Conversion of Hydrocarbons into Syn-Gas Stimulated by Non-thermal Atmospheric Pressure Plasma

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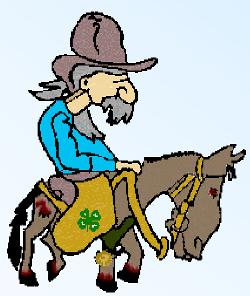
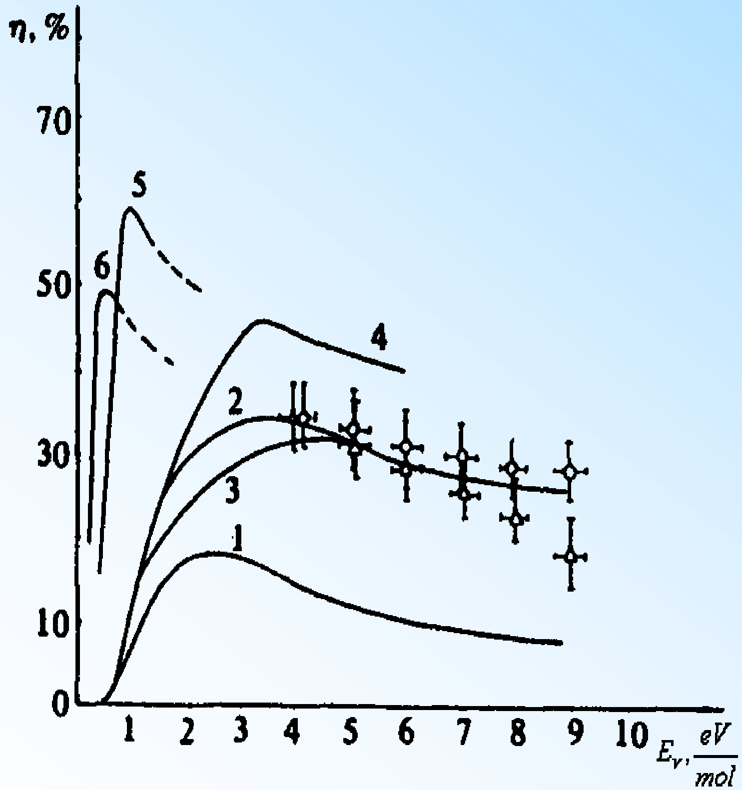
- Plasma Catalysis Vs. Plasma Processing
- Methane Conversion to Hydrogen
- Gliding Arc in Tornado
- Experiments and Modeling
- Plasma Catalytic Conversion of Hydrocarbons as Hydrogen Production Technology

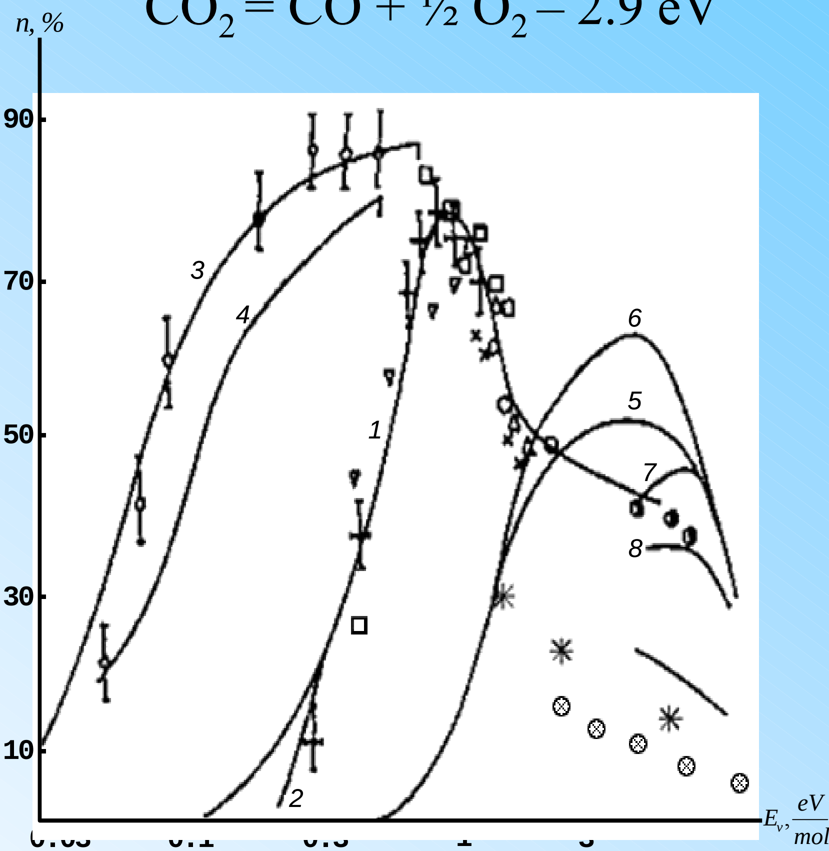


Plasma-Chemical Hydrogen Production from Water

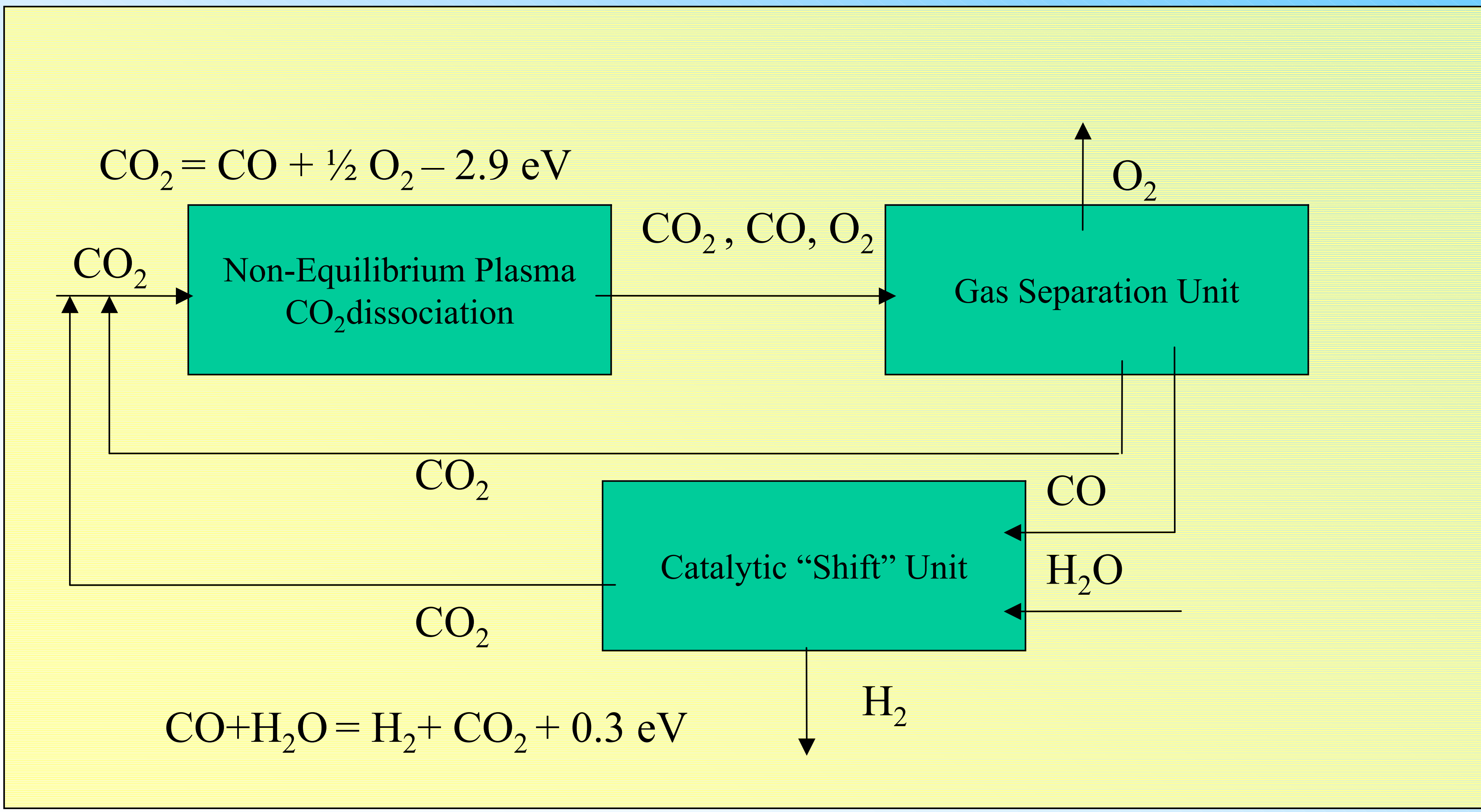
$H_2O = H_2 + \frac{1}{2} O_2 - 2.6\ eV$



$CO_2 = CO + \frac{1}{2} O_2 - 2.9\ eV$



Two Step Plasma Cycle for Hydrogen Production



Plasma Catalysis Vs. Thermo-Catalytic Partial Oxidation

$$CH_4 + 1/2\ (O_2 + 3.76\ N_2) \xrightarrow[\text{Temperature}]{\text{Catalysis}} CO + 2\ H_2 + 1.88\ N_2 + 36\ \text{kJ/mol}$$

Thermo-Catalytic Conversion:

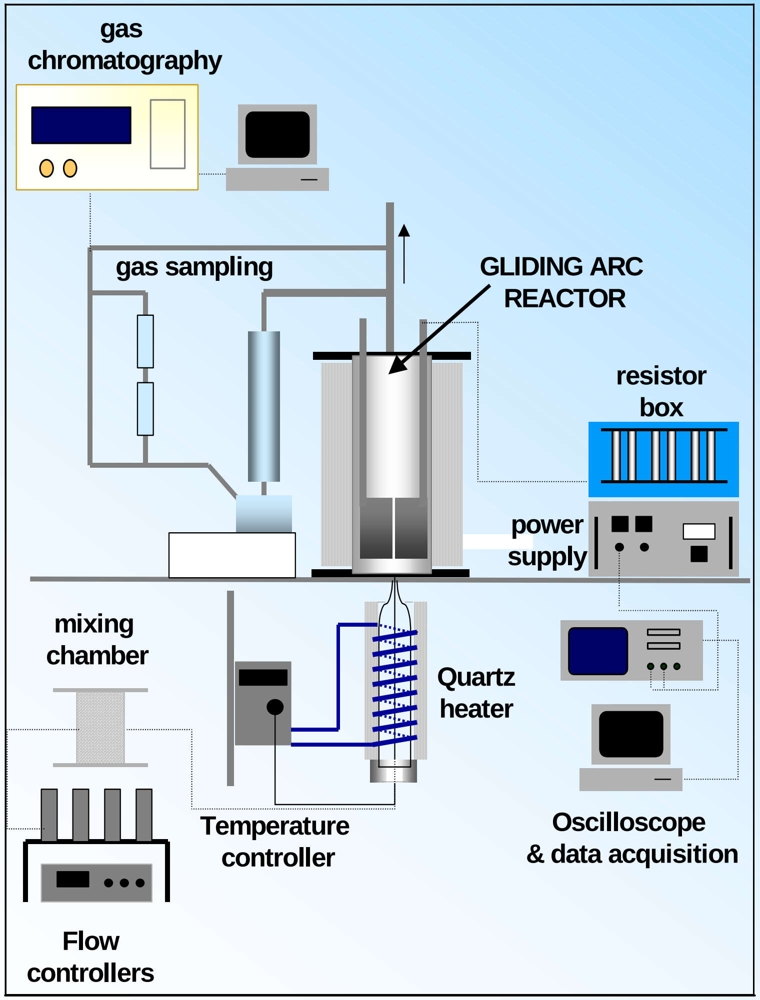
- High Temperature Requirements (>1100K)
- Large Specific Size of Reactor
- Special Materials Requirements and Reactor Design
- Sulfur from Natural Gas Causes Catalyst Poisoning
- Low Conversion at Moderate Equivalence Ratios (3.0-3.5)

Plasma-Catalysis:

- Low Temperature Operation (~750K)
- Large Specific Productivity
- Lower Temperature Requirements
- No Sensitivity to sulfur or other impurities
- Possibility to Operate at High Equivalence (3.5-4.5)

Plasma As Catalyst

Plasma Catalytic Hydrogen Production from Natural Gas



Plasma PO optimal parameters:

$$CH_4+0.5O_2 = CO + 2\,H_2$$

optimal equivalence ratio = 3.3,
[O2]/ [CH4]=0.6

Preheating temperature = Internal, 750K
Conversion = 92%
Electric energy cost :
- **experimental = 0.06 kWh/m^3**
- **modeling EQ = 0.11 kWh/m^3**
- **modeling NE = 0.07 kWh/m^3**

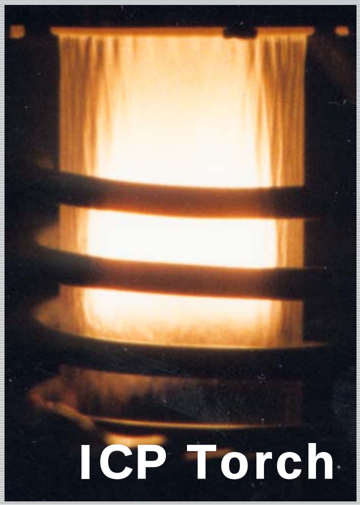
Output Syn-Gas energy = 3.00 kWh/m^3
power for 100,000 barrel/day of Liquid Fuel:
- **experimental = 4.5 MW**
- **modeling EQ = 8.2 MW**
- **modeling NE= 5.2 MW**

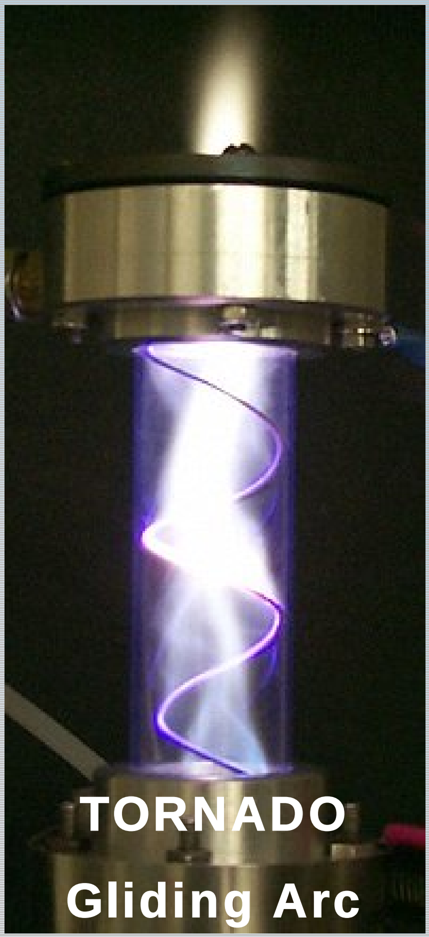
Which Plasma to Choose?

Thermal Plasma

Non-Thermal Plasma


X-ray view of the sun


ICP Torch


TORNADO Gliding Arc


Aurora


Corona Discharge

Gliding Arc as Transitional Non-Equilibrium Plasma:

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THERMAL PLASMA

- Very High Plasma power and density.
- High Gas temperature.
- No selective chemical process can be achieved.

NON-THERMAL PLASMA

- Low gas temperature and very high electron temperature.
- Low Power Density
- Chemical Selectivity can be achieved.

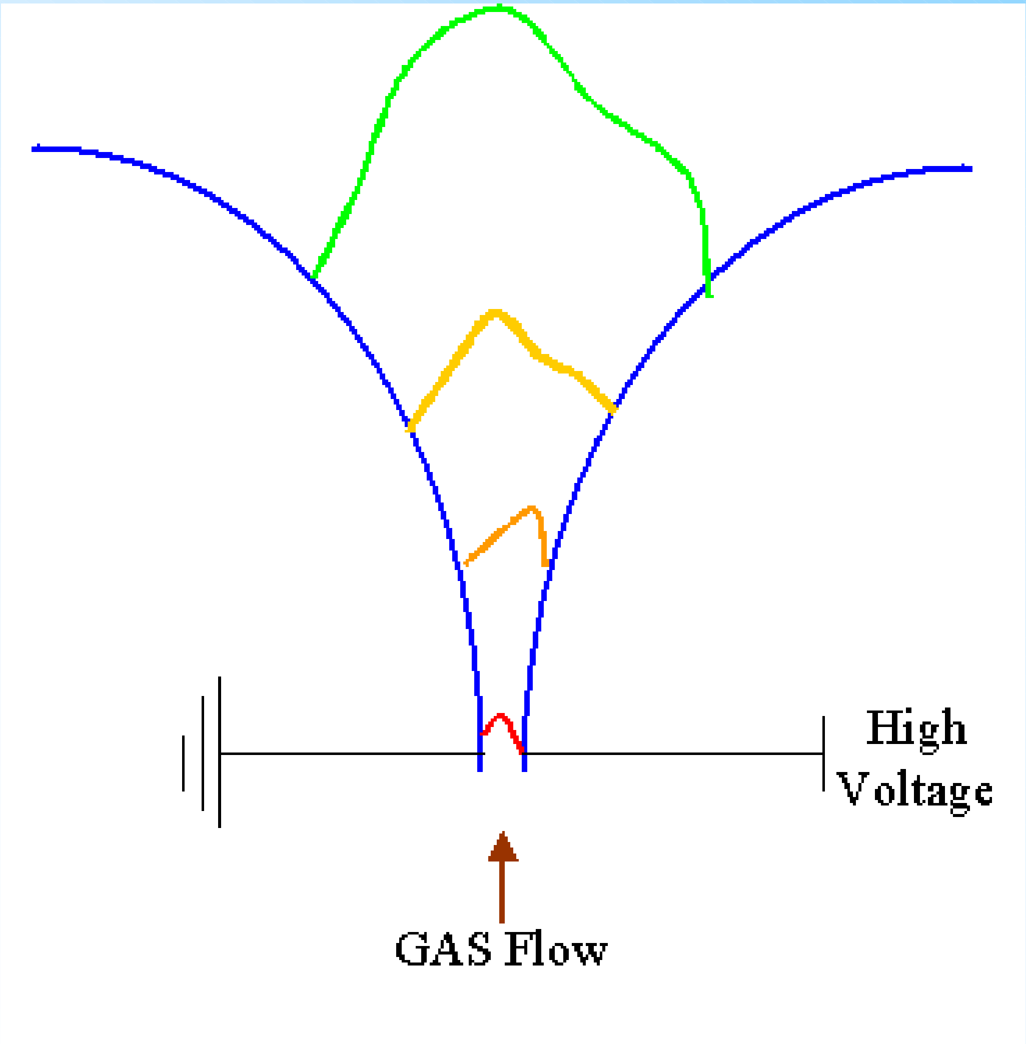
MAJOR CHALLENGES :

- Power Density & Productivity.
- Selectivity.

"Gliding Arc in Tornado"

"GLIDING ARC in Flat Geometry"

Fast Equilibrium to Non-Equilibrium Transition



•Arc starts in a narrow gap between diverging electrodes in a gas flow.

•Current increases very fast and the voltage on the arc drops.

•Gas flow forces the arc to move along the diverging electrodes and elongate. The growing arc demands more power to sustain itself.

•Arc cools down and becomes Non-Equilibrium to sustain itself with less power.

