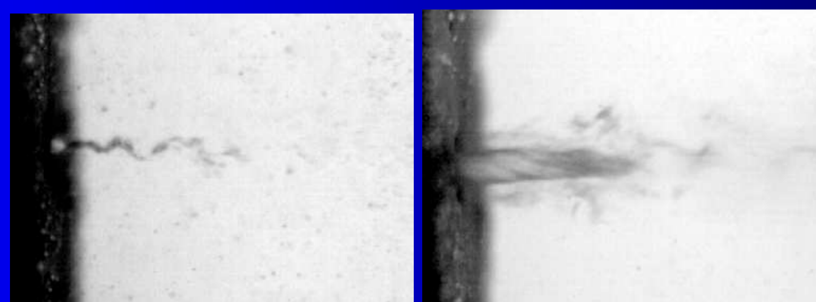
Application of Submerged Hydrodynamic Cavitating Jets (DynaJets®) to Oxidation Of Organic Compounds in Water



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November 17, 2010

AOT 16

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Outline

- Cavitation and Formation of Free Radicals
- Acoustic (Ultrasonic) Cavitation vs. Hydrodynamic Cavitation
- Hydrodynamic Cavitating Jets
- Oxidation / Reduction in Water
- Applications
- Conclusions

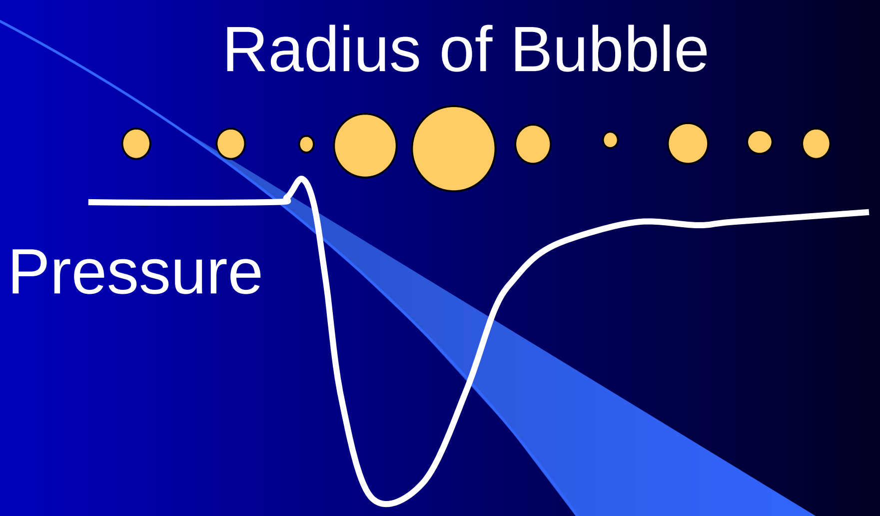
Underwater explosion from 6000 V spark.
Collapse is analogous to cavitation

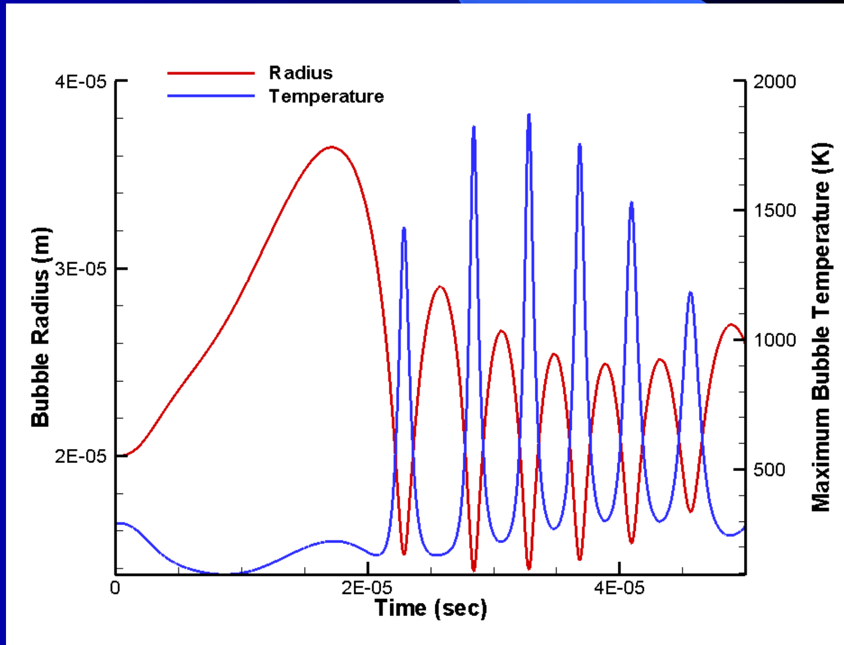
Cavitation

- Bubble nuclei in water expand & collapse when the local pressure changes very quickly.
- Collapsing bubbles produce tremendous pressures & temperatures in localized area (~5,200 K, ~200 Atm).
- Water vapor dissociates into OH• and H•

  $H_2O \rightarrow OH^{\bullet} + H^{\bullet}$
- Volatile compounds can also dissociate into radicals

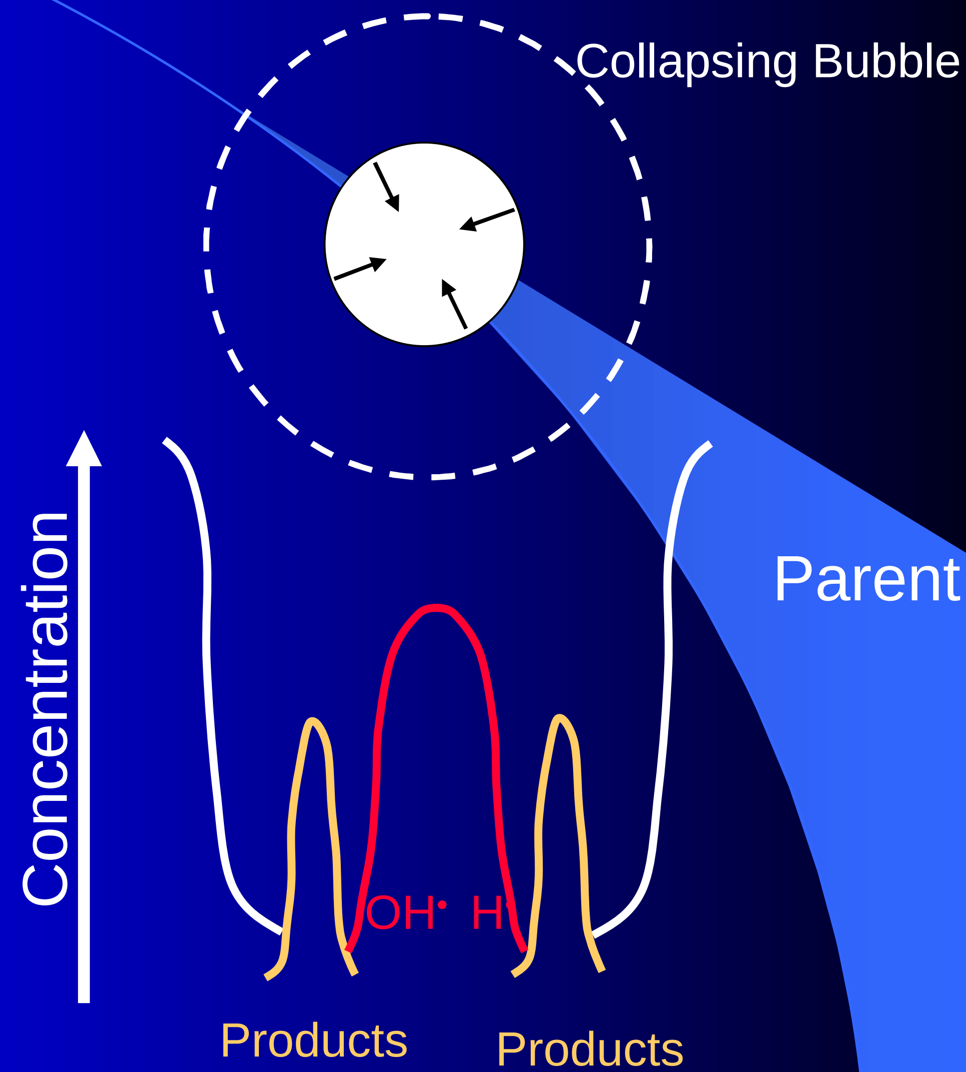
  $CCl_4 \rightarrow Cl^{\bullet} + Cl_3C^{\bullet}$





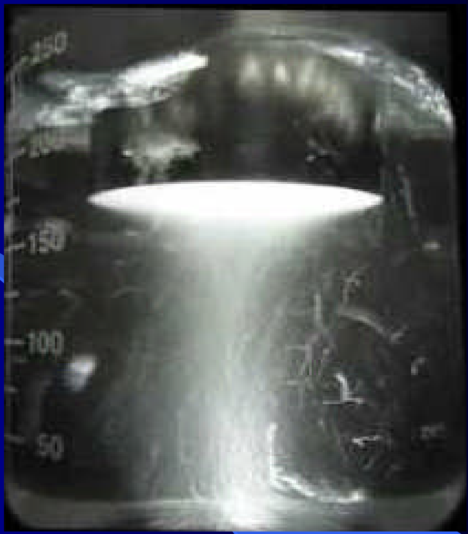
Reaction Location

- Inside collapsing bubble or at interface
- Volatile compounds enter the expanding bubble and decompose during collapse
- OH• and H• concentrations highest in center, decrease toward bubble wall
- Hydrophobic compounds partition to air-water interface
- Local depletion of starting compound and build up of products

