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Fabrication of Small Diesel Fuel Injector Orifices

George Fenske
Argonne National Laboratory

Sponsored by Jerry Gibbs
Propulsion Materials

DOE VEHICLE TECHNOLOGIES PROGRAM ANNUAL MERIT REVIEW
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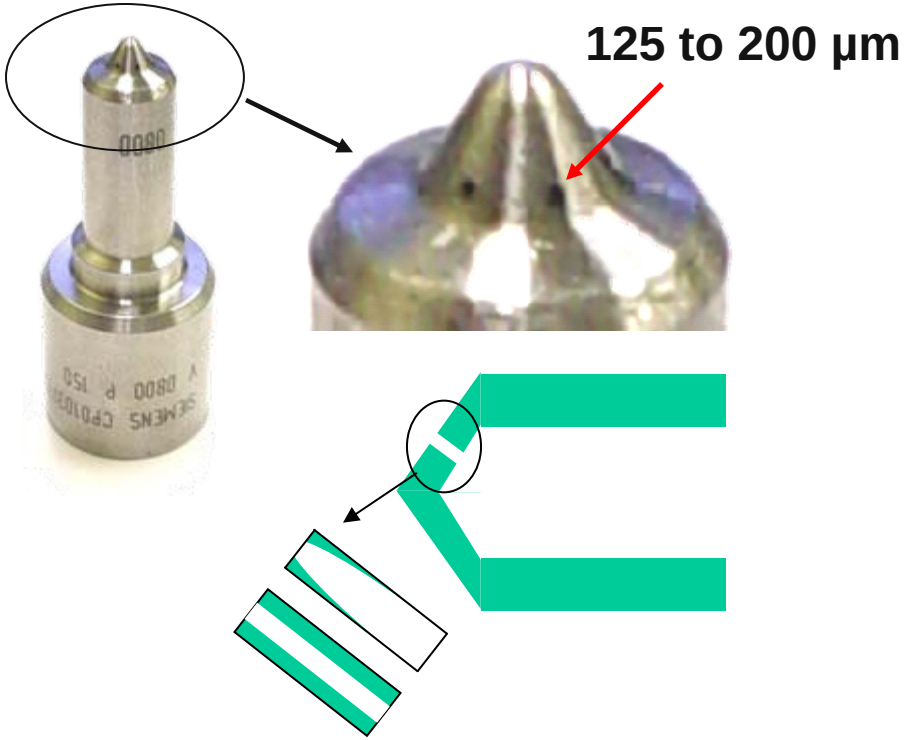
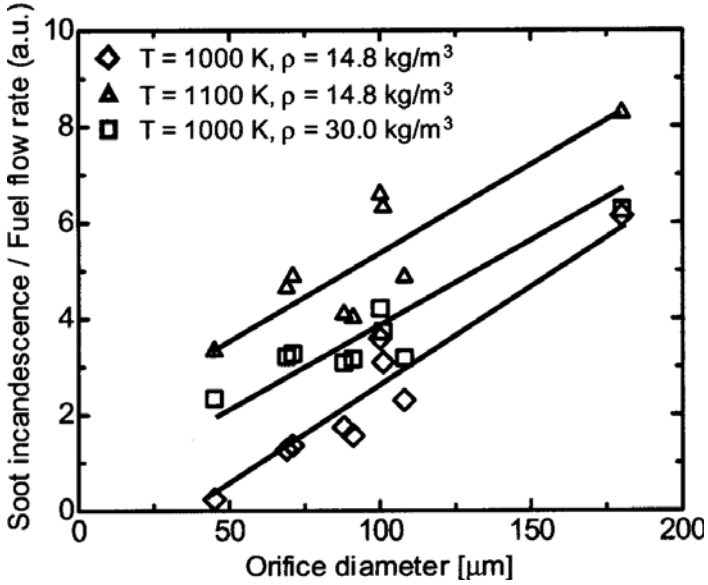
Outline

- Purpose of work
- Address Previous Review Comments (if applicable)
  - N/A
- Barriers
- Approach
- Performance Measures and Accomplishments
- Technology Transfer
- Publications/Patents
- Plans for Next Fiscal Year
- Summary

Purpose of Work

- Develop technologies to fabricate **50 µm diameter (or less) micro-orifices** for high-pressure diesel injectors
  - Reduce in-cylinder production of particulates ***(lower emissions)***
    - **with no fuel economy penalty**
  - Improve combustion of fuel ***(improved fuel efficiency)***





