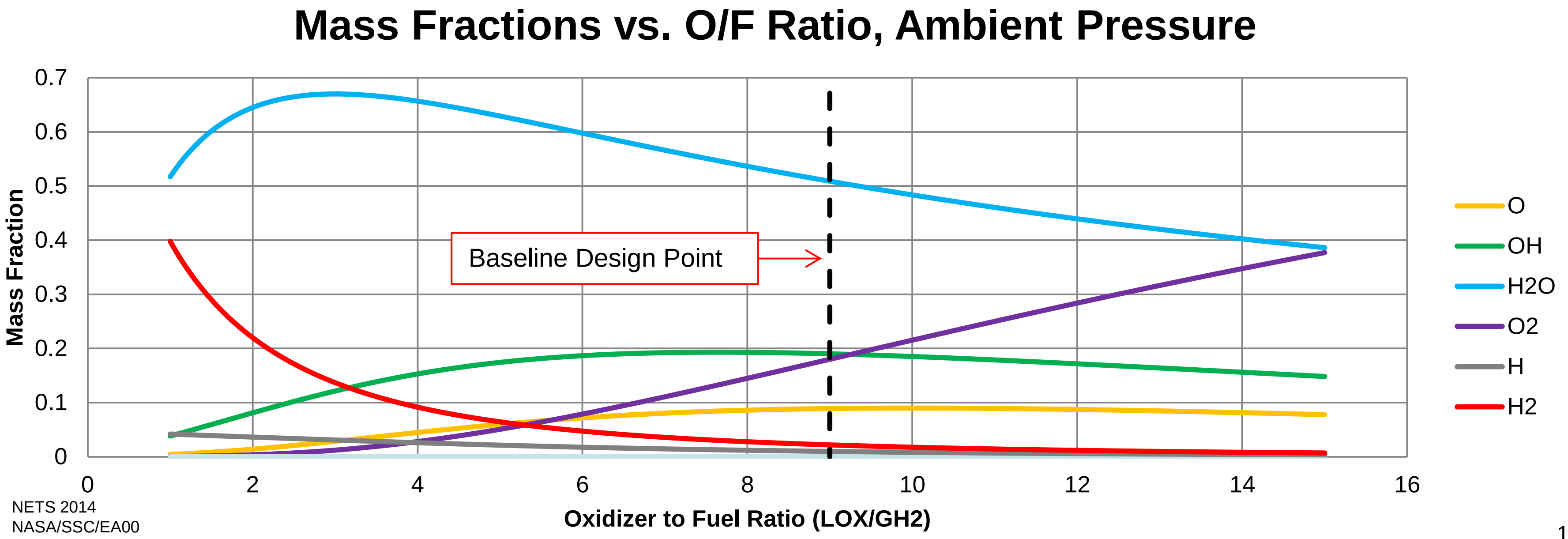
Assumptions:

- LOX is injected at its boiling point of 90.17 K.

Outcome:

- At an O/F of 9, most of the hydrogen is consumed.
- O/F = 9 baselined for diffuser sizing and other system analyses.