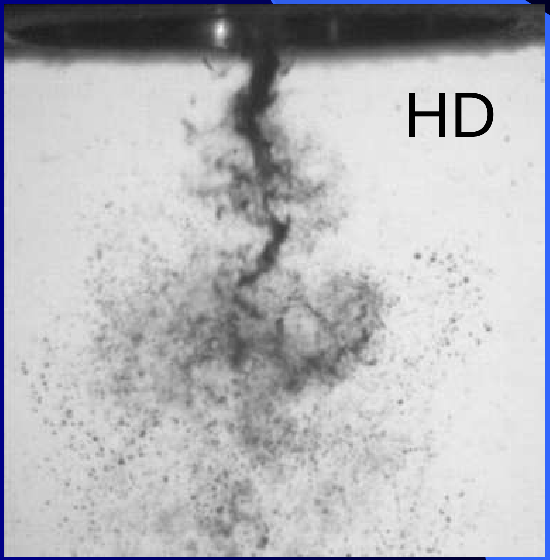


Hydrodynamic & Ultrasonic Cavitation

- Ultrasonic (US) cavitation produced by mechanical vibration in a liquid localized at the face of the probe.
- US- high intensity, localized cavitation, energy intensive, scaling up difficult
- Hydrodynamic Cavitation (HD) is produced by motion of fluid.
- Large pressure fluctuations in shear layer of the liquid cause cavitation.
- HD – wider area of cavitation, 1/10 – 1/100 energy required, easy to scale

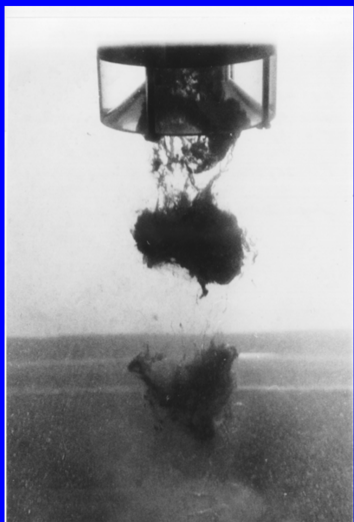


US

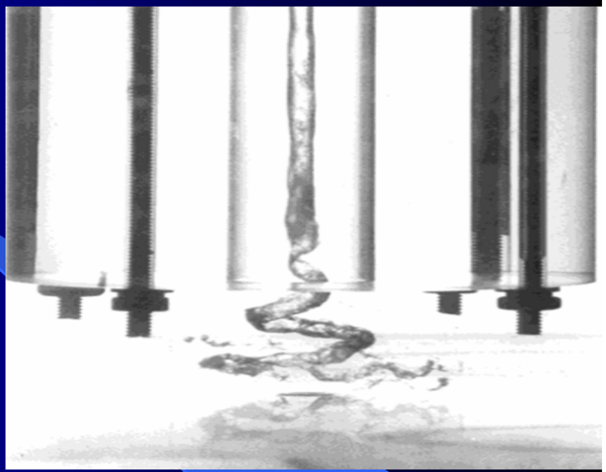


HD

DYNAJETS® Cavitating Jets

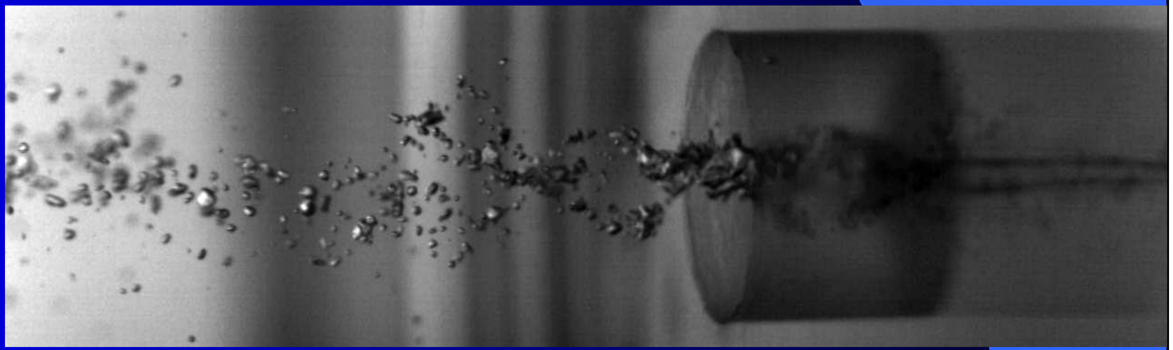


- Specially designed nozzles intensify cavitation and generate cavitation at lower pump pressures
- This is achieved through:
  - Passive acoustic excitation
  - Swirling the flow
- Both enhance vorticity and reduce pressure in the vortices



STRATOJET®

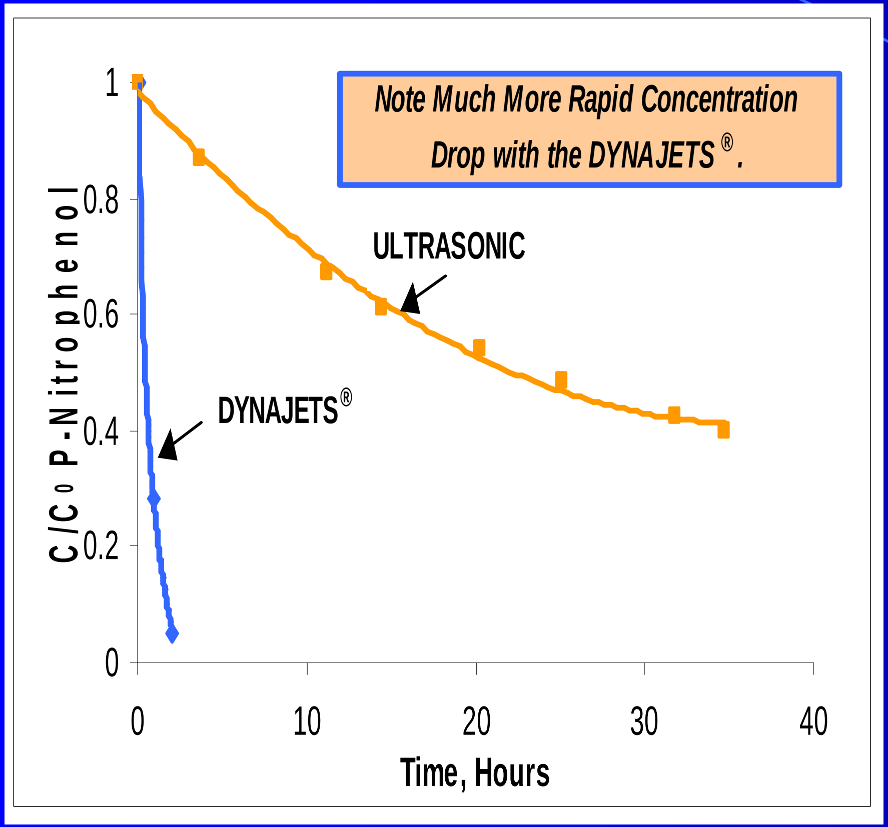
DYNASWIRL®

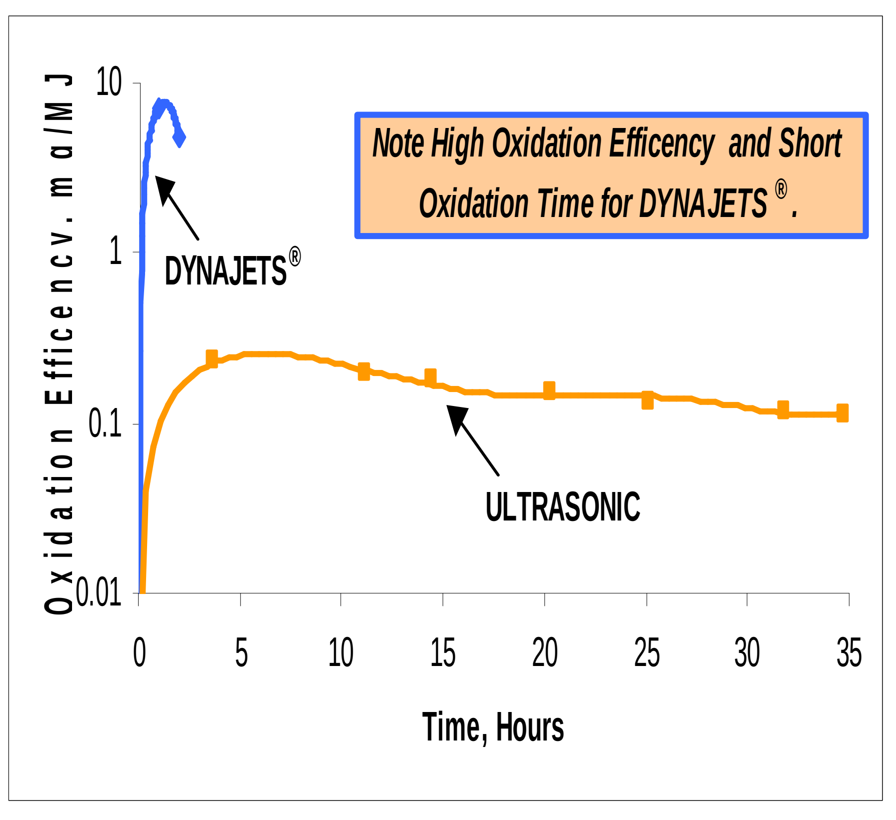


Hydrodynamic Cavitation for Oxidation

- Hydrodynamic cavitation can be 10 – 100 times more energy efficient than acoustic cavitation
- No addition of oxidizer
- Optical opacity or particulates are no problem
- Other than nozzle no special equipment required
- DYNAJETS®
  - Cavitation at lower pressures
  - Lower pressures lower electrical requirements
    - Hydraulic Energy = Flow Rate x Pressure change x time
  - Cavitation in wider area
  - Easier to scale up than US

