

Technology Assessment of a TRL 5 Microwave Plasma System under NASA Standards as a Portable and Efficient Energy-Transition Solution for the Oil-and-Gas and Aerospace Sectors in Colombia

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Abstract

This paper presents experimental results obtained with a 2.45 GHz, 1.5 kW MIRA atmospheric microwave plasma torch operated with compressed air and assisted by Helmholtz coils that generate an axial magnetic field of up to 20 mT. The study evaluates three complementary lines: (i) real-time nitrogen oxide (NO_x) measurement using a portable ECOM-D analyzer, (ii) external NO_x quantification by EPA Method 7 in an accredited laboratory (GSA SAS), and (iii) validation of the propulsive mode through net-thrust measurements. The results show that the magnetic field reduces cavity temperature by 3.1°C ($p = 0.001$; Cohen's $d = -2.55$), providing unequivocal macroscopic evidence of electronic confinement. The specific NO_x production efficiency increases by 14.3% when the coils are activated at 1.5 kW, and by 18.6% at 1.0 kW. In propulsive mode, the system generates up to 2.0 N of net thrust and a jet pressure of 3.76×10^4 Pa at full power with a flow rate of 18 000 mL/min, exceeding the adapted reference value from Ye et al. (2020). The theoretical framework links the findings to the extended Zeldovich mechanism and electronic Larmor-radius confinement.

Keywords: atmospheric microwave plasma, nitrogen oxides, magnetic confinement, Helmholtz coils, propulsive thrust, Zeldovich mechanism.

1 Introduction

Nitrogen fixation by non-thermal plasma has attracted increasing interest as a potentially lower-energy alternative to the Haber–Bosch process for the synthesis of fertilizers and nitric-acid precursors [1, 2]. In this context, atmospheric-pressure microwave plasmas are particularly attractive because they operate without solid electrodes, reducing erosion-related contamination and simplifying scale-up.

The 1.5 kW, 2.45 GHz MIRA system developed by RADOM Corporation also enables operation in two regimes: a chemical mode, in which plasma energy is used to activate nitrogen-fixation reactions, and a propulsive mode, in which the plasma acts as a heat source for a supersonic thermal jet capable of generating measurable thrust [3].

The objective of the research presented in this paper is to experimentally evaluate the effect of an axial magnetic field, generated by Helmholtz coils, on:

1. the real-time formation kinetics of NO_x ,
2. the total NO_x mass quantified by a standardized reference method, and
3. the propulsive performance of the discharge.

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2 Theoretical Framework

2.1 NO_x Formation: Extended Zeldovich Mechanism

In atmospheric air plasmas, nitric oxide is predominantly formed through the elementary Zeldovich reactions [1]:



Reaction (1) is rate-limiting, with an activation barrier $E_a \approx 318 \text{ kJ/mol}$. Its rate constant follows an Arrhenius-type dependence with exponential sensitivity to the electron temperature T_e :

$$k_1(T_e) = A \exp\left(-\frac{E_a}{k_B T_e}\right). \quad (4)$$

In non-thermal plasmas, N_2 dissociation occurs mainly through collisions with energetic electrons ($> 10 \text{ eV}$) rather than through translational gas temperature. Therefore, NO_x production is highly sensitive to electron density n_e and electron temperature T_e [2].

2.2 Magnetic Confinement and Larmor Radius

In the presence of an axial magnetic field B , a charged particle with perpendicular velocity $v_\perp$ follows a circular trajectory with radius:

$$r_L = \frac{mv_\perp}{qB}. \quad (5)$$

For electrons at $T_e \approx 1 \text{ eV}$ to 3 eV and fields from 1 mT to 20 mT , r_L falls in the millimeter range, far below the cavity radius. The direct consequences are: (i) increased n_e in the active region, (ii) a longer effective electron path length, and (iii) a higher volumetric power density.

2.3 Propulsive Mode and Residence Time

The net thrust generated by the plasma jet is calculated as:

$$F_{\text{net}} = (M - M_0)g, \quad P_{\text{net}} = \frac{F_{\text{net}}}{\pi R^2}, \quad (6)$$

where M is the threshold mass with active plasma, M_0 is the threshold mass with gas flow only, and R is the inner radius of the quartz tube [3].

