Flow Reactor Studies with Nanosecond Pulsed Discharges at Atmospheric Pressure and Higher

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19a. NAME OF RESPONSIBLE PERSON
Objectives (Thrust 2)

- Development and validation of detailed low-temperature plasma fuel oxidation and ignition mechanisms, starting with simple fuels and proceeding to surrogate fuels
- Development of reduced plasma chemical fuel oxidation, ignition, and flameholding mechanisms which can readily be incorporated into predictive multi-dimensional reacting flow codes
- Identification of specific processes critical to the enhancement of basic combustion phenomena by nonequilibrium plasmas, in particular processes involving radical and/or excited metastable species.
Tasks

- **Reaction kinetics studies** with spatially controlled plasma discharges at atmospheric pressure and higher
- **Effect of nanoparticle/catalyst** coupling with plasma enhanced combustion in flow reactors and flames
Approach – Reaction Kinetics

• *Flow reactor* experiments between pressures from 0.1 and 3 bar and a temperature range of ambient to 1200 K (quartz chamber).

• Perform *dilute hydrocarbon oxidation experiments* in excess nitrogen, argon, or oxygen to minimize the temperature rise of reaction and stretch the reaction spatially over a significant length.

• *Perturb the reaction at different extents of reaction* with a spatially defined plasma discharge.

• Measure *temperature and product species* by sample extraction and GC/FTIR analysis.

• Perform *kinetic modeling of the reaction kinetics* with sensitivity and Green’s function analysis, $\partial Y_i(x) / \partial Y_j(x')$. 
Progress

**Flow Reactor Experiments:**
- Experiments on the oxidation of C1-C7 alkanes with and without plasma assisted reaction performed for $T = 300 - 1250$ K and $P = 1$ atm (*to study interactions of plasma and thermal chemistry*).
- Experiments on H2 oxidation with and without plasma assisted reaction for $T = 300 - 1250$ K and $P = 1$ atm (*to study interactions of plasma and thermal chemistry*).
- *In-situ* OH LIF measurements in progress with and without plasma for H2 oxidation in collaboration with OSU (Walter Lempert and Igor Adamovich) (*to provide more constraints on model development and link data to other research groups*).
- Plasma assisted kinetics experiments with O2/N2/Ar mixtures as a function of temperature were conducted to quantify NxOy formation in the presence and absence of fuels (*to determine the levels of NOx, rates of oxides of nitrogen formation, and potential interaction with hydrocarbon chemistry in flow reactor experiments with N2*).
- Experiments initiated with nanometer aluminum and carbon particles introduced into flow stream coupled with plasma.

**Kinetic Modeling:**
- Collaborations were continued with OSU (Igor Adamovich) to model the PSU ethylene oxidation experiments with Hai Wang’s mechanism.
- Plasma model coupled to SENKIN and CHEMKIN with formal sensitivity analysis.
Plasma Flow Reactor
Plasma Discharge Assembly

Cross-Section View (Front)

- Copper Electrodes
- Square Fused-Quartz Reactor
- Ceramic Sheath
- Ceramic Electrode Housing

Actual Image of Assembly

Cross-Section View (Isometric)

- Ceramic Electrode Housing
- High-Voltage Wire (14 AWG)
- Ceramic Wire Tube (I.D. 1.64 mm x O.D. 3.18 mm)

- Circular Fused-Quartz Reactor (I.D. 7 mm x O.D. 9.5 mm)
- Copper Electrodes (L 45 mm x W 7.6 mm x 1.6 mm Thickness)
- Ceramic Sheath (L 50.8 mm x W 12.7 mm x 1 mm Thickness)
- Square Fused-Quartz Reactor (H 7 mm x W 9 mm x 1.3 mm Thickness)
Plasma Flow Reactor Assembly

- The plasma discharge assembly is housed in a quartz tube (58mm I.D.) with Teflon end caps
- Actual flow reactor length is 1524 mm (60 in.)