Energy: Acoustic & Hydrodynamic





25 ppm *p*-Nitrophenol

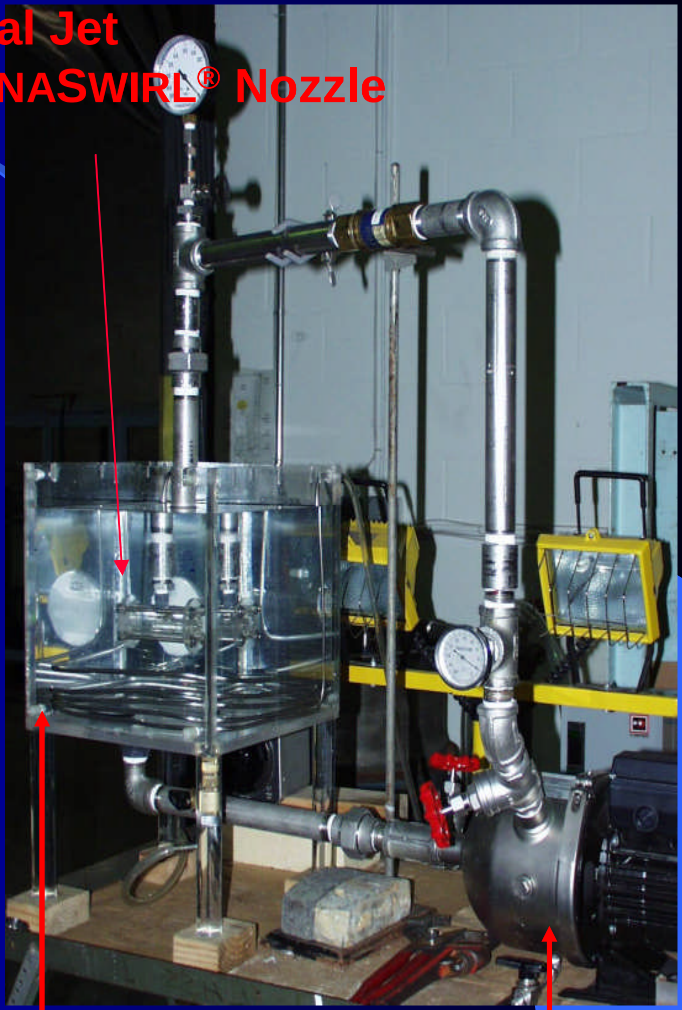
Hydrodynamic cavitation can be 10 – 100 times more energy efficient than acoustic cavitation*

*K.Kalumuck, G. Chahine, J. Fluids Eng., 122,(2000) 465.
S. Majumdar, P. S. Kumar, A. Pandit, Ultra. Sonochem., 5 (1998) 113.
K. Jyoti, A. Pandit, Water Res., 38 (2004), 2249.

Applications of DYNAJETS®

- Oxidation
  - Chlorinated solvents
  - Toluene, Acetone
  - Pesticides: Malathion, Carbaryl, 2,4-D
  - Pharmaceuticals and Personal Care Products
- Disinfection
  - Water
  - Wastewater
  - Storm water
- Recovery of Cellular Matter – Algae
- Pretreatment of lignocellulose biomass
- Biodiesel production

Dual Jet DYNASWIRL® Nozzle



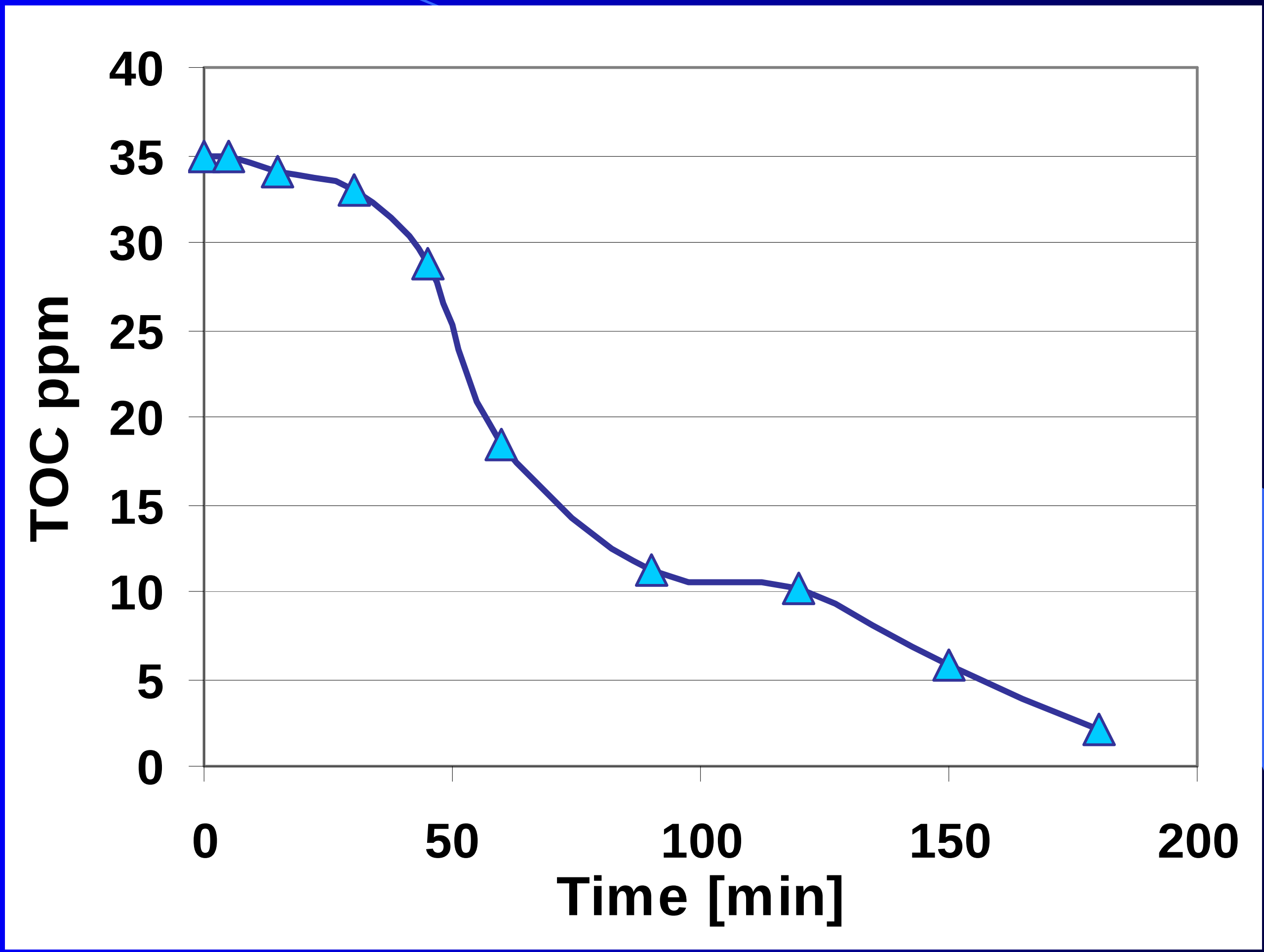
Reaction Chamber

Pump

Selectivity of HD Cavitation Oxidation

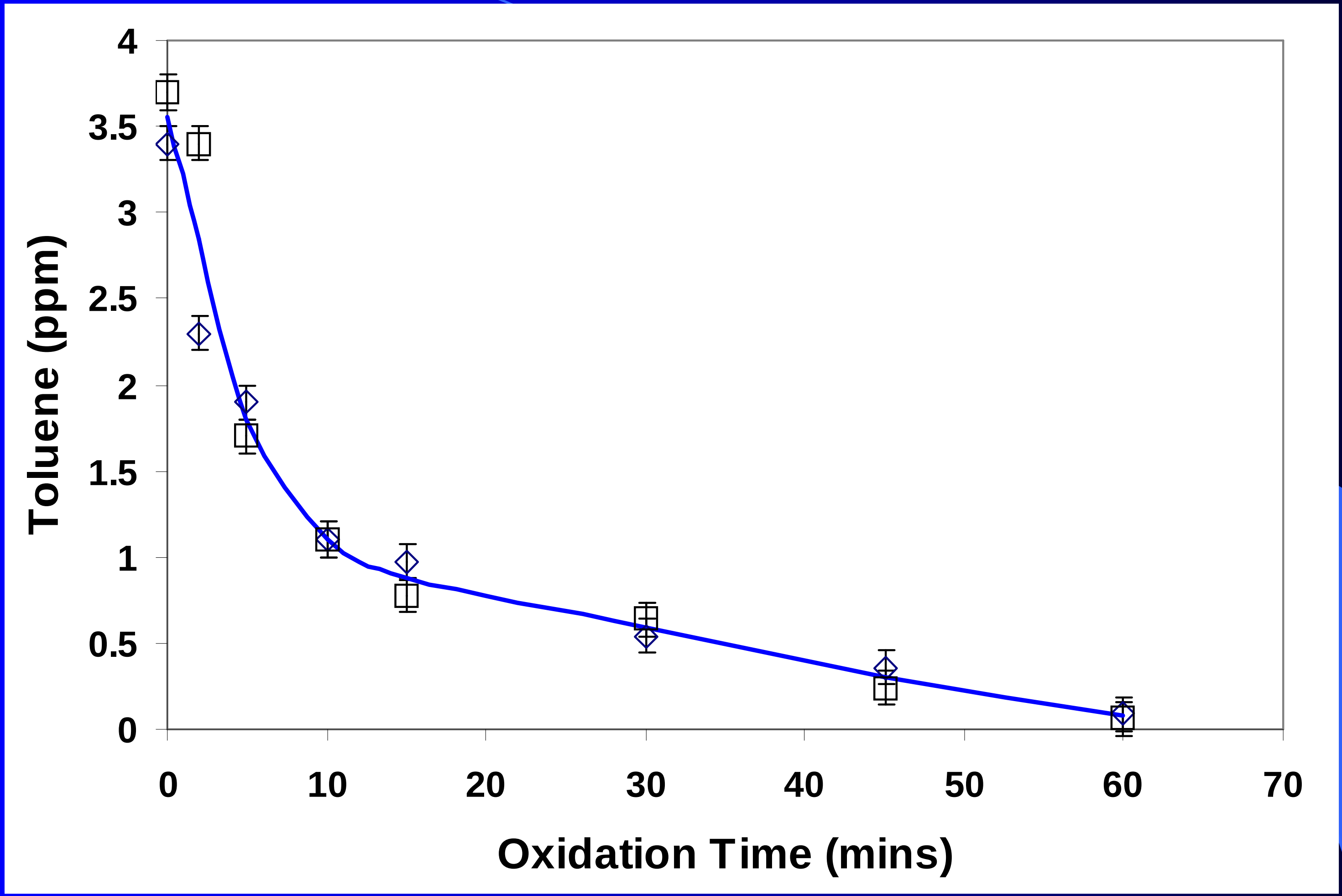
- Volatile (high vapor pressure) can be oxidized easily
- pH can be used to adjust degree of ionization of weak acids and bases
- Hydrophobic compounds (high octanol-water partition coefficient log K_{OW}) oxidize faster than hydrophilic compounds
- Reaction intermediates are formed in regions of high radical concentrations, lower by-product concentrations
- Operating parameters (pump pressure, jet velocity, etc.), and nozzle design can be varied to improve oxidation performance

