Fuel Injector Holes

(Fabrication of Micro-Orifices for Fuel Injectors)

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PM003

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Overview

Timeline

- Project start date FY04
- Project end date FY14
- Percent complete 80%

Barriers

- Emissions – reduction of in-cylinder formation of particulates
- Efficiency – improved combustion and mitigation of after-treatment fuel consumption

Budget

- Total Project Funding ~$2 M
  - DOE Share ~$1.5M
  - Collaborator Share ~$0.25M
- FY10 $400 K
- FY11 $200 K (CR)

Partners

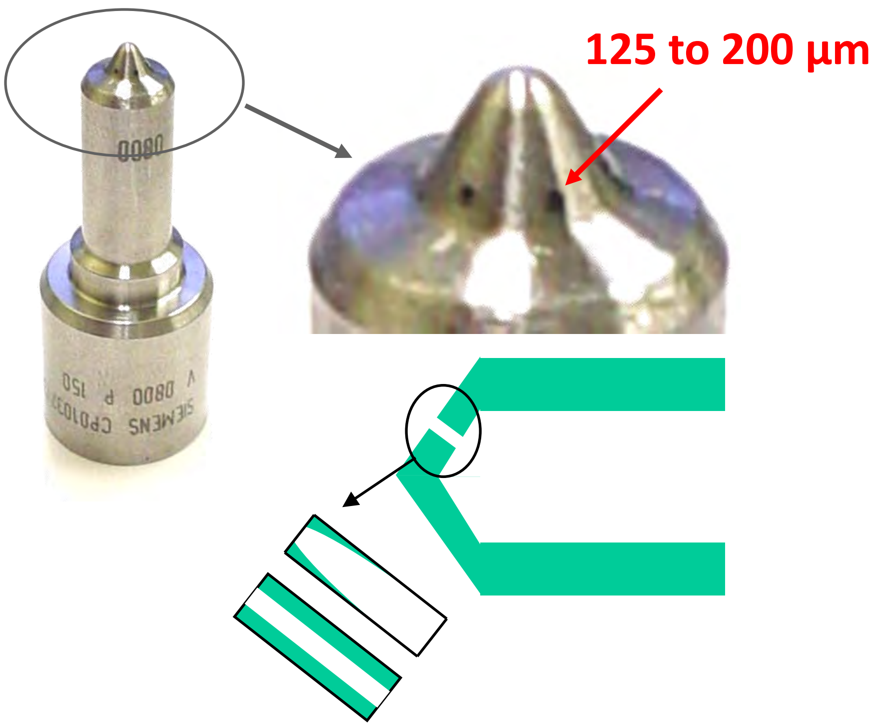
- Imagineering Finishing Technologies
- Fuel system OEMs
- Engine OEM
- Small business - integration of electroless nickel (EN) process into nozzle production line
- U.S. EPA

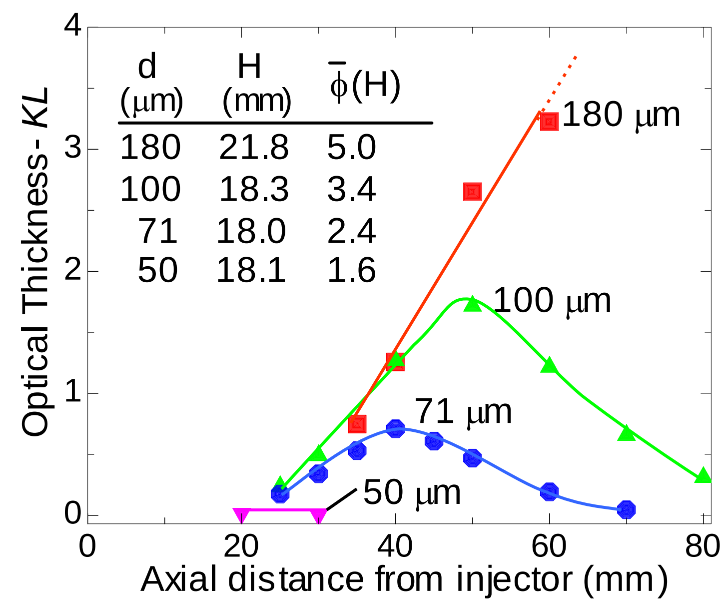
Project Objectives - Relevance

- Main objective/goal of the project is the development of fuel injector manufacturing technology to **reduce diesel emissions** by reducing in-cylinder production of particulates.
  - Potential secondary benefits are higher fuel efficiency through improved fuel atomization and combustion, and reduced use of fuel for regeneration of particulate matter (PM) traps.
- Multiple paths are being pursued by DOE & industry to reduce emissions:
  - After-treatment devices (NO_x and PM traps)
  - Alternative combustion cycles (homogeneous charge compression ignition and low temperature combustion)
  - **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 following 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 and simulation, etc.

