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Advanced Mixed Mode Combustor for Hydrogen F-Class Retrofit

Final Report

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SUMMARY

This objective of this project was to develop a retrofittable combustor module for the GE Vernova Operations LLC (GE Vernova, GEV) frame 7F gas turbine (GT) that would allow operation on blends of hydrogen in Natural Gas (NG) between 0% and 100%. The new system was to be part of a package that retained current cycle performance while limiting the increase in NO_x emissions to the equivalent of 25ppm (parts per million by volume dry at 15% O₂, ppmvd15) with consideration for the impact of hydrogen fuel on the O₂ correction. The expectation was that with the addition of Axial Fuel Staging (AFS), turndown within emission compliance would be extended to below 20% GT load. The original project plan included three budget periods (BPs): BP1 spanning October 1, 2022 through August 31, 2024; BP2 spanning September 1, 2024 through December 31, 2025; and BP3 spanning January 1, 2026 through September 30, 2026. See **Figure 1** for the original project schedule. **The project was terminated early by the DOE on October 10, 2025 about three months prior to the end of BP2. BP3 activities were therefore cancelled.** The program was on track to meet all objectives prior to the DOE termination. This Final Report covers work completed during BP1 and BP2 prior to the program termination.

The program's main design focus was the hydrogen capable AFS (H₂AFS) function in a Mixed Mode combustion system. The approach explored for H₂AFS deviates from the accepted premixer design philosophy at GEV, which places emphasis on a high degree of premixing accomplished generally through Micro Mixer style premixers. This program instead went after the concept of a hybrid premixed + non-traditional premixing approach, where the non-traditional premixing fuel may be injected via an immersed injector. Such combinations are novel and bring together benefits of both approaches. **Figure 2** shows a concept from the proposal, illustrating what such a hybrid H₂AFS injector might look like. The term "non-traditional premixing" refers to approaches that introduce fuel directly on the hot side yet still achieve some level of premixing before burning. The Mixed Modes refer to the operation of the system, shifting a greater portion of the total fuel to the H₂AFS stage when operating on hydrogen.

The final goal of the program was to create a conceptual combustor design with supporting work for a retrofittable "Mixed Mode" hydrogen Combustor. This would have been the last non-reporting Subtask, Subtask 4.3 for the project. This retrofittable system would have been designed and supported by test data and analysis but not built and tested within the 48-month program window. The approach was to use two major rounds of design/build/test, referred to as Gen I and Gen II, to develop and mature the H₂AFS and H₂AFS Stage to appropriate Technology Readiness Level (TRL). Gen I consisted mainly of rainbow tests with three distinctly different fuel injector concepts in each test. Gen II consisted of batches of the two down selected fuel injector concepts, where each injector featured more subtle variations. Gen II tests were still technically rainbow tests, but much more focused on optimizing the two down selected concepts. Table 1 summarizes the dates and Subtask numbers relating directly to the Gen I And Gen II Full Scale Fired Test campaigns.

Program Tasks and Subtasks are discussed in detail in the body of this document. A brief overview is provided below.

Table 1 – Full Scale Test Campaign Summary

Full Scale Fired Test	Focus	# Tests	Testing Window	Program Subtask	
				Design & Manufacture	Test
Gen I	H ₂ AFS Injectors	6	May – Oct '24 Complete	2.2 Injectors 2.4 Combustor	3.2
Gen II Early	H ₂ AFS Injectors	5	Feb - Sep '25 Complete	3.5 All	4.2
Gen II Late	H ₂ AFS Stage, Mixed Mode System	1	Mar '26 Planned		

Smaller subtasks provided fundamental data and/or closed knowledge gaps. These subtasks were completed prior to program termination and executed in parallel with the main Gen I and Gen II design/build/test activities.

- Subtask 2.3 Gen I subscale testing was a one-year effort at a university partner, consisting of multiple small-scale low-pressure experiments. These focused on NO_x, flame holding and Flashback with Methane and hydrogen.
- Subtasks 2.6 and 3.4 were Hydrogen Embrittlement Study and Hydrogen Embrittlement Test, respectively. These subtasks were focused specifically on issues that arise when real GEV premixer parts are 3D additively manufactured, using GEV's preferred alloys, with internal geometry similar to what would be inside of a fuel plenum, for instance.
- Subtask 2.5 was the Fuel Supply Design task. This subtask ensured that fuel connections to the lab parts were robust to breakage, to prevent safety issues during testing. The team also worked with the lab to determine the best way to deliver the required fuel blends to the test stand.
- Subtask 3.3, Hydrogen Fuel Startup Study, consisted of atmospheric ignition testing, and system concept design work to allow a gas turbine to start and load up from ignition safely on 100% hydrogen.
- Subtasks 2.1 and 3.1 – Map out the space that a successful retrofit combustor would need to run in, and build the test plans to evaluate the injectors over that space.
- Subtask 4.1 – Calculate performance derivatives for the 7F system.

During the Gen 1 test campaign the team had one injector reach 100% hydrogen in the very first of the tests. Throughout the course of the Gen I test campaign some injectors were able to run 100% hydrogen, and others were not. A formal downselect was completed and two Gen I concepts moved forward. During the Gen II campaign, seven of the nine injectors were able to run with 100% hydrogen and also pass flame holding tests.

In the most recent Gen II test, the team was able to operate the full combustor on 100% hydrogen fuel, with an exit temperature approximately 400 °F below full system exit temperature targets. The Gen II liner dampers and Gen II Micro Mixer damper package were shown to be well suited to address all forms of combustion dynamics while operating with 100% hydrogen. The team has operated the Micro Mixer head end on 100% hydrogen at F-class inlet temperature, pressure, and pressure drop with dynamics all less than 1psi peak-to-peak, albeit at reduced head end temperature. This is a major accomplishment, as high frequency dynamics have in the past been an obstacle for 100% hydrogen operation. **Figure 3** shows the Head end and H₂AFS injectors operating on 100% hydrogen as seen through two of the three in-combustor cameras.



Figure 3 – (a) Micro Mixer and two H₂AFS injectors on 100% Hydrogen (b) Hammer Head injector on 100% Hydrogen.

This program was a resounding success. The team intentionally stepped away from traditional GEV premixer design approaches to search for more capable approaches. The team not only created multiple hybrid premixed/non-traditional premixing H₂AFS injectors, but also novel premixer types within those arrangements. These hybrid H₂AFS injectors had better performance in terms of NO_x and pressure drop than traditional Micro Mixers, were easier to manufacture, and more robust to hydrogen. The team jumped almost directly into full scale testing which was driven by the DOE's requirements for a final TRL of 6, ready to transition to 7. This requirement added significant difficulty to the program and the team was able to rise to the challenge. The team anticipates that the final test (originally scheduled in 2026 until the program was terminated) would have demonstrated the system level performance defined in the project deliverables.

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FINAL PROGRAM MILESTONES AND TRL SUMMARY

Table 2 summarizes formal program milestones and their status. Items with planned completion dates after the termination date (10/10/2025) were on track but are listed as “cancelled”.

Table 2 – Milestone Status Report

Milestone Title/Description	Planned Completion Date	Actual Completion Date	Verification Method	Comments
Milestone 1.1.1 / Update Project Management Plan	Due 30 days after award	11/02/2022	PMP file	Submitted to DOE
SOPO Briefings/Technical Presentations– Kickoff meeting with DOE/NETL	12/30/2022	11/07/2022	Meeting Held	
Milestone 1.2.1 / Create Technology Maturation Plan	Due 90 days after award	12/21/2022	TMP file	Submitted to DOE
Milestone 2.4.1 / Complete Design of Gen I Test Hardware	03/31/2024	06/07/2024	Milestone Memo	Submitted to DOE
Milestone 3.2.1 / Complete Gen I Mixed-Mode Testing	09/30/2024	10/07/2024	Milestone Memo	Submitted to DOE
Milestone 3.4.1 / Down select Approach for Hydrogen Start	12/31/2024	12/13/2024	Milestone Memo	Submitted to DOE
Milestone 3.5.1 / Complete Fabrication of Gen II Test Hardware	12/31/2025	Cancelled	Cancelled	On Track
Milestone 4.2.1 / Complete Gen II Mixed-Mode Testing	03/31/2026	Cancelled	Cancelled	On Track
Milestone 4.3.1 / Complete Pre-CDR Review	07/31/2026	Cancelled	Cancelled	On Track
Milestone 5.1.1 / Complete Final Report	09/30/2026	2/17/2026	Report file	This document

Table 3 summarizes TRL statuses of key technologies. All items were on track to their TRL goal.

Table 3 – TRL Status

Technology	Starting TRL	Ending TRL	Current Status TRL
Hydrogen-capable Axial Fuel Staging (H ₂ AFS) Injector	TRL4	TRL6	TRL6
Hydrogen-capable Axial Fuel Stage	TRL4	TRL6	TRL5
Advanced Mixed-Mode Hydrogen Retrofit Combustor	TRL4	TRL6	TRL4

Supporting Details for TRL Status:

Hydrogen-Capable Axial Fuel Staging (H₂AFS) Injector

Gen II H₂AFS injectors have demonstrated significant margin to flame holding and flash back at cycle dP/P. In addition, testing with 100% hydrogen fuel has shown that NO_x emissions are compatible with system performance at less than 25 ppm NO_x when paired with a capable Micro Mixer. Turndown CO performance is similar to current AFS injectors, which will allow the system to meet the turndown objectives. The team made progress towards lowering metal temperatures to acceptable levels. The H₂AFS injectors have demonstrated all attributes for TRL6.

Hydrogen-Capable Axial Fuel Stage

The first Gen II test featured three identical Gen I “Hypermixer” H₂AFS injectors. The Hypermixers are a new type of premixer that have rapid but clean mixing. These Hypermixer geometries were intended to be larger scale alternatives to Micro Mixers. As a stage these injectors repeated the NO_x performance of the individual injector rainbow testing. As a further step, the final Gen II system test scheduled for Q1 2026 (test cancelled due to program termination) was to feature a five injector Transition Piece (TP) with the injectors positioned at residence times consistent with targets for a real system. This would have provided the best possible H₂AFS stage data with the five of the best style H₂AFS injectors. The current TRL is 5, with the final Gen II system test of five identical H₂AFS injectors reaching TRL6.

Advanced Mixed Mode Hydrogen Retrofit Combustor

Design of the preconceptual Mixed Mode combustor was not started due to the program termination by the DOE. Activities such as the Gen II Mixed Mode testing, Hydrogen Startup, and embrittlement testing would have fed into this design work. The data generated prior to program termination confirms that traditional system architecture would be sufficient to meet program goals. As such, the TRL of a combustion system with a Micro Mixer head end and Axial Fuel Staging is TRL8 for NG fuels, and the currently claimed TRL4 for a hydrogen fueled system is defensible.

TASK LEVEL ACCOMPLISHMENTS

Task 2 – Gen I Combustor Design and Fabrication

Subtask 2.1 – Define Preliminary Test Plans

GEV cycle modeling tools were first updated to reflect hydrogen fuel, then exercised to determine 1) the benefit of hydrogen on performance, and 2) how to trade that potential performance benefit for factors that increase the combustion system’s likelihood of success. Factors included reduced firing temperature, increased combustor pressure drop, decreased fuel heating, nitrogen injection, etc. The impact of existing performance packages was also evaluated to offset other performance trades. Separate strategies were formulated for simple and combined cycle applications. Moreover, the team created a framework to translate from individual injector emissions from reacting CFD simulations to overall combustor emissions.

Figure 4 shows a “comet chart”, which indicates the positive performance impact of running hydrogen fuel vs. NG, as well as the changes to the system that would result in positive or neutral impact on overall cycle performance. This is in effect trading back some of the performance benefits of running hydrogen to help keep either NO_x emissions or reactivity in check. Lowering firing temperature would reduce the amount of fuel injected into the combustor, which increases the combustor’s robustness to hydrogen-related failures such as flame holding and/or Flash Back.

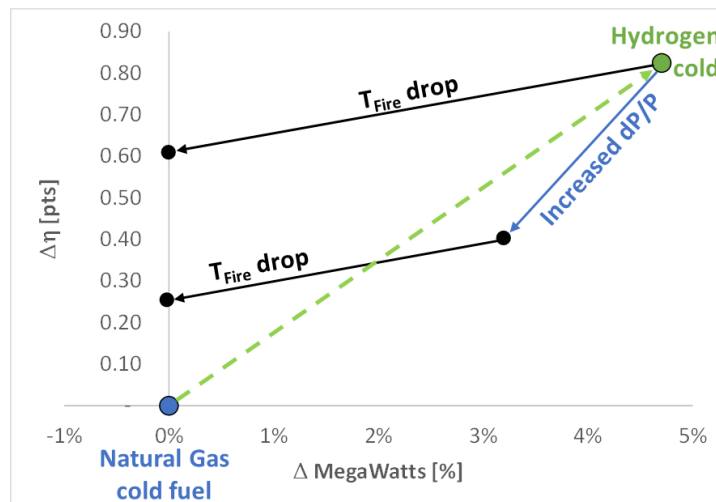


Figure 4 – Simple Cycle Comet Chart

The performance benchmark for this program is a 7F.03 plant in simple cycle configuration. Simple cycle engines almost exclusively run with unheated fuel, so fuel temperature is not shown in the comet chart above. Though not shown, GE Vernova offers Advanced Gas Path (AGP) packages that also significantly increase cycle performance and could be deployed if necessary to make up for any loss in performance with the final conceptual system that emerges from this program.

The team used these performance derivatives to determine the bounds for design of H₂AFS injectors, such as how much additional pressure drop could be allowed while still achieving a

successful design. This work also indicated the potential range of conditions that would need to be explored during fired testing.

Subtask 2.2 – Mixed Mode Hydrogen Injector Design and Fabrication

This subtask included design, fabrication, and instrumentation of hardware for both subscale and full-scale testing.

Design of Full-Scale Injector Concepts for Gen I Testing

Full scale injector concepts were intended to be a first attempt at the proposed hybrid injector designs, which combines premix and non-traditional premixing approaches in one injector. For these injectors to have low NO_x emissions, they would presumably be required to premix as much of the hydrogen fuel as possible with low pressure drop. The design team explored multiple types of premixing approaches throughout this subtask. Beyond the premixing technology, fuel that cannot be premixed must be injected via other means. The team explored multiple non-traditional premixing approaches such as Premixed Direct Injection (PDI), Lean Direct Injection (LDI), and legacy GEV Compact Premixers (CP). A successful hybrid H₂AFS injector would include one of the advanced premixing approaches combined with one of the non-traditional premixing approaches.

Hypermixers

A new type of premixer was developed with rapid but clean mixing. These geometries, termed “Hypermixers” for this program, were intended to be larger scale alternatives to Micro Mixers. Traditional Micro Mixers designed for hydrogen can require small features which limit options for manufacturing. **Figure 5** shows the aft face of two Hypermixer designs. One is tube-based, and the other slot-based. These designs were optimized using reacting steady Reynolds-Averaged Navier-Stokes (RANS) and unsteady RANS (URANS) analyses. Both Hypermixer types are compatible with non-traditional premixed fuel.