The gas residence time in the active cavity is modeled as:

$$t_{\text{st}} = \frac{\pi d^2 L T_0}{4 Q_0 T_p}, \quad (7)$$

where d is the inner diameter, L is the tube length, Q_0 is the standard flow rate, and T_p is the plasma temperature [4].

3 Materials and Methods

3.1 Plasma System

The MIRA torch operates at 2.45 GHz with adjustable power between 1000 W to 1500 W and a plasma-forming gas flow rate (compressed air) of 10 to 20 L/min. The quartz tube used in propulsive mode has an inner diameter $d = 26$ mm and length $L = 700$ mm. Telemetry (magnetron temperature, cavity temperature, real power, flow rate and optical signals) is automatically recorded by MICAP-LP software at 1 Hz.

3.2 Magnetic-Confinement Subsystem

A pair of Helmholtz coils was used, with radius $a = 3$ cm, separation $d = 3$ cm, 334 turns of AWG 18 copper wire per coil and variable current up to 5 A. The power dissipated in the coils was:

$$P_{\text{coils}} = (7.7 \text{ V} \times 5.07 \text{ A}) + (7.5 \text{ V} \times 5.05 \text{ A}) = 76.9 \text{ W}. \quad (8)$$

3.3 Methodology 1: Real-Time NO_x Measurement

The data come from eight files from the experimental session of April 29, 2026, grouped into two classes: SYS files (system telemetry at 1 Hz) and J2KDL files (Wohler/Testo gas analyzer, also at 1 Hz). Temporal matching was performed with a 2 s tolerance using `pandas.merge_asof`.

An automatic NO_x peak detector was implemented, defining peaks as segments in which concentration exceeded 500 ppm for at least 4 s. The quality filter retained only peaks with $[\text{NO}_x]_{\text{max}} \geq 6500$ ppm, duration ≥ 30 s and mean power > 100 W. Of 21 detected peaks, 14 met these criteria: 6 with coils at 5 A and 8 without coils.

For each valid peak, the following were calculated: NO_x peak, t_{90} (time to reach 90% of the maximum value) and initial formation rate $d[\text{NO}_x]/dt$. Statistical comparisons were performed using Welch's t -test, the Mann-Whitney U test and Cohen's d .

3.4 Methodology 2: External Quantification (EPA Method 7)

Eight gas samples were collected in capture balloons and sent to Gestion y Servicios Ambientales S.A.S. (GSA SAS, accredited by IDEAM under Resolution 1211 of 2024) for analysis according to EPA e-CFR Title 40 Part 60 Appendix A Method 7. Results are expressed as NO_x mass equivalent to NO_2 in micrograms (μg) per balloon. The four evaluated conditions were: 1.5 kW without coils (T1), 1.5 kW with coils at 5 A (T2), 1.0 kW without coils (Ref-S) and 1.0 kW with coils (Ref-C).

3.5 Methodology 3: Propulsive-Mode Validation

Tests were performed with the torch oriented vertically (nozzle upward). The threshold mass M required to keep a metallic sphere stationary above the tube outlet was measured with and

without microwaves, for five power levels $P_{\text{MW}} \in \{1100, 1200, 1300, 1400, 1500\}$ W and two flow rates $Q_0 \in \{14000, 18000\}$ mL/min. Net thrust and jet pressure were calculated using Eq. (6).

4 Results

4.1 Thermal Evidence of Magnetic Confinement

The most robust finding of the study appears in the reactor thermal balance (Table 1). The maximum cavity temperature decreases by 3.1 °C when the coils are activated (mean with coils: 21.0 °C; without coils: 24.1 °C; Welch $p = 0.001$; Cohen’s $d = -2.55$, very large effect). Gas temperature follows the same trend, with an average decrease of 27 °C.

Table 1: Statistical summary of main indicators (mean $\pm$ standard deviation).

