THERMAL PLASMAS: Properties, Generation, Diagnostics and Applications

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OUTLINE

- Thermal plasma and non-thermal plasma
- Composition, thermodynamic and transport properties of thermal plasmas
- Modeling of thermal plasma flows, arc modeling
- Generation of thermal plasmas
- Basic principles of arc plasma torches
- Factors influencing properties of plasma jet in arc plasma torches (design of the torch, properties of plasma gas)
- Plasma jet fluctuations
- Diagnostics of thermal plasma jets
- Thermal plasma processing
Electron temperatures and densities in plasmas

- Electron density [m^(-3)]
- Electron temperature [K]

- Fusion plasma
- Thermal plasma
- Glow discharges
- MHD generators
- Flame
- Ionosphere
- Solar corona
Nonequilibrium plasmas

\[ T_e \neq T_i \quad (T_e > T_i) \]

- plasma is not in thermodynamic equilibrium
- high values of E/p
- low pressures
- low densities of electric current

Thermal (equilibrium) plasmas

\[ T_e \cong T_i \]

- plasma is in thermodynamic equilibrium - LTE
- low values of E/p
- higher pressures
- high densities of electric current
Thermal plasmas

Basic plasma properties
Local thermodynamic equilibrium
Temperatures $T_e = T_h \sim 8 - 50 \times 10^3 \text{ K}$
Pressures 10 kPa - 1 Mpa
$E/p \sim 1 - 100 \text{ V/m.kPa}$

Common sources of thermal plasmas
- Inductively coupled discharges in gases
- Electric arcs – stabilized by gas flow
  – stabilized by vortex of liquid (Gerdien arcs)
Plasma in LTE

Properties of plasma in thermodynamic equilibrium are determined by pressure and temperature

Thermodynamic and transport properties of plasma depend on plasma composition

Composition of plasma
Monoatomic gas – electrons, ions, atoms

Eggert-Saha Equation:

\[
\frac{n_e n_i}{n} = \frac{2Q_i}{Q} \left( \frac{2\pi m_e kT}{h^2} \right)^{3/2} \exp \left( -\frac{E_i}{kT} \right)
\]

Dalton’s Law:

\[
p = (n_e + n_i + n)kT
\]

Quasineutrality:

\[
n_e = n_i
\]
# Thermal plasmas - composition

**Monoatomic gases: atoms, ions, electrons**

**Argon:** $\text{Ar, Ar}^+, \text{Ar}^{++}, \ldots, e$

**Molecular gases: molecules, atoms, molecular ions, atomic ions, electrons**

**Nitrogen:** $\text{N}_2, \text{N}, \text{N}_2^+, \text{N}^+, \text{N}^{++}, \ldots, e$

**Air:** $\text{N}_2, \text{O}_2, \text{Ar}, \text{NO, N}_2\text{O, NO}_2, \text{N, O, N}_2^+, \text{N}^+, \text{O}_2^+, \text{O}^+, \text{Ar}^+, \text{N}^{++}, \text{O}^{++}, \text{Ar}^{++}, \ldots, e$

**Calculation of composition:**

Equilibrium between dissociation, ionization and recombination

Minimization of Gibbs free energy

Depends on chemical potentials of different species present in plasma – can be determined from thermodynamic considerations
Plasma composition – monoatomic gas

Argon

\[ \text{Temperature [K]} \]

\[ \log n \]

-2  0  2  4  6  8  10  12  14  16  18  20  22

-5  -4  -3  -2  -1  0  1

-\( e^- \)  \( \text{Ar}^+ \)  \( \text{Ar}^{2+} \)  \( \text{Ar}^{++} \)
Composition of air plasma

Temperature [kK]
Thermodynamic properties

Mass density
Enthalpy
Internal energy
Specific heat
Entropy

Evaluated for given plasma composition by methods of thermodynamics

The evaluation of thermodynamic properties is based on calculated partition functions for all species:

\[ Q = \sum g_s \exp\left(-\frac{E_s}{kT}\right) \]
Plasma density

\[ \rho = \sum n_i m_i \]

- Temperature increase
  - Decrease of particle concentration
  - Disassociation, ionisation
- Increase of number of particles with low mass

