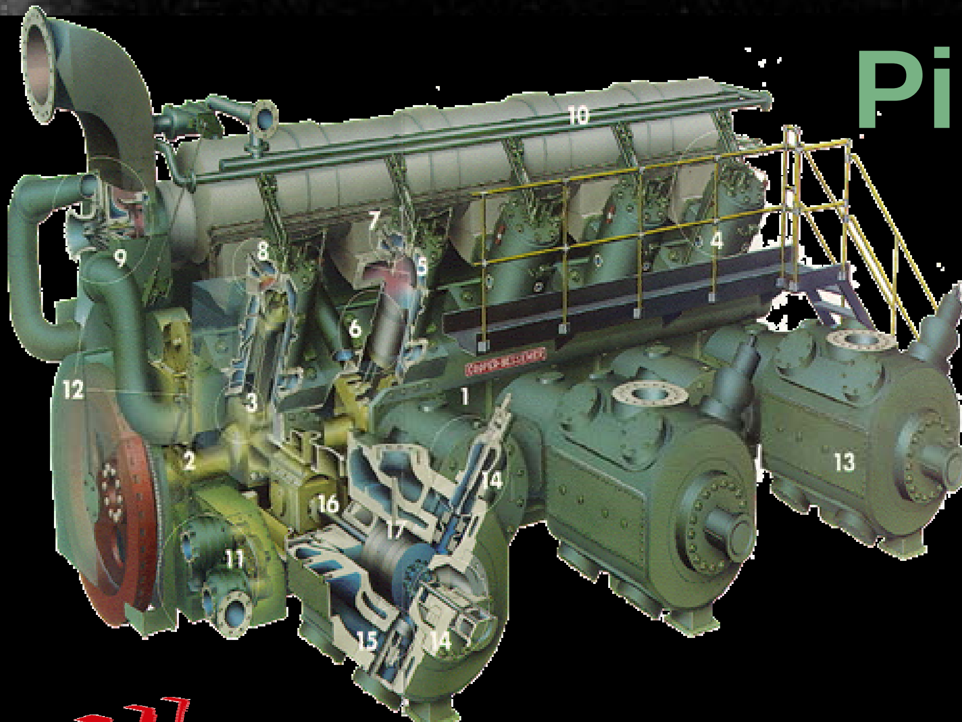
Retrofit of Micropilot Ignition for Pipeline Engines

April 9, 2003
Morgantown, W.Va.



WOODWARD

PRCI
Technology for Energy Pipelines

DEPARTMENT OF ENERGY
UNITED STATES OF AMERICA

Colorado State University
Knowledge to Go Places

Micro-Pilot Update

- **Program Overview**
- Hardware
- Combustion Test Chamber Results
- Engine Test Results
- Conclusions from Phase I
- Plan for Phase II
- Schedule & Budget

DOE Micropilot Program

<u>Program Objective</u>: Increase the reliability of the U.S. natural gas pipeline infrastructure

<u>Micro-Pilot Project Objective</u>: Demonstrate improved compression reliability through the use of micropilot ignition

<u>Prime Contractor</u>: CSU Engines & Energy Conversion Laboratory

<u>Project Funding</u>: DOE, Gas Technology Institute, Pipeline Research Council International, Woodward Governor

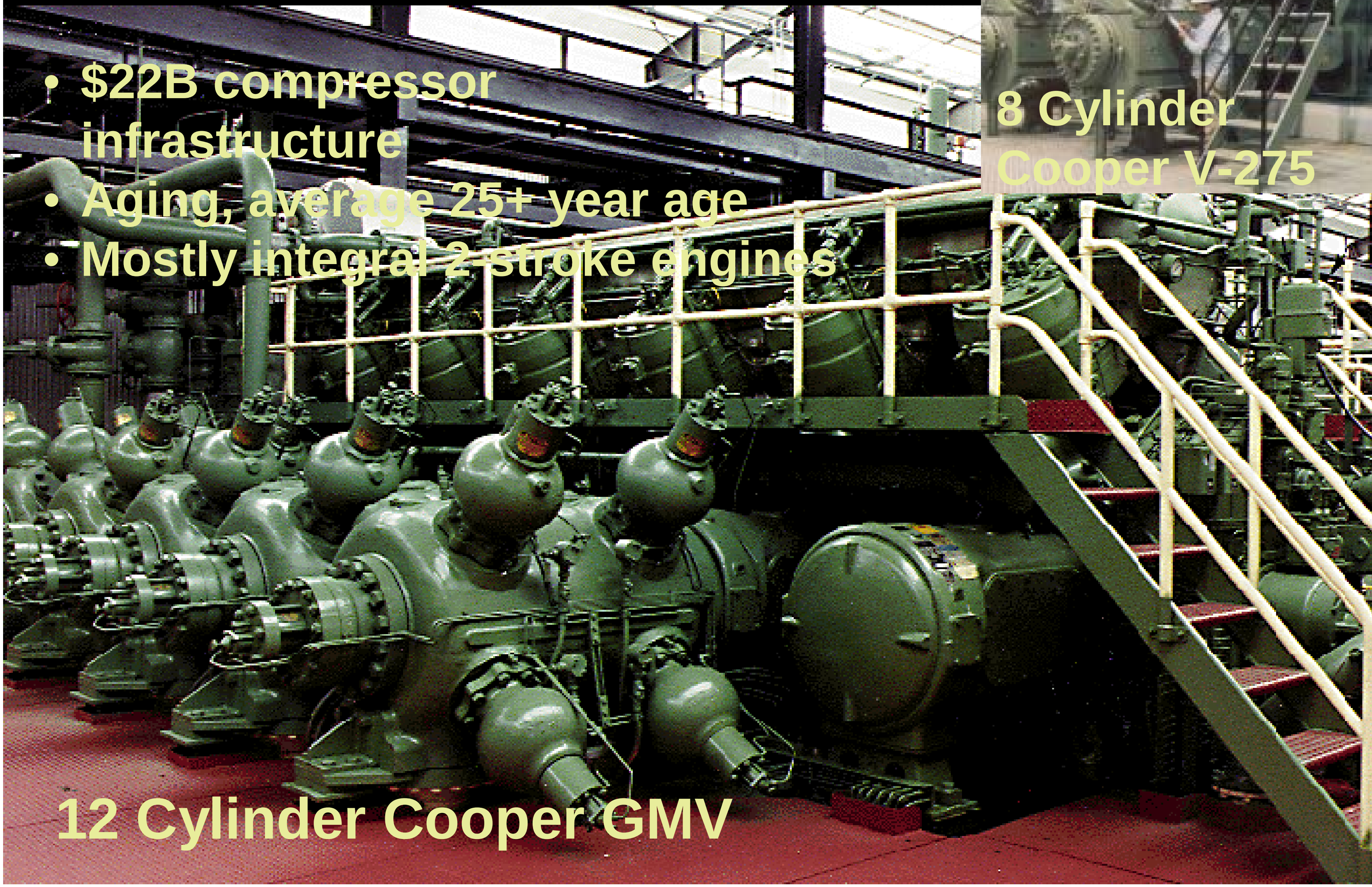
"By 2020 Americans will be consuming 50 percent more natural gas than today."

-Energy Secretary Abraham

Typical Field Engines Used for Gas Compression

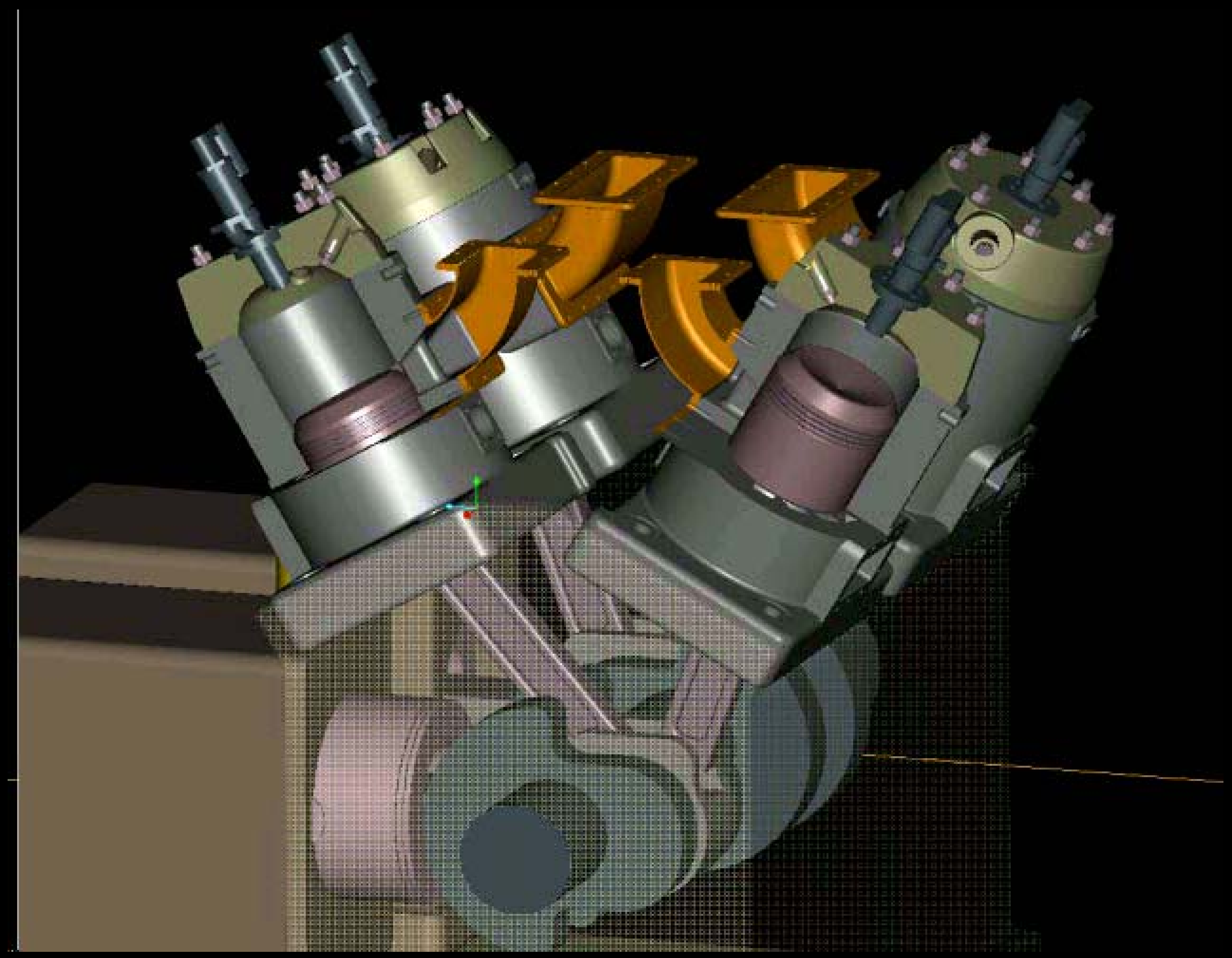
- $22B compressor infrastructure
- Aging, average 25+ year age
- Mostly integral 2-stroke engines

8 Cylinder Cooper V-275

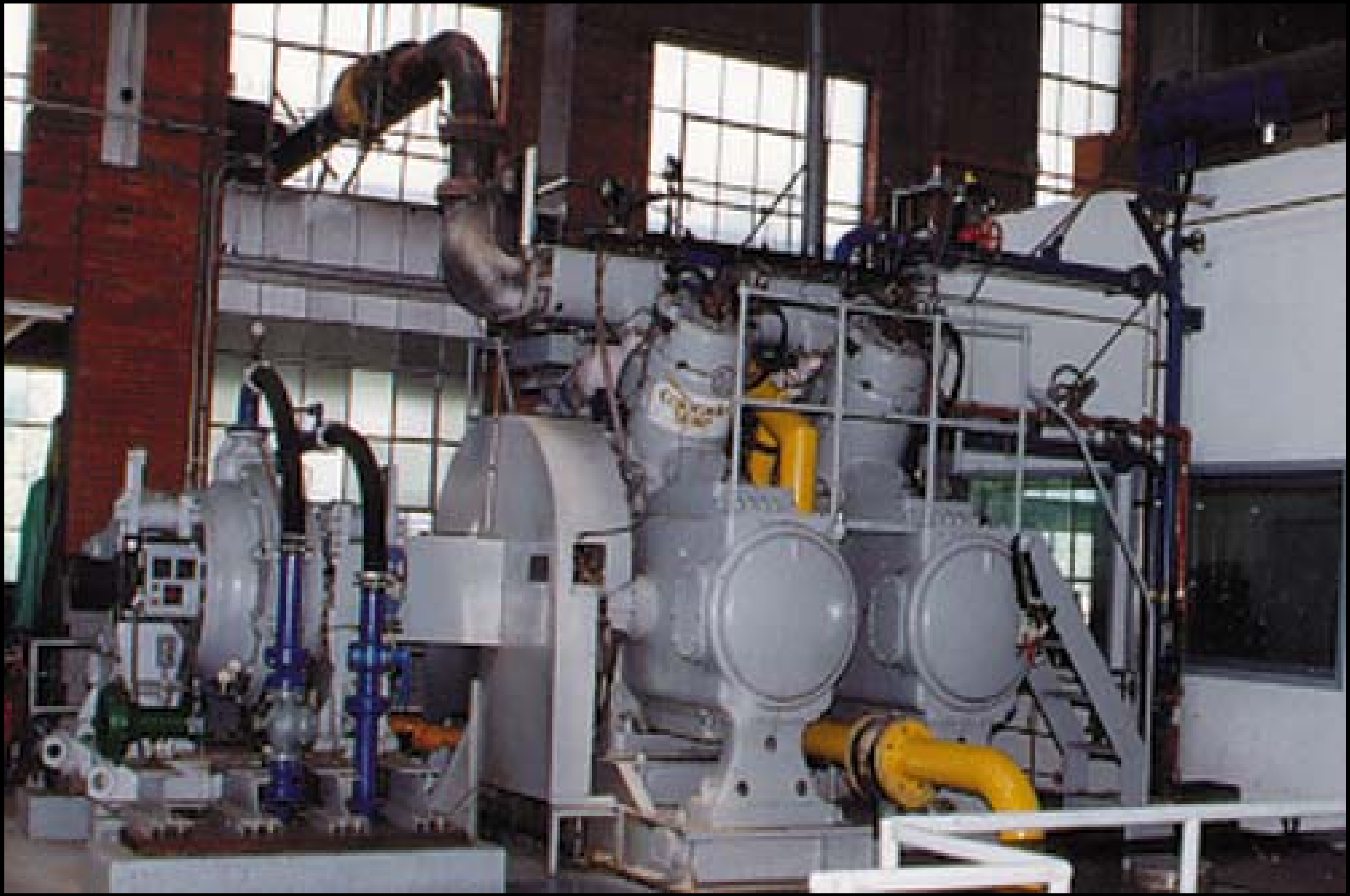


12 Cylinder Cooper GMV

Typical 2-Stroke Gas Engine: Cooper-Bessemer GMV



PRCI-Funded
Large Bore Engine Testbed



Large Engines at the EECL, 2003

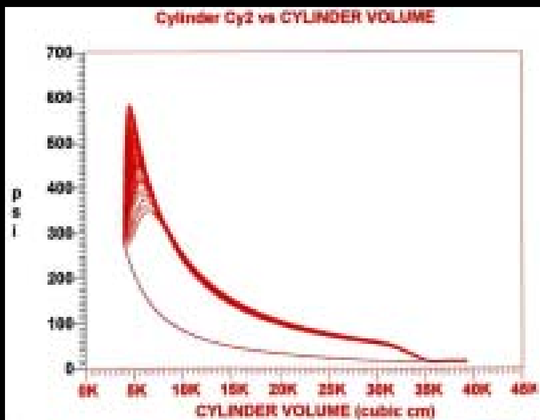
2-stroke lean burn gas engine
Cooper-Bessemer GMV-4

