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ASSESSING GAS TURBINE FLEET READINESS FOR A LOW-CARBON FUTURE

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ABSTRACT

Many entities in and around the power industry are investigating hydrogen as a possible replacement for carbon-containing fuels in gas turbines. This paper is presented in order to provide the user community with information pertinent to assessing hydrogen readiness for their gas turbine fleets. It is important to understand the capability of current fleets to utilize H_2 containing fuels as part of a potential gas turbine fuel transition. The information provided here is deemed widely important in the existing fleet transition to H_2. This delves into the site, unit, and component considerations. On a site level, unit to unit considerations and commonality are considered, as well as site to site variation in timing and investment. On a unit level, more detailed technical information around a unit capability is discussed, such as the H_2 capability limits, H_2 flow requirements, and component considerations such as the combustion system, hot gas path, fuel delivery and other systems impacted by H_2 fuelling. The intent is to provide the reader a practical reference of the requirements around gas turbine transition to high H_2 fuels and to be an unbiased view to the requirements and capabilities currently in the representative fleets studied.

INTRODUCTION

Hydrogen testing and operation experience as well as numerous gas turbine hydrogen blending demonstrations and studies have been used to provide the information contained here. Participation in these demonstrations provided the opportunity to see commonality in the requirements of H_2 utilization in gas turbines. One demonstration discussed by Pigeon (2023) includes lessons learned through multiple demonstrations, which can be used to provide guidance for permanent transition to H_2 operation. A major aspect here is to provide the reader experiential insights on items to consider in the conversion from NG to H_2 fuelling. The information provided is intended to be general to all land-based heavy duty (~5 MW or larger) gas turbines though some information may be specific to a subset as will be noted.

As with the theme of a broad array of considerations for existing plants, some aspects prohibit providing more detail than is contained here (e.g. length constraints, complexity and variation of designs, etc.).

NOMENCLATURE

A_e	Fuel Nozzle Effective Area
ASME	American Society of Mechanical Engineers
CFD	Computational Fluid Dynamics
CGA	Compressed Gas Association
CO	Carbon Monoxide
CO_2	Carbon Dioxide
CWI	Certified Welding Inspector
DLN	Dry Low NOx
FEA	Finite Element Analysis
GA	General Arrangement
GT	Gas Turbine
HRSG	Heat Recovery Steam Generator
H_2	Hydrogen
LDF	Leak Detection Fluid
IGV	Inlet Guide Vane
LFL	Lower Flammability Limit
LHV	Lower Heating Value
$\dot{m}$	Mass Flowrate
MWI	Modified Wobbe Index
NG	Natural Gas
NO_x	Nitrous Oxides (NO, NO_2, N_2O summation)
OEM	Original Equipment Manufacturer
P	Pressure
PE	Professional Engineer
P_R	Pressure Ratio Across Fuel Nozzle

R	Universal Gas Constant
SG	Specific Gravity
SME	Subject Matter Expert
T	Temperature
$\dot{V}$	Volumetric Flowrate
γ	Ratio of Fuel Gas Specific Heats
μ_i	Molecular Weight of "i" Component

HYDROGEN COMBUSTION CAPABILITY ASSESSEMENT

Webb et al. (2023), provides extensive documentation of current known capability and projections for gas turbines. The H_2 capability of a gas turbine is heavily based on the type of combustion system that is used – the primary limiter. Broadly these types can be divided into three groups: diffusion, pre-mixed, and next generation combustors. Diffusion combustors separate the fuel and air until they reach the flame front in the combustor. These are also referred to as "standard combustors" and are used in many older frames including many aeroderivatives. These combustors can generally burn high H_2 content fuel, up to 100% depending on the gas turbine model. Since these combustors do not control flame temperature as a pre-mixed combustor does, the introduction of H_2 will increase flame temperature and therefore effect emissions. To address this, many diffusion combustors use water injection in order to suppress flame temperature to maintain compliant emissions.

Pre-mixed combustors enhance the mixedness of the fuel and air by combining them upstream of the flame front. These combustors can be controlled to a constant flame temperature, which means there is not a need for water injection when high H_2 content fuel is introduced. However, because of the chemical properties of H_2, energy density, volume based heating value and increased flame speed there are other concerns that limit the H_2 capability of pre-mixed combustors. These types of combustors can typically have up to 20-35% H_2 by volume capability. Importantly, these have extensive field experience and are prevalent on large frame gas turbines along with being options for smaller frames and aeroderivatives because of emission benefits.

Next generation combustors are combustors that leverage other technologies along with enhanced pre-mixing to further improve performance. As discussed in ETN (2022), there are a range of designs that are being investigated. Some of these technologies include fuel staging, improved mixing schemes, and advanced manufactured components. These combustors are in the early stage of introduction and are generally capable of 50-60% of H_2 by volume. However, the OEMs are looking to continually improve these technologies on the way to 100%.

As an important insight, Table 1~~Table 1~~ was shared in Harper et al. (2023) which outlines the important chemical and combustion properties to considered in the changes required for H_2 operation. The properties of H_2 relative to NG impact system and component design, safety features and procedures, and exhaust products; all topics discussed here. The first three properties in the table are all relative at any condition, and the combustion parameters are based off F class combustion conditions. Details around each property can be found in Harper et al. (2023).