Volatile Compounds: Mineralization of Chloroform



2-Jet DYNASWIRL® 65 psi, Chloroform = 344 mg/L
Vapor Pressure = 160 mm Hg @ 20 C

Oxidation of Toluene

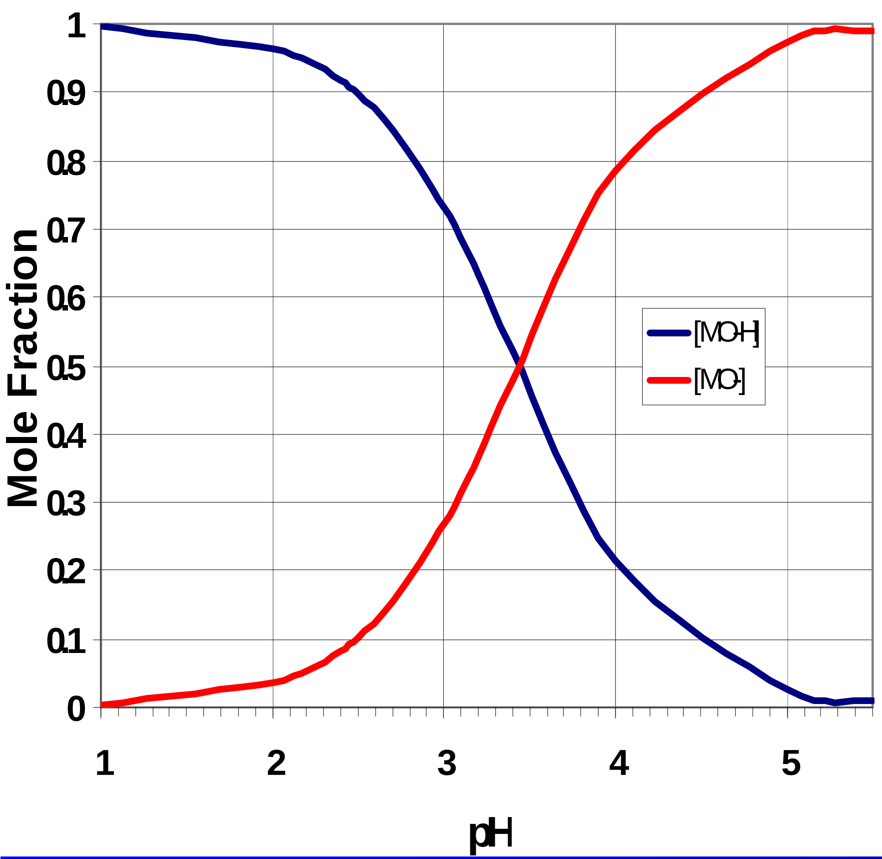


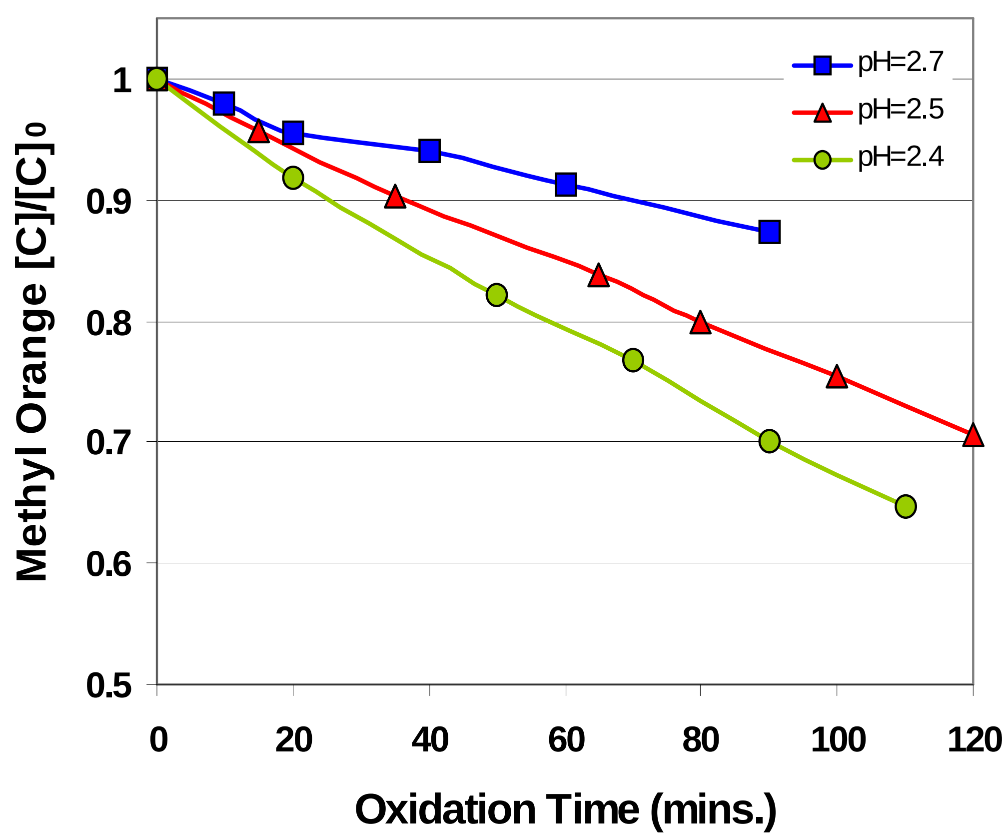
DYNASWIRL® 30 psi

Toluene:
Vapor Pressure= 28.4 mmHg @25 C
Log K_{OW}=2.69

Hydrophobicity: pH effects & Methyl Orange

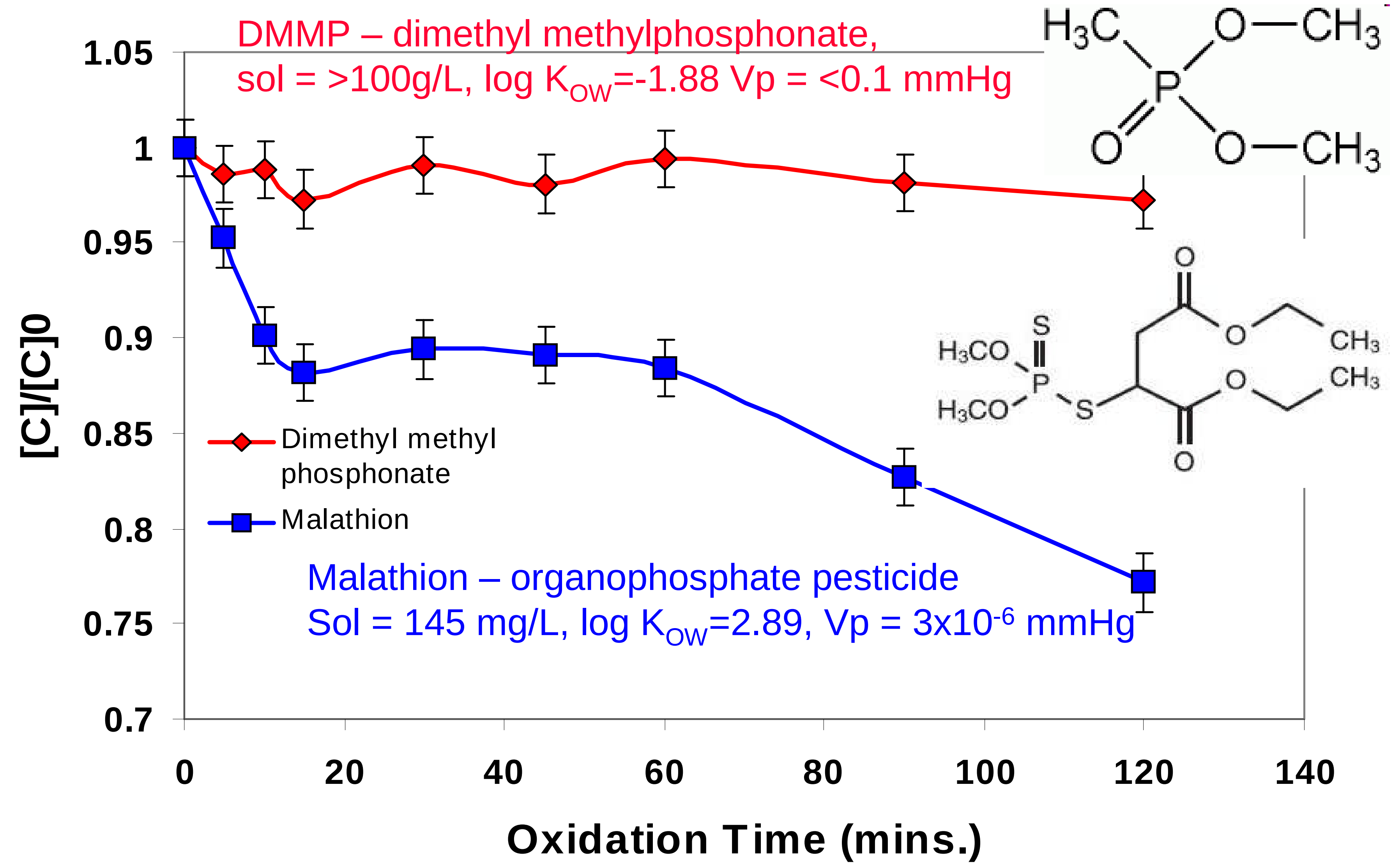
Decoloration of acid dye, Methyl Orange –pKa = 3.44





