

# TAKING GAS TURBINE HYDROGEN BLENDING TO THE NEXT LEVEL



September 2022



## Introduction

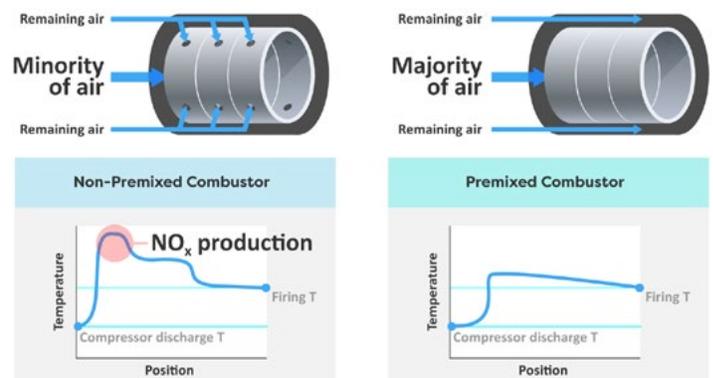
*Climate change, energy independence, renewable power, and the hydrogen economy* are among the terms used in recent years and decades to describe society’s most pressing challenges. Although the best way to face these challenges is a topic of controversy, it is important to estimate the potential of candidate technologies for reaching the goals before society commits to them completely. It is common to look for a quick fix, but solutions almost always require numerous technologies implemented throughout the entire energy value chain, involving millions of people and costing hundreds of billions (if not trillions) of dollars. These solutions are also likely to involve technologies that require incremental steps to prove that parts of the process are feasible. This typical case around technology innovation encapsulates the successful testing expounded on in this white paper. Moreover, for gas turbines, Noble et al. give a basis for the current capabilities on hydrogen inclusion for large-scale units [1].

*Combustion* or gas turbines are a highly valuable power generation and heating commodity. In many gas turbines, natural gas (NG) is the fuel used. NG is generally a low-cost and relatively high-energy-density fuel with a lower carbon content than coal or liquid fuels. This leads to reduced carbon emissions relative to those of fossil fuels. However, while burning NG, carbon dioxide (CO<sub>2</sub>) remains a primary constituent of the exhaust emissions. Therefore, shutting down gas turbines or re-envisioning them for a low-carbon future is a popular focus of research, discussion, and development. One such proposed reconfiguration is blending hydrogen (H<sub>2</sub>) with the NG fuel stream to further reduce CO<sub>2</sub> emissions.

The reduction in CO<sub>2</sub> emissions trends generally with the mass ratio of H<sub>2</sub> in the fuel—burning 100% H<sub>2</sub> reduces CO<sub>2</sub> emissions by 100%. Note that the reduction of CO<sub>2</sub> is nonlinear with volume % of H<sub>2</sub> in the fuel, with the largest reductions being realized at the higher H<sub>2</sub> volumetric percentages (20% by volume is 3% by mass; 80% by volume is 33% by mass). Since the early 1980s, reduction of emissions such as oxides of nitrogen (NO<sub>x</sub>) and carbon monoxide (CO) has been a part of development efforts by the original equipment manufacturers (OEMs) of gas turbines. This has led to the advent of multiple varieties of dry, low-NO<sub>x</sub> (DLN) or dry, low-emissions (DLE) combustion systems. DLN systems are considered “dry” because they have eliminated the need for water injection into the gas turbine as a way to reduce regulated emissions. Older-style combustion systems that required water injection are generally referred to as *non-premixed* or *diffusion systems*, whereas DLN systems are generally referred to as *premixed systems*. These names refer to how thoroughly the fuel and air are mixed before combustion occurs. Diffusion systems typically combust fuel and air without premixing, resulting in combustion at the interface between the fuel and air. Consequently, the fuel-to-air ratio in the local combustion zone is usually high, with no control over combustion temperatures. Premixed combustion systems mix the fuel and air upstream of the combustion zone, controlling the fuel-to-air ratio more closely. This localized reduction in fuel-to-air ratio results in lower combustion temperatures and lower NO<sub>x</sub> emissions. Figure 1 is a visual representation of these architecture differences and the resulting lower-temperature regions, even if the desired reference firing temperature is the same for both styles of combustors. Figure 2 gives a chronological progression of NO<sub>x</sub> emission capabilities with combustor architecture evolutions from non-premixed combustors to current state-of-the-art DLN systems.

