Al_2O_3 Reduction in N_2–H_2 RF Plasma

Next-Generation Clean Aluminium Production

W W W . P L A S M A C O M B U S T I O N . C O M

10 December 2025
Applied Plasma Technologies, Corp.

CONTENT

Applied Plasma Technologies

OUR COMPANY

1,500 plasma products in operation

chemically pure, hi-temp RF plasma

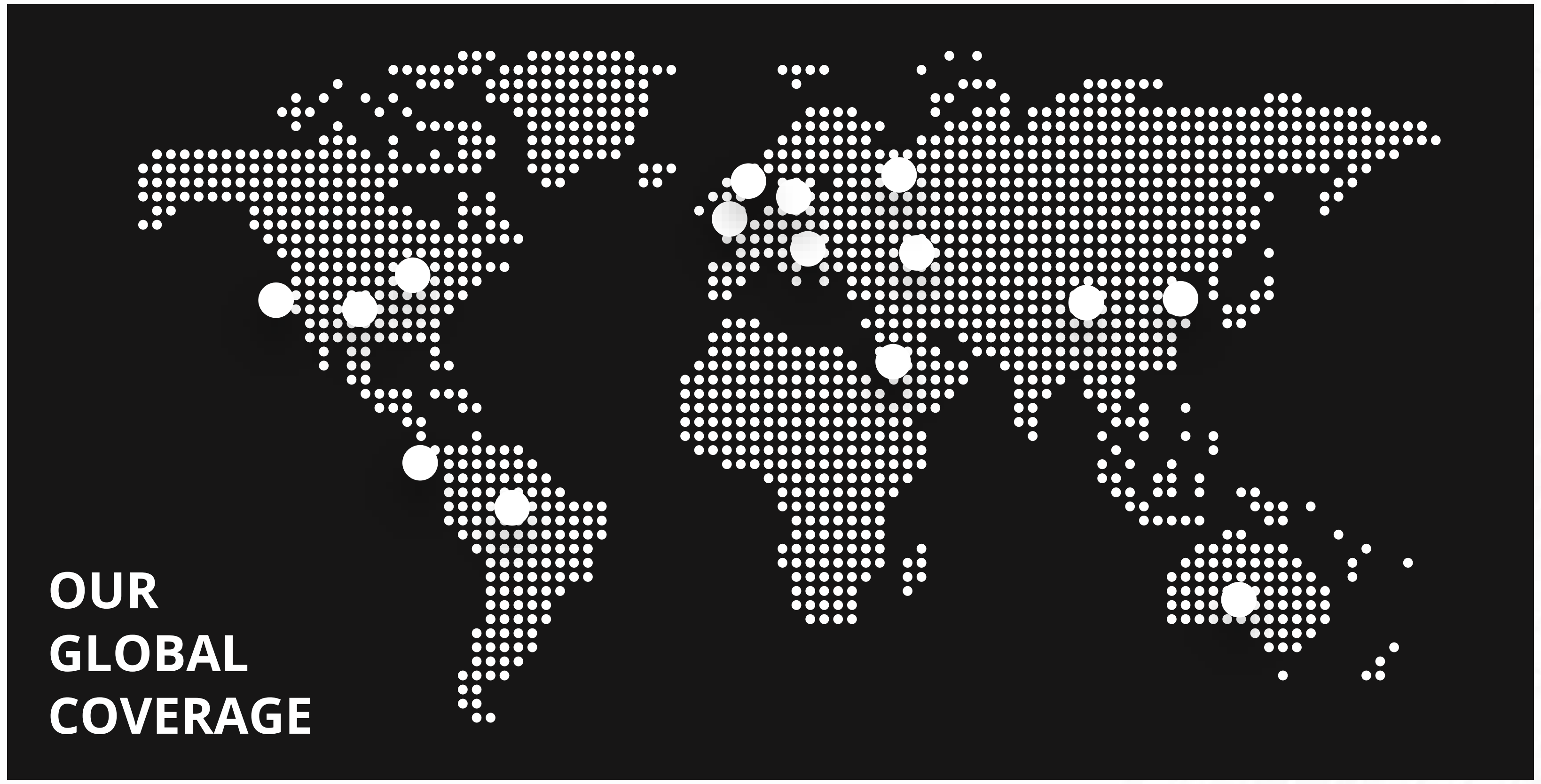
from vaccum to 5 bar of pressure

air, He, Ar, N2 , CO2, steam and different blends

5 continents

13 countries

DARPA certified



Universities	Corporations	Space Agencies	National Labs
30	18+	7	5

ICP/RF Plasma Systems	Boron Nitride Nanotubes Production	Ammonia Combustors
Coal and Waste Gasification	ICP/RF Plasma Gasifiers	Plasma Synthesis of New Materials
Plasma Ignition and Flame Control	Plasma Assisted Combustors & Reactors	Fertilizer Production
Testing Aerospace Materials	Plasma Thrusters	Plasma Mineralogy

GE Aerospace

United Technologies

SIEMENS energy

Kawasaki

LEARN MORE

ABOUT OUR FOUNDER

Dr. Igor Matveev is a globally recognized expert in Plasma-Assisted Technologies with 3 published books and over **1,500 plasma systems** developed under his leadership and deployed around the world.

He received his Ph.D. in Mechanical Engineering in 1984 with a dissertation titled "Development and Implementation of Plasma Ignition Systems for Naval Gas Turbines", which laid the groundwork for his pioneering work in plasma-assisted technologies.

Since 2003, Dr. Matveev has served as President and CEO of **Applied Plasma Technologies** in Marshall, Virginia, driving innovation in high-power plasma systems for industrial, energy, and environmental applications.