DYNASWIRL® dual jet 30 psi

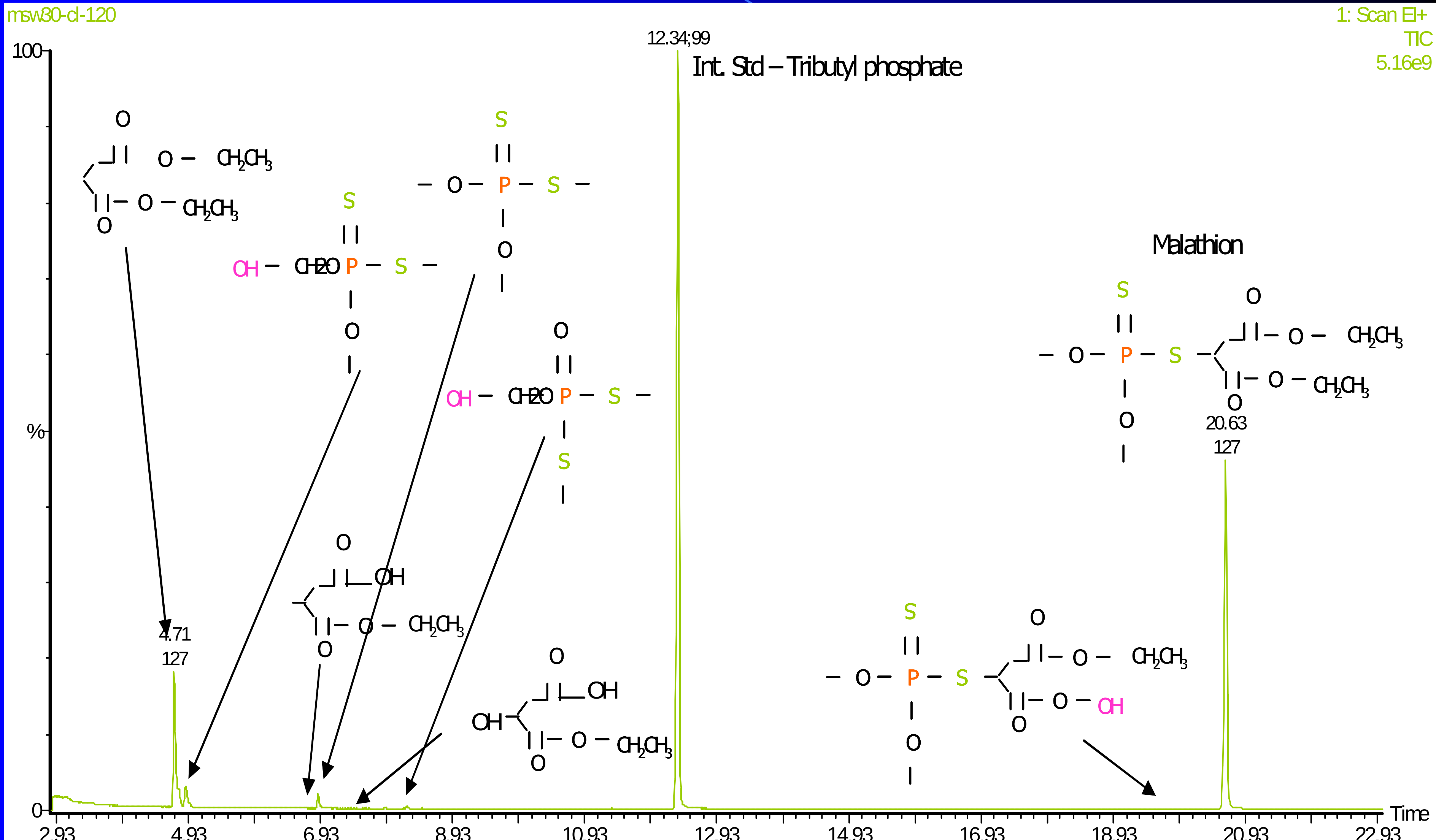
Solubility Effects: DMMP and Malathion



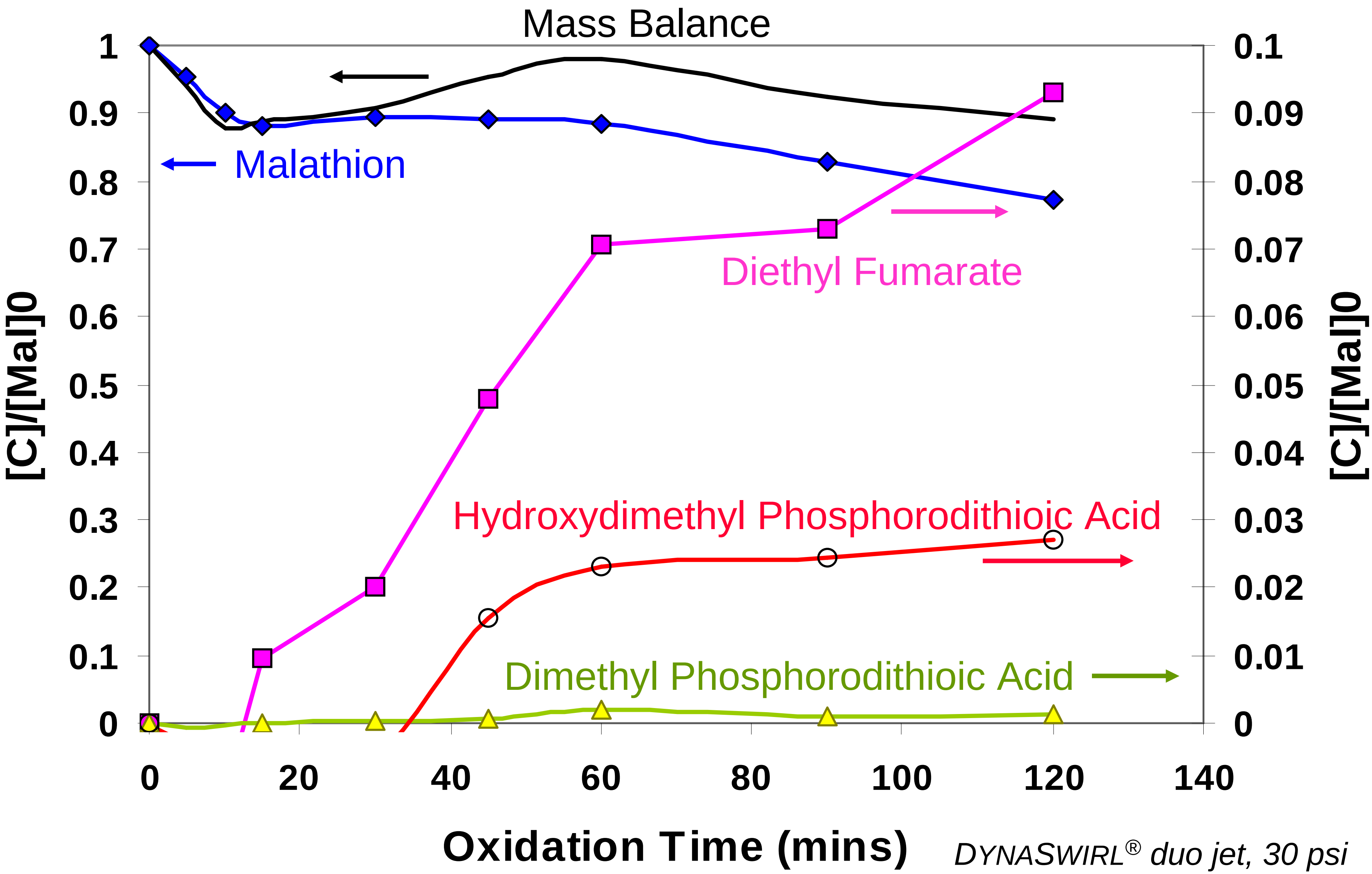
Dual Jet DYNASWIRL® at 30 psi

Malathion Oxidation Products

GC/MS data from Malathion oxidation: Dual Jet DYNASWIRL® at 30 psi



Mass Balance Of Malathion Oxidation

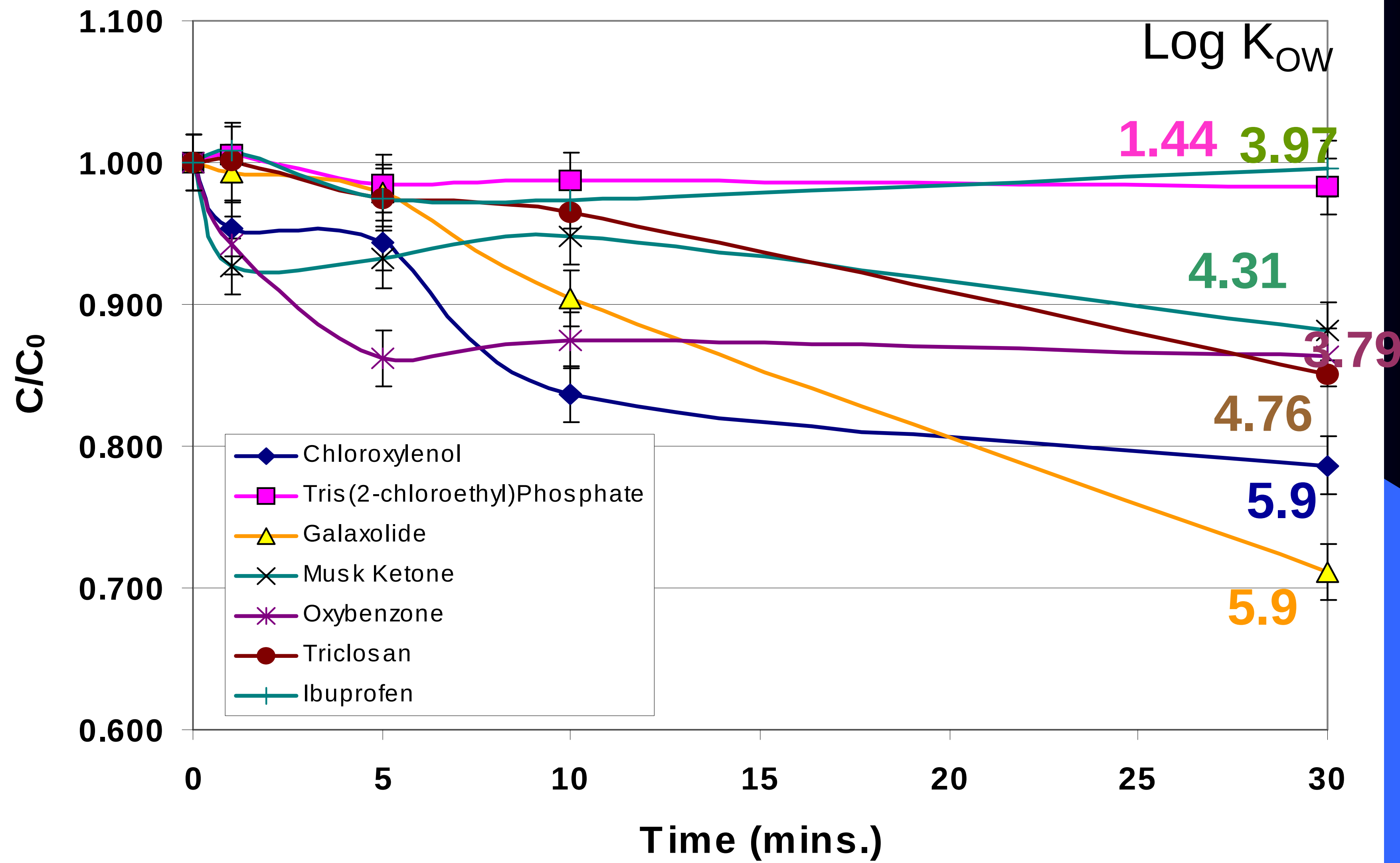


DYNASWIRL® duo jet, 30 psi

Selective Oxidation of Mixtures: log K_{OW}

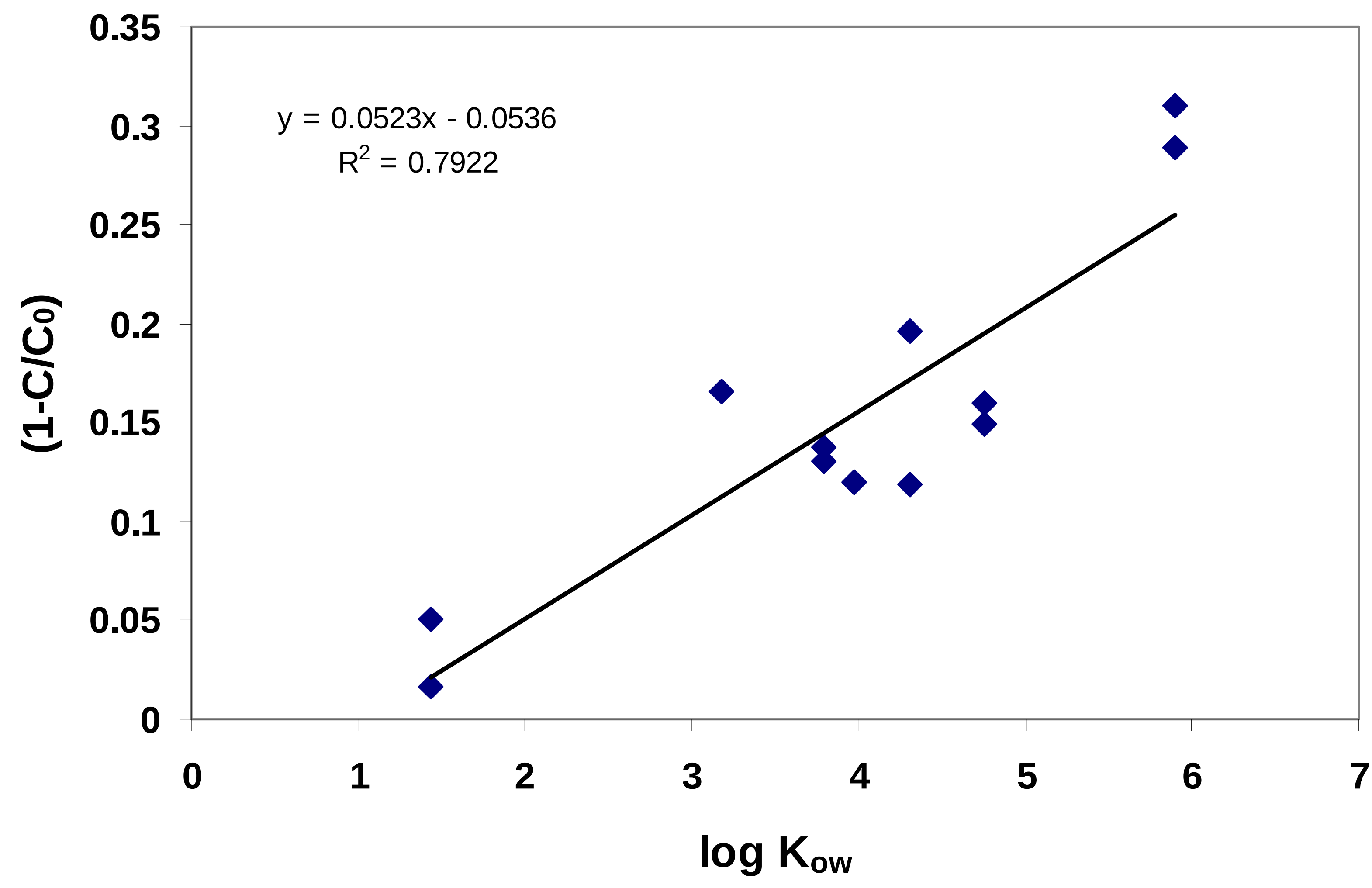
- 7 pharmaceuticals and personal care products were mixed in wastewater treatment plant effluent