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**Figure 1. Comparison of non-premixed (diffusion style) versus lean-premixed (DLN style) combustors [2]**



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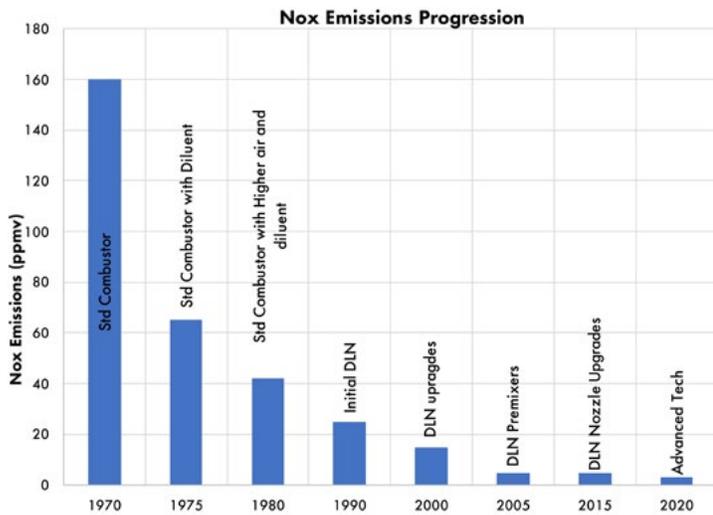


Figure 2. Progression of NO<sub>x</sub> emissions over time with emissions controls and DLN technology development

For many years, gas turbine combustion systems have burned gases that contain H<sub>2</sub>—even as much as 100% H<sub>2</sub>. To some degree, it would seem possible to easily convert gas turbines to H<sub>2</sub>-burning systems if enough H<sub>2</sub> were readily available. However, two facts are important to consider.

The first fact is that, in most cases, the H<sub>2</sub> used in gas turbines to date has not been from a dedicated H<sub>2</sub> source, but rather from a process that produces H<sub>2</sub> as part of a large commercial operation. Thus, the H<sub>2</sub> source, H<sub>2</sub> blending, and H<sub>2</sub> control typically used, although valuable in some sense for the present investigations, are not typical of the H<sub>2</sub> systems that will be used in potential future power generation applications.

Second, systems that have historically combusted H<sub>2</sub> are typically older, non-DLN, diffusion-type systems. (Some DLN systems have been running H<sub>2</sub> as well, but generally in very low percentages of less than 5%. Exceptions include the W501D5As at Sweeny Cogeneration facility in Texas, which has four gas turbines that have consumed refinery off-gas with H<sub>2</sub> blended at a rate of 15–35% H<sub>2</sub> using DLN combustors). These combustion systems have advantages over DLN systems in burning H<sub>2</sub> due to the combustion process used. An H<sub>2</sub> flame reacts, or burns, much faster than an NG flame, and there is a risk of flashback. When H<sub>2</sub> and air are premixed, there is a possibility that the flame will move upstream due to flashback, and it can lead to the flame reaching upstream parts of the combustion hardware that

are not designed to withstand flame temperatures. This can cause catastrophic damage to the gas turbine's internal components. Because fuel and air are near each other only at the point of combustion in diffusion systems, the flashback risk is low, and the risk of combustion hardware damage is minimized.