His commitment to advancing the field extends to academia and professional service. Since 2004, he has been a **Guest Editor for the IEEE Transactions on Plasma Science** special issues on Plasma-Assisted Technologies. He also served as Organizing Committee Chair for the 2nd through 12th International Conference on Plasma-Assisted Technologies (ICPAT).

THE CHALLENGE: HALL–HÉROULT PROCESS

For nearly **140 years**, the Hall–Héroult process has dominated aluminium production. But this century-old method is reaching its theoretical limits: it consumes on average **14–15 MWh per ton*** of aluminium, generates **1.6–2.0 tons of CO_2 per ton**, and releases powerful greenhouse gases (**CF_4 and C_2F_6** with a global warming potential up to **9,200 times higher than CO_2**).

In addition, it produces **toxic HF emissions** and hazardous spent pot lining (SPL).

**one of the world's leading Al producer confirmed number as 14.6MWh/t*

OUR VISION

We envision a truly **clean aluminium** production process — zero emissions, powered by **renewable electricity**, and operating within a **closed H_2–H_2O cycle**.

Our **modular, scalable** plasma reactors **eliminate carbon and fluorine**, while producing high-value **AlN ceramics as a by-product**.

This approach aligns directly with **global ESG strategies** and **net-zero targets**.

LEARN MORE

TECHNOLOGY

Overview:

- **Plasma reduction of Al_2O_3** has been known since the 1960s.
- RF N_2/H_2 plasma produces **atomic hydrogen**, enabling **rapid surface reduction** of molten alumina.
- The concept was proven, but past technologies lacked **efficiency, control**, and **scalable quenching**.
- Industrial viability requires **high-enthalpy plasma, atomic H flux, continuous feed**, and **ultra-fast quenching**

"The chemistry has been known and demonstrated. The challenge was engineering scalability."

Historical challenges:

- Low-efficiency RF power supplies (≤40%) → industrial energy cost impractical
- Argon-dominated plasmas → weak heat transfer, poor H_2 activation, low conversion
- No viable quenching technology → rapid re-oxidation of molten aluminum droplets
- MW-scale electrode-less RF/ ICP plasma systems were experimental only

1962–1965
First plasma reduction experiments (Grosse, Stokes)

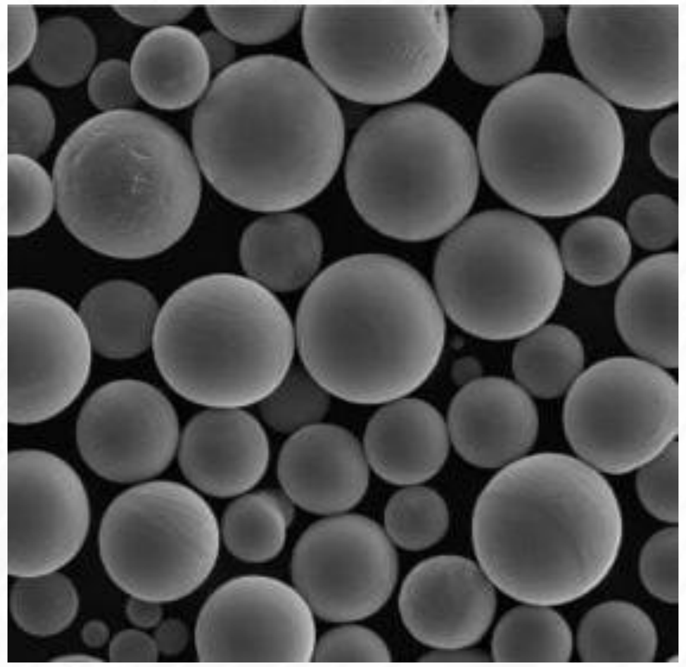
1968–1971
RF plasma reduction of Al_2O_3 demonstrated (Rains, Univ. Michigan)

1970–2000
Continued lab-scale studies; scalability remains unsolved

2000-2020
Advancements in diagnostics, ceramics, modeling; still no industrial path

2020–2025
Solid-state RF power (>95% efficiency), high-enthalpy N_2/H_2 plasma, ultra-fast quenching → first viable industrial configuration

WHY IT WORKS NOW



Power

MW-scale solid-state RF power
~95% efficiency
Industrial and scalable (1-15MW)

Plasma chemistry

N_2/H_2 plasma gas
atomic hydrogen,
rapid reduction of Al_2O_3
advanced phases separation.