Objective of Work

- Combustion studies have demonstrated that reducing the orifice diameter on an injector decreases the amount of particulates formed during combustion.
- Objective of research is to 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).***





Courtesy L. Pickett SNL-Livermore

Project Milestones

- **FY 2010**
  - Preparation of multi-sized (40/145 µm) micro-orifices on commercial nozzles for spray visualization studies at the U.S. EPA (completed)
    - EPA contact no longer involved in spray visualization studies, seeking alternative partner for flow studies
  - Establishment of collaborative agreements with engine and nozzle OEMs to accelerate technology validation
    - Separate agreements in place with international injector OEM and domestic engine OEM (FY 11); proposal with vehicle OEM developed and submitted to DOE (FY 11)
- **FY 2011**
  - Demonstration of x-ray absorption imaging technique for nondestructive evaluation (NDA) of internal coated orifice surfaces (completed)
  - Evaluation of ASTM Method G32-09 to determine cavitation erosion performance of plated nozzles (completed)
    - Cavitation erosion studies (in progress)
  - Preparation of 2nd generation multi-orifice nozzles (50/110 µm) for nozzle OEM evaluation (in progress)
    - Two collaborations in progress (engine OEM, injector OEM)

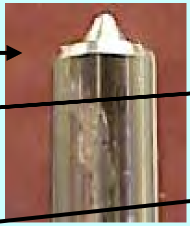
Approach

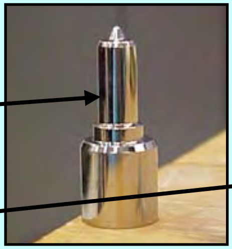
- Identify potential micro-orifice fabrication techniques
  - No technology exists to economically produce robust 50 µm orifices
- Down select – 50 µm, maturity, cost, scale-up
- Demonstrate feasibility (lab)
- Identify and resolve technical barriers
  - Uniformity, adhesion, deposit formation, hardness, fatigue, reduced flow, etc.
- Treat prototypic components (Tech Transfer)
- Conduct spray visualization studies (EPA)
  - Single-size orifices (50 µm)
- Prepare multi-sized orifices (e.g., 40 µm and 145 µm) on the same nozzle to maintain fuel flow capability and improve combustion
  - Detailed microstructural analysis
- Conduct NDE of multi-size orifices (x-ray imaging)

- Manufacturing optimization (re-grind)
- Pop-testing (QA – prior to spray studies)
- Cavitation erosion studies
- Engine emission and efficiency studies

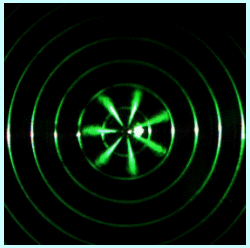
Electrodischarge (current process), plating (**aqueous**, CVD/PVD), laser processing, LIGA, …

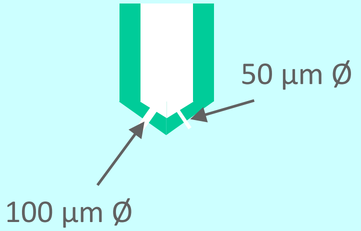
Electroless Nickel (EN) – autocatalytic deposition of Ni from aqueous solution

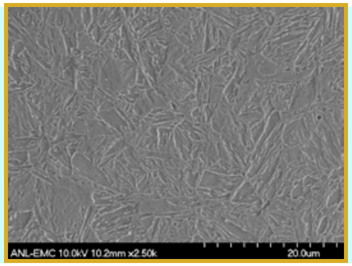


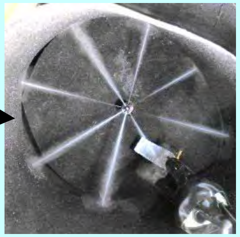


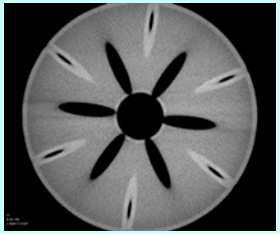
USEPA NVFEL





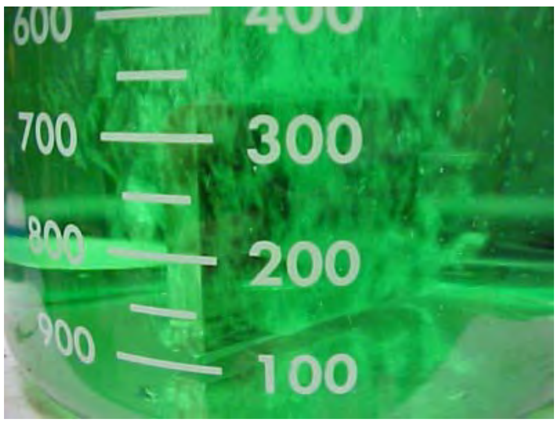


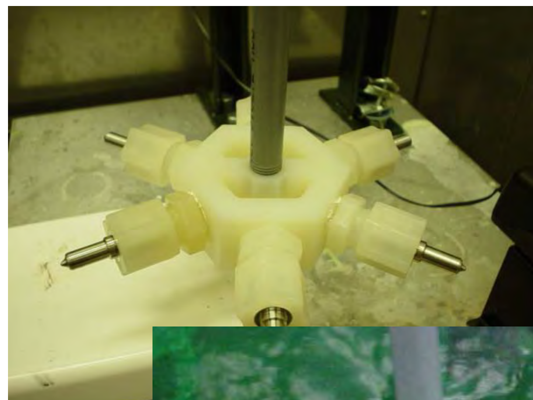


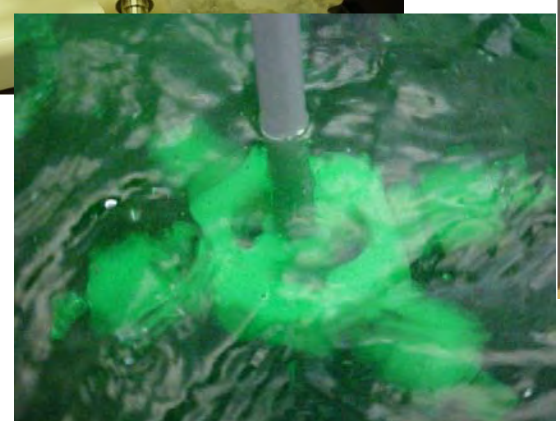


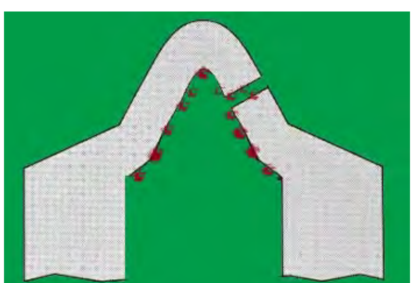
<u>Accomplishment</u> – Demonstrated feasibility to coat interior surfaces of small injector orifices using EN.