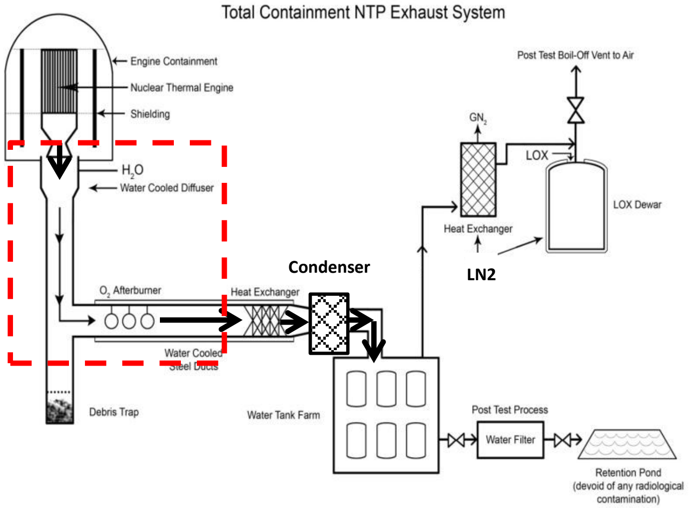


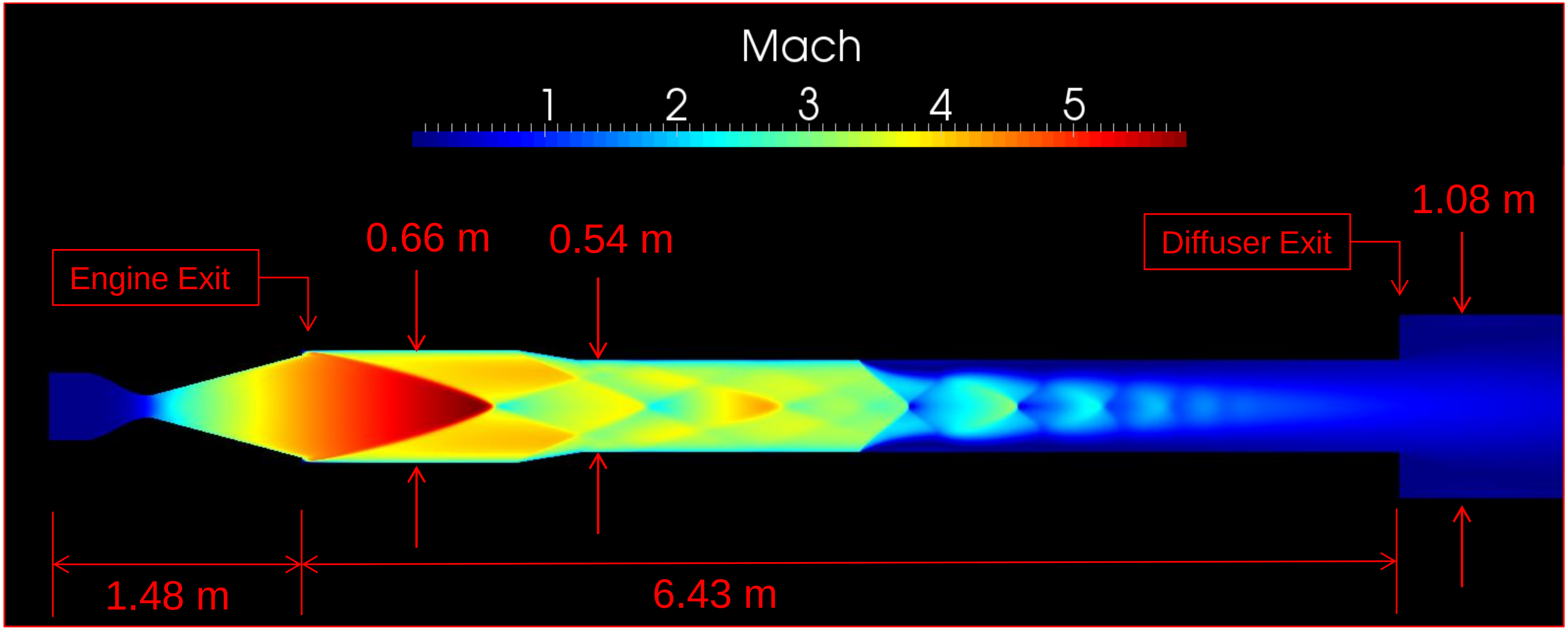
Diffuser Performance Assessment

Mach Number Contours

Results:

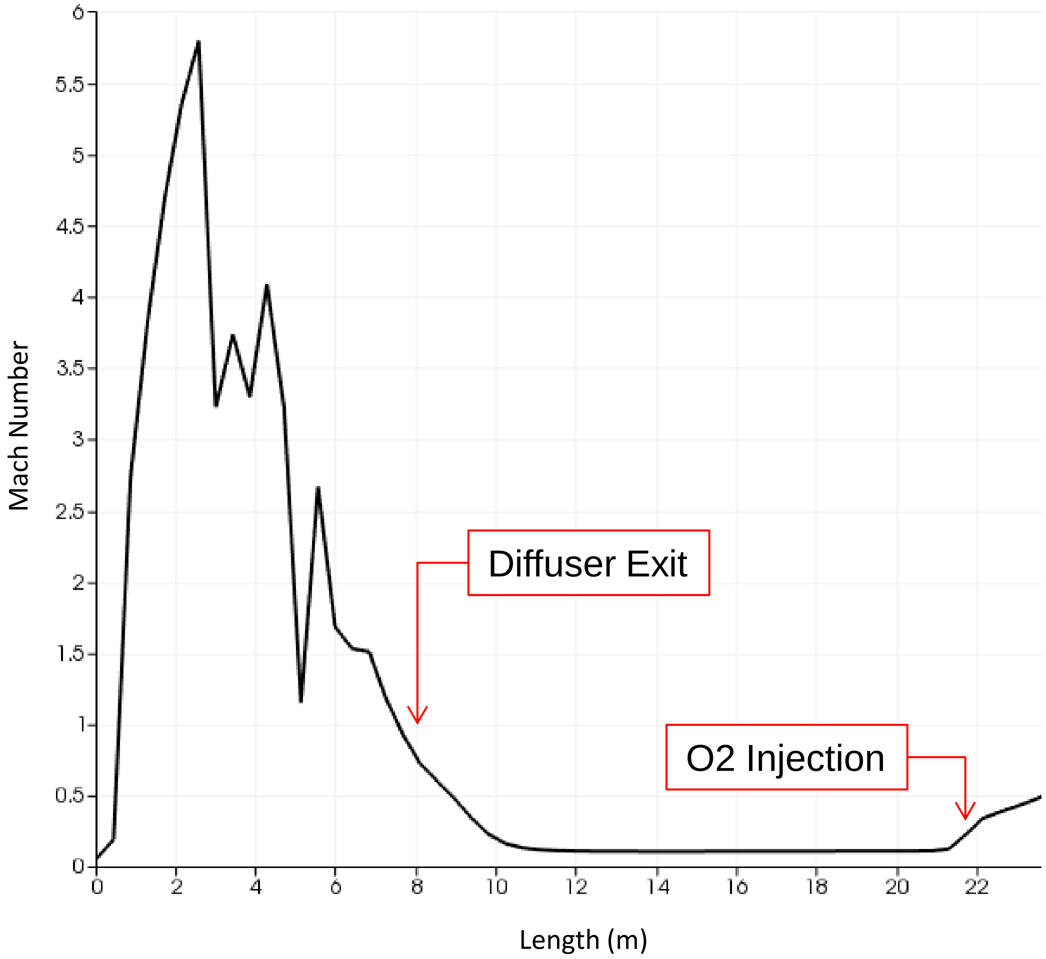
- Diffuser Length = 6.43 m.
  - Based on adiabatic system.
- Flow is subsonic at diffuser exit.
- Diffuser isolates engine from higher downstream pressure.

