# Technical Synthesis: Transitioning DLE Combustion Systems to 100% Hydrogen Operation

## 1. The Physics of Hydrogen Transition: Flame Speed and Flashback Propensity

As the global energy landscape pivots toward a hydrogen economy, the aerospace and power generation sectors face a fundamental strategic necessity: redefining the kinetic boundaries of existing gas turbine hardware. Central to this transition is the understanding of laminar flame speed ($S_L$). For a Principal Engineer, $S_L$ is not merely a laboratory metric; it is the primary determinant of hardware safety and the "kinetic firewall" against catastrophic failure. In the transition from Natural Gas (methane) to Hydrogen, $S_L$ dictates how quickly the fuel-air mixture is consumed and, crucially, whether the flame can propagate upstream into the injection hardware—an event known as flashback.

Research leveraging the Cantera perfectly stirred reactor (PSR) network model reveals that hydrogen's laminar flame speed can be up to 50 times higher than that of methane. This massive increase fundamentally alters the risk profile for industrial mixers. As the equivalence ratio ($\phi$) increases, the ratio of hydrogen flame speed to methane flame speed rises sharply, indicating that richer mixtures are exponentially more susceptible to flashback and flame-holding events.

When evaluating combustion architectures, Dry Low Emissions (DLE) systems demonstrate a clear strategic advantage over Rich-Quench-Lean (RQL) or diffusion-based systems. DLE systems typically operate at low equivalence ratios (often $\phi < 0.75$), where the increase in flame speed is significantly more modest compared to the high-equivalence-ratio zones inherent in RQL designs. By maintaining a lean environment, DLE hardware provides a higher margin of safety against hydrogen-related flashback. However, while steady-state flame speeds define the boundaries of operation, the transient risks of flame holding must be quantified using the Blow Off Time (BOT) metric.

## 2. Classification of Operational Stability: The Three BOT Regimes

The Blow Off Time (BOT) serves as the critical numerical indicator for assessing a mixer's resistance to flame holding. Defined as the minimum residence time required for a fuel-air mixture to achieve heat release, BOT allows us to predict whether a mixer can "clear" a flame that has been inadvertently induced into the hardware. If the BOT is higher than the residence time within the mixer, the system is resistant; if it is lower, flashback becomes an imminent threat. In the field, failure to address these flame-holding limits can result in millions of dollars in losses due to hardware damage and forced outages.

To ground our understanding in known fuel behaviors, we must note that 100% propane—a traditionally "reactive" fuel baseline—exhibits a BOT of roughly 3.5 microseconds. Critically, this benchmark is equivalent to only 43% hydrogen. Above this concentration, we are pushing legacy fluid dynamics into a dangerous and unfamiliar kinetic regime. Based on PSR network modeling (23 atm, 785K), hydrogen operation is classified into three regimes:

- **Regime 1 (0% - 30% $H_2$):** In this phase, BOT trends remain similar to the propane baseline. Operation is relatively manageable, and traditional hardware can likely handle these concentrations without significant modification.
- **Regime 2 (30% - 80% $H_2$):** As concentrations surpass 30%, the BOT begins an accelerating decline. Behavior diverges sharply from traditional hydrocarbons, requiring more stringent control over mixer velocities to prevent stabilization inside the nozzle.
- **Regime 3 (> 80% $H_2$):** This represents the "aggressive requirement" phase. While propane levels off at 3.5 microseconds, the BOT for hydrogen continues to plummet, falling below 1 microsecond at 100% concentration. This requirement is nearly four times faster than the propane limit, necessitating a fundamental rethink of nozzle residence times.

Operational stability is further dictated by external parameters. Air preheat temperature ($T_3$) is the primary driver of instability; higher $T_3$ drastically reduces BOT, presenting a major constraint for high-pressure-ratio engine cycles. Conversely, operating pressure has a comparatively minor impact. Furthermore, a "danger zone" exists between $\phi = 0.47$ and 1.5, where BOT is critically low. This suggests that unless a system is perfectly premixed or extremely lean, hardware must rely on sophisticated design features rather than fuel chemistry to avoid flame holding.

## 3. The Mixedness Framework: Bridging the Model-to-Data Gap

To predict turbine emissions, we utilize Chemical Reactor Network (CRN) modeling, specifically the Cantera PSR-PFR architecture. While these models show excellent agreement for perfectly premixed natural gas, the transition to 100% hydrogen reveals a significant discrepancy between predicted "entitlement" and experimental reality.

At a flame temperature of 1935K, the standard PSR-PFR model predicts a 45% increase in $NO_x$ when switching from natural gas to hydrogen. However, experimental data from advanced GE mixers—originally designed for natural gas—shows a staggering 1200% increase. This discrepancy is not a failure of chemical kinetics, but a failure of hardware fluid dynamics to maintain "perfectly premixed" performance when fuel properties shift. This is further complicated by "bi-modal" behavior or hysteresis (bifurcation) observed around 1935K (3025°F), where flame shape and emissions change based on whether temperatures are increasing or decreasing—a significant hurdle for operational stability.

**The Mixedness Framework Deconstructed:**

- **Jet Momentum Ratio:** Pure hydrogen fuel has a jet momentum ratio of 1.25 relative to natural gas. This higher momentum causes the fuel-air mixing profile to become "center-peaked," as the fuel jet does not spread as effectively as natural gas.
- **Hot Spot Assumption:** This center-peaking creates stoichiometric "hot spots" operating at \phi = 1, representing the worst-case NO_x formation scenario.
- **Mixedness Deterioration Factor:** A calculated 6% deterioration in un-mixedness is sufficient to account for the 1200% experimental NO_x increase.

Ultimately, this framework proves that hardware designed for natural gas cannot maintain its perfectly premixed entitlement under 100% hydrogen. Restoring mixedness will reduce the impact, but cannot eliminate it.

## 4. Mitigation Strategies and Regulatory Re-evaluation

In high-hydrogen environments, the strategic trade-off shifts. Because 100% hydrogen operation eliminates CO emissions, we can reduce combustor residence time to mitigate NO_x without the traditional risk of "incomplete combustion" pollutants.

Experimental results show that NO_x can be successfully abated by increasing the pressure drop (\Delta P/P) to reduce residence time. Shifting from 8 ms to 5.6 ms reduced NO_x by over 60%. At 1900K, the "Impact of Residence Time" derivative is 20 ppm/ms. For every millisecond shaved off residence time, NO_x drops by 20 ppm, providing a clear design path for future compact combustors. Strategic analysis also reveals that the relative NO_x penalty of hydrogen actually decreases as flame temperature increases, dropping from a 65% penalty at 1750K to a 40% penalty at 1950K.

Finally, we must address the mathematical penalty inherent in the current NO*{x15} (corrected to 15% Oxygen) regulatory standard. Hydrogen flames produce exhaust with approximately 2% higher O_2 content compared to natural gas at the same temperature. When the standard EPA correction formula is applied, this higher oxygen content artificially inflates the reported NO_x value. The actual physical impact of hydrogen on raw NO_x is approximately 50% lower than the impact reported via the NO*{x15} metric.

**Conclusion** The path toward carbon-free propulsion requires a move toward compact, short-residence-time combustor architectures that capitalize on the 20 ppm/ms abatement derivative. Furthermore, regulatory reform is essential; shifting from NO_{x15} to raw NO_x will ensure that hydrogen technologies are assessed on their actual environmental impact rather than mathematical artifacts of legacy formulas. Succeeding in this transition will enable the industry to maintain NO_x levels comparable to natural gas while achieving zero carbon emissions.