4-stroke lean burn gas engine
Waukesha F18

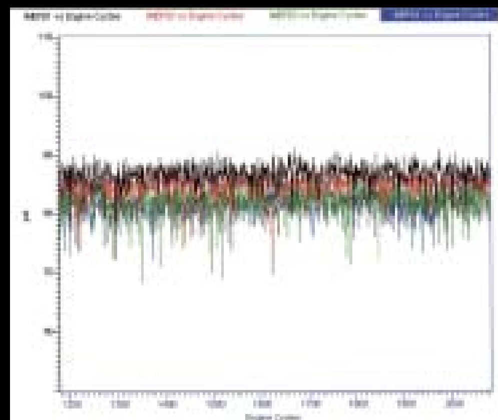
4-stroke lean burn gas engine
Cummins QSK

4-stroke rich burn gas engine
Superior 6G-825

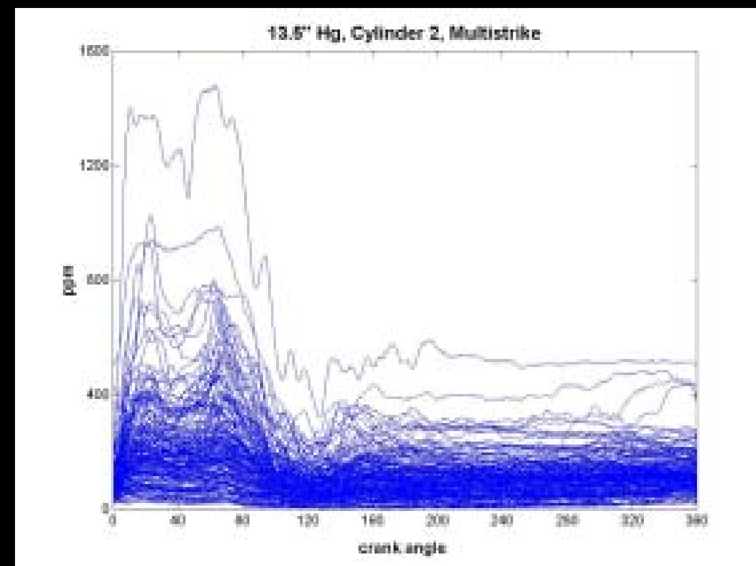
Motivation: Increased Reliability & Stability

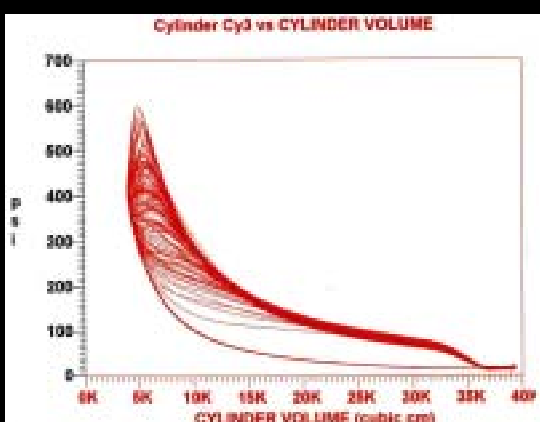


PV Diagrams
Stable Combustion

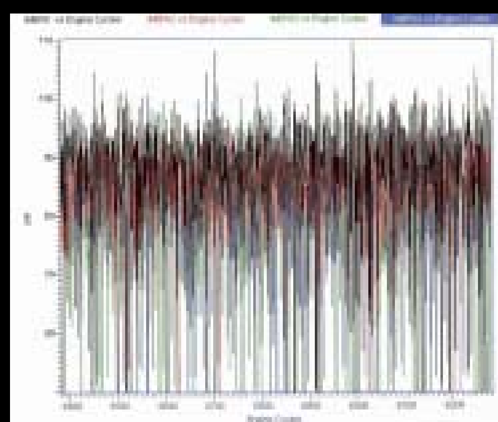


IMEP
Stable Combustion

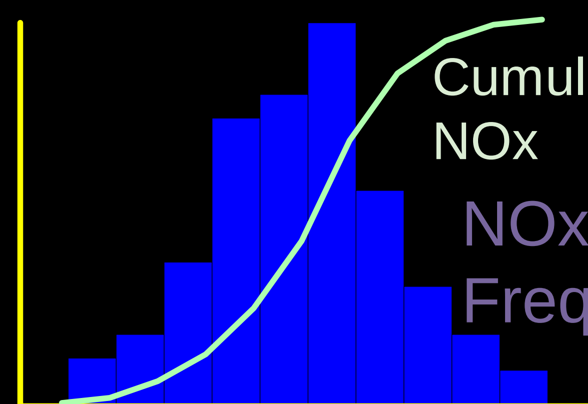




PV Diagrams
Near Lean Limit



IMEP
Near Lean Limit



Micro-Pilot Ignition

Definition:

Ignition of a natural gas mixture through compression ignition of a small quantity of high cetane pilot fuel

Pilot Quantity:

Variable between 0.1% - 1.0% of energy content

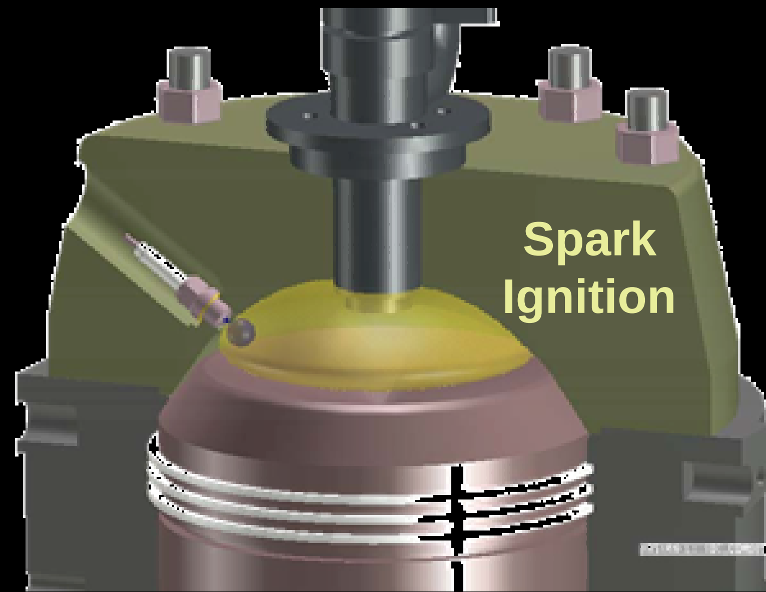
Typically, 1 µL-10 µL (1 mm^3 -10 mm^3)

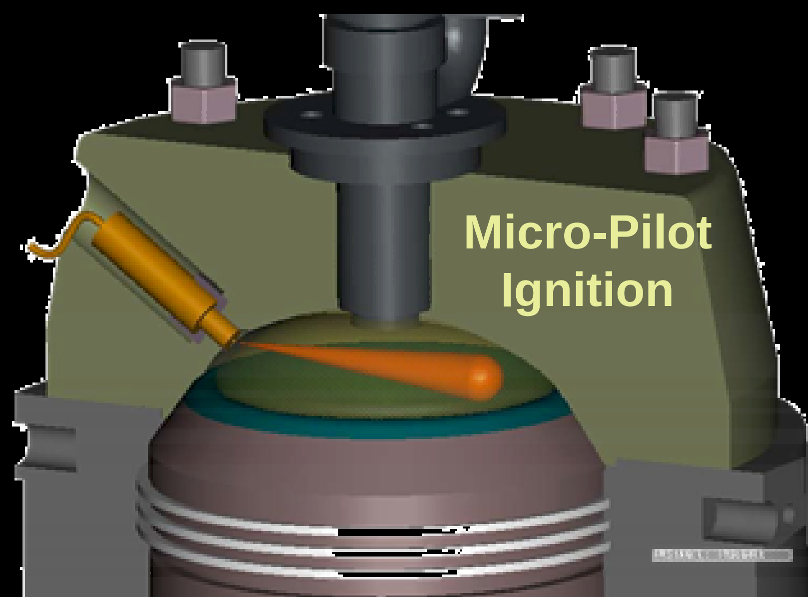
Pilot fuel(s):