Density of nitrogen plasma
Specific heat capacity

Increase of temperature

\[ C_p = C_f + C_r \]

- Increase of kinetic energy of thermal motion - $C_f$
- Dissociation
- Ionization

\[ C_p \text{ total} \]
Specific heat capacity of various gases

Hydrogen
Helium
Nitrogen
Argon
### Transport properties

**Diffusion coefficient** $D$  
\[ \vec{\Gamma} = D \ \text{grad} \ n \]

**Thermal conductivity** $k$  
\[ \vec{q} = k \ \text{grad} \ T \]

**Electrical conductivity** $\sigma$  
\[ \vec{j} = \sigma \ \text{grad} \ V \]

**Viscosity** $\mu$  
\[ \vec{f}_x = \mu \ \text{grad} \ v_x \]

Computations of transport coefficients is based on solution of Boltzmann equation. Knowledge of collision cross sections for all collisional interactions between particles is crucial. Transport coefficients for more complex mixtures are frequently unknown.
Thermal conductivity

Heat transfer

- Molecules – $k_m$
- Atoms - $k_a$
- Ions - $k_i$
- Electrons - $k_e$
- Dissociation – $k_D$
- Ionization - $k_I$

Copper $k = 390 \text{ W/mK}$
Iron $k = 75 \text{ W/mK}$
Water $k = 0,6 \text{ W/mK}$

$k = k_m + k_a + k_i + k_e + k_D + k_I$


Electric conductivity

**Electric conductivity**

- **Copper** $\sigma = 5.8 \times 10^7$ S/m
- **Iron** $\sigma = 9.5 \times 10^6$ S/m
- **Graphite** $\sigma = 1.0 \times 10^5$ S/m

Temperature $[10^3 \text{ K}]$

Pressure: 100 kPa
Plasma radiation

Complex modeling of radiation transfer in plasma with high spatial gradients of temperature is extremely difficult due to strong dependence of absorption and emission coefficients on temperature. Integration over all wavelengths along the optical path in plasma is necessary. Re-absorption of emitted light is main problem.

Concept of net emission coefficient is frequently used. Net emission coefficient represents radiation from isothermal cylinder of plasma with radius R.
Components of total radiation emission coefficient for $SF_6$ at 1 atm.

Absorption coefficient of $SF_6$ for temperatures of 300 K and 20 000 K
Non-equilibrium effects

Deviations from LTE are caused by various mechanisms in thermal plasma flows.

- Flows with high spatial gradients of temperature in the direction of flow
  - “frozen” plasma composition corresponding to the upstream position
- High spatial gradients of temperature – diffusion of species
  - Higher concentrations of electron in fringes of thermal plasma jets
  - De-mixing of plasma gases - ambipolar diffusion of ions with different coefficients of diffusion
- Rapid changes of plasma temperature
  - Effect of kinetics of reactions (dissociation, ionization, recombination) in plasma
Plasma can be described as a fluid with thermodynamic and transport properties depending on pressure and temperature.

Models of thermal plasma flows are based on solution of equations of balances of mass, momentum and energy. Equations of fluid dynamics are used with terms representing dissipation of energy by Joule heating, radiation energy transfer and effect of electromagnetic forces.

Plasma properties are represented by transport and thermodynamic coefficients often calculated separately and given in tables giving dependence on temperature and pressure.
Model of arc column in axial gas flow

continuity equation:
\[ \frac{\partial}{\partial t} \rho + \frac{1}{r} \frac{\partial}{\partial r} (r \rho v_r) + \frac{\partial}{\partial x} (\rho u) = 0 \]