HYDROGEN AVAILABILITY

The quantity of hydrogen available for power generation will be important for all involved in upgrading power generating assets for hydrogen usage. The detailed impact of hydrogen availability is complicated and not addressed in this paper, it is mentioned here as it is an important parameter that will be part of any upgrade consideration.

However, hydrogen today accounts for less than 0.2% of electricity generation, with most of this associated with off gas from the steel industry, petrochemical plants, and refineries (IEA: Future of Hydrogen)

The overwhelming majority of hydrogen today is produced from fossil fuels. There is a small, but growing proportion produced through water electrolysis. Figure 1 shows a dramatic increase in this area (IEA: Future of Hydrogen). This projection suggest that hydrogen may be available in high enough quantities to make upgrades to the power generation assets feasible from a financial point of view.

Table 1: Chemical and Combustion Properties of Hydrogen relative to Natural Gas

Property	H_2 relative to NG	Result
Kinetic Diameter	0.75	More leak propensity
Energy per unit mass	2	Lower GT fuel mass flow
Energy per unit volume	0.29	Higher GT fuel volume flow
Adiabatic Flame Temperature	1.15	For same combustor and conditions higher NOx, lower CO
Flame Speed	9	Higher propensity for flame holding and flashback
CO_2 emissions	0 (at 100% H_2)	Reduced carbon, higher heat load to Turbine
Required Ignition Energy	0.1	Light off and safety

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Lower Flammability Limit	0.8	Light off and safety
Upper Flammability Limit	3	Safety and Handling

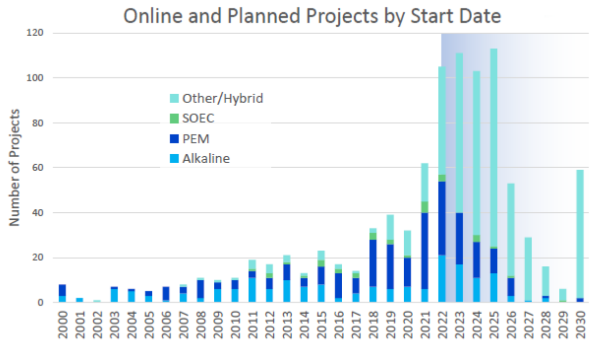

Figure 1: Worldwide Electrolyzer Projects (IEA 2023)

SITE TOPICS

On a site level H_2 operation will require changes to hardware and operation. Those hardware changes that are not specific to the gas turbine or H_2 supply are discussed in this section and those that are specific to the gas turbine are discussed in the unit topics section. Procedures that impact safety, component reliability, and regulatory emissions will likely see process and procedure changes and are discussed here. The Gas Turbine operator will have the ultimate responsibility to develop and own these changes. OEMs and independent experts can provide guidance.

A list of codes relevant to the use of H_2 fuel is contained in Table 2~~Table 2~~ for reference. This is not claimed to be all inclusive list of those codes to be considered in H_2 operation, regional codes may differ, and experts should always be consulted for specific code applicability. These codes listed provide hydrogen upgrade guidance and regulatory information regarding safety, operation, and handling. The number of codes that could be applicable is part of what should be appreciated; ensuring all codes and regulations have been properly accounted for is a significant task. Equipment, system designs, and procedures should meet all applicable codes and standards.

Table 2: Hydrogen Fueling Addition Applicable Regulations and Codes

ASME B31.12	NFPA 70	CGA G-5.5	CGA P-29	CGA S-1.1 Through S-1.3
ASME B31.3	NFPA 497	CGA G-5.6	CGA P-86	CGA V-10
ASME Section VIII	NFPA 850	CGA H-4	CGA P-50	CGA V-12
ASME Section XII	CGA C-7	CGA H-5	CGA P-53	API RP 500
ASTM D7606	CGA E-4	CGA H-14	CGA P-74	ISO Standards
NFPA 2	CGA G-5	CGA P-16	CGA PS-46	NACE-11295
NFPA 55	CGA G-5.4	CGA P-18	CGA PS-48	UL 2075

Specific site impacts will vary based on the current configuration and location. A site detailed review is required to determine more specific site changes required.

In general, site procedures that have reporting, operational, and safety aspects are likely to require update for H_2 operation.

Design and operational principles and procedures utilized at the site will also see change. These procedures include the following list which are described in more detail below:

- Material Selection and Component Design Requirements
- Startup and shutdown
- Pressure and leak testing
- Gas line Flushing / Cleanliness
- Purging and Gas charging

Startup and shutdown procedures will change based on either the use of hydrogen to start and shutdown or managing the transition between a start on natural gas and hydrogen operation. Pre-start and post shutdown procedures in either case will need review and likely be changed.

Leak testing and pressure testing should be performed to the applicable regional codes. Two references are CGA G5-4 and ASME B31.12. These references provide hydrostatic and leak detection procedures and criteria. They also provide alternative solutions such as if there are reservations to perform a high pressure compressed gas leak test such as using a low pressure He leak test.