- Autocatalytic EN process generates hydrogen bubbles that adhere to surface and prevent uniform coverage.
- Multiple mechanical techniques are being pursued to mitigate adhesion of H_2 bubbles.



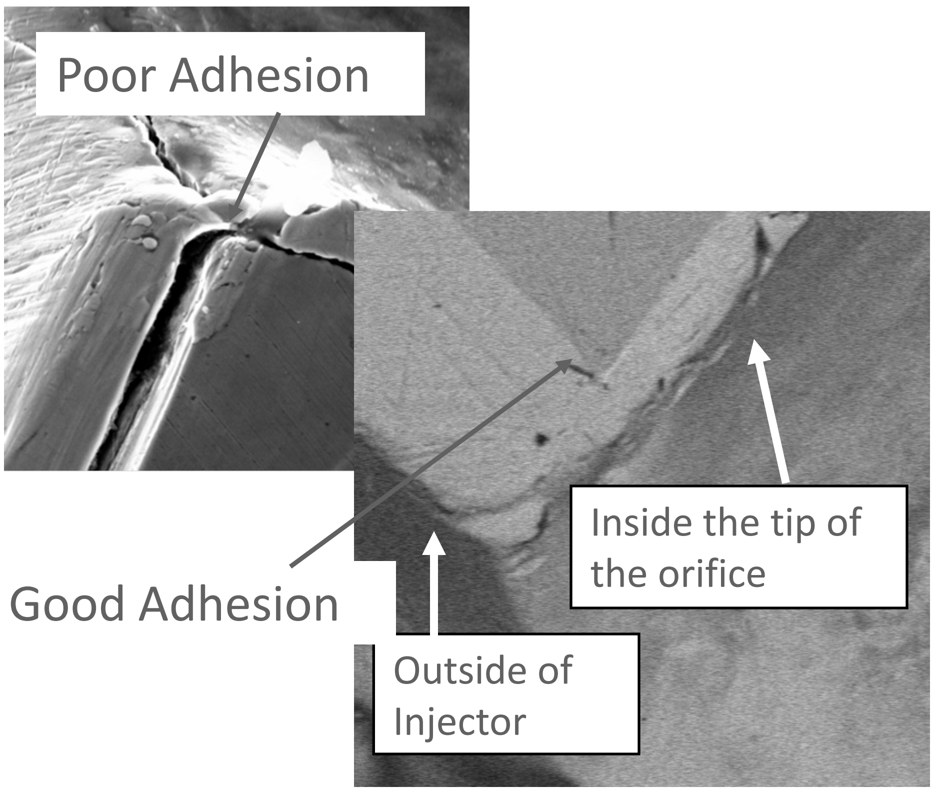






Accomplishment: Addressed and resolved early issues related to coating adhesion.

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



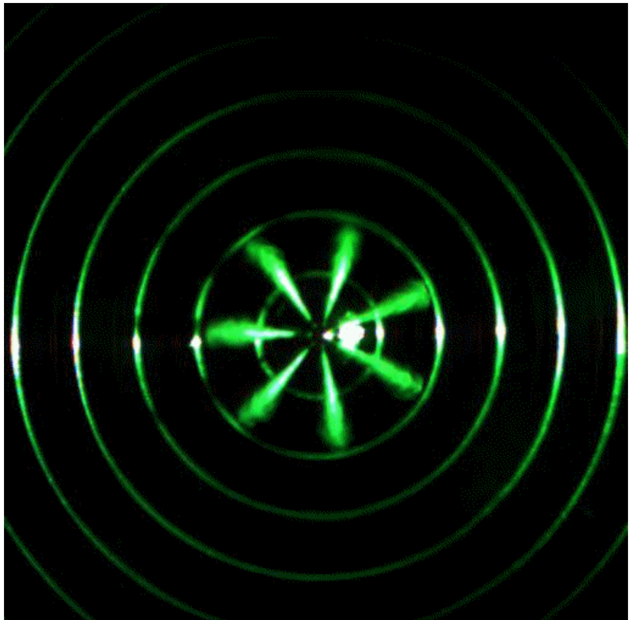
Accomplishment: Transferred concept/technology to industrial plater/coater.

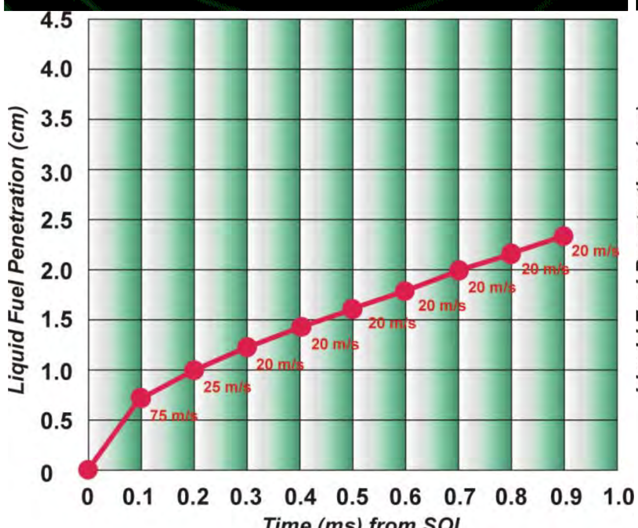
- Lab-scale process transferred to commercial size operation.