However, OEMs have been working for many years to prove out or upgrade their combustion systems for higher H<sub>2</sub> content than which they were originally designed. Mitsubishi Power has been doing this same work for its M501G advanced-class gas turbine.

Getting to an H<sub>2</sub> economy that provides H<sub>2</sub> into gas turbines for low- or no-carbon emissions will require many technology advancements. This fact should not dissuade the reader. These advancements appear achievable because several OEMs and third-party vendors are working on viable options. This white paper details the work of Mitsubishi Power, the Electric Power Research Institute (EPRI), and Southern Company, who have joined forces to advance the technology. The value of this project cannot be overstated. The project will allow the industry and society to view H<sub>2</sub> as a real potential fuel source for modern turbines, one that will reduce emissions of CO<sub>2</sub> and allow further flexibility of operation of gas turbines with no, or minimal, changes to NO<sub>x</sub> emissions compared to traditional natural-gas turbines.

## Hydrogen Impacts on Gas Turbines

The impacts of H<sub>2</sub> on gas turbines are varied and often misunderstood. Recent publications and reports in development provide more information around the impacts of H<sub>2</sub> on emissions, performance, durability, and service life. This white paper will not restate that information in detail; however, some information is pertinent to the project covered herein.

### Flame Speed

As indicated in Figure 3, the flame speed of H<sub>2</sub> is much faster than that of NG. As a result, the combustion system design must account for this flame speed in multiple ways, including the control of fuel-to-air ratios in the combustor. In some combustion systems, this might lead to the inability to run high levels of H<sub>2</sub>. In others, it might not significantly affect durability, operability, or emissions. The H<sub>2</sub> flame speed will not impact each combustion system equally; analysis and testing are required to determine the capability of each system.



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Figure 3. Stoichiometric property comparisons between NG and H<sub>2</sub> [1]

### Heating Value

The heating value (a measure of the amount of energy contained in a “chunk” of fuel) of H<sub>2</sub> is significantly different from that of NG. It is the impact of the low density of H<sub>2</sub> that makes the comparison with NG heating values a topic that can lead to incorrect conclusions. Figure 3 compares the heating values of H<sub>2</sub> and NG in mass and volume bases.

First, the volume basis heating value (or energy density) of H<sub>2</sub> is less than one-third of NG’s, which will impact fuel circuit sizing. Valves, piping, metering devices and their control systems, and so on can also be significantly impacted by this change in energy density. However, the volume-based heating value of H<sub>2</sub> (see Figure 4) should not significantly impact gas turbine performance because the same amount of energy is added to the gas turbine regardless of the fuel.

A second important factor to consider is that gas turbines control fuel flow based on reaching a particular total energy, generally measured by temperatures post-combustion with compressor and turbine pressure ratios or inlet conditions to the gas turbine. Fuel flows will change based on the energy content of the fuel. Although the power of the gas turbine will increase slightly (described later), the combustion exit temperatures are generally unchanged going from NG to H<sub>2</sub> or H<sub>2</sub>-NG blends because the fuel flows are adjusted by the gas turbine control system to hold constant temperatures or loads (power). A general process map of gas turbine control and a typical gas turbine temperature control curve are shown in Figures 5 and 6.

### Fuel Supply Power Input to GT

Mass Flow - ~2% of Energy Supply to GT  
Heating Value - Chemical Energy Content (released during combustion) 98% of Energy Supply to GT