H_2 upgrades will need to be constructed or modified specifically for H_2 service in accordance with current piping and pipeline codes and other relevant standards and/or recommended practices. Design drawings and fabrication procedures for H_2 equipment should be reviewed in detail by codes and standards experts within all stakeholder organizations and/or sub-contractors.

Hydrogen blending with NG will be subject to flammability class changes dependent on the blend ratios of H_2. SMEs and PE's who are experts in the field need to be consulted for specific code requirements and breaks for H_2 service and blending.

Codes such as ASME B31.12 provide guidance on materials selection, design, construction, testing, and acceptance criteria to ensure a minimum level of safety for piping systems operating with H_2 gas.

Below are a list of take-away points to be considered for code compliance and safety in H_2 fueling operation.

- Code requirements for H_2 piping are outlined in ASME B31.12; however, where specification/code breaks exist, the change in requirements between the different codes may not be well defined. ASME 31.12 indicates that it is the "owner's responsibility to select the Code section that most nearly applies" and that the "owner is responsible for imposing requirements supplementary to those of the Code section, if necessary, to assure safe piping for the proposed installation."
- Ensure that code experts, equipment OEMs, and site are all clear on which codes are going to be applied and to which areas. P&ID's that show the code breaks and blend ratios in each zone are advised.
- Welding procedures and qualifications records are of critical importance in code compliance.
- All Skids, skid enclosures and skid components need to be certified / stamped for use with Hydrogen per applicable codes.
- Independent individuals with knowledge of codes and are qualified in the safe handling of H_2 should take part in site walkdowns, equipment/piping inspections and applicable code reviews.
- Site Safety Plans (SSP) need to be developed collectively with all interested participants.
- Per the guidance in Compressed Gas Association (CGA) G5-4 300-series austenitic stainless steels, specifically 316/316L, are recommended for gaseous H_2 service for components such as piping, pipe fittings, values and other in-line equipment.
- Manufacturing shops should have certified welding inspectors (CWI) that are responsible for inspections. Hydrostatic testing should be performed separately on all fabricated pipe spools and vessels.
- As per the guidance in Section 5 of CGA G-5.4, piping systems are cleaned before being placed into H_2 service to ensure proper function of moving parts, such as valves, to avoid damage to critical components.

Hydrogen storage, generation, blending, delivery are all possible changes that will impact the plant general arrangement. It should be expected that at any site adding H_2 operation will see changes to the site general arrangement. Area classifications, such as hazardous areas with H_2, will also change affecting the general arrangement, drawings, and site access.

Hydrogen combustion results in the changes in exhaust products shown in Figure 2~~Figure 2~~. Those changes will drive the need to evaluate other plant systems such as Heat Recovery Steam Generators (HRSG), Duct Burners, and exhaust emissions after-treatments systems such as ammonia catalysts (SCR) and CO catalysts. The fuel, exhaust products, gas turbine performance and pollutant emissions changes with H_2 combustion will impact each of these systems.

The HRSG is subject to the GT exhaust conditions and can be impacted by the exhaust flow rate, temperature, and composition. During normal operation the change in exhaust products as shown in Figure 2~~Figure 2~~ along with gas turbine performance differences discussed in a following section of this report. Implications of this change could vary and may need analysis to determine impact on life or design changes required, if any. Hydrogen fuelling will not directly affect the exhaust gas temperature (Harper, 2023) however, gas turbine controls could be adjusted with hydrogen to account for changes in emissions or performance of the GT with hydrogen.

Any change in pollutant emissions such as NO_x and CO due to H_2 fuel are subject to current research such as that discussed in Breer et. al. (2022). Any current or future emissions aftertreatment system will need evaluation and consideration with H_2 service at the specific site, even if such systems will not require any change.

The change in fuel to the gas turbine may be significant to duct burner operation for those sites which include auxiliary firing. The fuel source may be common between duct burners and the gas turbine. Thus, any change to the gas turbine fuel may either require a change to the duct burner operation or specific piping and control to operate the duct burners on only NG. As gas turbine H_2 operation will change exhaust products, as discussed earlier, this change in oxygen and water content in the exhaust can impact the combustion of fuel in the duct burners. Testing or analysis of this impact on emissions or operation may be required.

Hydrogen operation will impact gas turbine exhaust products. While NOx emissions are a subject of active research and development, exhaust products and reporting are impacted by the increased H_2 content. This is discussed in Harper et. al. (2023) and Noble et. al. (2022). Figure 2~~Figure 2~~, also shown in Harper et. al. (2023) shows this change in exhaust products.

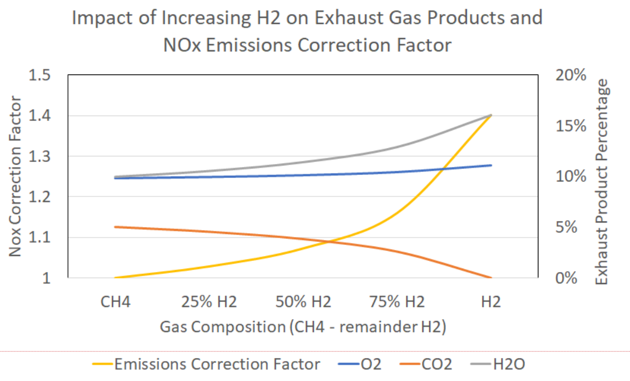

Figure 2: Exhaust Products with H_2

The increase in oxygen in the exhaust results in a change in the calculation of the corrected dry emissions commonly used in reporting emissions. This change is of critical importance for operators to understand. Regulatory changes may be required to ensure emissions reporting meets the intent of the regulations.

