

TECHNOLOGY INSIGHTS

SELECTIVE CATALYTIC REDUCTION DESIGN CONSIDERATIONS FOR GAS TURBINES FIRING HYDROGEN AND AMMONIA FUELS

THE TECHNOLOGY

Although hydrogen and ammonia are potential low-carbon fuels for existing gas turbines (GTs), they could generate higher NO_x concentrations than natural gas. This is where the capability of existing post-combustion NO_x control systems—specifically, selective catalytic reduction (SCR) technology—comes into focus.

THE VALUE

GTs capable of producing power from low-carbon fuels, such as hydrogen and ammonia, could enable natural gas assets and infrastructure to be leveraged as a resource for decarbonization. Post-combustion SCR systems might play a critical role in this transition.

LCRI'S FOCUS

The Low-Carbon Resources Initiative (LCRI)¹ is exploring opportunities for research, development, and demonstration of low-carbon fuels for GTs.

INTRODUCTION

In the United States, selective catalytic reduction (SCR) systems for post-combustion NO_x control are installed downstream of most large-scale industrial and utility gas turbines (simple and combined-cycle) to meet stack NO_x permit requirements. These systems use ammonia as a reagent and are designed to handle gas turbine (GT) outlet (that is, SCR inlet) NO_x levels in the range of 10–25 ppmv (at 15% O₂, dry) with the GT firing natural gas. They are generally capable of providing 90% NO_x reduction with less than 5 ppmv of unreacted ammonia (also called *ammonia slip*) as a byproduct. This allows GTs to comply, in some cases, with NO_x permit levels as low as 2 ppmv at the stack.

In a low-carbon future, GT engines modified to fire pure hydrogen, pure ammonia, or hydrogen and ammonia fuel blends (HAFs)² may generate higher NO_x concentrations compared to natural gas [1]. Hydrogen and ammonia behave differently as fuels, including the primary mechanisms for NO_x formation. Although hydrogen might produce marginally more “thermal NO_x” than natural gas due to higher flame temperatures, ammonia (NH₃) causes greater concern because it contains nitrogen and

can exhibit significantly higher NO_x conversion rates (“fuel NO_x”) when burned. Ultimately, the extent of the potential NO_x increase depends on the fuel mix and combustor design, and researchers are working to develop low-NO_x, retrofit GT combustors designed to fire HAFs. However, in the near term, it is important for the industrial and power generation sectors to consider the potential ramifications of higher GT and duct burner NO_x levels generated while firing HAFs. This is where SCR system design parameters and potential modifications come into focus.

This technical brief touches on several important SCR design parameters impacted by higher inlet NO_x levels, including ammonia reagent use, catalyst lifetime, and catalyst inlet NH₃/NO_x distribution uniformity. Using a generalized F-class GT as an example, scenarios are presented to introduce the possible options and relative costs for modifying existing SCR systems to meet stack NO_x and ammonia slip permit levels as a function of increasing inlet NO_x levels. For the purposes of this brief, exhaust gas flow rates are assumed to be similar in all scenarios (see Box 1).

¹ The LCRI is a joint project between the Electric Power Research Institute (EPRI) and Gas Technology Institute. More information can be found at www.lowcarbonLCRI.com.

² In this brief, *HAFs* denotes pure hydrogen, pure ammonia, or hydrogen-ammonia blends used as fuels for GTs.

BOX 1. F FACTOR IMPACTS

HAFs may generate different volumes of combustion components per unit of heat content compared to natural gas, changing the “F Factors” used for converting NOx measurements from a volume basis (ppmv) to a mass basis (lb/MMBtu or lb/hr). Although beyond the scope of this brief, regulators and system owners must consider how these changing factors might impact operating permits and NOx reduction requirements when firing HAFs. For additional information, see F Factor calculation procedures in EPA Method 19 [2].