- The copper electrodes are connected to ceramic insulated terminal feed-throughs
Reactor Assembly for $1 < P < 3$ atm

- Modular plasma discharge reactor can be interchanged with redesigned pressure shell to perform kinetic studies at $P > 1$ atm
Plasma Flow Reactor Experimental Facility

- Heating is achieved using a **three-zone tube furnace** with a length 609 mm (24 in.).
- Product species analysis performed using **NDIR (online)** and **Gas Chromatography (offline)**.
• **FTIR** (online) connected to exhaust stream of reactor
• Capable of detecting hydrocarbon and nitrogen-containing species (i.e. NO, NO2, N2O)
The measured temperature profiles are used to establish an empirical correlation with the tube furnace temperature over a range of $350 \text{ K} < T_{\text{iso}} < 1250 \text{ K}$. The correlation is used for kinetic modeling.

Experiments verify that heating from the plasma discharge is negligible in the diluent flow.

In Ar/O2 flow, ~10 K increase in gas temperature observed at the maximum voltage setting for a given reactor temperature of 814K.
Operating Conditions - Plasma Discharge

*Experimental Conditions:* $P = 1$ atm, $Q = 1$ LPM Ar, Gate = 10 µsec

*Plasma Discharge:* $V_{\text{plasma}} = 15$ kV, $\nu = 1$ kHz

**ICCD Single Pulse Images**

- **298 K**
- **427 K**
- **620 K**
- **814 K**

**ICCD Multiple Images (average of 50)**

- **298 K**
- **427 K**
- **620 K**
- **814 K**
Brief Review of Previous Results


22-24th October 2013, Basic Research Innovation Collaboration Center, Arlington, VA
**C₂H₄ Pyrolysis and Oxidation Experiments**

**Thermal**

**Experimental Conditions:**  
P = 1 atm, Q = 1 LPM, 800ppm C₂H₄/3000ppm O₂ / Ar by balance

**Plasma Assisted**

**Experimental Conditions:**  
P = 1 atm, Q = 1 LPM, 800ppm C₂H₄/3000ppm O₂ / Ar by balance

**Plasma Conditions:**  
10 kV, \( v = 1 \text{ kHz} \)
Modeling Results for a Single Experiment

**Modeling Conditions:** P = 1 atm, Q = 1 LPM, T = 863 K, 800ppm C2H4 / 3000ppm O2 / Balance Ar

**Plasma Conditions:** 0.043 meV/molecule/pulse

- Most of the reaction is isolated in the plasma region, with some further reaction occurring in the isothermal region
- Experimental results correspond to species concentration at the exit of the reactor
C\textsubscript{1}-C\textsubscript{7} Alkanes Plasma Assisted Oxidation
Thermal Explosion Limits


**C₁-C₇ Alkane Fuel Consumption**

**Experimental Conditions:** P = 1 atm, Q = 1 LPM, 1600ppm CₓHᵧ/3000ppm O₂ / Ar balance

**Plasma Conditions:** 10 kV, v = 1 kHz

- Without the plasma, onset of fuel consumption occurs for T > 900 K. With the plasma, onset of fuel consumption occurs at T = 420 K for all the fuels.
- The plasma also lowers the temperature for complete consumption of all fuels (the temperature for onset of high temperature ignition).
- For C₃ and larger fuels, a transition in reaction rate is observed 600 and 700 K.
Major Intermediate Species Generation

**Experimental Conditions:**  P = 1 atm,  Q = 1 LPM,  1600ppm CxHy/3000ppm O2 / Ar balance

**Plasma Conditions:**  10 kV,  ν = 1 kHz

- Before the onset of thermal effects, the plasma has a consistent effect on the formation CO; once the thermal effect is initiated both the plasma and thermal reactions contribute to forming and consuming CO.
- Below 960K, very little heat producing CO2 is formed.
- With the exception of CH4, all fuels appear to form similar amounts of C2H4 from 420K until the temperature where C2H4 consumption exceeds its formation.
Kinetic Scheme of Primary Oxidation Reactions of n-Alkanes

\[ X + RH \]

- \( R\cdot \)
- \( + O_2 \)
- \( \rightarrow \) \( \beta\)-Decomposition products
- \( \rightarrow \) \( HO_2\cdot + \) Conjugate alkenes
- \( \rightarrow \) \( \cdot OH + \) Cyclic ethers
- \( \rightarrow \) \( \cdot OH + R'CHO + CnH_2n \)

- \( ROO\cdot \)
- \( \cdot QOOH \)
- \( \cdot OOQOOH \)
- \( OQOOH \)