Pickett & Siebers, JOURNAL OF ENGINEERING FOR GAS TURBINES AND POWER-TRANSACTIONS OF THE ASME 127 (1): 187-196 JAN 2005

Barriers

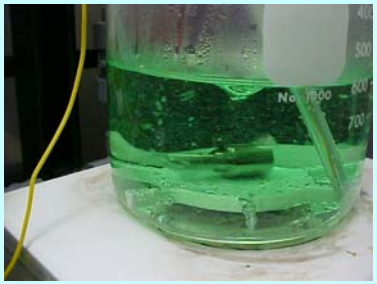
- Vehicle Technologies Barriers *(MultiYear Program Plan):*
  - Energy Efficiency …"**maintaining efficiency and low NOX while keeping PM down**…"
    - *Emission compliant engine systems with 50% efficiency by 2010, stretch goal of 55% thermal efficiency in prototype engines.*
  - Emission Control "Meeting EPA requirements for oxides of nitrogen and particulate matter emissions standards **with little or no fuel economy penalty** will be a key factor for market entry of advanced combustion engines"; ….." The fuel injection system pressure and fuel spray development influence the spray penetration and fuel-air mixing processes and thus combustion and emissions formation within the combustion chamber…."
- Multiple paths being pursued to reduce emissions
  - Aftertreatment devices (NOx & PM traps)
  - Alternative engine cycles (HCCI, LTC)
  - **Improved fuel injector designs – fuel atomization (in-cylinder reduction of particulates)**
- DOE Workshop "**RESEARCH NEEDS RELATED TO FUEL INJECTION SYSTEMS IN CIDI AND SIDI ENGINES**" identified specific needs:
  - **Manufacturing technologies** that would be used for cost-effectively producing ultra-small holes and controlling dimensions with ultra precision.
  - Materials and coatings to resist fatigue, wear, and corrosion; sensors and controls; non-traditional fuel injection; modeling & simulation, …

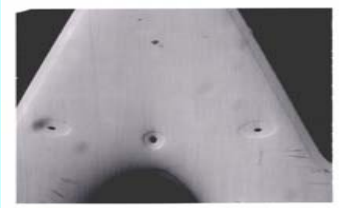
Approach

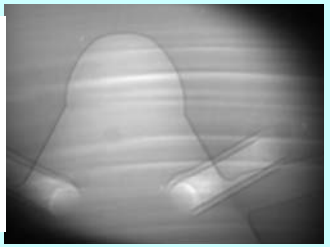
- Identify potential micro-orifice fabrication techniques
  - No technology exists to economically produce robust 50 µm orifices
- Downselect – 50 µm, maturity, cost, scale-up
- Demonstrate feasibility (lab)
- Identify and resolve technical barriers
  - Uniformity, adhesion, deposit formation, hardness, fatigue, reduced flow …
- Treat prototypic components (Tech Transfer)
- Spray visualization studies
- Engine emission & efficiency studies

Electrodischarge (current process), Plating (**aqueous**, CVD/PVD), Laser-processing, LIGA, …