NOx TERMINOLOGY

Before exploring SCR design parameter impacts, it is useful to review the relationship between the different NOx terms used in this brief. These include SCR inlet NOx concentration (NOx_{in}), outlet or stack NOx concentration (NOx_{out}), and percentage of NOx reduction across the SCR catalyst (dNOx%). If the design NOx_{in} for a given SCR system increases and the target NOx_{out} remains unchanged due to local regulatory requirements, the design dNOx% must increase.

Table 1 shows the required dNOx% levels for multiple NOx_{in} and NOx_{out} cases. Throughout this brief, NOx_{in} = 25 ppmv is used in examples as the baseline level for an F-class GT firing natural gas fuel. The other cases in Table 1 represent a wide range of NOx_{in} levels two to four times higher than baseline. It is important to note that the examples in this brief do not imply a prediction of future NOx_{in} concentration ranges from GTs firing HAFs. As previously explained, this is an ongoing area of research, and the available data sets are extremely limited. Rather, the purpose is to illustrate the sensitivities of key SCR design parameters to increasing worst-case NOx_{in} levels.

Table 1. Required dNOx% levels for multiple NOx_{in} and NOx_{out} cases (Source: EPRI)

	Natural Gas	Potential HAFs		
NOx _{in} (ppmv)	25	50	75	100
dNOx% at NOx _{out} = 5 ppmv	80	90	93.3	95
dNOx% at NOx _{out} = 2.5 ppmv	90	95	96.7	97.5

REAGENT USE

If the required dNOx% exceeds the original SCR system design level, as might be the case when firing HAFs, multiple factors must be considered in modifying the SCR system for this scenario. The first factor to consider is ammonia reagent use.

There are two basic SCR reaction pathways between the ammonia reagent and NOx_{in} molecules (which include NO and NO₂) on the catalyst surface. These reactions are as follows:



In practical terms, these reactions indicate that in order to maintain a constant NOx_{out} concentration, the ammonia reagent feed rate must be increased when NOx_{in} increases. An increase in reagent feed rate will increase dNOx% to ensure that NOx_{out} permit levels are not exceeded. However, the extent of the required increase in reagent feed rate will depend on the fraction of NO₂ present in the total NOx_{in} (NO₂/NOx_{in}) because Reaction 2 requires more ammonia per mole of NOx than Reaction 1.³ In most cases with GTs firing natural gas, NO₂/NOx_{in} can vary widely (for example, 20–80%), depending on load and other operating parameters. However, NO₂/NOx_{in} in the GT exhaust gas while firing HAFs is currently unknown and is an important research question. Ultimately, the required ammonia feed rate depends on the total NOx_{in} concentration and the fraction of NO₂ present.

Increased reagent use means higher annual reagent costs. Table 2 summarizes the cost, relative to the natural gas baseline of NOx_{in} = 25 ppmv, as a function of increasing NOx_{in} levels that could result from firing HAFs based on Reaction 1 (that is, assuming that all NOx_{in} is in the form of NO). Table 2 assumes a target NOx_{out} of 5 ppmv, but this might vary with local regulatory requirements.

Table 2. Relative reagent cost as a function of increasing SCR inlet NOx concentration based on Reaction 1 (25 ppmv represents the baseline NOx_{in} level while firing natural gas. NOx_{out} = 5 ppmv in all cases.) (Source: EPRI)

NOx _{in} (ppmv)	25	50	75	100
Annual NH ₃ reagent cost	\$X	\$2.3X	\$3.5X	\$4.8X

Ammonia storage and feed systems must also be considered. These systems might need to be modified or replaced to meet higher ammonia demand when HAFs are fired. There is a limit to how much reagent can be stored and moved for an existing system design. Ammonia supply systems include tanks, piping, pumps, vaporizers, meters, and automated flow control valves that have fixed design flow ranges. Complete or partial replacement of ammonia storage and supply systems could compound the increased reagent costs.