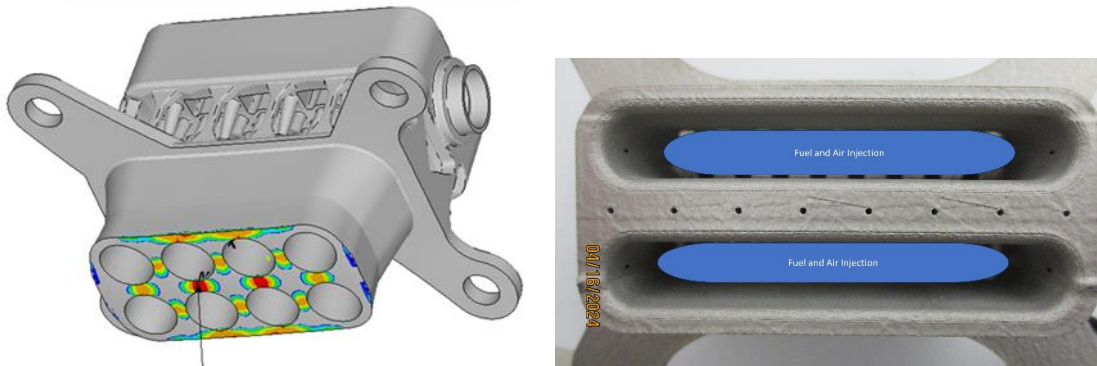


Figure 5 – Hypermixer Designs (a) Tube-Based, (b) Slot-Based

DLN Evo Style Ejectors

The team also attempted to increase hydrogen capability of ejector-style injectors. These are high quality premixers, geometrically compact, and allow the system to operate with low system pressure drop. They are macro-scale injectors, consisting of a large slot that receives both a high-pressure and a low-pressure post-cooling air source. Multiple approaches were explored to remove problem areas that were highlighted via analysis. Three injectors were designed and tested during the Gen I test program: injectors A2, A4, and A19. **Figure 6** shows the A4 injector.

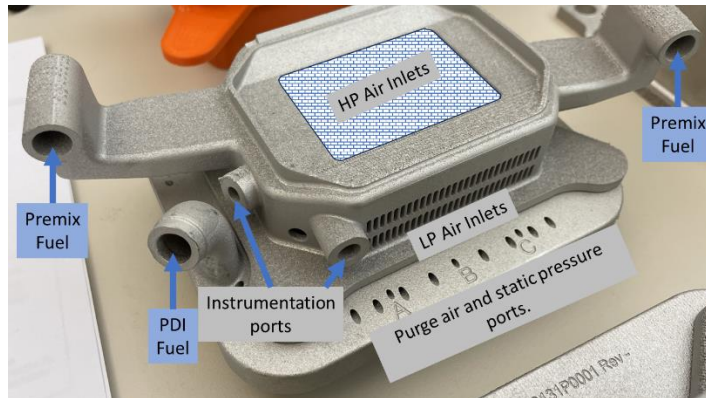


Figure 6 – A4 Ejector Slot Concept

Shark Fins

The Shark Fin designs go back to the original project proposal concept art, as shown in **Figure 1 2**. The original immersed “Late Lean Injection”, precursor to GEV’s AFS nomenclature, was NO_x capable despite running fuel rich. These Shark Fin designs join multiple attempts at non-traditional premixing fuel injection with an immersed style injector to reduce the NO_x penalty associated with that fuel. They represent an alternative to a simple PDI approach.

The proposal art shown in **Figure 2** is a hybrid premix + non-premix H₂AFS injector. The premixing devices were intended originally to be a Micro Mixer variant. As the Shark Fin development occurred late in the Gen I design phase, the team had available the Hypermixers, which were applied as the premixing element. This allowed the team to focus on the Shark Fin section itself with its associated non-traditional premixing injection approach.

The various Gen I Shark Fins featured different fin shapes and fuel injection approaches. Fuel injection approaches included PDI, LDI, and CP.

Micro Mixers

The team also created two Micro Mixer derivatives for use as a reference design for direct comparison. One of these featured a PDI circuit, which injected fuel near the exit of the tubes – see **Figure 7**.

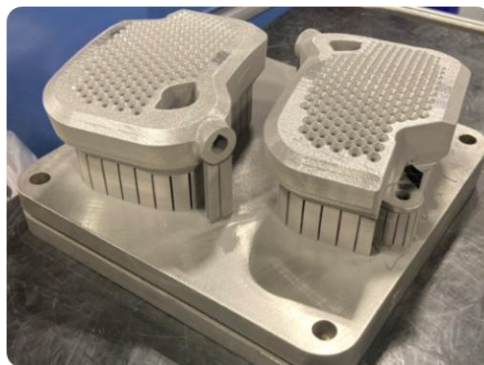


Figure 7 – Micro Mixer Derivative AFS Injector

Design of Hardware for Subscale Testing

The focus of subscale testing was to fill gaps in fundamental knowledge related to hydrogen combustion. These gaps cover a range of topics including both emissions and robustness to reactivity. The team targeted three different gaps using a rig at the University of Central Florida (UCF) that had previously been used for small scale AFS experiments with NG under NETL DE-FE0031227. Previous work was limited to NG fuel but was deemed to be very successful. Testing under the current program was executed by the same research team under Dr. Kareem Ahmed's leadership.

Phase 1 – Impacts of Hydrogen & Mixing on NO_x

Internal GEV full-scale data and data from open literature show that NO_x can significantly increase when NG fuel is replaced with hydrogen. The increase can be anywhere between 150% and 300%, and these figures are observed in systems that would generally be considered to be well-mixed. One-dimensional calculations, however, do not indicate this level of NO_x increase. The intent of this testing was to gather NO_x data over a range of hydrogen and unmixedness levels to determine if the increase in NO_x is potentially caused by an increased sensitivity to unmixedness.

The approach for this test was similar to that used in previous UCF experiments. A central injector lance was used in a length of mixing duct to allow on-the-fly adjustment of unmixedness at the exit of a simple round mixing duct – see **Figure 8**. With the injector fully retracted, unmixedness is at a minimum. With the injector flush with the exit, the unmixedness is maximized. Unmixedness was estimated using RANS CFD for both hydrogen and NG mixtures at multiple recession distances – see **Figure 9**. One major test assembly was designed and manufactured.

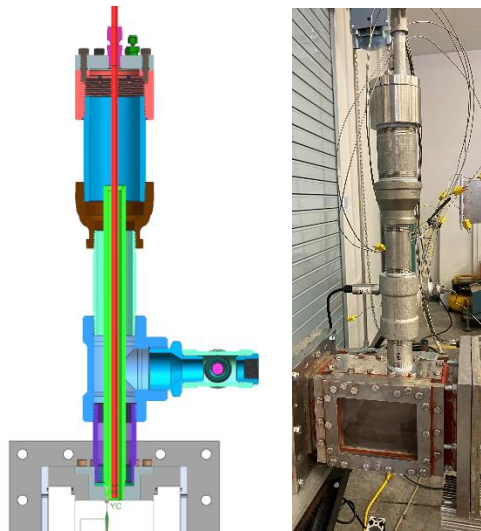


Figure 8 – Phase I Subscale Hardware

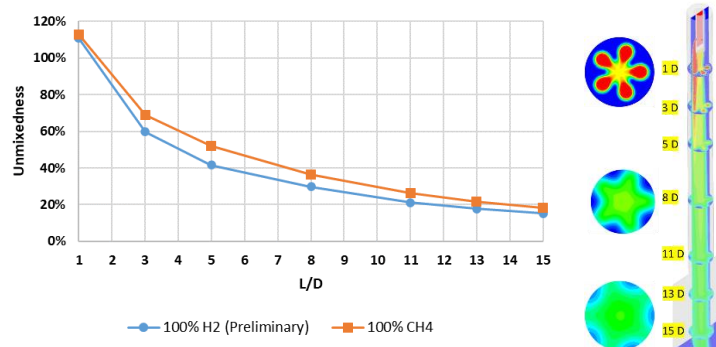


Figure 9 – Lance Design for Hydrogen and Natural Gas

Phase 2 – Impacts of Turbulence Intensity and Wall Temperature on Flame Holding

The second phase of testing focused on understanding the effects of two key variables on flame holding. It is known that the temperature of the walls in a premixer affects the Flash Back capability of that premixer. The team desired to understand if there is also a significant effect of wall temperature on flame holding. Additionally, the team wanted to understand how different methods of artificially increasing turbulence impact flame holding.

A modular Micro Mixer was designed and manufactured. This Micro Mixer featured tube and fuel hole dimensions and parameters that were geometrically similar to the most capable Micro Mixer designs recently developed for 100% hydrogen. The tubes are spaced farther apart than normal to allow an air jacket to pass cold or heated air through to control the temperature of the area downstream of fuel injection. Multiple inlet plates were designed to create minimal, moderate, and large scales and quantities of inlet turbulence to the incoming air. Multiple tube bundles were provided, ranging from as-printed rough walls to polished walls. Each tube bundle was instrumented in multiple locations with thermocouples and pressures to detect flame holding. The UCF rig also featured windows to allow video to be recorded during the events.

Referring to the left image of **Figure 10** there is a small side inlet to the right of the top main air inlet. This was for the hydrogen torch with spark ignitor, which is required for flame holding testing.

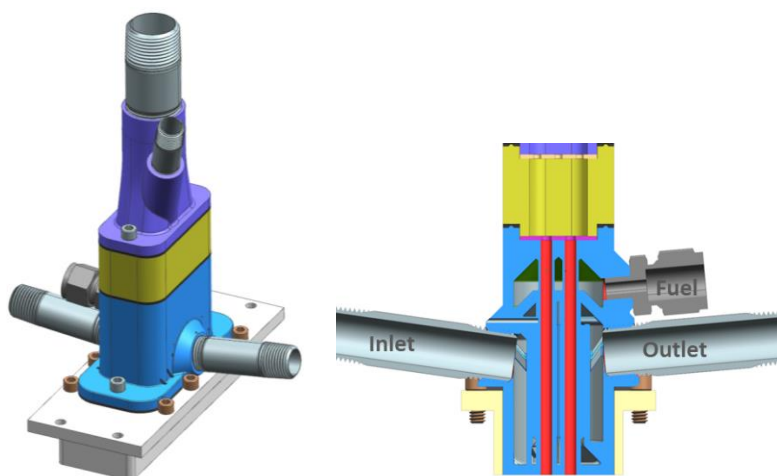


Figure 10 – Phase II Subscale Hardware

In addition to the Phase 2 test articles, other rig upgrades were required to execute the test program. Phase 2 called for heated AFS air and a separate heated air stream that could run for long periods of time to pre-heat the test articles. With a blow down rig, if the parts are not pre-heated, they return to room temperature. As the aim of Phase 2 was to control the wall temperatures, the heaters were added to facilitate that aspect of the testing – see **Figure 11**.



Figure 11 – Phase II Hardware Installed

Phase 3 – Quenching and Flash Back

The third and final phase focused on quenching distances with high temperature hydrogen air mixtures at moderate velocity. Data for quenching distances with hydrogen-air mixtures seems to be limited to quiescent mixtures between two large platens, which is very different from the highly turbulent and non-zero velocity conditions inside gas turbine premixing devices.

To determine the quenching parameters, the team created multiple actively cooled quenching aft faces with different slot widths starting at 0.100” and going down in width. The total area of the slots was fixed for all designs. Smaller slot widths required more and longer slots. **Figure 12** shows a preliminary design of the Phase 3 hardware. Note that like Phase 2, this hardware also included an air plenum that allowed heated or cold air to travel through to either pre-heat the part, before testing, or cool the part during testing.

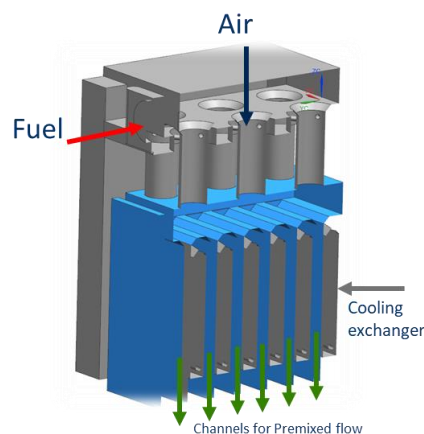


Figure 12 – Preliminary Phase 3 Design

Figure 13 shows the aft and forward faces of one of the Phase 3 test articles. Note that in the right image the three thermocouples (TCs) intended to sense Flash Back are visible.

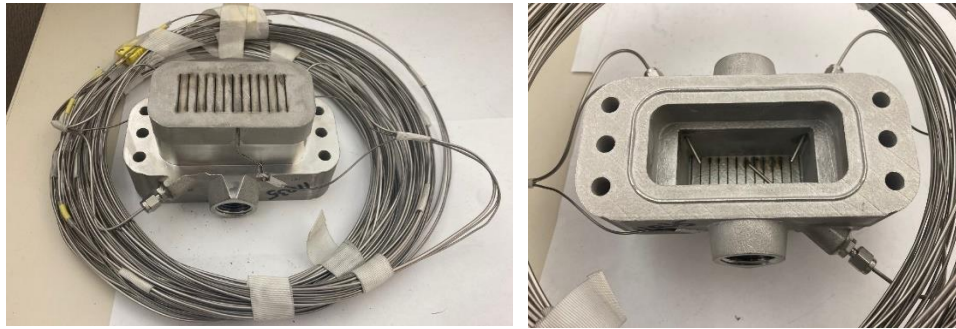


Figure 13 – (a) Slot Aft Face (b) Slot Forward Face with Flash Back TCs

Subtask 2.3 – Gen I Subscale Hydrogen Injector Testing

This subtask was focused on execution of fired testing using the subscale hardware designed under Subtask 2.2. The vendor's period of performance spanned 12 months. Over the course of the 12 months, the GE Vernova and UCF teams met weekly, and at key times daily. Doing such subscale testing at a university facility using a blow down rig instead of a continuous flow rig as would be used in house GE Vernova Advanced Research Center came with a significant learning curve for both teams.

Phase 0 – Safety Standdown and Safety Reviews

The team enlisted the help of the GE Vernova Product Safety team and used their tools for identifying, cataloging, and modelling safety risks. Several safety risks were identified and required mitigation. Mitigation came in the form of design changes to the test articles to minimize the risk of an unplanned event as well as any damage that could be caused by hardware failure. Mitigations also included added instrumentation and administrative controls. The safety assessment was revisited several times during the testing, as the team worked through issues and needed to make changes to how the testing was executed. The team regularly updated the safety assessment to ensure that any new risks were identified and retired.

