Modeling and Simulation of a Nuclear Fuel Element Test Section

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ABSTRACT

"The Nuclear Thermal Rocket Element Environmental Simulator" test section closely simulates the internal operating conditions of a thermal nuclear rocket. The purpose of testing is to determine the ideal fuel rod characteristics for optimum thermal heat transfer to their hydrogen cooling/working fluid while still maintaining fuel rod structural integrity. Working fluid exhaust temperatures of up to 5,000 degrees Fahrenheit can be encountered. The exhaust gas is rendered inert and massively reduced in temperature for analysis using a combination of water cooling channels and cool N_2 gas injectors in the H_2-N_2 mixer portion of the test section. An extensive thermal fluid analysis was performed in support of the engineering design of the H_2-N_2 mixer in order to determine the maximum "mass flow rate"-"operating temperature" curve of the fuel elements hydrogen exhaust gas based on the test facilities available cooling N_2 mass flow rate as the limiting factor.

NOMENCLATURE

Isp	Specific Impulse (seconds)
H_2	Hydrogen Gas
N_2	Nitrogen Gas
^oF	degrees Fahrenheit
psi.	Pounds per Square Inch
lb/s	Pounds per Second
"	Inches
PVWD	Pressure Vessel Wall Delta
ASME	American Society of Mechanical Engineers
GUI	Graphical User Interface

INTRODUCTION

Few rocket propulsion concepts offer the combination of high thrust and reasonable efficiency that can be obtained from a Nuclear Thermal Rocket. Long considered one of the most basic forms of Nuclear Propulsion, the solid-core nuclear thermal rocket engine concept typically employs a uranium fueled nuclear reactor core and hydrogen (H_2) gas working fluid. The H_2 gas acts first as fuel rod coolant as it passes through the nuclear reactor core followed by rocket working fluid when the then super heated hydrogen is expanded out of a nozzle in order to produce thrust.

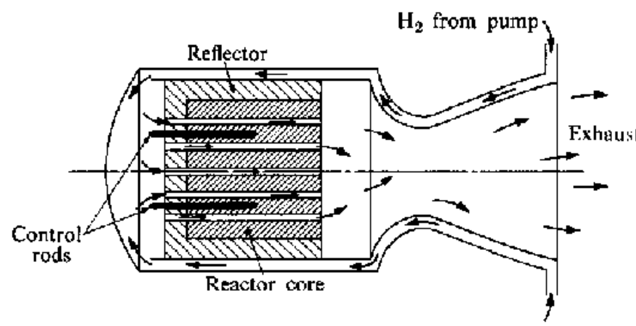

Fig 1. Solid-Core Nuclear Thermal Rocket Engine [(1)]

Famously the Nuclear Engine for Rocket Vehicle Application, or NERVA test program of the 1960's extensively demonstrated the feasibility of the nuclear thermal rocket design concept testing nearly 30 nuclear thermal rocket engines such at the KIWI-B4 which produced approximately 75,000 pounds of thrust with an efficiency (isp) of 825 seconds.

In order to support the potential future design and development of a nuclear thermal rocket, an elaborate testing system has been created; which simulates many of the environmental conditions that a nuclear fuel rod would be exposed to when utilized for such an enterprise. The Nuclear Thermal Rocket Element Environmental Simulator (NTREES) test section employs a unique system of electrical induction coils to heat depleted Uranium fuel rods in order to simulate the operating conditions of a thermal nuclear rocket while avoiding the personal and legal hazards typically encountered during experimentation with fuel grade uranium.

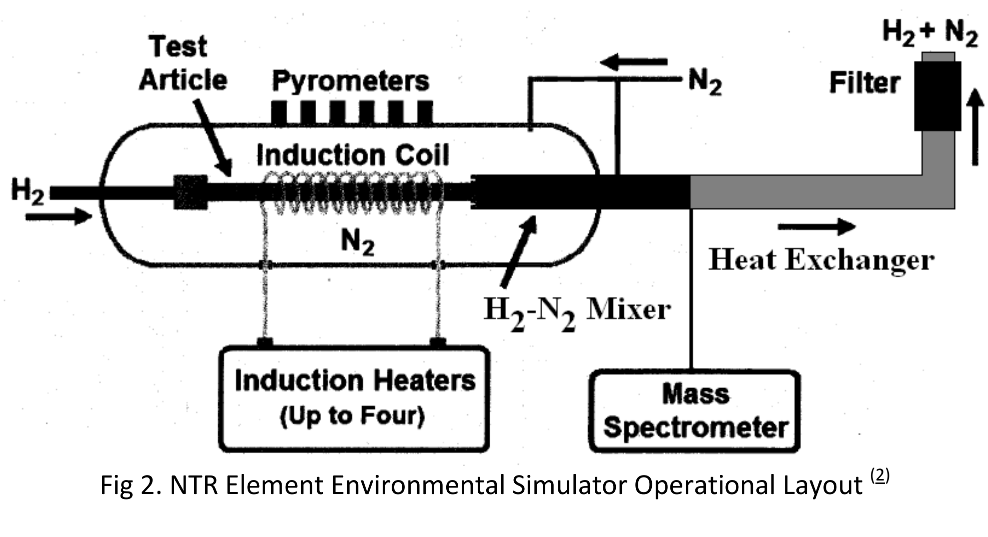

Fig 2. NTR Element Environmental Simulator Operational Layout [(2)]

The purpose of the testing is to determine the ideal fuel rod characteristics for optimum thermal heat transfer to the coolant/working fluid while still maintaining their structural integrity. I.E. a large fuel rod surface area ideally shaped to promote heat transfer to the hydrogen working fluid while simultaneously avoiding structural degradation due to the high operating pressures and temperatures it will be exposed to. The level of material degradation is determined via a spectral analysis of the fuel elements hydrogen exhaust gas using a mass spectrometer.

The NTREES testing system is currently undergoing a major upgrade in order to more closely simulate the operating conditions encountered during nuclear thermal rocket operation. This includes modifications for the testing of larger fuel rods at higher operating temperatures and hydrogen working fluid mass flow rates.

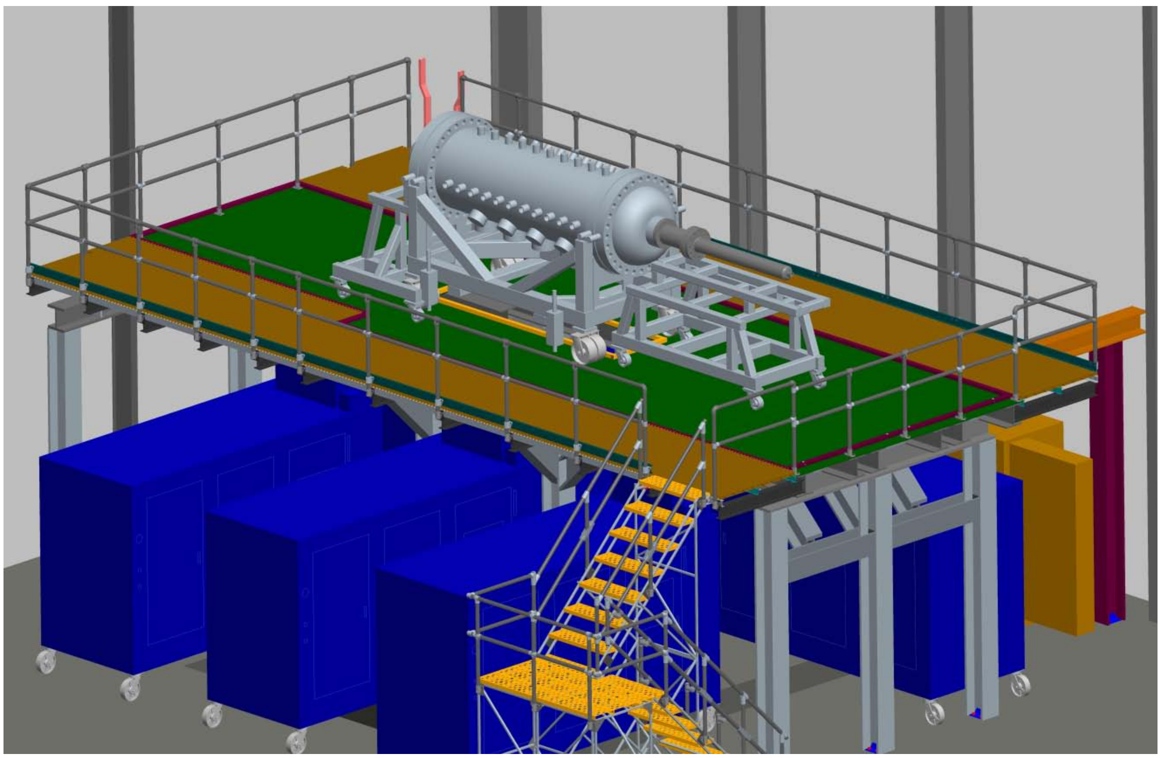

Fig 3. CAD Rendition of the Upgraded NTREES testing system.

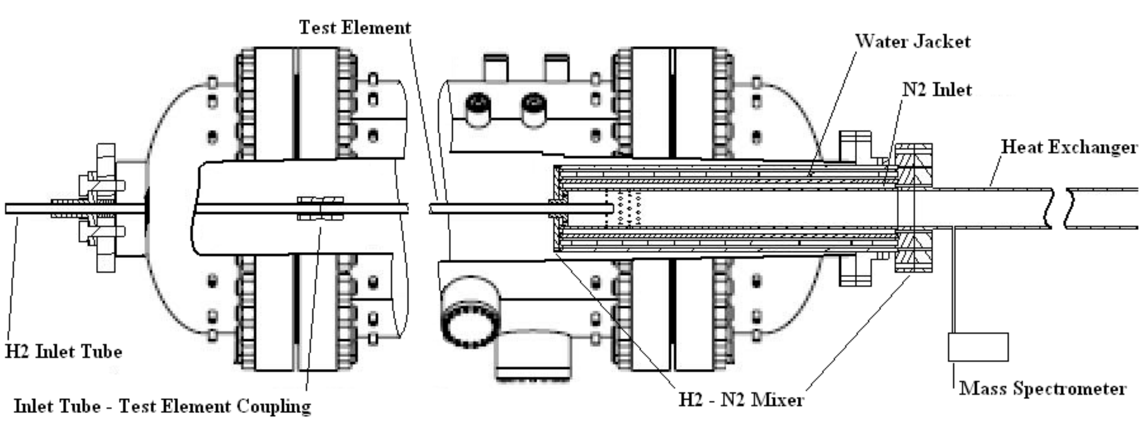

Fig 4. Cutaway view of (NTREES) [3]

The upgraded NTREES will be capable of testing NERVA sized fuel rods of up to 52 inches long; with working fluid mass flow rates of hydrogen gas of up to 0.22 lb/s encountering exhaust temperatures of up to 5000 ^{0}F at an operating pressure of approximately 1,000 psi. In order to ensure employee safety and proper analysis of the hydrogen exhaust gas that is ejected from the fuel element it must be both rendered inert and massively reduced in temperature for safe handling. This will be accomplished using a combination of water cooling channels and N_2 gas injectors in the H_2-N_2 mixer and heat exchanger sections of the NTREES test system.

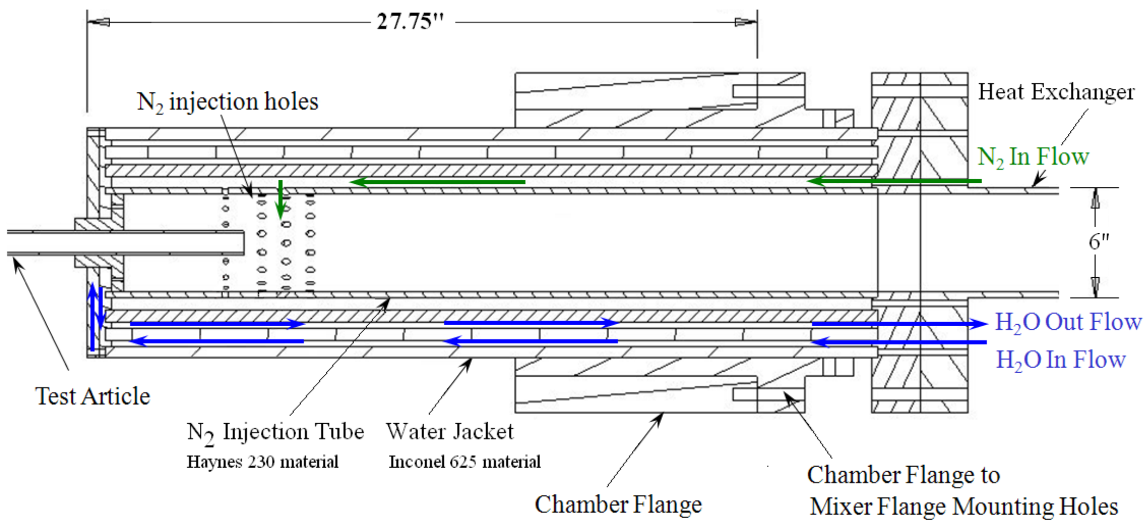

Fig 5. Preliminary design of the Mixer Internal Flow Passages [(3)]

An extensive thermal fluid and structural analysis was performed in support of the engineering design of the H_2-N_2 mixer and heat exchanger test sections. An integral portion of the thermal fluid analysis entailed the modeling and simulation of the H_2-N_2 mixer water cooling channels and nitrogen injectors in order to determine the maximum mass flow rate-operating temperature curve of the fuel elements hydrogen exhaust gas based on the NTREES test facilities available N_2 mass flow rate as the limiting factor.

The NASA fluid system program GFSSP or Generalized Fluid System Software Program was used for heat exchanger design. GFSSP supports rapid design changes at the system level combined with an intuitive user friendly graphical user input.

FLUENT the Computational Fluid Dynamics (CFD) program was utilized extensively for the thermal fluid analysis of the H_2-N_2 Mixer. FLUENT's unique capability to couple the analysis of thermal fluid and structural thermal conductivity proved valuable during the initial design phase. This solution coupling provided a process for rapidly determining the required mass flow rate of nitrogen exhaust gas and accompanying wall temperatures based on the mass flow rate and temperature of the fuel elements hydrogen coolant exhausted into the H_2-N_2 Mixer.