  - Reduced small-batch chemistry variations.
  - Standardized cleaning and post-deposition treatments.
  - Access to knowledge base.

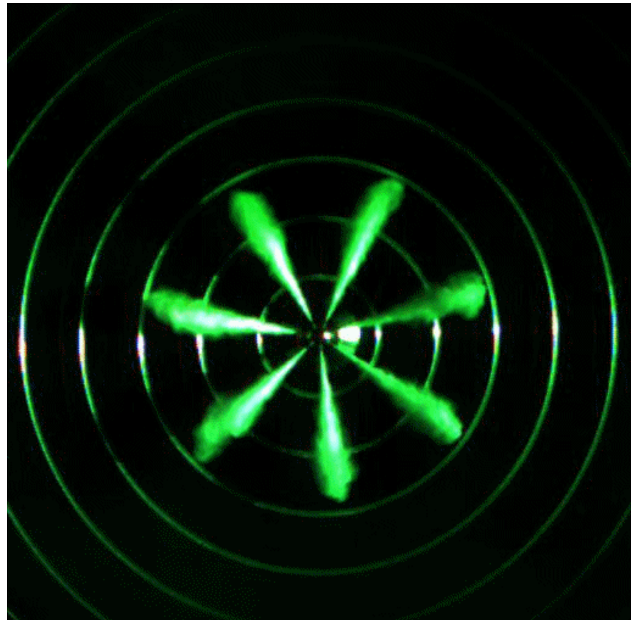
Progress/Accomplishment: Flow Visualization - Demonstrated enhanced flow characteristics in single-size orifices (100, 75, and 50 µm) at 3000 bar.