Phase 1 – Hydrogen & Mixing

The team had multiple successes. First and foremost, the hardware was not what would be traditionally used as a successful hydrogen premixer. Despite the use of cold air to the AFS, there was some concern of Flash Back into the premixer during testing at higher hydrogen levels. This did not occur, and there was no damage or indications of flash back on the instrumentation at any point throughout the testing.

The initial shake-down period lasted multiple months, and over that time several issues were identified and resolved. The first issue was the stability of the head end premixer and pilot. Chemiluminescence videos at the AFS plane initially showed that there was a significant amount of fluctuation still visible at the AFS plane, indicating that the head end was unstable. In the end, the team switched the head end over to run on methane, and modified the main injector flame temperature, the fraction of heat release to the pilot, and the air bypass split to find conditions where the head end was hot enough to facilitate AFS testing but also remain quiet. This was a major step; however, the head end NOx was high which made its overall contribution to the exit NOx higher than is ideal.

The second issue was with the emissions measurement equipment. Initial emissions data were unsteady with time. The oxygen concentration was indicating that there was a leak, allowing air from the atmosphere to enter the sample. After some diagnosis, it was found that a check valve/solenoid was leaking. In addition, the sample hose was itself porous. The volume of the emissions collection tank was potentially allowing air to collect in the corners, so that was modified. And lastly, it was necessary to purge the emissions collection tank with an inert gas to get the previous sample out prior to starting a new test point. After all of this was worked through, confidence in the emissions sampling train was high.

After the data were recorded, it was found that the higher hydrogen points showed lower NO_x than the equivalent NG point. That result was contrary to expectations. Evaluation of standard quality checks used during GE Vernova fired testing showed that the amount of oxygen in the emissions sample was significantly higher than expected given the indicated conditions. Ultimately the problem stemmed from an issue with hydrogen flow measurement. This rendered any test points with significant hydrogen during Phase I unusable.

The UCF team was able to collect chemiluminescence videos with multiple fuel blends. Only the NG conditions would have been as indicated. **Figure 14** shows example images.

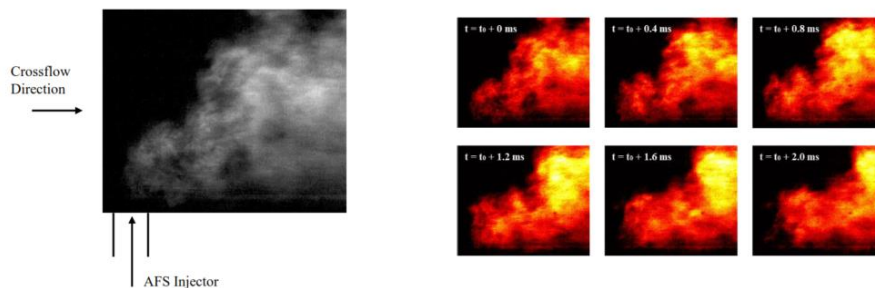


Figure 14 – Phase I Chemiluminescence Images

Phase 2 – Impacts of Turbulence Intensity and Wall Temperature on Flame Holding

The team spent more than a month proactively working through the test setup to identify and correct any issues with the air and fuel flow measurements. A series of unfired tests were completed to allow the team to focus the small number of pressure transducers on the location important for ensuring that the flow measurement devices were all operating at sonic conditions. Fixes were implemented to address issues when found.

It proved difficult to use the available instrumentation to determine if a given condition was resulting in a failed flame holding test. This came down to three things:

1. The normal speed camera showed so much activity (flashes, orange, etc.) from the head end that it was rendered useless for judging flame holding.
2. Instrumentation displayed strange behavior, including unexpected temperature increases upstream of the AFS fuel injection, which should not be possible. Ultimately it was determined that the temperature rise upstream of AFS fuel injection could only be explained by high dynamics in the rig which were forcing flame back up through the pre-mixer and into the upstream plenum even without any AFS fuel. The rig did not include dynamics pressure measurements, so the team was left to infer this from available data.

It appears there are combinations of head end and AFS conditions that may be quiet, or loud. These loud points might push some hot gas up into the premixer. If we had been able to run the rig for more than ~5 seconds, then this may have stabilized out, allowing capturing of data. However, with an uncooled blowdown rig, total fired test time is limited.

3. With low pressure, the heat release into the part was down significantly from observations at higher pressure conditions, yet the thermal mass of the part is the same. This led to slow heat up of the part during the flame holding or Flash Back conditions, which when coupled to a very short test duration makes it difficult to determine whether flame holding or Flash Back are present. By comparison, during high pressure testing, the opposite is true: the failure is so aggressive that the part can be damaged before action can be initiated to get out of the Flame Hold or Flash Back.

These issues with subscale testing limited the full value of the resulting data. The team overcame multiple challenges to move towards successful data collection. In the end it was not possible to gather the entire range of desired data using the available instrumentation, rig, and hardware. It appears that this type of GE Vernova-specific flame holding testing is not a good fit for an uncooled blow down rig. Experience gathered during this program may allow a future blowdown AFS rig to successfully capture data. However, that was beyond the scope of this program.

Despite the overall outcome, the team did have some successes in Phase 2. The team was able to gain confidence that the test conditions were accurate, particularly in using the GE Vernova parts as calibrated flow orifices to confirm the sonic choke orifice numbers. In addition, this was the first time that the team had run with heated AFS air and with the test article heating air. Both worked well, and we were able to achieve the target temperatures. **Figure 15** shows the slow temperature rise for the test article heating jacket and the AFS inlet air temperature. The test article is slowly heated from -1,400 seconds until the testing is complete at +8 seconds. The AFS air is heated from ~-400 seconds to the same +8 seconds. After the testing, the air needs to flow through the heaters to do a controlled shutdown to avoid damage to the heaters, and during this time from +8 seconds to +300 seconds, the temperature of the part decreases nearly back to the starting value. Again, the test windows are from 0 to ~+8 seconds. This sequence was locked down and repeated for every test point.

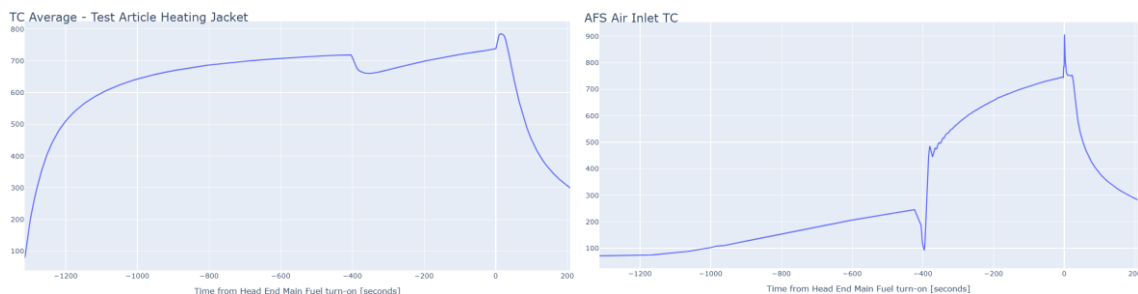


Figure 15 – Phase II Heat Up Plot

Phase 3 – Quenching and Flash Back

At this point in the program the rig and supporting hardware were well characterized. The team was able to begin testing immediately. Prior to testing the team again did some tests with the head end fired, but without AFS fuel to verify that no head end hot gas was pushed upstream through the slots into the Flash Back TCs, as was observed during Phase 2 - see **Figure 16**. The three Flash Back TCs were also moved to a better location than was used in Phase 2.

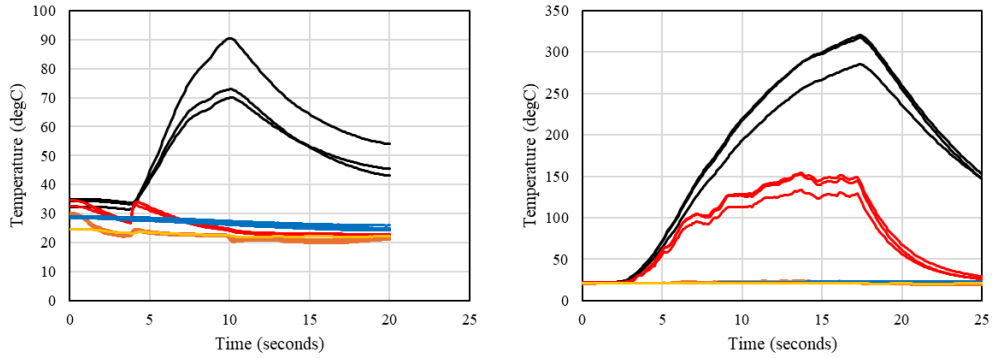


Figure 16 – Unfired AFS With (a) No Back Flow, (b) Back Flow

Armed with the knowledge that a quiet head end condition existed, the team continued testing with 100% hydrogen AFS fuel. The UCF team ran tests over a number of conditions, with multiple geometries, to gather Flash Back data. As shown in **Figure 17** the presence of Flash Back was clearly visible using the high-speed camera.

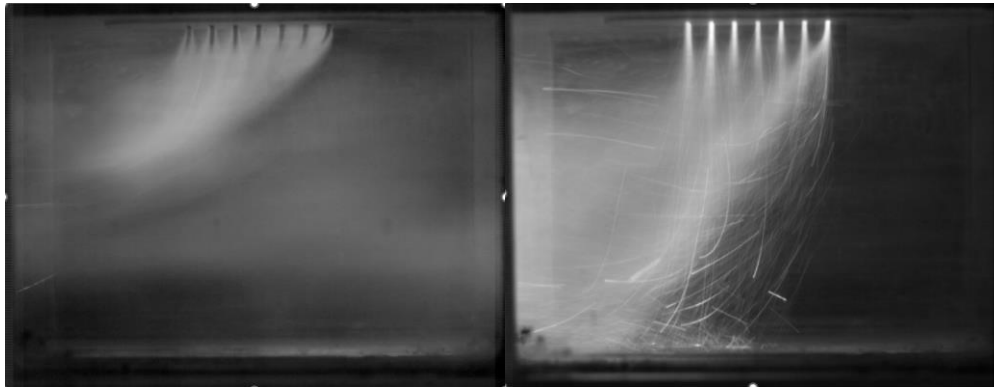


Figure 17 – Phase II High Speed Imaging (a) Prior to Flash Back (b) During Flash Back

Flash Back TCs were similarly definitive – see Figure 18. The team was able to identify several thresholds. Unfortunately, the data suggests that even with the smallest slot width at F-class temperature and pressure conditions the quenching approach would likely be no better than a purpose-designed Micro Mixer.

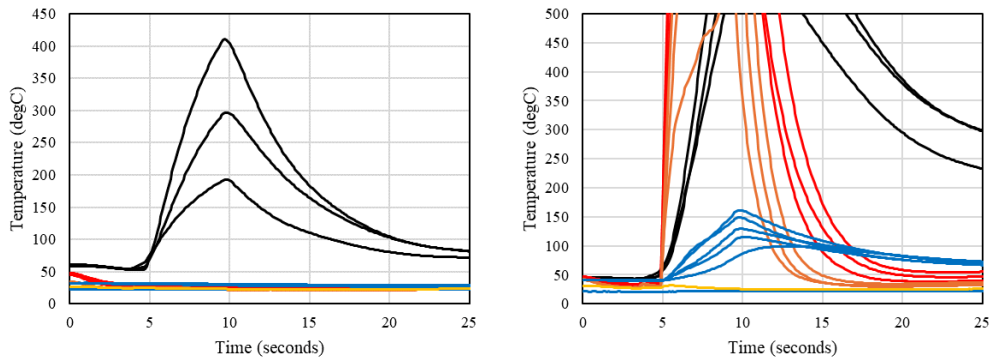


Figure 18 – Flash Back Threshold. (a) No Flash Back (b) Flash Back

Subtask 2.4 – Gen I Mixed Mode Combustor Design and Fabrication

The Gen I Mixed Mode combustor was the test vehicle for Gen I full scale H₂AFS injectors. **Figure 19** shows the Gen I system in cross section. This combustor is made up of some new hardware and some existing GE Vernova assets that were either used as-is or modified.

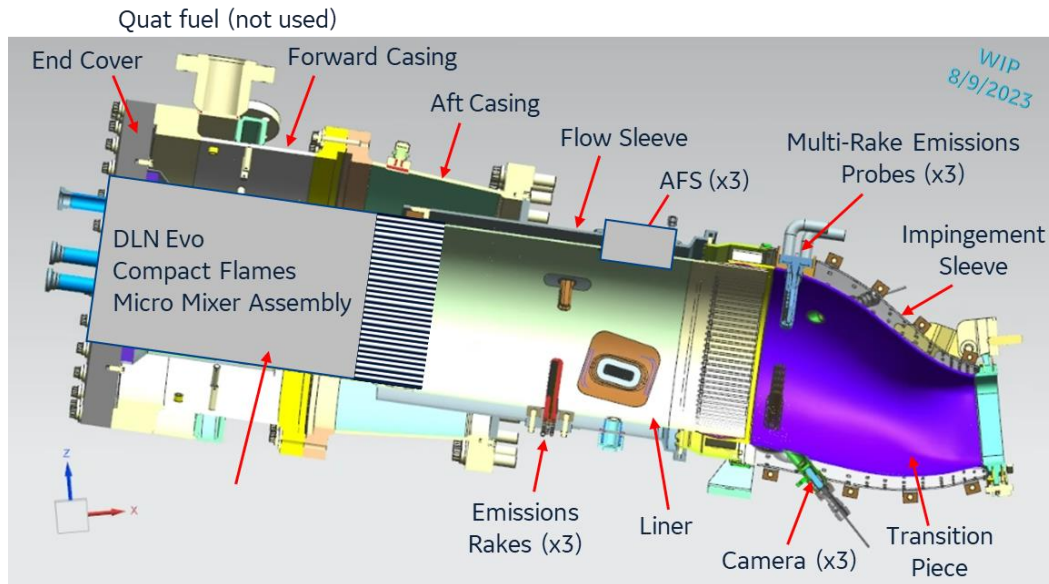


Figure 19 – Gen I Mixed Mode Combustor

The vision for the Gen I system was to screen three different H₂AFS injector concepts in one build, generating high quality data for each. There are three harmonized H₂AFS mounting bosses located in the liner. Each of the H₂AFS injectors are designed to fit into this harmonized boss to facilitate rapid hardware change-outs. There are single element Micro Mixer emissions rakes upstream of and between AFS injectors to measure the O₂, CO₂, unburned hydrocarbons (UHCs), and NO_x coming at the AFS injectors from the head end. In this case single element refers to one water cooled rake with multiple sample ports that are internally ganged. The “from scratch” Micro Mixer head end is a derivative of the highly successful and capable DLN Evo Compact Flames Micro Mixer, whose design was adapted to pass more flow for this configuration. The downstream Transition Piece (TP) contains three cameras, each aimed at one H₂AFS injector upstream to allow the team to clearly visually detect flame holding or Flash Back. There is also one multi-element emissions rake behind each AFS injector to measure the local gas composition behind each AFS injector. By evaluating the difference between the upstream and downstream rakes, the NO_x increase across each AFS injector as well as the AFS air split can be determined. There was also a well-mixed emissions measurement in the exhaust duct downstream of the test stand.