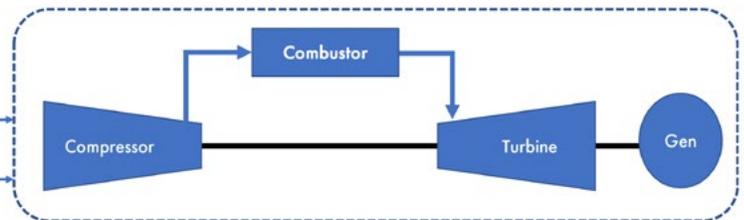


Figure 4. Fuel supply relation to overall power of a gas turbine

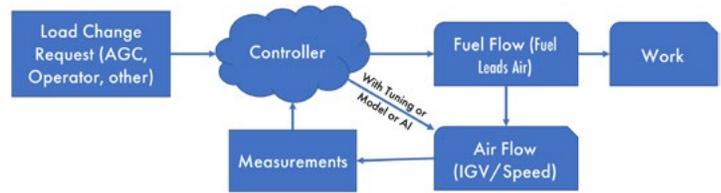


Figure 5. Gas turbine control simplified flow diagram

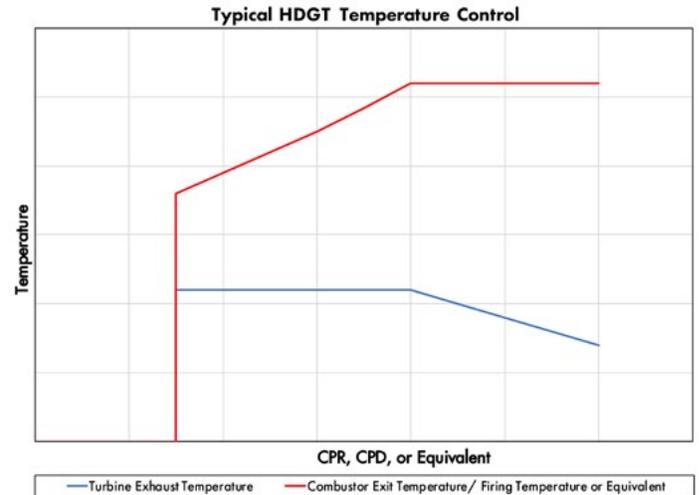


Figure 6. Typical part and baseload combustion and exhaust temperature “control curves”

### Performance and Emissions

An increase of H<sub>2</sub> in the fuel will positively influence a gas turbine’s performance and efficiency; however, it is not due to volumetric or mass-based heating value impacts. The impact is related to the exchange of CO<sub>2</sub> emissions for H<sub>2</sub>O emissions with hydrogen. As CO<sub>2</sub> decreases in the exhaust, the concentrations of other constituents, namely, oxygen and water, increase. Figure 7 shows the general trend of exhaust products with increasing H<sub>2</sub>.



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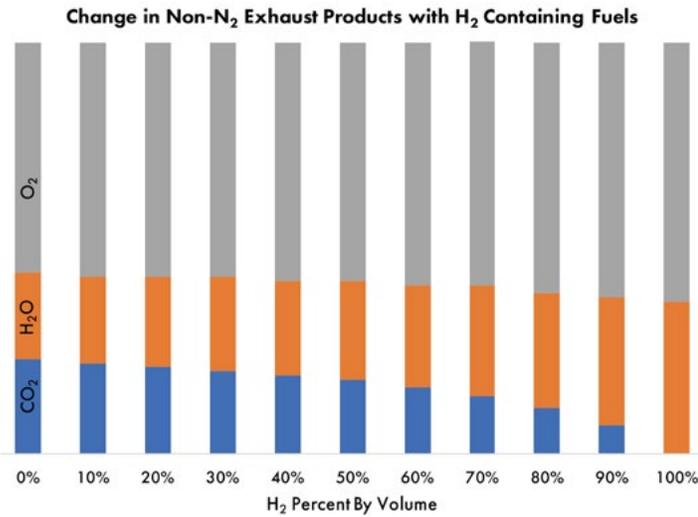


Figure 7. Exhaust constituents relative to increase in H<sub>2</sub> fuel percent

This change in exhaust products has a twofold impact. First, in performance, the change in exhaust products results in an exhaust with a higher energy content relative to its temperature (specific heat,  $c_p$ ). This results in more work for the same temperature and/or higher efficiency of the gas turbine, depending on the type of control used. This nominal trend in efficiency, performance, and CO<sub>2</sub> reduction with increasing H<sub>2</sub> is shown in Figure 8. This is shown for a nominal turbine, and specific benefits will be model-specific. Measurable impacts of efficiency and performance can be seen with H<sub>2</sub>, though those impacts are more pronounced at higher percentages. Notably, an improvement in heat rate was seen at the Southern Company test by holding the firing temperature constant as the H<sub>2</sub> percentage was increased, as is shown in Figure 8.