Branching Products

\[ + \cdot OH \]
Thermal Oxidation of $\text{C}_3\text{H}_8$


Experimental Conditions: $P = 1$ atm, $Q = 1$ LPM, 533 ppm $\text{C}_3\text{H}_8$/3000 ppm $\text{O}_2$ / Ar balance
C$_3$H$_8$ Plasma Oxidation

**Experimental Conditions:**  P = 1 atm,  Q = 1 LPM,  533ppm C$_3$H$_8$/3000ppm O$_2$ / Ar balance

**Plasma Conditions:**  10 kV,  $v$ = 1 kHz

---

**Major Species**
- CO$_2$
- C$_2$H$_4$
- CH$_3$CH$_2$CHO, propanal
- CH$_3$COCH$_3$, acetone

**Minor Species**
- CH$_4$
- C$_2$H$_6$
- C$_3$H$_6$
- C$_4$H$_4$
- C$_4$H$_8$
- CH$_3$CHO, acetaldehyde
- CH$_3$COCH$_3$, acetone
- CH$_3$CH$_2$CHO, propanal

---
Thermal Oxidation of C$_4$H$_{10}$


**Experimental Conditions:** P = 1 atm, Q = 1 LPM, 400ppm C$_4$H$_{10}$/3000ppm O$_2$ / Ar balance
C\textsubscript{4}H\textsubscript{10} Plasma Oxidation

**Experimental Conditions:**  \( P = 1 \) atm, \( Q = 1 \) LPM, 400ppm C4H10/3000ppm O2 / Ar balance

**Plasma Conditions:** 10 kV, \( v = 1 \) kHz

| Temperature [K] | C\textsubscript{4}H\textsubscript{10} | C\textsubscript{2}H\textsubscript{4} | CO | CO\textsubscript{2} | C\textsubscript{3}H\textsubscript{6} | CH\textsubscript{4} | C\textsubscript{2}H\textsubscript{6} | C\textsubscript{2}H\textsubscript{2} | C\textsubscript{3}H\textsubscript{8} | C\textsubscript{6}H\textsubscript{12} | C\textsubscript{4}H\textsubscript{8} | C\textsubscript{5}H\textsubscript{12} | C\textsubscript{4}H\textsubscript{6} | \text{Minor Species} |
|----------------|-----------------|-----------------|-----|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| 400            | 0               | 0               | 0   | 0               | 0               | 0               | 0               | 0               | 0               | 0               | 0               | 0               | 0               | 0               | \text{CH\textsubscript{3}CHO} |
| 600            | 20              | 20              | 20  | 20              | 20              | 20              | 20              | 20              | 20              | 20              | 20              | 20              | 20              | 20              | \text{C\textsubscript{3}H\textsubscript{6}O, propanal} |
| 800            | 40              | 40              | 40  | 40              | 40              | 40              | 40              | 40              | 40              | 40              | 40              | 40              | 40              | 40              | \text{C\textsubscript{4}H\textsubscript{8}O, MEK, butanone} |
| 1000           | 60              | 60              | 60  | 60              | 60              | 60              | 60              | 60              | 60              | 60              | 60              | 60              | 60              | 60              | \text{C\textsubscript{4}H\textsubscript{8}O, butanal} |
| 1200           | 80              | 80              | 80  | 80              | 80              | 80              | 80              | 80              | 80              | 80              | 80              | 80              | 80              | 80              | \text{NA.1 - 15.416 min} |
| 1400           | 100             | 100             | 100 | 100             | 100             | 100             | 100             | 100             | 100             | 100             | 100             | 100             | 100             | 100             | \text{NA.2 - 19.768 min} |
| 1600           | 120             | 120             | 120 | 120             | 120             | 120             | 120             | 120             | 120             | 120             | 120             | 120             | 120             | 120             | \text{NA.3 - 23.498 min} |
| 1800           | 140             | 140             | 140 | 140             | 140             | 140             | 140             | 140             | 140             | 140             | 140             | 140             | 140             | 140             | \text{NA.4 - 22.880 min} |

**Signal Area [pA*s]**

<table>
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<th>Temperature [K]</th>
<th>NA.1 - 15.416 min</th>
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H₂ Plasma Assisted Oxidation


22-24th October 2013, Basic Research Innovation Collaboration Center, Arlington, VA
**H₂ Thermal and Plasma Assisted Oxidation**