CATALYST LIFETIME AND REACTOR POTENTIAL

Another important factor in modifying an existing SCR system design for higher NOx_{in} is catalyst lifetime. SCR catalyst elements slowly deactivate when exposed to the GT exhaust stream, gradually losing the ability to efficiently promote the SCR reaction (see Box 2). This efficiency loss causes the ammonia feed rate and ammonia slip to increase over time as the control system adjusts to meet the NOx_{out} target. Ultimately, the charge of catalyst elements reaches its end of life (EOL) when the desired dNOx% can no longer be achieved without exceeding the maximum ammonia slip stack permit level, which can vary according to local regulatory districts.

The design of a given SCR system includes a catalyst lifetime estimate for a new charge of catalyst elements, which then defines the catalyst replacement frequency. This is an important budgetary consideration for plant owners because a catalyst replacement event for a typical 200-MW, F-class GT can approach \$500,000 in SCR catalyst costs alone. Catalyst

3 The NO₂/NOx fraction can also impact catalyst activity, K, a term introduced later in this brief. Catalyst suppliers often define catalyst performance guarantees assuming NO₂/NOx < 50%.

BOX 2. SCR CATALYST DEACTIVATION

SCR catalyst elements in simple or combined-cycle GT applications rarely exhibit rapid or premature deactivation while firing natural gas, and this is not expected to change with HAFs. Combined-cycle process conditions for SCR usually do not materially compromise the catalyst elements—the conventional operating temperatures of 625–750°F (329–399°C) enable use of catalysts with a broad experience base. Catalyst deactivation can be accelerated due to trace contaminants, such as sodium (introduced by adjacent saltwater bodies or water in aqueous reagents) or phosphorous (introduced by engine lubricants). Simple cycle applications risk sintering some catalyst types if inlet temperatures exceed 850°F (454°C) [3].

lifetime guarantees are provided by catalyst suppliers and typically range from 5 to 10 years (or approximately 40,000–80,000 operating hours) for natural gas-fired GTs, depending on the application and needs of the system owner. Longer catalyst lifetime guarantees generally come with higher capital costs because performance margins and risk become more important.

A key dimensionless parameter used by catalyst vendors to estimate and guarantee catalyst lifetime is known as *reactor potential* (RP).⁴ If the required design dNOx% for a given SCR system increases when switching from natural gas to HAFs, the RP must also increase to ensure that the same lifetime is maintained. Assuming a fixed catalyst geometry (that is, surface area per unit volume) and exhaust gas flow rate, RP is directly related to the catalyst volume, V, and catalyst activity, K. As a result, modifying the SCR system by increasing V and/or K beyond existing design levels is a potential option for maintaining the original catalyst lifetime when firing HAFs. Alternatively, a system owner could decide not to increase V or K at the expense of a shorter catalyst lifetime and more

frequent catalyst replacement events. These scenarios are covered in more detail in this brief, and associated tradeoffs are summarized in Table 3.

SCENARIO 1: NO CHANGE TO REACTOR POTENTIAL

If NO_{x,in} levels are significantly increased and no action is taken to increase RP, the negative impact on catalyst lifetime is extreme. Table 3 and Figure 1 show an example⁵ of a new catalyst charge with relative volume of V₀ = 1.0 and a relative lifetime of t₀ = 1.0 on an F-class GT. The NH₃/NO_x distribution RMS is assumed to be 10%, the importance of which will be addressed further in the Scenario 3 discussion. For Scenario 1, as the NO_{x,in} design point doubles from 25 ppmv to 50 ppmv, catalyst life is reduced by nearly 60%, and two catalyst replacement events are required within the original t₀ timeframe to stay below 5 ppmv ammonia slip. Tripling NO_{x,in} to 75 ppmv reduces catalyst life by more than 90% and requires 16 catalyst replacement events, which might be cost-prohibitive. If NO_{x,in} significantly exceeds 75 ppmv, it is not possible to maintain less than 5 ppmv ammonia slip for any significant period without increasing RP. As a result, NO_{x,in} = 100 ppmv is not a practical consideration under these conditions.

