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Review of NO_x Formation and Mitigation Strategies in Hydrogen Combustion Engines

Analysis of Hydrogen Combustion Mechanisms and Strategies for
Low- NO_x Emission

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1 Introduction

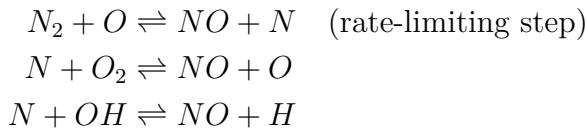
Nitrogen oxides (NO_x) are a group of highly reactive gases that include nitric oxide (NO) and nitrogen dioxide (NO_2). These pollutants are primarily emitted from stationary sources (e.g., power plants and industrial boilers) and mobile sources (e.g., internal combustion engines) [?, ?]. NO_x plays a critical role in atmospheric chemistry, acting as a precursor to tropospheric ozone (smog) and nitric acid (acid rain), thereby necessitating stringent regulatory controls globally [?]. The minimization of these emissions is crucial for public health and environmental protection.

1.1 NO_x Formation Mechanisms

Emissions from jet engines are a major concern in aviation. Kerosene-based fuels produce nitrogen oxides (NO_x), sulfur oxides (SO_x), and carbon dioxide (CO_2) [1, ?]. NO_x forms primarily as NO , which later oxidizes to NO_2 , and these are typically reported together as NO_x . SO_x contributes to acid rain and particulate pollution, while CO_2 is a major greenhouse gas. In contrast, hydrogen combustion eliminates carbon and sulfur emissions, producing mainly water vapor [?]. Only small amounts of NO_x are formed when burning hydrogen, making it a promising alternative fuel for reducing harmful emissions.

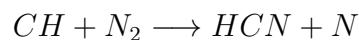
NO forms through several mechanisms in combustion, including:

- **Thermal NO (Zeldovich mechanism):** Produced from nitrogen and oxygen in the air at high flame temperatures (typically around 1800 K) from combustion systems using fuels with negligible nitrogen content, such as natural gas [?, ?]. It is formed by the oxidation of N_2 in the atmosphere. In hydrogen combustion, thermal NO is the dominant contributor to total NO_x , becoming significant above 1850 K. The primary steps involve the oxidation of atmospheric nitrogen:



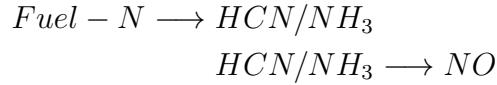
The dissociation of N_2 in the first step requires very high activation energy, making this pathway highly sensitive to peak flame temperature.

- **Prompt NO (Fenimore mechanism):** Prompt NO_x forms rapidly within the flame front, particularly in the fuel-rich primary combustion zone, and is important even at temperatures below the threshold for Thermal NO_x [?]. It involves the reaction of N_2 with hydrocarbon free radicals (CH or C_2H_2), leading to nitrogen-containing intermediates. A key initial reaction in the prompt pathway is:



The intermediate species, such as hydrogen cyanide (HCN) and cyanogen (CN), are subsequently oxidized to form NO .

- **Fuel NO:** Fuel NO_x is generated by the oxidation of nitrogen chemically bound within the fuel itself (e.g., in coal, heavy fuel oil, or biomass) [?]. This mechanism is highly dependent on the nitrogen content of the fuel and the local oxygen concentration. The fuel-bound nitrogen is typically released as volatile intermediates, such as HCN and ammonia (NH_3), which then react with oxygen radicals to form NO:



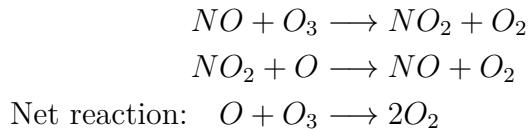
In rich-combustion zones, these intermediates can also be reduced back to stable N_2 , which is the principle behind many primary reduction techniques. This mechanism is absent in both kerosene and hydrogen combustion and is therefore not relevant here.

The nitrous oxide (N_2O) mechanism produces only low levels of N_2O and has minimal impact in either hydrogen or kerosene combustion under high engine load conditions [?].