UNIT TOPICS

Changes to the gas turbine operation and gas turbine and gas turbine accessory design with hydrogen are discussed in this section. While this document is intended to provide information to the user as to changes which may occur to the site and unit based on hydrogen operation, some of the changes discussed here may be completed by the OEM or 3rd parties.

The gas turbine performance based on the change in fuel to H_2 can result in an improved gas turbine output and heat rate. (Burnes 2019) This is due to the change in exhaust products and the corresponding change of those products heat capacity at a given temperature. A general trend of power and heat rate is shown in Figure 3~~Figure 3~~. The magnitude of the change in performance and heat rate will depend on the gas turbine baseline performance and the methods used to control the gas turbine load and temperatures. The Figure 3~~Figure 3~~ and Figure 4~~Figure 4~~ trends are based off simulation using an F class gas turbine digital twin model. In the simulation the gas turbine is run at its maximum open IGV angle and constant combustion firing temperature and exhaust temperature. A pure methane fuel gas is replaced with hydrogen gas to generate the relationships shown in the graph.

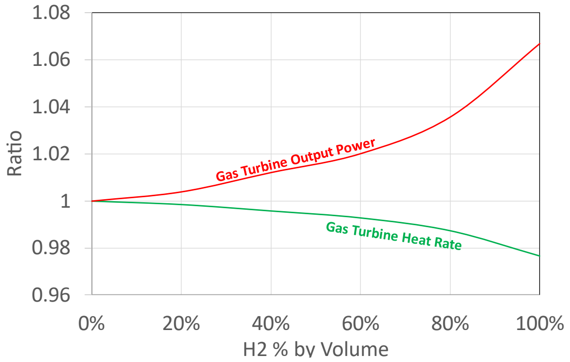

Figure 3: Power and Heat Rate with H_2

The exhaust products change with H_2 has been discussed. This change will result in a heat capacity and flow change in the hot gas path as shown in Figure 4~~Figure 4~~. This change may impact how the gas turbine is controlled, any change in control would be subject to design criteria of each OEM.

The hot gas path of the turbine is subject to the gas products temperature from the combustion system. It is reasonable to expect for most configurations this temperature will be similar between H_2 and NG only fuelling, subject to some control adjustments for performance or lifing. Changes to the H_2 fuel and resultant changes in either combustion internal fuel scheduling/control or wholesale combustion system component change can result in changes to the *profile or pattern factor* of temperature to which the hot gas path is subject. The pattern factor refers to the temperature distribution across the exit profile plane of the combustion system at the entrance to the 1st stages of the hot gas path. Any change to this profile can impact how the hot gas path is cooled and feasibly its life intervals. This will be accounted for in the gas turbine design for H_2 and based on the combustion system design change resulting in a change in pattern factor, but not definitively as the change in combustion system may result in an insignificant change in pattern factor. This is a case-by-case dependency.

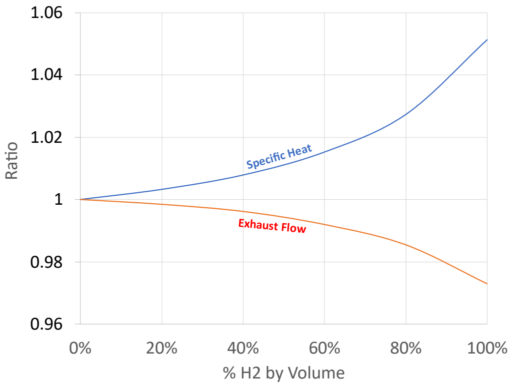

Figure 4: Trend of Expected Gas Turbine Exhaust Products Specific Heat and Exhaust Mass Flow with Hydrogen Fuel Blending relative to natural gas only

The gas turbine fuel delivery system will change with H_2 addition, and this is shown in a generic system graphic in Figure 5~~Figure 5~~. This is not representative of a specific configuration. Each configuration will have specific requirements. This information is provided to show an order of magnitude and general example of changes to the fuel delivery system. In addition to the H_2 supply, and mixing H_2 with the NG supply, additional venting, inert gas purging and instrumentation can be required. This system is also shown with H_2 gas as a supplied media without any storage information which will add additional changes.

Form

Blended fuel gas piping downstream of the H_2 gas addition to the gas turbine itself will need review for code applicability and sizing to ensure velocity and system pressure drop meets all applicable design criteria. High H_2 blend ratios may need to meet the same code specifications as 100% H_2. The blend limit for H_2 service code applicability can vary even in review by SMEs. Having multiple SMEs review code requirements and provide justification for the decisions is important and valuable.