Diesel fuel

Lube oil

On-board fuel, i.e. dimethyl ether

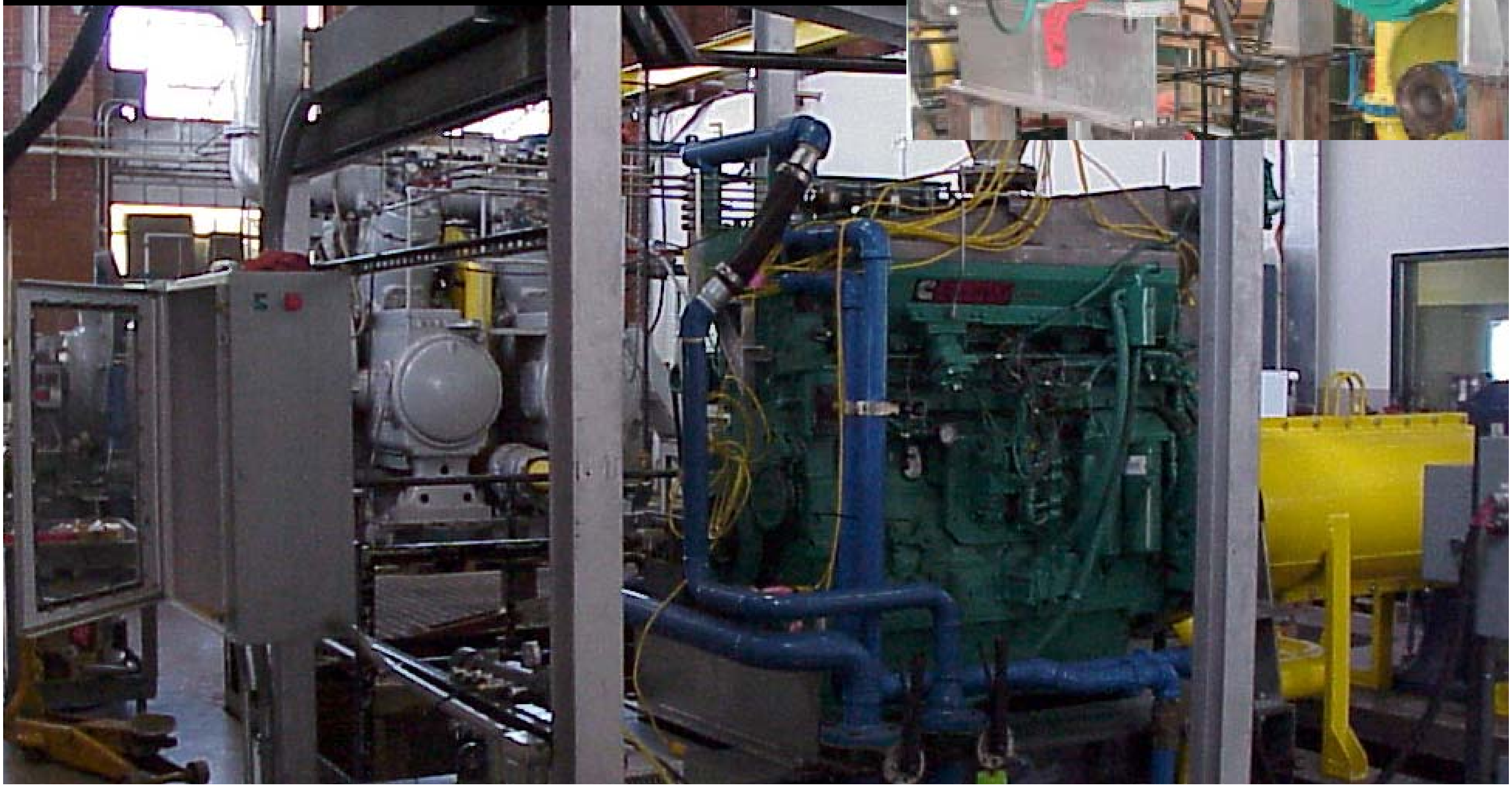




Program Elements

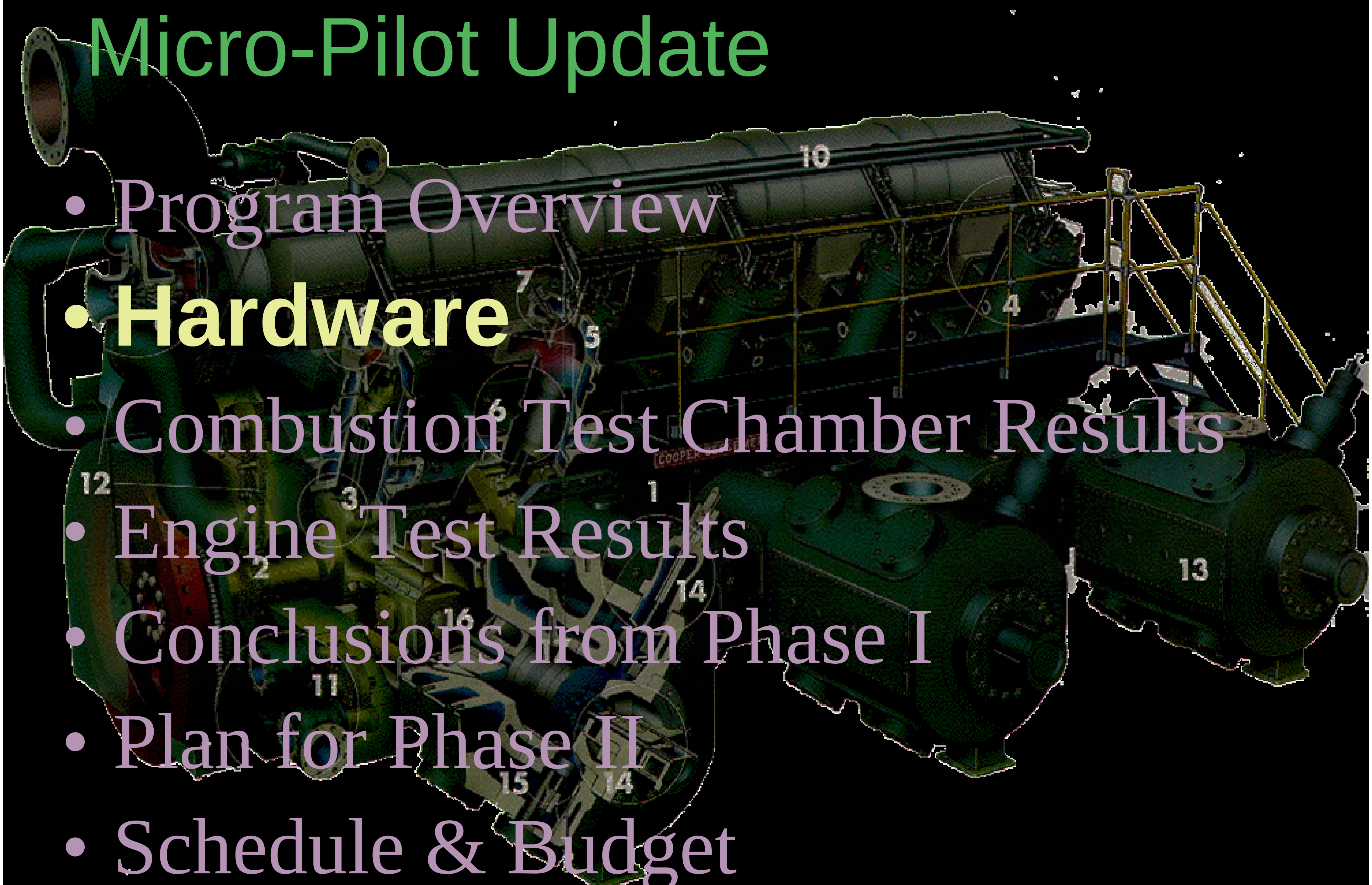
- **Phase I – Feasibility, Oct 1 2001, 12 tasks**
- Literature review
- Stationary Single Cylinder
  - Design & build single-cylinder prototype
  - Performance test of stationary single-cylinder unit
- 4 Cylinder Test
  - Design, build, install
  - Performance test
- **Phase II – Optimization Proposed, 11 tasks**
- Compression ratio tests
- Evaluation of pilot fuels
- Finalization of design for field test
- **Phase III – Field Test** Proposed, 9 tasks
- Field test
- Durability testing

Complementary Program: Micropilot Ignition on 19 Liter Cummins QSK Engine



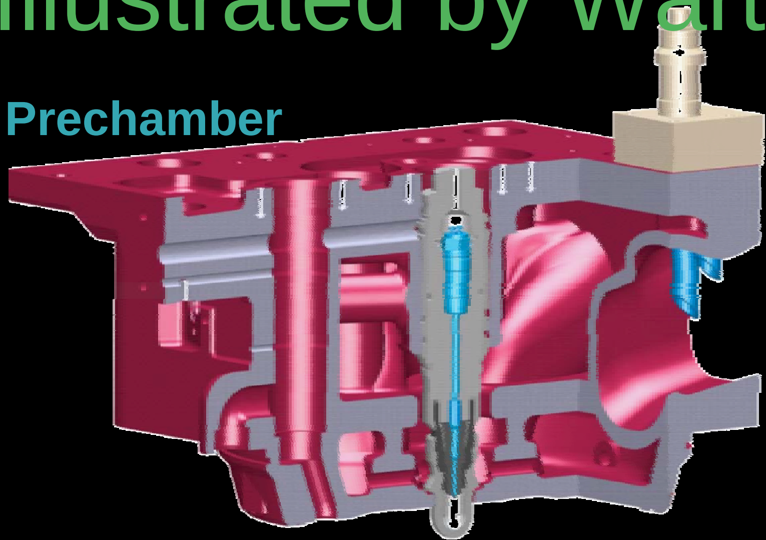
Micro-Pilot Update

- Program Overview
- **Hardware**
- Combustion Test Chamber Results
- Engine Test Results
- Conclusions from Phase I
- Plan for Phase II
- Schedule & Budget

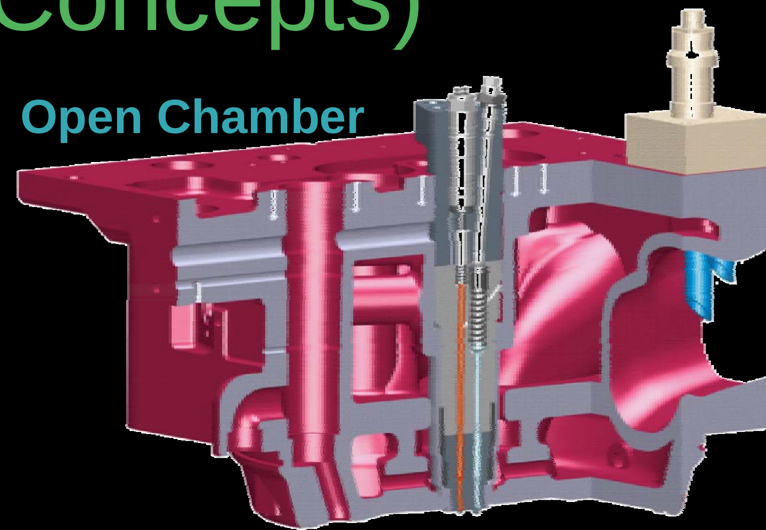


Alternative Approaches
(Illustrated by Wärtsilä Concepts)

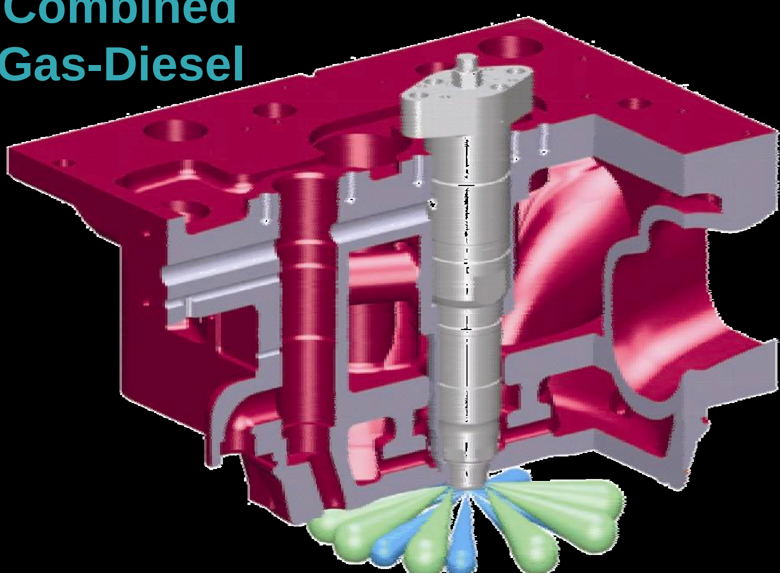
Prechamber



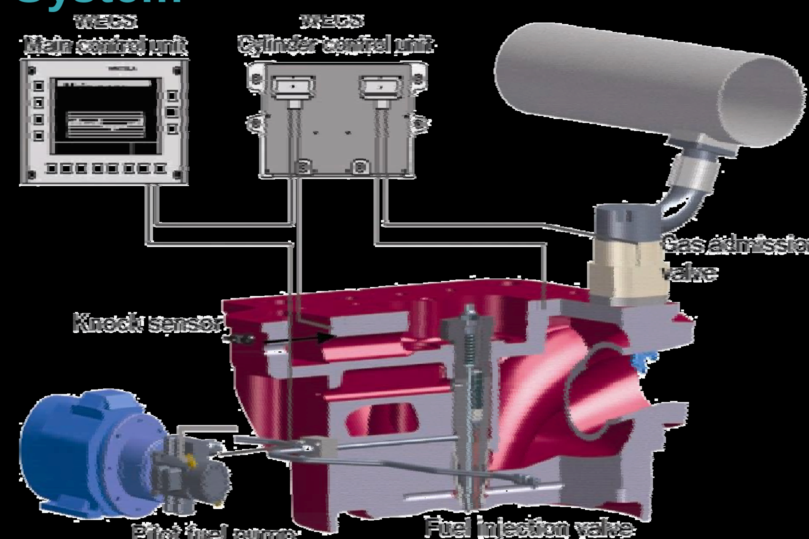
Open Chamber



Combined Gas-Diesel

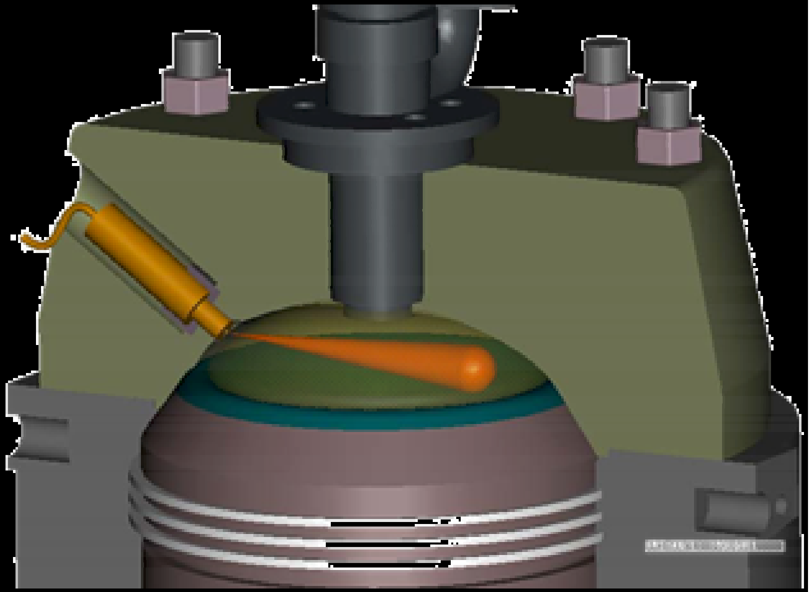


System



CSU Micro-Pilot Approach

- Open chamber
- Common rail
- Injector mounting through spark plug
- Spark ignition for cold start
- Diesel pilot in Phase 1 – other fuels considered in Phase 2
- Standard compression ratio in Phase 1 – increased CR considered in Phase 2



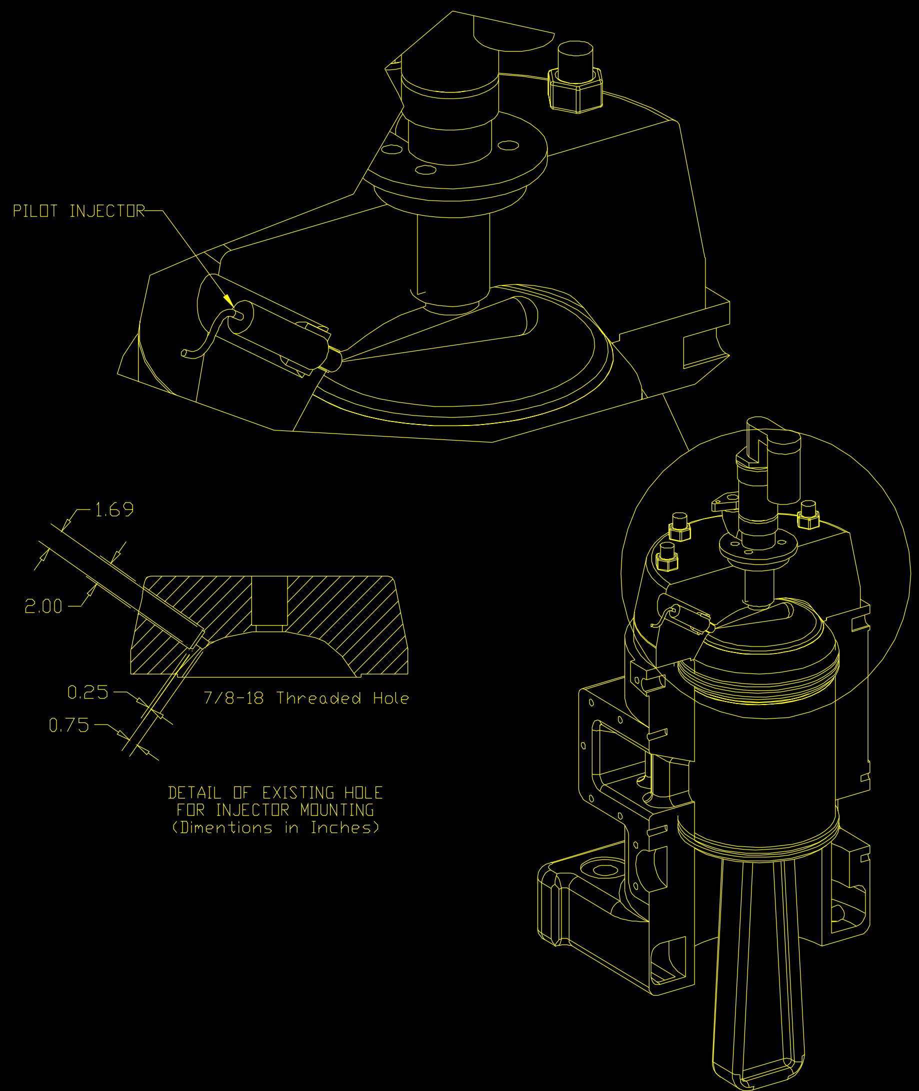
Injector Specifications

Pulse Width – Injector should be capable of delivering 5-10 mm^3 of fuel in a minimum of 0.5 milliseconds. Nominal operation will be between 0.5 and 4 msec. 10 msec will be the maximum pulse width.