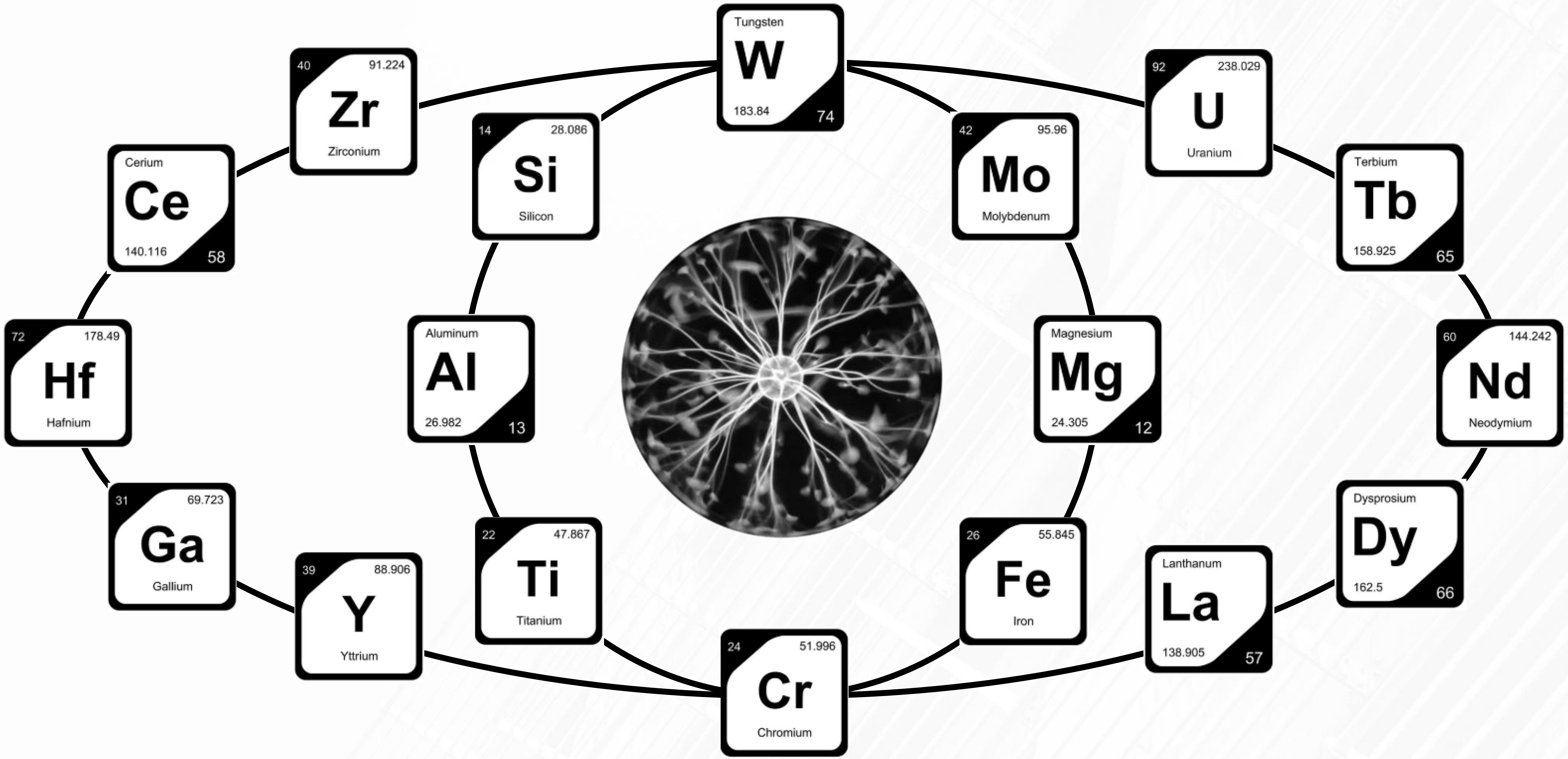
Quenching

10^5–10^6 K/s cooling of Al droplets. Prevents re-oxidation, stabilizes the metal/ powder

Validation & IP

Patented in 2025 – process, reactor and quench architecture
Confirmed by RUSAL, Stanford, Princeton, NTUA, Metlen, Alba.