Electroless Nickel – autocatalytic deposition of Ni from aqueous solution



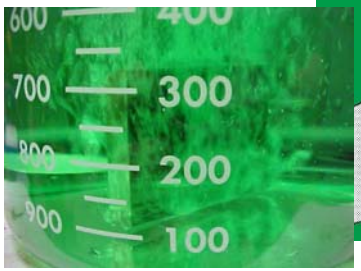


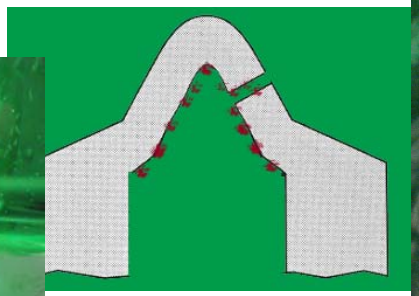


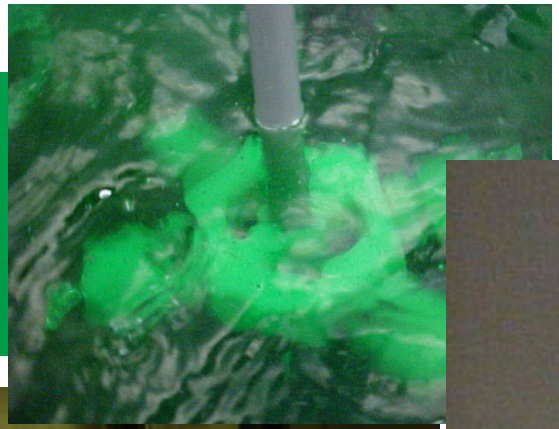
USEPA NVFEL

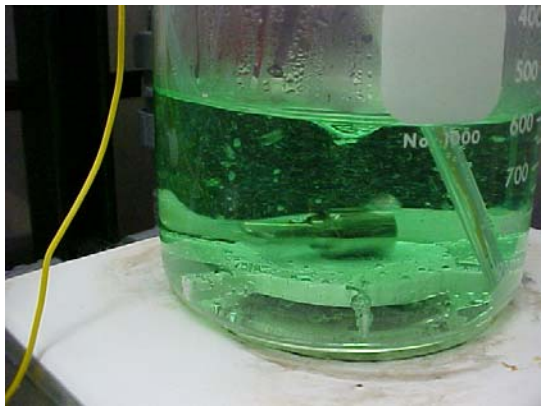
Demonstrate Feasibility

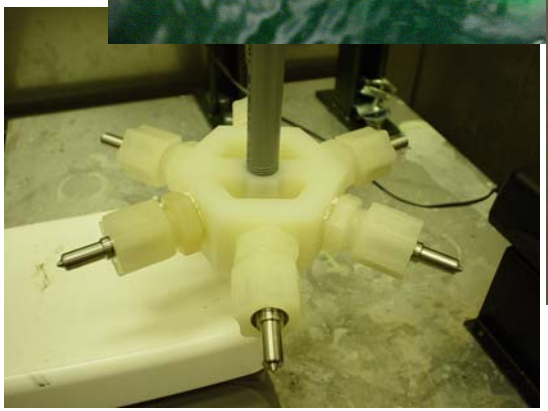
- Release of hydrogen during autocatalytic deposition impaired uniformity.
- Multiple electroless nickel (EN) approaches were investigated in a lab setting to mitigate buildup of hydrogen bubbles on internal surfaces.
  - Beaker, beaker & magnetic stirring, pump-through, spin-through, ultrasonic agitation