Rail Pressure – A rail pressure between 10,000 and 20,000 psi

Orifice Diameter – The injector orifice hole will be produced by a specialty nozzle manufacture if possible. This will allow the lab to evaluate identical injectors with different orifice diameters. Orifice holes are expected to be between 0.1mm and 0.2 mm.

Injector Size – The fuel injector must be small enough to allow installation through an existing 18mm spark plug hole.



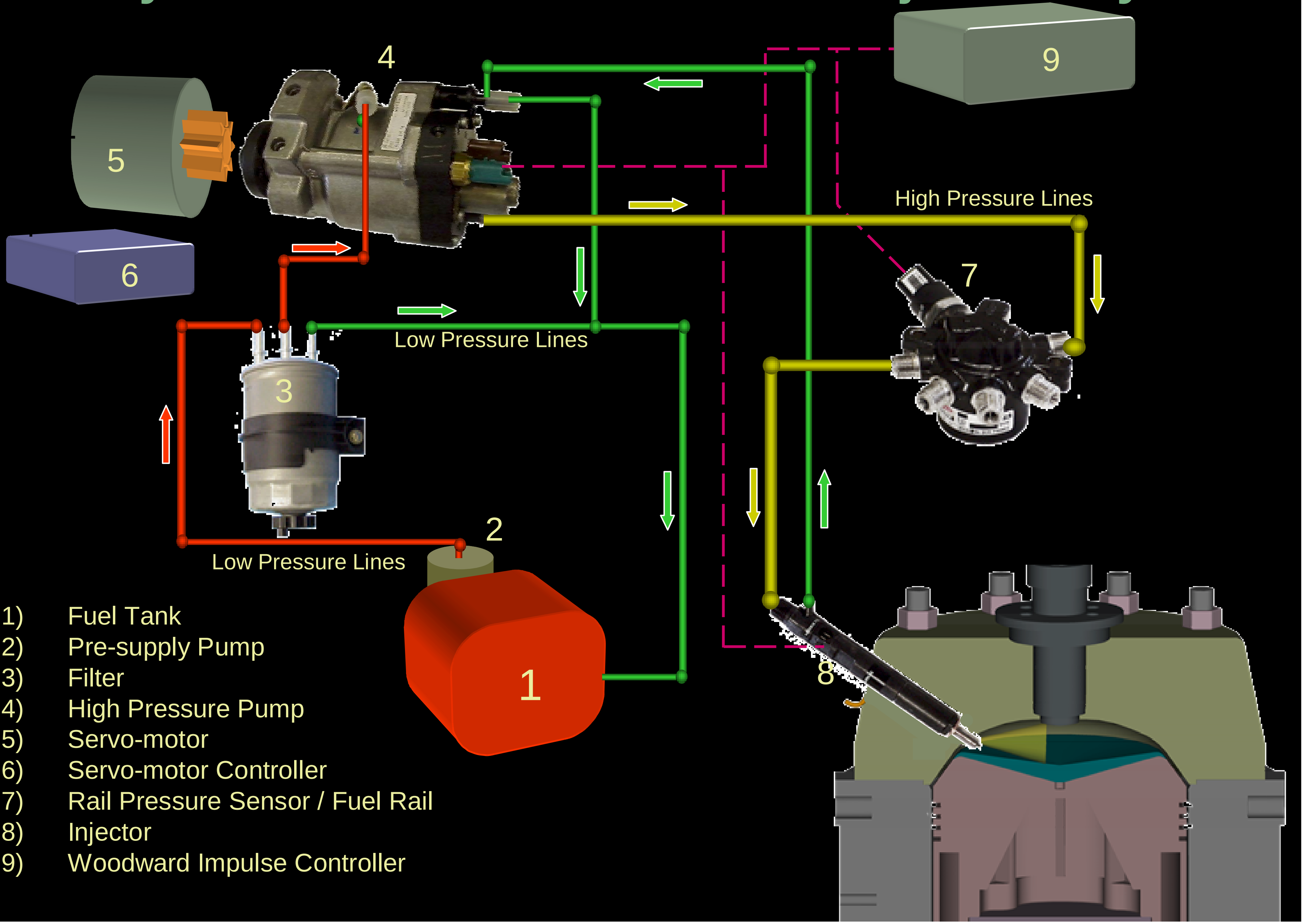
Supplier Selection

- Supplier survey produced 2 preferred suppliers: Bosch & Lucas / Delphi
- Both systems rely on automotive CR technology
- Woodward purchase of Lucas / Delphi / Bryce created opportunity for beneficial development arrangement with Delphi Diesel systems for use of Delphi common-rail injection system

Bosch

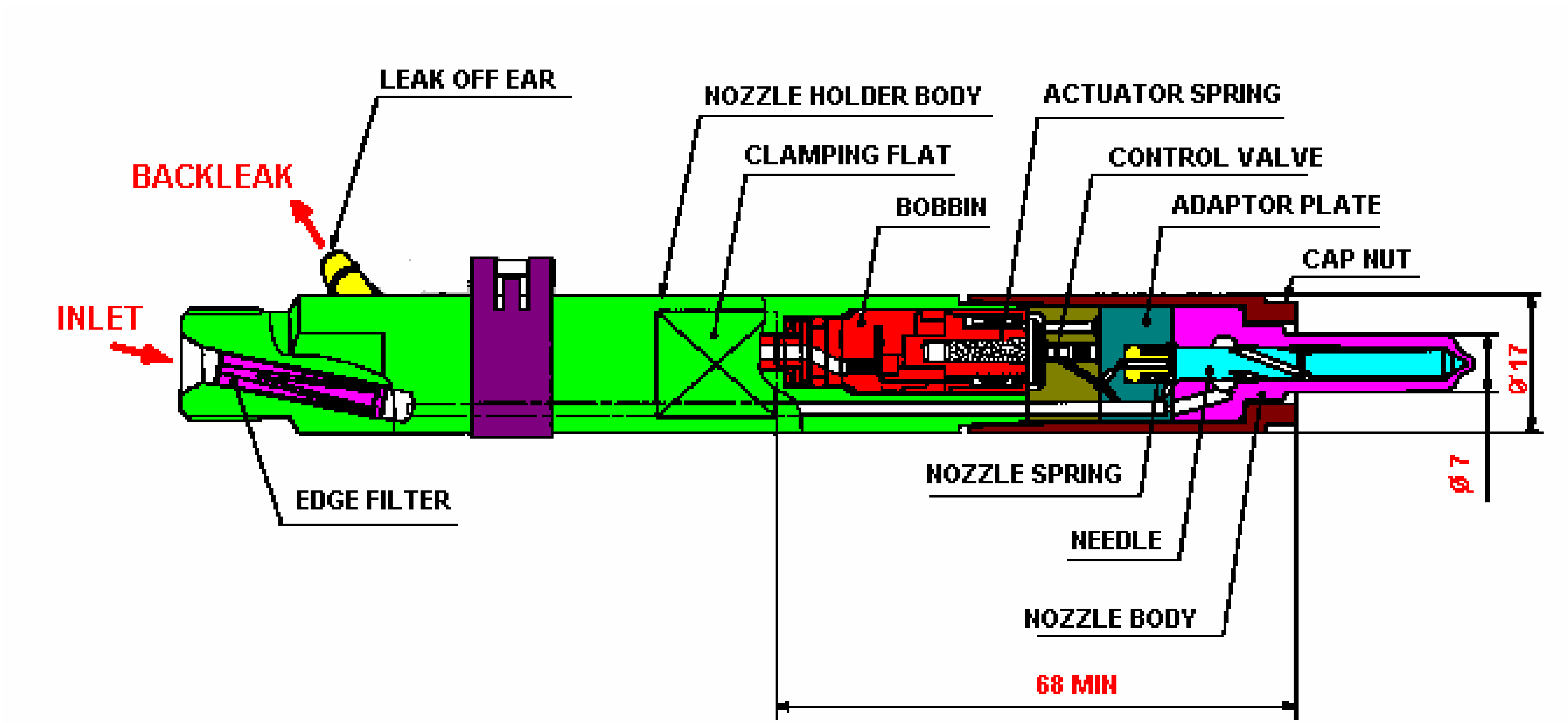
Delphi

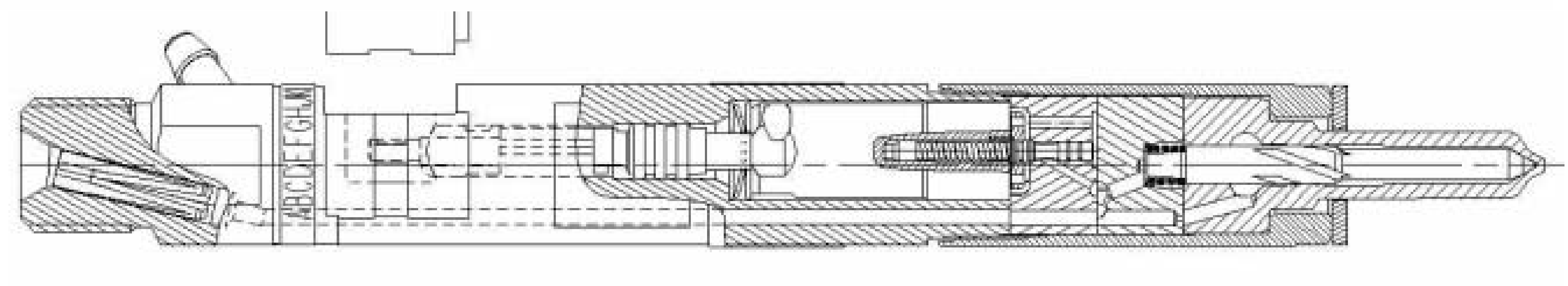
Fuel System for Common Rail Fuel-Injection System



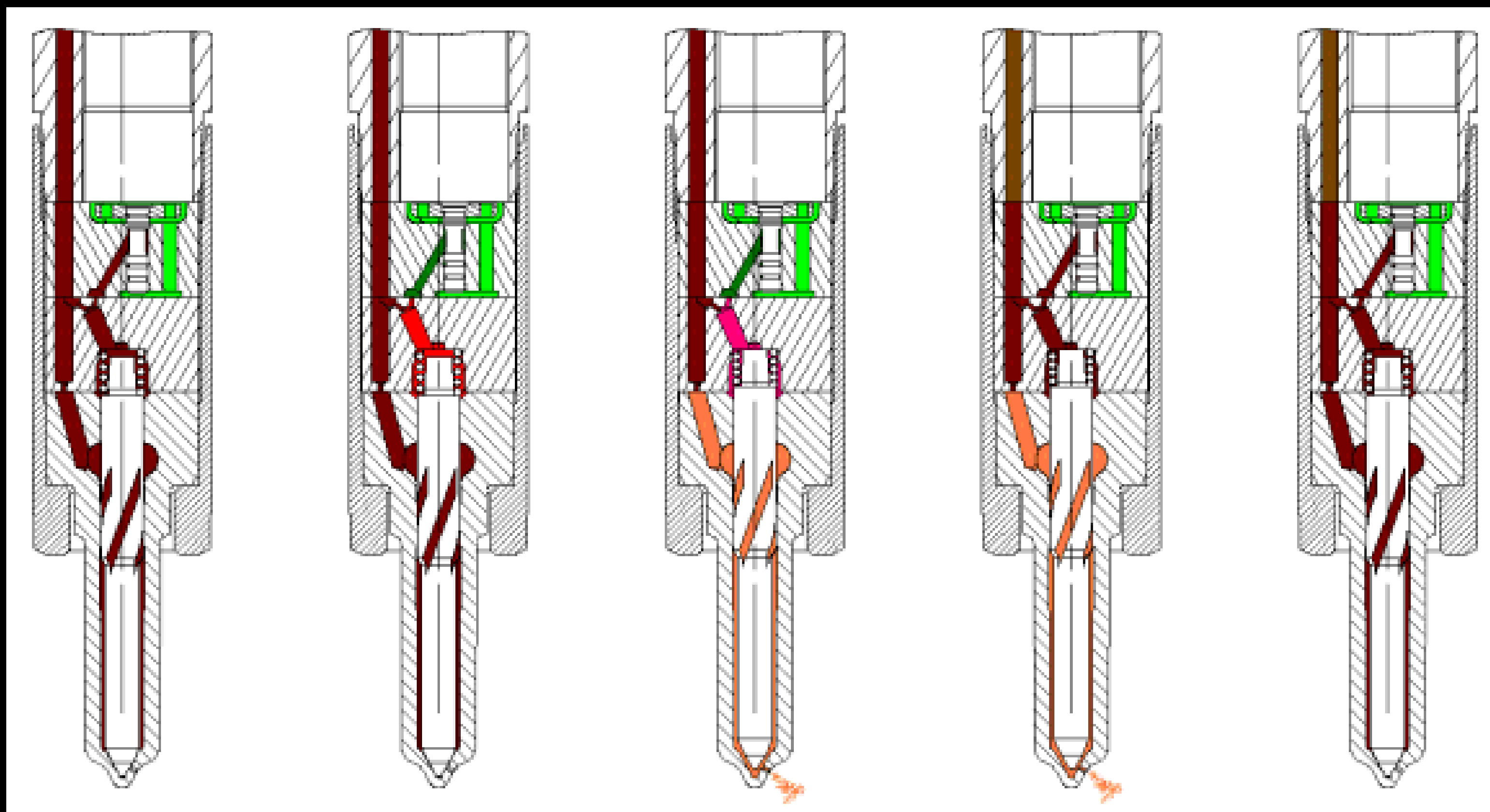
1) Fuel Tank
2) Pre-supply Pump
3) Filter
4) High Pressure Pump
5) Servo-motor
6) Servo-motor Controller
7) Rail Pressure Sensor / Fuel Rail
8) Injector
9) Woodward Impulse Controller