**Experimental Conditions:** $P = 1$ atm, $Q = 1$ LPM, $2000$ ppm H₂/$3000$ ppm O₂ / Ar balance

**Plasma Conditions:** $10$ kV and $15$ kV, $v = 1$ kHz

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**H₂/O₂ Explosion Limits**

- **First limit**
- **Third limit**
- **No explosion**

---

**Flow Reactor**

- **Species Concentration [ppm]**
  - $H₂$
  - $O₂$

- **Temperature [K]**
  - $400$ to $1000$

**OH LIF Experiments**

- $T = 668$ K
- $T = 814$ K

---

**0D Kinetics Model with Sensitivity Analysis**

**SENKIN (CHEMKIN)**
- Calculate $k(T)$
- Time integration
- Isothermal region modeled as constant T and P process
- Temperature ramps currently not included
- Plug flow assumption

**ZDPlasKin, a Boltzmann equation solver**
(University of Toulouse, LAPLACE, 2008)
- Calculate rates for electron-impact reactions
- Electron impact cross sections are fed
- Calculate $v_{\text{drift}}$

**Circuit module**
- Calculate $E/N$
- Assumed homogeneity across discharge planes
  \[
  \frac{dV_{\text{gap}}(t)}{dt} = \left(1 + \frac{2l_d}{eL}\right)^{-1} \left(\frac{dV_{\text{app}}(t)}{dt} - \frac{2l_d}{e_0\epsilon} J_p(t)\right)
  \]

**Preliminary H2 Chemical Reaction Mechanism (39 species, 527 reactions)**

*Electron-impact reactions (Van Gaens and Bogaerts, 2013 and Kossyi et al., 1992)*
- Excitation, Deexcitation, Dissociation, Ionization, Recombination
*Excited and ionized species (Van Gaens and Bogaerts, 2013, Kossyi et al., 1992 and Popov, 2011)*
- Ar/H/O atoms
*Neutral, ground state species*
- $H_2/O_2$ Mechanism (Popov, 2008), $O_3$ Chemistry (Bromly et al., 1996)
*Wall quenching of positive ions*
**H₂ Oxidation (0D Kinetic Model)**

**Conditions:**  
- \( P = 1 \text{ atm} \), \( Q = 1 \text{ LPM} \), \( 2000 \text{ppm} \)  
- \( \text{H}_2/3000\text{ppm O}_2 / \text{Ar balance} \)  

**Plasma Conditions:**  
- 10kV and 15 kV, \( v = 1 \text{ kHz} \)

---

**Graphs:**

- **Temperature vs. Species Mole Fractions:**
  - \( \text{O}_2 \), \( \text{H}_2 \) for 10kV and 15kV.

- **Time vs. Species Mole Fractions:**
  - \( \text{O}_2(a^1\Delta_g) \), \( \text{O}_2(b^1\Sigma_g^+) \), \( \text{O}^1\text{D} \) over time.

---

**T = 800K, 10kV, \( v = 1 \text{ kHz} \)**

**Electrode Region**
• *in-situ* OH LIF implemented into existing flow reactor experiment in collaboration with OSU group (Zhiyao Yin and Kraig Frederickson)

• ICCD camera mounted on **translational stage** to obtain measurements along the length of the reaction zone
**OH LIF Experiments**

**Experimental Conditions:** $P = 1$ atm, $Q = 1$ LPM, 2000 ppm H$_2$/3000 ppm O$_2$ / Ar balance 600 Shots On- ICCD Accumulations

**Laser Excitation:** $Q_1(4)$ in OH A-X (1,0), $\sim$1mJ/pulse

---

**OH 0D Plasma Chemical Kinetics Code**

Thermal, $T = 916$ K

Laser Excitation: $Q_1(4)$ in OH A-X (1,0), $\sim$1mJ/pulse

---

Thermal, $T = 916$ K

Plasma 10 kV, $v = 1$ kHz, $T = 814$ K

---

Plasma 10 kV, $v = 1$ kHz, $T = 800$ K
Transient Behavior of OH at a Specific Reactor Location

Conditions:  \(P = 1 \text{ atm}, T = 668 \text{ K}, Q = 1 \text{ LPM}, 2000\text{ppm H}_2/3000\text{ppm O}_2 / \text{Ar by balance}