- Mixture oxidized using DYNASWIRL® nozzle at 60 psi for 30 minutes
- Mixture had a range of log K_{OW} values 1.4 – 5.9
- More hydrophobic compounds reacted faster

Oxidation of Mixture of PPCP in Wastewater



DYNASWIRL® nozzle at 60 psi

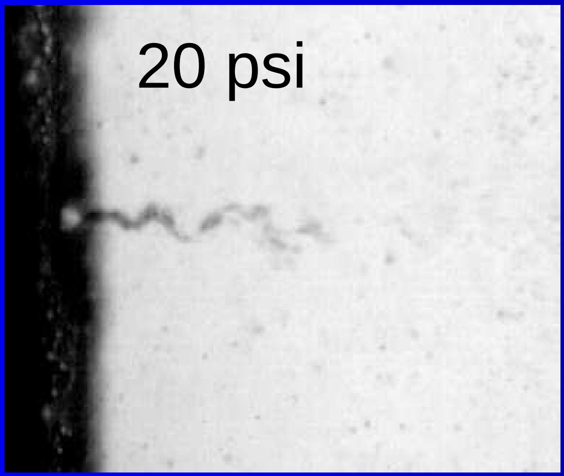
Log K_{ow} and Reaction Extent

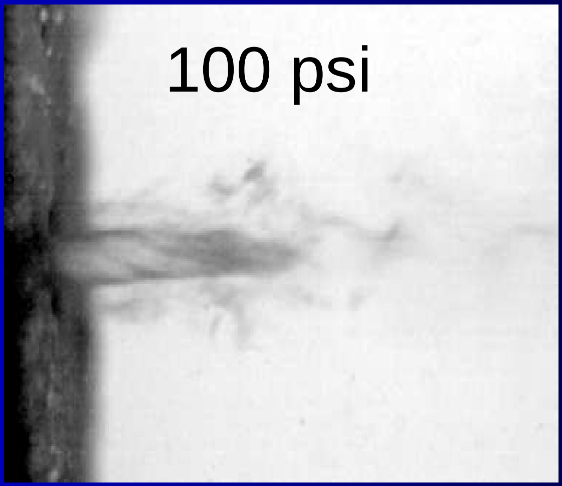


In a mixture more hydrophobic compounds react faster

Increasing Reaction Rates

- Nozzle design
- Pressure drop through the nozzle affects the quality of cavitation and oxidation efficiency
- Tweeking the system can increase reaction efficiency