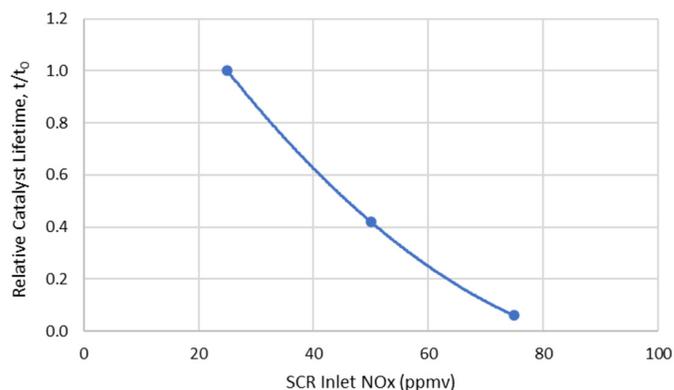


Figure 1. Example of relative catalyst lifetime versus increasing SCR inlet NO_x: Scenario 1, no change in RP (Source: EPRI)

⁴ RP = (K*V*As) / Q, where K = catalyst activity (m/hr), V = catalyst volume (m³), As = specific catalyst surface area (m²/m³), and Q = exhaust gas flow rate (m³/hr).

⁵ All examples assume a 200-MW, F-class gas turbine SCR with a baseline NO_{x,in} = 25 ppmv, fixed NO_{x,out} = 5 ppmv, and EOL ammonia slip = 5 ppmv. The same catalyst deactivation curves are assumed for all scenarios. Data for all examples were generated using EPRI's CatReact SCR process model and are intended to demonstrate general trends. Specific values and percentages might not apply to all applications.

Table 3. SCR system modification scenarios, F-Class GT example (Source: EPRI)

Scenario	Baseline (Natural Gas)	1. HAFs; No RP Change with Increasing NO _{x,in}				2. HAFs; Increase RP (Volume) to Maintain Catalyst Lifetime t ₀ = 1.0			3. HAFs; Improve NH ₃ /NO _x Root-Mean-Square (RMS) and Increase RP (Volume)		
		25	50	75	100	50	75	100	50	75	100
NO _{x,in} (ppmv)	25	50	75	100	50	75	100	50	75	100	
NO _{x,out} (ppmv)	5	5	5	5	5	5	5	5	5	5	
dNOx%	80	90	93.3	95	90	93.3	95	90	93.3	95	
Ammonia slip limit (ppmv)	5	5	5	5	5	5	5	5	5	5	
NH ₃ /NO _x distribution RMS %	10	10	10	10	10	10	10	5	5	5	
Relative catalyst volume	V ₀ = 1.0	1.0	1.0	1.0	1.55	2.02	2.60	1.48	1.79	2.05	
Relative catalyst lifetime	t ₀ = 1.0	0.42	0.06	—	1.0	1.0	1.0	1.0	1.0	1.0	
Catalyst replacement events during t ₀	0	2	16	—*	0	0	0	0	0	0	

* It is not possible in this scenario to maintain <5 ppmv ammonia slip.

Catalyst pressure drop (dP) is another important design factor. Increasing dP downstream of a GT impacts the heat rate and maximum load output and must be included in long-term operational cost calculations [3]. One positive outcome for Scenario 1 is that dP does not increase because no additional catalyst volume is added. In fact, dP savings could occur with firing HAFs if a unit is currently equipped with a CO oxidation catalyst layer. This is because CO is not formed while firing 100% HAFs; as a result, the CO oxidation catalyst can be removed.

SCENARIO 2: INCREASING THE RP BY ADDING CATALYST VOLUME

Alternatively, to keep catalyst life expectancy at $t_0 = 1.0$, catalyst volume can be added (thereby increasing RP) to counteract higher $\text{NO}_{x\text{in}}$ levels, as shown in Table 3 and Figure 2. Doubling $\text{NO}_{x\text{in}}$ from 25 ppmv to 50 ppmv requires 55% more catalyst volume, whereas tripling $\text{NO}_{x\text{in}}$ to 75 ppmv requires just over 100% more volume.