Internal Injector Components





Injector Operation



Control valve off

Control pressure above needle at supply pressure

Pressure holds needle closed

Control valve on

Control pressure reduced

Needle begins to rise

Control valve on

Needle lifts

Injection begins

Control valve off

Control pressure rises to supply pressure

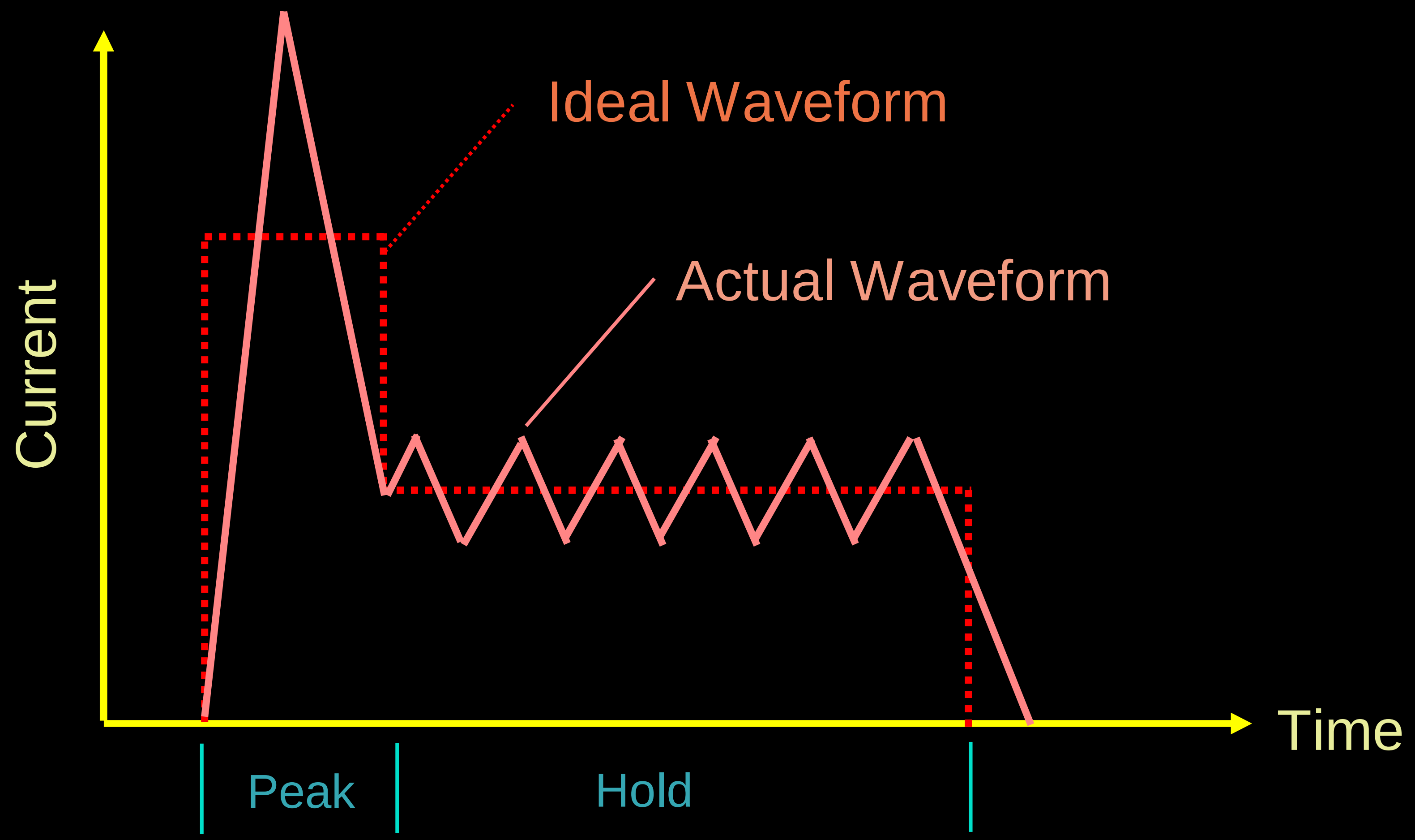
Needle beings to close

Control valve off

Control pressure at supply pressure

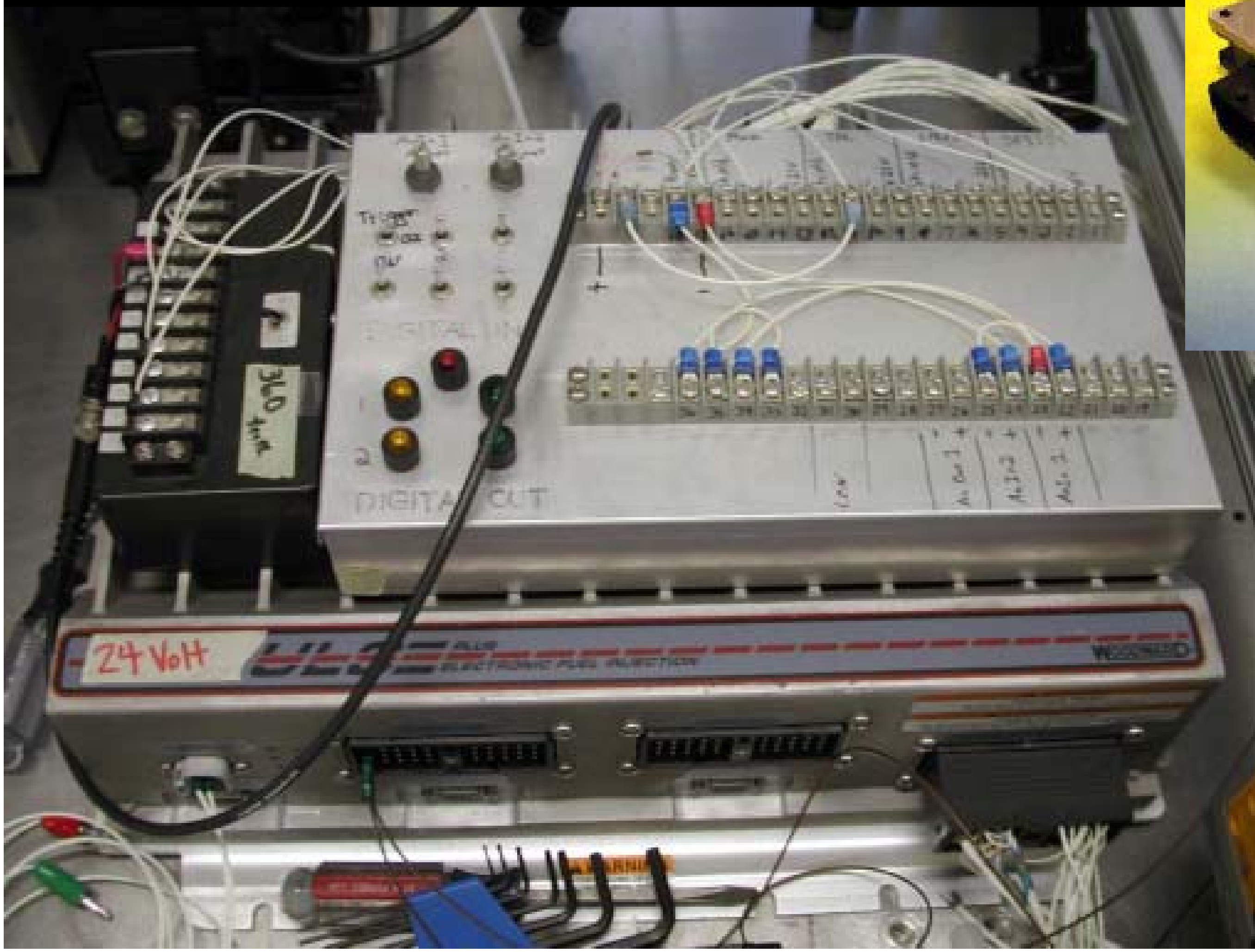
Needle beings to closed. Injection off

Peak and Hold Fuel Injector Driver



Fuel Injector Controller

Delphi Automotive Controller



Woodward In-Pulse Injector Controller

Micro-Pilot Update

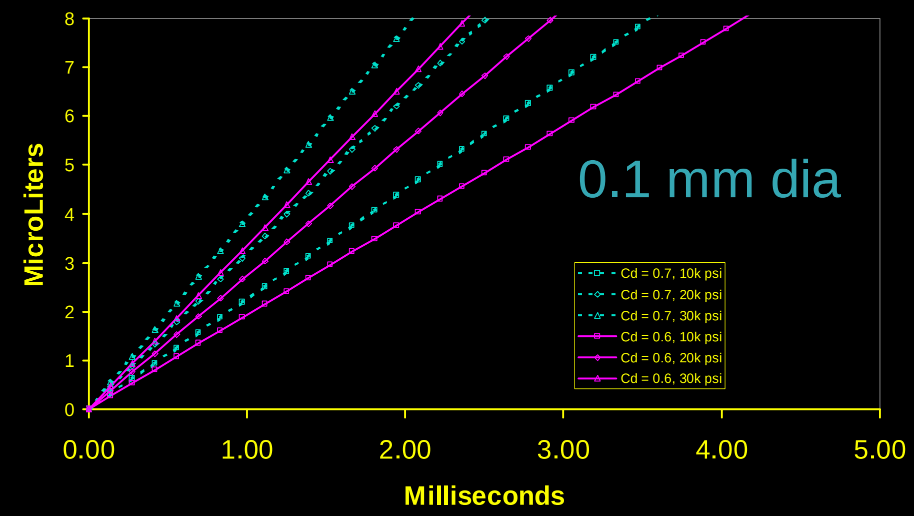
- Program Objective
- Background
- Heuristic Model
- **Numerical Modeling**
- Combustion Test Chamber - Results
- Preparations for Engine Test
- Status / Schedule