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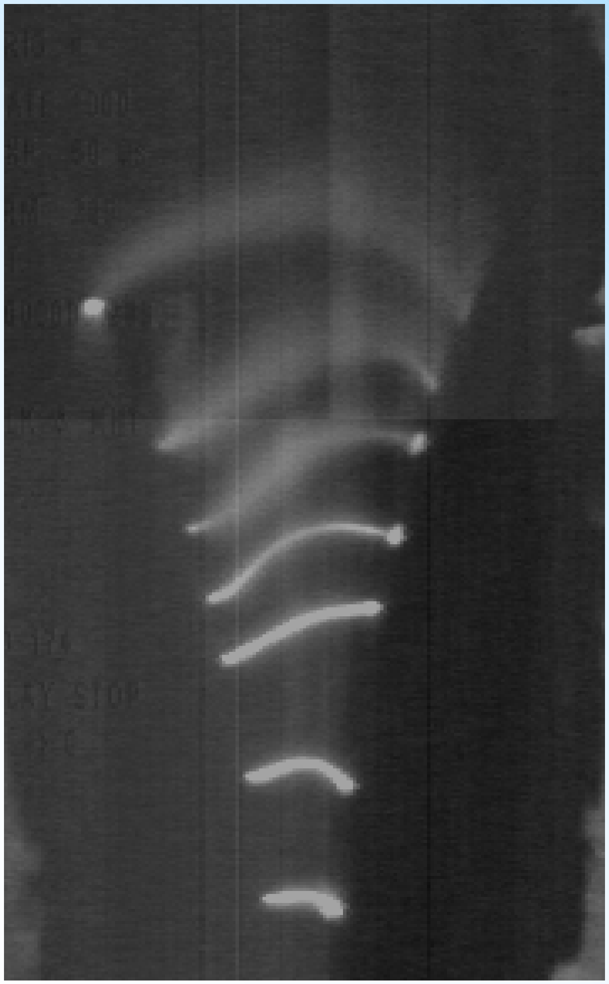
"GLIDING ARC in Flat Geometry"

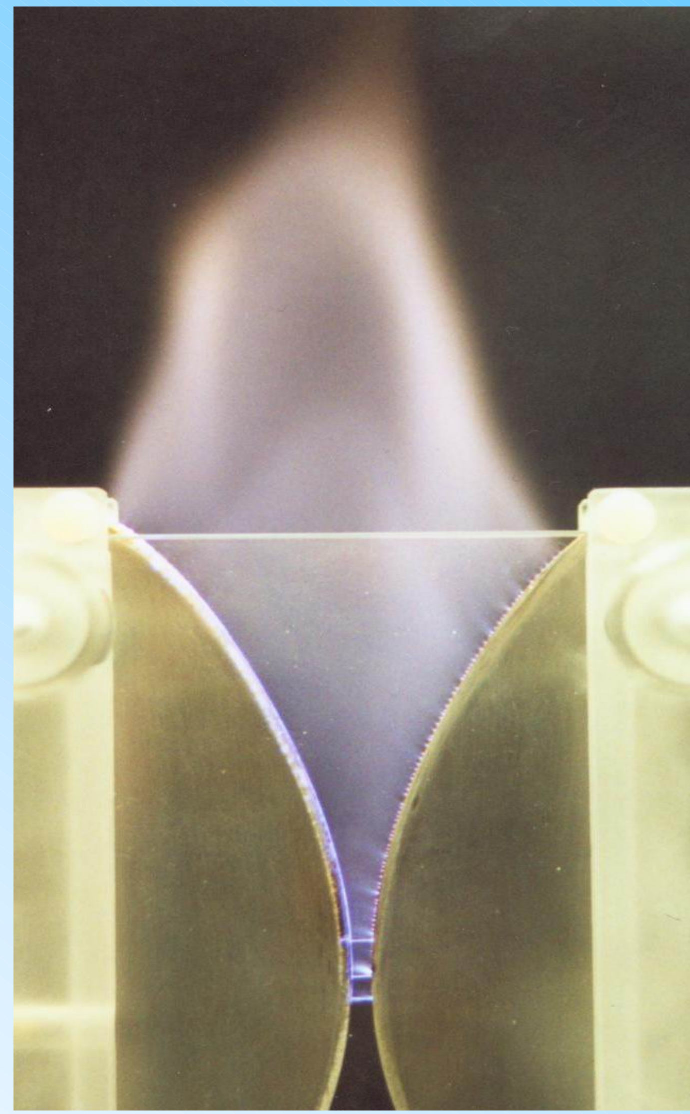
Fast Equilibrium to Non-Equilibrium Transition