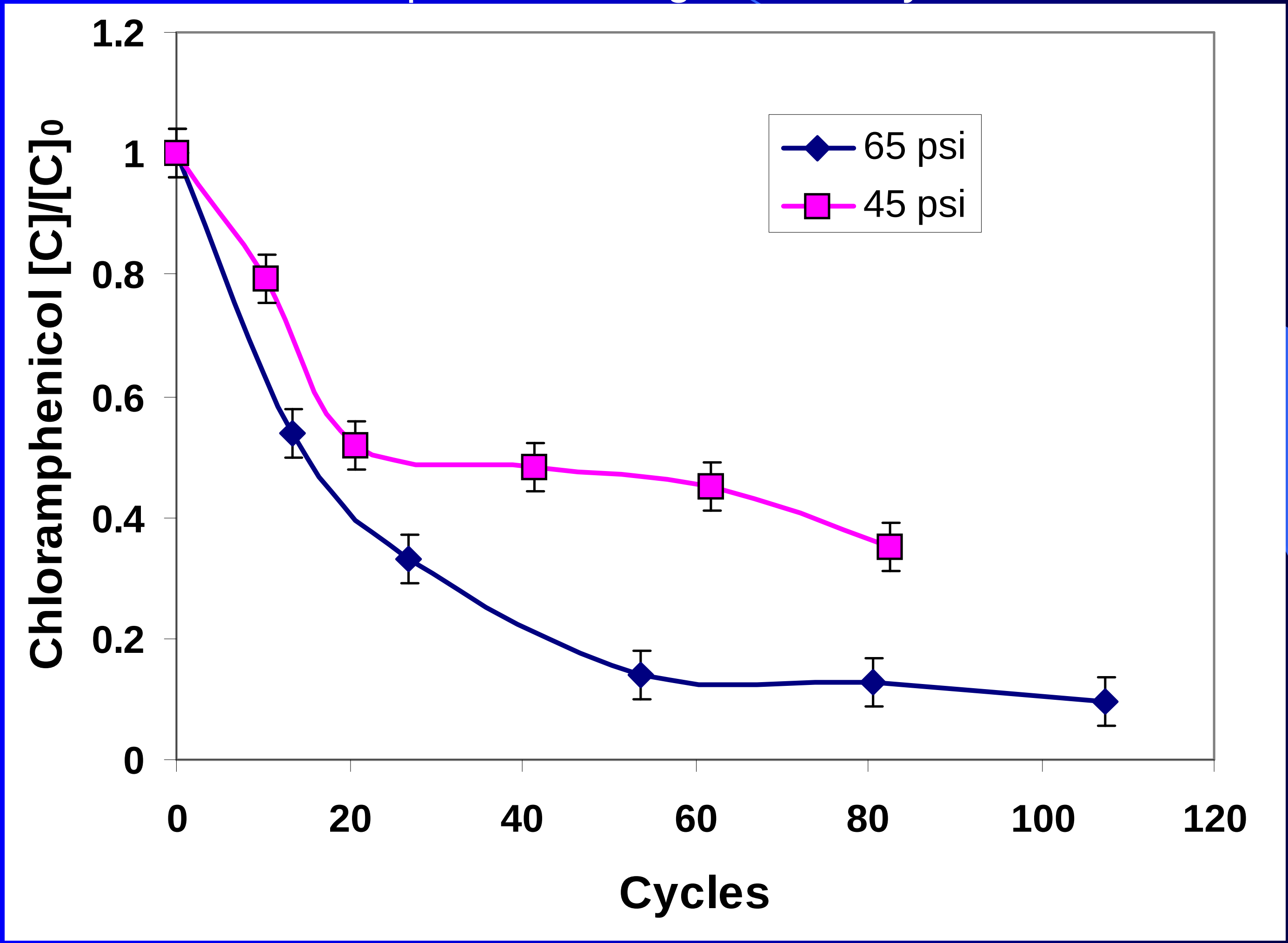


DYNASWIRL® nozzle

Effects of Operating Pressure

Chloramphenicol antibiotic used in aquaculture and veterinary applications

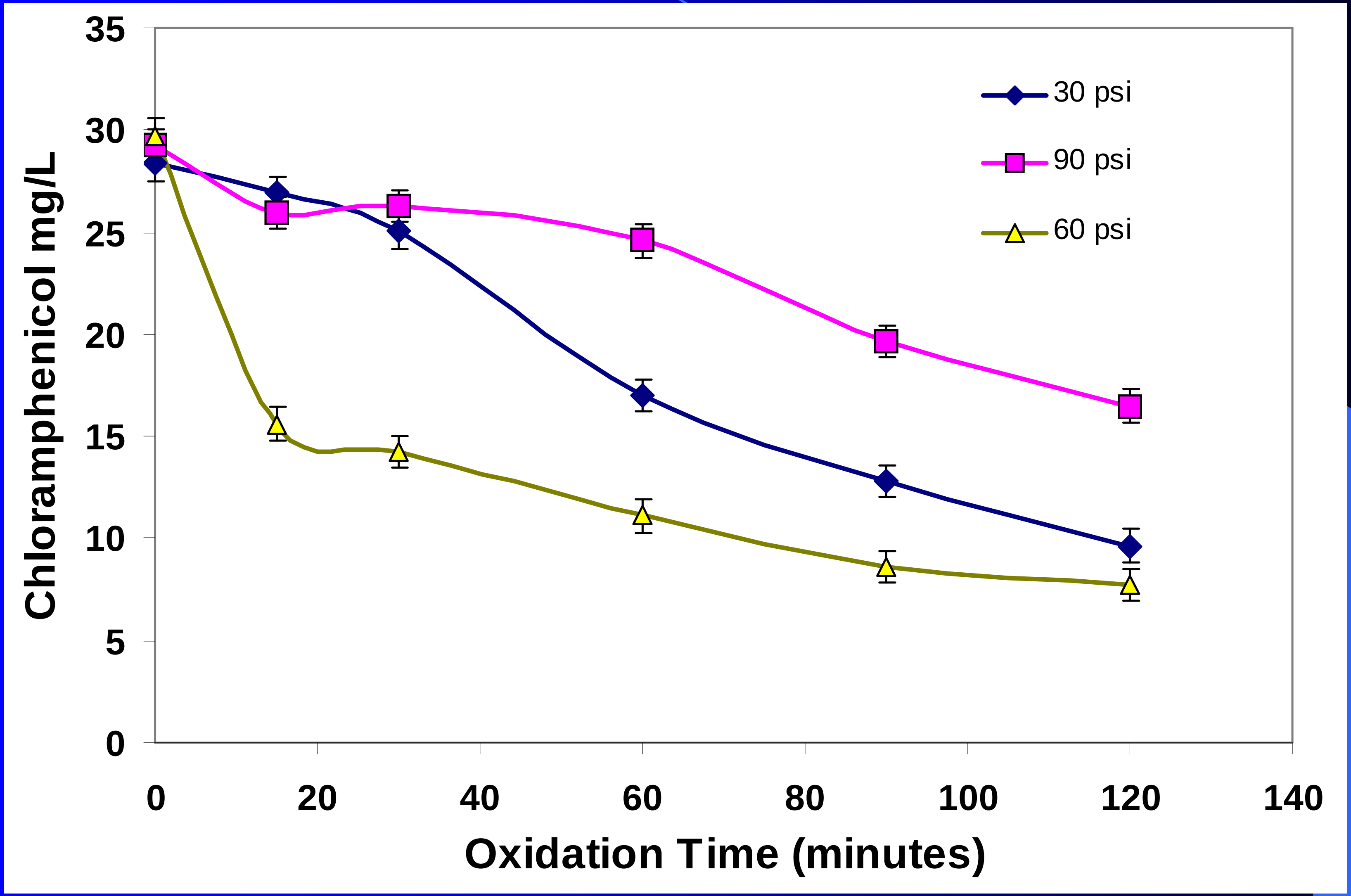
Removal of Chloramphenicol using centerbody CaviJet at 45 and 65 psi



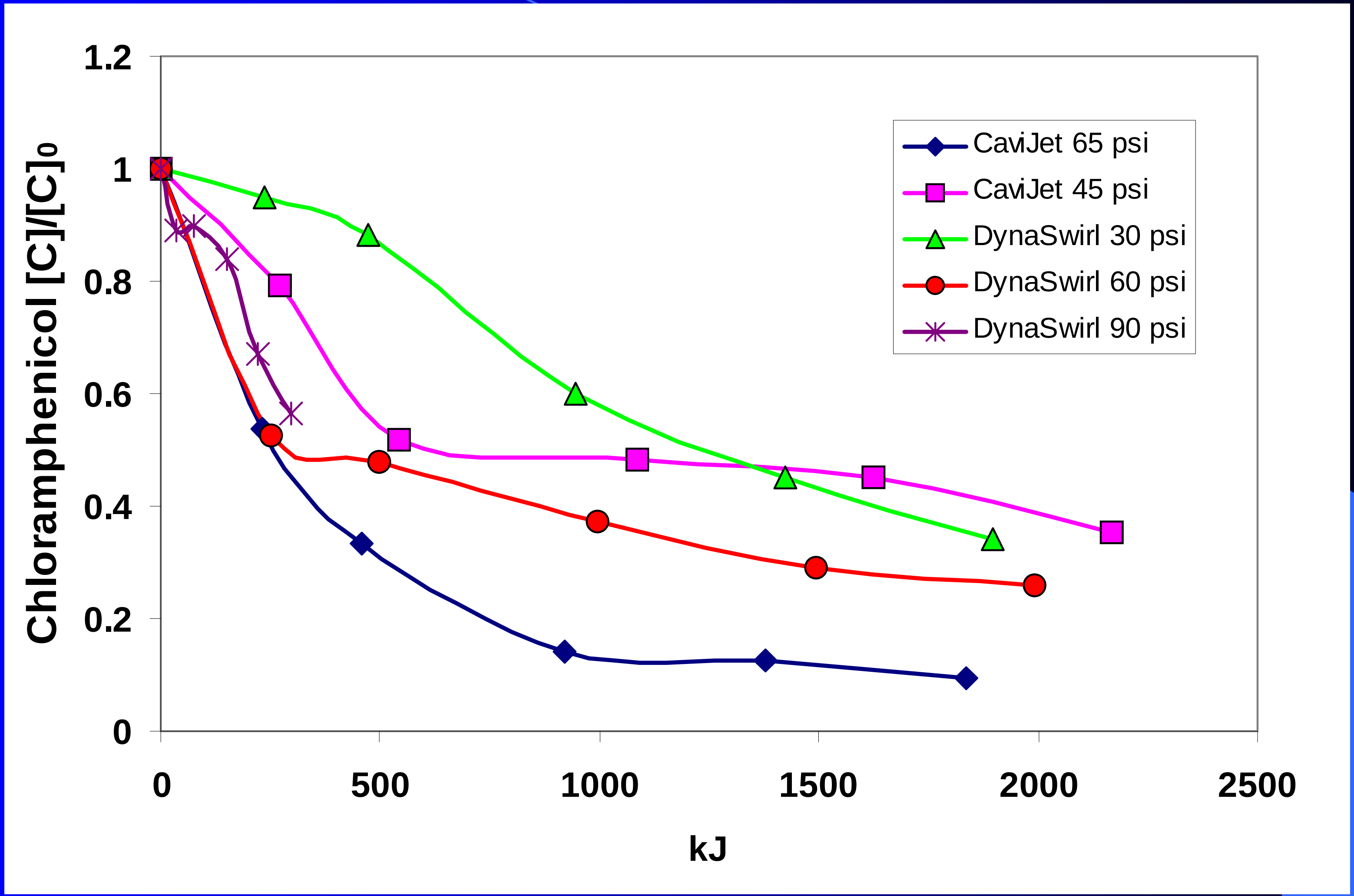
Initial concentrations = 27 mg/l, and total volume 11 liters