momentum equations:
\[ \frac{\rho}{\partial t} \frac{\partial u}{\partial t} + \rho v \frac{\partial u}{\partial r} + \rho u \frac{\partial u}{\partial x} = -\frac{\partial p}{\partial x} + \frac{j_r B_\theta}{2} - \frac{2}{3} \frac{\partial}{\partial x} \left[ \eta \left( \frac{1}{r} \frac{\partial}{\partial r} (rv) + \frac{\partial u}{\partial x} \right) \right] + \frac{\partial}{\partial x} \left( 2 \eta \frac{\partial u}{\partial x} \right) + \frac{1}{r} \frac{\partial}{\partial r} \left[ r \eta \left( \frac{\partial u}{\partial r} + \frac{\partial v}{\partial x} \right) \right] \]
\[ \frac{\rho}{\partial t} \frac{\partial v}{\partial t} + \rho v \frac{\partial v}{\partial r} + \rho u \frac{\partial v}{\partial x} = -\frac{\partial p}{\partial r} - j_x B_\theta - \frac{2}{3} \frac{\partial}{\partial r} \left[ \eta \left( \frac{1}{r} \frac{\partial}{\partial r} (rv) + \frac{\partial u}{\partial x} \right) \right] + \frac{\rho w^2}{r} + \frac{\partial}{\partial r} \left( 2 \eta r \frac{\partial v}{\partial r} \right) - \frac{2}{r^2} \frac{\partial}{\partial x} \left[ \eta \left( \frac{\partial u}{\partial r} + \frac{\partial v}{\partial x} \right) \right] \]
\[ \frac{\rho}{\partial t} \frac{\partial w}{\partial t} + \rho v \frac{\partial w}{\partial r} + \rho u \frac{\partial w}{\partial x} = \frac{1}{r} \frac{\partial}{\partial r} \left( \eta r \frac{\partial w}{\partial r} \right) + \frac{\partial}{\partial x} \left( \eta \frac{\partial w}{\partial x} \right) - \frac{\rho w v}{r} - \frac{\eta w}{r^2} - \frac{w \eta}{r} \]

energy equation:
\[ \rho c_p \frac{\partial T}{\partial t} + \rho v c_p \frac{\partial T}{\partial r} + \rho u c_p \frac{\partial T}{\partial x} - \frac{\partial p}{\partial t} = u \frac{\partial p}{\partial x} + v \frac{\partial p}{\partial r} + j_r E_r + j_x E_x + \]
\[ \frac{1}{r} \frac{\partial}{\partial r} \left( r \lambda \frac{\partial T}{\partial r} \right) + \frac{\partial}{\partial x} \left( \lambda \frac{\partial T}{\partial x} \right) + \frac{5 k}{2 e} \left( j_x \frac{\partial T}{\partial x} + j_r \frac{\partial T}{\partial r} \right) - \dot{R} \]

charge continuity equation:
\[ \frac{1}{r} \frac{\partial}{\partial r} \left( r \sigma \frac{\partial \Phi}{\partial r} \right) + \frac{\partial}{\partial x} \left( \sigma \frac{\partial \Phi}{\partial x} \right) = 0 \]
Inductively coupled plasma torches

Inductively coupled discharge is maintained in an open tube in the presence of streaming gas. Low velocity plasma jet is formed at the exit.

Frequencies: 100 kHz – 100 MHz
Power: 1 kW – 1 MW
Pressure: $10^4$ – $10^6$ Pa
Plasma temperature: 6 000 – 10 000 K
Plasma velocity: 10 – $10^2$ m/s
Electric arcs

- High current densities
  - arc column \( \sim 100 \, \text{A/cm}^2 \)
  - electrode spots \( \sim 10^6 \, \text{A/cm}^2 \)

- High radiation intensity

- Low electrode potential drops \( V_c \sim 10 \, \text{V} \)

- Discharge current often limited only by power supply

- Arc currents \( 1 \, \text{A} – 10^6 \, \text{A} \)

- Intensity of electric field \( 1 \, \text{V/cm} – 10^3 \, \text{V/cm} \)

- Arc column length \( 1 \, \text{mm} – 10^1 \, \text{m} \)
Principles of arc stabilization

Gas-stabilized arc

• Gas flows along the arc in the nozzle
• Usually gas flow has vortex component for better stabilization and for anode spot movement
• Anode created by exit nozzle or transferred arcs
• Power level: 1 kW – 10 MW
• Plasma temperatures: 6 000 – 20 000 K

Liquid-stabilized (Gerdien) arc

• Liquid vortex is created in cylindrical chamber with tangential injection
• Arc is stabilized by its interaction with the vortex
• Anode is outside of arc chamber
• Power level: 10 – 200 kW
• Plasma temperatures: 8 000 – 50 000 K
Gas-stabilized arc plasma torches