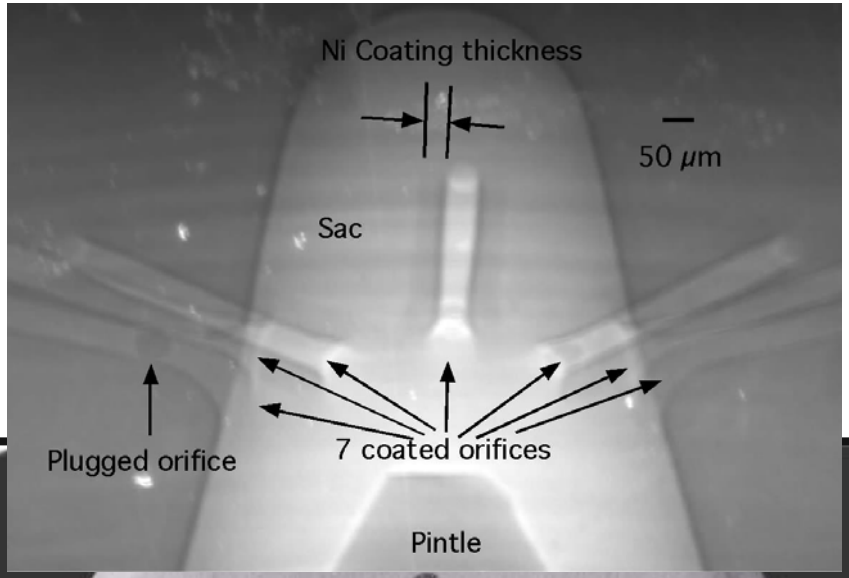


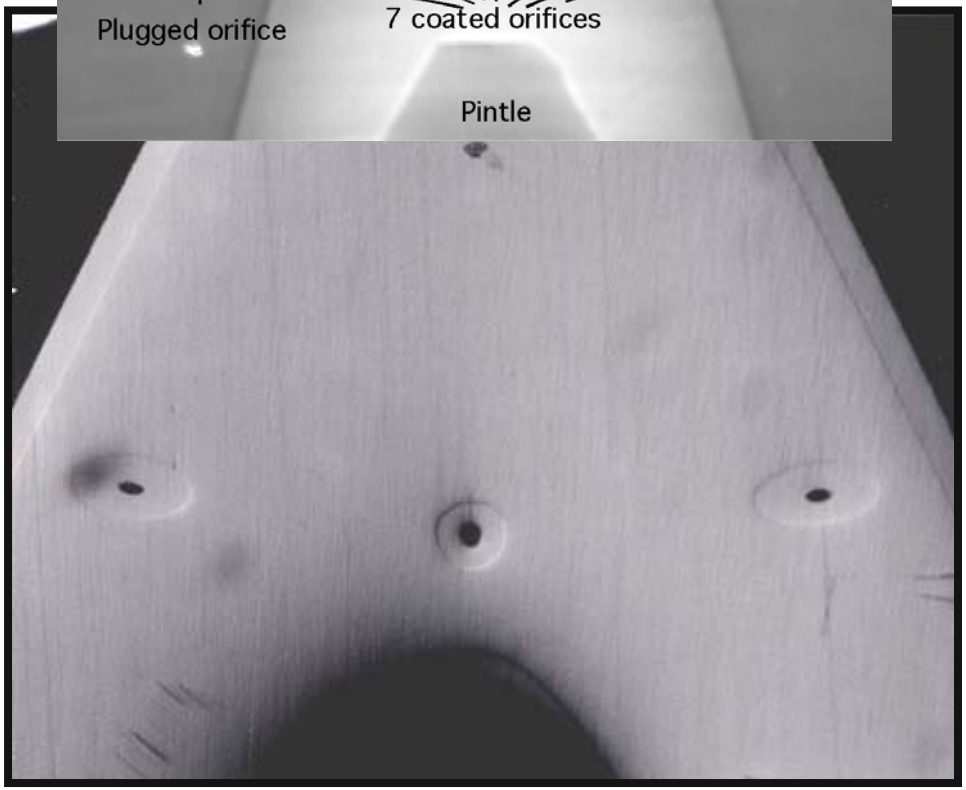


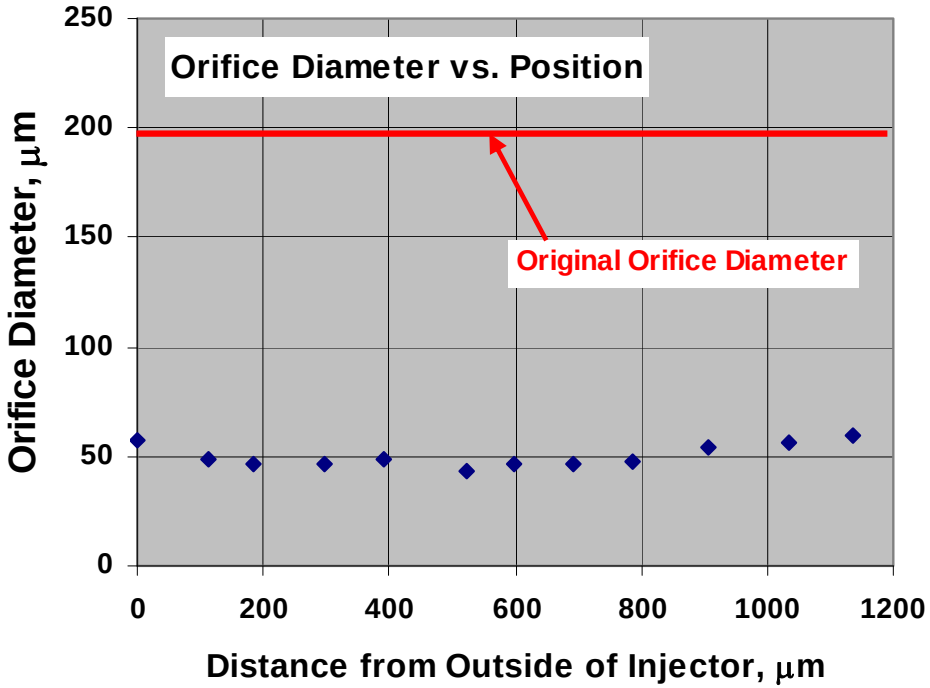


Coating Uniformity

- Metallography and phase-contrast X-Ray imaging (NDE) of EN - coated nozzles provide quantitative information on coating uniformity