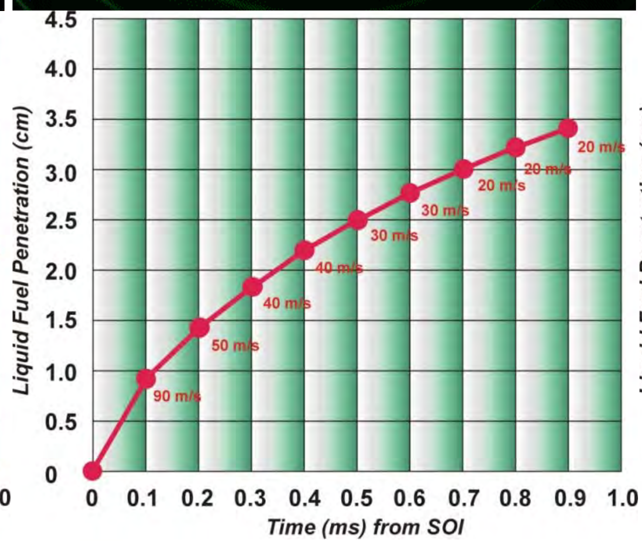
Argonne Nozzle: 7x0.05x157



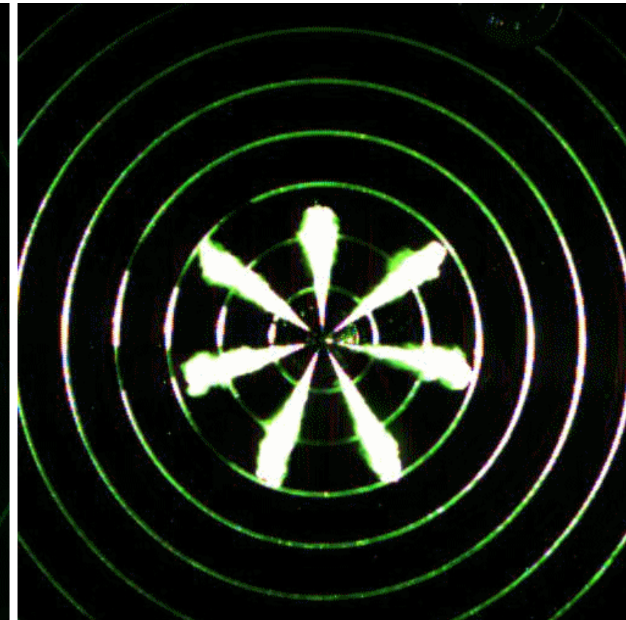


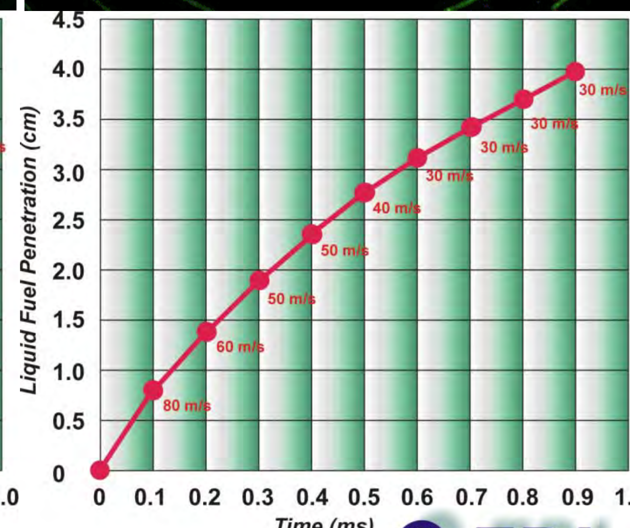
Argonne Nozzle: 7x0.075x157





Ann Arbor Nozzle: 7X0.10mmx160



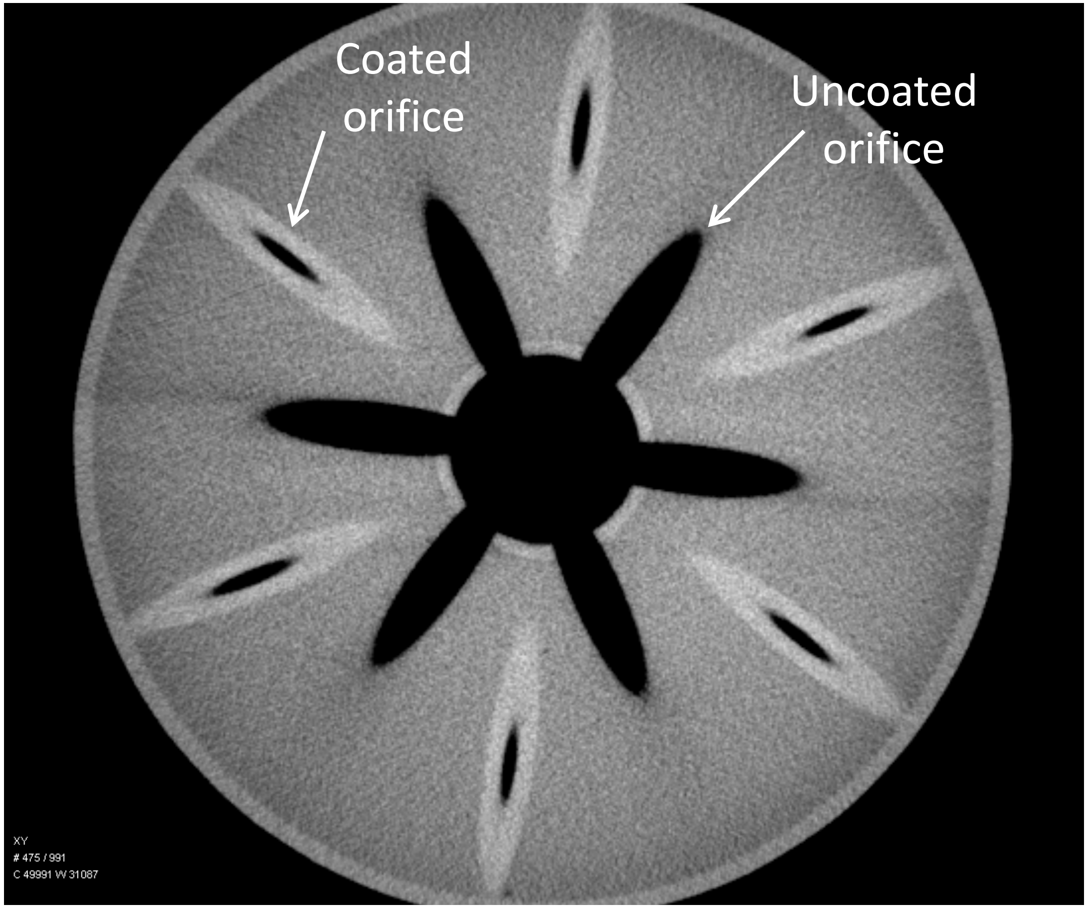


Courtesy – Ron Schaefer, USEPA/NVFEL

Accomplishment – Demonstrated feasibility of 3-D x-ray imaging to examine the uniformity of EN coatings applied to commercial fuel injectors (multi-size orifice).