Non transferred arcs

- Hot cathode
- Cold cathode

Transferred arcs

- Gas plasma
- Electrode
- Swirl Ring
- Nozzle
- Shield
- Workpiece
Water Stabilized Plasma Torch

- **arc current:** 300 - 600 A
- **arc power:** 80 - 176 kW
- **arc voltage:** 267 - 293 V
- **exit centerline temperature:** 19 000 - 28 000 K
- **exit centerline velocity:** 2500 - 7000 m/s
- **centerline plasma density:** 0.9 - 2.0 g/m$^3$
Basic factors determining properties of plasma jet in arc torches

Principal design factors: arc chamber geometry, arc current, plasma gas, gas flow rate

Dominant mechanisms of energy balance of unit length of arc column in axial flow:

- Energy dissipation by Joule heating
- Increase of axial enthalpy flux
- Power loss by radial conduction
- Power loss by radiation

Following simple relations can be derived from energy balance equation for basic torch parameters:

**Torch Efficiency:**

\[ \eta = \left( 1 + \frac{4\pi^2 \theta_G}{\theta_F} \frac{R^2 L}{G} \frac{\varepsilon_n h}{h} + \frac{2\pi \theta_G L S}{G h} \right)^{-1} \]

**Torch Power:**

\[ P = I.U = I.\left( \frac{\theta_F \theta_\sigma L G h}{\eta \theta_G \pi R^2 \sigma} \right)^{1/2} \]
Properties of plasma gases

Torch operation parameters are determined by physical properties of plasma gas. Decisive gas properties:

**Power:**
- ratio between enthalpy and electrical conductivity

**Efficiency:**
- Ratio between enthalpy and heat conductivity
- Ratio between enthalpy and radiation emissivity

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**Graphs:**
- **Left:** Graph showing variations of enthalpy ($h$) with temperature for different plasma gases.
- **Middle:** Graph showing variations of electrical conductivity ($\sigma$) with temperature.
- **Right:** Graph showing variations of radiation emissivity ($\varepsilon$) with temperature.

**Legend:**
- Blue: steam
- Purple: argon/hydrogen 3:1
- Orange: argon
- Green: nitrogen/hydrogen 2:1
Efficiency of utilizing plasma enthalpy for processing

Efficiency of utilizing plasma enthalpy for processing

Plasma in

Temperature $T_0$

Enthalpy $h_0$

Enthalpy flow rate $G.h_0$

Reactor space

Reaction Temperature $T_R$

Reaction Temperature $T_R$

$\geq 0$

Enthalpy $h$ $\geq h_R$

Enthalpy flow rate $G.h_R$

Plasma and reaction products out

Temperature $T \geq T_R$

Treated material

Only enthalpy $\Delta H = G.h_0 - G.h_R$ can be used for the treatment of material

Process efficiency:

$$\eta_R = \frac{G.(h_0 - h_R)}{G.h_0} = 1 - \frac{h_R}{h_0}$$
Operation regimes of gas-stabilized and water-stabilized dc arc torches

Operation regimes are expressed by the relation between arc power and mass flow rate

Mean plasma enthalpy:

Gas torches: 10 – 40 MJ/kg

Water torches: 100 – 300 MJ/kg
Hybrid gas/water dc arc plasma torch

Principle of hybrid gas/water plasma torch

Operation regimes of dc arc plasma torches
### Typical parameters of dc arc plasma spraying torches

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<td>N₂</td>
<td>700</td>
<td>180</td>
<td>40</td>
<td>8.0</td>
<td>3.6</td>
<td>3 000</td>
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<td>300</td>
<td>115</td>
<td>32</td>
<td>6.4</td>
<td>2.9</td>
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<td>Ar/H₂ (65/3)</td>
<td>500</td>
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<td>1.93</td>
<td>0.15</td>
<td>15.3</td>
<td>10 800</td>
</tr>
<tr>
<td>N₂/H₂ (235/94)</td>
<td>500</td>
<td>200</td>
<td>5.0</td>
<td>0.10</td>
<td>24</td>
<td>6 200</td>
</tr>
<tr>
<td>Ar/H₂ (33/10)</td>
<td>750</td>
<td>25</td>
<td>0.98</td>
<td>0.08</td>
<td>13.5</td>
<td>12 100</td>
</tr>
<tr>
<td>water</td>
<td>300</td>
<td>84</td>
<td>0.2</td>
<td>0.004</td>
<td>252</td>
<td>15 800</td>
</tr>
<tr>
<td>water</td>
<td>600</td>
<td>176</td>
<td>0.33</td>
<td>0.006</td>
<td>320</td>
<td>17 500</td>
</tr>
</tbody>
</table>
Thermal efficiency of water-stabilized and gas-stabilized torches