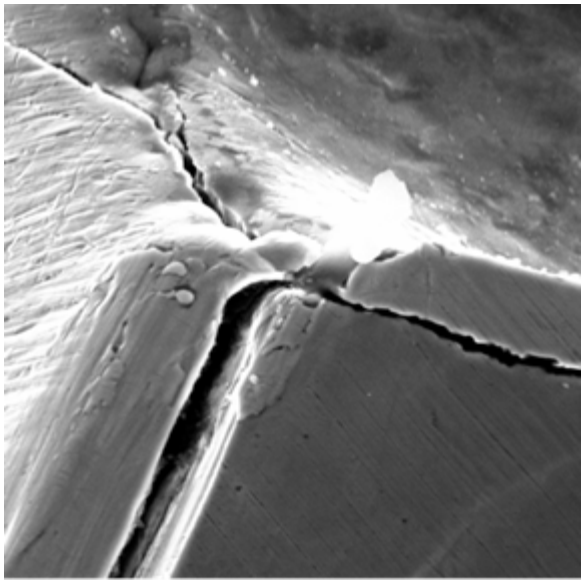


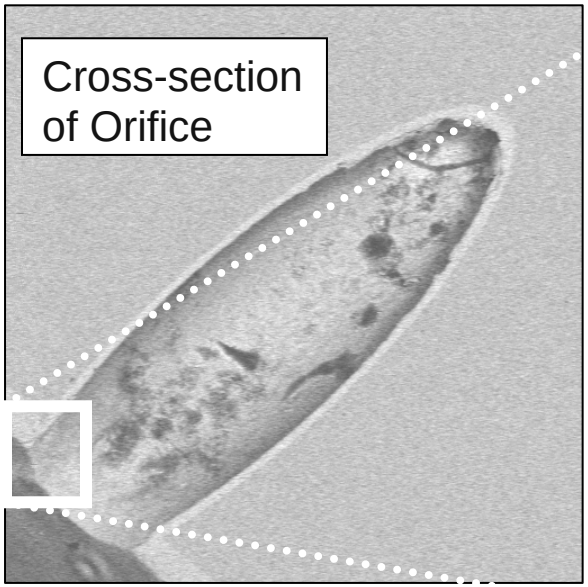


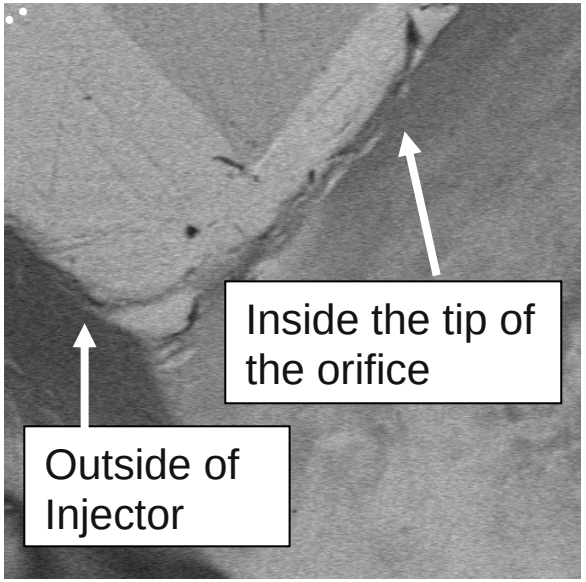


Adhesion

- Initial adhesion issues were addressed and resolved with proper control of precleaning/etching, control of solution chemistry, and post-deposition annealing