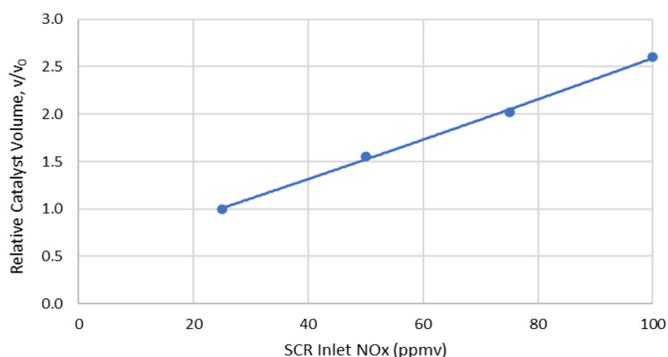


Figure 2. Example of catalyst volume required to maintain catalyst lifetime (t_0) with increasing SCR inlet NOx (RMS = 10%); Scenario 2 (Source: EPRI)

Because the cross-sectional area of a catalyst reactor is fixed for an existing SCR system, the catalyst depth (in the direction of flow) typically must increase in order to add catalyst volume. Adding catalyst volume in this fashion will increase the catalyst dP approximately linearly with depth. As a practical limit, most existing SCR reactors are designed with space for approximately two times the original catalyst volume, or two times the catalyst depth. If additional volume is needed, modifications to the heat recovery steam generator (HRSG) duct and catalyst support structures might be required.

If applicable, an existing CO oxidation catalyst could be removed, potentially offsetting dP impacts. As another mitigating option, some catalyst vendors are marketing “low dP” reactor designs with higher catalyst inlet surface geometries to maintain a given catalyst volume with a reduced depth [4]. For example, a pleated catalyst inlet face provides more inlet surface area than a typical flat-face design. However, this could come at the expense of non-uniform exhaust gas flow distribution across the angular face and must be evaluated at the design stage. Also, retrofit costs might be higher if the existing internal catalyst guide frames and support structures must be modified.

Note that increasing the RP by increasing catalyst activity, K, is also an option that does not increase dP if the catalyst cell geometry is unchanged. However, catalyst manufacturers are generally limited to a smaller range

of increase in K (for example, 10–20%) because this value is already maximized in the geometry designs and active ingredient formulations (see Box 3).

BOX 3. SCR CATALYST FORMULATIONS

The most prevalent GT SCR catalyst formulations use vanadium pentoxide (V_2O_5) as the key active ingredient. The V_2O_5 enabled catalyst—sometimes augmented with tungsten oxide (WO_3)—in a typical embodiment is homogeneously combined into a substrate of titanium dioxide (TiO_2). Increasing catalyst activity, K, will generally involve an increase in the active ingredient concentrations [3].

REAGENT DISTRIBUTION

A third but equally important factor in modifying an existing SCR system design for higher $\text{NO}_{x\text{in}}$ levels is the uniformity of the NH_3/NO_x distribution at the SCR catalyst inlet. Improving this uniformity, as determined by the RMS of the measured profile, reduces ammonia slip and thereby increases catalyst lifetime. This is illustrated in Figure 3 for a typical F-class gas turbine SCR design with $\text{NO}_{x\text{in}} = 25$ ppmv. As the NH_3/NO_x uniformity is improved (that is, the profile RMS% is reduced), the ammonia slip at a given dNOx% is reduced.

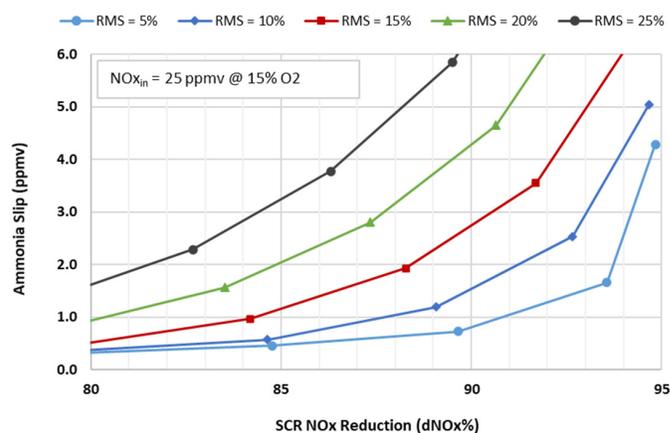


Figure 3. Relationship between SCR NOx reduction (dNOx%) and ammonia slip with NH_3/NO_x profile RMS% (Source: EPRI)