In hydrogen-fueled engines, thermal NO dominates NO_x emissions. Reducing flame or combustor temperatures lowers NO_x formation, making cycle temperature control critical for cleaner combustion. Hydrogen enables engines to maintain performance at lower temperatures, highlighting its potential both as an alternative fuel and as a pathway for novel engine designs in aviation [1].

1.2 Environmental Impact of NO_x

The reaction mechanism shows that NO catalyzes the destruction of ozone molecules in the stratosphere [?, ?]:



Removal of O_3 from the stratosphere allows harmful ultraviolet solar radiation to penetrate to the Earth's surface. That's why the European Union and the U.S. Environmental Protection Agency (EPA) are applying pressure on the International Civil Aviation Organization, which sets standards and regulations necessary for aviation safety, security, efficiency, and environmental protection, and regulates aircraft emissions, in particular additional nitrogen oxide reductions [?].

In general, NO_x emissions influence both local air quality and global climate by causing smog and reduced visibility due to particulates, nitrates, and NO_2 , driving acid rain, contributing to the destruction of stratospheric ozone, and increasing exposure to harmful ultraviolet radiation.

While high-speed hydrogen aircraft eliminate CO_2 , CO , soot, and SO_x , NO_x emissions remain the critical environmental concern [1, ?].

1.3 Fundamental Combustion Properties of Hydrogen

Hydrogen and kerosene behave differently in gas turbine combustors [?, ?]. Although hydrogen has a higher stoichiometric flame temperature than kerosene, it has a much wider flammability range, especially on the lean side. This allows the combustor to operate farther into the lean region at all engine loads, which leads to lower NO_x emissions. Kerosene burns near stoichiometric conditions at high power, creating very hot flames and high NO_x , whereas hydrogen's wider lean flammability range allows the engine to run leaner, helping to reduce NO_x formation.

Hydrogen also has an advantage because it is a gas. Liquid fuels like kerosene form droplets that can create small, extremely hot regions, producing extra NO_x even when the overall mixture is lean. Hydrogen avoids these hot spots. Furthermore, hydrogen burns much faster than kerosene, which enables a shorter combustor, better air mixing, lower flame temperatures, and shorter residence times in the hottest region. All of these factors contribute to reduced NO_x emissions. Finally, hydrogen does not produce CO , unburned hydrocarbons, or soot, which makes it easier to design the combustor for minimum NO_x .

Haglind and Singh [1] examined how a V2527 A5 turbofan performs when hydrogen is used instead of kerosene. They show that the engine can maintain the same thrust, or even increase it slightly, while operating at a lower combustor outlet temperature. Lowering the cycle temperature reduces NO_x formation, and energy-specific fuel consumption also improves slightly.

2 NO_x Reduction Strategies

2.1 Hydrogen Combustion Design

Hydrogen as an aviation fuel introduces unique opportunities and challenges for gas turbine combustors. Its physical and chemical properties differ significantly from conventional hydrocarbon fuels like kerosene, affecting flame temperature, burning velocity, emission characteristics, and combustor design [1, ?]. Hydrogen combustors need redesigned mixing strategies because conventional diffusive combustors do not mix hydrogen and air well. Poor mixing creates large diffusion flames with very hot regions where NO_x forms easily. To reduce NO_x , the focus is on lowering flame temperature, avoiding hot spots, and limiting the time gases stay in the hottest zones. This section reviews engine performance, combustor design strategies, and advanced concepts for minimizing nitrogen oxide (NO_x) emissions while maintaining engine efficiency.

2.1.1 Residence Time Effects on NOx Formation

Recent experimental work by Kim et al. [?] highlights the critical role of residence time in hydrogen-fueled combustion. In a non-premixed industrial burner, a 52% reduction in residence time within the primary combustion zone led to a 42.8% decrease in NOx emissions, without compromising flame stability or temperature uniformity. This indicates that residence time control is an effective parameter for mitigating thermal NOx formation in hydrogen-rich combustion environments, and it is potentially applicable to

turbojet combustor design.