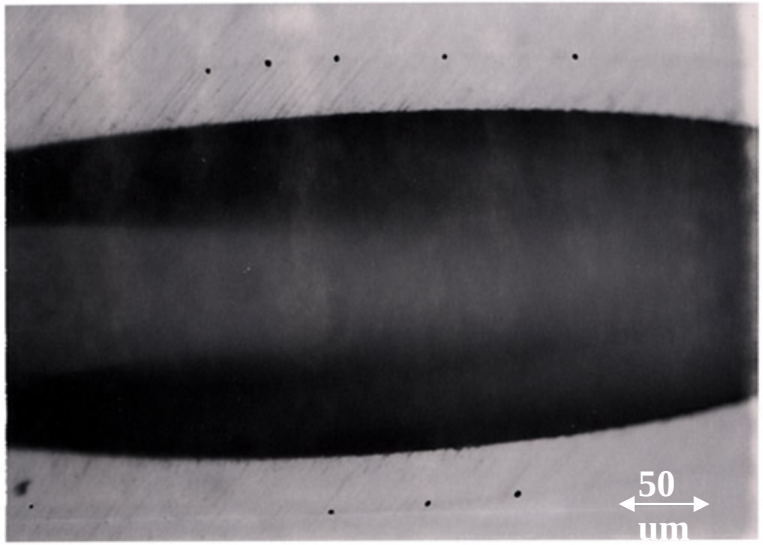


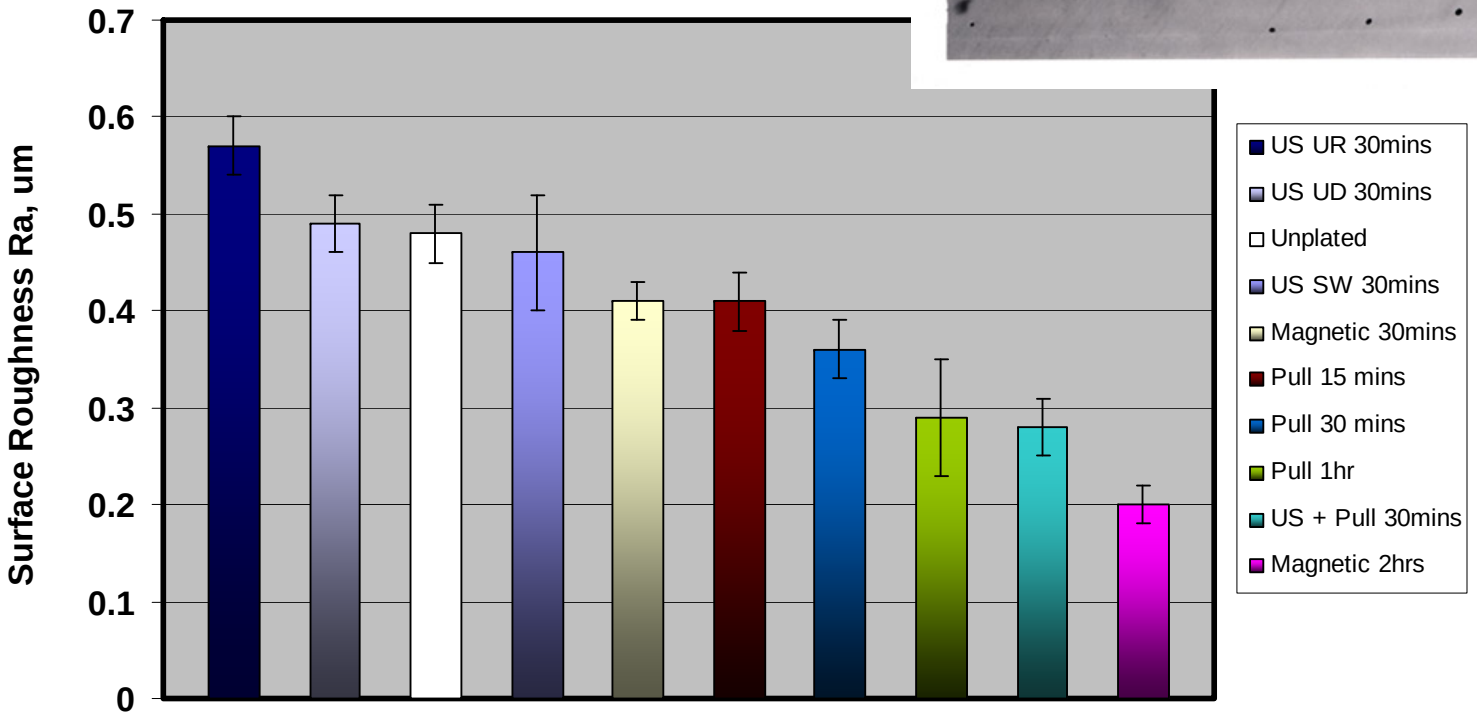




Surface Finish

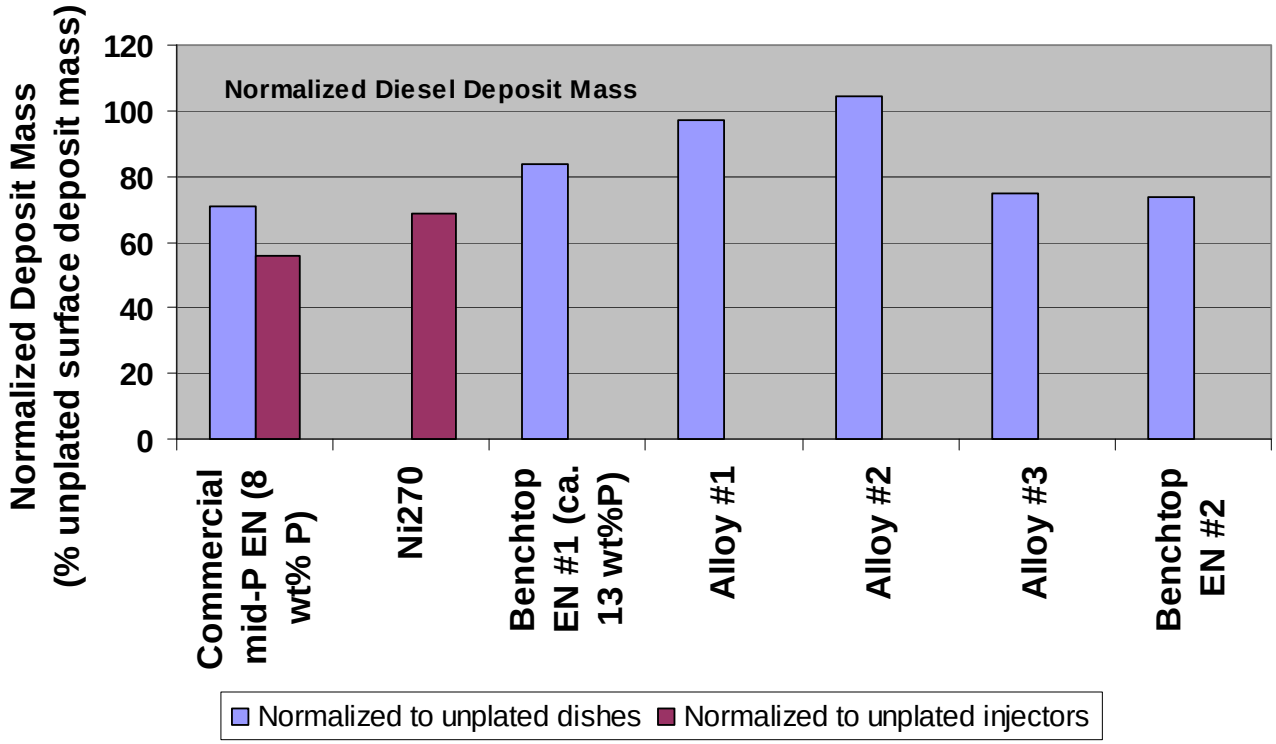
- Roughness measurements of the internal orifice surface indicate EN process ‘levels’ surface asperities
  - Increase Cd for individual micro-orifices – improved flow properties





Deposit Formation

- Smaller orifices are more prone to plugging due to the formation of deposits
- Lab tests demonstrate EN coatings (Ni-P) are less prone to deposit formation