The ability to improve the NH_3/NO_x uniformity depends on the location and design of the ammonia injection grid (AIG). The AIG typically has hundreds of injection orifices distributed equally on a grid of lances installed upstream of the SCR catalyst (see Figure 4). Manual butterfly valves are generally incorporated with a manifold to allow adjustment of ammonia flow to different areas of the grid. This allows the operator to manually “tune” the AIG to account for inherent pipe flow imbalances and for any NO_x stratification in the GT exhaust stream. However, AIGs are typically installed very close to the SCR catalyst (such as 10–20 ft [3.0–6.1 m]) to reduce the footprint and cost of the reactor ductwork. Despite the number of injection holes and tuning valves, the lack of exhaust gas residence time for mixing typically limits the improvement of the NH_3/NO_x RMS to approximately 10–20%.

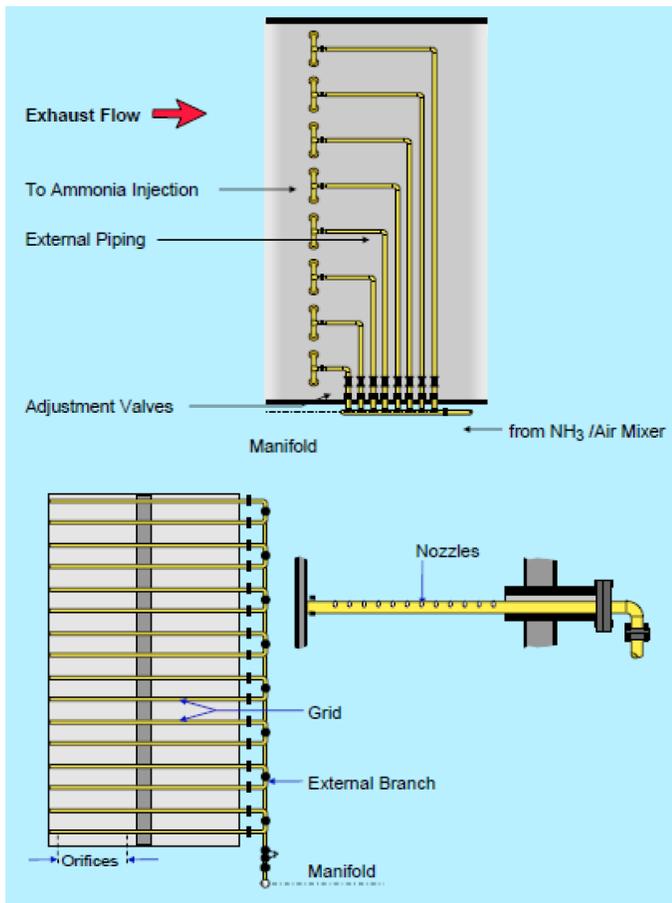


Figure 4. Example of an AIG: views from the side of the exhaust duct (top) and with exhaust flow out of the page (bottom) [3]

With additional cost, AIG systems can be modified to achieve better flexibility for tuning or moved further upstream to increase residence time. Installing AIGs upstream of the SCR duct expansion, directly at the engine outlet, has been considered as an advanced design concept because there would be no CO oxidation catalyst to interfere by oxidizing the injected ammonia. However, for combined-cycle units with HRSG duct burners, potential oxidation of the ammonia by the duct burners would need to be investigated.