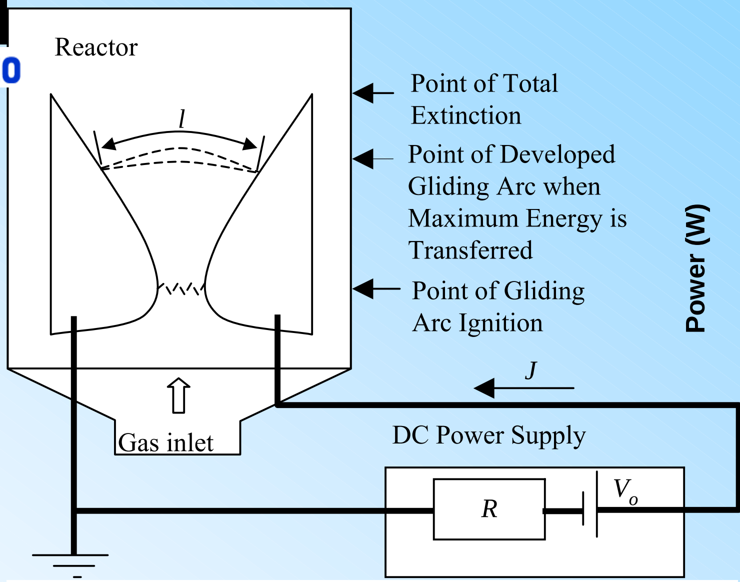
Extinction

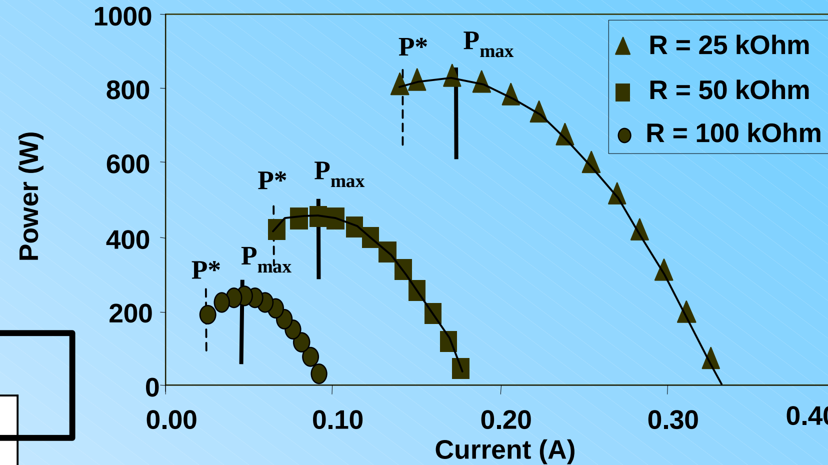
Elongation

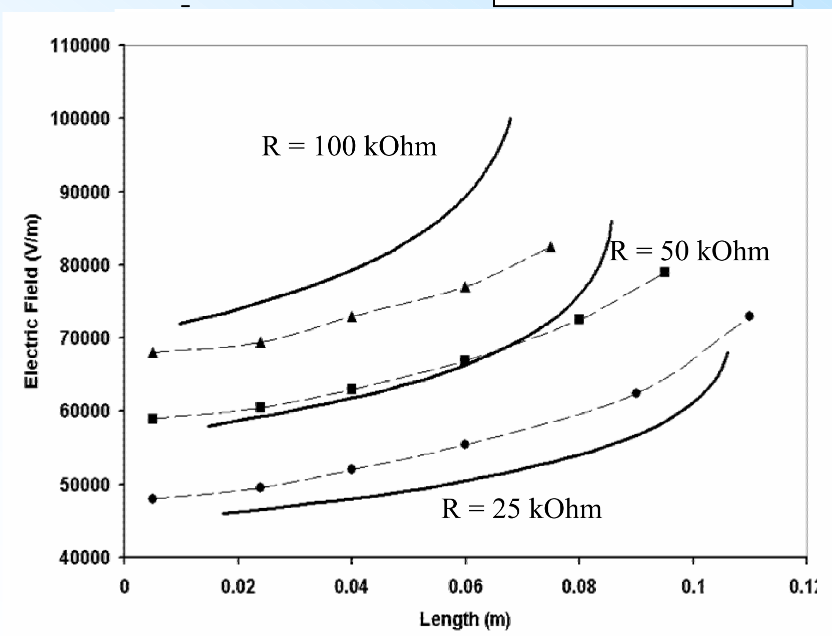
Initial Breakdown

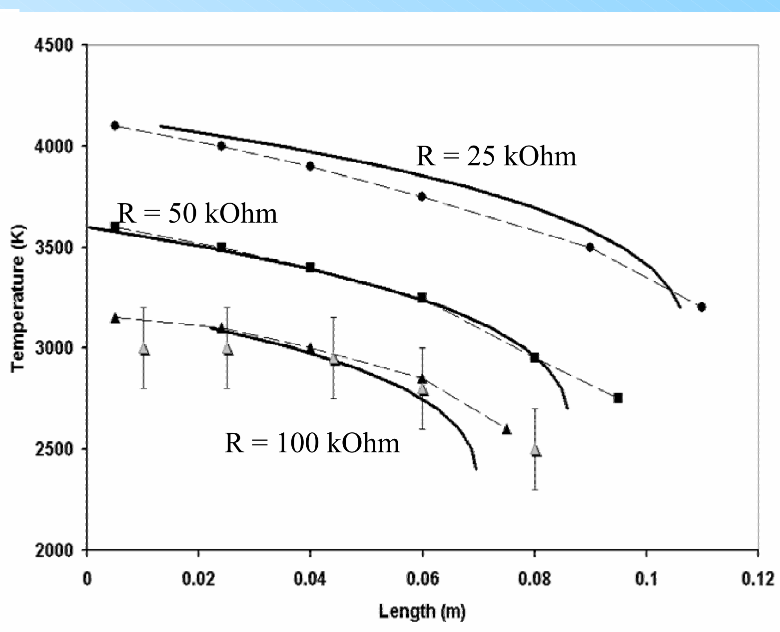


Non-Equilibrium Gliding Arc

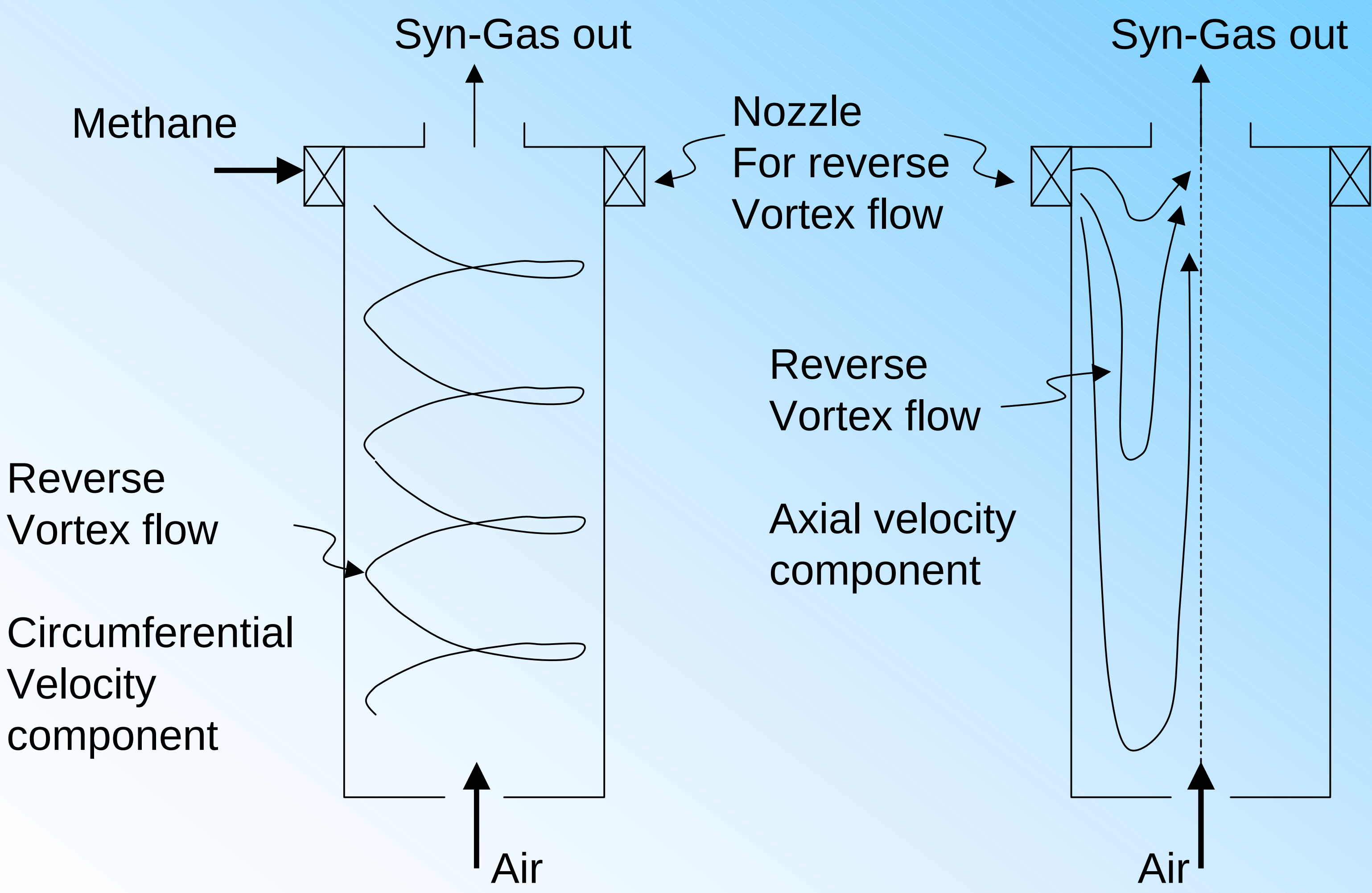








Reverse Vortex Flow (Tornado) Stabilization of Gliding Arc



Gas Burner with Reverse Vortex Flow, "Tornado" Stabilization of Flame

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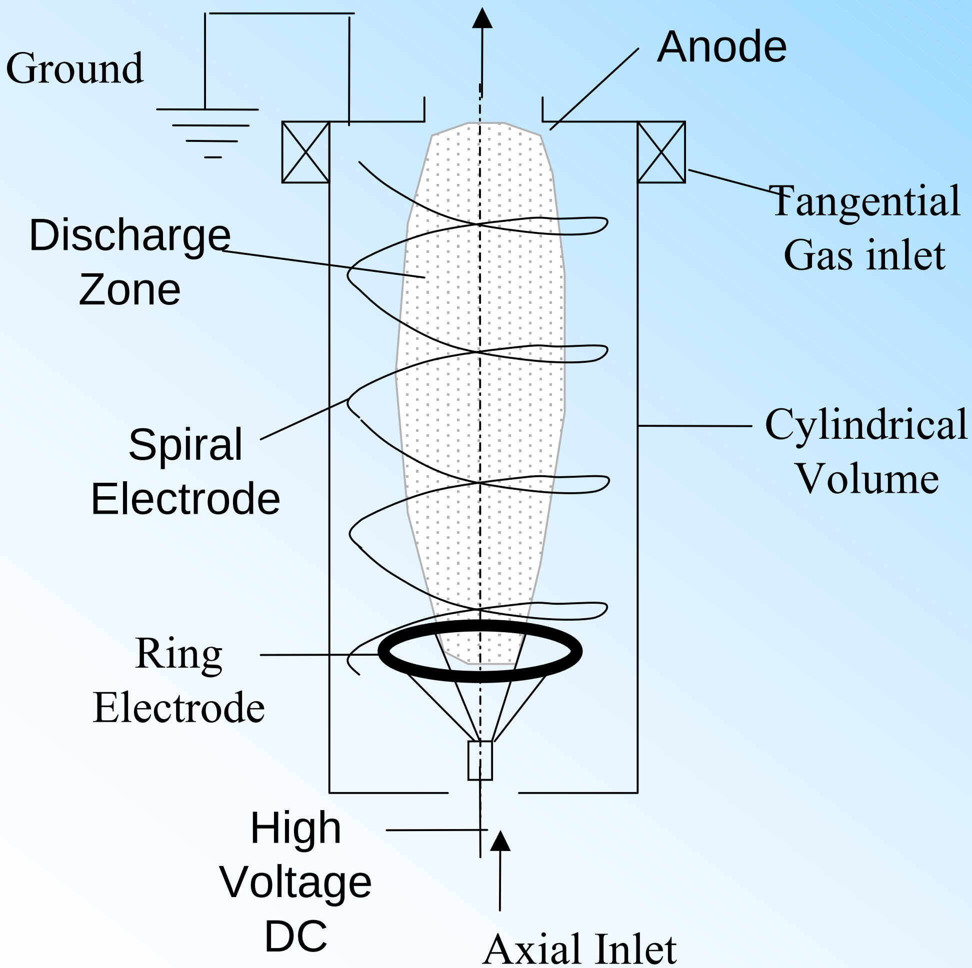
ε ~ 0.5

ε ~ 1.1

ε ~ 1.8

"THE GLIDING ARC IN TORNADO"

Gliding Arc in Tornado Flow



Schematic Diagram for GAT reactor.

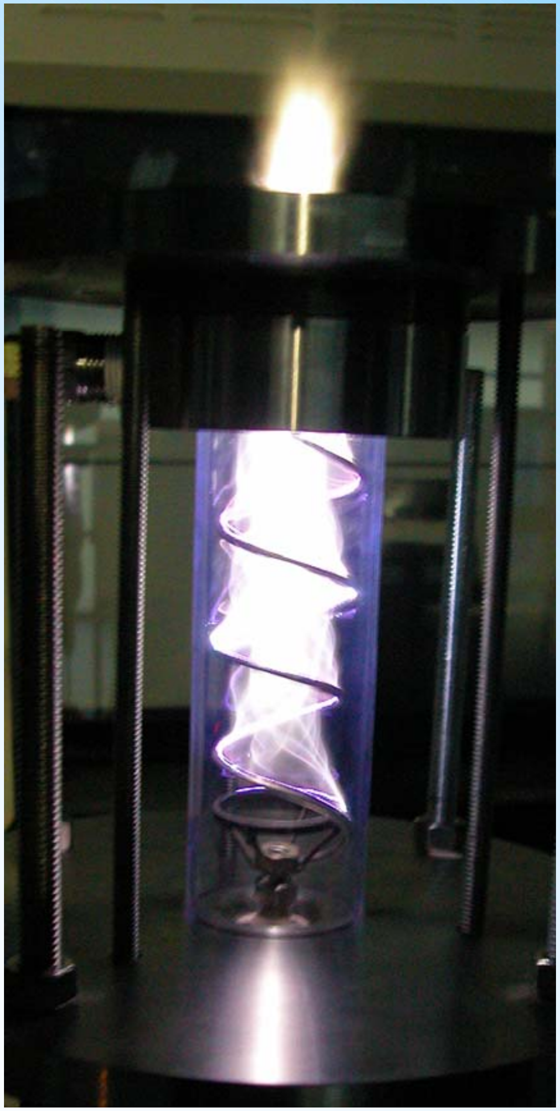
•Gliding Arc in Tornado works in a Reverse Vortex Flow setup.

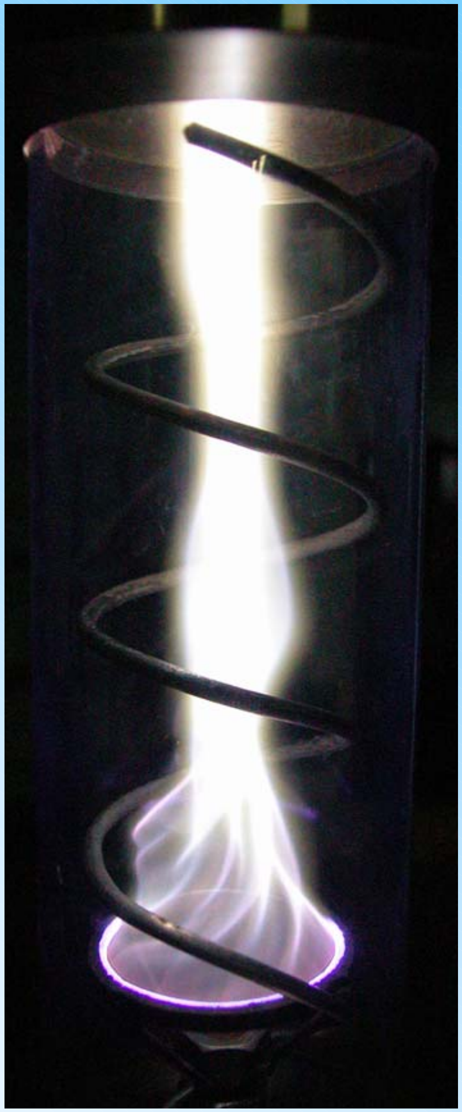
•A circular and spiral electrode is placed in the plane of the flow act as diverging High Voltage DC Electrodes.