\[ \eta = \frac{P_{\text{jet}} - G \cdot h_T}{P_{\text{jet}}} = 1 - \frac{h_T \cdot G}{P_{\text{jet}}} \]

\[ h_T = h(T) \sim T \sim S(T) \]
In most plasma generators gas (water) is supplied into the discharge chamber and plasma jet is produced at the exit nozzle.
Plasma Jet Instabilities

Gas dynamic instabilities:
- Fluctuations and turbulences in the arc chamber
- Interaction of plasma jet with ambient gas outside the arc chamber

Arc instabilities:
- Fluctuations of arc power due to ripple of rectified arc current
- Arc column instabilities, changes of arc length
- Instabilities caused by electrode processes
Plasma jet interaction with ambient gas

Production of vortex structures at the jet boundary
Entrainment of cold gas into plasma flow
Formation of plasma flow turbulence
Development of gas-dynamic instability and effect of anode attachment

Arc voltage and light fluctuations at various axial positions.

Positions of diodes: $z_{d1} = 2.4$ mm
$z_{d2} = 4.3$ mm
$z_{d3} = 6.2$ mm
Jet instability caused by anode attachment

Arc anode attachment:
- anode jet
- movement in the restrike mode

Jet instability caused by anode attachment

Laminar jet
Jet instability
Entrainment of cold gas
Anode jet

Exposure time 3 µs
Anode restrike and movement of anode attachment

Fluctuations of arc voltage  ➡️ Fluctuations of arc power

Sequence of four images of anode region of plasma jet

exit nozzle

anode
**Effect of fluctuations of arc current**

For classical 6-way rectifiers:

\[ \Delta I/I = 0.1 - 0.15 \]

Frequency: 300 Hz

Amplitude of fluctuations of arc power depends on relation between \( \tau_I \) and \( \tau_a \)

1. \( \tau_I \ll \tau_a \)
   - Arc has constant conductance: \( U = U + R_s \cdot \Delta I \)
   - Amplitude of fluctuations of arc power: \( \Delta P/P = 2 \Delta I/I + (\Delta I/I)^2 \)
   - For \( \Delta I/I = 0.1 - 0.15 \) \( \Delta P/P = 0.21 - 0.32 \)

2. \( \tau_I \gg \tau_a \)
   - Arc voltage follows static characteristic:
     - Constant arc voltage: \( \Delta P/P = \Delta I/I \)
     - Falling static arc characteristic: \( \Delta P/P < \Delta I/I \)
Diagnostics of thermal plasma jets

**Plasma jet core:**
- High gradients of temperature and velocity
- Laminar flow

**Turbulent jet:**
- Smooth T and v profiles
- Heterogeneous mixture of plasma and cold gas

**Fluctuations:**
- Spatial distribution
- Frequency spectra
- Phase velocity of oscillations

**Time averaged characteristics:**
- Temperature profilers
- Velocity profiles
- Plasma composition

**Shape of the jet**
**Jet structure**
Basic plasma characteristics evaluated
from measurements:
- Electron number density
- Temperature
- Molar concentrations of components

Basic methods:
- Absolute intensities of spectral lines
- Line intensity ratios
- Stark Broadening

Problems:
- Non LTE conditions
- High gradients of temperature
electron diffusion
de- mixing of plasma gases
- Non symmetrical cross section of the jet
Enthalpy probe

**Isokinetic coefficient**

\[ K_{iso} = \frac{G}{\pi R^2 \rho_p V_p} \]

**Measurements:**

1. Tare – no plasma flow
   
   \( Q \) – Heat flow rate
   
   \( P \) – Pressure

2. Sampling – plasma flows into the probe
   
   \( Q \) – Heat flow rate
   
   \( G \) – plasma flow rate

3. Mass spectrum
Evaluation of plasma jet characteristics from enthalpy probe measurements

Plasma enthalpy:
\[ h_0 = \frac{Q_{\text{sample}} - Q_{\text{tare}}}{G_g} + C_{pg} T_g \]