The Air Force computational model generator PILGRIM was utilized for computational grid construction. PILGRIM produces block to block structured grids in the plot 3-d formatted list (P3dF) format. PILGRIM proved ideal for constructing simplified 2-d models based off of blueprints and allowed for easy grid modification during trade studies of N_2 injector size and location. The combination of coupled thermal fluid and structural thermal conductivity FLUENT analysis with rapid grid modification via PILGRIM allowed for a sizable number of solutions to be produced in a relatively short period of time.

RESULTS AND DISCUSSION

Mixer Details:

The upgraded mixer design is based off of the low power Mixer design currently utilized by NTREES. Structural analysis of thermal results indicated that the low power Mixer would fail due to buckling in several regions of the N2 injector sleeve and had been rated for low power runs accordingly. Thermal buckling was prevented in the High Power Mixer with a combination of expansion slots, nitrogen film cooling, and superior manufacturing materials. Figure 6 highlights the expansion slot employed to prevent lateral buckling of the nitrogen injector tube due to thermal expansion. In addition the 35^o angled N_2 injector holes were retained from the previous design in order to promote a film cooling layer along the inside of the N_2 injector tube wall to aid in reducing thermal expansion. The selection of Haynes 230 and Inconel 625 materials significantly improved the designs capability to run at higher temperatures thus reducing the required mass flow rate of N_2 coolant. The design phase was plagued by the test facilities low availability of N_2 coolant so every effort was made to reduce requirements for N_2 gas wherever possible. The Haynes 230 is a Nickel-Chromium-Tungsten-Molybdenum super alloy with exceptional strength at temperatures as high as 2,100 ^{o}F and long term stability without warping or surface degradation such as oxidation or scaling [(4)]. So it was determined to be the ideal material for the nitrogen injector tube, and was available in the required 6 inch diameter in 6 foot or longer lengths. Inconel 625 is a Nickel-Chromium super alloy which offers good strength at temperatures as high as 2,000 ^{o}F and has excellent resistance to corrosion and oxidation [(5)]. So it was selected for the remaining H_2-N_2 Mixer components due to its significantly lower cost when compared to the Haynes 230. It was hoped that the higher temperatures that that these materials could safely operate at would translate into a requirement for less nitrogen gas coolant.

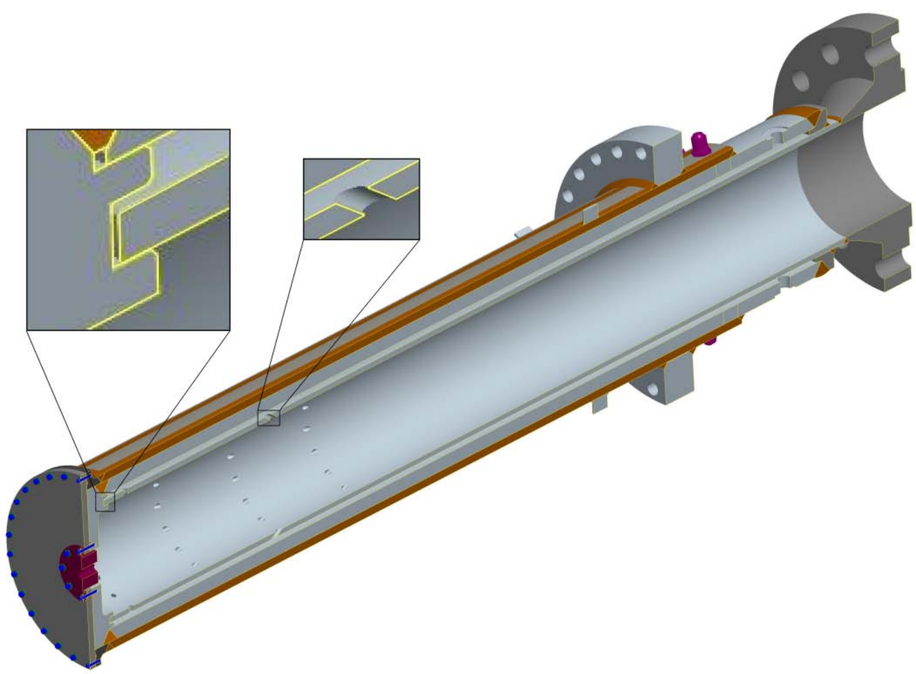

Fig 6. Cut away view of Mixer with zoom-in detail of the nitrogen injector tube expansion slot, and N2 injector hole.

Heat Exchanger Details:

Haynes 230 will also be used for the Heat Exchanger section of the system. With a fan blade shaped titanium insert placed at the exit of the H_2-N_2 Mixer, a conservative estimate of fully mixed fully turbulent Mixer exit flow could be made. This would result in a heat exchanger inlet wall temperature boundary condition that is equal to the average Mixer exit temperature. Two Heat exchanger models are currently being explored, one with a system exit boundary condition of 180 ^oF, and a second with a heat exchanger exit boundary condition of 800 ^oF. Either Heat Exchanger model selected will then mate up to the test facilities previously installed 6 inch diameter 304 stainless tubing, followed by filtration, and exit to atmosphere.

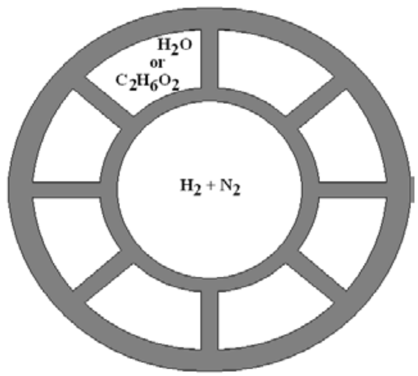

Fig 7. Channel Walled Heat Exchanger Cross Section

Heat Exchanger Model one would consist of 4 channel walled, 6 inch inner diameter, 6 foot sections assembled with in-series cooling provided by either water or ethylene glycol. This would be followed up with a 5^{th} section cooled in parallel for expediency. With this model it is estimated that Heat Exchanger exit temperatures of 180 ^oF or lower can be achieved. However a 6^{th} 6 foot section may prove necessary. It is currently planned that NASA's Generalized Fluid System Software Program (GFSSP) will be used at a later date to determine these details.

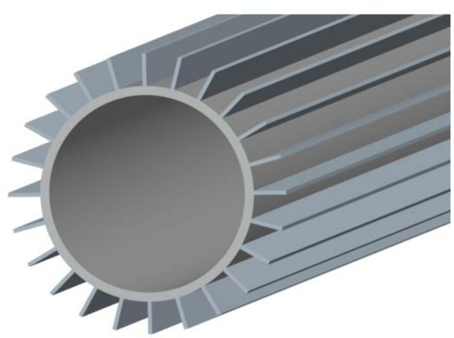

Fig 8. Finned Wall Heat Exchanger

Heat Exchanger Model two would consist of 6, 6 inch diameter, 6 foot, finned, air cooled sections. With this model it is estimated that Heat Exchanger exit temperatures of 800 ^oF or lower can be achieved. Here again additional 6 foot sections may be required, and it is currently planned that NASA's Generalized Fluid System Software Program (GFSSP) will be used at a later date to determine these details. A safety grate surrounding the heat exchanger would be required in order to prevent burns.

Structural Requirements:

One structural requirement that significantly influenced the design of both H_2-N_2 Mixer, and Heat Exchanger sections was the “Pressure Vessel Wall Delta” (PVWD). The pressure vessel wall delta is a requirement that pressure vessel components; which in this case will be exposed to pressures of approximately 1000 psi have a maximum allowable temperature delta across vessel walls.

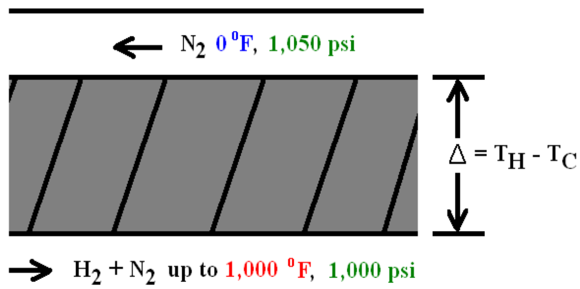

Fig 9. Pressure Vessel Wall Delta

This requirement is essentially a one-dimensional equation for example adding hoop strengtheners to a wall that exceeds its temperature delta requirement would simply cause it to fail between the hoops until an infinite number of hoops were added, and all other things remaining the same it would then fail across the two combined materials. Efforts to design the nitrogen injector tube as non-structural with expansion slots holding it at both ends also failed.

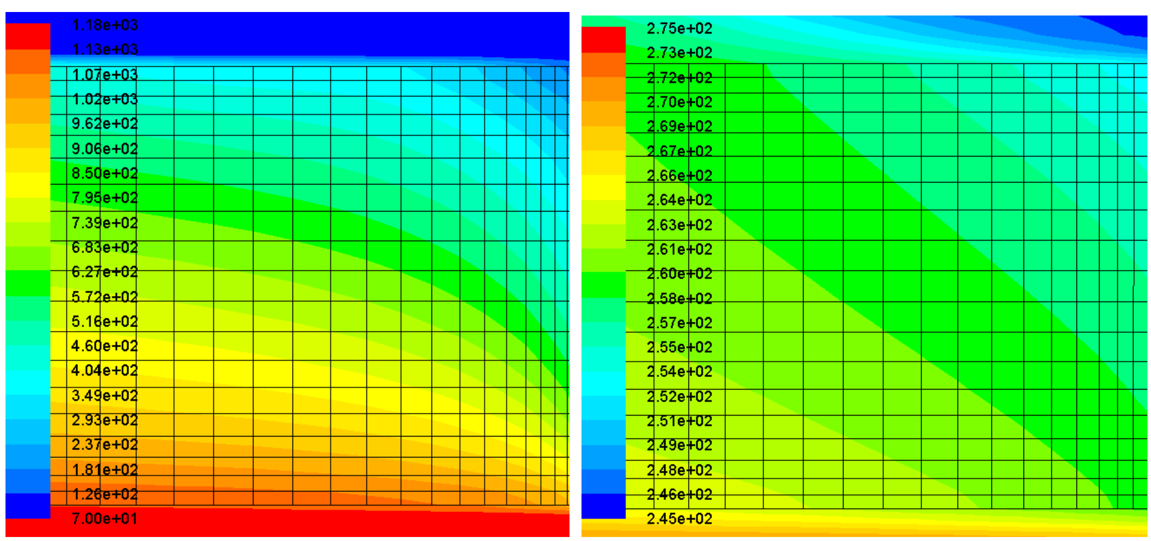

Fig 10. Filled Contour of Static Temp (°F). Wall That Failed PVWD vs wall that passed PVWD.

In the case of the N_2 injector tube utilizing the Haynes 230 material the pressure vessel wall delta is 330 °F. In reality the actual structural requirement and analysis are of course non-linear, so slight deviations from the linear requirement of 330 °F in regions such as corners, injection holes, and even small hotspots are permissible. But for the most part a sound thermal design would have no continuous regions that exceed a delta across the wall of 330 °F or it would fail to meet the American Society of Mechanical Engineers (ASME) pressure vessel code requirements.

Thermal Fluid Inputs:

FLUENT is a Computational Fluid Dynamics program capable of modeling flow, heat transfer, turbulence, and reactions. FLUENTs extensive capabilities are tailored for the modeling and simulation of a diverse range of physical phenomenon ranging as far as the internal combustion engine with sliding or deforming mesh to the flow over a high speed aircraft. FLUENT has also managed to combine that diversity with a user friendly graphical user interface. For example Fluent easily modeled the physics of the H_2-N_2 Mixer; which consisted of multiple N_2 injectors with both mass flow and pressure inlet boundary conditions, the H2 mass flow inlet boundary condition, H_2-N_2 mixing, heat conduction across multiple materials comprising the Haynes 230 N_2 injector tube and a Silica fabric insulator, and 2-dimensional analysis with a axis symmetry line. FLUENT also supported temperature dependent fluid, and material properties such as piecewise linear inputs for Specific Heat, Thermal conductivity, and viscosity. The graphical user interface offers a host of fluid, and material properties to support a quick set up, and FLUENT also supports a variety of grid topologies including the Plot-3d Formatted List (P3dF) format employed for this analysis. However 2-dimensional rather than 3-d grids were employed for this analysis in order to reduce run times. By taking into account hydraulic diameter during calculation the width of N2 injector slots can be converted into the available area for N_2 injector holes for manufacturing thus eliminating the need for a 3-dimensional analysis. With proper ramping of residuals, solutions would typically reach convergence in less than 700 iterations. FLUENT also offers a series of grid modification options which were used to rapidly turn on, off, or move the mixers N_2 injector slots without having to make a new grid.

General problem setup information

Solver Type	Pressure Based
Velocity Formulation	Absolute
Time	Steady State Solution
Space	2-dimensional, Axi-symmetric
Turbulence Model	Spalart-Allmaras (1 eqn) or K-epsilon (2 eqn) with wall functions
Species Model	Species Transport of an inert mixture

Solution Method

Scheme	Simple Scheme with Pressure-Velocity Coupling

Spatial Discretization

Gradient	Least Squares Cell Based
Pressure	Standard
Density	First Order Upwind
Momentum	First Order Upwind
Modified Turb Vis	First Order Upwind
N2	First Order Upwind
H2	First Order Upwind
Energy	First Order Upwind

The physical model is currently being expanded for a new computational grid to include the addition of water cooling, and thermal conductivity across several additional materials comprising an Inconel 625 water cooling jacket, depleted uranium fuel element, and a Molybdenum-Rhenium insert that fastens the fuel element to the mixer.

Computational Model:

The United States Air Force's computational model construction program, or grid builder, named PILGRIM was used for grid construction and editing. PILGRIM is a block to block structured grid builder. It uses a classic point, line, surface, volume construction approach that is well suited for cases such as this one where model construction began from blue prints. PILGRIM has a user friendly menu based Graphical User Interface (GUI), with simultaneous scripting that can easily be edited. This is accomplished by modifying the text based script, and then re-running the script. For example the size or number of nitrogen injectors in a given test case could easily be modified using a text editor by adjusting the position of the points that the grid was originally built off of in the script. Using the PILGRIM GUI to select and run the edited script would then produce the new grid.