The Gen I system made use of an existing test stand (not shown) as well as existing pressure vessel casings (forward and aft). The head end assembly, consisting of the end cover and the Micro Mixer assembly was built 100% for this testing. A used TP with its associated Impingement Sleeve (IS) was heavily modified to accept cameras, emissions rakes, and high frequency dampers. The liner and flow sleeve assembly were designed and built with the harmonized bosses and head end rakes specifically for this program.

Figure 20 is a borescope image taken inside the combustor from the aft end looking upstream at the Micro Mixer. This was taken shortly before the first test. It shows two AFS injectors in the

foreground at approximately two o'clock and 7 o'clock and the three single-element liner rakes which are positioned upstream of the AFS injectors, each ~1-foot downstream of the Micro Mixer.



Figure 20 – Liner Emissions Rakes

Figure 21 shows the heavily modified TP assembly. From the outside image, the camera ports, dynamics dampers, and emissions rake bosses can be clearly seen. In the right image, the three multi-element emissions rakes and the three camera ports are visible with a wooden shipping pallet in the background.



Figure 21 – Modified Transition Piece (a) External, (b) Internal

Figure 22 shows the DLN Evo based Compact Flames Micro Mixer assembly. This is a tidy package that can be manufactured rapidly and has excellent operability and performance. For Gen I testing the team ran this head end only on NG.

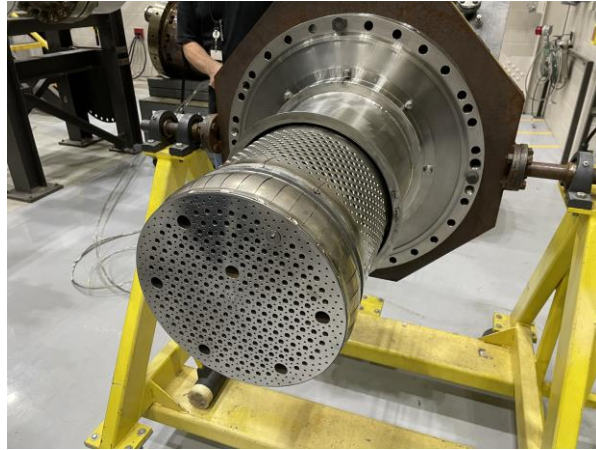


Figure 22 – Compact Flame Micro Mixer Head End Assembly

Subtask 2.5 – Hydrogen Fuel Supply Design and Fabrication

Fuel piping routing and supports were designed using computer-aided design (CAD). Finite Element Analysis (FEA) of the near-final Gen I H₂AFS injector geometry was initiated, including assumed loads from the fuel supply piping. This modeling informed any changes to the full-scale injectors to avoid fuel leaks prior to manufacturing of the injectors and fed into a safety review of the AFS fueling for the Gen I full-scale testing.

As shown in **Figure 23** the H₂AFS fueling uses a direct flex hose approach rather than the production style fueling as would be used on a production GT. Due to differences between injectors, it was not reasonable to implement a standard fueling geometry. Instead, simple flex hoses enter the stand via hard piping and are then routed to the H₂AFS injectors.

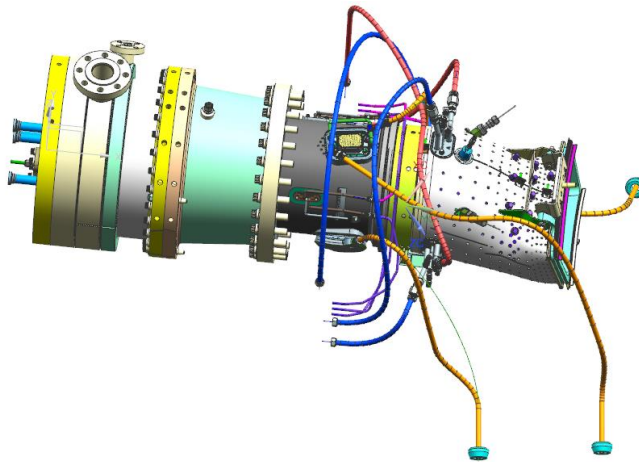


Figure 23 – Test Stand Internal Fuel and Water Plumbing

There was a risk that the weight and stiffness of the armored flex hoses could transmit load to the H₂AFS injectors, causing the injectors to fail at the fuel connection. As such, each injector was analyzed for modal response using FEA tools. Modes are highly dependent upon the load applied from the flex hoses and other fuel piping, which are difficult to model analytically. The decision was made to do a ping test of the final as-installed injector and fueling, after all the fueling had

been clamped and safely wired in place. For the first three injectors, the overall injector response was close to background noise level. The detected modes have multiple peaks and were highly damped. As a result, the test team did not have to try to avoid any specific dynamics tones to preserve the AFS fueling. In the future the team will not be required to do ping testing as this activity has shown the fueling to be robust.

Subtask 2.6 – Hydrogen Embrittlement Study

GE Vernova has an ongoing hydrogen embrittlement test program that is looking at all materials that are in contact with hydrogen fuel. This internal activity predominantly uses the appropriate specimens for the specific type of mechanical property being tested. For example, the team may print a sample, and then machine it into a round smooth bar, which is then notched. In this case, any of the non-idealities that come along with 3D printing, such as increased roughness on an as-printed surface are removed. The topics identified for this program are focused specifically on the realities and non-idealities of additive manufacturing for specific parts, materials, and printers as are used at GEV.

In support of subtask 2.6, GEV Materials staff completed a literature survey. The search yielded some general direction, such as roughness introduces additional sites for hydrogen breakup, and may make embrittlement worse or more rapid. As hydrogen embrittlement is a complicated phenomenon that is influenced by many factors, it should be anticipated that specific data for a specific scenario is largely unavailable in open literature. The study did solidify interest in three key areas as described below.

1. Impacts of local roughness on internal features of printed parts, and their effects on hydrogen uptake and hydrogen trapping. Examples of these locations would be roofs of printed parts, as roofs are known to be particularly rough surfaces. These surfaces are not accessible post-print to perform clean-up. Literature searches returned general guidance on increased surface area increasing the rate of uptake and trapping of hydrogen, but nothing specific to printed parts. It stands to reason that this effect could be significant for rough additive surfaces. Currently there are materials available that appear impervious to hydrogen embrittlement. The team wanted to evaluate the embrittlement impacts on these materials with rough additive surfaces to verify that they do not become susceptible in these areas.
2. Impact of EDM recast layer on local hydrogen embrittlement. Key for combustion parts are fuel holes, when created via Electrostatic Discharge Machining (EDM) using an electrode. There are two effects. First, creation of a differing material at the microstructural level at the site of the machining, is known in the literature. The second effect is that the electrode can leave microscopic contamination on the surface of the parts. The team felt that it would be warranted to test some samples that have undergone processing using EDM.
3. Options to reduce hydrogen embrittlement. Two paths were explored: Internal coatings and dopants. Dopants are known in the literature to slow or prevent embrittlement. This highlighted the desire to test combustion parts with dopants at near 100% hydrogen levels in the presence of dopants to determine the effect of doping as an option to mitigate embrittlement.

Task 3.0 – Gen I Combustor Testing, Gen II Combustor Design and Fabrication

Subtask 3.1 – Finalize Gen I and Gen II Test Plans

The team created detailed test plans and spreadsheets that were used for the fired full-scale testing of the Mixed Mode combustor. Each test consisted of emissions and hydrogen robustness testing. Injectors with nonpremixed fuel would also see the fuel split within the injector perturbed to quantify NO_x sensitivity. Each test included approximately twelve hours of fired testing split between the three H₂AFS injectors, with additional time for heat up and checkout before ignition.

Example Gen I Test Plan:

- Ignite and load up to target condition.
- Head end emissions using liner emissions rakes.
- AFS1 Emissions on Natural Gas using AFS rakes.
 - Flame temperature sweeps.
 - Non-premixed fuel sweeps, if equipped.
- AFS2 &3 Emissions on Natural Gas (repeat above).
- AFS1 Hydrogen testing:
 - Emissions on hydrogen blends. 50%, 70%, 80%, 90%, 95% H₂.
 - Flame holding on hydrogen blends. 70%, 80%, 90%, 95%.
 - Emissions on 100% hydrogen.
 - Tflame sweeps.
 - non-premixed fuel sweeps if equipped.
 - Flame Holding on 100% hydrogen.
 - Start at moderate dP/P and go up in Tflame to find a hold.
 - Lower dP/P, and repeat the above.
 - Non-premixed fuel sensitivities if time permits.
- AFS2 &3 Hydrogen testing (repeat above)

Gen II testing followed a similar test plan to Gen I. Due to the confidence that the team had with the injectors' robustness to hydrogen, and to maximize test time on 100% hydrogen, the team skipped the NG / hydrogen blends and tested only with NG and 100% hydrogen. Blend testing was useful in Gen I test when operation on 100% hydrogen was not a certainty and there was a risk of damaging the hardware before getting any data if flashback occurred at a lower hydrogen level. With the Gen II designs, however, operation with 100% hydrogen was the expectation and the hardware was known to be tolerant of repeated Flame Holds. Below is an example test plan from the Gen II tests.

Example Gen II Test Plan:

- Ignition and load up to target condition.
- Head end emissions using liner emissions rakes (minimal).
- AFS1 Emissions on Natural Gas (minimal).
 - Flame temperature sweeps.
 - Non-premixed fuel sweeps, if equipped.
- AFS2 & 3 Emissions on Natural Gas (repeat above).
- AFS1 Hydrogen testing:
 - Emissions on 100% hydrogen.
 - Tflame sweeps.
 - Non-premixed fuel sweeps.
 - Flame Holding on 100% hydrogen.
 - Start at moderate dP/P and go up in Tflame to find a hold.
 - Lower dP/P, and repeat the above.
 - Non-premixed fuel sensitivities if time permits.
- AFS2 & 3 Hydrogen testing (repeat above)

Subtask 3.2 - Gen I Mixed Mode Testing

The engineering and lab teams completed the detailed test request that was used to formalize and document the parameters for Gen I full scale testing. This information included details such as fuel hook-ups, flow rates, dynamics pressure measurement counts and locations, torches, leakage sniffers, cameras, emission measurement locations and ranges, etc. **Figure 24** shows the test stand in use for this program, which is an existing GE Vernova 7F full combustor full scale test stand.

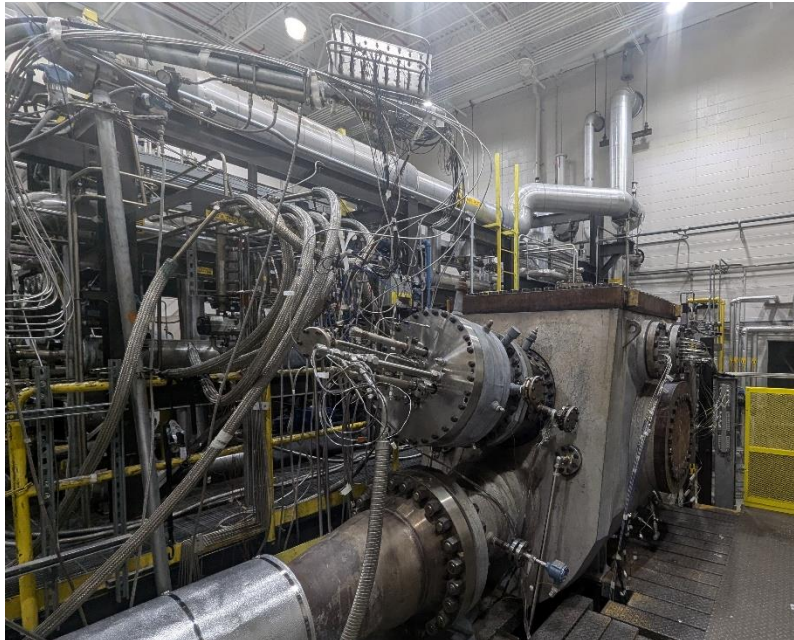


Figure 24 – 7F Test Stand, Fully Built, Ready to Run

Figure 25 shows one of the three AFS cameras from the first test. In this image, the H₂AFS injector featured is running on 100% hydrogen fuel. The head end Micro Mixer is running on lab NG, and the resulting mismatch in brightness and camera auto-shutter speed makes the H₂AFS

injector flame essentially appear non-existent. The TBC surrounding the injector is clearly hot. In the image cross flow from the head end is travelling from top to bottom.



Figure 25 – One of Three H₂AFS Injector Cameras

Gen I H₂AFS Rainbow Test Results Summary

A total of nine new H₂AFS concepts and two baseline Micro Mixer designs were manufactured for Gen I. Table 4 summarizes the Gen I H₂AFS Injector performance. The report sections afterward go a level deeper on discussing the results.

DLN Evo Style Ejector Injectors:

There were three attempts to extend the DLN Evo Ejector/injectors' capability from 80% hydrogen to 100%. A successful approach would have produced a compatible set of 100% hydrogen capable "top hats", requiring little system redesign to make the Evo system compatible with the new injector. The DLN Evo system had excellent NG NO_x, pressure drop, and was an outstanding combustion system in general, making this a worthwhile effort.

The first two injectors, A4 and A19, showed flame holding on the edge of the top hat, which was not a region where the team had placed significant focus. The A4 injector looked to be cold with no signs of temperature related discoloration. The thought is that the limit for this injector was reached before the premixers themselves were challenged. The A19 injector had discoloration from elevated gas temperatures on the end of each of the high-pressure jet exits. For the A19 injector, the limits of the fundamental design were determined. The A2 injector was the last of the DLN EVO derivative injectors, and at the time of its design, the burning at the ends of the top hats was a known issue. The team modified the design to update the shape of the top hat corners and the air inlets. Testing of the A2 injector indicated that burning at the ends has been entirely eliminated. This injector performed the best of the three but still held flame at 90% hydrogen and approximately 400 °F below the target flame temperature (T_{flame}).

Table 4 – Gen I H₂AFS Injector Results Summary

Description	Test #	H ₂ NO _x Capability	Pressure Drop, dP/P	100% H ₂ Capable?	Damaged 100% H ₂ after flame hold or flashback
Evo-Style Ejectors					
A2	4	N/A	High	No	Could not run at 100% H ₂ . No damage observed at lower H ₂
A4	1,2,5	N/A	High	No	Could not run at 100% H ₂ . No damage observed at lower H ₂
A19	3	N/A	High	No	Could not run at 100% H ₂ . No damage observed at lower H ₂
Micro Mixers					
Micro Mixer	1	Good	Moderate	Yes Cold	Not robust. Extreme damage.
Micro Mixer + PDI	3,6	Good. Worse w/o PDI	High	Yes Cold	Not robust. Burned out between tubes.
Hypermixers					
B6	1,2,5	Good up to 2550F	High	Hold @ 2200F	Not robust. Melting occurred
B8	3,4	Moderate	Moderate	Hold @ 2900F	Very robust. No damage, minimal discoloration.
B10	2,4	Very Good	High	No	Not robust. Melting occurred
Shark Fins					
E16	6	Poor	Cycle	Yes	Robust. No damage, minimal discoloration.
E15	6	Poor	N/A	Overheated at 70%	Not Robust. Overheated
E18	5	Very good	Moderate	Hold at unexpected	Robust. No damage. Discoloration on the Shark Fin.