•The flow conditions and the characteristics of the power supply determine the shape of the spiral electrode.

Gliding Arc "Tornado"

From the Spiral to the Ring





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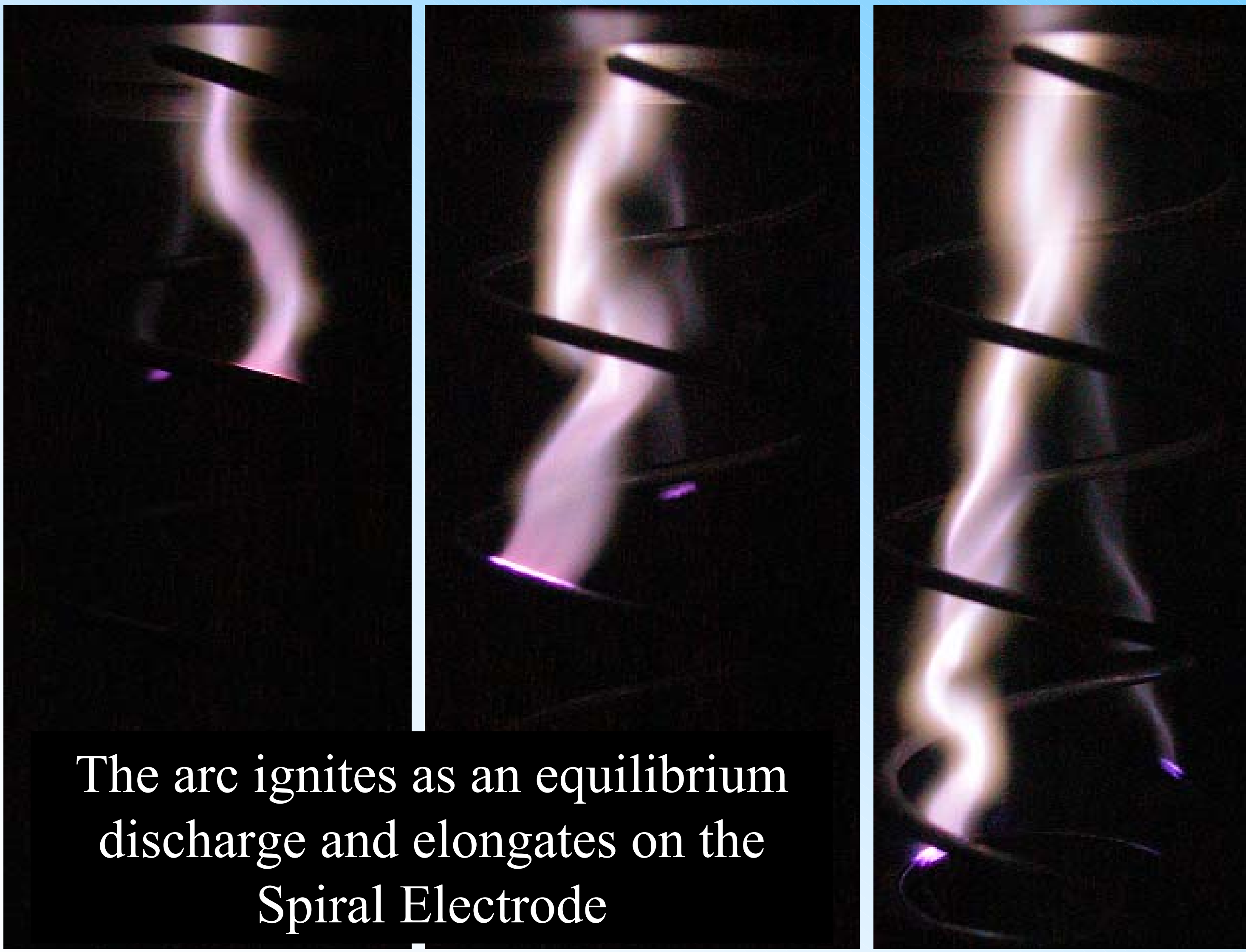
Gliding of Arc on Spiral Electrodes in Reverse Vortex Flow



The arc ignites as an equilibrium discharge and elongates on the Spiral Electrode

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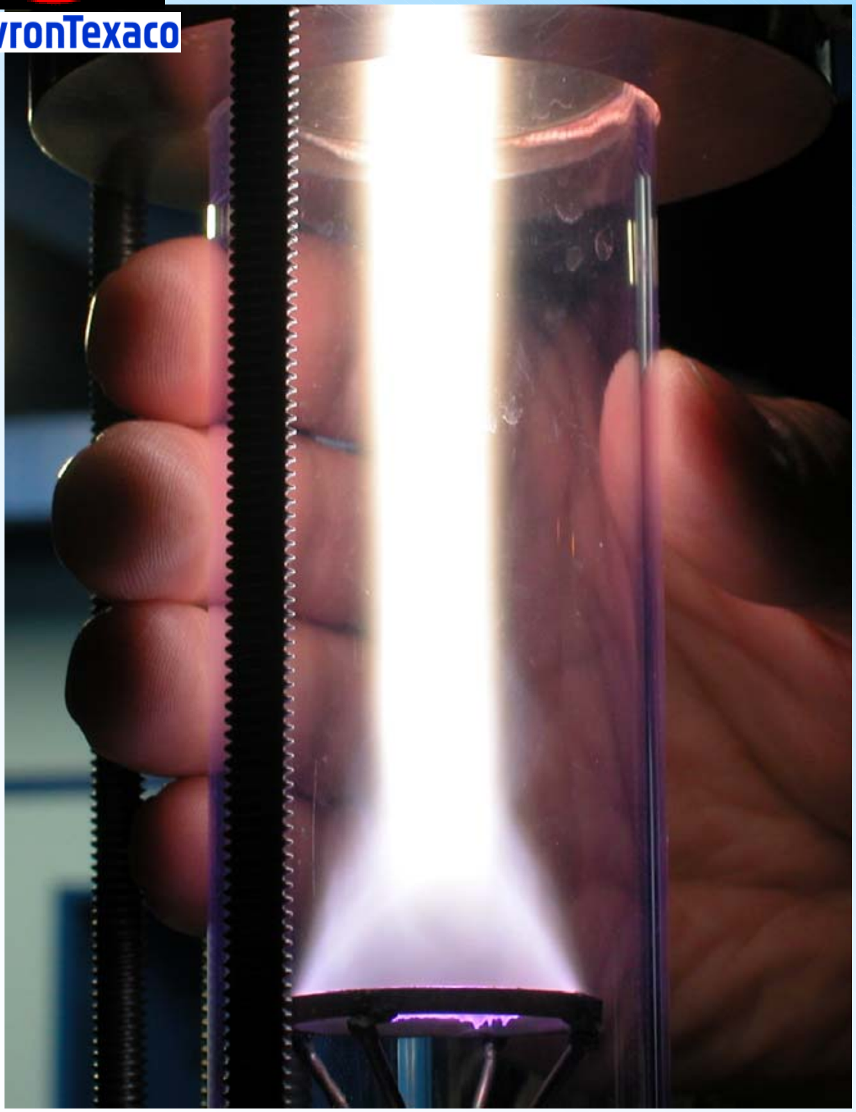
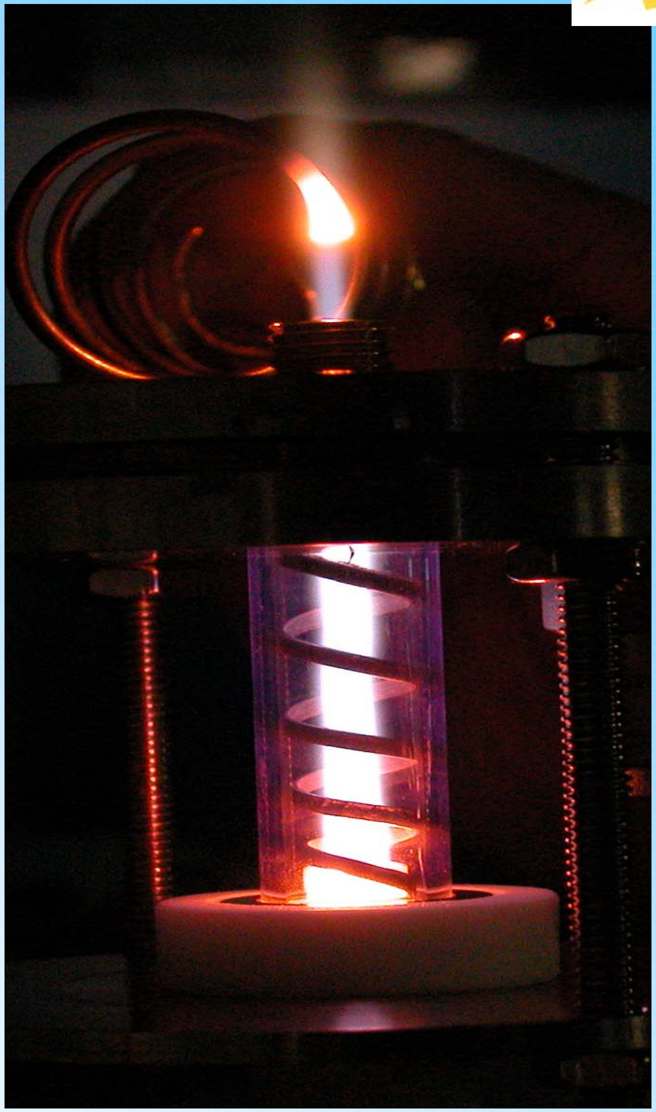
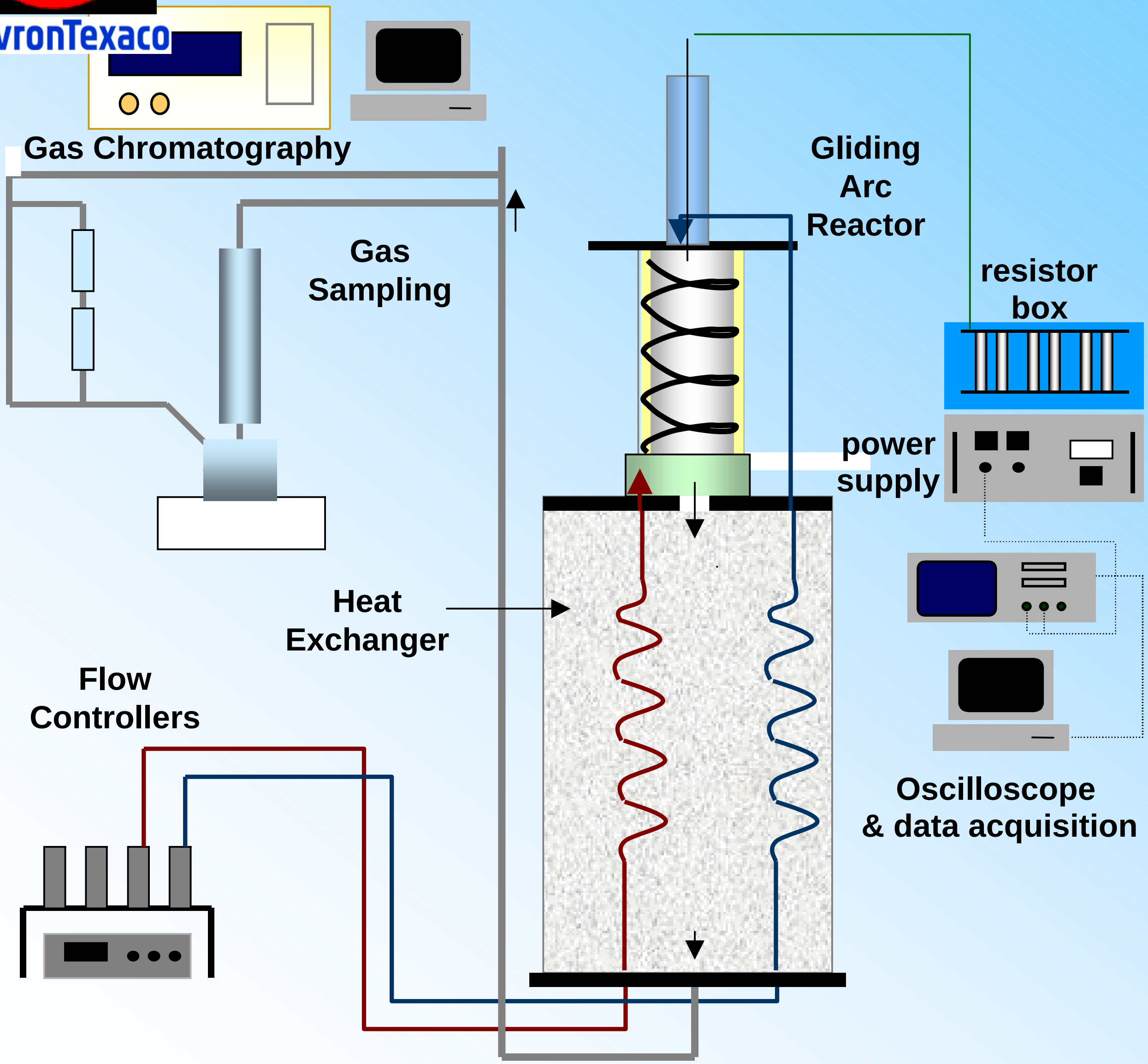
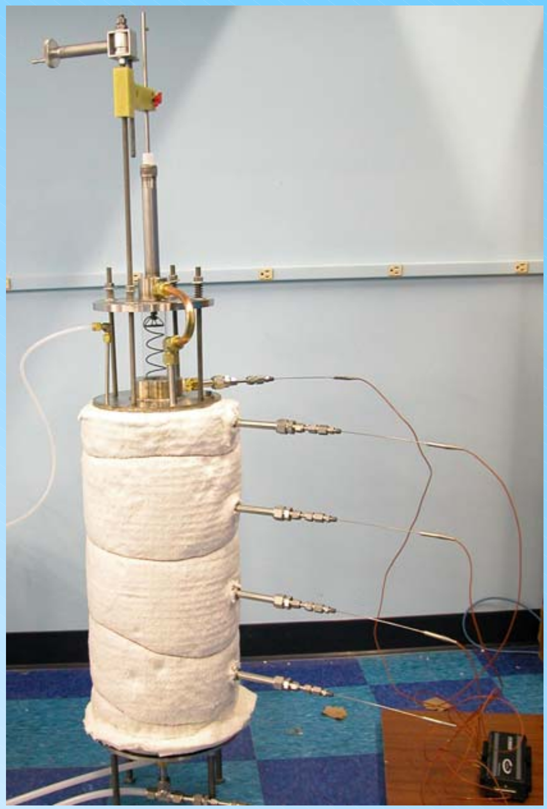
"It Can Melt a Metal Rod But You Can Touch It"