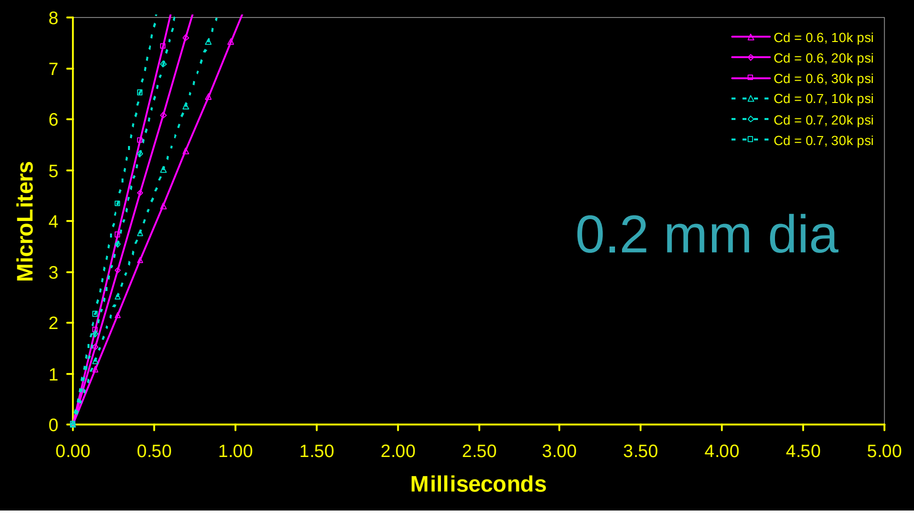
Calculated Mass Flow Rate

- Injection duration varies with orifice size & pressure

Low: 0.5 msec @ 30,000 psi w/ 0.2 mm

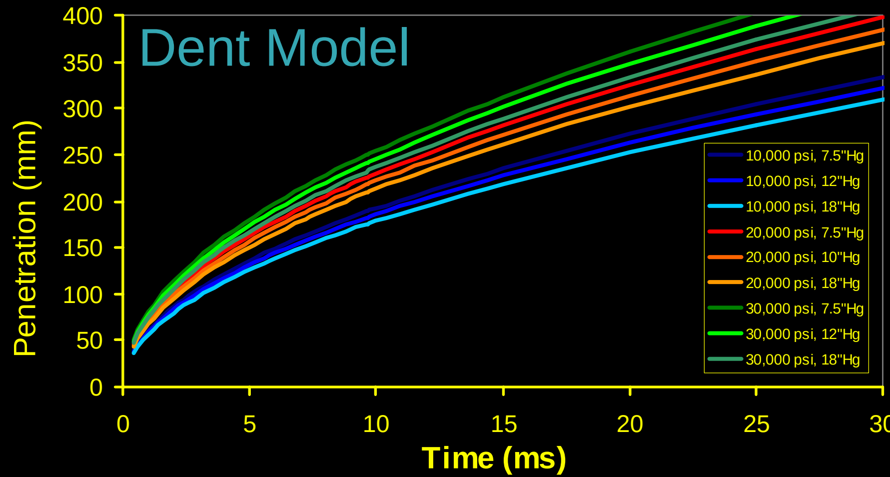
High: 4 msec @ 10,000 psi w/ 0.1 mm

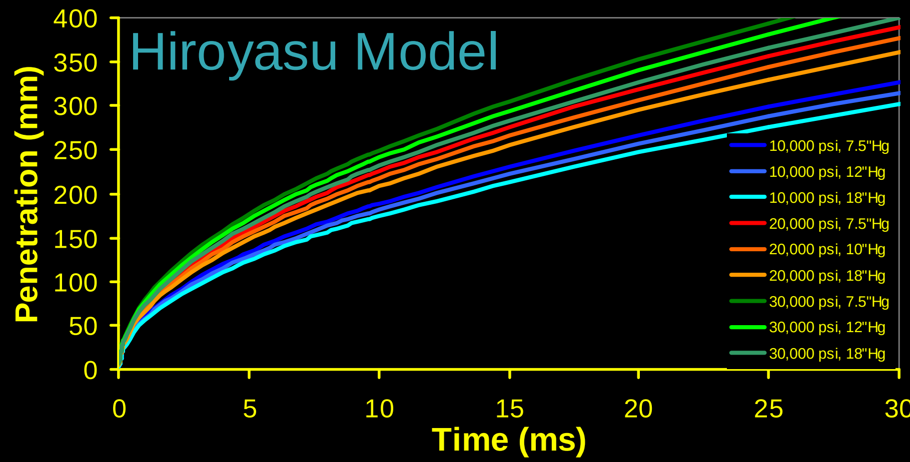




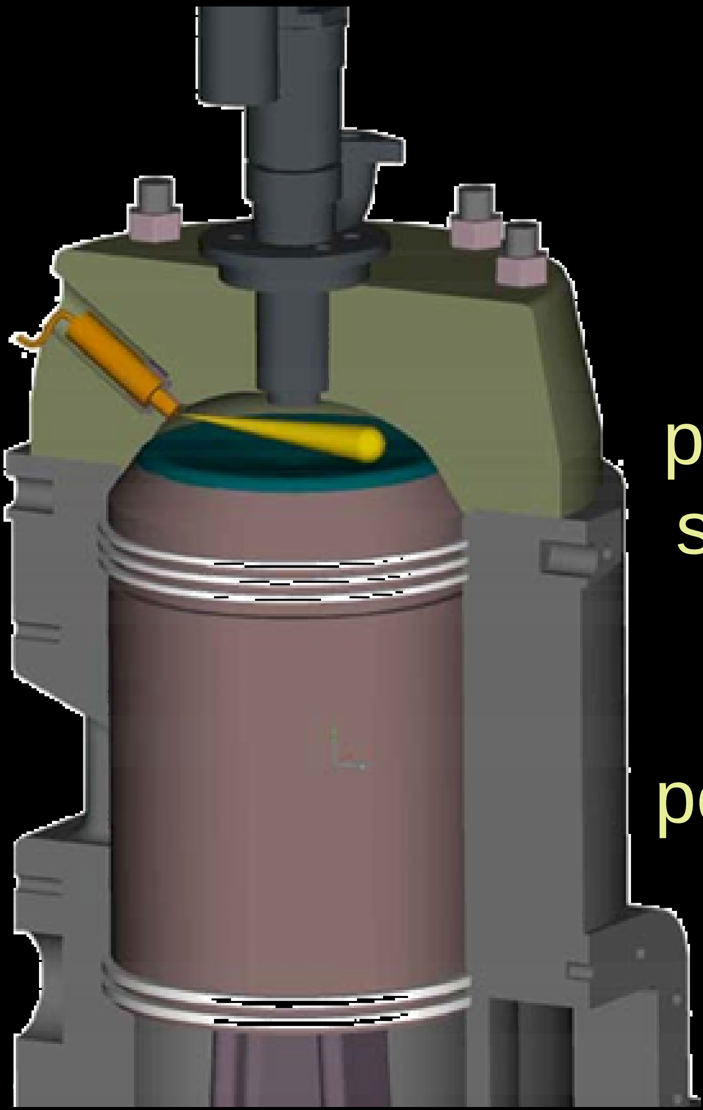
Spray Penetration

- Cold-flow models used to predict non-evaporating penetration
- Models developed for much higher mass flow
- Delphi has performed evaporative modeling, predicting liquid spray lengths of 20-30 mm

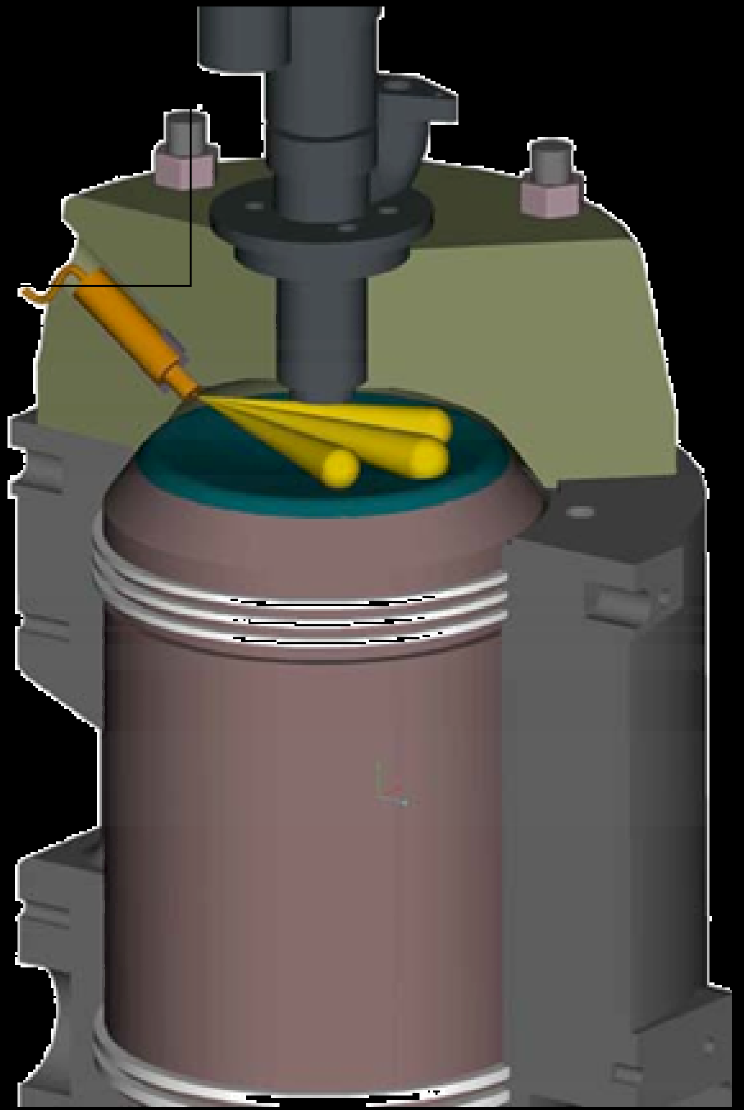




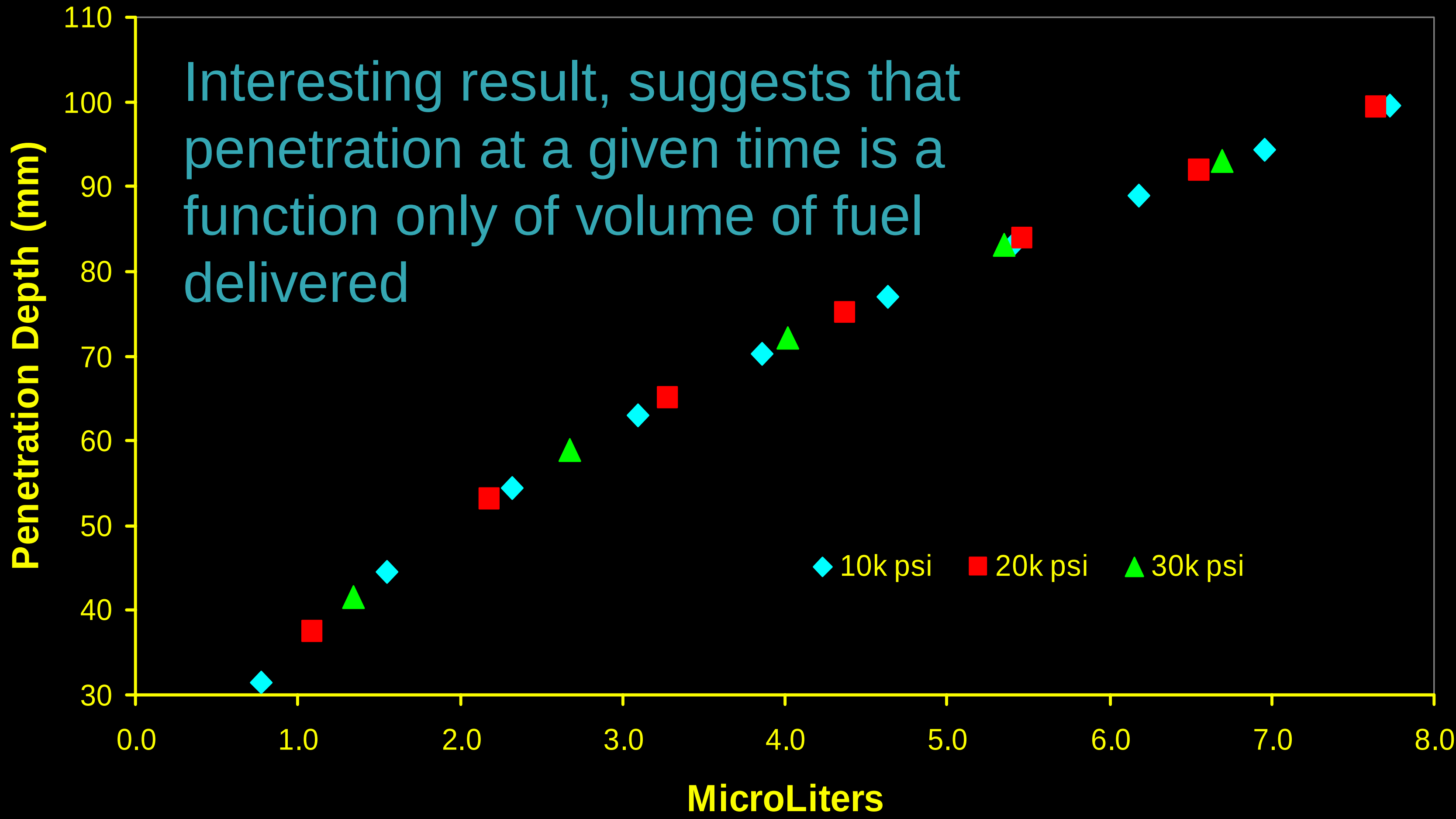
Number of Holes



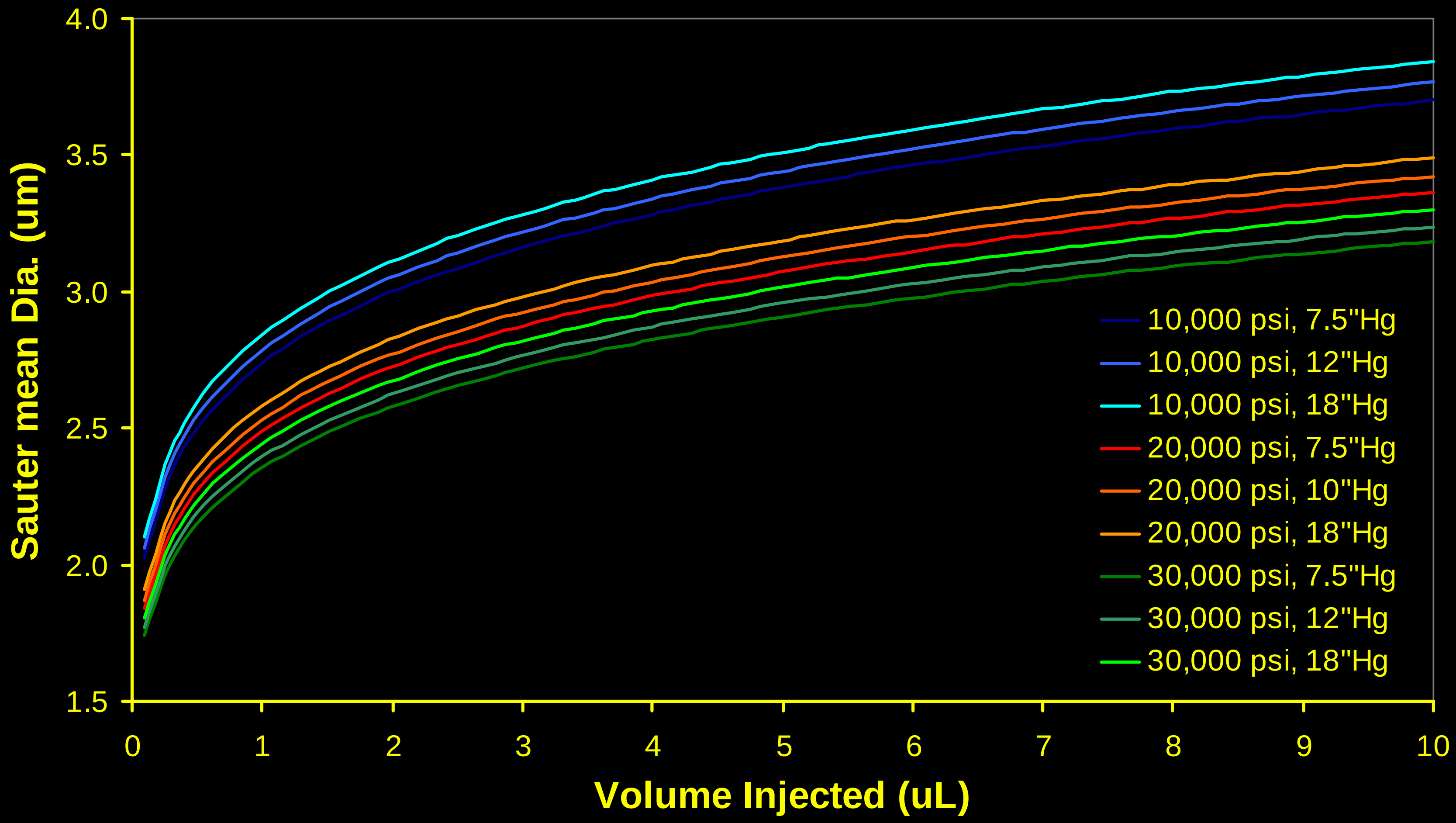
Modeling indicates preference for single hole to provide greatest penetration for given fuel volume



Penetration Depth vs. Flow
(7.5” Hg Boost, Cd=0.6)