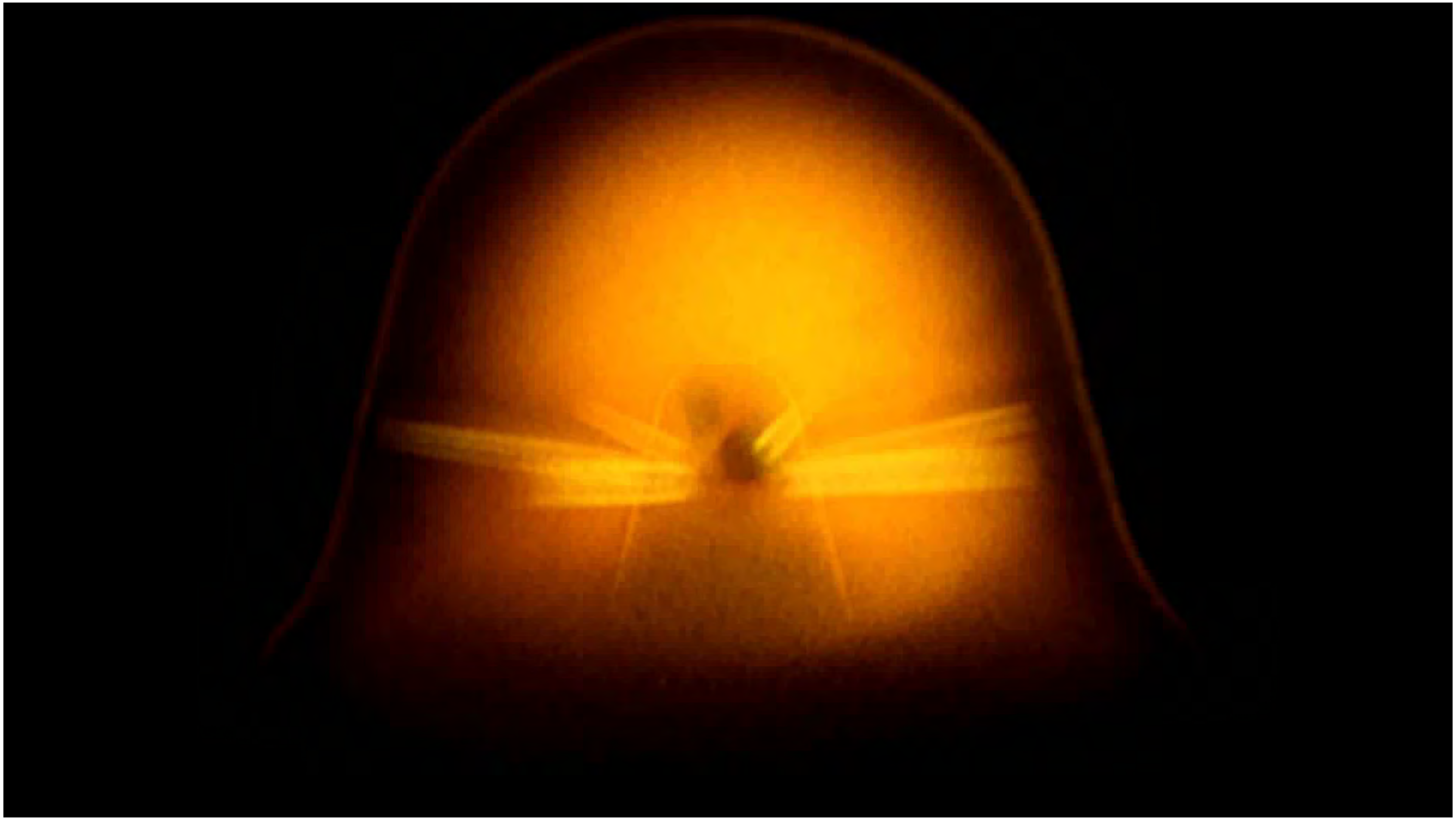
- Potential of a high-resolution (< 2 µm) x-ray absorption technique was investigated to image the internal volume of the orifices after plating.
  - Original expectation was to image the void regions only.

- Imaging capabilities exceed original expectations.
  - In addition to imaging the void region, the technique was able to delineate the coating (Ni-P alloy) from the ferrous injector alloy.

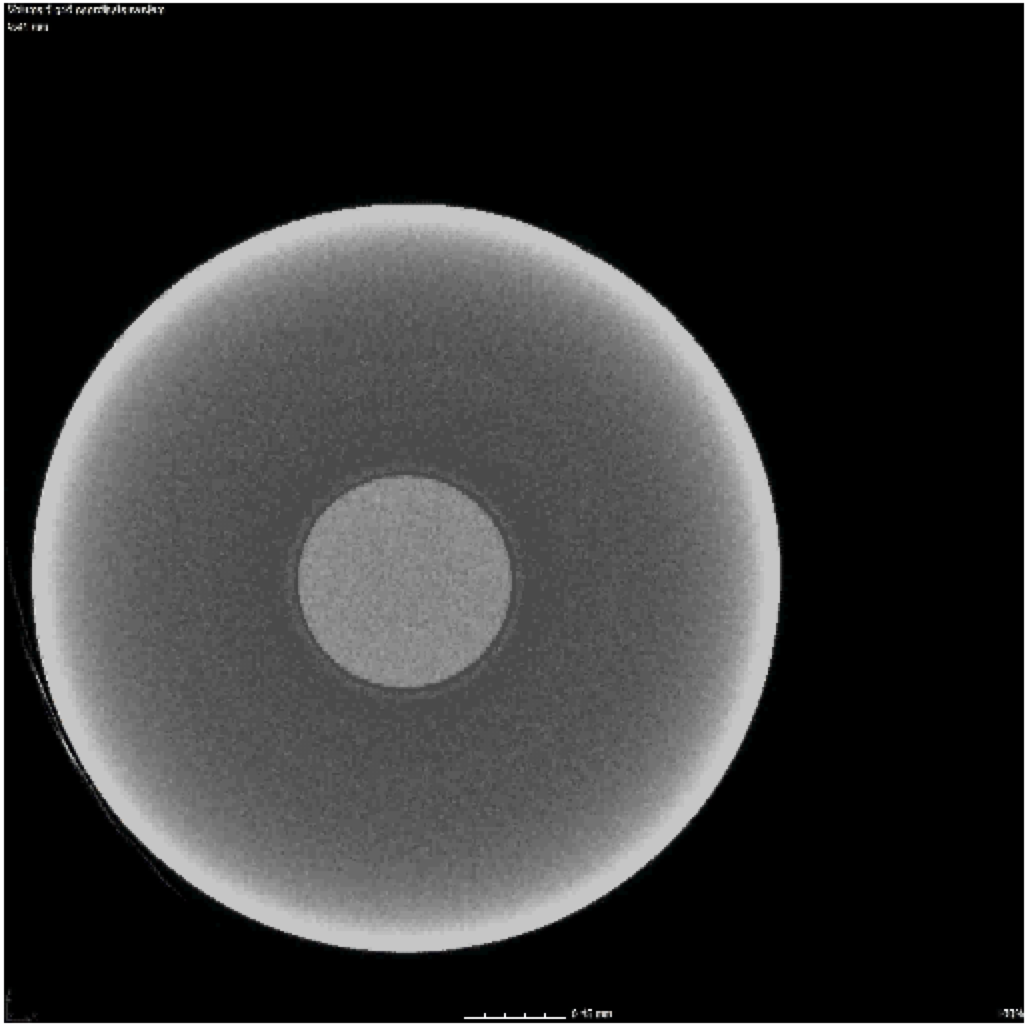


X-ray absorption image of commercial nozzle containing coated and uncoated orifices