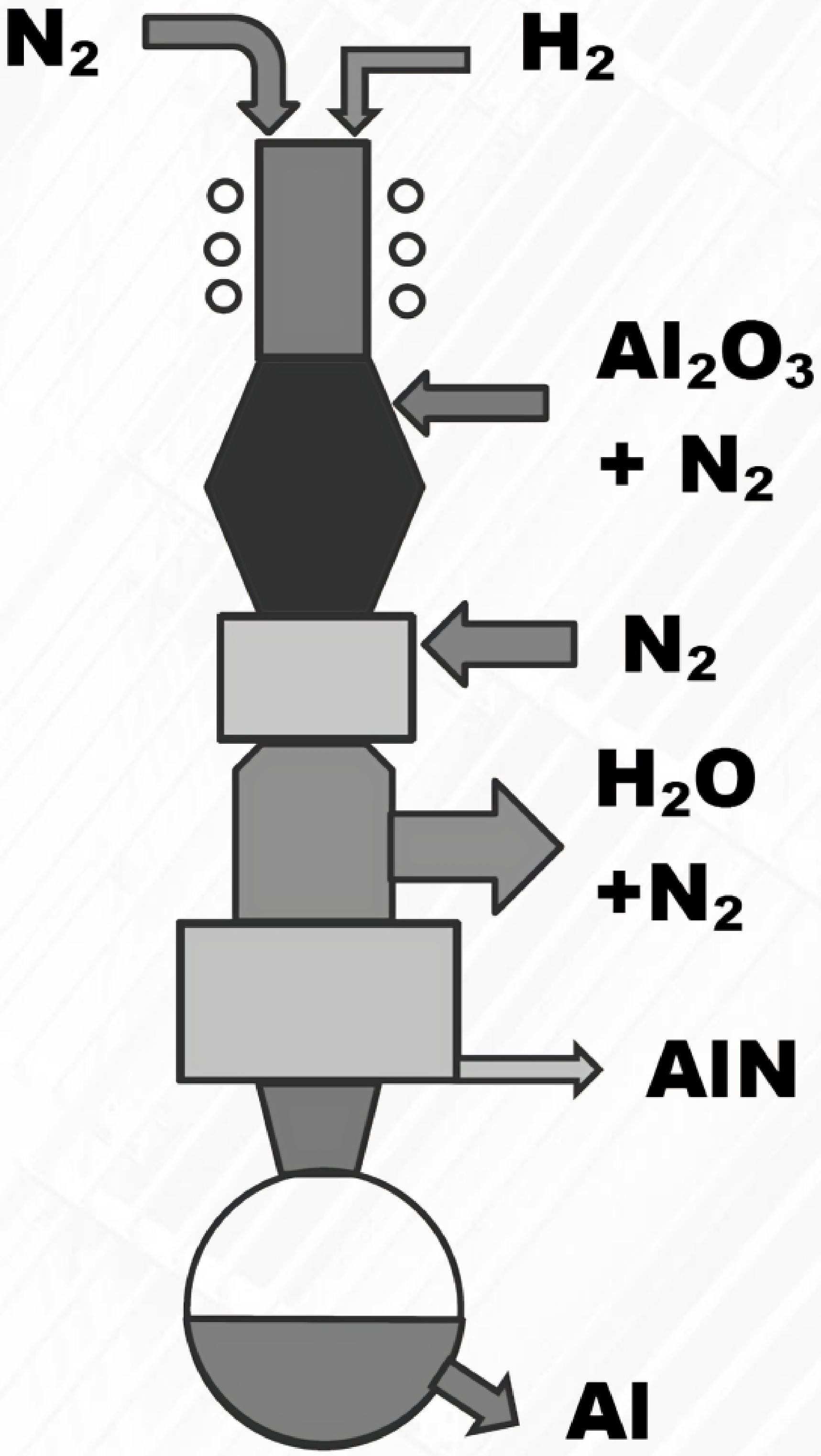
UMBRELLA TECHNOLOGY



10 December 2025
Applied Plasma Technologies, Corp.

PROCESS OVERVIEW

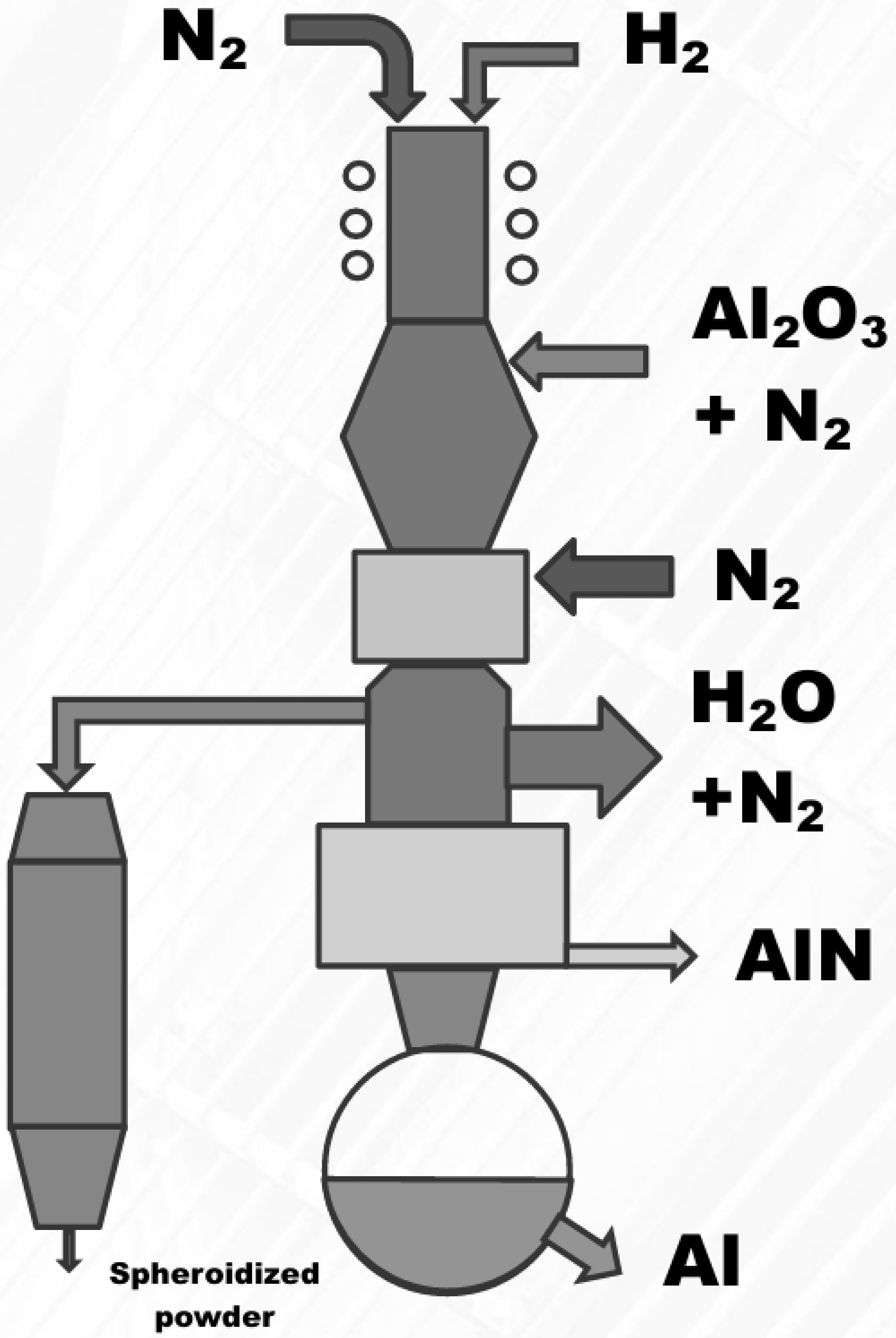
FEEDSTOCK	N_2, H_2, Al_2O_3
FLOW	RF Torch → Reactor → Quenching Module → Separator → Furnace
OUTPUTS	Aluminium, AlN ceramics, Water, Nitrogen



Operation at elevated pressure (up to ~5 bar) enables kinetics and control; direct molten Al feed to furnace reduces remelt losses.

PROCESS OVERVIEW

FEEDSTOCK	N_2, H_2, Al_2O_3
FLOW	RF Plasma → Alumina injection → Metal microdroplets → Rapid quenching →
OUTPUTS	Spherical powder, Water, Nitrogen



Operation at elevated pressure (up to ~5 bar) enables kinetics and control; direct molten Al feed to furnace reduces remelt losses.