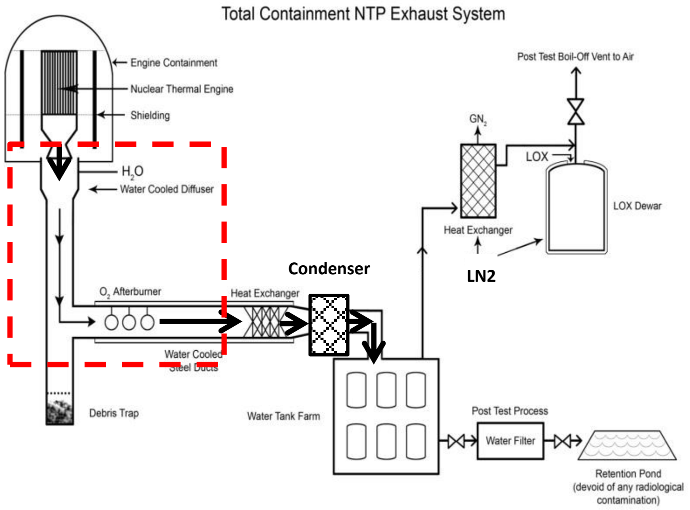




Diffuser Performance Assessment

Mach Number Along the Centerline

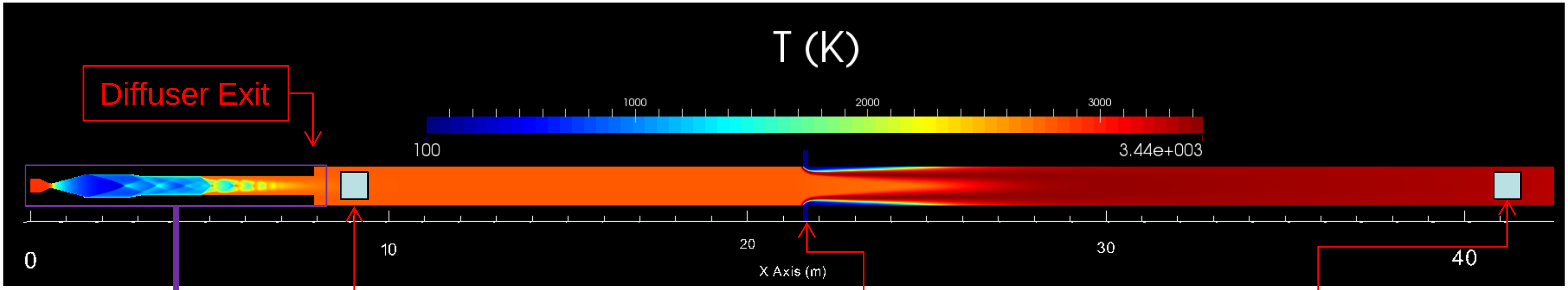




- Flow is subsonic at diffuser exit
- O2 combustion increases back pressure on the diffuser.
- Mach Number ~0.15 at O2 injection point