Effect of Pressure Drop on Removal Rate

Initial conc = 30 mg/L, Volume = 10 L. Oxidation with DYNASWIRL®



Chloramphenicol Removal per kilowatt-hour



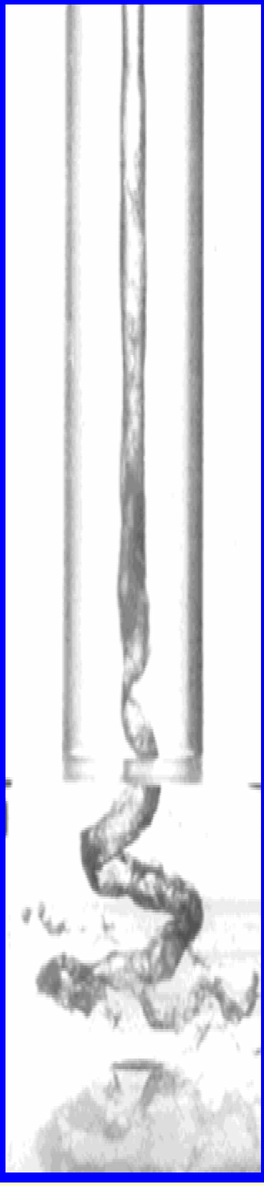
Conclusions

- Cavitation initiated reactions are similar regardless of how the cavitation is initiated
- Hydrodynamic cavitation can be more energy efficient and easier to scale up than ultrasonic devices
- Selective removal of volatile and hydrophobic compounds can be accomplished
- Selective removal by pH adjustment
- Oxidation rates have non-linear dependence on pump pressure
- Nozzle geometry can effect oxidation rates

Collaboration

- www.dynaflow-inc.com, technology descriptions and papers
- Testing, design, and production services
- Collaborative research
  - Feasibility studies
  - Small business STTR
  - Grant proposal writing

Acknowledgements & Contact Information



- US Environmental Protection Agency
- NASA
- Office Naval Research
- NOAA
- NIEHS

- DYNAFLOW, INC.

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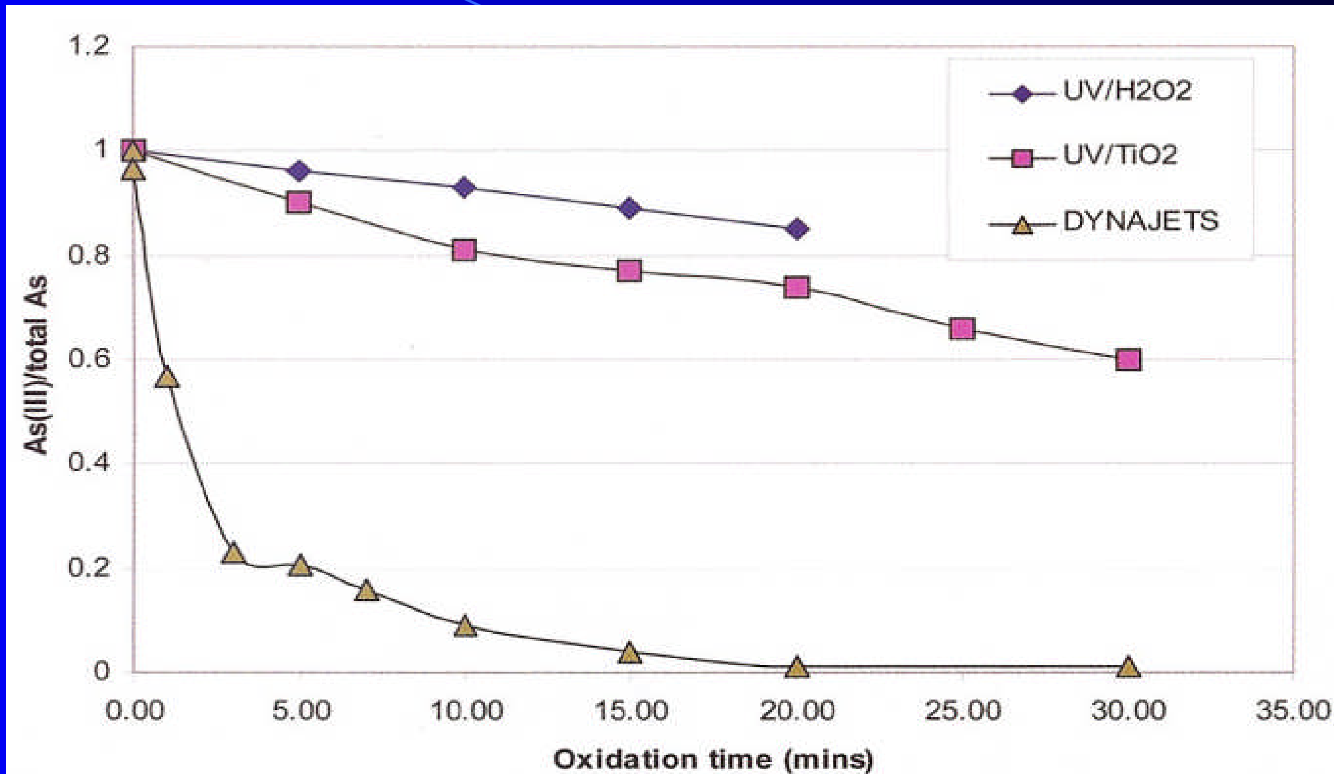
Oxidation of As (III) to As(V)

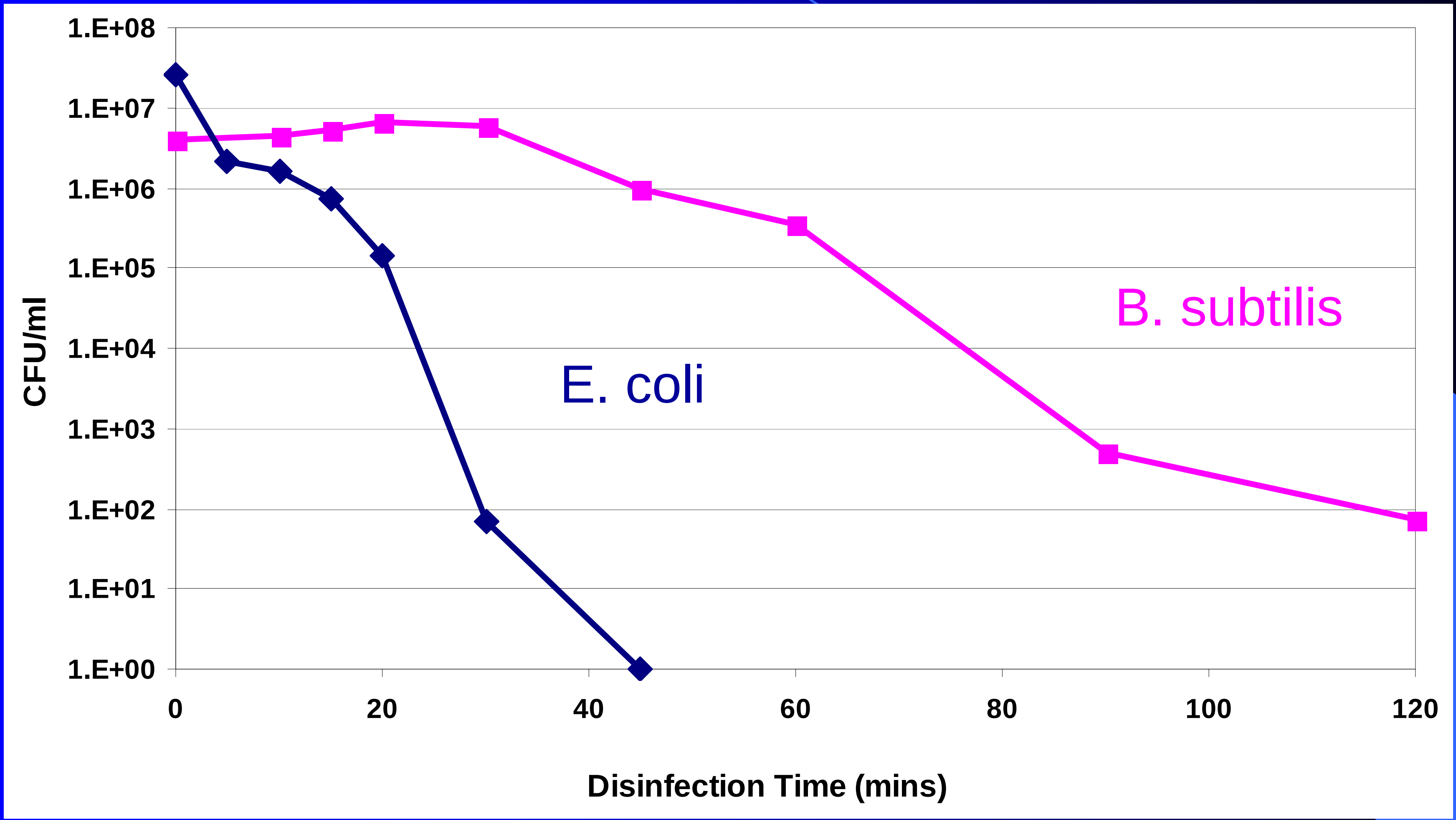


AOP	Lamp Power kW	Pump Power kW	kW/1000 gal
UV/H_2O_2	0.004		31
UV/TiO_2	0.004		17.4
DYNAJETS®		0.173	4.6

UV/H_2O_2 & UV/TiO_2 data Yoon and Lee 2005

Disinfection Efficiency: E coli & B subtilis

Effects of nozzle geometry, and nozzle pressure were investigated using E. coli and B. subtilis.



Same conditions - DYNASWIRL® nozzle at 2.1 bar