The team anticipates that a combination of the changes to the top hat from the A2 injector, and premixing details from the A4 injector may be able to achieve 100% hydrogen capability. With limited time available, however, this design direction was not down selected for Gen II development.

The Hypermixers

The three Hypermixers tested varied greatly in mixing approach, geometry, unmixedness, and expected robustness to flame holding. This was clear in fired testing. Two of the three injectors were not robust to hydrogen, failing flame holding testing. One of these, analytically, was the best in terms of robustness, and the team found debris inside the part which may have hindered its performance. The other design that was not robust had excellent mixing, and very low NO_x, and lack of robustness was an expected trade-off. The third Hypermixer was very robust, achieving good flame holding performance at reasonable dP/P, and crucially was not damaged while holding flame for extended periods.

The Shark Fins

The Gen I Shark Fins varied widely in terms of performance. Initial analytical design work showed NO_x benefit, however later models that included cooling air and modeling practice updates degraded the NO_x capability when the designs were essentially complete. One of the Shark Fins overheated, with the other two doing well on temperatures. Of the two cooler designs, one had

very poor emissions, and the other was the best of any of the injectors. The team did test flame holding on the Hypermixers, though only as a way to get more data on those designs.

The Micro Mixers

Two Micro Mixers functioned as a baseline for comparison to best available technology. Other teams within GEV have developed these proprietary designs, however their data is at different cycle conditions, or in subscale test environments. To compare directly to the H₂AFS injectors created under this program, it was necessary to create baseline data in this same Gen I Mixed Mode combustor apparatus. The team made an improvement on the GEV design, via addition of a non-premixed PDI (Premix Direct Injection) fuel circuit to each tube. As with other PDI approaches, the fuel injection is into the premixing duct (tube) shortly before the exit of the duct.

NO_x was acceptable, but flashback and flame holding were lacking as compared to the Hypermixer. Using the PDI fuel to bypass up to 30% of the fuel around the premixed region (making this a hybrid injector) the flashback and flame holding improved, but the NO_x monotonically increased with PDI fuel split.

Summarizing Non-Premixed Fuel Injection Across Injectors

Figure 26 and Figure 27 show the response of NO_x emissions to non-premixed fuel split for Gen I H₂AFS injectors for NG and hydrogen fuels, respectively. Note that each plot also shows a Micro Mixer with PDI for comparison. While the Micro Mixer shows a significant increase in NO_x with PDI fuel split, the Gen I H₂AFS injectors show NO_x as flat, or in some cases reduced. Hypermixer based designs were not all well mixed, but even so the NO_x penalty was less than expected for intentionally bypassing raw hydrogen fuel around the premixer.

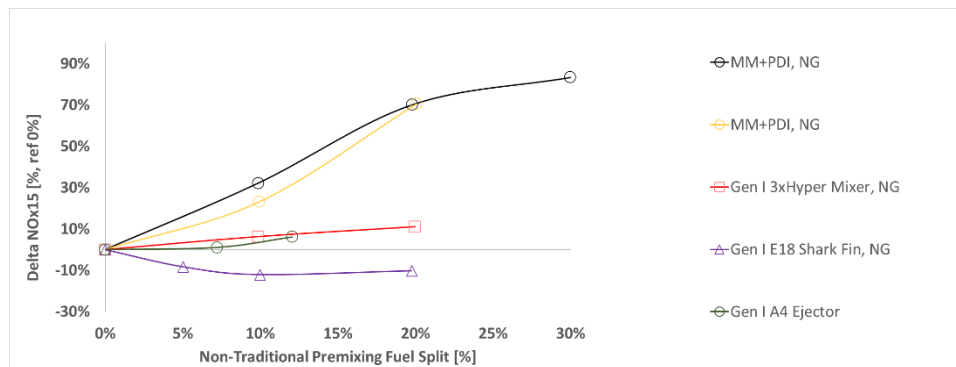


Figure 26 - Nonpremixed Fuel Impact on NOx Emissions, LDI & PDI Designs, Natural Gas

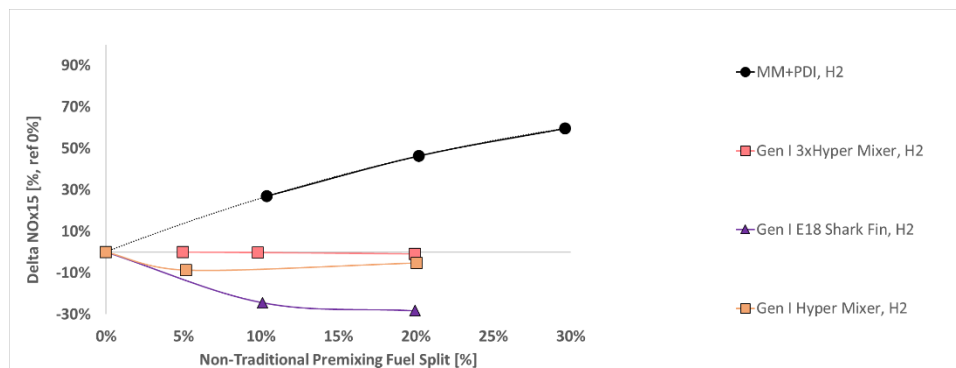


Figure 27 - Nonpremixed Fuel Impact on NOx Emissions, LDI & PDI Designs, Hydrogen

Figure 28 shows the NO_x response for the sole Compact Premixer design. The Compact Premixers air split was approximately 30% of total injector air. Interestingly, the best fuel split, while near the air split for NG, is significantly higher for hydrogen. Though this premixed Shark Fin was not down selected for Gen II development, the team thought favorably of the Compact Premixers and incorporated these into Gen II design variants.

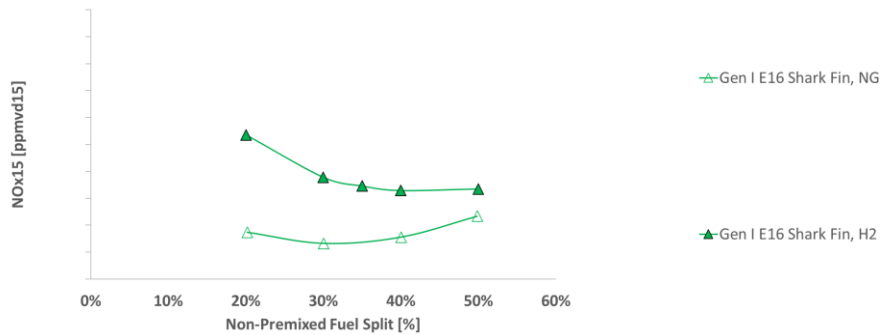


Figure 28 - Nonpremixed Fuel Impact on NO_x Emissions, Compact Premixer Designs

NO_x Emissions

Figure 29 shows the overall NO_x from the Gen I full-scale test campaign. This plot is simply the measured NO_x emissions on the AFS rake behind each injector minus the NO_x measured on the same rake at the same head end condition when the AFS was unfueled. The X axis divisions are 200 °F, and the typical best AFS Tflame range for the target cycle is shown in green. For these test points, the head end ran NG, and the AFS 100% hydrogen. These Gen I H₂AFS injectors cover a wide range of geometries and air splits, and as a result the AFS emission rakes pick up different fractions of AFS products compared to the total mixture of head end + AFS. It is possible that one concept could appear to make higher NO_x than another, but if the air split were higher for that injector, they may in fact produce similar NO_x – noting that the parameters influencing the NO_x are also being measured. **Figure 29** is not corrected for the impacts of hydrogen on the 15% O₂ correction, as such a calculation requires the effective fuel as measured by the AFS rakes.

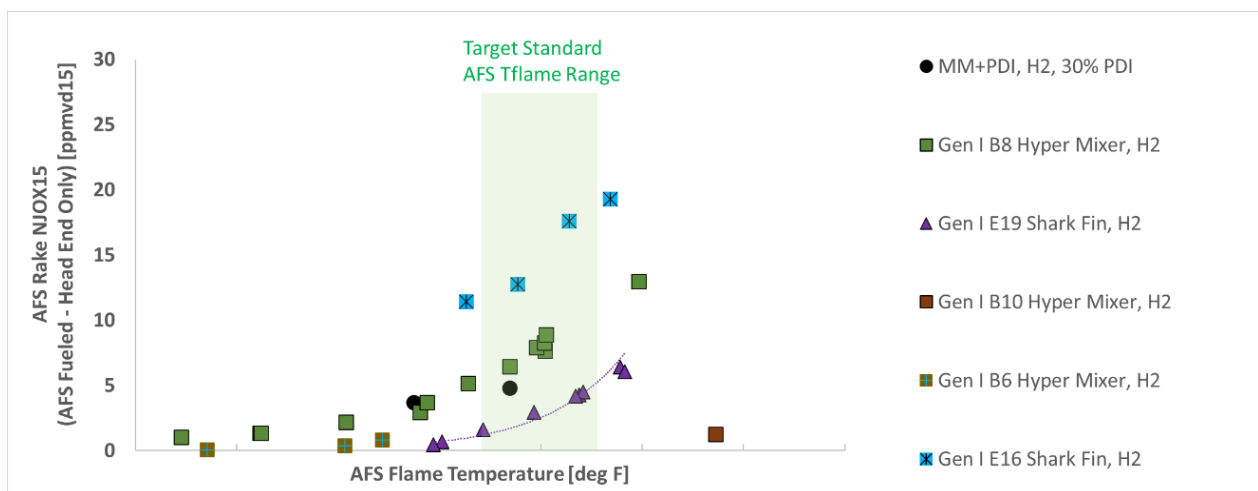


Figure 29 - Gen I H₂AFS NO_x Summary

A simple take away is that the NO_x capability covers a wide range. The best injectors would have not only good NO_x capability, but also low pressure drop, and good robustness to hydrogen.

H₂AFS Injector Downselect:

After detailed review of the Gen I data and hardware condition, the team down selected one of the Hypermixer variants and one of the Shark Fin variants for further development under Gen II. The team thought favorably of some of the design aspects applied in injectors which were not down selected, so those design aspects were adapted and improved for use in the Gen II designs. The ejectors and the Micro Mixers were not chosen to move forward into Gen II.

Subtask 3.3 - Hydrogen Fuels Startup Study

This subtask focused on exploring options to eliminate use of start-up fuel and enable a GT to start up on 100% hydrogen.

Critical Questions

Discussion of 100% hydrogen startup scenarios led to a set of critical questions.

1. Will a Micro-Mixer flashback or hold flame at ignition conditions on 100% hydrogen?
2. Can a PDI pilot ignite and provide a stable flame on 100% hydrogen?
3. Will a PDI pilot provide improved probability of light-off compared to premix fuel only?

A test program was created using available hardware to collect data at atmospheric conditions to quantify the capabilities and risks of the top ranked options.

Ideally the system that can light off in a stable manner with the lowest total fuel flow of hydrogen would be advantaged from the standpoint of avoiding combustible hydrogen air mixture in the downstream structures such as the GT exhaust duct. This is the reason for interest in lighting off on smaller pilot circuits, like the PDI holes.

Lab Test Setup

An existing atmospheric rig was utilized and prepared for a first-of-its-kind atmospheric test at the GE Vernova test facility – see **Figure 30**. The rig uses an airbox with an adapter to mount test articles in a vertical arrangement. A liner is sized to replicate the downstream dump velocity that a full combustor would have if the test article geometry were scaled for that purpose. Air is delivered to the test article through ports at the bottom of the air box and the facility can be configured with to deliver flow rates necessary to cover the velocity range of interest for the hardware. Fuel, either methane or hydrogen, is supplied via bottles. Nitrogen is supplied to purge the lines and test article between ignition attempts.

The rig features a head end torch that fires through the tube bundle as well as a liner torch approximately two inches downstream of the tube bundle exit – see **Figure 31**. Only one torch fires at a time, but the setup allows for testing of both configurations within a given test. Fiber optics are installed via a port on the liner downstream of the tube bundle and are used to detect ignition. The test articles were instrumented to measure temperatures in the aft face of the tube bundle and in the case of premix light-offs, tube wall temperatures that could indicate a flame hold or flashback. A camera is mounted above the box with a view down the liner to observe light-off and flame structure. All data and video were recorded to lab data systems for post-processing.