Oxygen Injection and Combustion

Temperature Contours

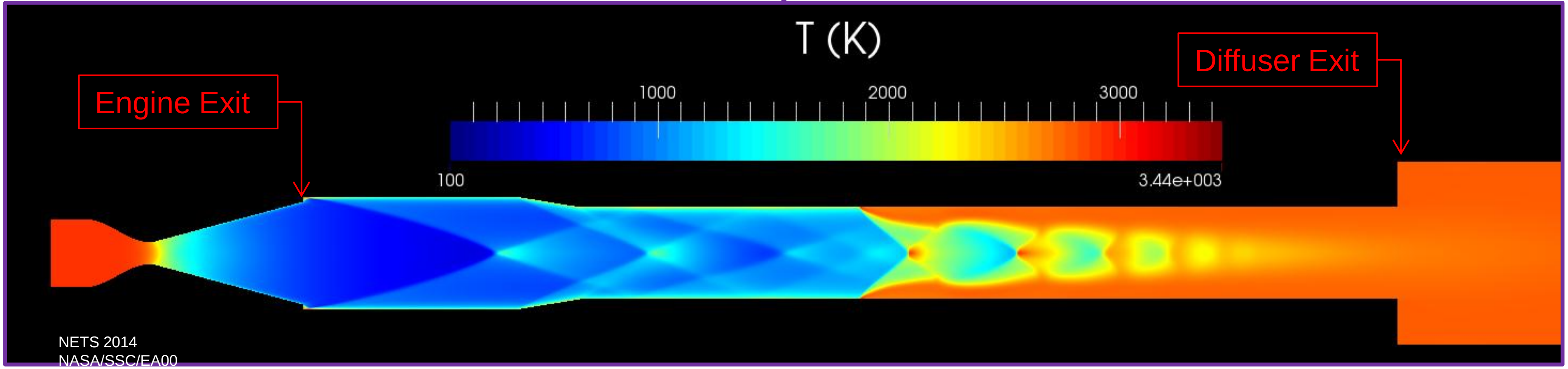


Chemical Composition:
- 99.8% H_2
- 0.02% H

O2 Injection

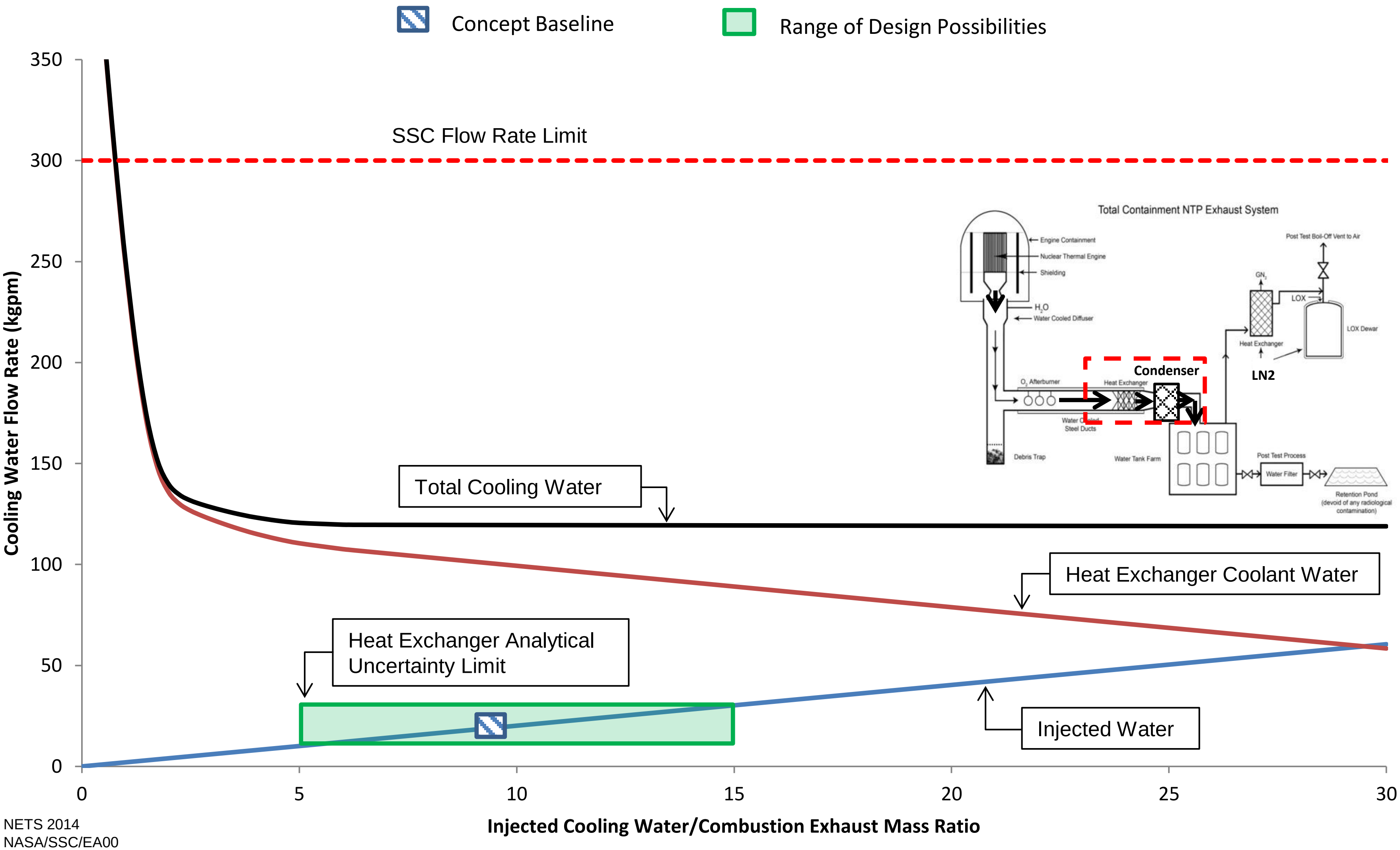
Chemical Composition:
- 58.0% H_2O
- 16.2% OH
- 15.9% O_2
- 6.4% O
- Remainder: H, H_2

Note:
Radicals will disappear when the flow is doused with cooling water.