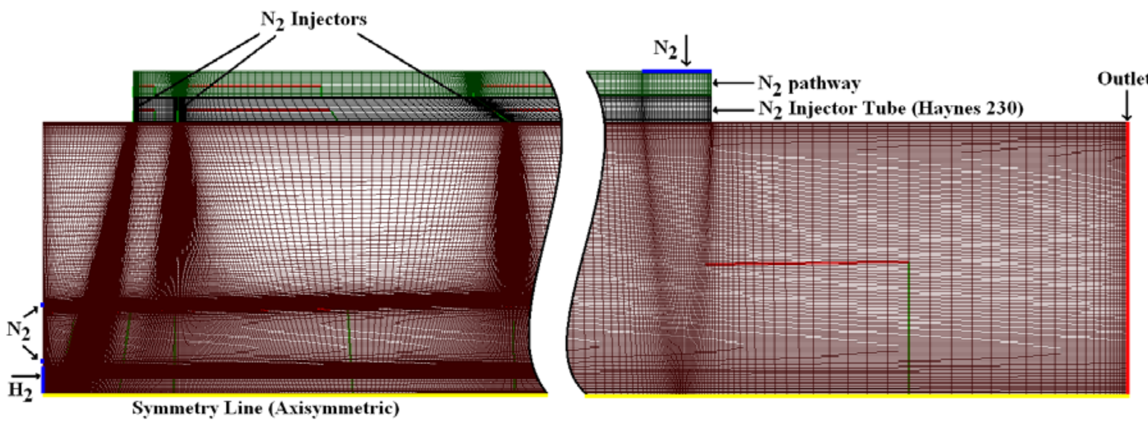

Fig 11. Typical Computational Grid Model

This 2-d grid is typical of those tested all N_2 injector slots were comprised of at least 5 cells across their width, and all remaining walls have inviscid wall spacing of 0.01 inches. The grid is comprised of a generous 162,908 cells.

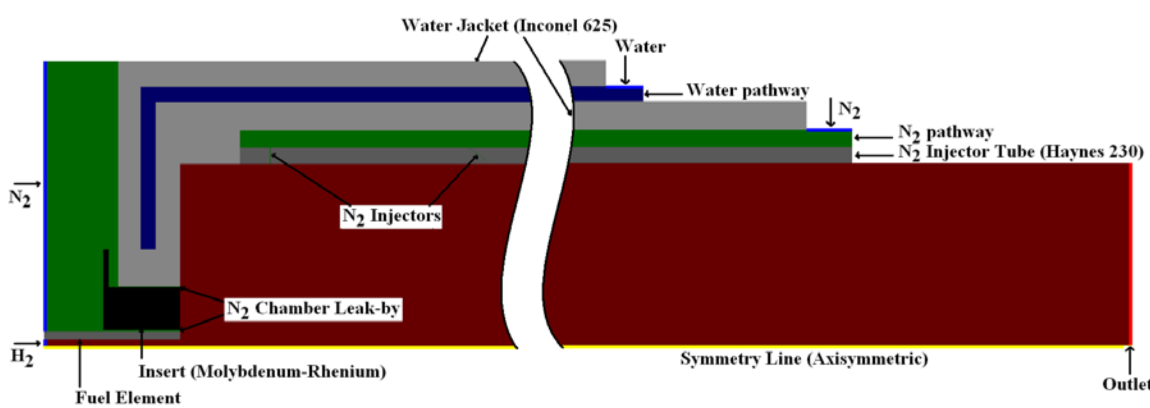

Fig 12. Filled Plot of Upgraded Computational Grid Model

A new grid is currently being input into FLUENT that is comprised of 190,597 cells. It will model the water, Inconel water jacket, Molybdenum-Rhenium insert which holds the fuel element, part of the fuel element, and part of the NTREES pressure vessel, in addition to the N_2 channel and injector tube of the previous model.

Thermal Fluid Results:

Case 45

Met Pressure Vessel Wall Delta	√
N_2 Chamber Leak-by Temp	400 ^oF
N_2 Leak-by Mass Flow Rate	1.3 lb/s
H_2 Inlet Temperature	5211 ^oF
H_2 Mass Flow Rate	0.22 lb/s
N_2 Inlet Temperature	0 ^oF
N_2 inlet Mass Flow Rate	11.38 lb/s
Mixer Average Exit Temp	1183.82 ^oF

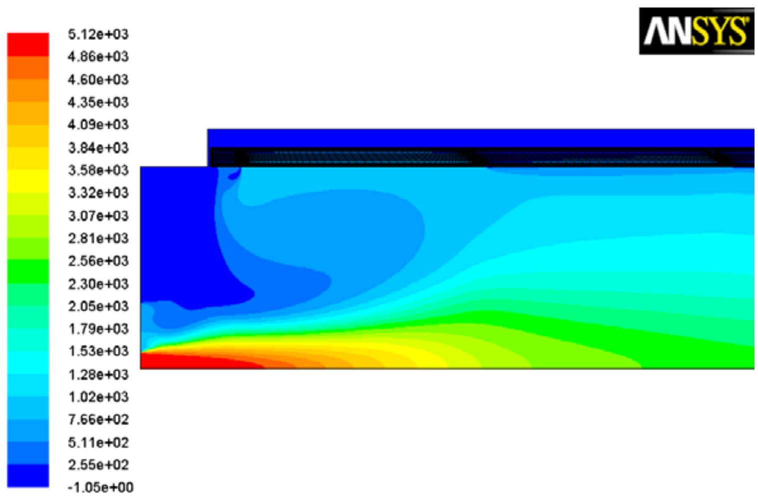

Fig 13. Contours of Static Temperature (f)

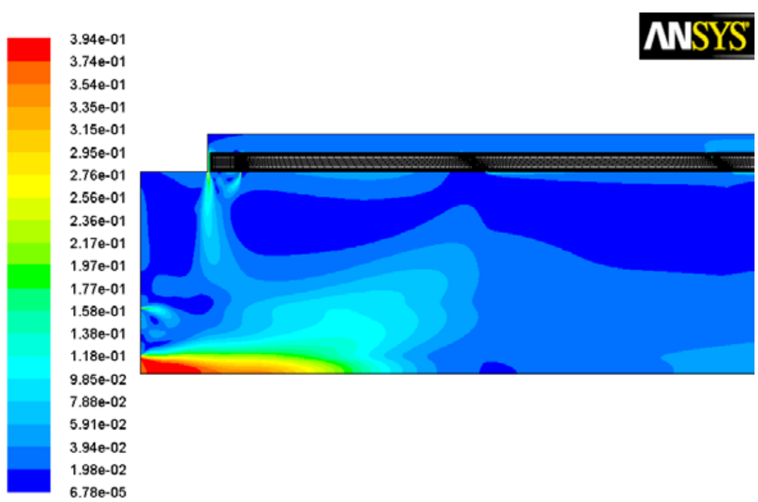

Fig 14. Contours of Mach Number

Fig 15. Contours of Static Pressure (psi)

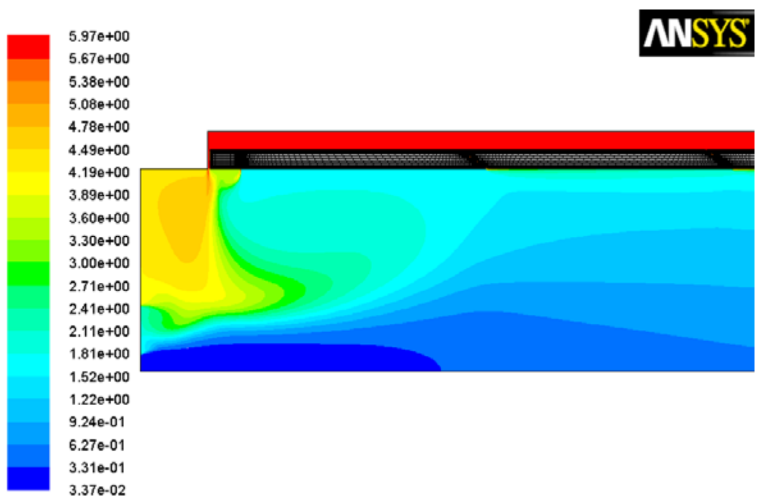

Fig 16. Contours of Density (lbm/ft3)

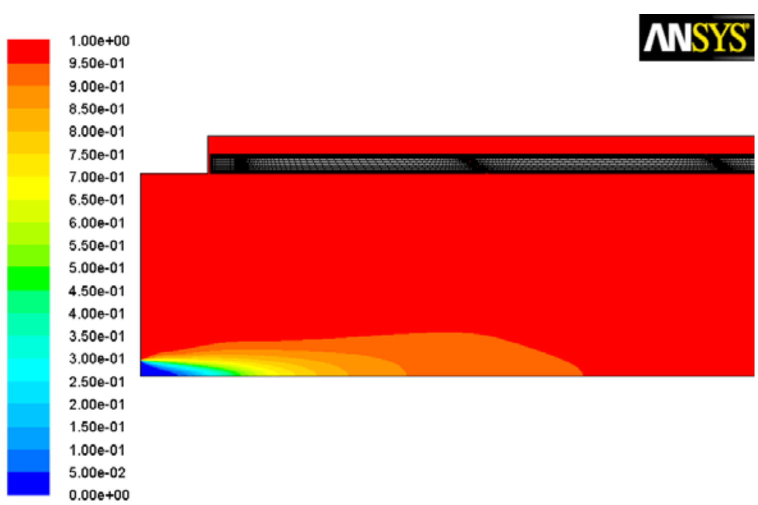

Fig 17. Contours of Mass fraction of n2

The Mixer average exit temperature (1183.82 ^oF) also concurred with the energy balance equation.

Specific Heat Energy Balance Equation:
$Q_H = m_H * C_{PH} * (\Delta T) = m_H * C_{PH} * (T_{inH} – T_{outH})$
$Q_C = m_C * C_{PC} * (\Delta T) = m_C * C_{PC} * (T_{outC} – T_{inC})$
Q = Heat transferred in thermal units per time (kW or Btu/h)
m = Mass flow rate
Cp = Constant Pressure Specific Heat
T = Temperature
H = Hot fluid
C = Cold fluid

Assuming perfect adiabatic heat transfer from the Hot fluid to the Cold fluid with zero loss to the environment through pipe walls, i.e. Q_H equals Q_C and T_{outH} equals T_{outC}.

Constant Pressure Specific Heat (C_p) of Hydrogen, and Nitrogen gas at 1071 ^oF
C_{pH2} = 3.5278 BTU/lb ^oF
C_{pN2} = 0.2709 BTU/lb ^oF

Mass Flow Rates (m) of Hydrogen, and Nitrogen gas
m_{H2} = 0.22 lb/s
m_{N2} = 11.38 lb/s

Temperature (T) of Hydrogen, and Nitrogen gas
T_{H2} = 5211 ^oF =
T_{N2} = 0 ^oF =

0.22 lb/s * 3.5278 BTU/lb ^oF * (5211 ^oF – T_{H2out}) =
11.38 lb/s * 0.2709 BTU/lb ^oF * (T_{N2out} - 0 ^oF)

0.7761 lb/s ^oF * (5211 ^oF – T_{H2out}) = 3.0828 lb/s ^oF * (T_{N2out} - 0 ^oF)

4044.2571 lb/s – (0.7761 lb/s ^oF * T_{H2out}) =
3.0828 lb/s ^oF * T_{N2out}

4044.2571 lb/s =
0.7761 lb/s ^oF * T_{H2out} + 3.0828 lb/s ^oF * T_{N2out}

4044.2571 lb/s = 3.8589 lb/s * T_{out}

1048 ^oF = T_{out}

This is well within the margin of error considering that an additional 1.3 lb/s at 400 ^oF is being added as n_2 leak-by from the main chamber.

Case 45 passed thermal and structural analysis. However this analysis also confirmed that it would require a massively higher mass flow rate of N_2 gas then was currently available at the test facility in order to operate at an H2 mass flow rate of 0.22 lb/s. In addition assuming that the Heat Exchanger inlet wall temperatures are equal to the average Mixer exit temperatures due to fully mixed fully turbulent flow exiting the mixer, then the projected Mixer average exit temperature would result in unreasonably high inlet temperatures for the heat exchanger portion of the system. At those temperatures it would be particularly difficult to set up a channel wall heat exchanger that could meet the pressure vessel wall delta requirement.

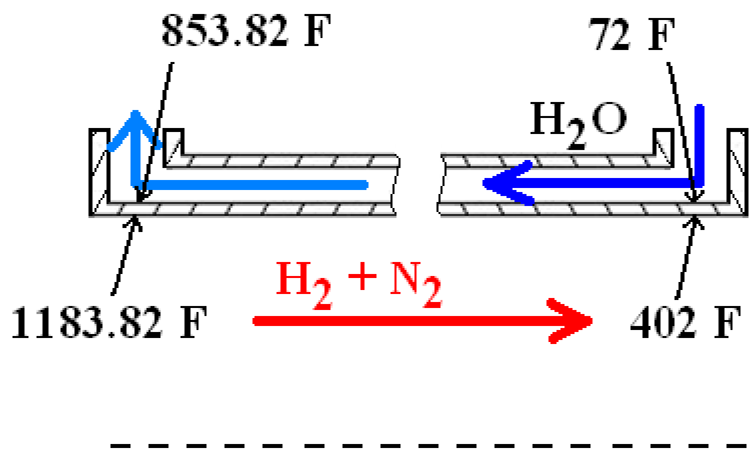

Fig 18. Balancing Mixer Exit Temperature vs Heat Exchanger Coolant for Case 45.

For example assuming water as coolant the water would need to exit at the heat exchanger inlet at 853.82 ^oF in order to be within the required pressure vessel wall delta (PVWD) of 330 ^oF of the 1183.82 ^oF heat exchanger H_2-N_2 gas inlet temperature. Unfortunately the critical temperature for water is 705.44 ^oF so it would be impossible to apply enough pressure to maintain water as a liquid at 853.82 ^oF. This Heat exchanger would also be unrealistically long as the heat exchanger H_2-N_2 gas would need to exit at no more than 402 ^oF in order to remain within 330 ^oF of the anticipated 72 ^oF water inlet and thus meet the PVWD requirement at the exit. Essentially meeting the pressure vessel wall delta at the inlet and exit determines the length of the heat exchanger, the mass flow rate of the coolant, and the viability of coolant options.

Current funding does not support the power requirements for the induction heating of 0.22 lb/s of hydrogen gas to 5211 ^oF. However the NTREES test system has been designed from the beginning to be upgradable to the 5 MW induction coil system that would be required to create that supply of hydrogen. It is also anticipated that funds would become available to upgrade the test facilities N_2 gas supply as part of any further NTREES upgrades. Therefore it was decided that the H_2-N_2 Mixer would be designed for easy bolt together assembly/disassembly. This will allow for modifications to the Mixers N_2 injector tube, increasing the size and number of injectors to match the test facilities available N_2 gas supply commensurate with any increase to the H_2 mass flow rate at 5211 ^oF due to an induction system upgrade. Modeling and simulation then focused on the H_2 mass flow rate and temperature of 0.0317 lb/s at 5211 ^oF which is more consistent with the current NTREES upgraded 1.2 MW induction coil system.