Plasma Conditions: 10kV, \(v = 1 \text{ kHz}

Example of Experimental OH Signal @ \(t = 900 \mu\text{s}

Experimental Result

Numerical Result
**OH Production and Sensitivity**

**Conditions:** P = 1 atm, T=800 K, Q = 1 LPM, 2000ppm H2/3000ppm O2 / Ar by balance

**Plasma Conditions:** 10kV, $v = 1$ kHz

**Pulse #22**

Discharge at 77 ns, $V_{peak}$ at 100 ns

---

**Graphs:**

1. **OH Production Rates**
   - OH production rates over time in mol/(g s)
   - Reactions shown include:
     - $e^- + OH -> OH(A) + e^-$
     - $e^- + H_3O^+ -> 2H + OH$
     - $Ar^+ + H_2O -> Ar + OH + H$
     - $Ar_2^* + H_2O -> 2Ar + OH + H$
     - $Ar^{**} + H_2O -> Ar + OH + H$
     - $H_2 + O(D) -> OH + H$
     - $OH(A) + H_2O -> OH + H_2O$
     - $OH + HO_2 -> H_2O + O_2$
     - $H + HO_2 -> 2OH$

2. **Normalized Sensitivity Coefficient**
   - Normalized sensitivity coefficient over time
   - Reactions shown include:
     - $H + O_2 + M -> HO_2 + M$
     - $OH + H_2 -> H + H_2O$
     - $O + H_2 -> H + OH$
     - $O + H_2 -> H + OH$
     - $H + O_2 -> O + OH$
     - $OH + HO_2 -> H_2O + O_2$
     - $H + HO_2 -> 2OH$
     - $H_2 + O_2 -> H + HO_2$
Summary

- Alkane (C1-C7) oxidation has been studied with and without plasma enhancement:
  - Fuel consumption across $T = 420 - 1250$ K has been significantly enhanced for all fuels, the plasma also lowers the temperature for complete fuel consumption (*the temperature for onset of high temperature ignition*)
  - Experimental results indicate an extension of RO2 low temperature (cool flame) chemistry to lower pressures (*identification/quantification of select species will be improved i.e., aldehydes*)

- H2 oxidation has been studied with and without plasma enhancement:
  - H2 and O2 consumption measured ex-situ GC analysis, modifications to the current facility have been made to perform in-situ OH LIF measurements in conjunction with OSU group
  - Zero-D plasma kinetic model has been developed based on SENKIN to derive detailed sensitivity analysis
  - Qualitative comparisons of model and experiment indicate current plasma assisted combustion models for hydrogen oxidation perform well.

- Experiment and model analysis of low temperature C2H4/N2/O2/Ar mixtures suggest intermediate formation of nitromethane. Formation of such nitro and nitrate compounds at low temperatures may be a means to enhance ignition.
Team Interactions/Collaborations

• Collaborative research with Ohio State on plasma kinetic modeling of PSU pyrolysis and oxidation experiments.
• Collaborative research with Ohio State on *in-situ* OH LIF measurements.
• Plasma Assisted Combustion MURI Kinetics Working Group
Secondary Slides


22-24th October 2013, Basic Research Innovation Collaboration Center, Arlington, VA
0D Kinetics Model

- **Isothermal** region modeled as constant Temperature and Pressure process
- Temperature ramps ignored (to be implemented in the future)
- Assumed homogeneity across discharge planes
- Plug flow assumption
- Convert distance to time based on experimental flow rate

![Graph showing temperature vs. reactor length with data points and annotations]
Preliminary Chemical Reaction Mechanism
114 species, 1461 reactions

- Electron-impact reactions (Mainly from Van Gaens and Bogaerts, 2013 and Kossyi et al., 1992)
  - Excitation
  - Deexcitation
  - Dissociation
  - Ionization
  - Recombination
- Excited and ionized species (Mainly from Van Gaens and Bogaerts, 2013 and Kossyi et al., 1992)
  - Ar/H/N/O atoms
- Interactions of hydrocarbons with excited species
- Neutral, ground state species
  - Hydrocarbon oxidation (Bromly et al., 1996)
  - NO\textsubscript{x} Mechanisms
    - Zel’dovich (Bromly et al., 1996)
    - Prompt, N\textsubscript{2}O and NNH (GRI-Mech 3.0)
Plasma Effects on NO\textsubscript{x} Formation at Various Temperatures