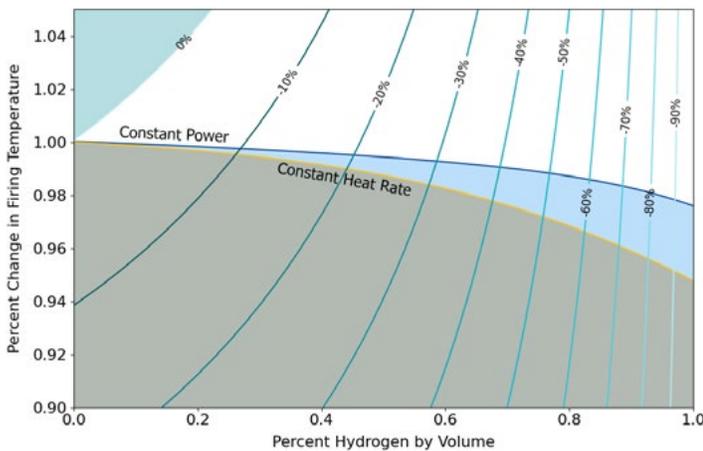


Figure 8. CO<sub>2</sub>, performance, and efficiency typical impacts with H<sub>2</sub> percent increase (nominal)

At this point, it is important to realize that mass NO<sub>x</sub> production or some energy weight ppmvd is volumetric and should be a comparison focus because volumetric corrections artificially increase NO<sub>x</sub> values [3, 4]. Typically, emission-regulated pollutants, such as NO<sub>x</sub> and CO, are reported on a dry basis with correction to a constant oxygen percent. Because both water and excess oxygen increase in the exhaust, this results in corrections that inflate the reported corrected emissions. Figure 9 shows the trend of the correction factor typically used versus the CO<sub>2</sub> percent in the exhaust.

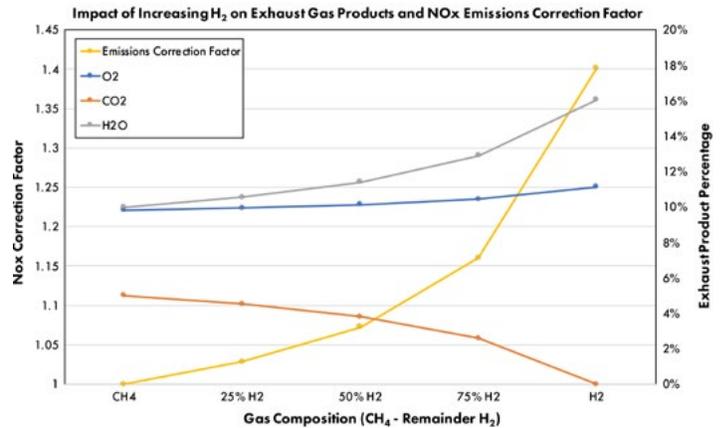


Figure 9. Emissions correction trends with CO<sub>2</sub>% in exhaust

Direct, uncorrected NO<sub>x</sub> emissions is a topic of active research relative to the H<sub>2</sub> content of fuels. It is true that the impact of H<sub>2</sub> can result in many detailed changes in the combustion process that are outside of the scope of this paper. To account for those changes, some fuel scheduling and control values could change. Likewise, some designs might need to be altered. Direct impacts of H<sub>2</sub> could result in some increase in NO<sub>x</sub> emissions; however, as indicated in this white paper, this can often be mitigated through fuel scheduling changes without negative impacts otherwise.