ENERGY EFFICIENCY – PLASMA TORCH

METAL

η ≤ 70%

Traditional metallic torches (known since the 1950s–60s) suffer from **eddy current losses** (Foucault currents) and **high radiative heat flux**, wasting much of the input power.

CERAMICS

η ≤ 85%

The world's first ceramic plasma torch:
a breakthrough in energy efficiency and design

- **No eddy currents:** ceramic body is non-conductive.
- **~10% wall losses only** (vs 30–40% typical).
- Combined with **solid-state RF power supplies (95% efficiency)** → total system efficiency **>70%**, nearly **2× higher** than existing designs.

REACTION THERMOCHEMISTRY

REAGENT	REACTION	ΔH^{O}(kJ/mol)	Operational notes (+ endothermic, − exothermic)
Molecular H_2	Endothermic $Al_2O_3 + 3\ H_2 \rightarrow$ $2\ Al + 3\ H_2O$	**+950 kJ/mol**	− Requires bulk T often > 2000 °C for useful rates (slow kinetics at 2000 °C) − Large sensible heating of N_2 carrier (low energy efficiency) − Stronger back-recombination near surface, limited H coverage − At high T, N_2 activation ↑ → risk of AlN (esp. at low pressure) − Bigger reactor / longer residence; wall & radiative losses
Plasma/ atomic H	Exothermic $Al_2O_3 + 6\ H \rightarrow$ $2\ Al + 3\ H_2O$ activation − chemical return	**1308 − 358 = 950 kJ/mol**	+ High reactivity at ≤ 2000 °C outlet (radicals at surface) + Chemical step returns ~358 kJ/mol as heat right at particles + Can localize energy input; fast quench possible + At elevated pressure, N_2 dissociation suppressed → less AlN + Better controllability (on/off, spatial focusing) and higher throughputs

* Both routes sum to ≈ +950 kJ/mol from an H_2 feed. Plasma shifts where energy is spent (dissociation vs. sensible heating) and boosts kinetics at moderate outlet temperatures.

** The form of hydrogen determines whether external energy is needed, or the reaction is self-sustaining

*** Standard enthalpy at 298 K; H_2O as gas.

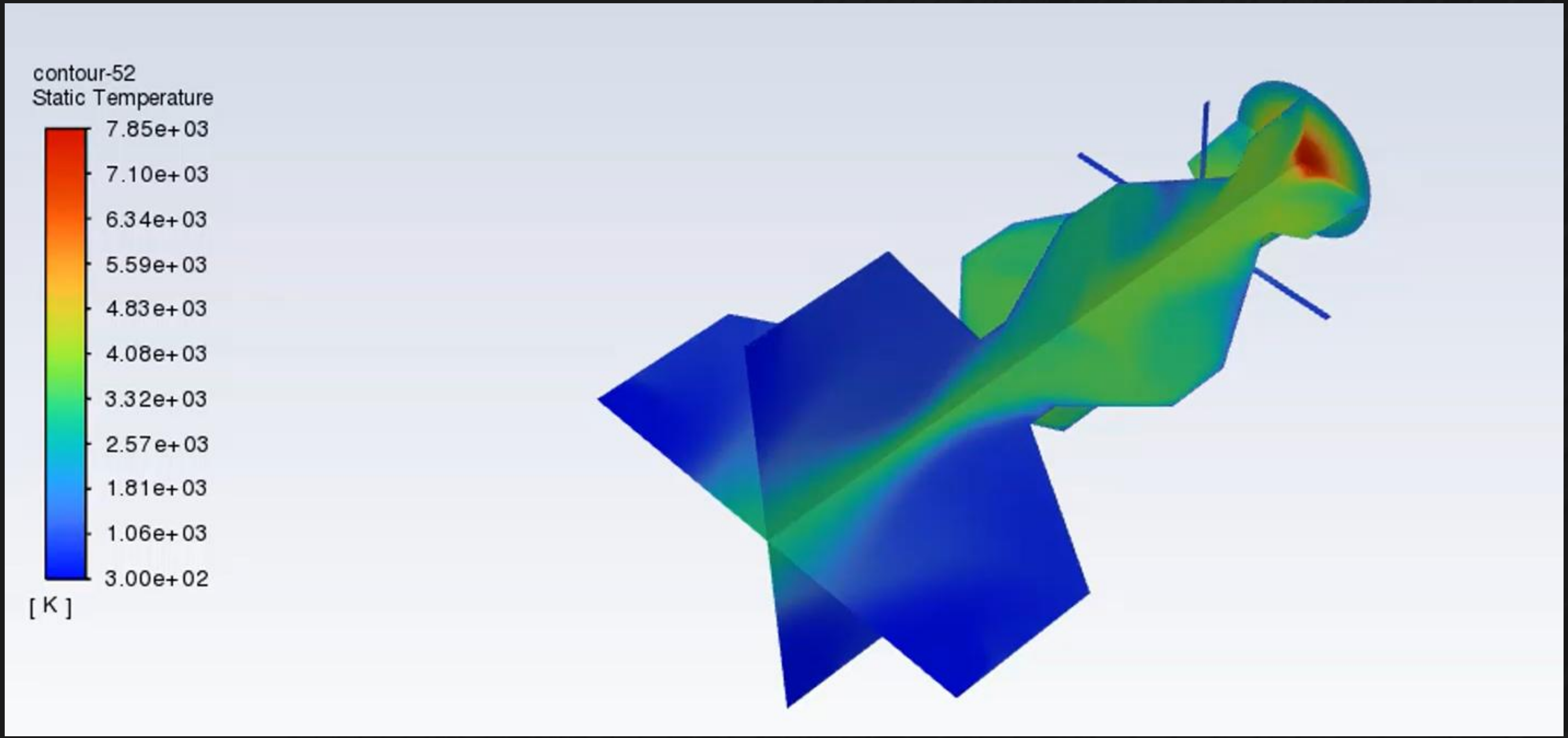
KEY TAKEAWAY

Plasma/atomic H shifts energy from bulk sensible heating to dissociation near particle surfaces → faster kinetics at ≤~2000 °C outlet.