Case 63

Met Pressure Vessel Wall Delta	√
N_2 Chamber Leak-by Temp	400 ^oF
N_2 Leak-by Mass Flow Rate	1.3 lb/s
H_2 Inlet Temperature	5211 ^oF
H_2 Mass Flow Rate	0.0317 lb/s
N_2 Inlet Temperature	0 ^oF
N_2 inlet Mass Flow Rate	2.987 lb/s
Mixer Average Exit Temp	650 ^oF

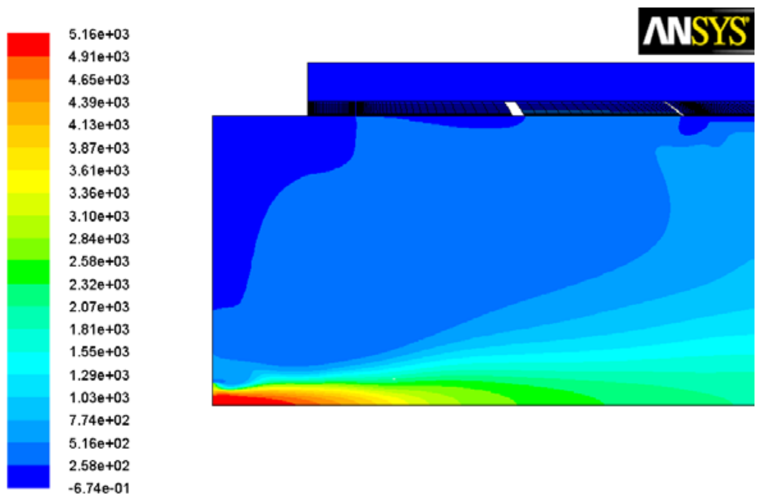

Fig 19. Contours of Static Temperature (f)

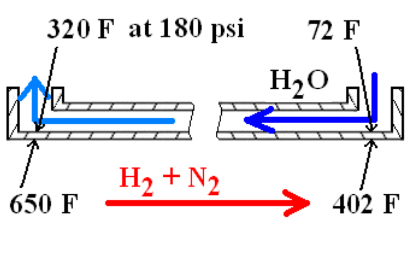

Fig 20. Balancing Mixer Exit Temperature vs Heat Exchanger Coolant for Case 63.

These H2-N2 Mixer results allow for a viable heat exchanger. Assuming water as the heat exchanger coolant, the water would need to exit at the heat exchanger inlet at 320 ^oF in order to be within the required pressure vessel wall delta (PVWD) of 330 ^oF of the 650 ^oF heat exchanger H_2-N_2 gas inlet temperature. This would require a water pressure boost pump to 180 psi. This Heat exchangers H_2-N_2 gas would need to exit at no more than 402 ^oF in order to remain within 330 ^oF of the anticipated 72 ^oF water inlet and thus also meet the PVWD requirement at the exit. A second much smaller Heat Exchanger section cooling in parallel would then remove the remaining heat in order to reach the required exit boundary condition of 180 ^oF. Both the length of the Heat Exchanger and the mass flow rate of the water coolant will be determined at a later date using NASA's Generalized Fluid System Software Program (GFSSP). Boundary conditions will be driven by the pressure vessel wall delta.

Case 65

Met Pressure Vessel Wall Delta	√
N_2 Chamber Leak-by Temp	400 ^oF
N_2 Leak-by Mass Flow Rate	1.3 lb/s
H_2 Inlet Temperature	5211 ^oF
H_2 Mass Flow Rate	0.0317 lb/s
N_2 Inlet Temperature	0 ^oF
N_2 inlet Mass Flow Rate	2.39 lb/s
Mixer Average Exit Temp	780 ^oF

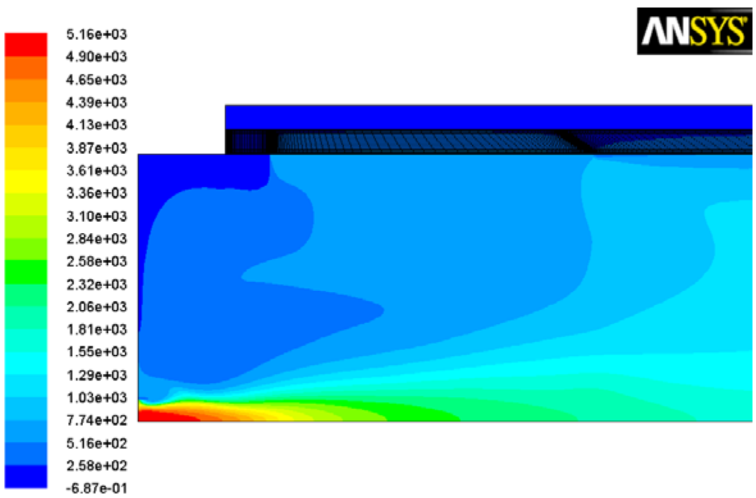

Fig 21. Contours of Static Temperature (f)

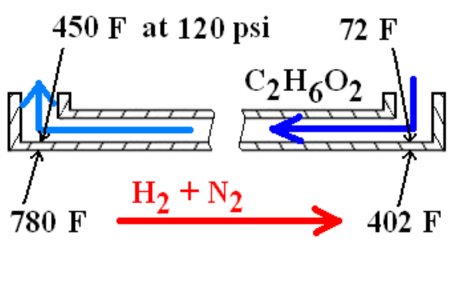

Fig 22. Balancing Mixer Exit Temperature vs Heat Exchanger Coolant for Case 65.

These H2-N2 Mixer results allow for a viable heat exchanger at a lower N_2 mass flow rate. Assuming ethylene glycol as the heat exchanger coolant, the ethylene glycol would need to exit at the heat exchanger inlet at 450 ^oF in order to be within the required PVWD of 330 ^oF of the 780 ^oF heat exchanger H_2-N_2 gas inlet temperature. This would require a ethylene glycol pressure boost pump to 120 psi. This Heat exchangers H_2-N_2 gas would need to exit at no more than 402 ^oF in order to remain within 330 ^oF of the anticipated 72 ^oF ethylene glycol inlet and thus also meet the PVWD requirement at the exit. A second much smaller Heat Exchanger section cooling in parallel would then remove the remaining heat in order to reach the required exit boundary condition of 180 ^oF. Both the length of the Heat Exchanger and the mass flow rate of the water coolant will be determined at a later date using NASA's Generalized Fluid System Software Program (GFSSP). Boundary conditions will be driven by the pressure vessel wall delta.

Case 73

Met Pressure Vessel Wall Delta	√
N_2 Chamber Leak-by Temp	400 °F
N_2 Leak-by Mass Flow Rate	1.3 lb/s
H_2 Inlet Temperature	5211 °F
H_2 Mass Flow Rate	0.0317 lb/s
N_2 Inlet Temperature	0 °F
N_2 Inlet Mass Flow Rate	1.54 lb/s
Mixer Average Exit Temp	963 °F

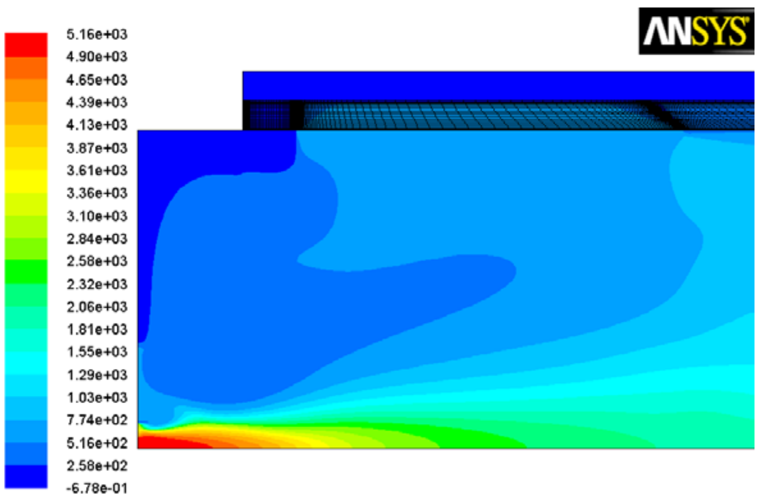

Fig 23. Contours of Static Temperature (f)

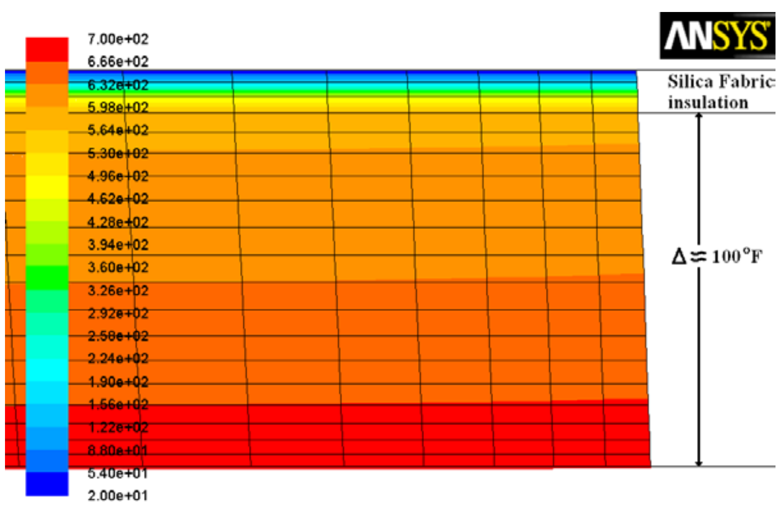

Fig 24. Contours of Static Temperature (f)

The addition of a 0.030" Silica fabric insulator to the outside of the N2 injector tube easily alleviates the troubling pressure vessel wall delta by normalizing the temperature across wall. These fabrics can operate at temperatures as high as 2,000 °F and are bonded to metal with adhesives that can withstand temperatures as high as 4,000 °F.

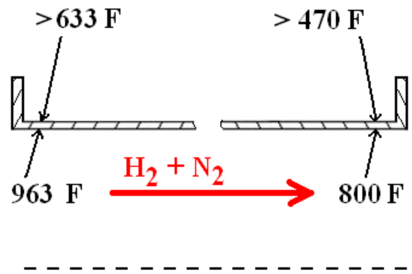

Fig 25. Balancing Mixer Exit Temperature vs Heat Exchanger Coolant for Case 73.

As previously demonstrated in case 45 it can be difficult to derive a viable Heat Exchanger that can operate at high H_2-N_2 Mixer exit temperatures, and pressures. However these H2-N2 Mixer results do allow for a viable heat exchanger at a lower N_2 mass flow rate provided a waiver for the Heat Exchanger exit boundary condition of 180 ^oF can be obtained. This is required in order to achieve a realistic Heat Exchanger length. A NASA safety waver can be granted by piping the high temperature H_2-N_2 gas out several feet above the roof of the test facility. Assuming an Air cooled heat exchanger, the outer wall of the heat exchanger would need to remain above 633 ^oF in order to be within the required PVWD of 330 ^oF of the 963 ^oF heat exchanger H_2-N_2 gas inlet temperature. At the Heat Exchanger exit the outer wall would need to remain above 470 ^oF in order to remain within 330 ^oF of the anticipated H_2-N_2 gas exit temperature of 800 ^oF and thus also meet the PVWD requirement at the exit. The Heat Exchanger H_2-N_2 gas exit temperature or required length for an 800 ^oF exit will be determined at a later date using NASA's Generalized Fluid System Software Program (GFSSP). Boundary conditions will be driven by the pressure vessel wall delta.

SUMMARY AND CONCLUSIONS

A viable H_2-N_2 Mixer, Heat Exchanger system; which employs an extremely low nitrogen mass flow rate has been identified. This system has also been designed to be scalable to higher hydrogen mass flow rates at an operating temperature of 5211 ^oF. Modeling and simulation of the H_2-N_2 Mixer inconel water jacket and water coolant is ongoing. The focus of that analysis will be to determine the effects of the heated fuel element, conduction through the Molybdenum-Rhenium insert, and pressure vessel heated N2 gas on the H_2-N_2 Mixer end cap.