3-D x-ray movie of coated injector (illustrating EN coating on interior orifices)

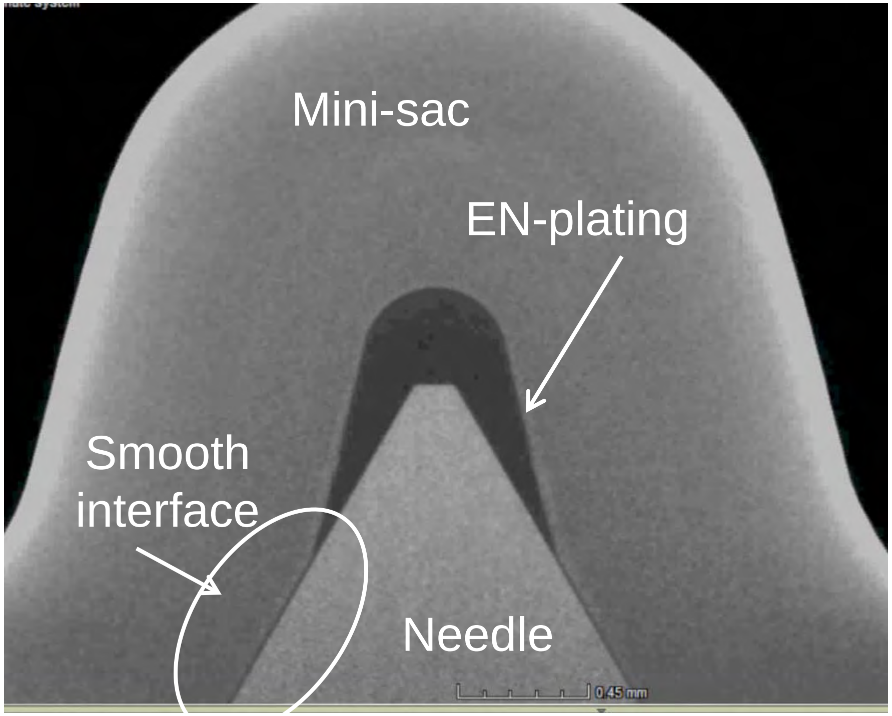


3D imaging of plated nozzle with needle



Accomplishment – Recent trials to mask critical regions show promise to eliminate additional manufacturing step to regrind barrel after EN.

- Current protocols to fabricate micro-orifices require a separate re-grind step to remove EN plating from the nozzle bore.
- Recent efforts were initiated to explore application of masks to eliminate EN plating in critical regions.
- Initial results suggest coating in seat area is sufficiently smooth and may not require re-grinding.
  - Additional analysis at higher resolution planned to examine surface finish at needle/seat interface.



Slice from 3D CAT scan of EN-plated nozzle showing the mini-sac region with needle. Note smooth cross section of plating adjacent to needle in the seat.

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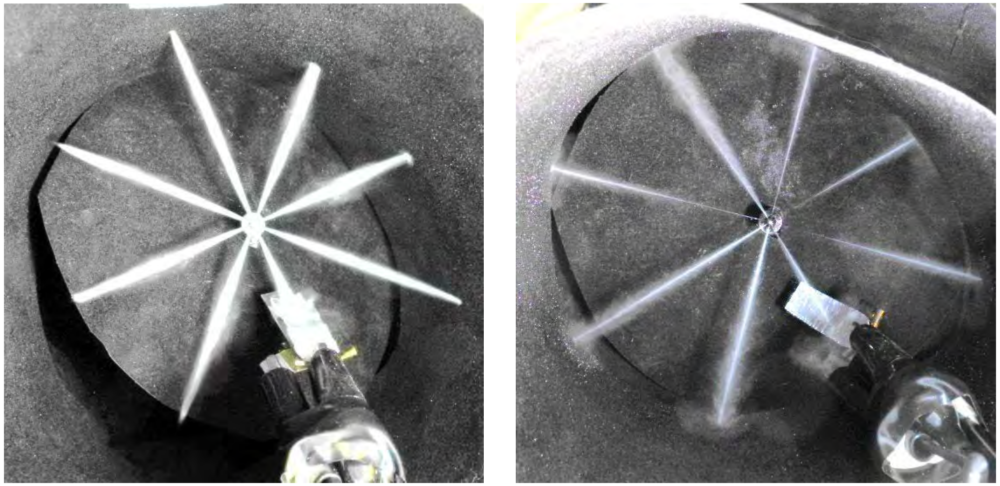
Accomplishment - Masking nozzle barrel and “pop” test validation of injector performance

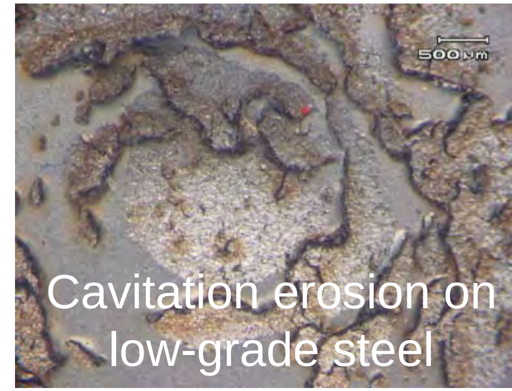
- Similar to previous discussion on masking critical areas to mitigate need to re-grind the nozzle, efforts to mask the barrel region showed promise.
- Several nozzles were plated with a special mask that covered the barrel region. Subsequent tests indicated the original needle (fitted to a tolerance of several microns) was able to be re-inserted into the plated nozzle without re-grinding the barrel.
- Subsequent pop-tests (at 3-5 ksi) on plated nozzles demonstrate micro-orifices are open (after mechanical agitation to remove plating salts).