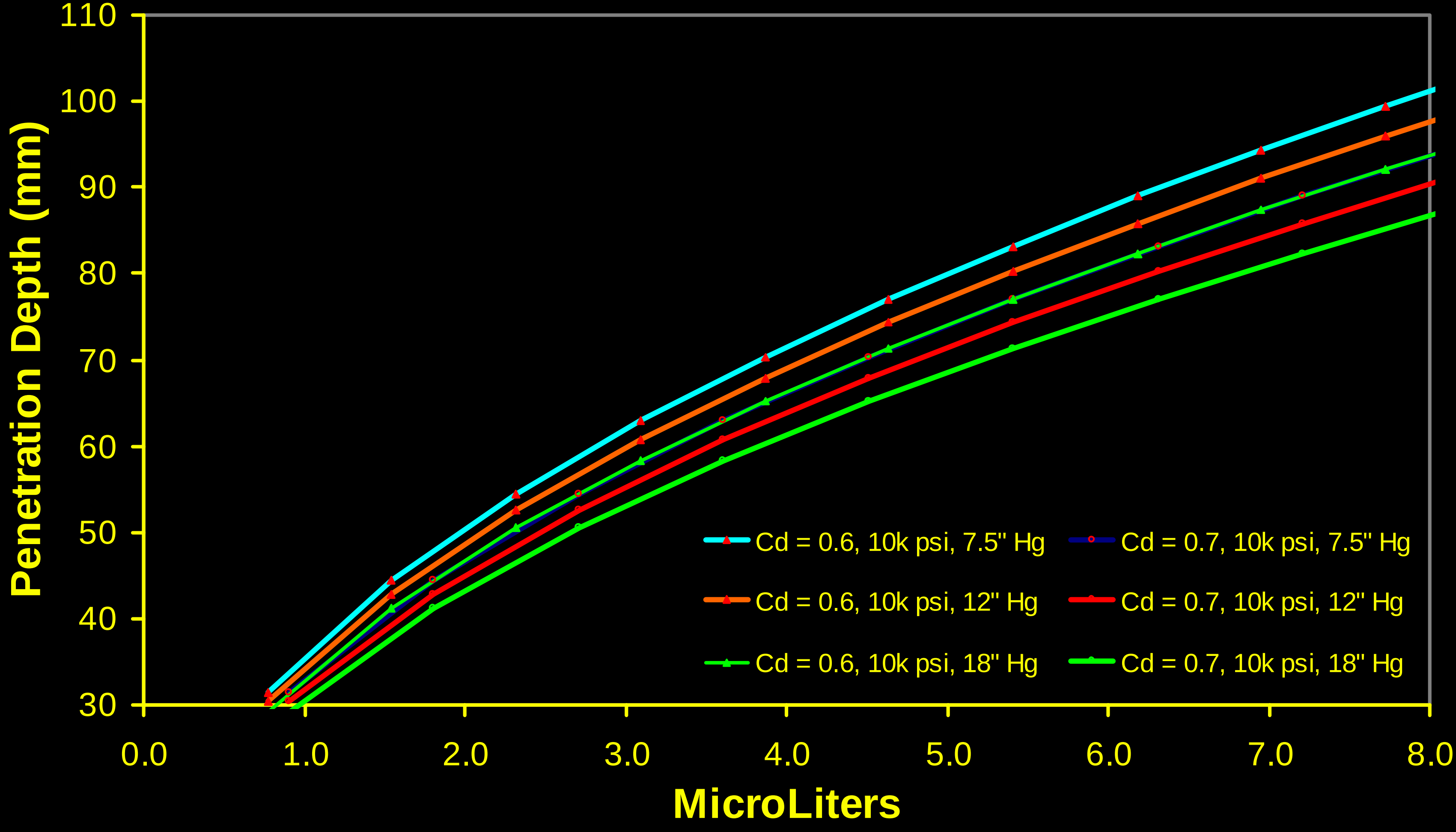


Sauter Mean Diameter

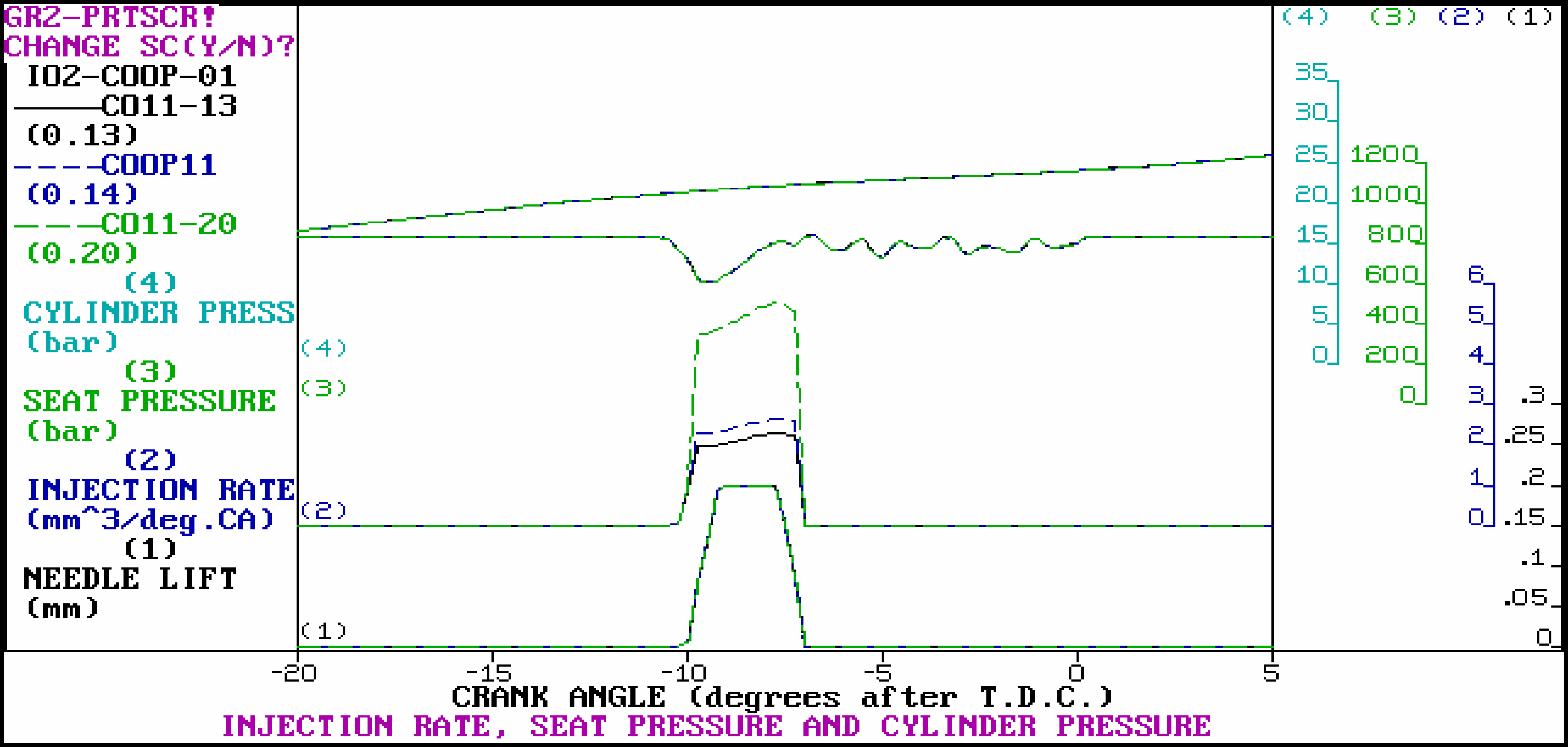


Normally, higher pressure preferred for finer atomization, but larger droplets penetrate farther. Tradeoff to be explored experimentally.

Penetration Depth vs. Flow
(10,000 psi, 0.1 mm dia orifice)



Delphi Modeling Results



Limitations of Modeling

- Injection models largely based on empirical data
- Micro-pilot target is 5-10 mm^3 (μL) of fuel
- “Typical” diesel event injects 10x-100x as much fuel
- Semi-empirical models not well “tuned” for the earliest transient processes in the injector
- Current models do not accurately predict droplet size distribution
- Experimental validation of modeling required for confidence

Micro-Pilot Update

- Program Overview
- Hardware
- **Combustion Test Chamber Results**
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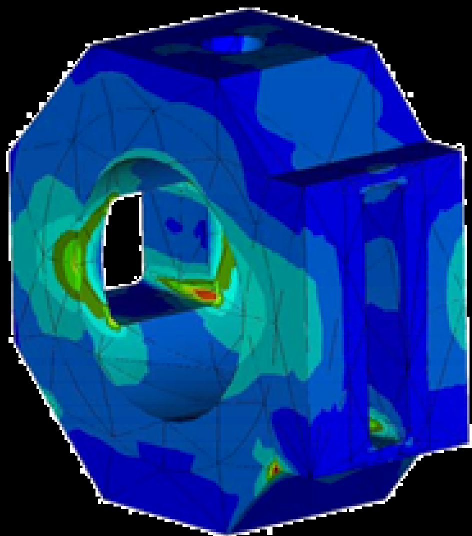
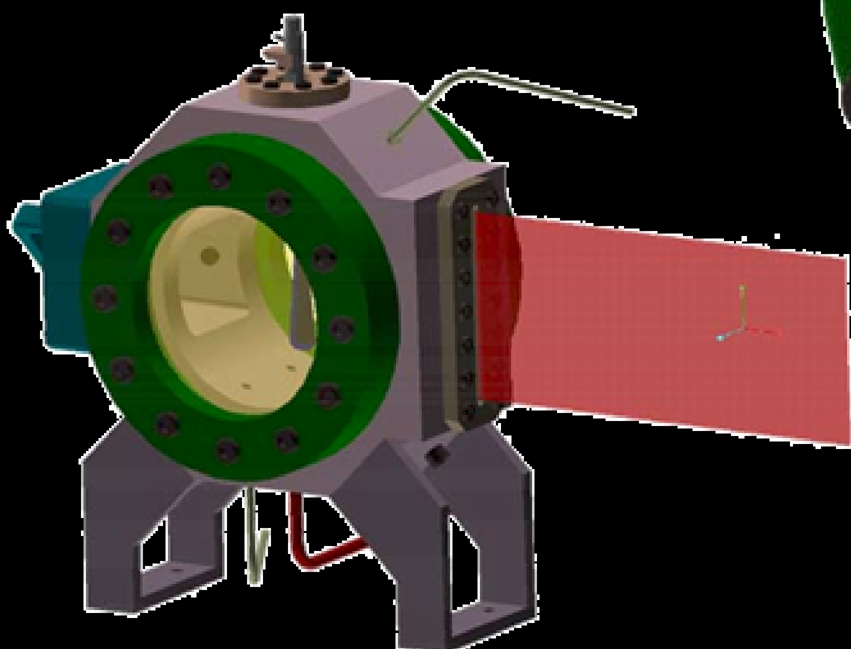
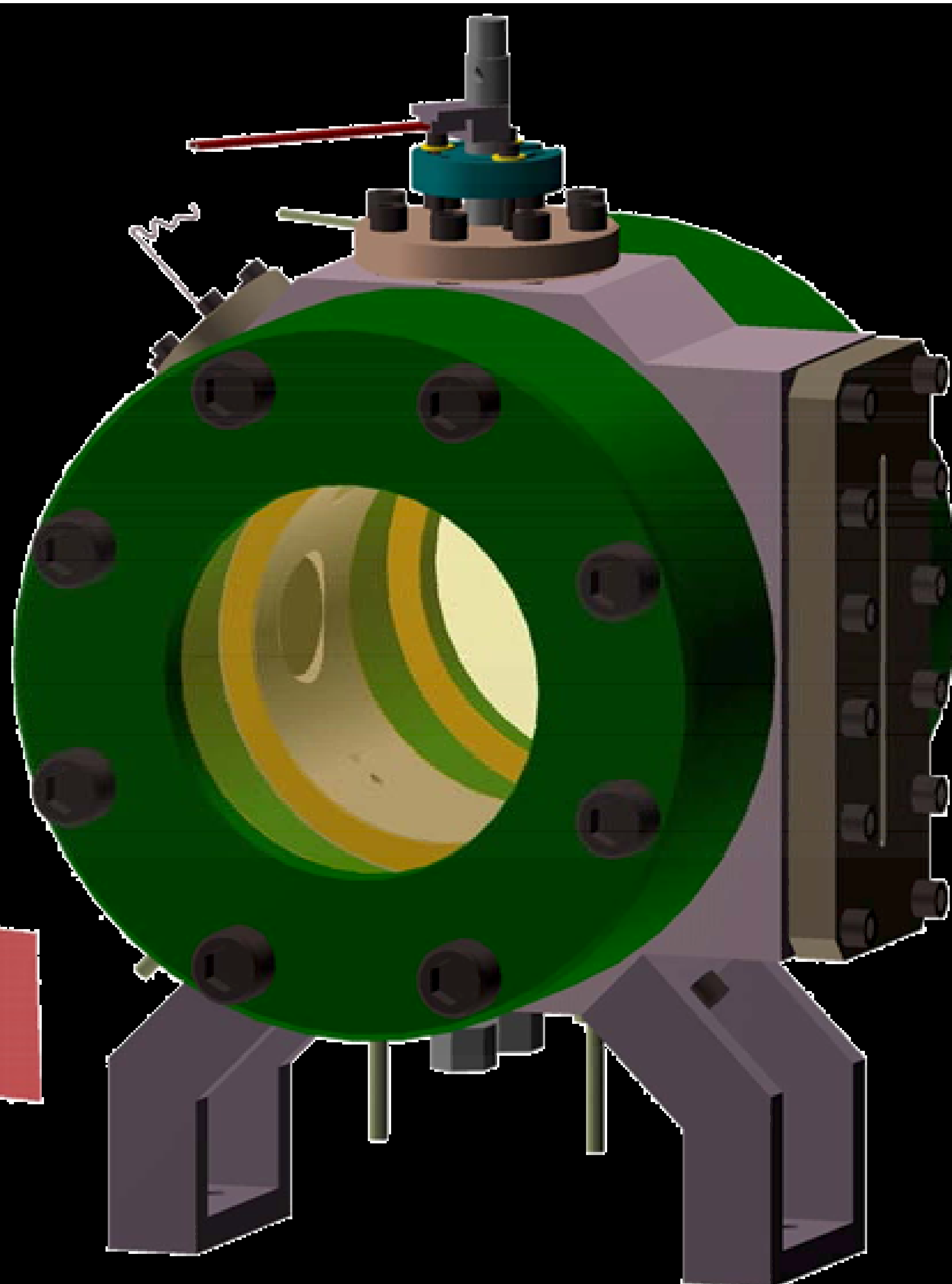
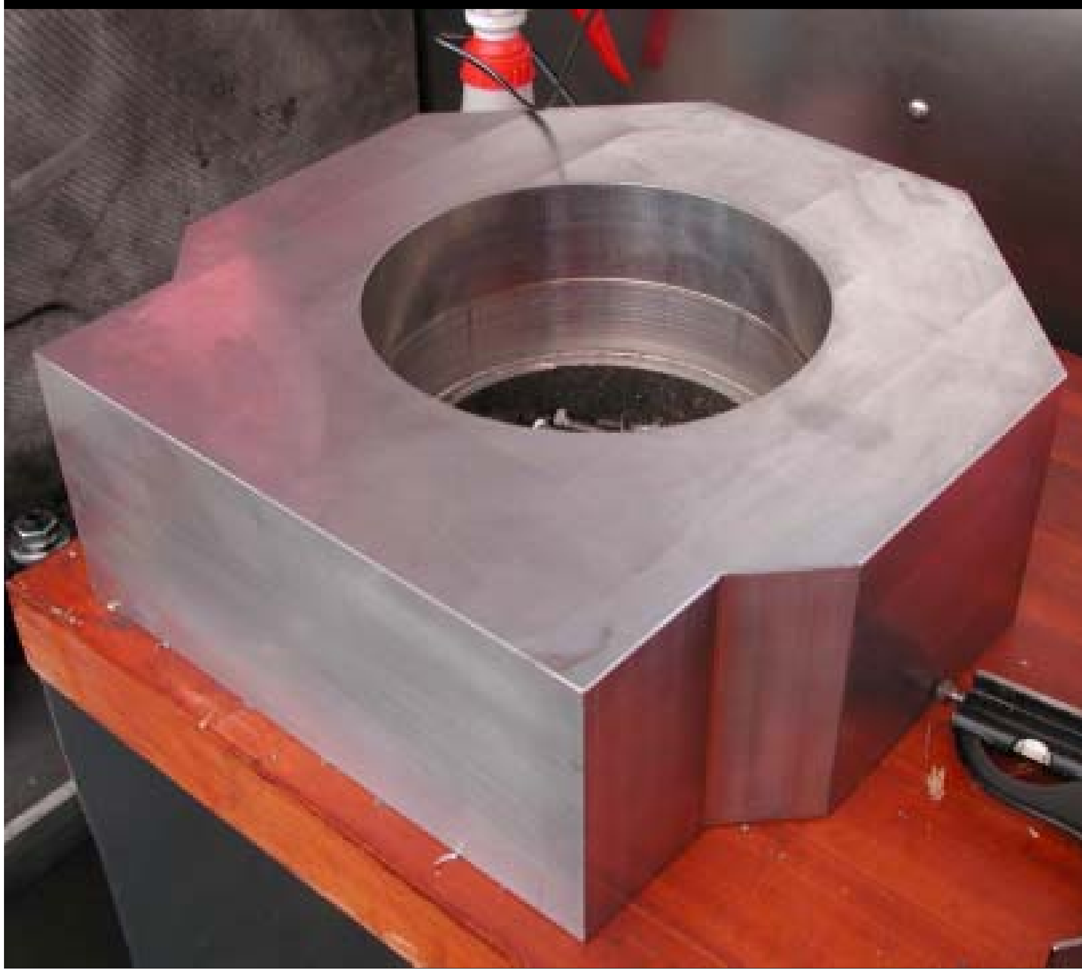
CTC Design