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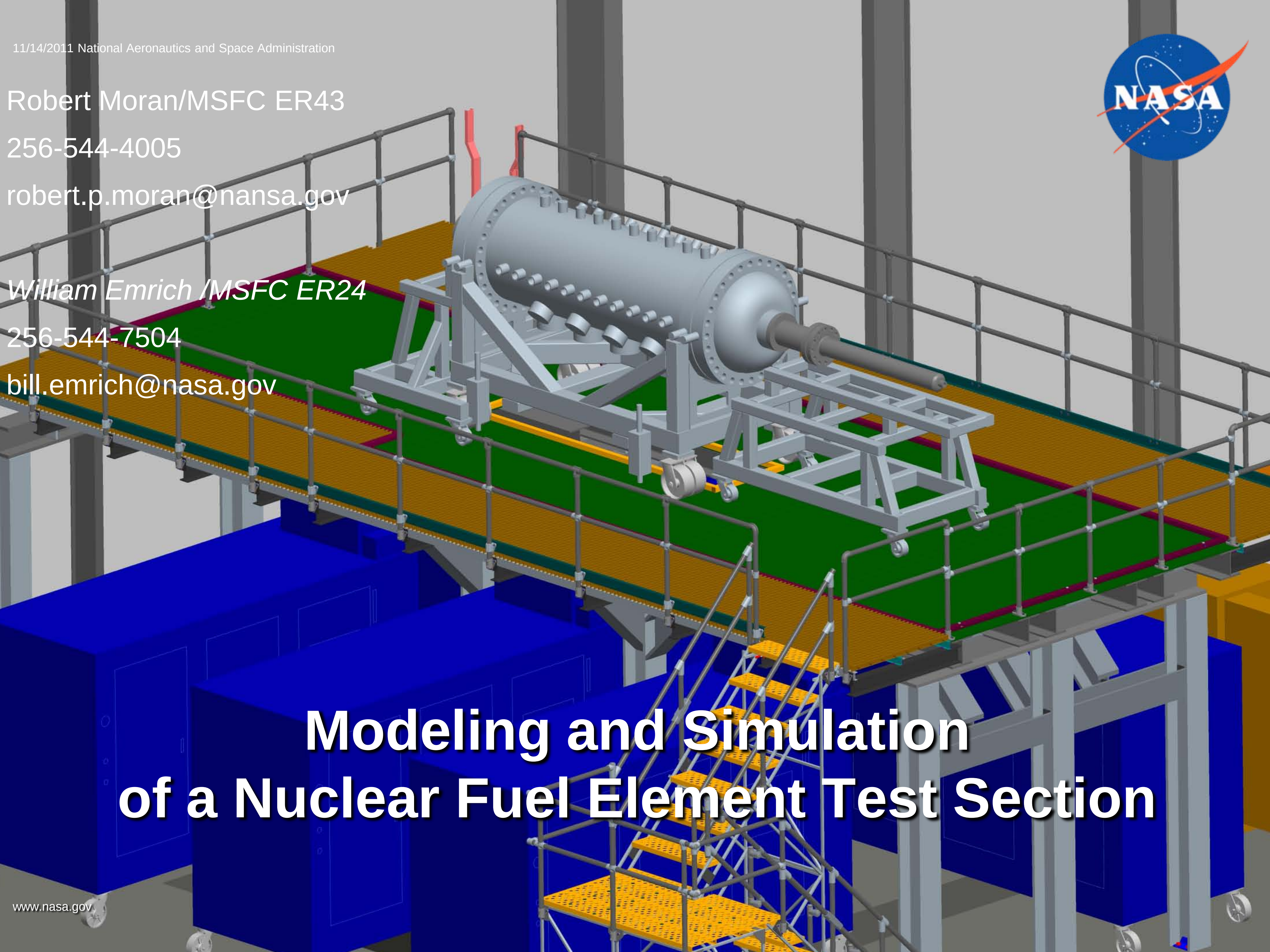
1. Philip G. Hill and Carl R. Peterson, *Mechanics and Thermodynamics of Propulsion*, Reading, MA: Addison-Wesley Publishing Company, 1965, p. 478.
2A William J . Emrich, Jr, Nuclear Thermal Rocket Element Environmental Simulator (NTREES), Pg 3
3. Daniel R. Kirk, Florida Institute of Technology, Alabama Space Grant Consortium Presentation, 2005, p2.
4. Barry Battista, NASA Marshall Space Flight Center, Haynes_230_Props, 2011, pg1.
5. Barry Battista, NASA Marshall Space Flight Center, Inconel_625_Props, 2011, pg1.



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Modeling and Simulation of a Nuclear Fuel Element Test Section

General Background

- Nuclear Thermal Rocket propulsion concept offers a combination of high thrust and efficiency
  - typically employs a uranium fueled nuclear reactor core and hydrogen (H_2) gas working fluid

- The H_2 gas acts first as fuel rod coolant as it passes through the nuclear reactor core followed by rocket working fluid when the then super heated hydrogen is expanded out of a nozzle in order to produce thrust.
  - Prototype KIWI-B4 produced approximately 75,000 pounds of thrust with an efficiency of 825 seconds

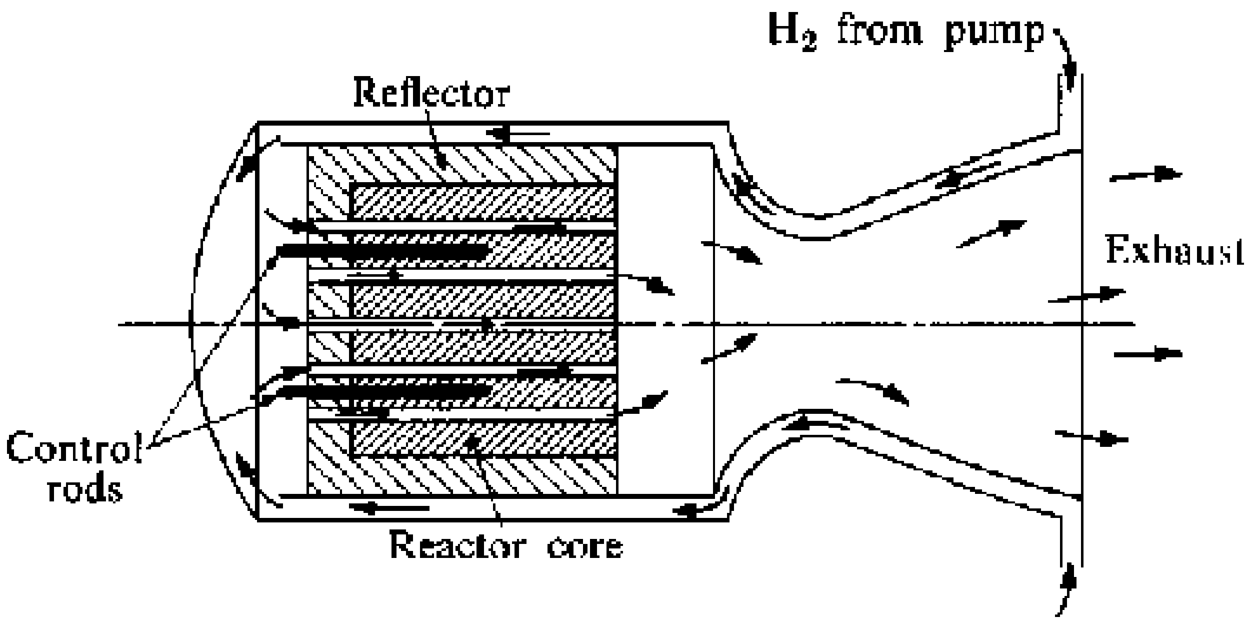


Fig 1. Solid-Core Nuclear Thermal Rocket Engine [(1)]

NTREES Background

- The Nuclear Thermal Rocket Element Environmental Simulator (NTREES) test section closely simulates the internal operating conditions of a nuclear thermal rocket for the design of fuel rods
- The NTREES test section employs a unique system of electrical induction coils to heat depleted Uranium fuel rods, and fuel rod materials
- Avoids the personal and legal hazards typically encountered during experimentation with fuel grade uranium. (Radioactive Fuel Rods pose a particularly dangerous hazard to living tissue)

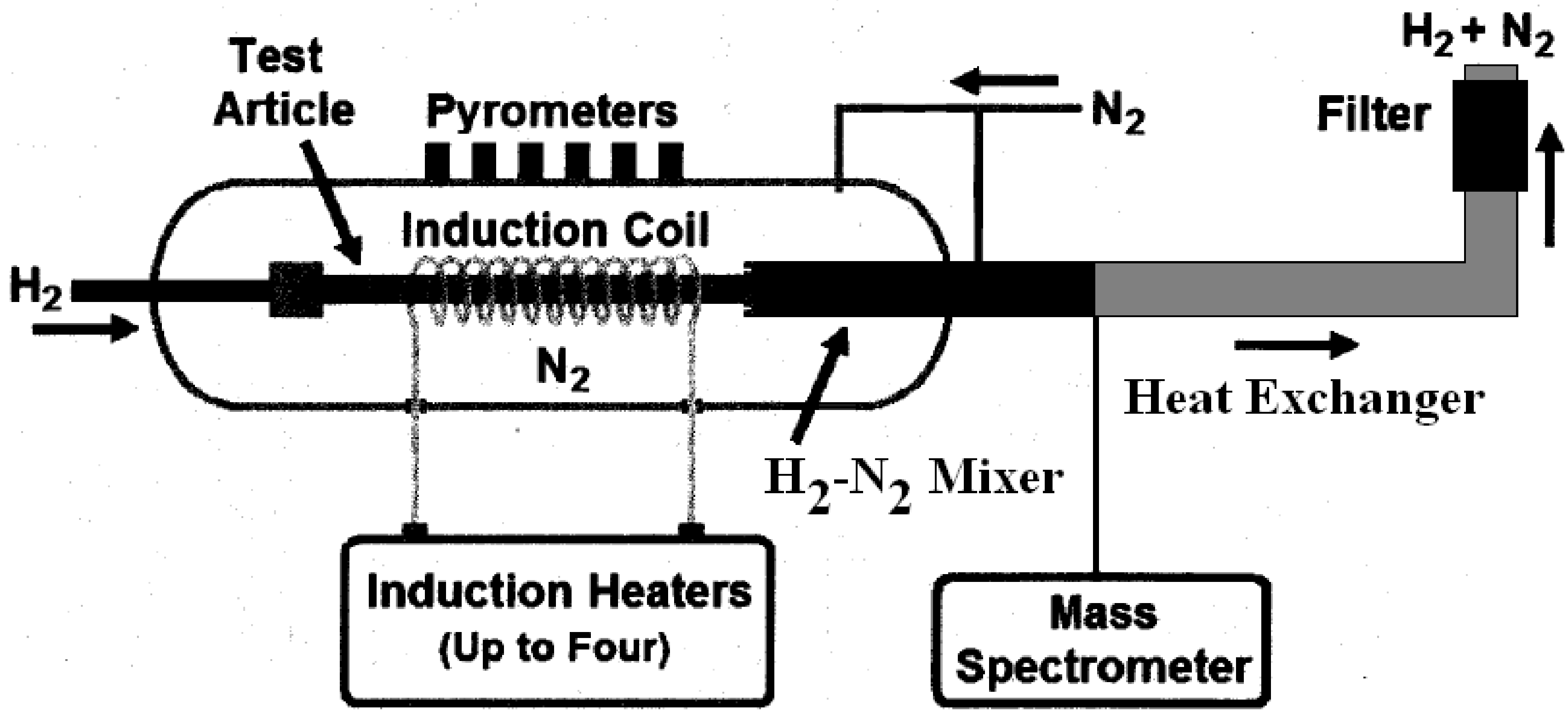


Fig 2. NTR Element Environmental Simulator Operational Layout [(2)]

NTREES Profile

- Cutaway view of the H2-N2 Mixer and Heat Exchanger incorporated into the NTREES Nuclear Fuel Rod testing and development system

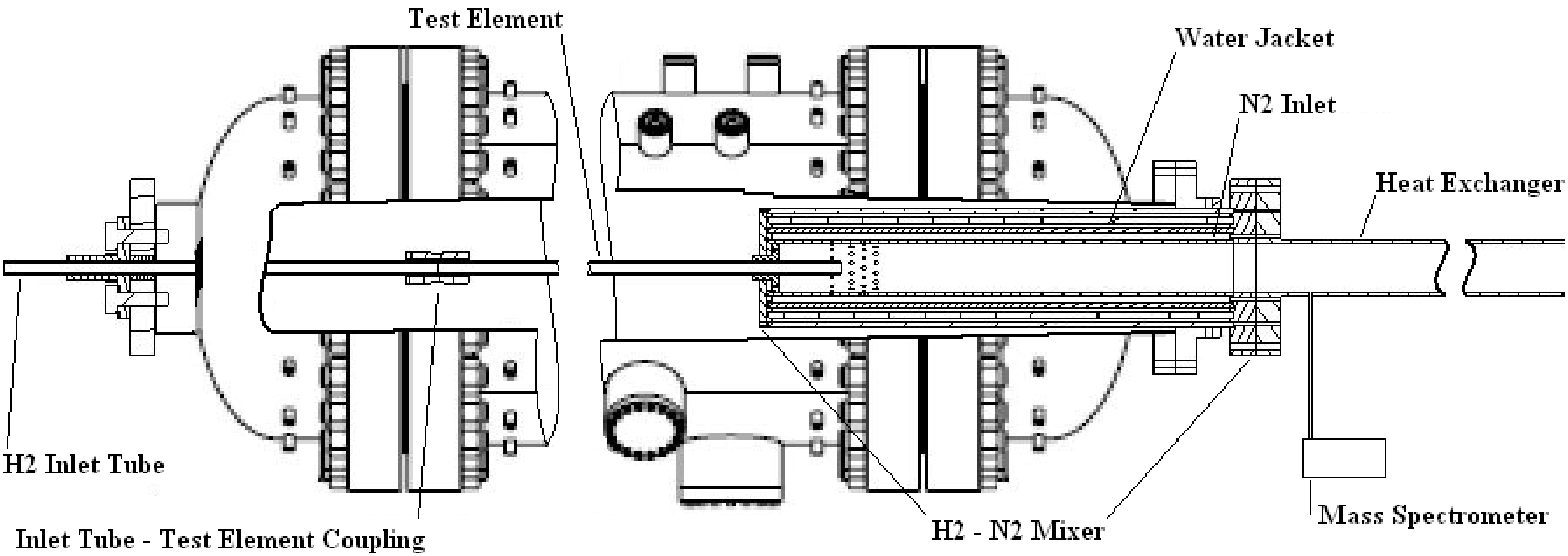


Fig 3. Cutaway view of (NTREES) [3]

NTREES Objectives

Primary NTREES Objective

- **The purpose of NTREES testing is to determine the ideal fuel rod characteristics for optimum thermal heat transfer to their hydrogen cooling/working fluid while still maintaining fuel rod structural integrity**
  - **Fuel rod test pieces can be sectioned and visually inspected for structural degradation (Made much easier due to lack of radiation)**
  - **Structural degradation can also be identified via spectral analysis of the fuel elements hydrogen exhaust gas using a mass spectrometer**
- **NTREES testing system is currently undergoing a major upgrade**
  - **More closely simulate the operating conditions encountered during nuclear thermal rocket operation**
  - **Test longer fuel rods at higher H_2 mass flow rates (mfr) (NTREES standard operating temp and pres)**
  - **Working fluid exhaust temperatures of up to 5,000 degrees Fahrenheit**
  - **Operating pressures are in excess of 1,000 psi**
  - **H_2 mfr of up to 0.22 lb/s with 5 MW of induction coils (current upgrade is H_2 mfr 0.0317 lb/s @ 1.2 MW)**

H2-N2 Mixer and Heat Exchanger Support Objectives

- **Complete the design and manufacture of a H2-N2 Mixer and Heat Exchanger system that will safely remove the inductively heated hydrogen exhaust gasses from the test facility**
  - **Scalable from the current upgrade of 1.2 MW induction coil heating 0.0317 lb/s of hydrogen gas to 5,000 ^{0}F to a 5 MW induction coil heating 0.22 lb/s of H_2 gas to 5,000 ^{0}F**
  - **Render hydrogen gas inert by mixing with nitrogen**
  - **Reduce hydrogen temperature for safe handling, spectral analysis, and filtration**