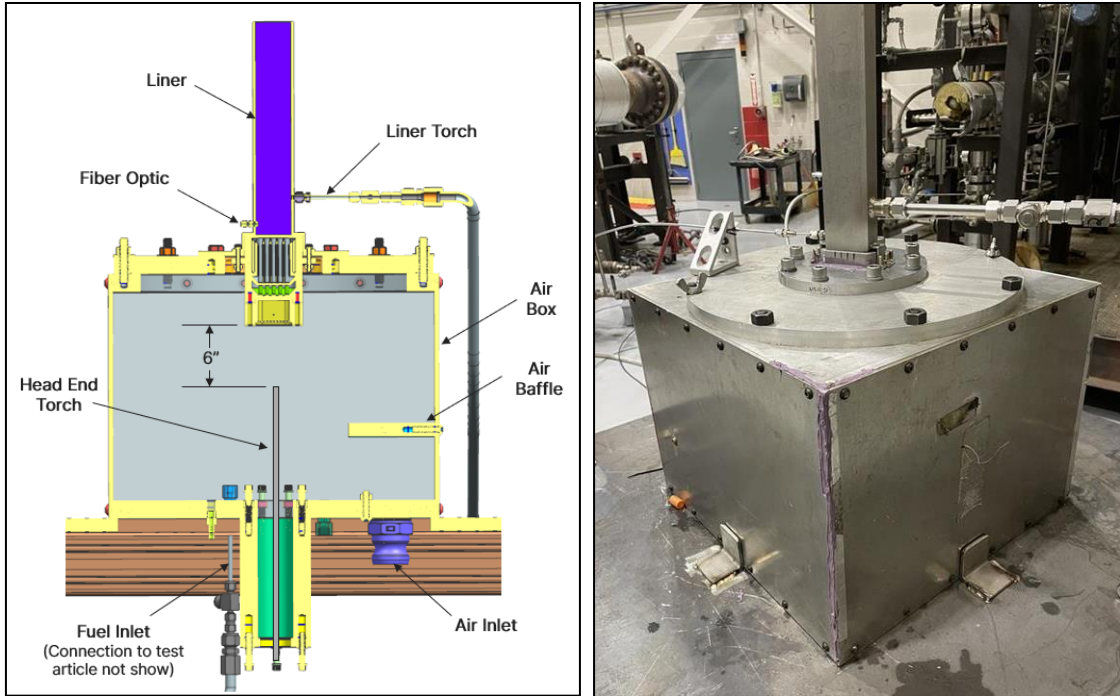


Figure 30 - Atmospheric Ignition Rig

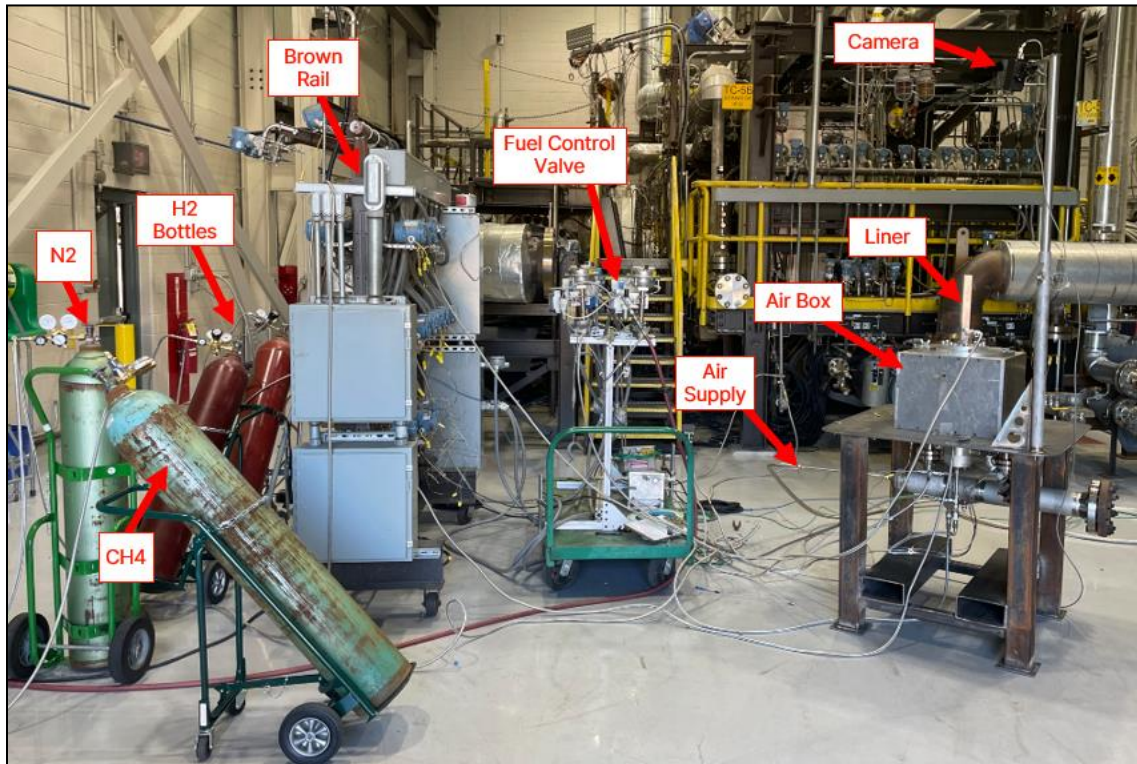


Figure 31 - Test Cell Setup

Test Execution and Overview

The first step in the test focused on finding the ignition boundary as a function of equivalence ratio across the tube velocity range expected at low-speed ignition conditions. Once the boundary was established, five test points were repeated at the boundary to collect statistical probability of light off at that equivalence ratio. If all five points were successful light offs, then the equivalence ratio setpoint was reduced slightly and five more points were attempted. Conversely, if within the first five points a single attempt failed ignition, then the equivalence ratio set point was increased and five more points attempted. This process was repeated to refine the ignition boundary and collect statistical probability of ignition data.

Once the flame stabilized after a successful light-off, the fuel slowly ramped down until the flame blew out. The fiber optics were the best indicators of light-off and blowout. At the low equivalence ratios, the flame is not visible on the camera and the TCs are much slower to respond.

Figure 32 shows typical ignition events with red showing the head end torch solenoid, black equivalence ratio, and green the fiber optic response. The top plot shows a failed ignition attempt. The middle plot illustrates a successful ignition. The bottom plot is a repeat point with successful ignition followed by a ramp down to blowout.

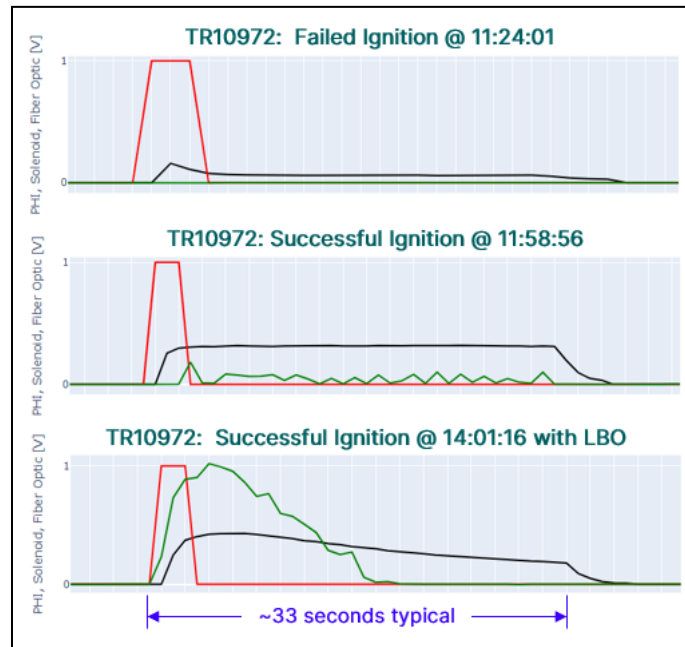


Figure 32 - Ignition Trends. Red = Torch Solenoid, Black = Equivalence Ratio, Green = Fiber Optic

Figure 33 shows the test timeline for ignition on premixed fuel and illustrates 1) test point conditions, 2) torch cycles, equivalence ratio, and fiber optic response, 3) tube thermocouples used to detect flame holding, and 4) aft face thermocouple response.

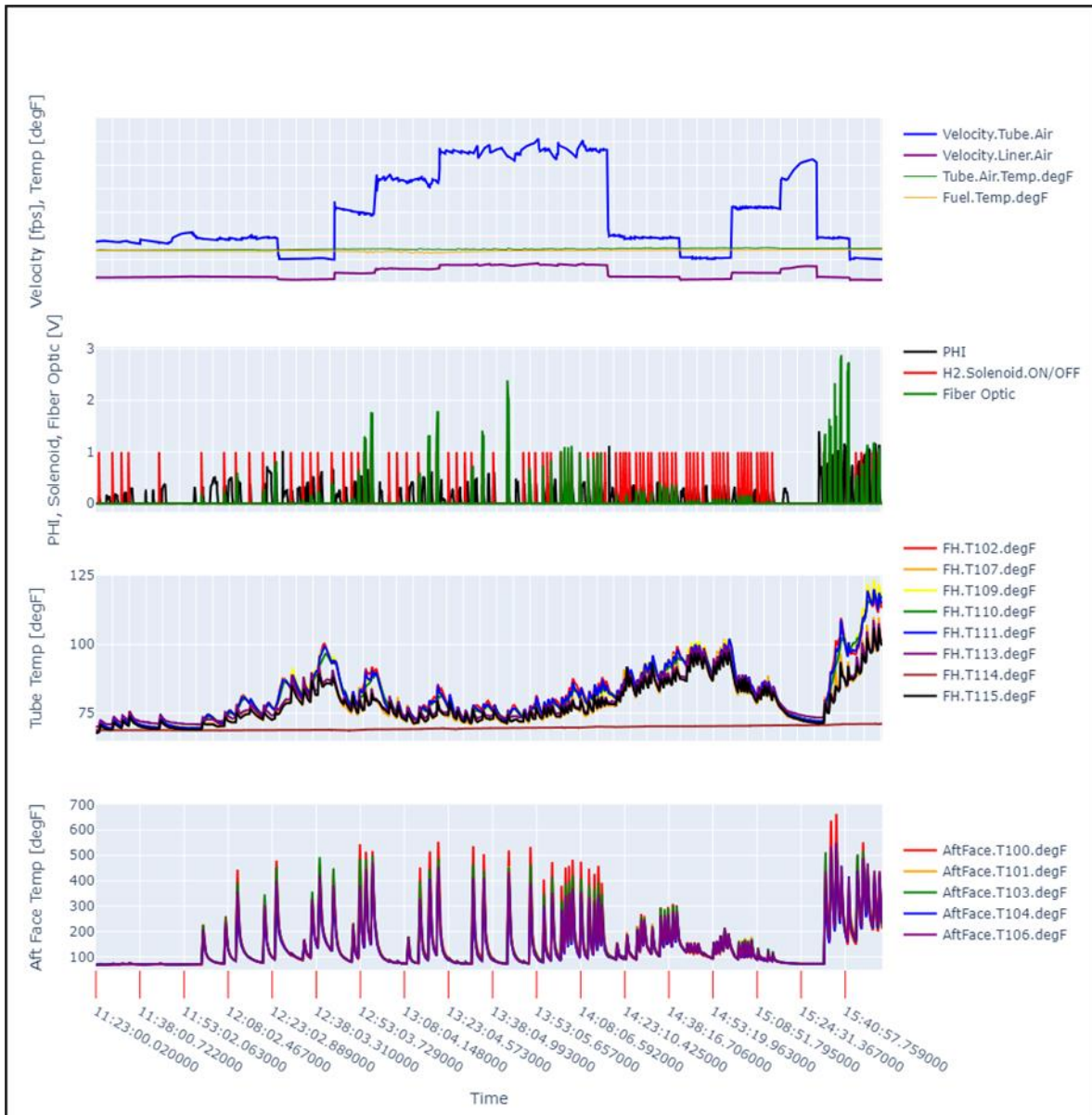


Figure 33 - Test timeline for premixed ignition illustrating 1) test point conditions, 2) torch cycles, equivalence ratio, and fiber optic response, 3) tube thermocouples used to detect flame holding, and 4) aft face thermocouple response

Test Results

Certain Micro Mixer tube geometries showed successful light-off capability over a wide range of tube velocity at low equivalence ratios without evidence of flame holding or flashback. Other geometries showed poor light-off capability. Camera views of flame structure after a successful light-off at nominal GT tube velocity and for a range of equivalence ratios are shown in **Figure 34**.

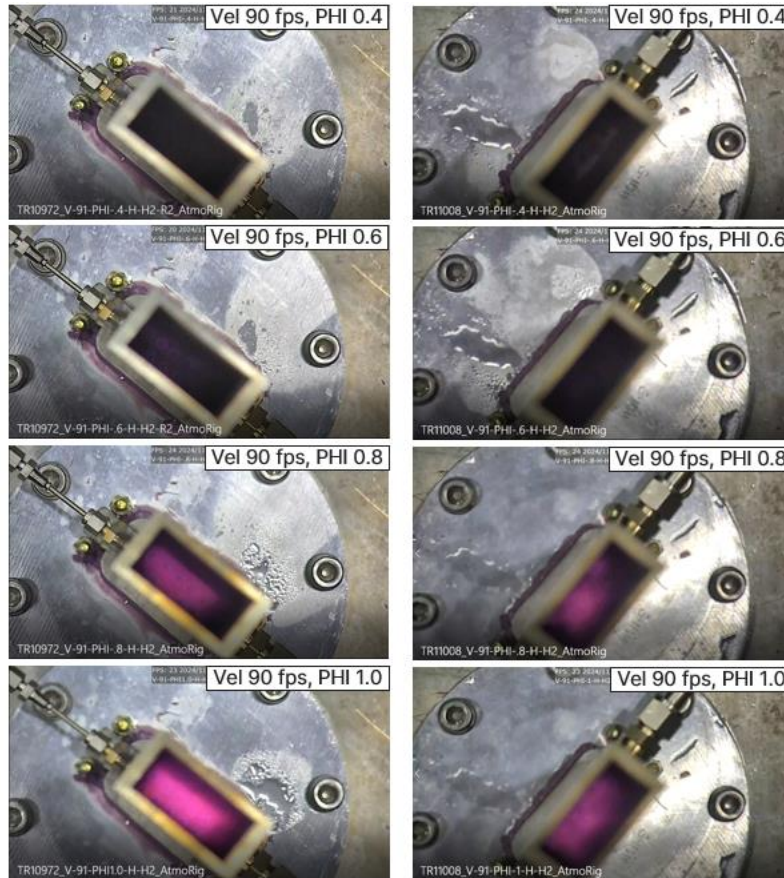


Figure 34 - Comparison of camera views across tests at nominal GT light-off tube velocity for a range of equivalence ratios.

Critical Questions Answered

The test data allowed the critical questions to be answered.

1. Will a Micro-Mixer flashback or hold flame at ignition conditions on 100% hydrogen?
No flame hold points were observed for the velocity and PHI ranges tested.
2. Can a PDI pilot ignite and provide a stable flame on 100% hydrogen?
Ignition of the PDI fuel is possible, but specific to the Micro Mixer tube geometry.
3. Will a PDI pilot provide improved probability of light-off relative to premix fuel only?
The benefit of PDI fuel ranged between geometries. Some geometries experienced lower total fuel flow using PDI. Others could not successfully ignite.

Recommended GT Ignition Approach

Given the test results, an approach to ignition on 100% hydrogen for a gas turbine was assembled and reviewed by the appropriate teams.

Subtask 3.4 - Hydrogen Embrittlement Materials Tests

The key areas of interest for the subtask were identified during the hydrogen embrittlement study, Subtask 2.6. They center on understanding and mitigating hydrogen embrittlement in additively manufactured materials exposed to hydrogen fuel. The study highlighted three main concerns:

1. Assessing how local surface roughness on internal features of printed parts affects hydrogen uptake and trapping and verifying whether typical combustion materials remain resistant under these conditions.
2. Examining the impact of EDM (Electrostatic Discharge Machining) recast layers and contamination around fuel holes, which could contribute to hydrogen embrittlement.
3. Evaluating the use of dopants as a strategy to reduce or prevent embrittlement in combustion parts operating at high hydrogen levels. Subtask 3.4 focused on these three key interests.