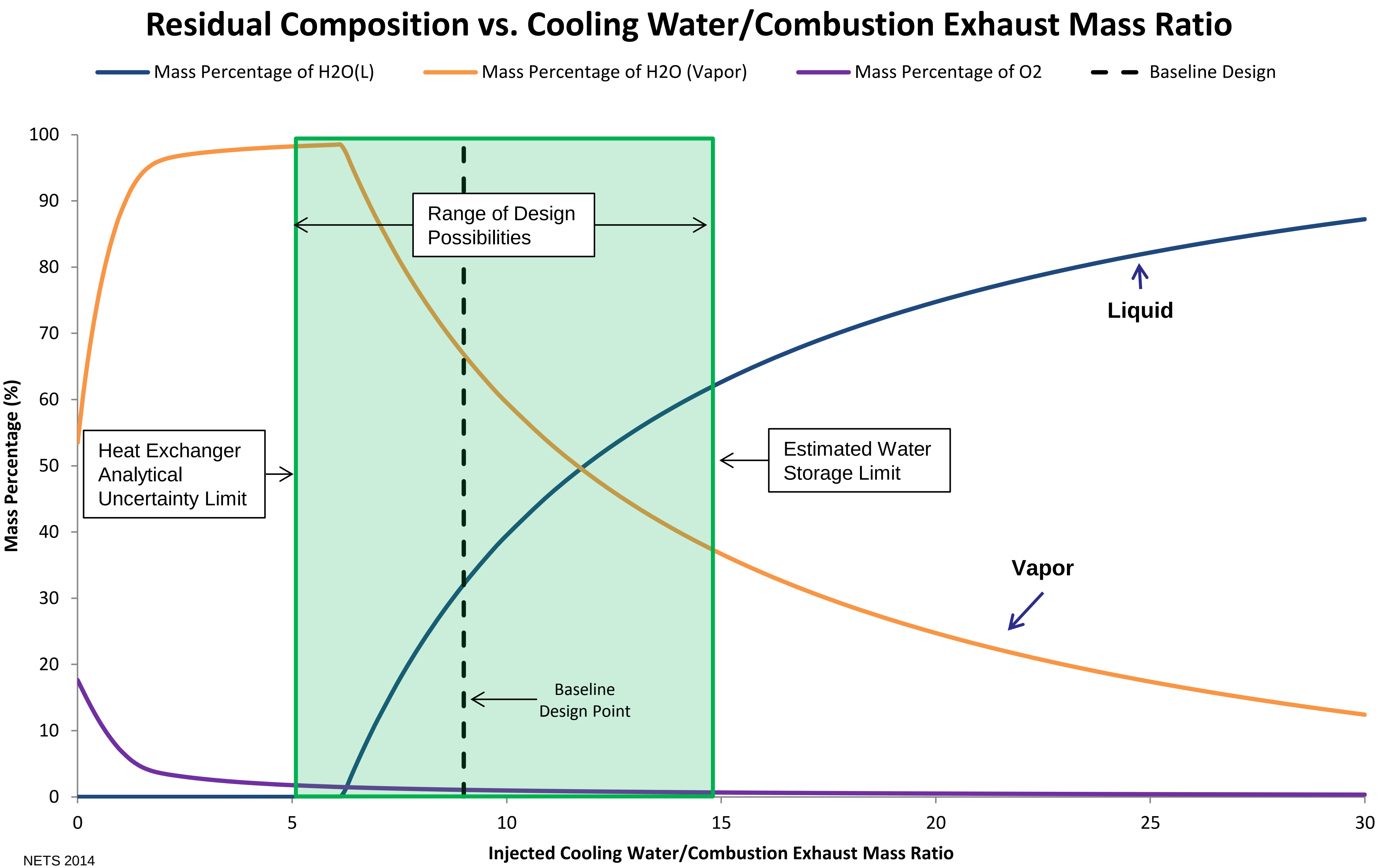
Water Injection and Heat Exchanger Flow Rate Assessment

Cooling Water Flow Rate Considerations



Cooling Water Injection

Steam Condensation



Range of Design Possibilities

Heat Exchanger Analytical Uncertainty Limit

Estimated Water Storage Limit

Baseline Design Point

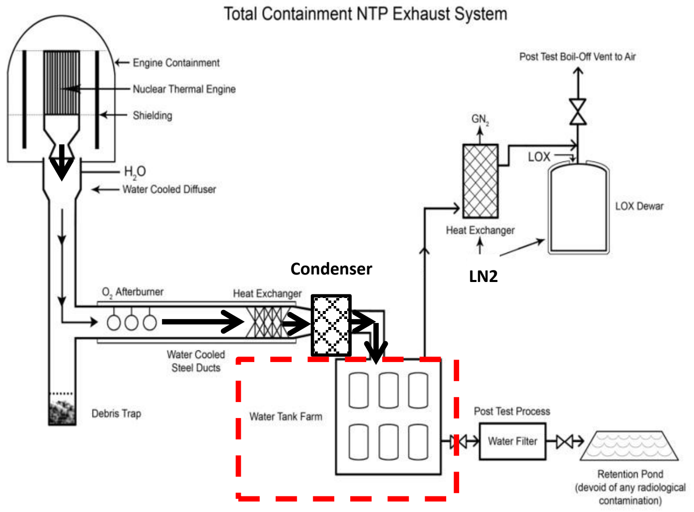
Water Collection Tank

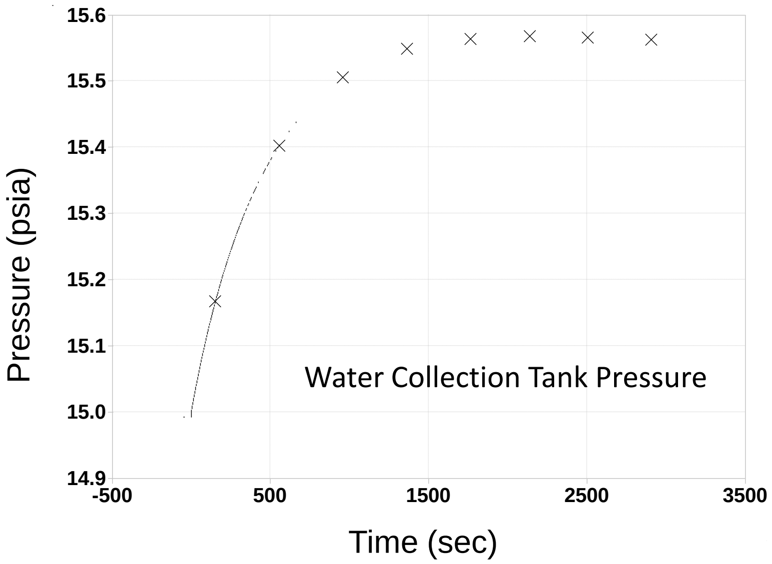
Task:

- Size water tank to collect exhaust water and external cooling water.
- Determine vent flowrate required to keep tank below 1 psig during loading process.
- Used in-house Rocket Propulsion Test Analysis (RPTA), Fortran-based code to model water collection tank.
    - 2,800 lbm/sec water flow rate @ 660°R (200°F).
    - 25% ullage at the end of test.