INFLUENCE OF HYDROGEN FORM ON THE THERMOCHEMISTRY OF Al_2O_3 REDUCTION

- High-temperature reduction in N_2–H_2 RF plasma
- Hydrogen consumed, oxygen bound as water
- Products: Aluminium + high-purity water

AL_2O_3 POWDER INJECTION INTO PLASMA STREAM



10 December 2025
Applied Plasma Technologies, Corp.

ENERGY BASELINE & OPTIMIZATION

Our plasma method reduces specific energy consumption to nearly half of today's industrial average, **approaching the thermodynamic minimum of ~6.5 MWh/t.**

- Thermodynamic minimum: ~6.5 MWh/t Al
- Hall–Héroult: 6.2 MWh/t theoretical, ~15 MWh/t industrial average
- **Plasma Pilot: ~12.1 MWh/t**
- **Plasma Optimized: ~6.7 MWh/t (close to theoretical limit)**

BY-PRODUCTS AND ADDED VALUE

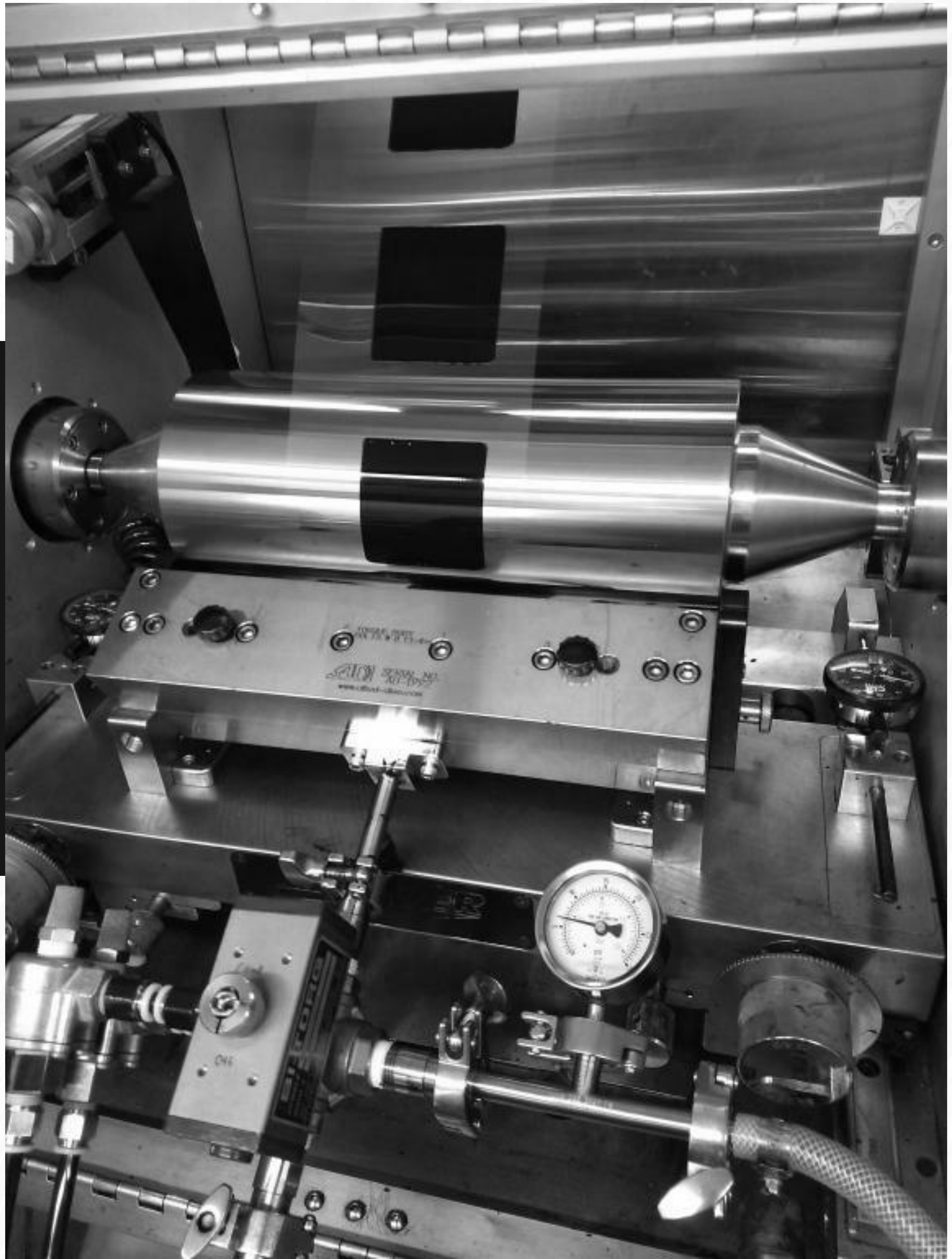
Aluminium Nitride (AlN):
Corrosion resistance, high thermal conductivity, electrical insulation and almost no chemical reaction with any substance, widely used in petroleum, chemical 1, food and other industries that need contact with strong oxidant and reducing agent

Aluminium Nitride (AlN):

- High-value advanced ceramic
- Applications: electronics, automotive, defense
- **Market price: $20,000–45,000 per ton**
- **Production: 1-10% adjustable as per preference**

SAFETY ASPECTS

- Hydrogen only inside reactor
- At outlet: $H_2 \rightarrow H_2O$, inert downstream
- No cryolite, no carbon anodes, no fluorides
- Standard industrial plasma safety protocols



NB

Inside torch H_2 can be 40–45 vol%, ~33–35% in reactor; O_2 is consumed → downstream gas becomes non-flammable (below LEL risk).