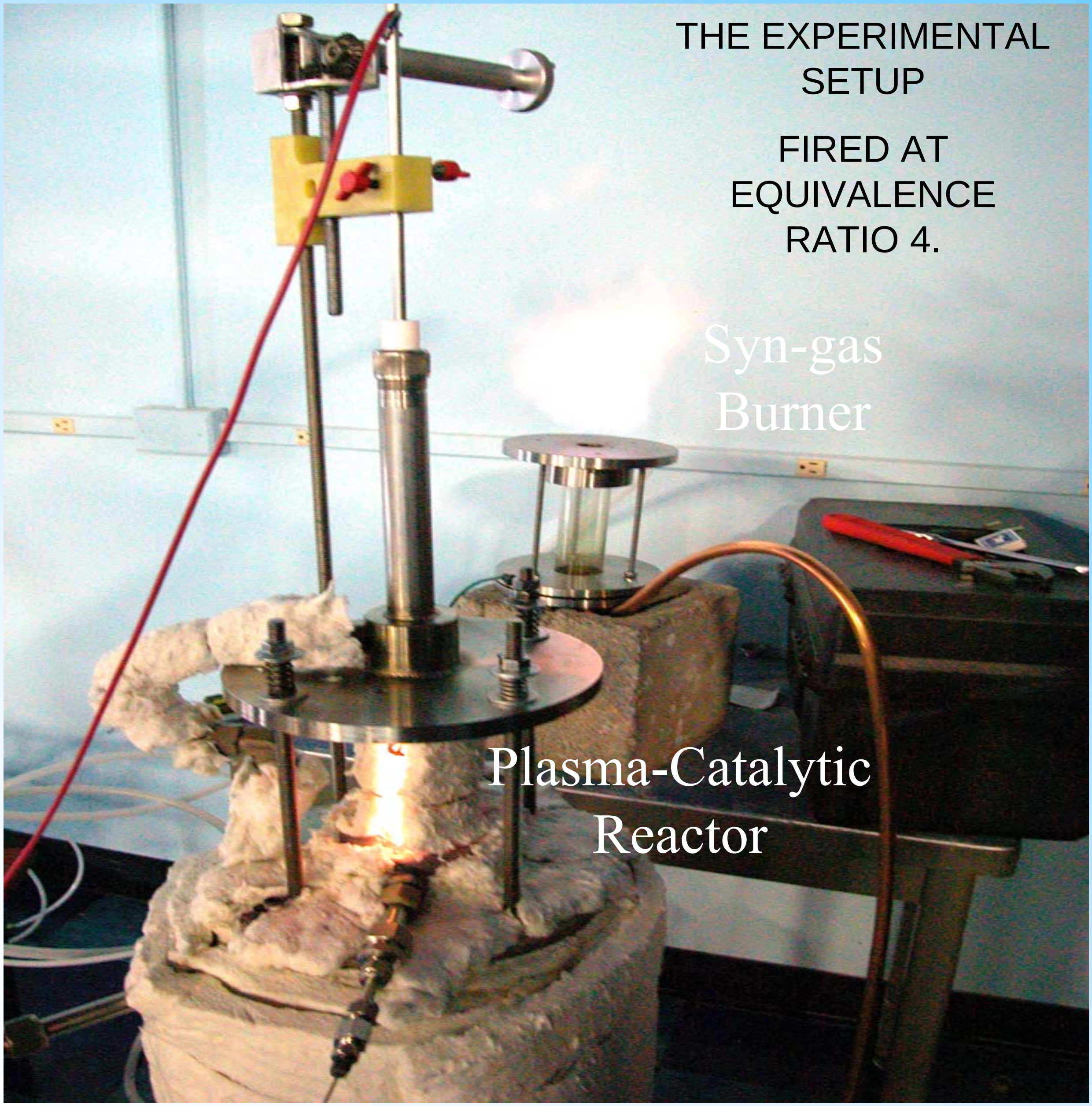


EXPERIMENTAL SETUP





Plasma Catalytic Methane Partial Oxidation



Chemical Kinetics Simulation

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The entire process includes three main stages:

1.) Electric discharge stage
2.) Mixing of air and post discharge methane.
3.) Post discharge regime .

- The neutral species chemistry was described by the GRI-MECH 2.11 kinetic scheme including 65 species and 200 reactions. In the post discharge region the gas mixture is allowed to react within a certain residence time, with small heat losses.