Results:

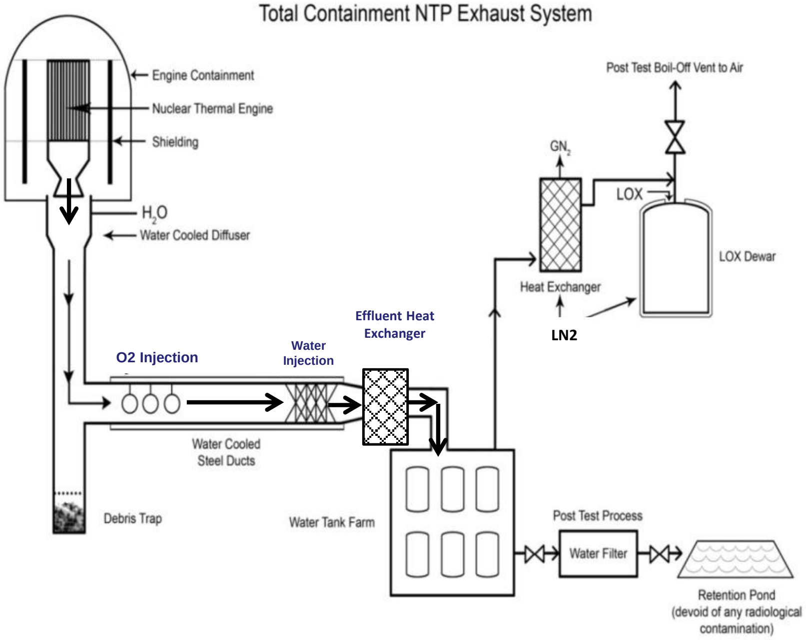
- Water tank volume: ~200,000 ft^3
- Required vent flowrate: ~ 34.0 lbm/sec.





Summary

- Proof of concept has been analytically demonstrated for an NTP engine test total exhaust containment system; salient features include
  - Primary engine exhaust ducting: <1m diameter, <40m length
  - Water requirements :<~150kgal/min (~2.5 kgal/min direct exhaust injection, ~100 kgal/min heat exchanger, + exhaust duct cooling)
  - Contaminant Storage: ~1.5 million gallons (water), ~165 kgal (LO2)
  - LH2/LO2/LN2 requirements well within Liquid Rocket Engine supply experience
  - Low pressure operations: < 60 psi throughout exhaust processing system


Total Containment NTP Exhaust System

- Analysis has not identified any significant technical issues with total exhaust containment approach
  - Preliminary, fully coupled, multi-physics CFD modeling of diffuser and O2 injection performance completed
  - Effluent transport and storage modeled with validated in-house and commercial facility fluid/thermodynamic codes

Forward Plans

FY14

- Complete preliminary concept definition and modeling
  - Exhaust heat exchanger sizing & operation (Water & LO2 systems)
  - O2 and water injection system designs
  - Exhaust debris containment system
- Complete ROM cost estimate of facility for NCPS project effort

FY15 & beyond

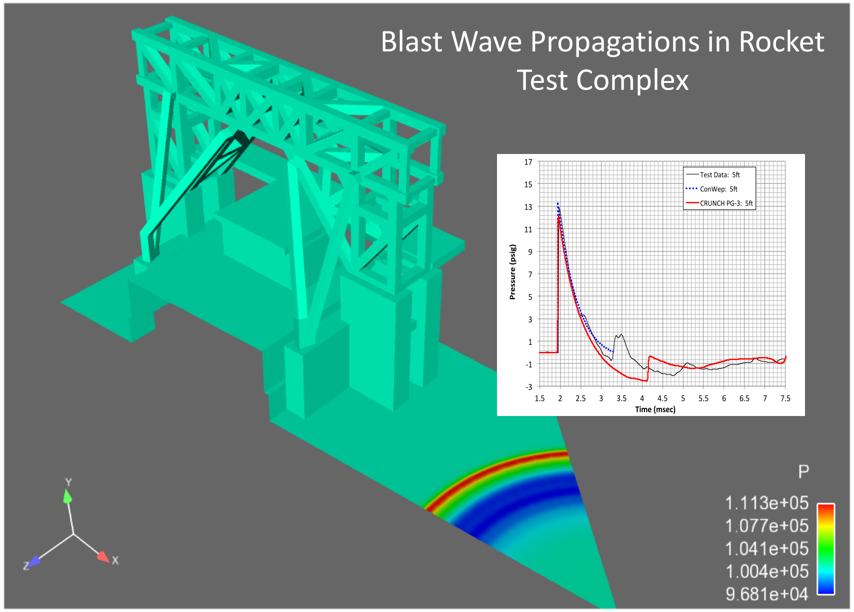
- Optimize system design:
  - O/F ratios for LO2 and water injection
  - O2 injection location
  - Exhaust debris containment system
- Subscale demonstration of concept (proposed)