ENVIRONMENTAL GAIN

Zero CO_2 emissions

Our process produces aluminium (or powder) without any carbon or fluorine emissions.

No CO_2 No PFCs (CF_4 and C_2F_6), no HF or SPL

Instead of toxic by-products, the outputs are aluminium (or powder), pure water, and valuable AlN ceramics.
This is the world's first truly zero-emission aluminium (or powder) production pathway.

MORE INFORMATION

TECHNOLOGY COMPARISON

Feature	Hall–Héroult	RF Plasma Method
Operating temperature	~970 °C	1,700 – 2,500 K
Carbon emissions	High (CO_2, CF_4, C_2F_6)	Zero
Electrodes required	Carbon anodes	No electrodes
Byproducts	Toxic fluorides, SPL	AlN (high-value ceramics, potential for further processing)
Theoretical efficiency limit	Reached	Not yet reached, room to grow
Reaction medium	Molten cryolite	Gas-phase plasma

OPEX VS HALL–HÉROULT

While energy and gas consumption are comparable to Hall–Héroult, our process eliminates major ancillary costs:

- Comparable in energy and gases
- No carbon anodes, no cryolite, no SPL disposal
- Closed water–hydrogen cycle reduces inputs
- Potential for lower long-term costs

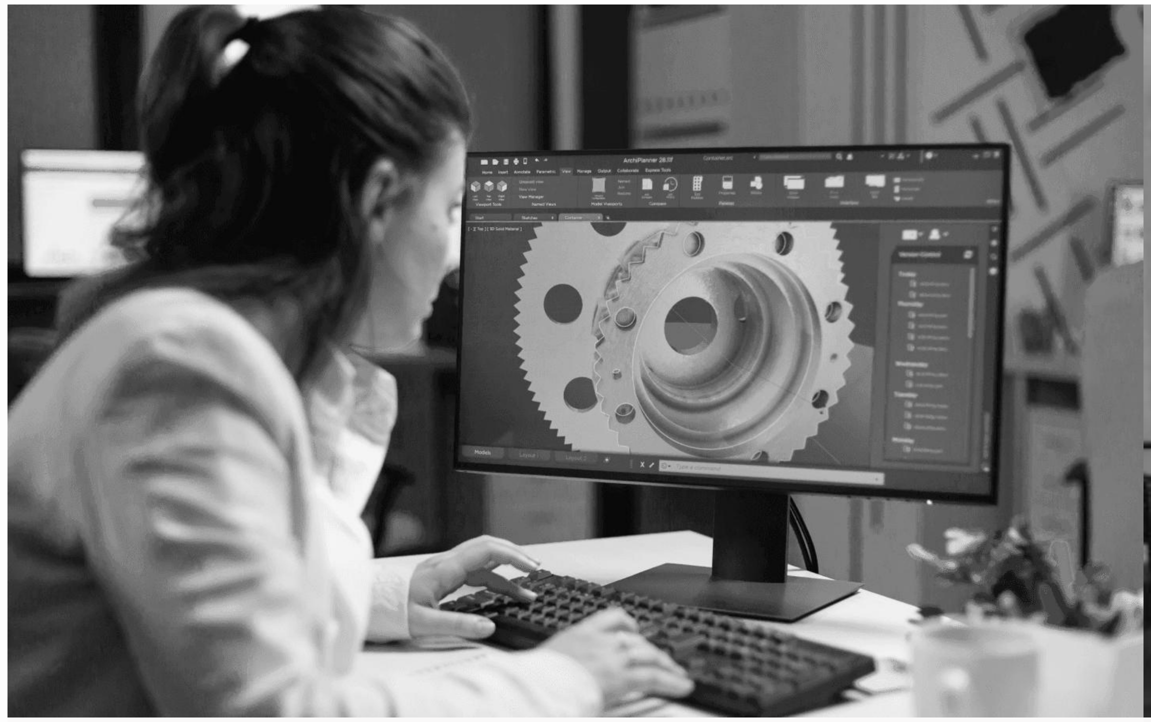
Together, these savings create significantly lower long-term operating costs.

SCALABILITY

1MW	=	~1 kt/ year
5MW	=	~5 kt/ year
15MW	=	~15 kt/ year

100 kt/year → 15–20 modules
CAPEX: ~$4M per 1 MW module

PILOT PROJECT ROADMAP (1-12M)



Modeling & Design (M1-M7)

Modeling & design of reactor, quench, separation/filtration, collection furnace; **CAD complete; RFQs** for tundish, heated crucibles, ceramic filters; production budget.

Outcomes: *TRL 5–6*

APT-100 tests (M1-M5)

APT-100 tests with high-H_2 N_2–H_2 plasma; build **H_2 feeding & dilution** (≥0.72 kg/h) and **N_2 system** (≥180 kg/h); capture experimental data for scaling.

TRL 7 (pilot)

Fabrication & Assembly (M4-M12)

Fabrication & assembly of metal/ceramic parts with coatings; procurement/tuning of feedstock feeders; tundish & tools; **cold tests** (feed mixing, transport gas →Al_2O_3 optimization).