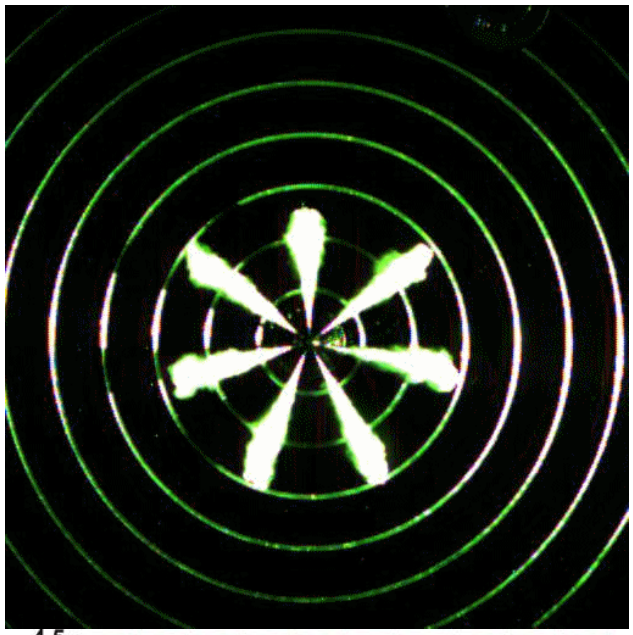
Scale-Up/Tech Transfer

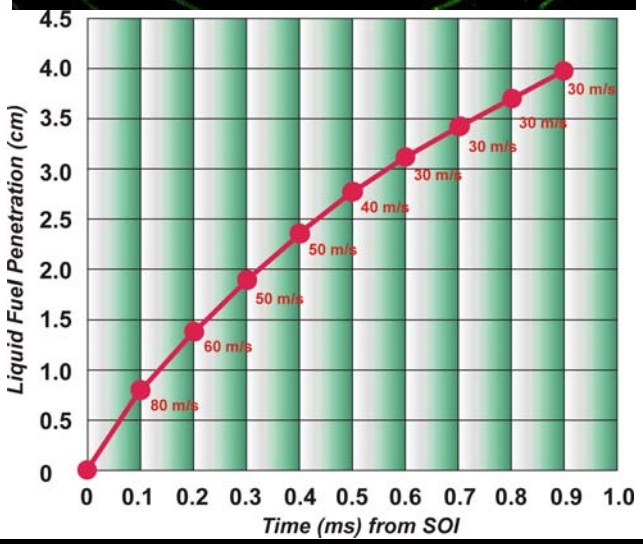
- Efforts initiated to transfer coating concept to a commercial coating firm
  - Access to experience and knowledgebase that a commercial firm can provide to address adhesion, hardness, hydrogen-buildup and coating of small orifices.
  - Experience in design and costing of systems for production.
  - Issues related to small-batch and day-to-day variations minimized.
- Collaborative efforts engine and fuel injector manufacturers
  - Fuel atomization, deposit formation, ….
- Collaborative efforts with USEPA – flow visualization studies