H2-N2 Mixer Profile

- **H2-N2 Mixer utilizes a series of water cooling channels and N_2 gas injectors for handling of the hydrogen exhaust gas**

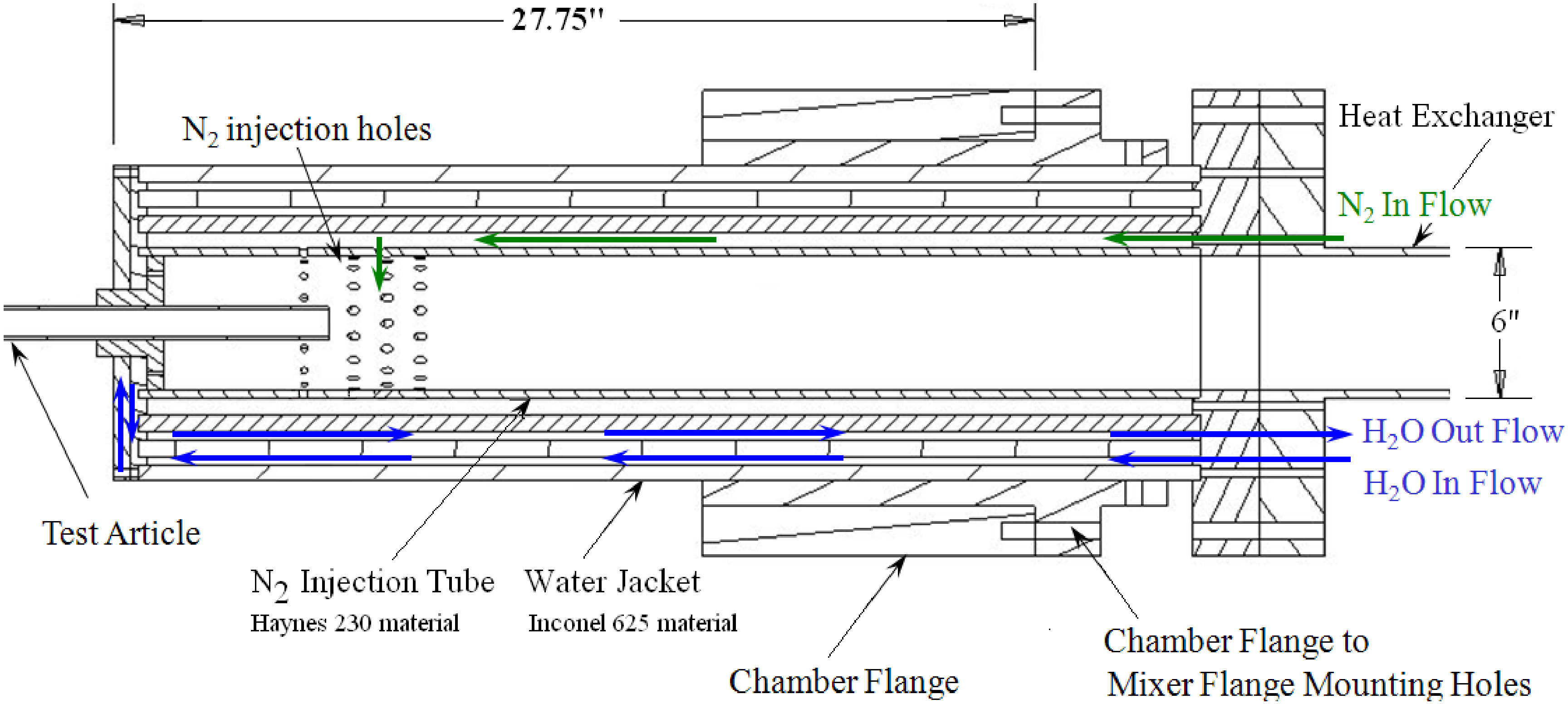


Fig 4. Preliminary design of the Mixer Internal Flow Passages (3)

H2-N2 Mixer Details

- **Thermal buckling was combated in the upgraded Mixer with a combination of expansion slots, nitrogen film cooling, and high quality manufacturing materials.**
  - **expansion slot employed to prevent buckling of the nitrogen injector tube due to thermal expansion**
  - **35^0 angled N_2 injector holes promote a film cooling layer along the inside of the N_2 injector tube**
  - **N_2 injector tube utilizes Haynes 230, a Nickel-Chromium-Tungsten-Molybdenum super alloy with exceptional strength at temperatures as high as 2,100 ^{0}F and long term stability without warping or surface degradation such as oxidation or scaling [(4)].**
  - **Outer shell utilizes Inconel 625, a Nickel-Chromium super alloy which offers good strength at temperatures as high as 2,000 ^{0}F and has excellent resistance to corrosion and oxidation [(5)].**

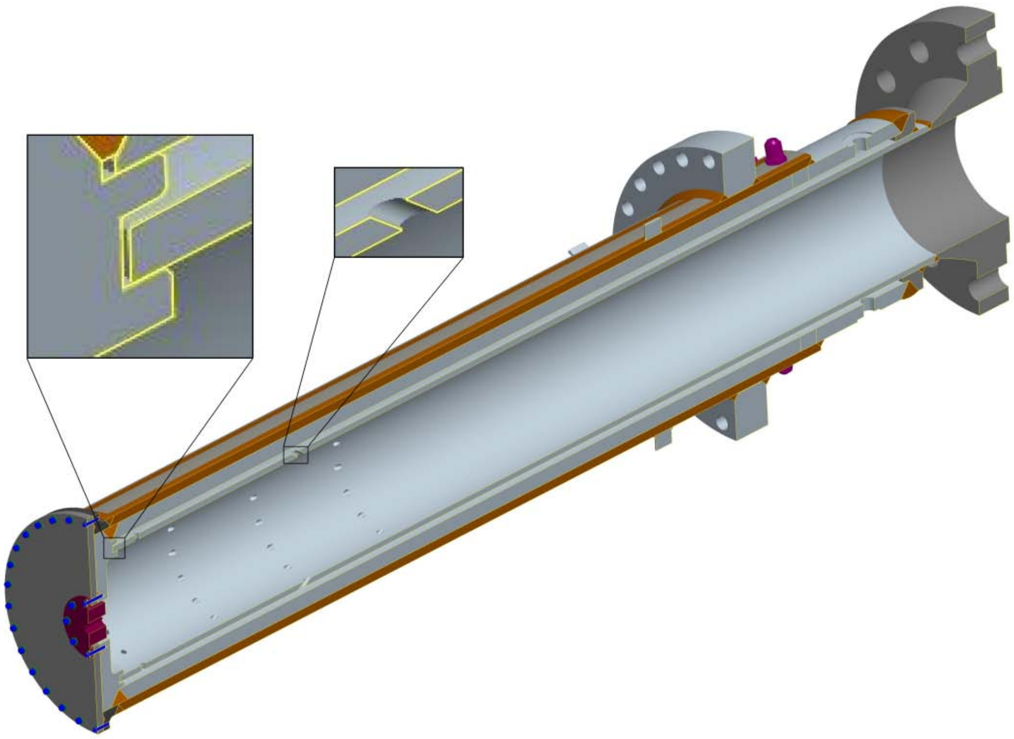


Fig 5. Cut away view of Mixer with zoom-in detail of the nitrogen injector tube expansion slot, and N2 injector

Heat Exchanger Details

- General Heat Exchanger design
  - ≈40 ft of 6 inch diameter Haynes 230 material
  - ≈ 40 ft of 6 inch diameter 304 stainless tubing (Already installed in the test facility)
  - A fan blade shaped titanium insert at inlet (Assume fully mixed fully turbulent Heat Exchanger inlet flow)
- Two potential Heat Exchanger designs
  - Channel wall- water or ethyl-glycol cooled
    - System exit boundary condition of 180 ^{0}F
  - Finned wall- air cooled
    - System exit boundary condition of 800 ^{0}F

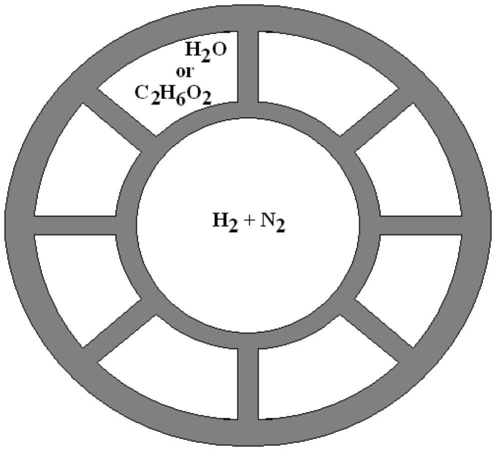


Fig 6. Channel Walled Heat Exchanger Cross Section

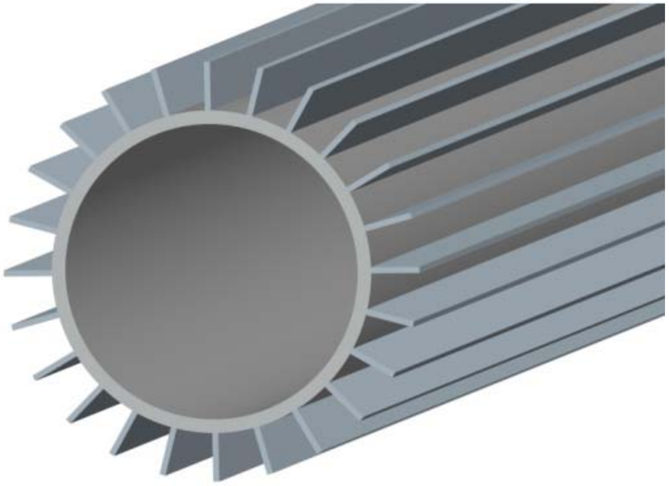


Fig 7. Finned Wall Heat Exchanger

H2-N2 Mixer Analysis

- **An extensive thermal fluid and structural analysis was performed in support of the engineering design of the H2-N2 mixer and heat exchanger test sections**
  - **FLUENT: Thermal Fluid Analysis program**
  - **PILGRIM : Air Force computational model (grid) generator**
  - **GFSSP: Generalized Fluid System Software Program**
  - **ANSYS: Finite Element Analysis (FEA) program**

- **Thermal fluid analysis of H2-N2 Mixer**
  - **Modeling and simulation of the H2-N2 mixer water cooling channel and nitrogen injectors**
  - **Rapid designing via Pilgrim and FLUENT during trade studies of N_2 injector size and location**
  - **PILGRIM scripting capability allowed for easy grid modification via text editing of the script**
  - **FLUENT's capability to couple the analysis of thermal fluid and structural thermal conductivity (Analysis of heat transfer from the fluid "through the wall")**
  - **Determine the maximum mass flow rate-operating temperature curve of the fuel elements hydrogen exhaust gas**

- **Limiting Design Factor**
  - **Test facilities nitrogen gas mass flow rate significantly impacts the allowable hydrogen exhaust gas mass flow rate at 5,000 ^{0}F**

Thermal Structural Requirement

- **Pressure Vessel Wall Delta (PVWD)**
  - **Requirement that pressure vessel components have a maximum allowable temperature delta across vessel walls in order to meet stringent factors of safety for stress**
  - **(American Society of Mechanical Engineers (ASME) pressure vessel code requirement)**
    - **Pressure dependant (1000 psi)**
    - **Temperature dependant (5000 ^{0}F)**
    - **Material dependant (Haynes 230)**
  - **Influenced the design of both H2-N2 Mixer, and Heat Exchanger sections**
  - **PVWD is 330 ^{0}F for the N_2 injector tube and Heat Exchanger system utilizing the Haynes 230 material**

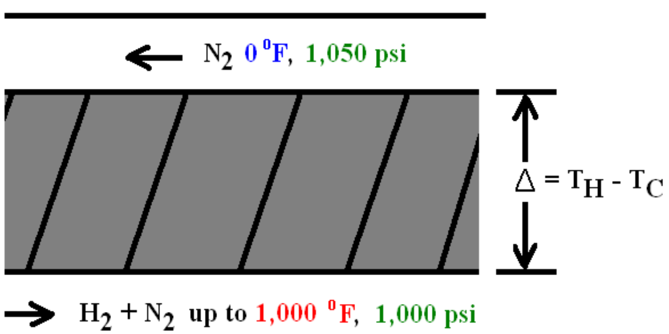


Fig 8. Pressure Vessel Wall Delta (Δ)

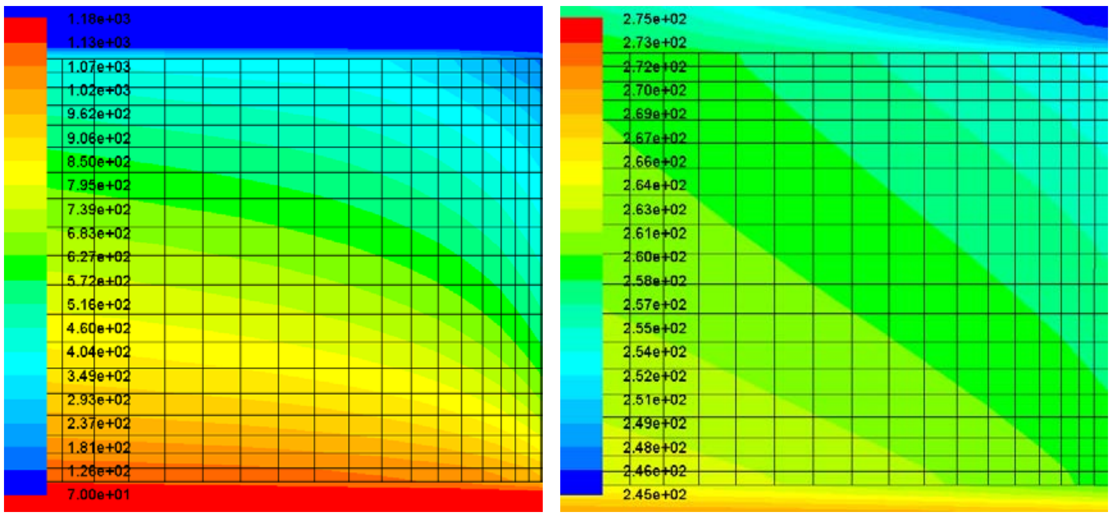


Fig 9. Wall That Failed PVWD vs wall that passed PVWD (Filled Contour of Static Temp (^{0}F))