A well-mixed blend of H_2 and NG will be important for flow into the gas turbine. This does not mean a dedicated flow mixing channel or device is required. EPRI demonstrations have been conducted without a designed mixing device without issue to date (Pigon 2023). Figure

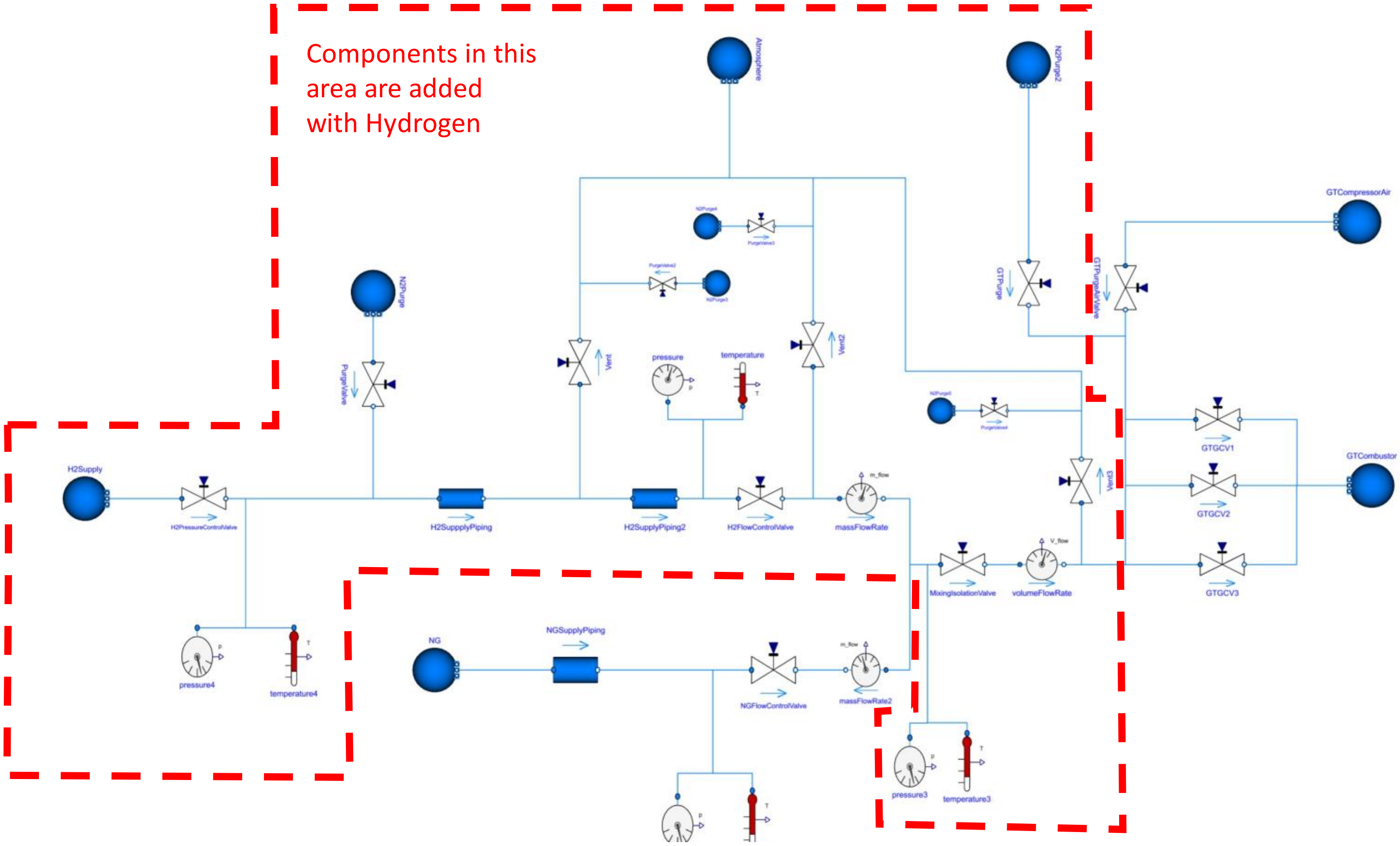

Figure 5: Graphical schematic representation of fuel gas supply changes with hydrogen

6~~Figure 6~~ shows a sample CFD result of a 50% by volume H_2 and NG blend. The pipe is 20mm in diameter for all sections and the mixing length is 230mm. Hydrogen flow rate is 1 kg/s and natural gas flow is 8.5 kg/s. The results suggest given a long enough mixing length that a well-mixed blend result. These results are subject to the type of piping and blends and flow rates, and it should be expected some mixing studies or designs with previous studies should be used to confirm the sample will be well mixed.

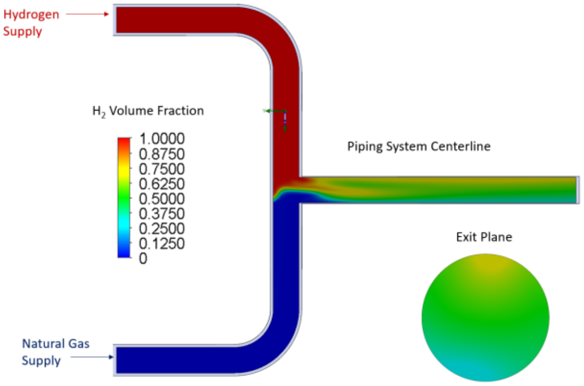

Figure 6: CFD blending example of Hydrogen and Natural Gas supply

Hydrogen fuel flow may be controlled by independent pressure and flow control valves depending on the configuration. Pressure control may be required for any high-pressure supply such as local high pressure gas storage which can be 7000 psi (48MPa). In addition, where H_2 and NG are blended there is the potential need for a valve which can isolate one gas from the system in the event of a gas turbine trip or other event to allow for continued operation on one gas supply while maintenance is performed with the other.