Development of Modeling Approaches for Nuclear Thermal Propulsion Test Facilities

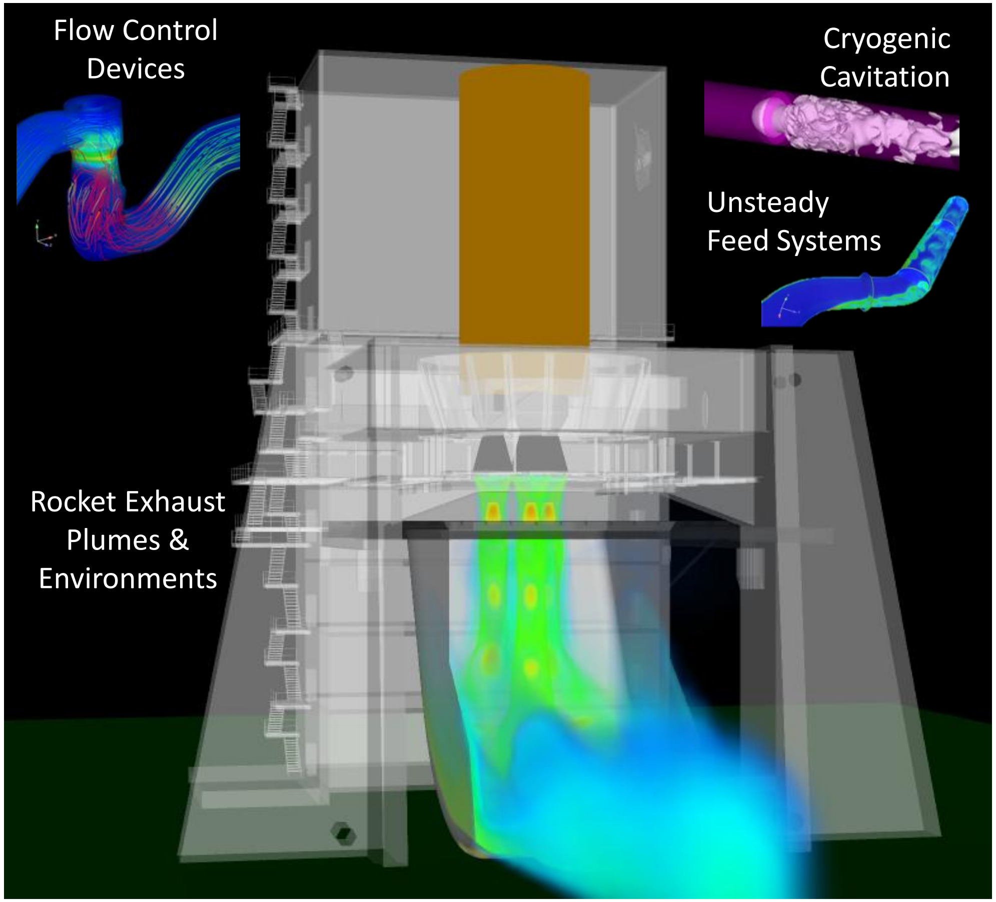
Back-Up Slides

NASA SSC CFD Capability

- NASA-SSC routinely conducts CFD analysis in support of rocket engine testing.
  - multi-species reacting plumes
  - propellant feed systems
  - cryogenic cavitation
  - thermal environments
  - blast-wave propagations in test complex
  - etc.



Blast Wave Propagations in Rocket Test Complex



Flow Control Devices

Cryogenic Cavitation

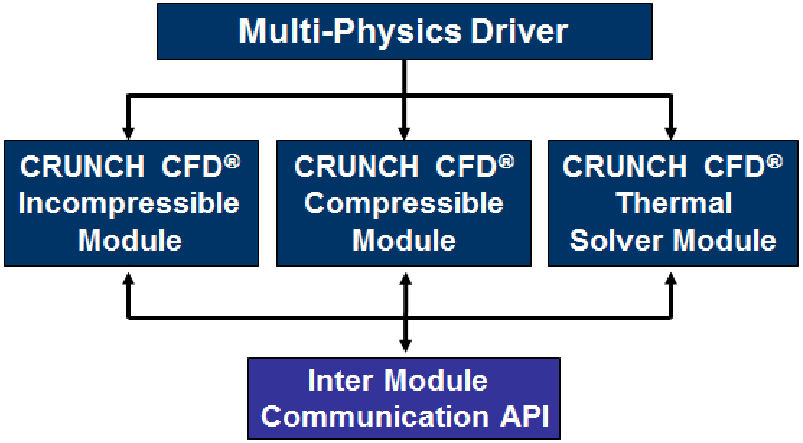
Unsteady Feed Systems

Rocket Exhaust Plumes & Environments

CRUNCH CFD® Multi-Physics Framework

Combustion Research and Flow Technology, Inc.

- CRUNCH CFD® is a multi-physics analysis tool that allows multiple domain-specific flow and heat transfer solvers to be used in a single simulation environment while still allowing efficient communication for time-accurate simulations.



Multi-Physics Driver

CRUNCH CFD® Incompressible Module

CRUNCH CFD® Compressible Module

CRUNCH CFD® Thermal Solver Module

Inter Module Communication API

Compressible Module:

Generalized "all-speed" preconditioned density-based solver for perfect gas, imperfect gas, real-fluid multi-phase and combusting flows.