Plasma composition

Plasma temperature
Thermodynamic and transport coefficients

Local plasma velocity
\[ V = \sqrt{\frac{2(P_S - P_a)}{\rho(T)}} \]
Measurement of flow velocity

*Enthalpy probe - Pitot tube*
*Time of flight of fluctuations - emitted light*
*- electric probe current*

*Propagation of waves in plasma*

**Diagnostics of jet fluctuations and instabilities**
Determination of flow velocity from propagation of disturbance caused by an anode restrike

Anode restrike in the position d3

Ua - Arc voltage

Signals of photodiodes:
- d1 = 1 mm \((z/D = 0.167)\)
- d2 = 4.3 mm \((z/D = 0.717)\)
- d3 = 7.7 mm \((z/D = 1.28)\)
- d4 = 11 mm \((z/D = 1.83)\)
- d5 = 14.3 mm \((z/D = 2.38)\)
Determination of flow velocity

Stream-wise and counter-stream-wise velocities of perturbations caused by a formation of new anode spot and flow velocity evaluated as their difference
Determination of flow velocity from phase shift of jet fluctuations

Fluctuations of emitted light at various distances from the torch exit

Velocity of movement of oscillations

\[ v = 2\pi D \frac{f}{\Delta \Phi} \]
Determination of flow velocity

Fourier spectrum and dependence of phase shift of oscillations on frequency – argon, 10 kW

\[ v = \frac{2\pi D f}{\Delta \Phi} = 300 \text{ m/s} \]
Schlieren photography

plasma jet produced in water stabilized arc

D = 5 mm

D = 1 mm
High speed photography

Interaction of plasma jet with arc anode attachment

t [$\mu$s]:

0 10 20 30
5 15 25 35
Electric probes in thermal plasma jets

Ion collecting electric probes are used for study of structure of plasma flow

High biasing resistance – probe potential close to floating potential
Low biasing resistance – probe current close to ion saturation current
Negative biasing voltage increases sensitivity of probe measurement

Determination of probe potential

\[ I = \frac{U}{R_b} \]

\[ I = \frac{U}{R_a} - U_B \]

\[ I = \frac{U}{R_a} \]
Structure of the jet boundary

Lines of the same probe current at the plasma flow in the jet boundary
Thermal plasma processing

Plasma technologies and decisive mechanisms

**Heat transfer**
- Plasma melting
- Plasma cutting

**Heat and momentum transfer**
- Plasma spraying
- Surface modifications

**Chemical processes – decomposition and/or synthesis**
- Waste treatment, gasification, vitrification
- Plasma CVD – production of films
- Plasma synthesis
Plasma spraying
Decomposition of Persistent Chemical Compounds and Waste Treatment

Gasification + vitrification

Plasma reactor

Treated material → Plasma torch → Syngas $\text{H}_2 + \text{CO}$ → vitrified lava

Plasma reactor
Operating Experience – Commercial Project
Toxic Waste Destruction Project at Plasma Center, Madison, PA

- Project using Pyroplasma Trailer
  Commenced in 1986
- Destruction of Liquid Toxic Waste
- MARC-11H Torch
  - 1 active, 1 spare
- Nominal Power:
  - Total System: 800 kW
  - Individual Torch: 600 – 800 kW
- Process gas: Oxygen
- Electrode Life:
  - Anode: 900 Hours
  - Cathode: 200 Hours

Westinghouse Plasma Corporation...Your Partner for Plasma Technology Solutions
CONCLUSIONS

- Basic thermal plasma jet properties:
  - Temperature and velocity profiles, plasma enthalpy, plasma composition
  - Flow structure and (in)stability

- Basic plasma torch design parameters:
  - Arc chamber geometry, length and diameter
  - Gas composition, gas flow rate

- Basic diagnostics for thermal jets
  - Spectroscopy
  - Enthalpy probes
  - High speed photography, schlieren photography
  - Electric probes

- Thermal plasma applications:
  - Metallurgy, welding, cutting
  - Surface modifications, coatings
  - Materials synthesis
  - Decomposition, waste treatment