The syn-gas production is characterized by two stages:

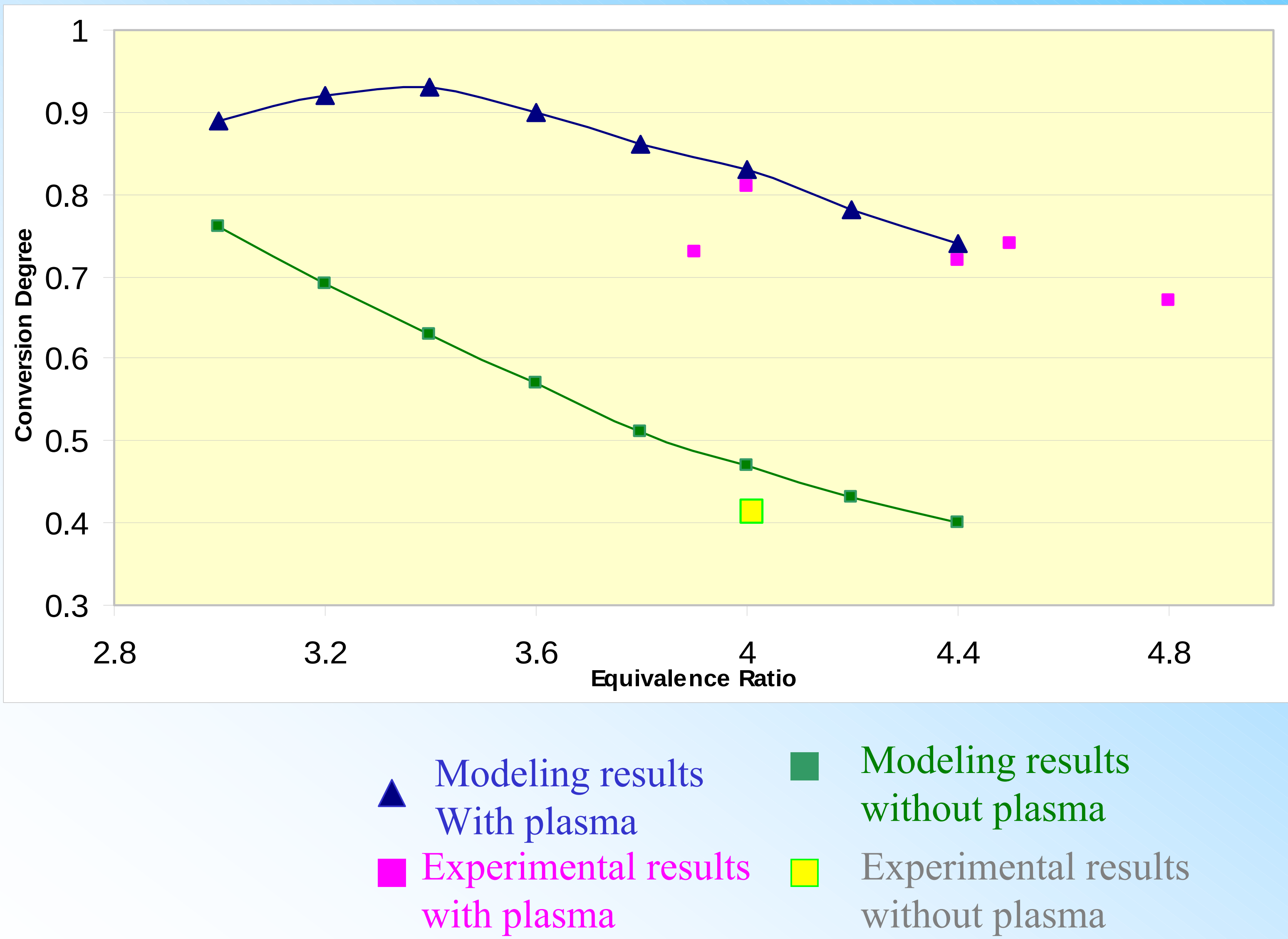
1.) The short combustion zone.
2.) The longer zone, which can be called as the reforming zone

- At the first stage the concentrations of O and OH radicals are relatively large, and it is characterized by very fast chemistry.

- At the second stage, much slower chemistry takes place. Water and CO2 are consumed, yielding hydrogen and CO, the corresponding reaction are endothermic ones, causing the observable temperature decrease.

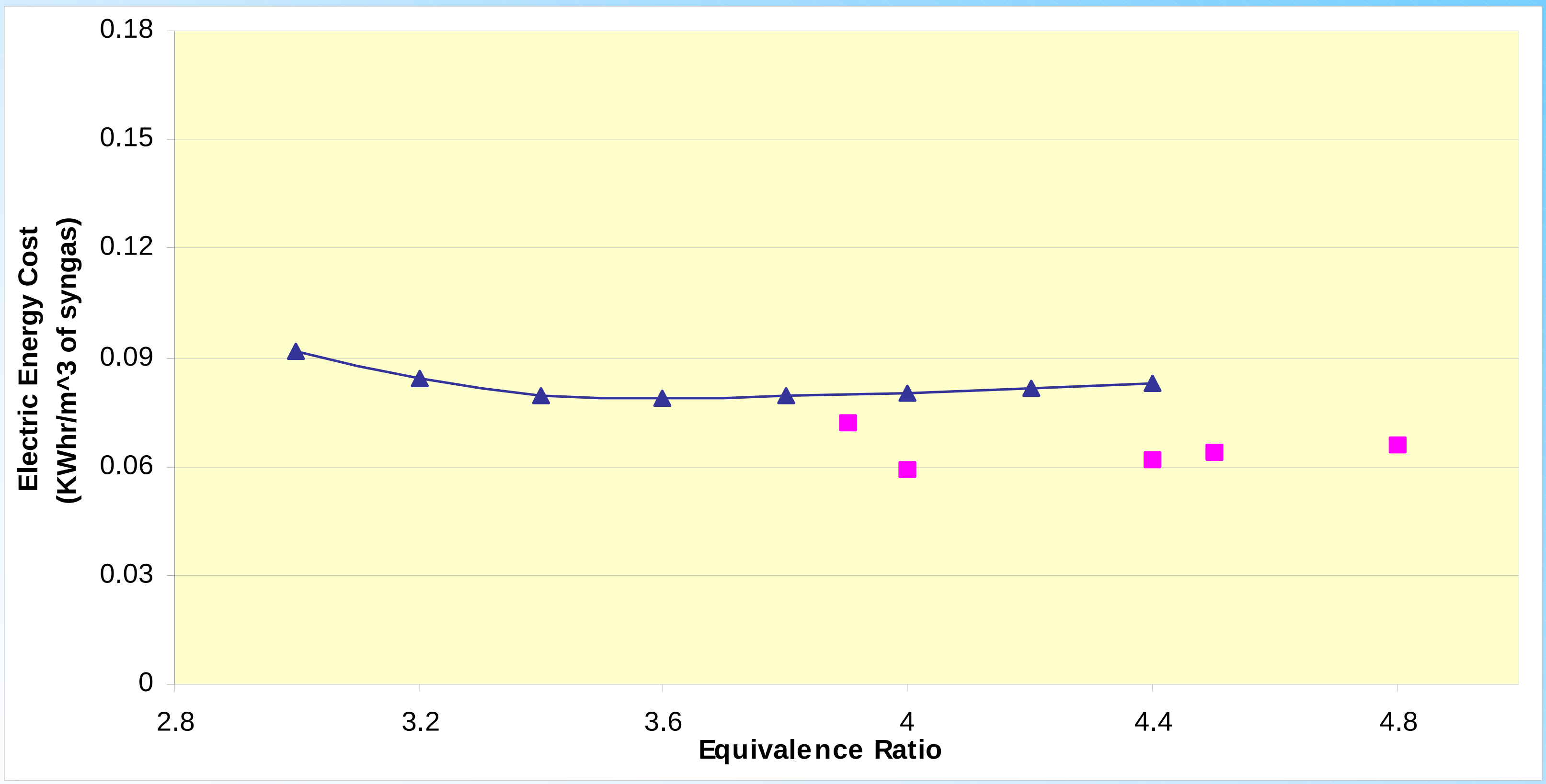
Simulation Vs Experiments

The conversion degree: $\alpha = ([H2] + [CO]) / 3[CH4]$



Simulation Vs Experiments

Electric Energy Cost = W_{el}(KW-hr)/ meter cube of Syn-Gas (Output Syn-Gas Energy = 3.00 kWh/m^3)