Method

To evaluate hydrogen embrittlement in as-printed materials typically used in combustion components, a small punch deformation test was performed following ASTM 3205. The test involved introducing a gaseous environment to one side of the metallic disc sample using a modified punch fixture, applying a constant 500 psi pressure and a punch rate of 0.5 mm/min. Maximum load and deflection at maximum load were recorded. After establishing a nitrogen baseline, samples of three materials with various finishes and printing orientations were immersed in pure hydrogen, then tested for load debits caused by embrittlement. The percentage change from the baseline was used to assess the impact of hydrogen. The small punch test produces a typical load versus displacement curve shown in **Figure 35**.¹

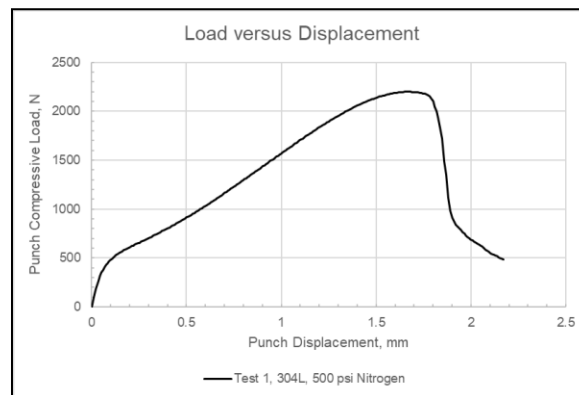


Figure 35 - Typical Ductile Punch Test Load vs. Displacement Curve

This test can be used to derive estimates of yield and tensile strength of materials up to 400° C. Post test, fractography was used to evaluate embrittlement layer qualitatively.

Test Fixture and Specimens

¹ ASTM E3205-20, Standard Test Method for Small Punch Testing of Metallic Materials, ASTM International, 2020, DOI: 10.1520/ E3205-20, www.astm.org

The modified ASTM 3205 punch test fixture uses the fixture requirements from the ASTM document with the modification of a gas chamber and O-ring for sealing. The test fixture was manufactured from 316L stainless, as it is known to be impervious to hydrogen embrittlement. The punch required a hardness specification of 55 HRC and a surface finish of $2\mu\text{m Ra}$.

The test gases included nitrogen (used as the baseline), hydrogen (the main test gas), and two doping gas mixtures—one with 4.75% air and the balance hydrogen, and another with 0.5% air and the balance hydrogen. Test specimens in different printed alloys were prepared in four conditions: as-printed, ground, EDM-processed, and as-machined. Samples were printed in three different orientations: 0° , 45° (both A up-skin and B down-skin sides), and 90° relative to the build plate. An MTS Criterion (Model 43) load frame was used for testing. This machine featured a 10kN load cell, measuring load (lbf), displacement or deflection (mm), and pressure (psig).

Figure 36 shows the test fixture and an in-situ photo of the setup, respectively.

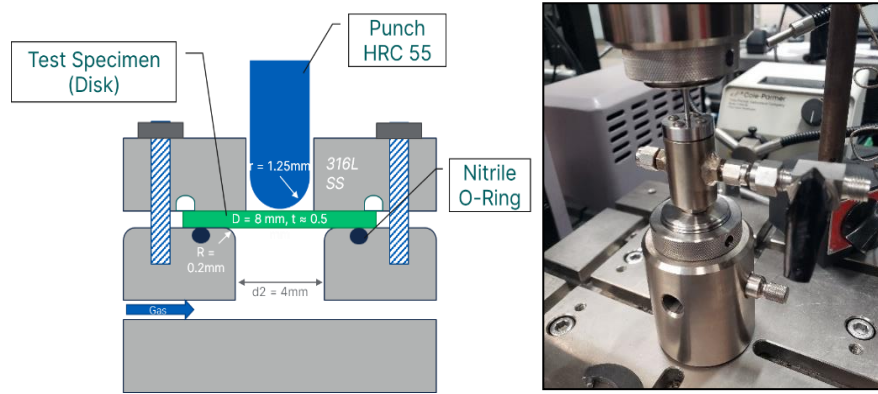


Figure 36 - Test Fixture Schematic and Fixture

To answer the questions related to the three areas of interest, the following approach was undertaken: Identify the materials typically used for additively manufacture combustion hardware. Establish a baseline for each material by exposing the target surface to nitrogen gas during each punch test. Next, establish the hydrogen soak time by evaluating samples of a known susceptible material using typically used durations. Both the baseline peak-load and the soak time were established using a sample that had been surfaced ground, marked as “GR”.

Conclusions

All planned testing was completed. A summary of the findings are as follows:

- Machining, finishing processes, and print orientation all affect peak load and peak load reduction in both nitrogen and hydrogen environments.
- Concern over contamination due to microscopic contamination due to wire EDM are unfounded.
- Print direction does have a significant impact on all materials, with considerable debits on capability for all materials. This is independent of hydrogen.
- Upskin vs. downskin as-printed surface had no impact on the two susceptible alloys tested. Increased roughness did not make the unsusceptible alloy susceptible to embrittlement. It did have an effect for a susceptible alloy, and the upskin surface was worse than the downskin in terms of added capability loss on hydrogen vs. Nitrogen. It was expected that the rougher upskin surfaces would have more drop due to added surface area than the comparatively smooth downskin surfaces (the top surface looking down on the part).

- Doping with Air was introduced for testing with a susceptible alloy to try to minimize the loss due to hydrogen. There was no significant reduction in capability loss with any of the blends. In select cases, air doping made the reduction in capability worse.

This testing generated both expected and unexpected data. GEV may further investigate in upcoming material test programs (not in the present project).

Subtask 3.5 - Gen II Mixed Mode Combustor Design and Fabrication

This subtask included the design and fabrication of both Gen II Mixed Mode System components and the H₂AFS injectors themselves. These components supported a full scale fired lab test campaign, consisting of six total planned tests as described in **Table 5** (noting that Test 6 was cancelled due to the program termination).

Table 5 – Gen II Test Campaign

Test	New Hardware
1	System Test: Micro Mixer Risk Mitigation, System NOx <ul style="list-style-type: none"> • Gen II Micro Mixer • 3x Hypermixers with PDI
2, 3, 4, 5	Rainbow test of Gen II H₂AFS Concepts <ul style="list-style-type: none"> • Gen II Liner with High Frequency dampers • 3x H₂AFS Injector Concepts for each test.
6*	System Test: Final Program System Test <ul style="list-style-type: none"> • GEV Micro Mixer • Five Injector Transition Piece • Five best-of-the-best Gen II H₂AFS Injectors

*Test planned for Q1 2026 but cancelled due to program termination

The Gen II combustor arrangement used for rainbow testing and Micro Mixer dynamics and flashback exploration is shown in **Figure 37**. The major addition here is the Gen II liner with high frequency damper.

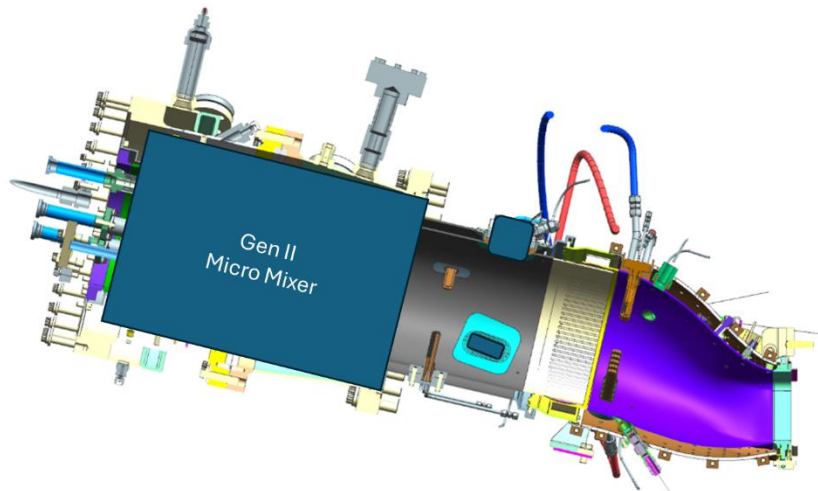


Figure 37 – Gen II Rainbow Test Configuration

The system configuration for the final Gen II system test originally planned for Q1 2026 (but cancelled due to the program termination) would have been as shown in **Figure 38** below. The Major addition being the five H₂AFS injector transition piece, GEV supplied Micro Mixer, and best-of the best H₂AFS injectors.

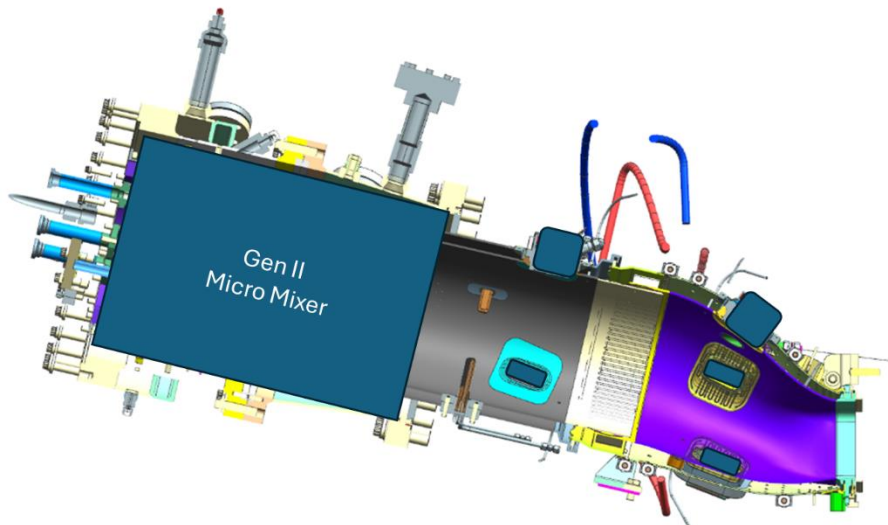


Figure 38 – Gen II Test 6 Configuration

Each of the major components will be discussed briefly in the sections below.

Gen II Micro Mixer

The Gen II Micro Mixer package is a derivative of the DLN Evo Micro Mixer package, as was the Gen I Micro Mixer. This hardware is fully dimensionally compatible with this program's Gen I and Gen II injectors. Lessons from internal GEV development programs have been applied, with the intent of raising hydrogen capability from 80% to 100%. This only requires the Micro Mixer to provide reasonable NO_x and not flash back. Durability and passive robustness to hydrogen (flame holding) is not a concern.

Gen II Liner

The Gen II Liner is the same as the Gen I liner, in that it contains provisions for three H₂AFS injectors, liner rakes, etc. The two round liner dampers were replaced with an alternative high frequency damper based on a GEV design.

Gen II Five Injector Transition Piece

The Gen II Five Injector Transition Piece moves the H₂AFS stage from the Liner to the Transition Piece – see **Figure 39**. This places residence time from the AFS to the exit of the combustor to a more reasonable number, closer to what it would be on an engine. It does remove the possibility of the AFS emissions rakes behind individual injectors, so only full sets of H₂AFS injectors can be fully characterized. It also has provisions for a total of five H₂AFS injectors, rather than the three on the liner. This raises the total AFS air split to a number that is in the range of today's large AFS combustion systems.

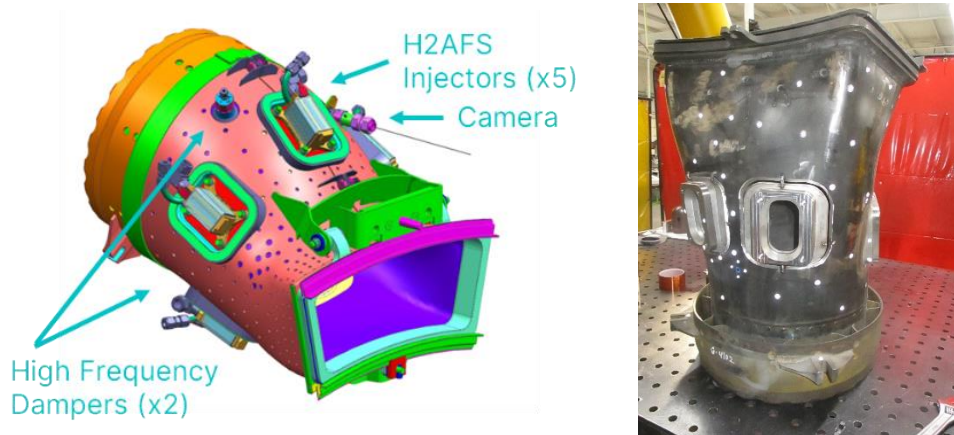


Figure 39 – Gen II Transition Piece (a) Model (b) In-progress Test Article

Gen II H₂AFS Injectors

Gen II H₂AFS injectors were variants of either the Gen I Hypermixer or Gen I Shark Fin. The Shark Fin itself uses the Hypermixer as the premixer, and the Shark Fin houses the non-traditional premixing fuel injection. At the outset of the Gen II design, the team incorporated a package of upgrades that apply to all injectors. Nine total injectors were designed and manufactured, six Hypermixers and three Shark Fins.

Each of the three Shark Fins received the Gen II upgrade package along with an upgrade to a Gen II Hypermixer. Shark fin designs were targeted towards lowering NO_x, as the Gen I Shark Fin was the lowest NO_x performer of the original Gen I designs. Hypermixer designs were targeted towards lowering dP/P while remaining robust to hydrogen.

Figure 40 summarizes the analytical results of mixing and URANS analyses used to design the injectors. These are the final cases, after analytical iterations on each. Each of the Gen II designs is a significant improvement on the Gen I Hypermixer (black triangles) in the top right. The best premixer would be down and to the left. As is typical with flame holding plots, hollow points are “no holds” (good) and solid points are “holds” (bad). These are analytical flame holding thresholds predicted via a URANS CFD process. Round symbols are Gen II Hyper Mixer variants, all of which were an improvement on the Gen I design.

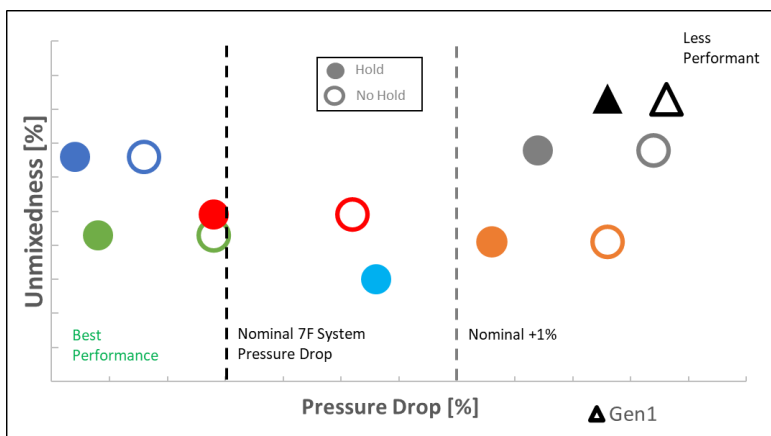


Figure 40 – Gen II Analytical Unmixedness & H₂ Robustness

Final Gen II H₂AFS Injectors for Q1 2026 System Test

A final set of five H₂AFS injectors were designed for the originally-planned Q1 2026 test. These injectors were on track to complete fabrication by 12/31/2025 but the program was terminated. The intent was to combine the best features of the nine previous Gen II injectors into two best-of-the-best arrangements.