- N atom production results from electron impact dissociation of N\textsubscript{2}.
- NO\textsubscript{x} forms by N+O\textsubscript{2}→NO+O. NO increases with temperature because of more N atom formation.
- Model overpredicts NO by a factor of 2. Most likely due to overprediction of N atom formation by electron impact dissociation. Total NO\textsubscript{x} measured also decreases for temperatures above 1050 K.
- Higher portion of NO\textsubscript{2} at low temperatures due to the reaction NO+O\textsubscript{3}→NO\textsubscript{2}+O\textsubscript{2}. O\textsubscript{3} decreases with temperature, so does NO\textsubscript{2}.

50% Ar / 50% Air
p = 1 atm
Plasma residence time, \( t_{\text{plasma}} = 100 \text{ ms} \)
\( V_{\text{peak}} = 15 \text{ kV} \)
Repetition rate, \( f = 1 \text{ kHz} \)

Discrete points: experimental results
Solid lines: numerical results
Plasma Effects on NO$_x$ Formation at Various Temperatures: Simulated Species History
NO Analyses (Production rate and Sensitivity)

Pulse #100 of 620.7K case

• NO production due to N+O_2=NO+O. Reverse reaction N+NO=N_2+O present because NO already built up.

• After 400 ns, NO is not sensitive to excited or ionized species any more.

• Sensitivity analysis shows three important mechanisms in the afterglow: Zel’dovich thermal NO_x mechanism, NO\leftrightarrow NO_2 cycle by O atoms, and oxidation to NO_2 by O_3.
Experimental results

- For $\Phi > 0.5$, NO$_x$ formation decreases with $\Phi$.
- Reaction rate constant of dissociative quenching of Ar* with fuel (Ar*+C$_2$H$_4$→Ar+C$_2$H$_3$+H or Ar*+C$_2$H$_4$→Ar+C$_2$H$_2$+H$_2$) is $\approx 10x$ faster than the one with N$_2$ (Ar*+N$_2$→Ar+2N).

Numerical results

- Large discrepancies between experimental and numerical results. The trends of C-containing species profiles are qualitatively similar, but the matching of N-containing species are miserable.
What is happening in the code?

- NO forms in plasma region, and quickly converted to NO₂ by NO+HO₂ at the exit of plasma region.
- Large amount of nitromethane (CH₃NO₂) forms within the plasma region, by CH₃+NO₂(+M)=CH₃NO₂(+M). Downstream, CH₃NO₂ then decomposes.
- Current model missing many secondary reactions of CH₃NO₂ decomposition.
The measured temperature profiles are used to establish an empirical correlation with the tube furnace temperature over a range of $350 \, \text{K} < T_{\text{iso}} < 1250 \, \text{K}$. The correlation is used for kinetic modeling.

Initial experiments verify that heating from the plasma discharge is negligible in the diluent flow.

In Ar/O2 flow, ~10 K increase in gas temperature observed at the maximum voltage setting for a given reactor temperature of 814K.
Operating Conditions - Plasma Discharge

*Experimental Conditions:* $P = 1$ atm, $Q = 1$ LPM Ar, Gate = 10 µsec

ICCD Multiple Images (average of 50)

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<th>Voltage ($V$)</th>
<th>Frequency ($v$)</th>
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<td>427</td>
<td>$10 \text{ kV}$</td>
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<tr>
<td>814</td>
<td>$10 \text{ kV}$</td>
<td>$1 \text{ kHz}$</td>
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</table>
Details of Individual Pulse

**Conditions:**  \( P = 1 \text{ atm} \), \( T = 800 \text{ K} \), \( Q = 1 \text{ LPM} \), 2000ppm H\(_2\)/3000ppm O\(_2\) / Ar by balance

**Plasma Conditions:** 10kV, \( \nu = 1 \text{ kHz} \)

**Pulse #22**
Discharge at 77 ns, \( V_{\text{peak}} \) at 100 ns

![Graph showing mole fraction of OH, H\(_2\), and H\(_2\)O over time](image)
Raw Data for Hydrocarbon Experiments
CH$_4$ Thermal Oxidation