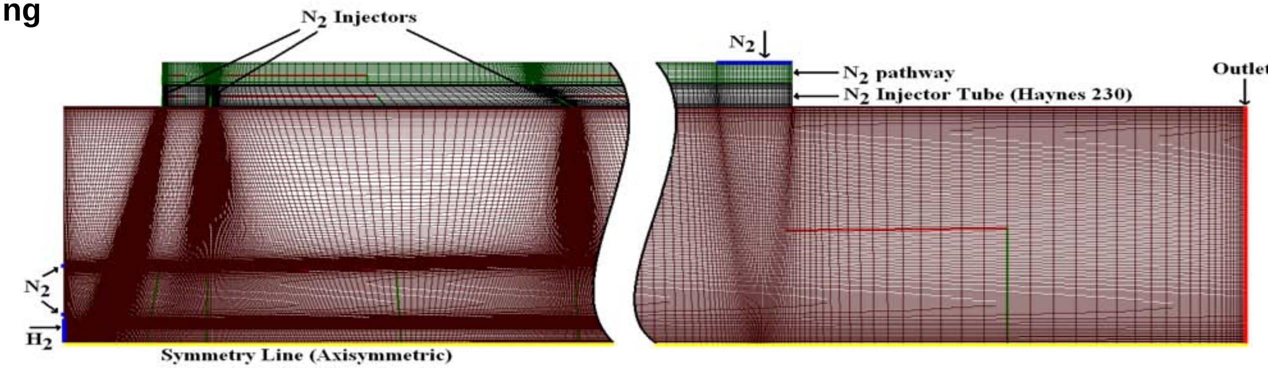
- **Actual Structural requirement and FEA analysis are non-linear, so slight deviations from the “Rule of Thumb” i.e. linear requirement of 330 ^{0}F in regions such as corners, injection holes, and even small hotspots are permissible**

Simulation Model

- **Physics Model of the H_2-N_2 Mixer**
  - **Multiple mass flow rate and pressure inlet boundary conditions for N_2 & H_2 gas, and liquid water**
  - **H_2-N_2 mixing**
  - **Heat conduction across multiple materials comprising the Haynes 230 N_2 injector tube, Silica fabric insulator, and Inconel water jacket**
  - **2-dimensional, Axisymmetric analysis**
  - **Piecewise linear temperature dependant properties (Specific Heat, Thermal conductivity, and viscosity)**
- **General problem setup information**
  - **Solver Type** — **Pressure Based**
  - **Velocity Formulation** — **Absolute**
  - **Time** — **Steady State Solution**
  - **Space** — **2-dimensional, Axi-symmetric**
  - **Turbulence Model** — **Spalart-Allmaras (1 eqn) or K-epsilon (2 eqn) with wall functions**
  - **Species Model** — **Species Transport of an inert mixture (Non-Reacting Flow)**
- **Solution Method**
  - **Scheme** — **SIMPLE Scheme with Pressure-Velocity Coupling**
- **Spatial Discretization**
  - **Gradient** — **Least Squares Cell Based**
  - **Pressure** — **Standard**
  - **Density** — **First Order Upwind**
  - **Momentum** — **First Order Upwind**
  - **Mod Turb Vis** — **First Order Upwind**
  - **N2** — **First Order Upwind**
  - **H2** — **First Order Upwind**
  - **H2O (L)** — **First Order Upwind**
  - **Energy** — **First Order Upwind**
  - **Y+** — **Range of 7 to 325**
- **Convergence Criteria**
  - **Low Residuals (<$1x10^{-4}$) with little fluctuation in residual value between iterations**

Computational Model

- **PILGRIM**
  - **United States Air Force computational model construction program, or grid builder**
  - **Plot-3d Formatted List (P3dF)**
  - **2-Dimensional Grids**
  - **≈ 200,000 Cells**
  - **0.01” wall spacing**



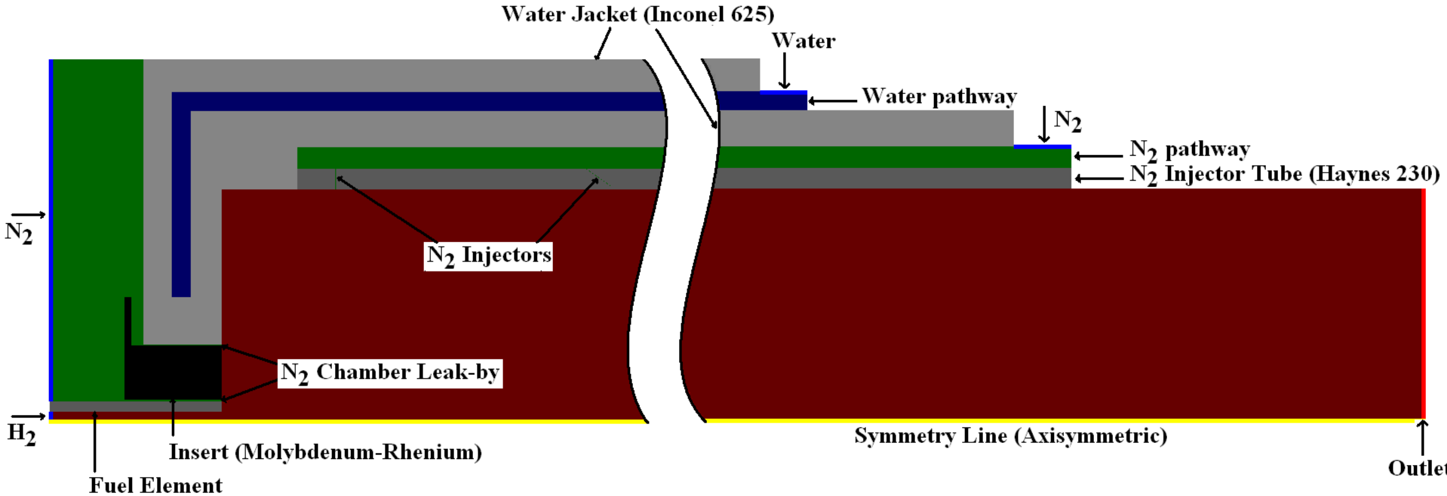


Fig 10. Typical Computational Grid Models

Thermal Fluid Results (Case 45)

- **Case 45**
  - **Met Pressure Vessel Wall ∆** √
  - **N_2 Chamber Leak-by Temp** 400 ^{0}F
  - **N_2 Leak-by Mass Flow Rate** 1.3 lb/s
  - **H_2 Inlet Temperature** 5211 ^{0}F
  - **H_2 Mass Flow Rate** 0.22 lb/s
  - **N_2 Inlet Temperature** 0 ^{0}F
  - **N_2 inlet Mass Flow Rate** 11.38 lb/s
  - **Mixer Average Exit Temp** 1183.82 ^{0}F

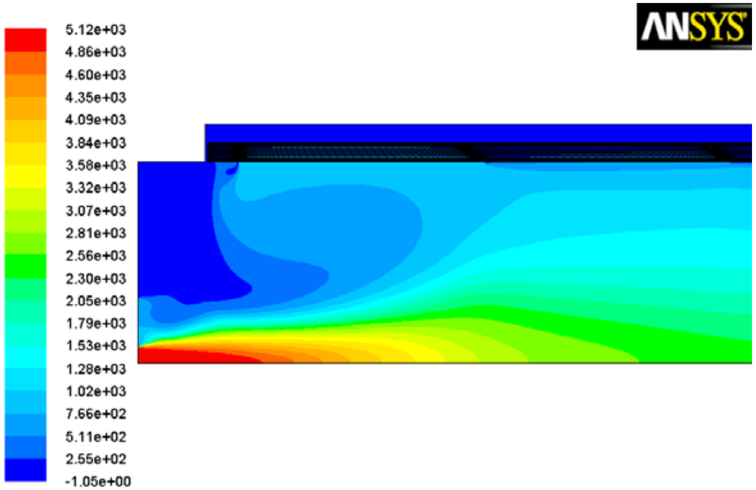


Fig 11. Contours of Static Temperature (f)

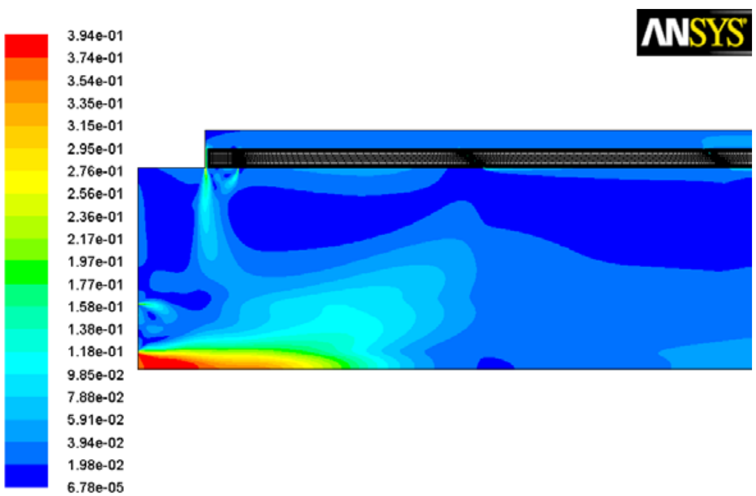


Fig 12. Contours of Mach Number

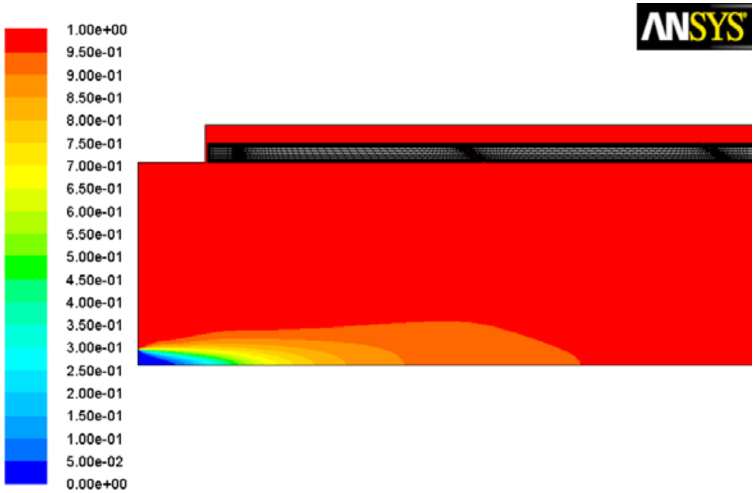


Fig 13. Contours of Mass fraction of n2

Validation Results Review

Case 45 Continued

- **Energy Ballance**
  - **Specific Heat Energy Balance Equation:**
  - $Q_H = m_H * C_{PH} * (\Delta T) = m_H * C_{PH} * (T_{inH} - T_{outH})$
  - $Q_C = m_C * C_{PC} * (\Delta T) = m_C * C_{PC} * (T_{outC} - T_{inC})$
    - **Q = Heat transferred in thermal units per time (kW or Btu/h)**
    - **m = Mass flow rate**
    - **Cp = Constant Pressure Specific Heat**
    - **T = Temperature**
    - **H = Hot fluid**
    - **C = Cold fluid**
  - **1048 ^{0}F**
  - **within the margin of error considering that an additional 1.3 lb/s at 400 ^{0}F is being added as n_2 leak-by from the main chamber**
  - **Also performed comparison with GFSSP**

- **Lessons Learned**
  - **Sound computer model**
  - **Sound design concept (Case 45 passed thermal and structural analysis)**
  - **It would require a massively higher mass flow rate of N_2 gas than was currently available at the test facility in order to operate at an H2 mass flow rate of 0.22 lb/s at 5000 ^{0}F (5 MW)**

Lessons Learned Continued

Case 45 Continued

- **Case 45 is not a viable solution for the heat exchanger**
  - **Mixer average exit temperature would result in unreasonably high inlet temperatures for the heat exchanger portion of the system.**

    (Assuming Heat Exchanger inlet wall temperatures equal to the average Mixer exit temperatures due to fully mixed fully turbulent flow exiting the mixer)

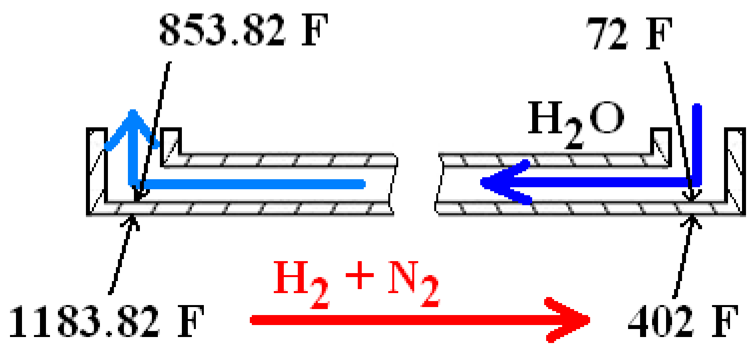


Fig 14. Heat Exchanger cross section (Case 45)

- **Water would need to exit at the heat exchanger inlet at 853.82 ^{0}F in order to be within the required pressure vessel wall delta (PVWD) of 330 ^{0}F of the 1183.82 ^{0}F heat exchanger H_2-N_2 gas inlet temperature.**
- **Critical temperature for water is 705.44 ^{0}F so it would be impossible to apply enough pressure to maintain water as a liquid at 853.82 ^{0}F**
- **The Heat exchanger would also be unrealistically long as the heat exchanger H_2-N_2 gas would need to exit at no more than 402 ^{0}F in order to remain within 330 ^{0}F of the anticipated 72 ^{0}F water inlet and thus meet the PVWD requirement at the exit.**
- **Meeting the pressure vessel wall delta at the inlet and exit determines the length of the heat exchanger, the mass flow rate of the coolant, and the viability of coolant options.**

Lessons Learned Continued

Case 45 Continued

- **The NTREES test system has been designed from the beginning to be upgradable**
  - **5 MW induction coil system is required to create 0.22 lb/s of H2 at 5000 ^{0}F**
  - **An upgrade to the test facilities N_2 gas supply will accompany any further NTREES upgrades.**
  - **The H_2-N_2 Mixer is designed for easy bolt together assembly/disassembly.**
    - **Allows for modifications to the Mixers N_2 injector tube, increasing the size and number of injectors to match the test facilities available N_2 gas supply commensurate with any increase to the H_2 mass flow rate at 5211 ^{0}F due to an induction system upgrade.**

- **All further design efforts focused on the H_2 mass flow rate and temperature of 0.0317 lb/s at 5211 ^{0}F which is more consistent with the current NTREES upgraded 1.2 MW induction coil system.**