2.2 Engine Performance with Hydrogen Fuel

Examine how a V2527 A5 turbofan behaves when hydrogen is used instead of kerosene. They show that the engine can keep the same thrust or even increase it slightly while running at a lower combustor outlet temperature [1]. If the goal is to keep the net thrust unchanged, the combustor outlet temperature can be reduced by about 33 K. When the cycle temperature is reduced, less NO_x is produced. Energy specific fuel consumption also improves a little when the temperature is lowered. They note that although the flame temperature of Hydrogen is higher than that of Kerosene, it has a wider flammability range, and in particular the lean limit is much lower. This means that the operating range can be shifted lower, thus reducing NO_x emissions. Hydrogen has an advantage over liquid fuels like kerosene because liquid fuel droplets can create small areas where the mixture burns very hot. These hot spots lead to high NO_x formation even when the overall mixture is lean. Since hydrogen is a gas, it does not create these hot spots as easily, so it produces less NO_x . Hydrogen and kerosene behave differently in gas turbine combustors. Kerosene burns near stoichiometric conditions at high power, which creates very hot flames and high NO_x . Hydrogen's stoichiometric flame temperature is even higher, but hydrogen has a much wider lean flammability range. This allows the engine to run leaner at all loads, which helps cut NO_x .

Hydrogen also burns much faster. This allows a shorter combustor, better air mixing, lower flame temperatures, and shorter time in the hottest region. All of these reduce NO_x . Because hydrogen is a gas, it avoids the hot spots created by liquid fuel droplets, which also prevents extra NO_x . And since hydrogen does not produce CO, unburned hydrocarbons, or soot, it is easier to design the combustor to minimize NO_x .

2.3 Hydrogen Combustor Design Strategies

Hydrogen's properties necessitate redesigned mixing strategies, as conventional diffusion combustors do not mix hydrogen and air effectively. Poor mixing can create large diffusion flames with high-temperature regions that are prone to NO_x formation. Two primary strategies for mitigating this are lean premixed combustion and micromix combustion [1, ?].

2.3.1 Nozzle Geometry and Temperature Uniformity

Kim et al. [?] demonstrated that minor modifications to burner geometry, specifically reducing the volume of the primary combustion zone, help distribute high-temperature regions more evenly. This geometric adjustment lowers localized flame hotspots, improves overall temperature uniformity, and thereby reduces NOx formation. Such strategies complement conventional approaches like lean-premixed or staged combustion in gas turbines.

2.3.2 Lean Premixed Combustion

Lean premixed combustion reduces local flame temperatures and therefore lowers NO_x formation [1]. However, it carries significant risks of flashback and auto-ignition, especially due to hydrogen's high reactivity.

2.3.3 Micromix Combustors

Micromix combustors utilize hundreds to thousands of small diffusion flames distributed across the burner. These miniaturized flames improve mixing, limit temperature spikes, and exploit hydrogen's fast-burning characteristics [1].

Third-generation micromix combustors have demonstrated NO_x reductions of 85–88% compared with kerosene combustion [?]. Testing from the Euro–Québec Hydro–Hydrogen Pilot Project showed that while lean premixed combustion achieves very low NO_x , its flashback and auto-ignition risks motivated the development of the micromix concept. By uniformly distributing more than 1,000 diffusion flames across the burner's cross section, the micromix design minimizes the geometric size of the combustion zone. In theory, the lowest NO_x production is achieved as the number of miniaturized flames approaches infinity.

Among many design iterations, the third-generation micromix combustor has delivered the lowest NO_x and the best stability. Tests on a Honeywell GTCP 36-300 APU showed that micromix combustion can reduce NO_x by about 85–88% compared with kerosene combustion or simple hydrogen-injection retrofits [?]. Future work must confirm long-term structural durability and reliable high-altitude performance.

2.3.4 RQL mechanism

The Rich-Burn, Quick-Mix, Lean-Burn (RQL) combustor concept was introduced in 1980 as strategy to reduce oxides of nitrogen [?].

Rich-burn, Quick-quench, Lean-burn combustor zones are characterized by the presence of two separate reaction zones, operating respectively in rich and lean conditions.