Indicator	Coils 5 A	No coil	$\Delta\bar{\mu}$	Welch p	Cohen’s d
$[\text{NO}_x]_{\text{max}}$ (ppm)	8193 ± 2	8156 ± 81	+37	0.234	+0.65
t_{90} (s)	6.5 ± 1.2	14.9 ± 23.4	-8.4	0.345	-0.51
$d[\text{NO}_x]/dt$ (ppm/s)	1327 ± 106	1382 ± 436	-55	0.736	-0.18
$T_{\text{cav,max}}$ (°C)	21.0 ± 0.7	24.1 ± 1.6	-3.1	0.001	-2.55
$T_{\text{gas,max}}$ (°C)	315 ± 19	342 ± 51	-27	0.199	-0.70

4.2 NO_x Production: Portable Analyzer

Both conditions reach the same apparent concentration ceiling (approximately 8200 ppm), which coincides with the analyzer saturation limit. The observed difference lies in the kinetics: with coils at 5 A, the plasma reaches 90% of the peak in $t_{90} = 6.5$ s (CV = 18.5%), whereas without coils the median is comparable but dispersion is much higher (CV = 156%), indicating a more stable and reproducible process under confinement.

4.3 NO_x Production: External Laboratory

Table 2: Specific NO_x production efficiencies for the four conditions.

Group	Condition	$\bar{m}_{\text{NO}_x}$ (μg)	P_{total} (W)	η (μg/W)
T1	1.5 kW without coils	23335.7	1500.0	15.56 ± 0.40
T2	1.5 kW with coils	28030.7	1576.9	17.78 ± 0.45
Ref-S	1.0 kW without coils	18403.1	1000.0	18.40 ± 0.47
Ref-C	1.0 kW with coils	23501.7	1076.9	21.82 ± 0.56

At 1.5 kW, the coils increase NO_x mass by 20.1% and specific efficiency by 14.3% ($\eta_{\text{T2}}/\eta_{\text{T1}} = 1.143$). At 1.0 kW, the effect is more pronounced: +27.7% in mass and +18.6% in efficiency ($\eta_{\text{Ref-C}}/\eta_{\text{Ref-S}} = 1.186$). At both power levels, the net increase substantially exceeds the energetic penalty of the coils (5.1% of P_{total}).

Table 3: Experimental propulsion results (June 9, 2026).

Q_0 (mL/min)	P_{MW} (W)	F_{net} (N)	P_{net} ($\times 10^4$ Pa)	I_p (N/kW)
18000	1500	1.9963	3.761	1.331
18000	1400	1.8934	3.567	1.352
18000	1300	1.8110	3.412	1.393
18000	1200	1.6160	3.045	1.347
18000	1100	1.4965	2.819	1.360
14000	1500	1.7650	3.325	1.177
14000	1400	1.3259	2.498	0.947
14000	1300	1.2162	2.291	0.936
14000	1200	1.0849	2.044	0.904
14000	1100	0.9702	1.829	0.882

4.4 Propulsive Mode

The relationship between net thrust and microwave power is highly linear for $Q_0 = 18\,000$ mL/min ($R^2 = 0.980$) and satisfactory for $Q_0 = 14\,000$ mL/min ($R^2 = 0.893$), consistent with a model of thermal enthalpy conversion into kinetic energy. Residence times calculated using Eq. (7) are $t_{\text{st}} = 95.0$ ms and 73.9 ms, respectively, both much greater than the reference kinetic time (approximately 10 ms at 3125 K), indicating that the system is not residence-time limited.

5 Discussion

5.1 Physical Interpretation of Magnetic Confinement

The significant reduction in cavity temperature ($\Delta = -3.1^\circ\text{C}$, $p = 0.001$, Cohen’s $d = -2.55$) constitutes a direct macroscopic signature of magnetic confinement. With active coils, electron trajectories are confined within a central cylinder of radius $r_L \ll R_{\text{cav}}$, which moves the plasma away from the walls and reduces thermal losses. Energy that would otherwise be dissipated as wall heat becomes available to sustain ionization and dissociation in the active region, effectively increasing n_e and T_e .

As predicted by Eq. (4), an increase in T_e exponentially accelerates the kinetic constant of the limiting reaction (1), explaining the higher NO_x production observed with both methodologies.