Thermal Fluid Results (Case 63)

- **Case 63**
  - **Met Pressure Vessel Wall Δ** √
  - **N_2 Chamber Leak-by Temp** 400 ^{0}F
  - **N_2 Leak-by Mass Flow Rate** 1.3 lb/s
  - **H_2 Inlet Temperature** 5211 ^{0}F
  - **H_2 Mass Flow Rate** 0.0317 lb/s
  - **N_2 Inlet Temperature** 0 ^{0}F
  - **N_2 inlet Mass Flow Rate** 2.987 lb/s
  - **Mixer Average Exit Temp** 650 ^{0}F

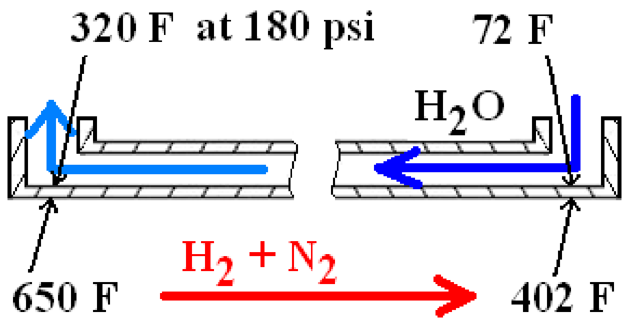


Fig 15. Heat Exchanger cross section (Case 63)

- **H2-N2 Mixer results allow for a viable heat exchanger**
  - **water cooled heat exchanger**
  - **Water would exit at the heat exchanger inlet at 320 ^{0}F**
    - **Would be within PVWD of 330 ^{0}F of the 650 ^{0}F heat exchanger H_2-N_2 gas inlet temperature**
    - **Requires a water pressure boost pump to 180 psi.**
  - **Heat exchangers H_2-N_2 gas would need to exit at no more than 402 ^{0}F**
    - **Would be within PVWD of 330 ^{0}F of the anticipated 72 ^{0}F water inlet**
  - **Second Heat Exchanger section would then cool to the required exit boundary condition of 180 ^{0}F.**
    - **Significantly Smaller (≈6 feet long)**
    - **cooling in parallel**
  - **The exact length of the Heat Exchanger and the mass flow rate of the water coolant will be determined using NASA's Generalized Fluid System Software Program (GFSSP).**
  - **Boundary conditions are driven by the pressure vessel wall delta.**

Thermal Fluid Results (Case 65)

- **Case 65**
  - Met Pressure Vessel Wall Δ √
  - N_2 Chamber Leak-by Temp 400 ^{0}F
  - N_2 Leak-by Mass Flow Rate 1.3 lb/s
  - H_2 Inlet Temperature 5211 ^{0}F
  - H_2 Mass Flow Rate 0.0317 lb/s
  - N_2 Inlet Temperature 0 ^{0}F
  - N_2 inlet Mass Flow Rate 2.39 lb/s
  - Mixer Average Exit Temp 780 ^{0}F

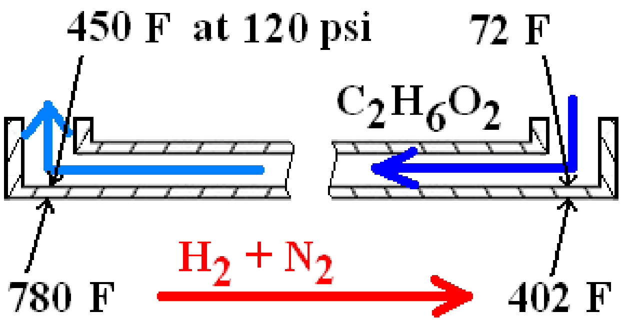
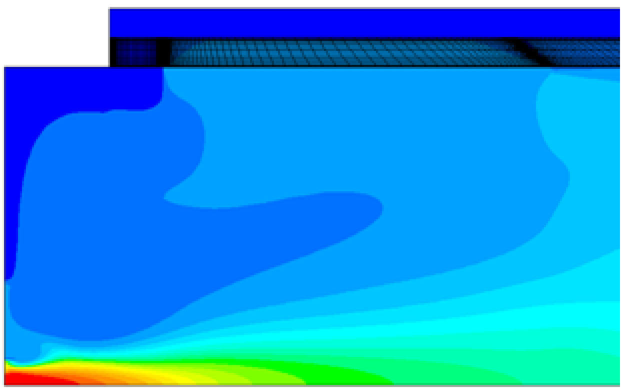


Fig 16. Heat Exchanger cross section (Case 65)

- **H2-N2 Mixer results allow for a viable heat exchanger**
  - ethylene glycol cooled heat exchanger
  - ethyl-glycol would exit at the heat exchanger inlet at 450 ^{0}F
    - Would be within PVWD of 330 ^{0}F of the 780 ^{0}F heat exchanger H_2-N_2 gas inlet temperature
    - Requires a ethyl-glycol pressure boost pump to 120 psi.
  - Heat exchangers H_2-N_2 gas would need to exit at no more than 402 ^{0}F
    - Would be within PVWD of 330 ^{0}F of the anticipated 72 ^{0}F ethyl-glycol inlet
  - Second Heat Exchanger section would then cool to the required exit boundary condition of 180 ^{0}F.
    - Significantly Smaller (≈6 feet long)
    - cooling in parallel
  - The exact length of the Heat Exchanger and the mass flow rate of the ethyl-glycol coolant will be determined using NASA's Generalized Fluid System Software Program (GFSSP).
  - Boundary conditions are driven by the pressure vessel wall delta.

Thermal Fluid Results (Case 73)

- **Case 73**
  - **Met Pressure Vessel Wall Δ** √
  - **N_2 Chamber Leak-by Temp** 400 ^{0}F
  - **N_2 Leak-by Mass Flow Rate** 1.3 lb/s
  - **H_2 Inlet Temperature** 5211 ^{0}F
  - **H_2 Mass Flow Rate** 0.0317 lb/s
  - **N_2 Inlet Temperature** 0 ^{0}F
  - **N_2 inlet Mass Flow Rate** 1.54 lb/s
  - **Mixer Average Exit Temp** 963 ^{0}F



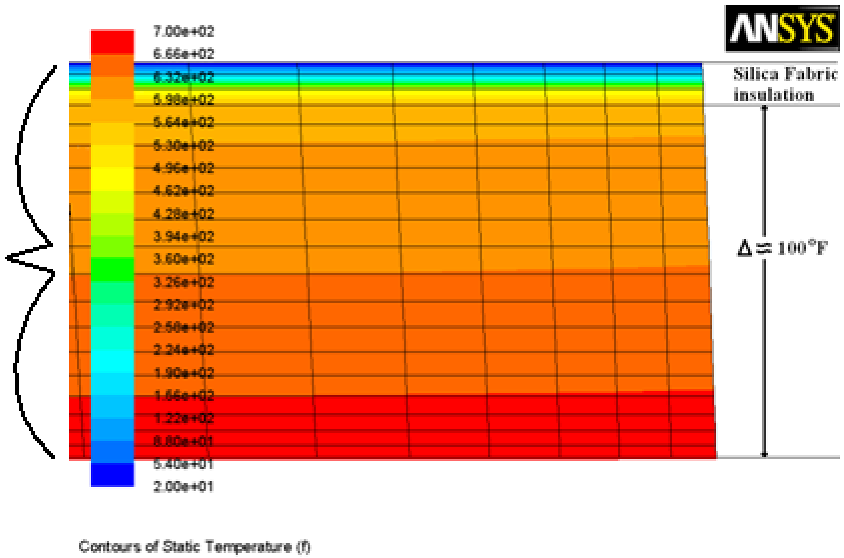


Fig 17. H2-N2 Mixer wall Temperature

- **Silica fabric insulator**
  - **Silica fabric can operate at temperatures as high as 2,000 ^{0}F**
  - **Bonded to metal with adhesives that can withstand up to 4,000 ^{0}F**
  - **0.030" thick addition to the outside of the N2 injector tube wall**
  - **Alleviates the PVWD by normalizing the temperature across wall**
  - **Moves the PVWD problem downstream**

Thermal Fluid Results Continued (Case 73)

- **H2-N2 Mixer results allow for a viable heat exchanger**
  - **waive the Heat Exchanger exit boundary condition of 180 ^{0}F**
    - **Required in order to achieve a realistic Heat Exchanger length**

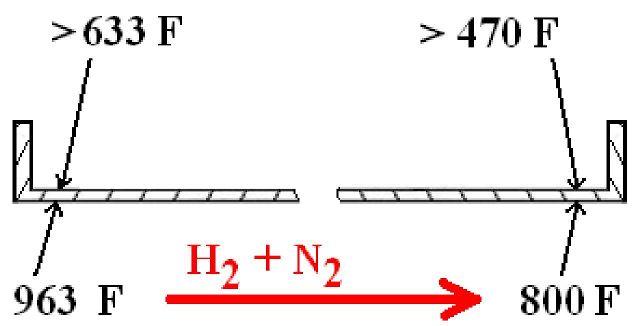


Fig 18. Heat Exchanger cross section (Case 73)

- **Air cooled heat exchanger**
- **Outer wall of the heat exchanger would need to remain above 633 ^{0}F at the heat exchanger H_2-N_2 gas inlet**
  - **Would be within PVWD of 330 ^{0}F of the 963 ^{0}F heat exchanger H_2-N_2 gas inlet temperature**
- **Heat Exchanger exit outer wall would need to remain above 470 ^{0}F**
  - **Would be within PVWD of 330 ^{0}F of the assumed 800 ^{0}F heat exchanger H_2-N_2 gas exit temperature**
- **The exact length of the Heat Exchanger or the required length for an 800 ^{0}F exit will be determined using NASA's Generalized Fluid System Software Program (GFSSP).**
- **Boundary conditions are driven by the pressure vessel wall delta.**

Thermal Fluid Results (Case 78)

- **Case 78**
  - Met Pressure Vessel Wall Δ √
  - N_2 Chamber Leak-by Temp 100 ^{0}F
  - N_2 Leak-by Mass Flow Rate 1.3 lb/s
  - H_2 Inlet Temperature 5211 ^{0}F
  - H_2 Mass Flow Rate 0.0317 lb/s
  - N_2 Inlet Temperature 0 ^{0}F
  - N_2 inlet Mass Flow Rate 1.54 lb/s
  - Mixer Average Exit Temp 963 ^{0}F

- **Water Jacket Analysis**
  - Water cooling sufficient for H2-N2 Mixer End Cap
    - Inconel water jacket
    - Water

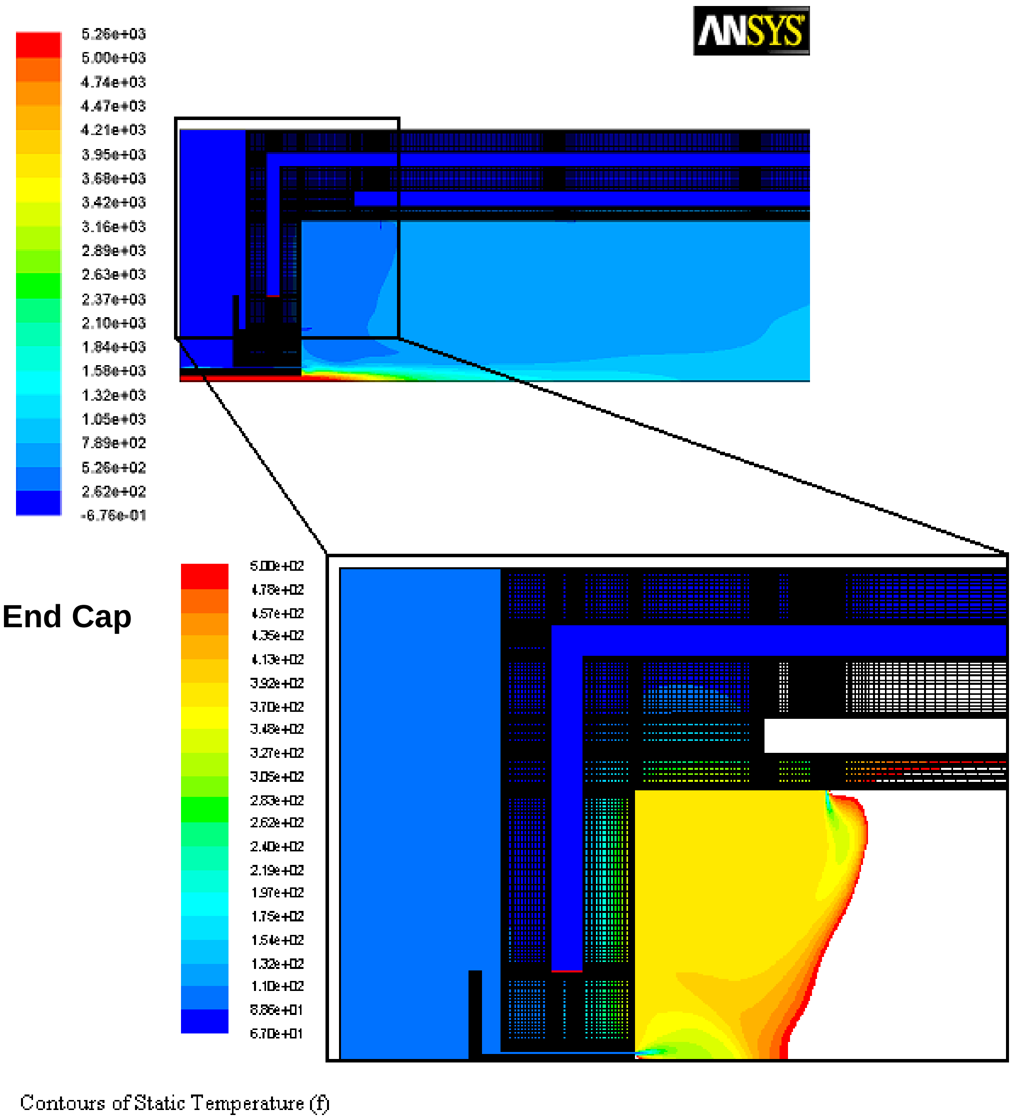


Fig 18. H2-N2 Mixer End Cap

Conclusion

- The design of a H2-N2 Mixer and Heat Exchanger system that will safely remove the inductively heated hydrogen exhaust gasses from the test facility is well underway with procurement and manufacturing to follow
- An elaborate thermal fluid model has been created and well documented in support of that effort

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