1. **Rich-Burn (Fuel-Rich Primary Zone)** First, a “rich-burn” condition in the primary zone (equivalence ratio., $\phi = 1.8$) enhances the stability of the combustion reaction by producing and sustaining a high concentration of energetic hydrogen and hydrocarbon radical species.

Secondly, rich burn conditions minimize the production of nitrogen oxides due to the relative low temperatures and low population of oxygen containing intermediate species. What comes out of the rich-zone? CO, H_2 , partially oxidized hydrocarbons, and pyrolysis products. These cannot be exhausted directly and must be further oxidized.

2. **Quick-Mix (Rapid Air Injection Zone)** The effluent emanating from the rich primary zone will be high in the concentration of partially oxidized and partially pyrolyzed hydrocarbon species, hydrogen, and carbon monoxide. As a result, the effluent cannot be exhausted without further processing. In particular, *the addition*

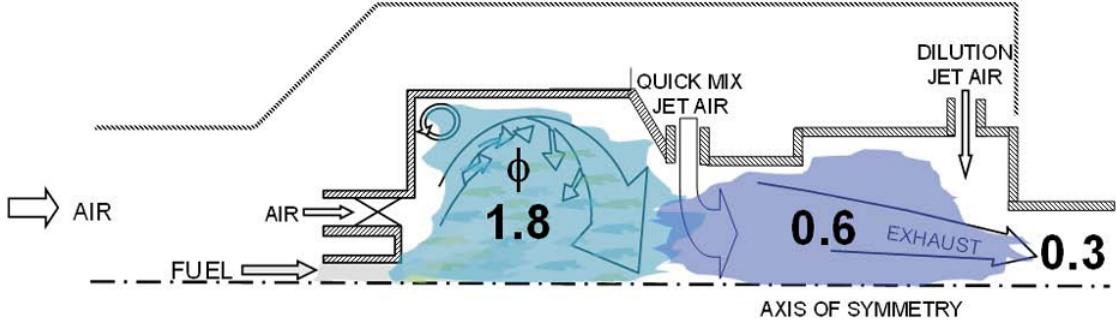


Fig. 1. Rich-Burn, Quick-Mix, Lean-Burn Combustor (Φ , Equivalence Ratio)

of oxygen is needed to oxidize the high concentrations of carbon monoxide, hydrogen, hydrocarbon intermediates. This is accomplished by injecting a substantial amount of air through wall jets to mix with the primary zone effluent and create a “lean-burn” condition prior to the exit plane of the combustor. The objective is to rapidly pass through the NO_x critical region (near $\phi \approx 1$)

3. **Lean Burn (Final Oxidation Zone)** In the stage the goal is complete the combustion under lean, low-temperature conditions to minimize NO_x production. After rapid air addition, the mixture becomes lean ($\phi < 1$), and the remaining CO, H_2 , and hydrocarbons are fully oxidized. In fact the Low flame temperature in this zone results in small additional NO_x formation.

Final Exhaust Consists Mainly of:

- CO_2 , H_2O , N_2 , and excess O_2 .
- Overall NO_x levels depend on:
- Quality of mixing in the Quick-Mix zone,
- Air preheat temperature,
- Fuel-bound nitrogen species formed in the rich zone.

Combustor Material A major challenge for the RQL is the selection of combustor liner material.

In the primary zone, for example, the use of air for cooling the liner wall is precluded in order to avoid the generation of near-stoichiometric mixture ratios and the associated production of nitrogen oxides in the vicinity of the wall.

As a result, the temperature and composition of gases in the primary zone create a demanding, reducing environment for the liner material.

The concentrations of hydrogen alone and the concomitant demands of hydrogen embrittlement in particular have combined to require a major investment in materials research in support of RQL technology.