SCENARIO 3: IMPROVING NH_3/NO_x RMS AND CHANGING RP BY ADDING CATALYST VOLUME

In addressing higher $\text{NO}_{x,\text{in}}$ levels from carbon-free HAFs, improving the uniformity of the NH_3/NO_x distribution lowers the RP required to maintain the baseline catalyst lifetime, t_0 . This allows the SCR designer to reduce the amount of added catalyst volume, as shown in Table 3 and Figure 5.

For example, by improving the RMS% from 10% to 5%, the added catalyst volume required to maintain catalyst lifetime at $t_0 = 1.0$ is reduced as follows:

- $\text{NO}_{x,\text{in}} = 50$ ppmv, 4.5% reduction
- $\text{NO}_{x,\text{in}} = 75$ ppmv, 11.4% reduction
- $\text{NO}_{x,\text{in}} = 100$ ppmv, 21.2% reduction

These reductions help counteract the cost of AIG modifications and long-term pressure drop impacts.

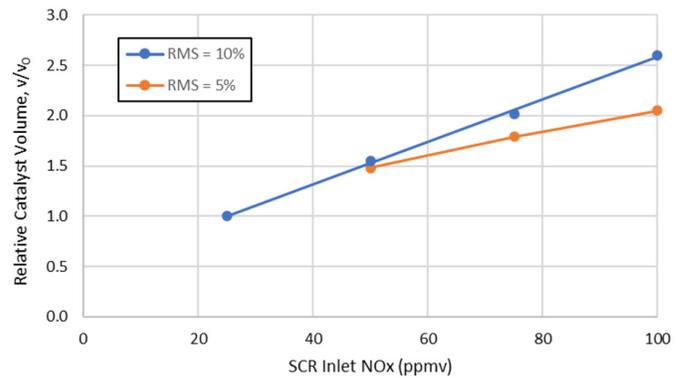


Figure 5. Example of catalyst volume required to maintain catalyst lifetime (t_0) with increasing SCR inlet NO_x (RMS = 10% and 5%): Scenario 3 (Source: EPRI)

CONCLUSIONS AND NEXT STEPS

Key takeaways and potential research areas are summarized as follows:

- In a low-carbon future, GTs and duct burners modified to fire HAFs may generate higher NO_x concentrations in the exhaust gas relative to natural gas. The industrial and power generation sectors must consider the potential ramifications of higher GT NO_x levels. This is where SCR design parameters and potential modifications come into focus. On the other hand, firing HAFs would eliminate the need for a CO oxidation catalyst layer.
- In order to maintain a constant $\text{NO}_{x,\text{out}}$ concentration, the ammonia reagent feed rate must be increased when $\text{NO}_{x,\text{in}}$ increases. The extent of the increase depends on the total $\text{NO}_{x,\text{in}}$ concentration and the fraction of NO_2/NO_x in the GT exhaust gas. Defining the fraction of NO_2/NO_x in the GT exhaust gas while firing hydrogen and ammonia fuel blends is a critical research need.
- Ammonia storage and feed systems for the SCR must also be considered. These systems might need to be modified or replaced to meet higher ammonia demand when HAFs are fired.
- If the required design $d\text{NO}_x\%$ for a given SCR system increases when switching from natural gas to HAFs, the RP must also increase to ensure that the same catalyst lifetime is maintained. Modifying the SCR system by increasing V and/or K beyond existing design levels is a potential option for achieving this objective.
- If $\text{NO}_{x,\text{in}}$ levels are significantly increased and no action is taken to increase RP, the negative impact on catalyst lifetime is significant. This approach might be feasible for relatively small $\text{NO}_{x,\text{in}}$ increases but is probably not economically viable for $\text{NO}_{x,\text{in}}$ increases above two times.
- Increasing dP downstream of a GT negatively impacts the heat rate and maximum load output and must be included in long-term operational cost calculations.