Per the procedures discussed earlier inert gas purging will be added for H_2 supply line pressure and leak testing and fuel gas charging. During normal operation there are configurations that will require inert purging during operation of the gas turbine. This inert gas purging can be used for pressure and leak testing, venting, as well as to ensure that the oxygen content in the gas lines is low enough before gas charging is conducted. Location of inert gas purging is critical to ensure all areas of the system are purged of air or fuel gas when required.

Inert purging can also be required after shutdown or after a unit trip for preparation for start-up with NG only or high percent of NG fuel. This requirement is a function of the fuel gas start-up requirements of a particular configuration.

Some combustion systems use an air purge in unused fuel gas circuits. During load changes these circuits can change from fuel to purge and back. When these changes occur with H_2 gas, it may be required, depending on the purge source (for instance a gas turbine compressor exit purge source) to use an inert purge to separate the H_2 blend fuel gas from the air purge.

In conjunction with inert gas purging and for safety and charging procedures venting of H_2, NG and blended gas will be required. Venting design will have to meet the code requirements of the codes listed in Table 2~~Table 2~~. Code requirements around vent valve, vent orifice, gas composition, gas velocity is all specified in codes that need to be accounted for in vent system design. Example codes are NFPA 2 and 56,, CGA G5.5 and API 521. An example of components included in a vent system to meet code requirements is shown in Figure 7~~Figure 7~~. Vent systems may differ in the exact configuration and still meet code.

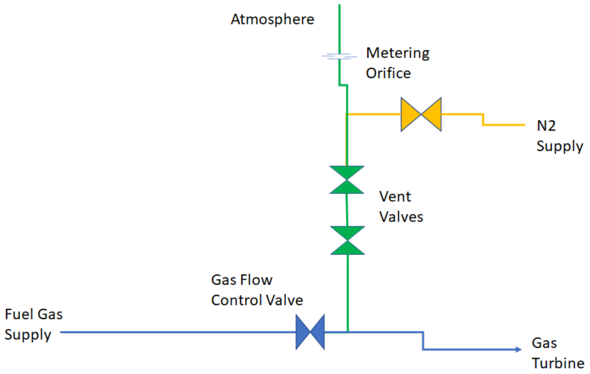

Figure 7: Example Vent Configuration

Depending on the H_2 supply and gas turbine fuel gas requirements there may be a need to add or adjust fuel gas temperature control or heaters. The energy and density properties as shown in Table 1~~Table 1~~ can drive a need to change the fuel nozzles or gas temperature control. Combustion system operability can be sensitive to changes in fuel. This can be described in parameters that combine heating value and gas temperature. Modified Wobbe Index (MWI) is an example of one used by the gas turbine industry. Equation 1 shows the relationship between MWI heating value, specific gravity, and fuel gas temperature. Specific gravity is a relative density measure and thus is much lower for H_2 than NG. Lower Heating Value (volumetric based in the MWI calculation) is much lower for H_2 than NG, per Table 1~~Table 1~~. As combustion systems may have a need to target a limited range of MWI, the fuel gas temperature may also need adjustment, both in design and in operation as blending ratios of H_2 are adjusted. As the LHV of hydrogen is 1/3 that of natural gas and the specific gravity is 1/8 that of natural gas, to maintain a constant MWI transitioning from natural gas to hydrogen the fuel gas temperature would need to be reduced by approximately 44%.

$$MWI = \frac{LHV}{\sqrt{SG*T_g}} \tag{1}$$

Figure 5~~Figure 5~~ shows the gas turbine gas control valves outside of the new components added with H_2 as these are valves already installed which control fuel to the gas turbine. However, these valves may need to be adjusted or changed. The mass and volume flow changes with H_2 may drive the gas control valves to operate at a higher stroke then with NG.

Significant additional instrumentation as shown in Figure 5~~Figure 5~~ will be required. Hydrogen blending ratios will need to be accurately monitored for control and reporting. This will involve additional flow meters, pressure, and temperature sensors. Multiple styles of flow meters may be included for different sections of the system. Hydrogen analysers of varying type will be required.

Gas flow can be monitored with volume or mass flow meters depending on the configuration and needs of the system. Mass flow meters such as Coriolis meters can be configured for multiple gas blends and possibly over a range of different blends. These meters are commonly used to monitor H_2 flow in demonstrations today in determining mass or volume blends. Mass flow measurements are valuable being mass flow is directly related to the energy input of fuel into the gas turbine.