A more demanding challenge is the design of the Quick-Mix section. A key to the success

of the RQL is the efficacy of mixing the air with the effluent exiting the primary zone. The mixing of the injected air takes the reaction through the conditions most vulnerable for the high production of oxides of nitrogen (near stoichiometric conditions where both the temperature and oxygen atom concentrations are elevated). The challenge then is to rapidly mix air into the rich-burn effluent in order to rapidly create the lean-burn conditions

Techniques and Design Methods for the Quick-Mix Section The Quick-Mix is engineered using a combination of geometric design rules, empirical correlations, and aerodynamic optimization. Some parameters must be set:

1. **Mass flow ratio (MR):** MR = mass of jet air / mass of rich crossflow For RQL: MR \approx 2.5, which is ten times higher than in conventional combustors (\approx 0.25). This ensures the enormous amount of air needed to convert the mixture from rich to lean.
2. **Momentum flux ratio (J):** Governed by jet velocity, crossflow velocity, and densities. Typical value used: J \approx 60.
This determines how deeply the jets penetrate.
3. **Orifice Geometry Optimization:** Numerous geometries have been tested:
 - round holes (standard)
 - slanted holes
 - triangular
 - tear-drop shaped

The conclusion from some researches:

No shape beats a simple round hole for penetration efficiency. **Thus, most Quick-Mix designs use round orifices.**

4. **Determining the Number of Orifices:** A NASA design method developed by Holdeman and co-workers defined a correlation that is used to design the jet mixing section of an RQL combustor utilizing round hole jets.
The correlation, derived a study of jet-to-mainstream momentum-flux ratio, establishes **the number of circular holes for optimum mixing.**

$$n = \frac{\pi\sqrt{2J}}{C}$$

Where:

n = Number of Circular Jet Orifices to Optimize Mixing

J = Momentum Flux Ratio

C = Empirical Constant = 2.5

5. **Orifice Size and Spacing:** Jet mixing in a crossflow has been studied in two primary mainstream geometries. The cylindrical geometry has been the most extensively researched and is directly relevant to combustor can configurations. In

contrast, the modern annular combustor configurations have spawned investigations of jets in the crossflow of rectangular geometries. For each, Holdeman has established the following procedures to design the most rapid mixing:

Cylindrical geometry :

- Typical Mass Ratio: 2.5
- Typical Momentum Flux Ratio: 60
- Optimal Number of Orifices:

$$n = \frac{\pi\sqrt{2J}}{C}$$

- (a) Orifice Size: Determined by the desired mass-flow ratio and the optimum number of orifices for the given momentum flux ratio.

Rectangular geometry :

- Typical Mass Ratio: 2.5
- Typical Momentum Flux Ratio: 60
- Optimal Orifice Spacing:

$$\frac{S}{H} = \frac{C}{\sqrt{J}}$$

Where: S = Orifice Spacing H = Channel Height

- Orifice Size. For a given momentum-flux ratio, determined by the desired mass-flow ratio and the optimum orifice spacing. For a rectangular duct the number of orifices is infinite. For an annulus, the number of orifices will depend on the diameter and height of the mixing section.
- Orifice Configuration. Can be either in-line or staggered. The selection will depend on the application, and include such factors as momentum-flux ratio. In-line configurations are usually preferred as the orifices are smaller. The optimum spacing for staggered jets is four times the optimum spacing for in-line configurations. As a result, the orifice diameter for staggered jets must be doubled for the same total orifice area.

The goal of this research was to identify key parameters for the NO_x reduction in order to define a technology for these pollutants abatement, keeping the engine performance. The strategy proposed is the Rich-Quick-Lean engine, whose characteristics, based on the NO_x behavior at the different equivalence ratios, permit to reduce the nitrogen oxides formation.

This combustor is namely divided into two stages, a rich and lean stage. The analysis of the effect of the residence time within each stage of the combustor has shown that the RQL strategy makes the combustor NO_x production independent on the overall residence time. The equivalence ratio in the rich stage has been shown to be a key parameter, affecting the quality of the mixing between the first stage exhausts and the secondary air and also producing a dramatic reduction of the NO_x formation.