TRL 8–9 (industrial)

DELIVERABLES

Key Deliverables:

- Operational N_2 (≥180 kg/h) and H_2 (≥0.72 kg/h) systems; safe dilution unit
- Experimental data on high-H_2 N_2–H_2 plasma (APT-100)
- Complete CAD of pilot Al_2O_3 reduction system; production budget
- RFQs: tundish, heated crucibles, ceramic filters
- Fabricated & assembled system; optimized feed mixing regime

Outcomes & TRL Progress:

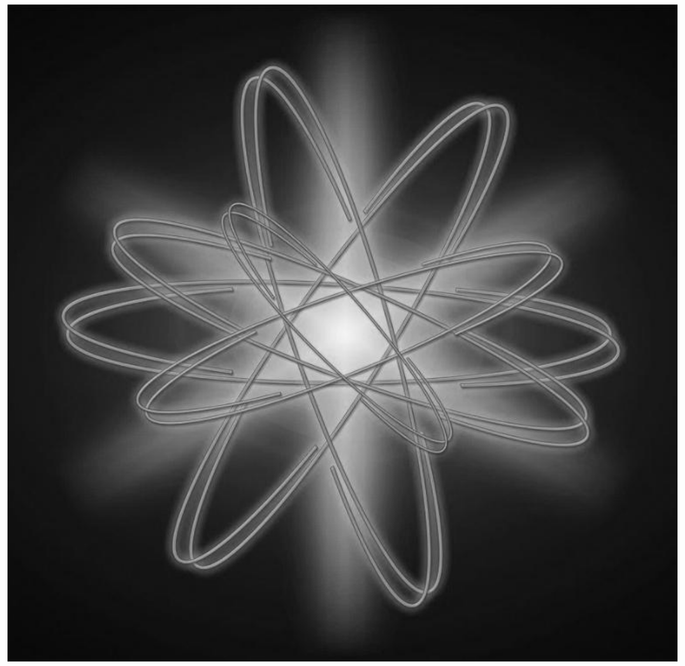
- Validated process data for industrial scaling
- Industrial Deployment Unit (IDU) ready for integrated tests
- Path to TRL 7 at end of M5; TRL 8–9 in M12 via pilot integration

M5: H_2/N_2 systems operational; dilution system ready

M7: Complete CAD; RFQs issued

M12: System fabricated & assembled; ready for tests

Q&A SUMMARY – TECHNICAL & PROCESS



Energy

6.7 MWh/t (optimized)
15 MWh/t (Hall–Héroult)

Gas consumption

H_2 = 112 kg/t Al
N_2 = 0.2–6 t/t Al

Mass production

1–5–15 MW units
1–15 kt/year

Safety

H_2 only inside reactor
inert downstream

Q&A SUMMARY – ECONOMICS & ESG

CAPEX

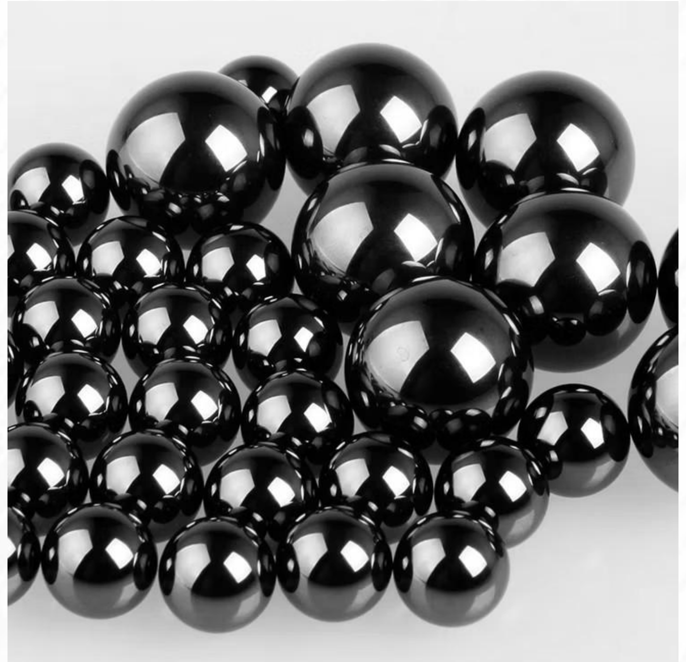
~$4M per 1 MW module
APT covers plasma part

★ ★ ★ ★ ★

OPEX

Comparable to Hall–Héroult
lower in ancillary costs

★ ★ ★ ★ ★



By-Products

AlN (60–80 t/year per MW
$20k–45k/t market

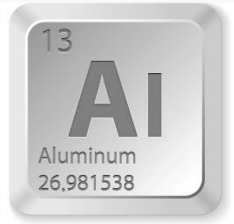
★ ★ ★ ★ ★

Environmental Gain

Zero CO_2, PFC, HF, SPL
by-product water cycle

★ ★ ★ ★ ★

CLOSING & CALL FOR PARTNERSHIP



Next-generation clean aluminium production

Our RF plasma process offers emission-free, modular, and scalable aluminium (powder) production for the net-zero era.

Zero-emission, modular, scalable process

No CO_2, no fluorine, no SPL — only aluminium (powder), water, and valuable AlN. Fully aligned with ESG and decarbonization goals.

Strategic partnership opportunity

By joining forces, we can pioneer the future of aluminium (powder) production and set a new global benchmark for green metallurgy — especially meaningful given commitment to a **30 % reduction in emissions by 2035**, en route to **net zero by 2060.**

THANK YOU

Follow us and learn more about our recent development

10 December 2025
Applied Plasma Technologies, Corp.

OUR CONTACT

Phone : +1 703 340 5545 (US), +971 55 318 8149 (UAE)

Website : www. plasmacombustion.com

Email : igor@plasmacombustion.com
max@plasmacombustion.com

Address : 4460 Whiting Road, Marshall, VA 20115, US