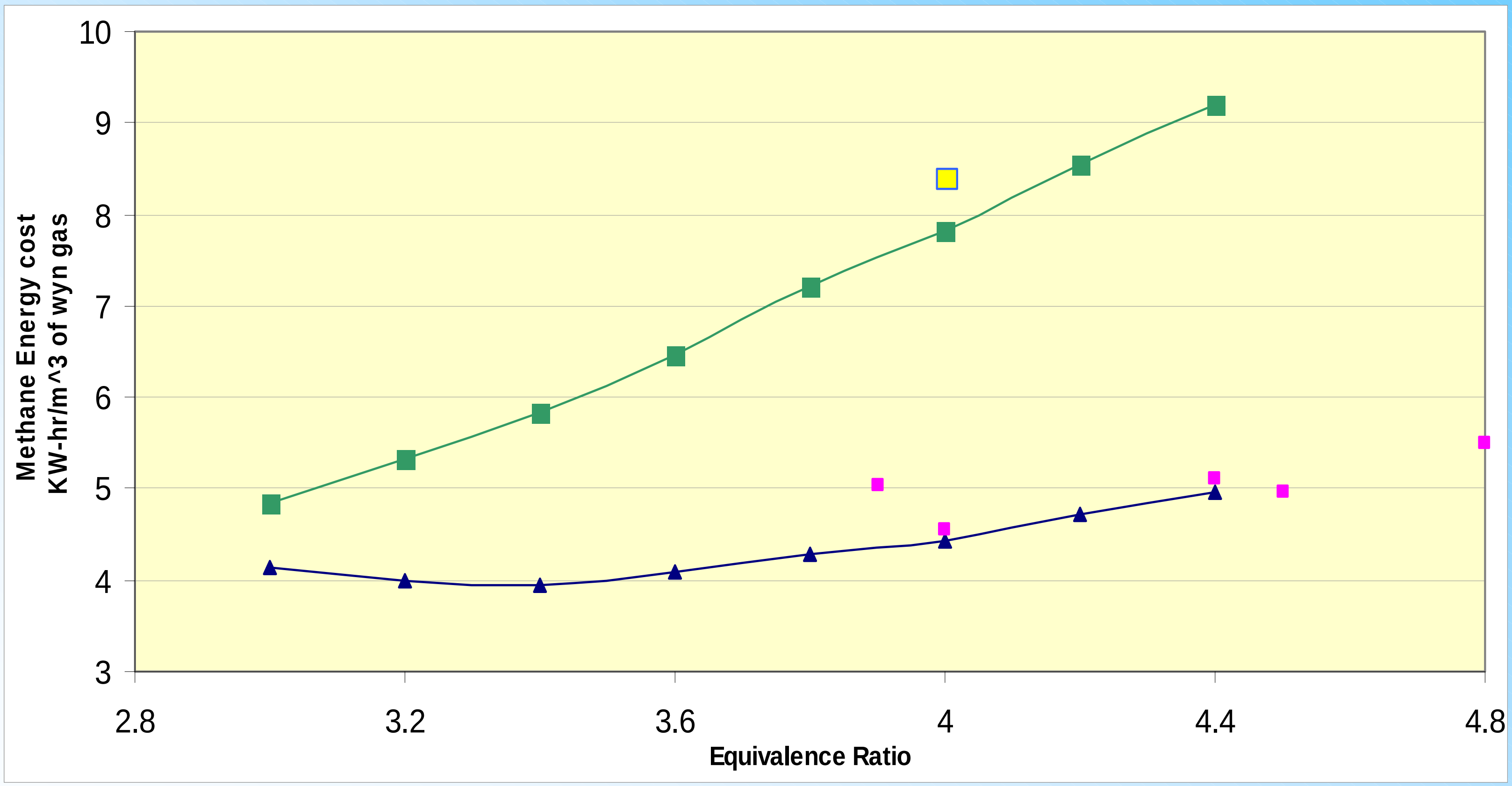


▲ Modeling results

■ Experimental results

Simulation Vs Experiments

Methane Energy Cost = [CH4] (KW-hr) per meter-cube of Syn-Gas



▲ Modeling results with Plasma

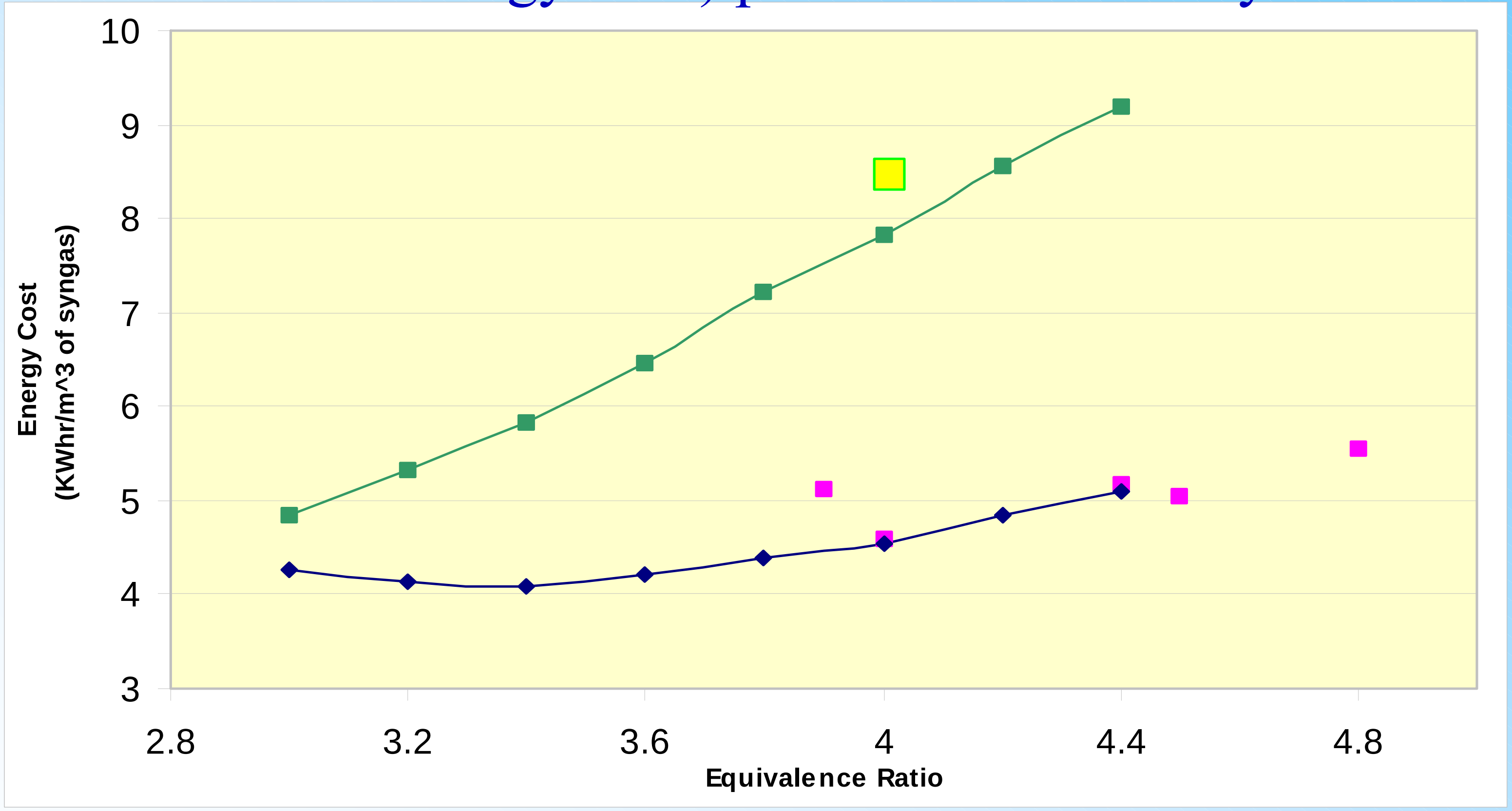
■ Experimental results with plasma

■ Modeling results without plasma

□ Experimental results without plasma

Simulation Vs Experiments

Total Energy Cost = (Electric Energy Cost + Methane Energy Cost) per meter Cube of Syn-Gas



Modeling results With plasma

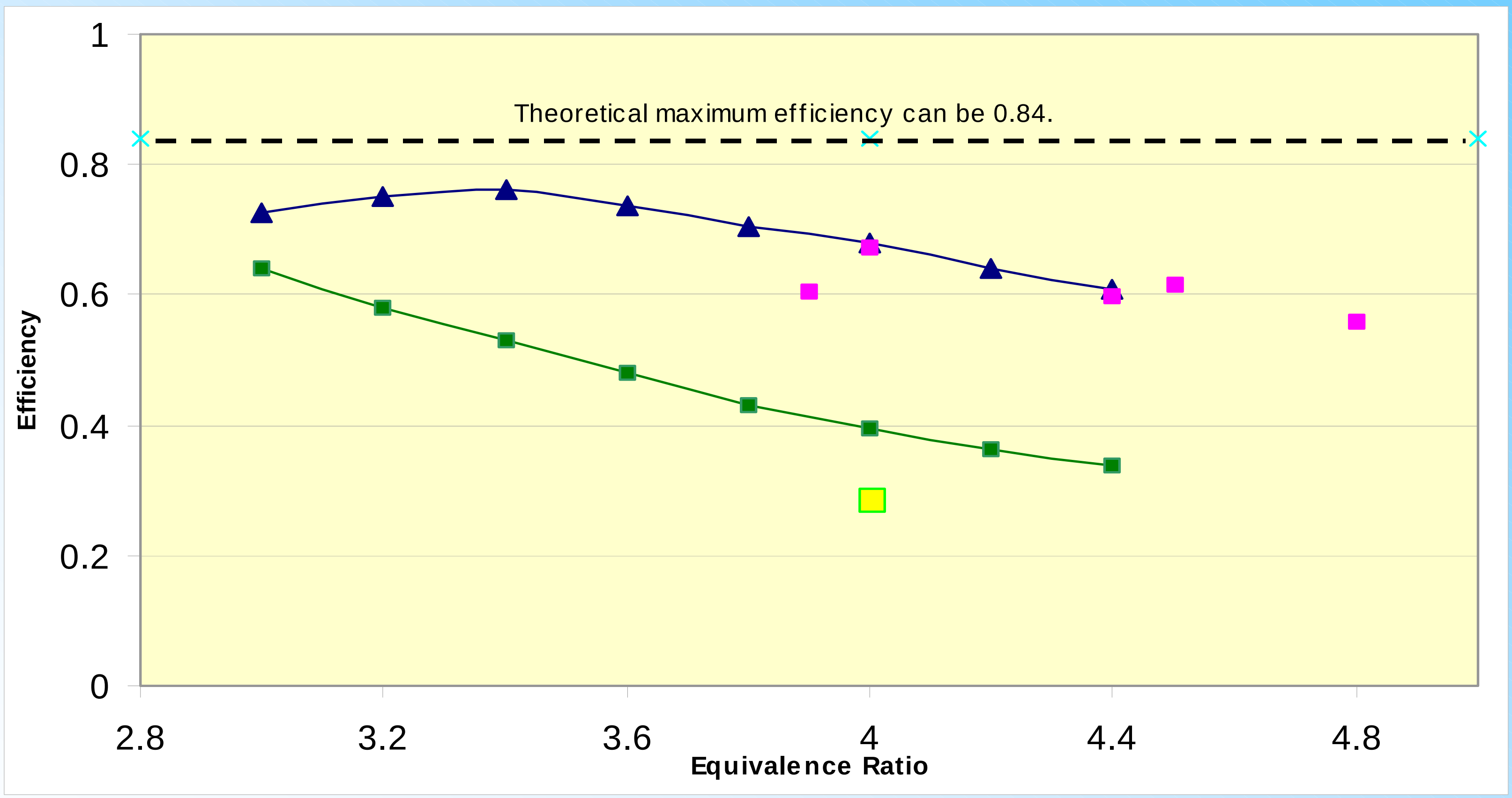
Modeling results without plasma

Experimental results with plasma

Experimental results without plasma

Simulation Vs Experiments

Efficiency = KW-hr of Syn-Gas Produced / Total Energy Input in KW-hr



Modeling results With plasma

Modeling results without plasma

Experimental results with plasma

Experimental results without plasma

Plasma Catalysis Highlights:

- Only 2.0% of Total Energy Consumption Required for Plasma Power
- Electric Energy Cost 0.06 kWh/m3 of syn-gas (energy from syn-gas = 3.0 KW-hr/m^3).
- 92% conversion at Equivalence ratio of 3.3.
- Internal Heat Recuperation (Preheating) at 750 K.
- No soot Deposition.
- Large Specific Production rates due to low residence times.
- Effective for Higher Hydrocarbon conversion to Syn-Gas.
- Not Sensitive to Sulfur and Other Impurities.


Philadelphia
LOVE
Best Regards, Chiranjeev Kalra from the city of brotherly love