2.3.5 Hydrogen Blending Considerations

Although increasing the hydrogen fraction in fuel tends to raise the adiabatic flame temperature, Kim et al. [?] showed that appropriate residence time control and geometric optimization can offset the resulting NO_x increase. These findings support the feasibility of integrating hydrogen into high-temperature combustors, including turbojets, while managing NO_x emissions effectively.

2.4 Fuel Additive Techniques (Pre-Combustion)

Adding appropriate additives to fuels can modify combustion processes to reduce NO_x formation. Water is one of the most widely used additives [?].

2.4.1 Water Injection or Emulsified Fuels

Water can be incorporated and distributed along with the fuel in the form of small droplets that explode when the fuel heats up during injection into the cylinder, ensuring optimal air-fuel mixing and more controlled combustion. Fuels prepared in this way are known as *emulsion fuels*, typically containing about 20% water by volume [?].

Mixing water with fuel also allows other additives to be dissolved, further modifying the combustion process. Water or steam injected into the intake or cylinder lowers peak combustion temperatures (and raises local heat capacity), dilutes the local O₂ concentration, and increases radical recombination — all of which strongly reduce thermal NO_x formation.

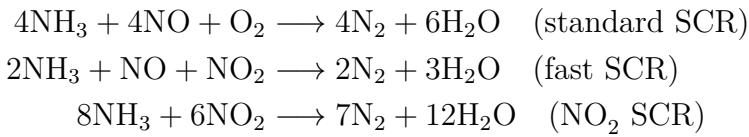
2.5 Secondary NO_x Minimization Strategies (Post-Combustion)

Secondary methods treat the flue gas after it leaves the combustion chamber, chemically converting NO_x back into non-polluting substances, typically nitrogen gas (N₂) and water (H₂O) [?].

2.5.1 Selective Catalytic Reduction (SCR)

SCR is the most effective post-combustion control technology, capable of removing 80% to over 95% of NO_x.

Process and Mechanism A reducing agent, typically anhydrous ammonia (NH₃), aqueous ammonia, or urea (CO(NH₂)₂), is injected into the flue gas. The mixture then passes over a catalyst bed within a specific temperature window (300°C–400°C). The catalyst facilitates selective reduction of NO_x by ammonia through several competing reactions:



The "fast SCR" reaction achieves optimal performance at an NO_2 to NO_x ratio of approximately 50%, which typically requires an oxidation catalyst upstream to convert NO to NO_2 . At lower NO_2/NO_x ratios, the slower standard SCR reaction dominates, while higher ratios can lead to increased ammonia consumption.

Catalyst Materials for Hydrogen Engines For hydrogen-fueled combustion engines, the choice between copper-zeolite and vanadium-based SCR catalysts involves important trade-offs [?]:

- **Copper-zeolite (Cu-SSZ-13) catalysts:** Demonstrate superior NO_x conversion rates (up to 99%), early light-off temperatures (starting below 200°C), high ammonia storage capacity, and reduced sensitivity to NO_2/NO_x ratio variations. However, they produce significant secondary N_2O emissions (up to 40 ppm), which is problematic since N_2O has 300 times the global warming potential of CO_2 .
- **Vanadium-based ($\text{V}_2\text{O}_5\text{-WO}_3\text{-TiO}_2$) catalysts:** Exhibit negligible N_2O formation with high N_2 selectivity and stable performance. However, they show slightly lower overall NO_x conversion rates, delayed light-off, greater sensitivity to NO_2/NO_x ratio variations (particularly poor performance at ratios below 25% or above 75%), and lower ammonia storage capacity.

Combined SCR Systems Recent investigations have demonstrated that a dual-stage SCR system optimizes both NO_x conversion efficiency and minimizes secondary emissions [?]. This configuration positions a vanadium-based catalyst in the first stage to reduce the majority of NO_x emissions with negligible N_2O formation, followed by a copper-zeolite catalyst in the second stage to efficiently remove remaining NO_x . Since the copper catalyst receives already-reduced NO_x concentrations, its secondary N_2O emissions remain minimal. In Worldwide Harmonized Light Vehicles Test Cycle (WLTC) evaluations, this combined approach achieved:

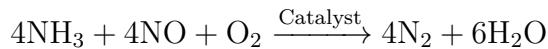
- NO_x conversion rates above 91%
- Over 50% reduction in N_2O emissions compared to copper-only systems
- Reduced water condensation effects during cold starts

Hydrogen-Specific Considerations Importantly, hydrogen concentrations up to 2000 ppm in the exhaust gas showed no significant impact on SCR performance for either catalyst type [?]. This finding eliminates concerns about unburned hydrogen interfering with SCR operation and reduces the strict requirement for complete hydrogen oxidation upstream. An oxidation catalyst remains beneficial primarily for achieving optimal NO_2/NO_x ratios rather than for hydrogen removal.

Advantages and Disadvantages **Advantages:** High efficiency, wide applicability across various fuels, proven technology with established infrastructure from diesel applications, and compatibility with hydrogen engine exhaust conditions.

Disadvantages: High capital cost, maintenance requirements, risk of unreacted ammonia passing through the system (NH_3 slip), potential for secondary N_2O emissions (catalyst-dependent), and sensitivity to temperature windows requiring proper thermal management or active heating strategies during cold starts.

1. **Process:** A reducing agent, typically anhydrous ammonia (NH_3), aqueous ammonia, or urea ($\text{CO}(\text{NH}_2)_2$), is injected into the flue gas. The mixture then passes over a catalyst bed (usually vanadium pentoxide/titanium dioxide) within a specific temperature window (300°C – 400°C).
2. **Reactions:** The catalyst facilitates selective reduction of NO_x by ammonia, with the main reaction being:



3. **Advantages:** High efficiency and wide applicability across various fuels.
4. **Disadvantages:** High capital cost, maintenance requirements, and the risk of unreacted ammonia passing through the system (NH_3 slip).

2.5.2 Selective Non-Catalytic Reduction (SNCR)

SNCR achieves NO_x reduction without a catalyst, relying instead on high temperatures within a specific range.

1. **Process:** A nitrogen-based reagent (NH_3 or urea) is injected directly into the flue gas stream in a high-temperature region of the boiler or furnace (850°C – 1050°C).
2. **Reactions:** Within this narrow temperature window, the reagent reacts with NO_x radicals to form N_2 and H_2O .
3. **Advantages:** Lower capital cost and easier retrofit than SCR.
4. **Disadvantages:** Lower efficiency (typically 30%–60%) and sensitivity to temperature fluctuations, which can lead to high NH_3 slip or insufficient reduction.

2.6 Engine Cycle Concepts for Reducing NO_x Emissions

2.6.1 Low Power Core Strategies

For hydrogen-fueled aircraft engines designed to minimize mission NO_x emissions, a low power core configuration is recommended. This approach involves reducing the combustor outlet temperature (COT) by approximately 100K (to 1,455K) and lowering the overall pressure ratio (OPR) to around 20, combined with a reduced bypass ratio (BPR). The

reduced COT and OPR directly suppress thermal NO_x formation by lowering combustor inlet temperatures and pressures.

Parametric simulation studies in [1] identified an optimal configuration featuring a low power core ($\text{COT} = 1,455\text{K}$, $\text{OPR} = 20$) with reduced BPR (3.8, approximately 20% lower than baseline), achieving mission NO_x reductions of 42% with relatively moderate penalties of 8.7% increased fuel consumption and 2.5% increased maximum take-off mass. The simulations adjusted OPR through high-pressure compressor pressure ratio modifications while maintaining constant polytropic efficiency. The lower BPR configuration provides increased specific thrust, actually reducing engine diameter by 2.7% compared to the baseline engine.

Importantly, engines designed for low NO_x emissions are based on proven, reliable technology that eliminates development costs, reduces production and maintenance costs, and increases engine durability compared to advanced high-temperature cycles. This contrasts with fuel-optimized configurations that require advancements in high-temperature materials and cooling technology.

References

- [1] Fredrik Haglind and Riti Singh. Potential of reducing the environmental impact of aviation by using hydrogen – part ii: Aero gas turbine design. *Aeronautical Journal (New Series)*, 110(1110):541–552, August 2006.

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