Incompressible Module:

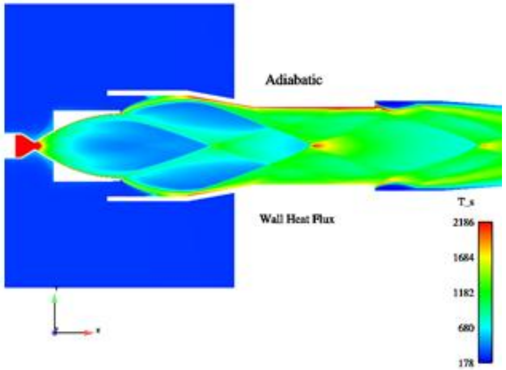
Flow solver capable of modeling liquid flows with strong thermal dependency (e.g. cryogens).

Thermal Module:

Transient heat conduction solver.

Example Problem: Rocket Conjugate Heat Transfer

- Module 1 - compressible reacting flow solver for plume
- Module 2 - thermal solver for wall conduction
- Module 3 - incompressible flow solver for water cooling channel



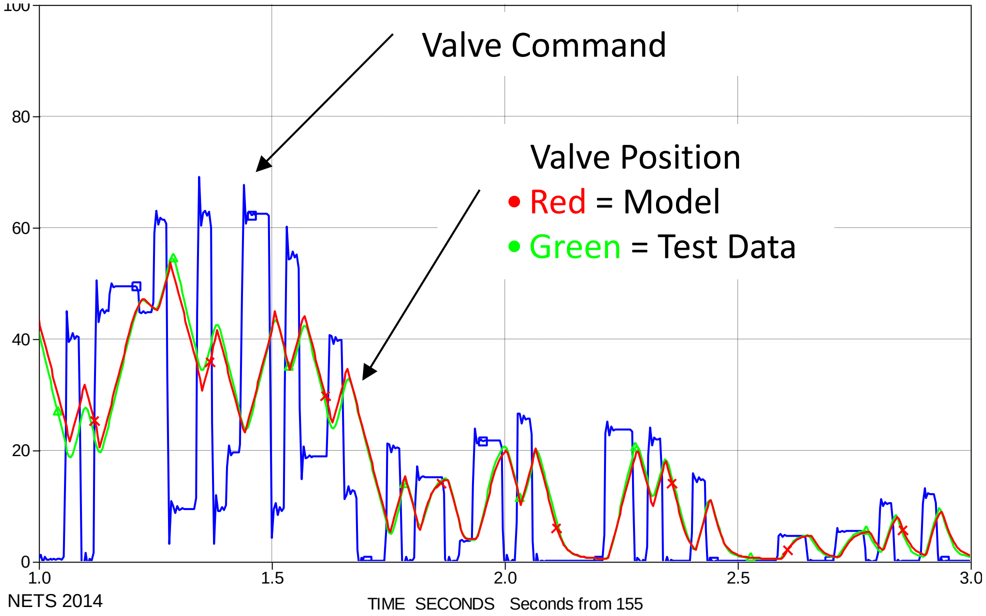
CRUNCH CFD Compressible Module Overview

NUMERICS	• Finite-Volume Roe/TVD Flux Construction, Vertex Storage
INTEGRATION	• Implicit GMRES, Implicit Gauss-Seidel, Explicit Four-Step Runge-Kutta
GRID ELEMENTS	• Unstructured: Tetrahedral, Hexahedral, Prismatic, Pyramid
PARALLEL PROCESSING	• Domain Decomposition MPI, Independent Grids with Noncontiguous Interfacing, Automated Load Balancing
DYNAMIC GRID CAPABILITIES	• Node Movement Solver (Implicit Elasticity Approach), Sliding Interfaces for Rotor-Stator Applications
GRID ADAPTATION	• Works with CRISP CFD®, keyed to both cell quality and flow gradients • Hands off mesh motion / adaptation using CRISP CFD®
THERMOCHEMISTRY	• Combusting Imperfect Gas Mixtures • Generalized Non-ideal Formulations for Gas/Liquid Mixtures and Supercritical Fluids • Cantera/Chemkin compatibility • Advanced Chemical Kinetic ODE Solver, ISAT/ANN Run Options
TURBULENCE RANS/LES	• k-e Based Formulations with Specialized Corrections • Scalar Fluctuation Model (SFM) → Variable Prandtl / Schmidt Number • Generalized Hybrid RANS/LES Formulation
MULTIPHASE FLOW	• Generalized gas/bulk liquid framework • Steady/unsteady cavitation model with bubble dynamics • Nonequilibrium Particle/Droplet Solvers (Eulerian Formulation)

Rocket Propulsion Test Analysis (RPTA) Model

- The Rocket Propulsion Test Analysis (RPTA) model is a FORTRAN-based in-house code used to simulate the temporal transient thermodynamic processes of integrated propellant systems.
- Thermodynamic Control Volume Solver Model Accurately Models High-Pressure Cryogenic Fluids and High-Pressure Gaseous Systems. Model Features Include:
  - High-Fidelity Pressure Control Valve (PCV) & Closed Loop Control System Model
- RPTA Model Validated Through Test Data Comparisons.

Pressure Control Valve (PCV) Model Developed & Validated



A Significant Advantage of the RPTA Model is the Coupling of Control Logic (Electro-Mechanical Process) with Thermodynamic Processes.