Volume flow meters can also be used in directly calculating volume flow and inferring percent by volume of H_2 blends. While volume flow meters do not have the advantage of monitoring gas flow that Coriolis meters have, volume flow meters can be used in blended gas lines, in concert with mass flow meters to validate H_2 blends independently of the H_2 gas analysers. This is done through gas density which is a function of the blended gas R constant and blended gas Molecular Weight. By calculating a change in gas density with those changes the volume flow and mass flow meters can be used to independently verify gas composition.

A separate option would be to solve for the blended gas molecular weight as shown in Equation 2. This molecular weight could be then used to correct a reported H_2 blend from a gas analyser, chromatograph or other instrument.

$$\mu = \left(\frac{\dot{m}RT}{P\dot{V}}\right) \qquad (2)$$

Configurations and uses of these in concert with H_2 percent measurement devices discussed below can vary based on the design and control and monitoring needs of the system. The user will have to weigh costs, complexity, maintenance and accuracy needs in order to determine the design best suited for their plant. Multiple acceptable configurations are possible and EPRI does not prefer one method over another.

Chromatographs and H_2 gas analysers directly measure the gas composition and thus have some advantage over other methods which infer those values. Gas analysers can have a disadvantage in resultant speed, cost, historical available reliability data (for those which are relatively new technologies) and lack of flow information that can be monitored with other devices. Even with potential disadvantages it is expected that most systems will include some direct measure of H_2 content.

Gas pressures and temperatures will be monitored all through the fuel delivery. Pressures and temperatures of supply and blended gas can be used for primary or secondary calculations of gas blending. Fuel gas system supply pressures will change with H_2 blend percentage. The reason for this is the energy content required by the gas turbine will remain relatively constant with the change to hydrogen, but the lower density of hydrogen will mean its volume flow will be much higher. Thus given the same fuel system sizing, the pressure required to flow the higher volume flow of hydrogen will lead to higher pressures. This relationship can be used to determine a H_2 content subject to some assumptions or additional measurements such as the NG fuel composition. Fuel gas pressures are also used in the fuel gas control and pressure reduction control valves used in the fuel gas supply system.

Gas detectors used today to detect gas leaks will require adjustment or change to account for the change in gas composition. Lower Flammability Leak (LFL) detectors are in areas such as the gas turbine enclosure and fuel control skids which are enclosed and have numerous gas connections and can have both air and fuel at high pressures. As H_2 gas is added to the system these leak detectors may need to be adjusted or changed.

There may be multiple H_2 combustion options to consider. There may be the option to keep the current combustion system for some. Others may require a full combustion system change. In between there may be the need to partially upgrade some combustion systems. MWI changes as discussed earlier may drive a need to modify combustion fuel nozzles. H_2 may also drive a need for hardware improvements such as enhanced thermal barrier coatings (TBC) to protect the combustion system components from the change in flame speed, shape and location with H_2. Thus, while a particular combustion system may be able to operate with a desirable level of H_2, it is possible that the exact configuration may need to be specific for H_2. Figure 9~~Figure 9~~ is a generic representation of an axial cut view of a can annular combustion system used in a heavy-duty frame gas turbine. Thus, it is not representative of all gas turbine combustors, However, it is shown to illustrate the components of the combustion system and those which possibly would need modification.

Fuel nozzles are components likely to see changes with H_2 operation. The pressure vessel components like the endcover which can be used to feed those would also then likely be modified. Liners and transition pieces may require change if changes are required to meet combustion parameters such as residence times or intermediate temperatures which impact emissions, operability, and durability of the combustion system.

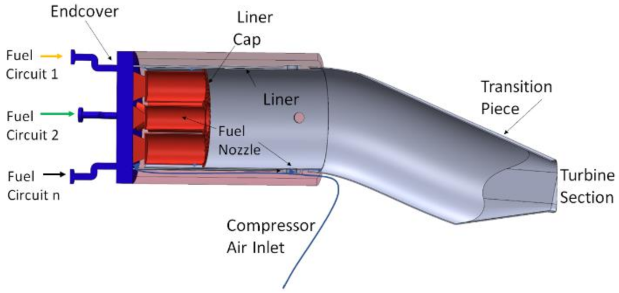

Figure 8~~9~~: Generic Can annular Combustor Axial Cut View

The mass and volume flow of fuel to the combustor will change with H_2 fuelling based on the heating value change, even when controlling to the same gas turbine load and combustion temperatures. This was described earlier and Harper et. al (2023) discusses this in more detail. This mass flow is subject to combustion system fuel nozzle sizing which refers to the flow area for fuel in the combustion system. The changes in fuel composition and temperature as discussed earlier will determine the sizing used for the combustion system.

The pressure ratio across the fuel nozzle can be an important parameter in satisfactory operability of the gas turbine combustion system. The pressure ratio is strongly correlated to the MWI which is why limits of operation are many times expressed in terms of MWI.

Hydrogen combustion has a higher flame speed as shown in Table 1~~Table 1~~. This can drive significant design changes to the combustion system to prevent combustion hardware damage. Even for combustion systems that do not require architecture change, there may be a need to add additional protections to ensure components meet the guaranteed life spans. Fuel Nozzles and liners could especially be subject to change.