Flow Visualization

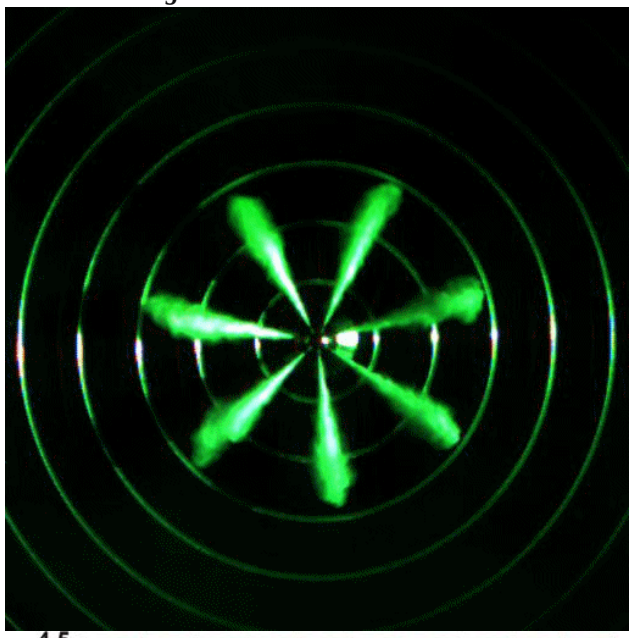
Courtesy – Ron Schaefer, USEPA/NVFEL

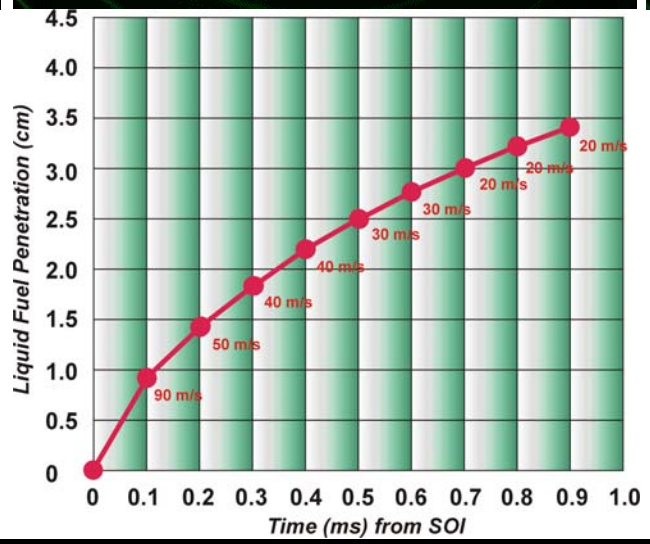
Ann Arbor Nozzle: 7X0.10mmx160



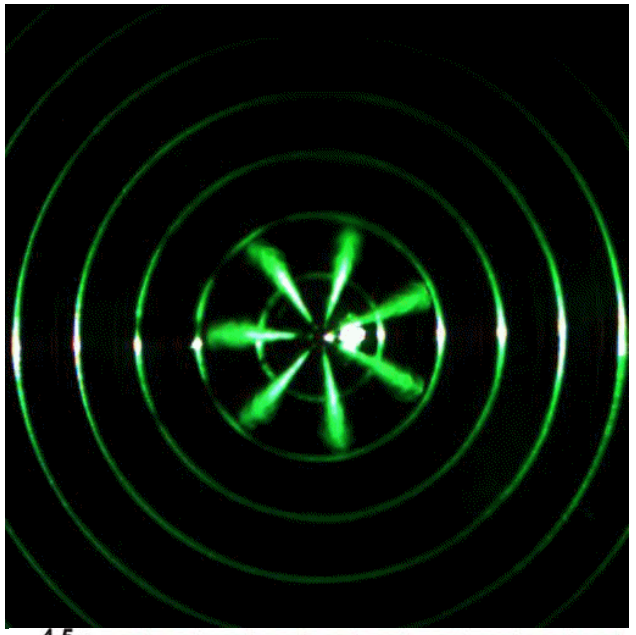


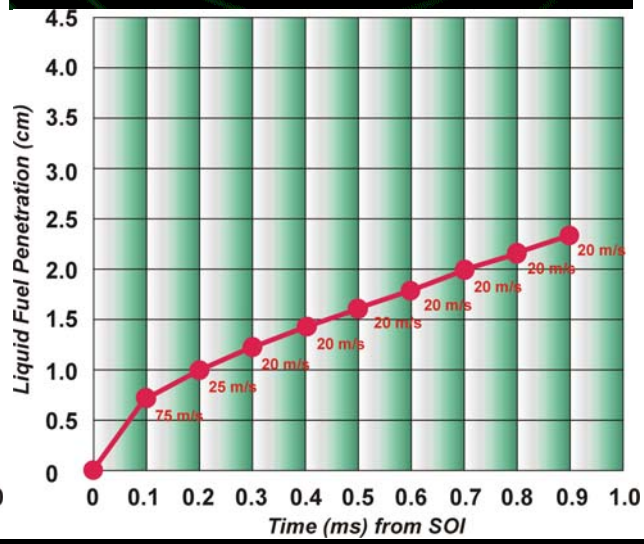
Argonne Nozzle: 7x0.075x157





Argonne Nozzle: 7x0.05x157





Future Plans

- EN – Plating
  - Flow visualization studies
    - *USEPA – NVFEL*
    - *X-ray imaging (APS)*
  - Multi-Size Orifices
- Engine Emission Studies
- Industry – durability, cavitation
- Alternative Micro-Orifice Fabrication
  - Nickel Vapor Deposition
  - Laser Micro-Drilling

NVD - Weber

Laser - Sparkle

Publications & Patents/Inventions

- Publications
  - Fenske, G., “Fabrication of Micro-Orifices for Diesel Fuel Injectors,” *2007 Annual Progress Report, Automotive Propulsion Materials,* U.S. Department of Energy, Washington, D.C., 2008.
  - Woodford, J. B., and Fenske, G. R., “Fabrication of Small-Orifice Fuel Injectors for Diesel Engines,” Argonne National Laboratory report ANL-05/06, Argonne, IL, 2005
  - George Fenske, John Woodford, Jin Wang, Ronald Schaefer and Fakhri Hamady, “Fabrication and Characterization of Micro-Orifices for Diesel Fuel Injectors”, 2008 SAE International Powertrains, Fuels and Lubricants Congress, Shanghai, China; Jun 23-25, 2008
  - Annual Report of Laboratory-Directed Research and Development Program Activities for FY 2006
  - Annual Report of Laboratory-Directed Research and Development Program Activities for FY 2007
- Patents/Inventions
  - *ANL-IN-02-048 – Electroless Nickel Plating to produce micro-orifices*
  - *ANL-IN-03-089 – Electroless plating to produce chemically active surfaces*
  - *ANL-IN-06-030 - Nickel Vapor Deposition Orifice Coatings*

Summary

- Based on studies that demonstrated significant reductions in soot production with decreasing orifice diameter, efforts were initiated to identify and develop processes to fabricate micro-orifices on commercial nozzles.
  - Improved fuel atomization reduces soot/particulate formation and improves air entrainment thereby improving combustion efficiency
- Multiple approaches were examined early in the project with a down selection to EN
- Demonstrated the EN process for fabricating micro-orifices on commercial fuel injectors.
  - EN process was applied to produce 50 µm diameter orifices on multi-orificed commercial nozzles (with original orifices ranging from 125 to 200 µm)
  - Process that can be incorporated into existing nozzle designs
- Worked with industry, technical barriers were identified and resolved (uniformity, adhesion, hardness)
- Internal LDRD funding supported development of advanced x-ray imaging techniques for NDE characterization of coating uniformity and orifice blockage
- Spray visualization studies in collaboration with the USEPA demonstrated:
  - Smaller orifices resulted in shorter liquid penetration length and an appreciably shorter spray core length.
  - Smaller orifices enhanced atomization.
- Efforts in FY08 to focus on spray visualization studies of multi-sized orifices
- Future efforts to focus on engine emission studies

Questions ???