5.2 Analyzer Saturation Limit

A relevant limitation of Methodology 1 is that the ECOM-D analyzer saturates around 8200 ppm. This prevents quantification of the real difference in peak concentration between conditions, because both reach the same ceiling. The kinetic signature of confinement is observable through faster saturation (lower t_{90} and lower dispersion with coils), but the absolute equilibrium concentration under magnetic field could only be estimated through Methodology 2.

5.3 Energy Efficiency and Confinement Cost

The energetic overhead of the coils (76.9 W, equivalent to 5.1% of P_{total} at 1.5 kW) is more than offset by the 14.3% to 18.6% increase in specific efficiency, depending on the power level. This

suggests that magnetic confinement has industrial scale-up potential for improving the profitability of plasma-based nitrogen-fixation processes.

5.4 Propulsive Performance

The maximum net pressure obtained ($P_{\text{net,max}} = 3.76 \times 10^4$ Pa) exceeds the adapted reference value from Ye et al. [3] (approximately 2.7×10^4 Pa at 1 kW). The specific performance index $I_p = F_{\text{net}}/P_{\text{MW}}$ ranges from 0.882 to 1.393 N/kW, below the Ye et al. criterion (28 N/kW), but this comparison is not direct because the systems differ in geometry, orientation and power range. The thrust-power linearity ($R^2 > 0.98$) validates the thermal-expansion model proposed in Deliverable 4.

6 Scale-Up and Future Development

For international research and technology-transfer purposes, the next phase should move from exploratory TRL 5 validation toward an optimized and instrumented platform with closed energy balances. Three scale-up routes are recommended:

1. **Nitrogen-fixation scale-up:** integrate a gas absorber downstream of the plasma torch to convert NO_x into diluted nitric acid, increase the sample size to at least $n \geq 6$ per condition, and target a benchmark above 25 g NO_x /kWh at bench scale.
2. **Plasma-assisted methane reforming (PSMR):** adapt the MIRA platform for controlled $\text{CH}_4/\text{H}_2\text{O}$ mixtures to evaluate syngas production ($\text{H}_2 + \text{CO}$), methane conversion, selectivity and specific energy consumption, with an initial laboratory target above 50% energy efficiency.
3. **Propulsive and thermal-jet development:** test sealed chambers and optimized nozzles, measure jet temperature and velocity directly, and target net thrust above 3 N at 1.5 kW under controlled pressure conditions.
4. **Digital-twin development:** couple electromagnetic, thermal-fluid, species-transport and magnetic-field models in COMSOL/CFD, using the experimental data reported here as validation points.

These routes would allow the system to evolve from a validated experimental platform into a research tool for energy efficiency, plasma chemistry, plasma-material interaction, hydrogen-related processes and advanced plasma propulsion.

7 Conclusions

The experimental results support the following conclusions:

1. Magnetic confinement is physically verifiable. The 3.1 °C reduction in cavity temperature with active coils ($p = 0.001$, Cohen’s $d = -2.55$) is clear macroscopic evidence that electrons are radially confined, concentrating the plasma in the axial region and reducing wall losses.
2. The coils improve NO_x production efficiency. At 1.5 kW, specific efficiency increases by 14.3%; at 1.0 kW, by 18.6%. The net gain substantially exceeds the energetic penalty of the coils (5.1%).

3. The portable analyzer reflects kinetic effects rather than equilibrium effects. The saturation time t_{90} is lower and more reproducible with coils, indicating a more stable plasma and faster reaction rate, although apparent peak concentration is identical due to the 8200 ppm instrument ceiling.
4. The propulsive mode is functional and predictable. The system generates net thrust from 0.97 to 1.996 N with a linear thrust-power relationship ($R^2 \geq 0.893$), consistent with the conversion of thermal enthalpy into kinetic energy. The maximum jet pressure (3.76×10^4 Pa) exceeds the adapted literature reference criterion.
5. Future work should use analyzers with a range above 8200 ppm, increase the external-laboratory sample size to $n \geq 6$ per condition, explore factorial designs that decouple magnetic-field effects from reactor initial thermal state, and develop scale-up routes for nitrogen fixation, PSMR and propulsive plasma systems.

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