Form

Hydrogen can result in improved [Harper et. al (2023)] combustion operability/ combustion dynamics, but this is not guaranteed for all systems. Some combustion dynamics frequencies under some combustion systems may see higher amplitudes with H_2. This may drive a change in combustion system component wear and changes to the components wear surfaces for protection.

In addition to hardware changes required, commissioning a gas turbine with H_2 blending operation will add time and complexity to the process. Initial operation on H_2 will need limits to be defined and procedures to control H_2 mixing within limits without data from prior operation. Below is a list of commissioning processes and tasks that will likely be impacted by H_2 operation. Due to length constraints the authors are not able to elaborate on the details of each of these processes in this document.

1. Pretest procedure completion and certifications
2. Loop / Electrical Continuity tests
3. Simulations, safety, interlock tests
4. Critical communication protocols
5. All safety critical procedures
6. Test equipment (gas detectors / other) validation
7. Any pre H2 testing completed (tuning, CNG)
8. All pretest checks of filters or other completed
9. Gas sampling
10. Shutdown procedures
11. Gas Control / Blending
12. Alarm protocol and alarm limits
13. Baseload / Partload Commissioning with Blending

Combustion Tuning is the specific process of adjusting the control of the gas turbine combustor to meet emissions and operability requirements. Combustion Tuning will be changed with H_2 blending. The tuning process will also be longer and more complicated based on the need to ensure the full blending range of fuels meets requirements. This is likely to be true for combustion systems using modern or even more traditional combustion system control.

Like the commissioning processes impacted by H_2 fuelling multiple steps will be added or complicated by H_2 fuel. Possible combustion tuning process change are listed here.

1. Gas Turbine Emissions Testing
    a. Emissions Guarantee Verification
    b. Combustion Fuel Emissions Mapping
2. Operability limit mapping
3. Fuel Mode transfers
4. Fuel Circuit Purge sequences

Gas turbine control will change significantly with H_2 fuel. As discussed earlier, there are likely combustion system and fuel delivery changes that will be part of any upgrade. These changes will drive the need for updated controls. These changes may only be software changes, but for some configurations, there may need to be hardware upgrades as well.

Below are sample lists (not comprehensive) of H_2 influences on controls operation. These includes normal operation and faults/trouble. These lists are provided here so the user may be armed with questions which could be asked of the OEM on how these control changes have been accounted for in the design they are procuring. With the space constraints of this paper the authors are not able to provide detail information about each of these.

<u>Hydrogen Operation Influences on Normal Control</u>

1. I/O (new and updated)
    a. Valves
    b. H2 Analyzers, Chromatographs/Wobbe
    c. Flow Meters: Mass/Volume
    d. LEL / H_2 leak detectors
    e. New Gas/Blend Pressure / Temperature
    f. H_2 calibrated flame detectors
2. Blending control / Fuel Scheduling
    a. Fuel Mode control with Blends
    b. Manage instrumentation and valve feedback
    c. Blend Control during all operation
3. Fuel Gas Purging

<u>Hydrogen Operation Influences on Fault Control</u>

1. Hydrogen Fault Requirements to be defined:
    a. Trip off H_2 flow
    b. Control shutdown H_2 flow
    c. GT load runback
    d. GT Trip
    e. Reduce H_2 blend or flow
    f. Vent H_2 system
2. Main causes related to fault/trouble requirements
    a. Hydrogen force off (push button or control force)
    b. Valve(s) position abnormal
    c. Hydrogen % deviation
    d. Hydrogen pressure low or high
    e. Hydrogen blend at max allowable
    f. Hydrogen gas temperature at limits
    g. Hydrogen gas pressure at limits
    h. Hydrogen rate of change at limits
    i. GT Trip, load rejection, islanding, shutdown
    j. Hydrogen leak detection (auto or manual)
    k. Fuel Temperature
    l. Combustion dynamics or emissions
    m. GT Operation general issues

CONCLUSIONS

The previous sections provide the reader with topics of importance in hydrogen fuelled combustion conversions and upgrades. The important topics here were separated into those generally related to a fleet, a site, and a gas turbine. This was done as the personnel dedicated to each may vary in organizations. Issues are presented in the paper and in some cases generic potential solutions are presented. In no cases should these solutions be taken to any individual fleet, site, or plant for implementation. These are presented as a general guide and suggestion only. The importance of the paper is in summarizing these topics in one location for interested parties to gain a more wholistic view of the subject. Solutions to these topics will vary across the gas turbine power generation fleet.

While upgrading gas turbines to operate with H_2 fuel is eminently possible, the subjects presented here are important to consider when preparing for such conversions. The importance lies in the capital and operational costs as well as the complexities involved in each fleet, site, and unit upgrade. The details of each upgrade will vary even for gas turbines of similar vintage there could be differences based on configuration detail, fuel, or other parameter of importance in hydrogen combustion. It is the hope of the writers that the information provided here will arm those considering such conversions with additional information to question and gain understanding for their individual planning and goals around carbon emissions reduction and hydrogen fuelled gas turbine power generation. The purpose of this paper has been to arm the user community with information for assessing their fleet readiness for hydrogen. It is the hope of the authors that this information will be valuable to the community during such assessments for their induvial power generation facilities.

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