- To maintain the original catalyst lifetime, catalyst volume can be added (thereby increasing RP) to counteract higher $\text{NO}_{x,\text{in}}$ levels. Although dP might increase with volume due to increased catalyst depth, the existing CO oxidation catalyst can be removed (if applicable), potentially offsetting dP impacts. Catalyst vendors are also marketing “low dP” designs, but these must be evaluated from an overall performance and cost perspective.
- Improving the uniformity of the NH_3/NO_x distribution at the SCR catalyst inlet, as determined by the RMS of the measured profile, reduces ammonia slip and thereby increases catalyst lifetime.
- In addressing higher $\text{NO}_{x,\text{in}}$ levels from carbon-free HAFs, improving the uniformity of the NH_3/NO_x distribution lowers the RP required to maintain the baseline catalyst lifetime. This allows the SCR designer to reduce the amount of added catalyst volume, helping to counteract the cost of AIG modifications and long-term pressure drop impacts.
- To improve NH_3/NO_x distribution uniformity, AIG systems can be modified to achieve better flexibility for tuning or moved further upstream to increase residence time. This is a critical area of research. Installing AIGs upstream of the SCR duct expansion, directly at the engine outlet, has been considered as an advanced design concept because there would be no CO oxidation catalyst to interfere by oxidizing the injected ammonia. However, for combined-cycle units with HRSG duct burners, oxidation of the ammonia by the duct burners would need to be investigated.

Recommended next steps for SCR-related research include examining the possible options and detailed costs, as a function of increasing SCR inlet NO_x levels, for modifying existing SCR systems on a range of existing gas turbine types to meet stack NO_x and ammonia slip permit levels while firing HAFs. In addition, SCR system requirements for next-generation GTs designed specifically for HAFs must be considered. Doing so will help the industrial and power generation sectors address a key technical hurdle on the path to decarbonization.

REFERENCES

1. *Technology Insights Brief: Ammonia and Hydrogen Fuel Blends for Today's Gas Turbines—Combustion Considerations*. EPRI, Palo Alto, CA: 2021. 3002020043.
2. *Method 19 – Determination of Sulfur Dioxide Removal Efficiency and Particulate Matter, Sulfur Dioxide, and Nitrogen Oxide Emission Rates*. USEPA, 2017. Downloaded from https://www.epa.gov/sites/default/files/2017-08/documents/method_19.pdf.
3. *Catalytic Environmental Controls Best Practices Operating and Maintenance Guideline for Gas Turbines and Combined Cycles*. EPRI, Palo Alto, CA: 2015. 3002006041.
4. *Multi-Function Environmental Control Catalysts for Gas Turbines: Commercial Overview and Assessment*. EPRI, Palo Alto, CA: 2019. 3002014141.

BIBLIOGRAPHY

Laboratory Testing Guidelines for Gas Turbine Selective Catalytic Reduction (SCR) and CO Catalysts. EPRI, Palo Alto, CA: 2015. 3002006042.

CONTACTS

Tom Martz, *Principal Technical Leader, Low-Carbon Resources Initiative*
949.395.9647, tmartz@epri.com

Robert Steele, *Technical Executive, Major Component Reliability*
980.229.2961, rsteale@epri.com

The Electric Power Research Institute, Inc. (EPRI, www.epri.com) conducts research and development relating to the generation, delivery and use of electricity for the benefit of the public. An independent, nonprofit organization, EPRI brings together its scientists and engineers as well as experts from academia and industry to help address challenges in electricity, including reliability, efficiency, affordability, health, safety and the environment. EPRI also provides technology, policy and economic analyses to drive long-range research and development planning, and supports research in emerging technologies. EPRI members represent 90% of the electricity generated and delivered in the United States with international participation extending to nearly 40 countries. EPRI's principal offices and laboratories are located in Palo Alto, Calif.; Charlotte, N.C.; Knoxville, Tenn.; Dallas, Texas; Lenox, Mass.; and Washington, D.C.

Together . . . Shaping the Future of Energy™

EPRI

3420 Hillview Avenue, Palo Alto, California 94304-1338 • PO Box 10412, Palo Alto, California 94303-0813 USA
800.313.3774 • 650.855.2121 • askepri@epri.com • www.epri.com