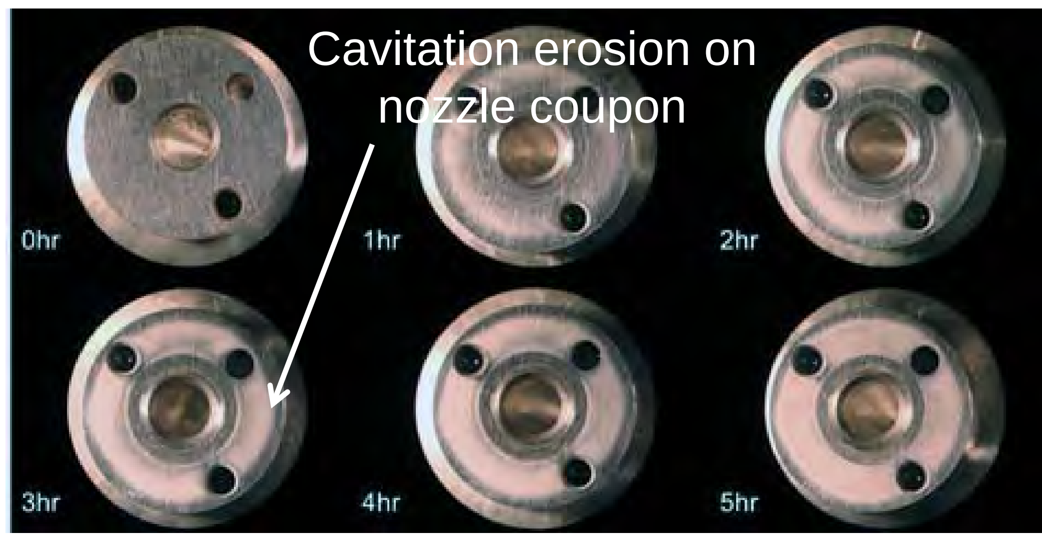


Pop-test images of injector spray
Left: unplated nozzle
Right: EN-plated nozzle, no re-grind

Cavitation Erosion – Demonstrated mechanical sonication can induce cavitation erosion in fuel injector coupons.

- Efforts continued to define technique to simulate cavitation with ASTM G 32-09 lab-scale technique.
- Initial tests with low-grade steel demonstrated fast erosion (within tens of minutes).
- Tests with coupons machined from commercial nozzles also demonstrated erosion, but at a much lower rate (hours).
- Custom fabrication of coupons from high-grade tool steel to simulate nozzle alloy is being investigated.





Collaborations/Coordination with Other Institutions

- Development of processes to fabricate micro-orifices on commercial nozzles involves coordination of different manufacturing steps:
  - Injector OEMs – providing nozzles for development efforts
  - Electrodischarge machining (EDM) of orifices on existing commercial nozzles (either nozzle blanks or nozzles with pre-existing orifices) [LEER (industry)]
  - High-pressure abrasive honing of EDM orifices to increase flow characteristics [Extrude Hone (industry)]
  - Electroless nickel plating of nozzles [Imagineering (industry)]
  - Tooling firm to re-grind nozzles [C&A Tooling]

- During FY11 several collaborative efforts were initiated, including*:
  - Nondisclosure agreement established with international fuel injector OEM
  - Work-for-others contract negotiations with an engine OEM
  - Development of a proposal for DOE with an integral team consisting of a vehicle OEM, engine OEM, injector designer/manufacturer, and plater.

- Collaborations with U.S. EPA being pursued on potential emission studies (subject to availability of funding)

* Names withheld subject to nondisclosure agreements.

Proposed Future Work

- Near Future (FY11/12)
  - Flow visualization studies by U.S. EPA
  - Preparation of single and multi-sized orifice nozzles for evaluation by OEMs
  - Cavitation erosion studies
  - Development of 3-D x-ray imaging for in-situ characterization of orifice surfaces and cavitation erosion

- Longer Term (parallel) Activity (FY 11/15)
  - Combustion studies on instrumented single-cylinder rigs (national labs or industry)
  - Engine emission studies
    - National labs
    - Engine OEM
  - Integration of overall fabrication processes
    - Nozzle and/or engine OEM

Summary

- Based on studies that demonstrated significant reductions in soot production with decreasing orifice diameter, initiated efforts 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.
- Examined multiple orifice fabrication approaches early in the project, selecting the EN process.
- Demonstrated the EN process for fabricating micro-orifices on commercial fuel injectors.
- Worked with industry: technical barriers were identified and resolved (uniformity, adhesion, and hardness).
- Completed spray visualization studies in collaboration with the U.S. EPA :
  - Smaller orifices resulted in shorter liquid penetration length and an appreciably shorter spray core length.
  - Smaller orifices enhanced atomization.
- Successfully demonstrated ability to fabricate multi-size orifices (6 @ 40 µm + 6 @ 145 µm).
- Demonstrated 3-D x-ray NDE technique to image orifice and coating on treated nozzles.
- Established multiple collaborations with industry to accelerate introduction of micro-orifice technology.
- Efforts in FY11/12 will focus on spray visualization studies of multi-sized orifices and performance evaluation with nozzle OEM.
- Future efforts will focus on engine emission studies.