As detailed in this white paper, based on the increased reactivity of H<sub>2</sub> and the reduction in carbon for the fuel, CO emissions with H<sub>2</sub> have been shown to reduce dramatically with increasing hydrogen. This decrease in CO can generally serve to expand the emissions-compliant load range of the turbine by decreasing the minimum emissions-compliant load because, typically, the limit of DLN systems in low load is CO emissions (some systems might be limited by an operability limit, such as lean blowout). CO emissions typically have a negative exponential relationship to combustion



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temperature, increasing dramatically as combustion temperature is decreased along with load. This was confirmed in the demonstration referred to in this white paper.

### Project Background

Hydrogen fuel in gas turbines is seen as a promising bridge to a low- or zero-carbon future power system. Because it contains no carbon, H<sub>2</sub> as a fuel directly reduces the carbon emitted by the gas turbine. Hydrogen fuel has a long history in gas turbines being part of synthetic (off) gases, which have been used for decades. Much of the experience until now has been in older turbines, which have low power ratings and lower efficiencies. These gas turbines are equipped with combustion sections that make high regulated emissions levels (NO<sub>x</sub>, CO), which are limited by water injection and/or after-treatment in the gas turbine exhaust.

The gas turbine power industry is highly interested in H<sub>2</sub> fuels to reduce CO<sub>2</sub> emissions. This white paper provides information on the execution of the H<sub>2</sub>-NG blending and burning project conducted at Southern Company/Georgia Power's Plant McDonough in the Atlanta, Georgia, metro area. The unit is a Mitsubishi Power M501G gas turbine with a nameplate load of 265 MW at baseload and a DLN combustion system. This plant is well suited to serve as an example to other projects given its practicality and commonality to other, modern gas turbines. The gas turbine fuel delivery modifications were done on a temporary basis given the nature of the test (proving the concept) and lack of available H<sub>2</sub> flowing locally that would be required to run the high level of H<sub>2</sub> needed to blend on a continual basis. The results of the preparation and testing execution exhibit positive results meeting the expectation of the testing. The testing showed that with proper design and review, a team atmosphere, and a receptive and engaged customer, success on a difficult goal, such as blending H<sub>2</sub> gas, can be achieved. These results are an example of where further steps can be taken to continue to increase hydrogen/low-carbon fuels blending.

The team members worked in conjunction to ensure that all testing could be done safely, without impacting the reliability of a commercial combined-cycle gas turbine power plant while gaining valuable information to be used now and in the future for the low-carbon and H<sub>2</sub> economy.

Table 1 shows the key takeaways of the project.

Table 1. Key takeaways of H<sub>2</sub> blending project

Test Parameter	Comparison	Results Comparison
General capability	Previous H <sub>2</sub> field experience	Higher blend than previously done in any combined-cycle gas turbine (20.9%)
NO <sub>x</sub> emissions	NG emissions compliance capability	Maintain emissions compliance capability with H <sub>2</sub> blend
CO emissions, emissions-compliant load range	Emissions-compliant load range with NG	CO emissions improved at low load, emissions-compliant load range extended to lower with H <sub>2</sub>
CO <sub>2</sub> emissions	CO <sub>2</sub> emissions with NG	7% reduction in CO <sub>2</sub> with 20% H <sub>2</sub> blend
Gas turbine control	Relative to GT control with NG	No issues with control of GT under test conditions
Durability	Relative to durability with NG	No degradation to system hardware during short-term testing (long-term not evaluated)

The major members of the project team are as follows:

- **Southern Company, power utility.** Southern Company has oversight and approval authority, and they funded the H<sub>2</sub> blending project.
- **Georgia Power, site owner.** Georgia Power, a subsidiary of Southern Company, is the site owner and operator of Plant McDonough. Plant personnel also actively engaged in executing the safety recommendations, maintained ownership of the overall plant operation, and kept the plant within emission compliance requirements during the testing activities.
- **Mitsubishi Power, OEM and design lead.** Mitsubishi Power is the OEM for the gas turbine and was the design and design modification lead of the H<sub>2</sub> test. They supplied flow control system components and upgraded the control system logic, contracted the fuel supplier, led development of commissioning and the operating procedure, and led the execution of the plan.
- **Certarus, contractor.** Certarus was a contractor to Mitsubishi Power, providing the compressed H<sub>2</sub> gas and pressure-reduction skid.
- **EPRI, contract and design review lead.** EPRI facilitated and participated in numerous project reviews and oversaw multiple project execution tasks, including design reviews, leak testing, code and procedure reviews, and test execution.



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- **Sargent & Lundy/Lectrodryer, contractors.** Sargent & Lundy and Lectrodryer were contractors to EPRI that provided a technical review of the proposed design and a review of applicable codes and standards.

### System Design Modifications

The gas turbine itself was not modified for testing, and hardware modifications were limited to the fuel supply. A temporary blending system was added to the NG supply to introduce H<sub>2</sub> gas to the fuel sufficiently upstream of the gas turbine to allow for adequate mixing, as shown in Figure 10.

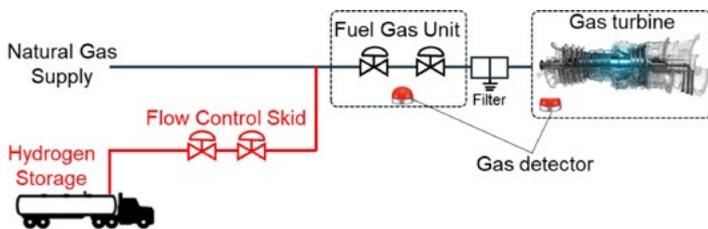


Figure 10. Plant McDonough system design update for H<sub>2</sub> gas blending

### Safety and Code Compliance

The importance of safety during the design and execution phases of the project cannot be overstated. All team members served critical roles in ensuring that all applicable design codes and regulations were reviewed and complied with. Systems constructed specifically for hydrogen service (fuel control skids) were designed in accordance with current American Society of Mechanical Engineers (ASME) B31.12 (latest revision) piping and pipeline code, and systems adapted for hydrogen service (such as the pressure-reduction skids) were evaluated and modified accordingly to be in compliance with ASME B31.12 (latest revision) and other relevant standards and/or recommended practices (NFPA, CGA, and so on). Design drawings and fabrication procedures for such equipment were reviewed in detail by codes and standards experts in each organization and/or subcontractor. Functional testing, final inspection, and review of quality documents (that is, material test reports, welding procedure specifications and procedure qualification reports, hydro- and leak testing, and system cleanliness requirements) were performed in person by qualified personnel from each member organization. Although the project itself was intended to operate for a very short test duration of four days of H<sub>2</sub> blending testing, the

systems were designed to comply with industry codes, standards, and appropriate safety protocols applicable to permanently installed and operated systems.

Work was performed in a cohesive environment where members from all organizations were encouraged to review all required data/documentation and provide the feedback necessary to ensure a safe and successful outcome. This team atmosphere and detailed review led directly to a successful test that resulted in data that will enhance the state of the art and serve as an example for future projects.

### Summary and Conclusions

This white paper provides information on the Mitsubishi Power M501G H<sub>2</sub> blending up to ~20.9% by volume, including the results of testing as well as preparations. This project constitutes the first of a kind in blending large-volume flows of H<sub>2</sub> in an advanced, high-efficiency gas turbine run in combined-cycle operation. The results of this testing can lead to significant investment decisions on further H<sub>2</sub> blending projects in power generation. Testing results show the promise that H<sub>2</sub> blending holds in the energy transformation to a low-/no-carbon future.

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*Gas Turbine Advanced Components and Technologies  
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