Task 4.0 – F-Class Retrofit Combustor Conceptual Design and Deployment Plan

Subtask 4.1 – Hydrogen F-Class Performance Studies

The required performance studies were completed as part of Subtask 2.1. Finding no fault with that analysis, the team had planned to use the work completed under Subtask 2.1 to design the pre-conceptual design system during Subtask 4.3 (cancelled due to program termination).

Subtask 4.2 – Gen II Mixed Mode Testing

The team was able to dramatically accelerate Gen II Mixed Mode testing relative to the original plan – see **Figure 41**. Test #1 was pulled forward to quantify a series of risks around the Gen II Micro Mixer’s Flashback and NO_x capability, giving the team a full year to mitigate the risk before test #6. Pulling the rainbow tests (2-4 planned plus a fifth bonus test) forward allowed the team to receive the data from the rainbow tests before the September 30th formal milestone (3.5.1) completing Gen II design. As a result, the team was able to select the features for Test #6 with all the learnings from the rainbow tests.

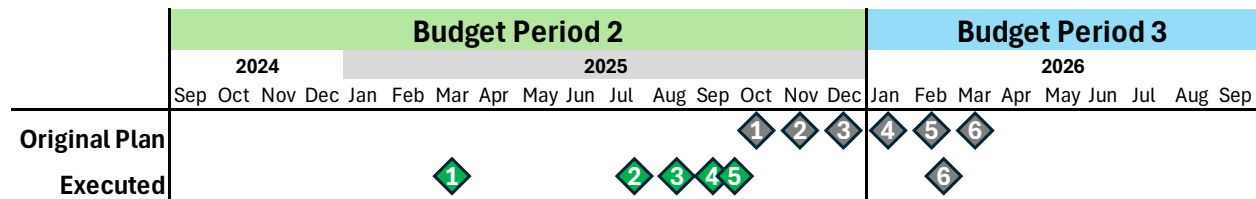


Figure 41 – Gen II Test Schedule

NO_x from Non-Traditional Premixing Fuel

All nine Gen II rainbow test injectors featured both premixed and non-traditional premixing fuel. One of the main goals of the program was to develop concepts that negate the NO_x penalty of the non-traditional premixing fuel, allowing large bypass of fuel around the premixing region. **Figure 42** shows the reduction in Premix Tflame for a concept that does not use air for the non-traditional premixing fuel, such as PDI or LDI.

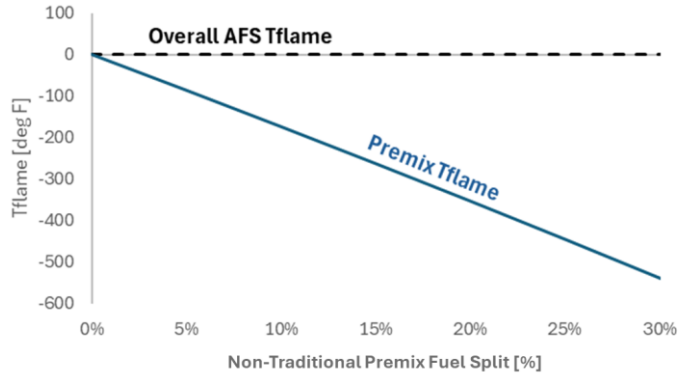


Figure 42 – Impact of PDI/LDI on Premixed Flame Temperature

Figure 43 and **Figure 44** show the response of NOx emissions to non-premixed fuel split for Gen II H₂AFS injectors for NG and hydrogen fuels, respectively. Note that each plot also shows a Micro Mixer with PDI for comparison. While the Micro Mixer shows a significant increase in NOx with PDI fuel split, the Gen II H₂AFS injectors show NOx as flat, or in some cases reduced. Gen II Hypermixers are much improved from Gen I in terms of unmixedness, however the NOx impact of nonpremixed fuel is low in all cases.

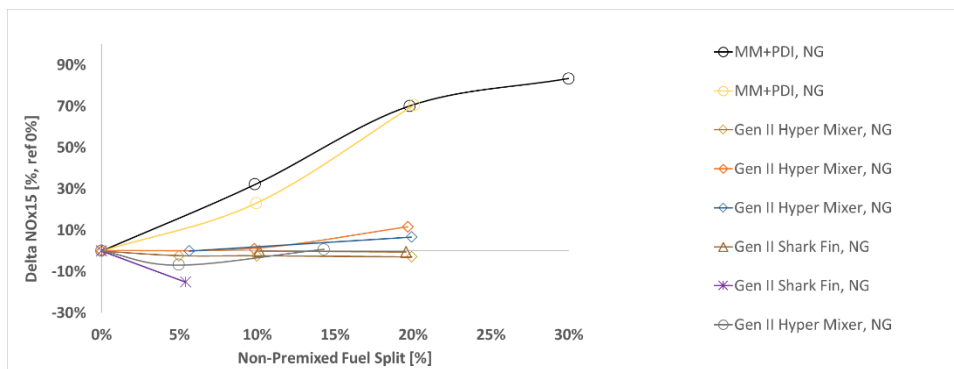


Figure 43 – Nonpremixed Fuel Impact on NOx Emissions, LDI & PDI Designs, Natural Gas

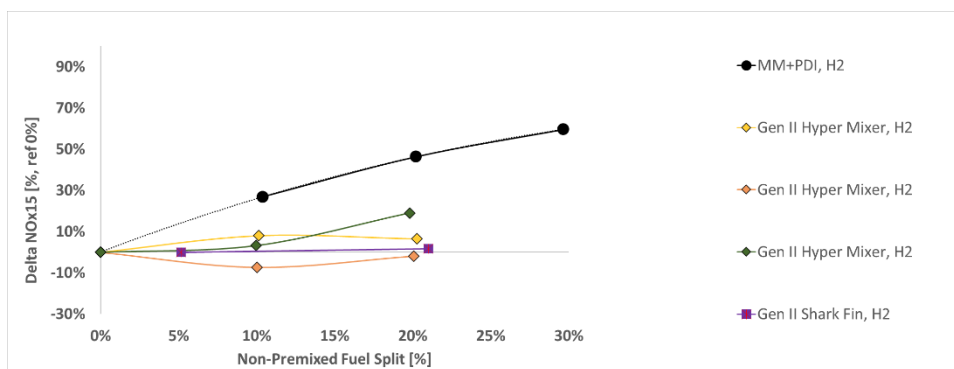


Figure 44 – Nonpremixed Fuel Impact on NOx Emissions, LDI & PDI Designs, Hydrogen

Overall H₂AFS Injector NO_x

NO_x capability of the later Gen II H₂AFS injectors looks to be able to achieve system < 25ppm system NO_x with or without nonpremixed fuel. **Figure 45** is the Measured NO_x on the AFS Rakes minus the NO_x measured at the same location with AFS unfueled. This plot shows only data with the H₂AFS fueled on 100% hydrogen. Each division on the X-axis is 200F. With all these injectors being Hypermixers of Shark Fins, which are based on the Hypermixer, the spread in AFS air split as measured on the rakes is similar. In addition, this is as-measured on the analyzers, with no adjustment for O₂ correction impacts of hydrogen. Correcting the data would be complex as the head end is fueled on NG, and only the H₂AFS is fueled on hydrogen. The range of flame temperatures in which the H₂AFS injectors are anticipated to operate is outlined in the green box. The contribution towards the overall system NO_x is Gen I Hypermixer would be on the order of 10-20 ppm. Gen II Hypermixers are on the order of 3-10 ppm. The best Shark Fin appears to be artificially low, on the order of 1ppm, though the team has not found reasons to discount this data. That same design was also the best of the Gen I designs.

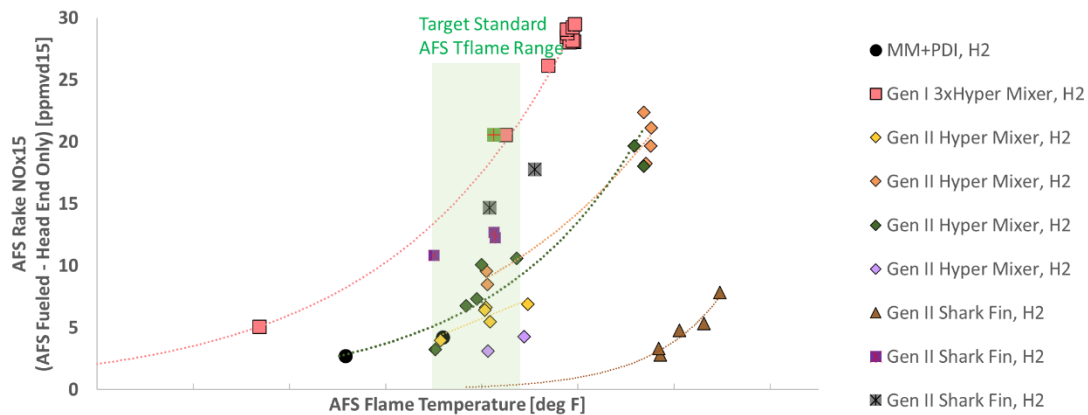


Figure 45 – Gen II H₂AFS NO_x Summary

System NO_x emissions are a combination of the contributions from Micro Mixer and H₂AFS. The H₂AFS has been the focus of this program, and the NO_x production from the H₂AFS injectors has steadily improved throughout the course of the program. NO_x production is now on the order of or below what we see from well mixed Micro Mixers, but with considerably increased robustness to hydrogen than existing Micro Mixer AFS designs.

Hydrogen Robustness and Flame Holding

GEV requires that premixers be passively robust. If a flame is forced to exist inside of the premixing duct, that flame must be expelled without intervention when the initiating event is removed. For this program hydrogen fueled torches were used to force flame to exist inside the premixer.

Figure 46 shows the flame holding data for one of the better Gen II Hypermixers. Small points were gathered with one type of torch. Large points were gathered with a more aggressive type of torch. Solid points are “holds”, meaning the injector failed to expel the flame on its own. Hollow points indicated that flame was expelled without intervention, a “no hold”. The X axis features 0.25% divisions. The Y axis divisions are 200 °F. The nominal 7F system pressure drop is indicated as a vertical dashed line.

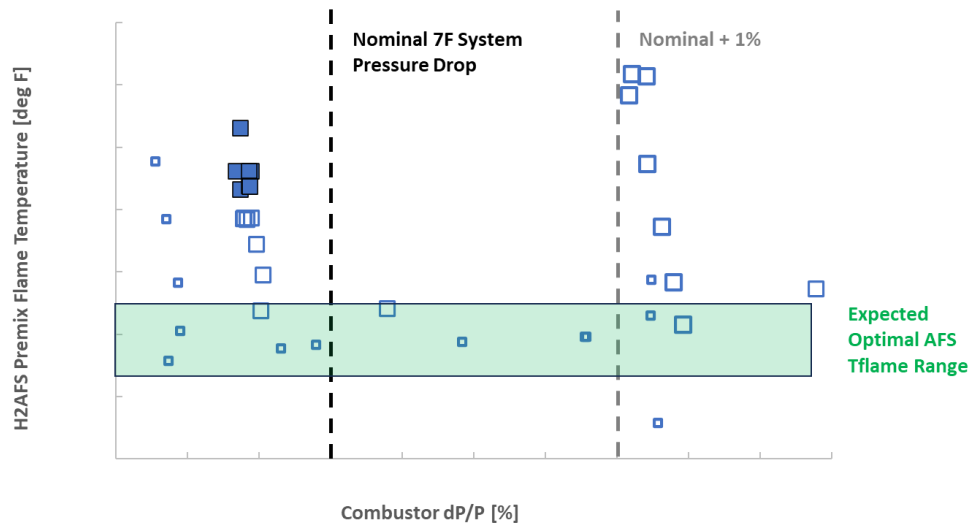


Figure 46 – Gen II H₂AFS Flame Holding Data

Multiple injectors generated “no hold” points at below nominal 7F system pressure drop, and above the expected optimal AFS Tflame region. The green band of expected optimal AFS Tflame range is for the overall injector. When coupled with nonpremixed fuel, the overall temperature may be many hundreds of degrees Fahrenheit above the premix Tflame shown on the plot. GEV’s margining practices for product design are beyond the scope of this document. However, this level of margin would clearly support a product design for the 7F cycle. Further, based on these data, the system pressure drop does not need to increase from the current pressure drop, which means that there will be no detrimental performance impact on the cycle.

H₂AFS Injector Summary

Table 6 summarizes the combined pressure drop, NO_x, and flame holding performance of the Gen II H₂AFS injectors. There was one clear best Hypermixer, and one Clear best Shark Fin. There are other injectors that do one or two things well and are worthy of future study.

Table 6 – Gen I H₂AFS Injector Results Summary

Description	Test #	H ₂ NO _x Capability	Min dP/P Δ% from cycle	100% H ₂ Capable?	Damaged after 100% H ₂ flame hold or flashback
Hypermixers					
Gen I	1	Poor	+2%	Yes	No. Very robust.
Gen II Variant	2,5	Good	0%	Yes	No. Very robust.
Gen II Variant	2,5	Moderate	N/A	Yes	N/A. Torch did not work.
Gen II Variant	2	Moderate	+0-1%	Yes	No. Very robust.
Gen II Variant	3	Very Good	+1%	Yes	No. Very robust.
Gen II Variant	3	Unknown	N/A	No	Minimal time at 100% H ₂ .
Gen II Variant	4	Poor	0%	Yes	No. Very robust.
Shark Fins (All use one Hypermixer Variant)					
Gen II Variant	3,5	Excellent	N/A	Yes	No. Very robust.
Gen II Variant	4	Poor	N/A	Yes	N/A. Not torched
Gen II Variant	4	Moderate	0%	Yes	Yes. Part of the Shark Fin melted due to blocked cooling channels.

Micro Mixer Performance

The Micro Mixer is a key part of the system, and its performance determines the conditions at which the H₂AFS injectors are required to operate. Lack of Micro Mixer capability was a risk elevated early in the program. The first test of Gen II campaign was pulled in specifically to determine if that risk would manifest. Multiple solutions were explored. Mitigations were progressing at the time that the program was terminated. It is anticipated that with the new Micro Mixer in the final system test, previous limitations would have been removed allowing the system to run at full exit temperature with well less than 25ppm NO_x.

Final State

As of the program’s termination, the Gen II H₂AFS performance demonstrated in the first five Gen II fired tests show clearly improved performance over Gen I. The level of performance observed for the Gen II hardware exceeds that required to field an F-class system with adequate margin. The final test of the system will not be run for this project (due to the early termination), and so directly measured system emission and performance are not available.

Subtask 4.3 – F-Class Retrofit Combustor Conceptual Design and Deployment Plan

This subtask was cancelled due to the program termination.

Task 5.0 – Final Report

Subtask 5.1 – Final Report

This abridged report was prepared, as required, within 120 days of the notice of project termination.