**Experimental Conditions:** P = 1 atm, Q = 1 LPM, 1600ppm CH$_4$/3000ppm O$_2$ / Ar by balance
CH₄ Plasma Oxidation

**Experimental Conditions:**  P = 1 atm,  Q = 1 LPM,  1600ppm CH₄/3000ppm O₂ / Ar by balance

**Plasma Conditions:**  10 kV,  v = 1 kHz

---

![Graph 1](image1.png)

![Graph 2](image2.png)
C$_2$H$_6$ Thermal Oxidation

**Experimental Conditions:**  
P = 1 atm,  Q = 1 LPM,  800ppm C$_2$H$_6$/3000ppm O$_2$ / Ar by balance

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**Major Species**

<table>
<thead>
<tr>
<th>Temperature [K]</th>
<th>C$_2$H$_6$</th>
<th>CO</th>
<th>CO$_2$</th>
<th>C$_2$H$_4$</th>
<th>C$_2$H$_2$</th>
<th>C$_3$H$_8$</th>
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**Minor Species**

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<th>Temperature [K]</th>
<th>CH$_4$</th>
<th>C$_2$H$_2$</th>
<th>C$_3$H$_8$</th>
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C$_2$H$_6$ Plasma Oxidation

**Experimental Conditions:** P = 1 atm, Q = 1 LPM, 800ppm C$_2$H$_6$/3000ppm O$_2$ / Ar by balance

**Plasma Conditions:** 10 kV, $v = 1$ kHz

![Graph showing major species concentration vs. temperature](image1)

**Major Species**

- C$_2$H$_6$
- CO$_2$
- CO
- C$_2$H$_4$

![Graph showing minor species concentration vs. temperature](image2)

**Minor Species**

- C$_2$H$_2$
- CH$_4$
- C$_3$H$_8$
- C$_3$H$_6$
- C$_4$H$_{10}$
**C$_2$H$_6$ Plasma Oxidation**

*Experimental Conditions:*  
$P = 1$ atm, $Q = 1$ LPM, 800ppm C$_2$H$_6$/3000ppm O$_2$ / Ar by balance

*Plasma Conditions:*  
10 kV, $v = 1$ kHz

---

**Unknown Species**

![Graph showing signal area vs. temperature](image-url)
**C\textsubscript{7}H\textsubscript{16} Thermal Oxidation – Major Species**

*Experimental Conditions:* $P = 1$ atm, $Q = 1$ LPM, 228ppm C\textsubscript{4}H\textsubscript{10}/3000ppm O\textsubscript{2} / Ar by balance
**C7H16 Thermal Oxidation – Minor Species**

**Experimental Conditions:**  
P = 1 atm, Q = 1 LPM, 228ppm C4H10/300ppm O2 / Ar by balance

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**Graphs:**  
- **Species Concentration [ppm]** vs **Temperature [K]**
  - CH4
  - C2H6
  - C3H6
  - C4H8
  - C5H12
  - C6H12
  - C4H6
  - C2H2
  - C3H8
  - C3H4

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**C7H16 Plasma Oxidation – Major Species**

*Experimental Conditions:* $P = 1 \text{ atm}$, $Q = 1 \text{ LPM}$, 228 ppm C4H10/3000 ppm O2 / Ar by balance

*Plasma Conditions:* 10 kV, $v = 1 \text{ kHz}$

**Major Species**

![Graph showing species concentrations vs. temperature](image-url)
C7H16 Plasma Oxidation – Minor Species

Experimental Conditions:  
P = 1 atm,  Q = 1 LPM,  228ppm C4H10/3000ppm O2 / Ar by balance

Plasma Conditions:  10 kV,  ν = 1 kHz

![Graph showing species concentration vs. temperature]

- Species Concentration [ppm]
- Temperature [K]
**C7H16 Plasma Oxidation – Unknowns**

**Experimental Conditions:** P = 1 atm, Q = 1 LPM, 228ppm C4H10/3000ppm O2 / Ar by balance

**Plasma Conditions:** 10 kV, $v = 1$ kHz

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The diagram shows the signal area [pA*s] as a function of temperature [K], with various markers representing different samples (N.A.1 to N.A.11) and their corresponding retention times. The x-axis represents temperature in Kelvin, ranging from 400 to 1400 K, and the y-axis represents signal area in pA*s, ranging from 0 to 40 pA*s.