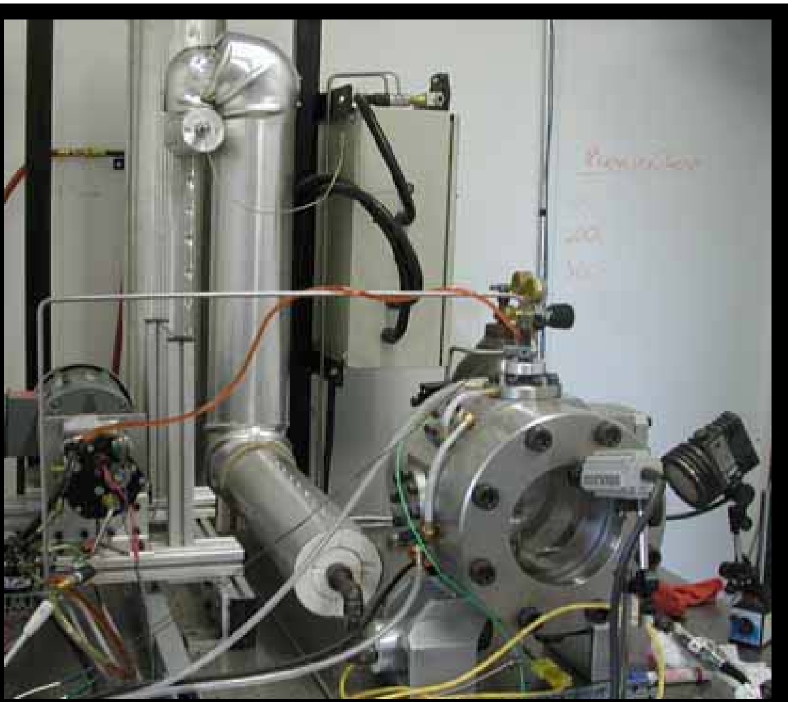


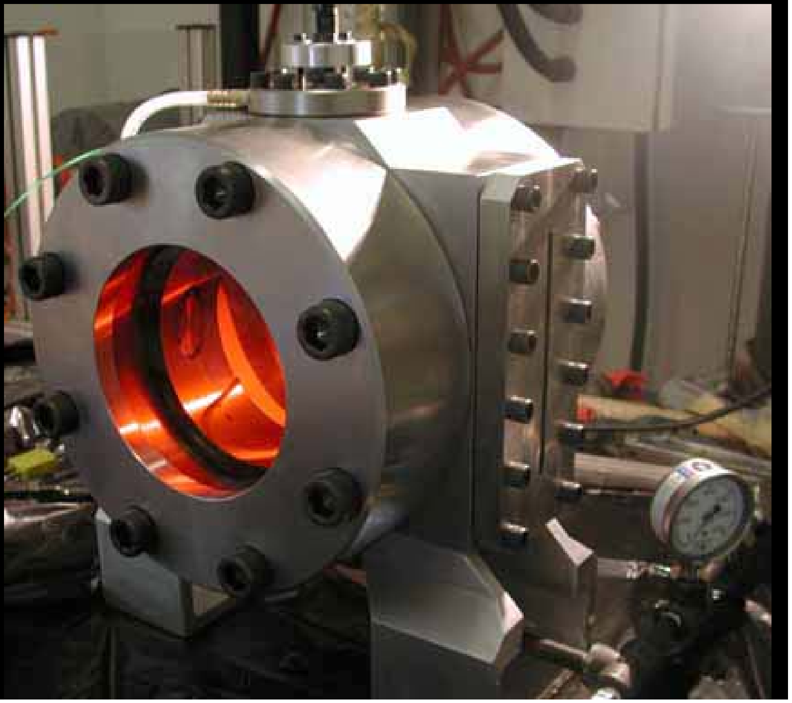
CTC Fabrication



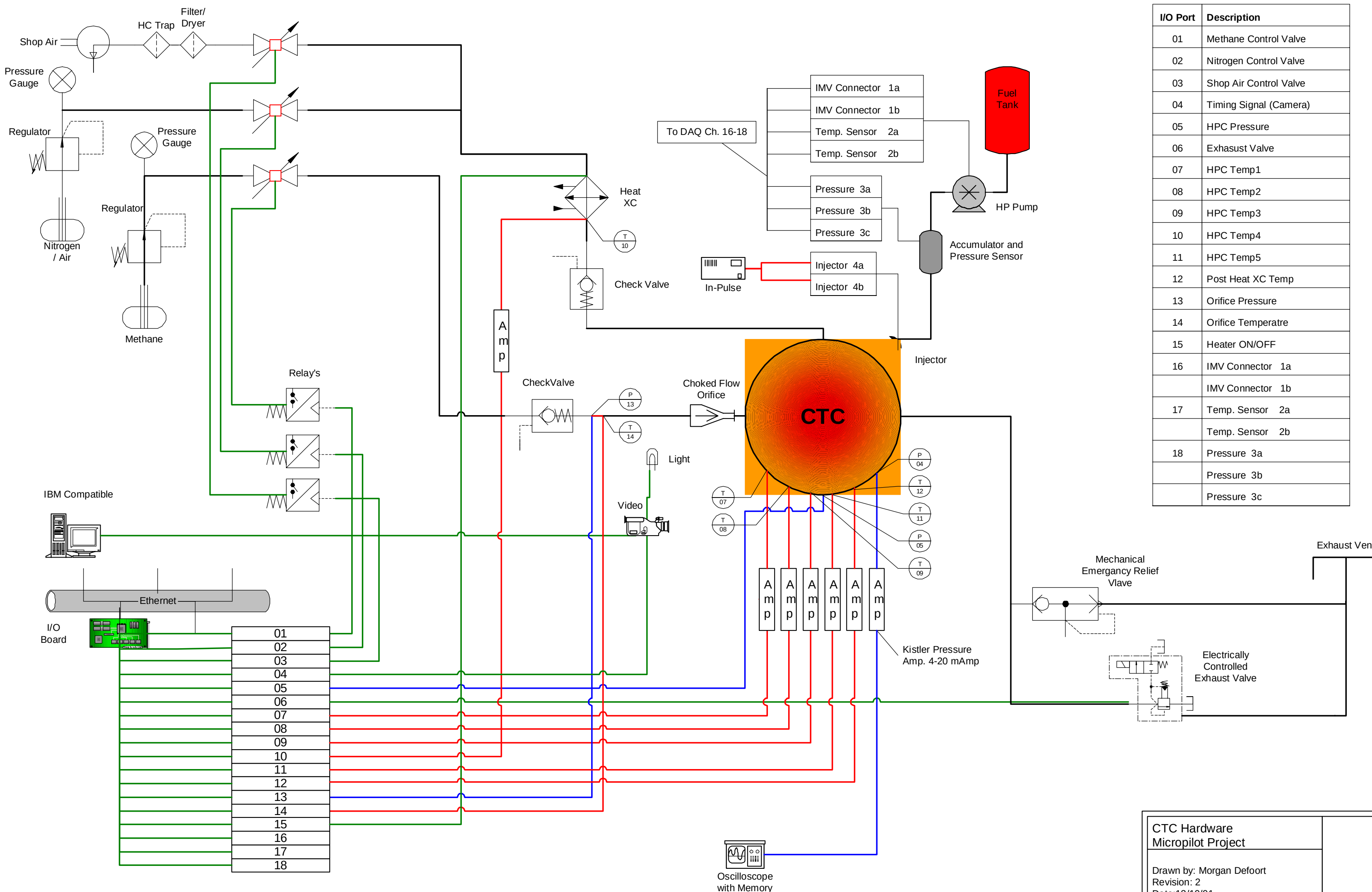
Combustion Test Chamber Capabilities

- Temperature tested to 750K (890° F), capabilities to 810K (1000° F),
- Pressure to 70 atm (1000 psi)





CTC Instrumentation Schematic

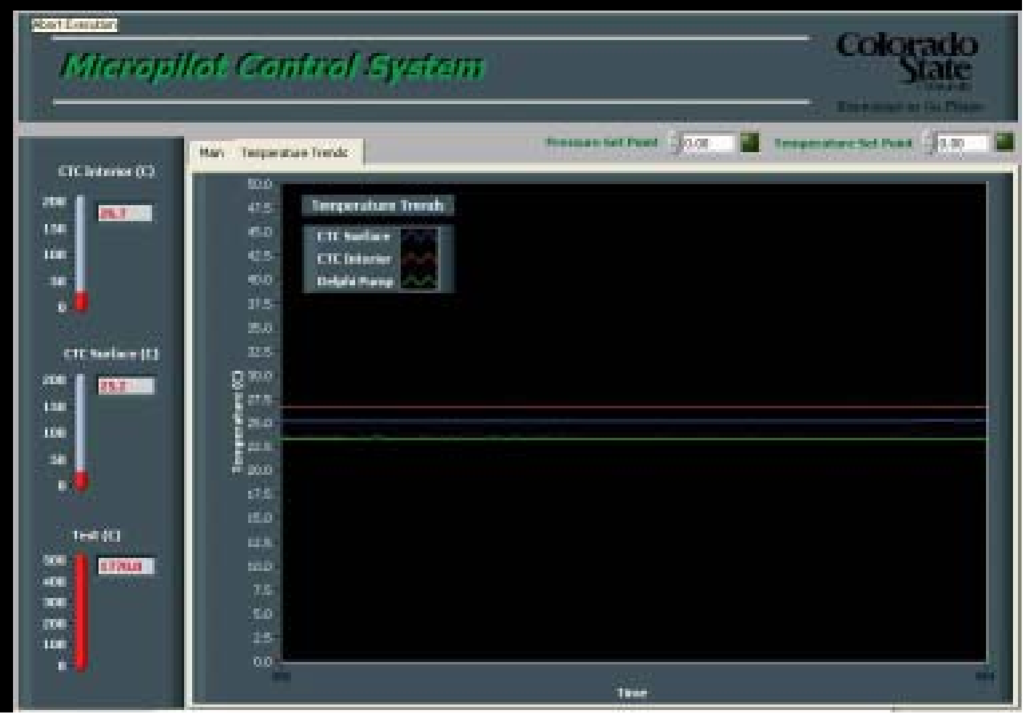


I/O Port	Description
01	Methane Control Valve
02	Nitrogen Control Valve
03	Shop Air Control Valve
04	Timing Signal (Camera)
05	HPC Pressure
06	Exhasust Valve
07	HPC Temp1
08	HPC Temp2
09	HPC Temp3
10	HPC Temp4
11	HPC Temp5
12	Post Heat XC Temp
13	Orifice Pressure
14	Orifice Temperatre
15	Heater ON/OFF
16	IMV Connector 1a
	IMV Connector 1b
17	Temp. Sensor 2a
	Temp. Sensor 2b
18	Pressure 3a
	Pressure 3b
	Pressure 3c

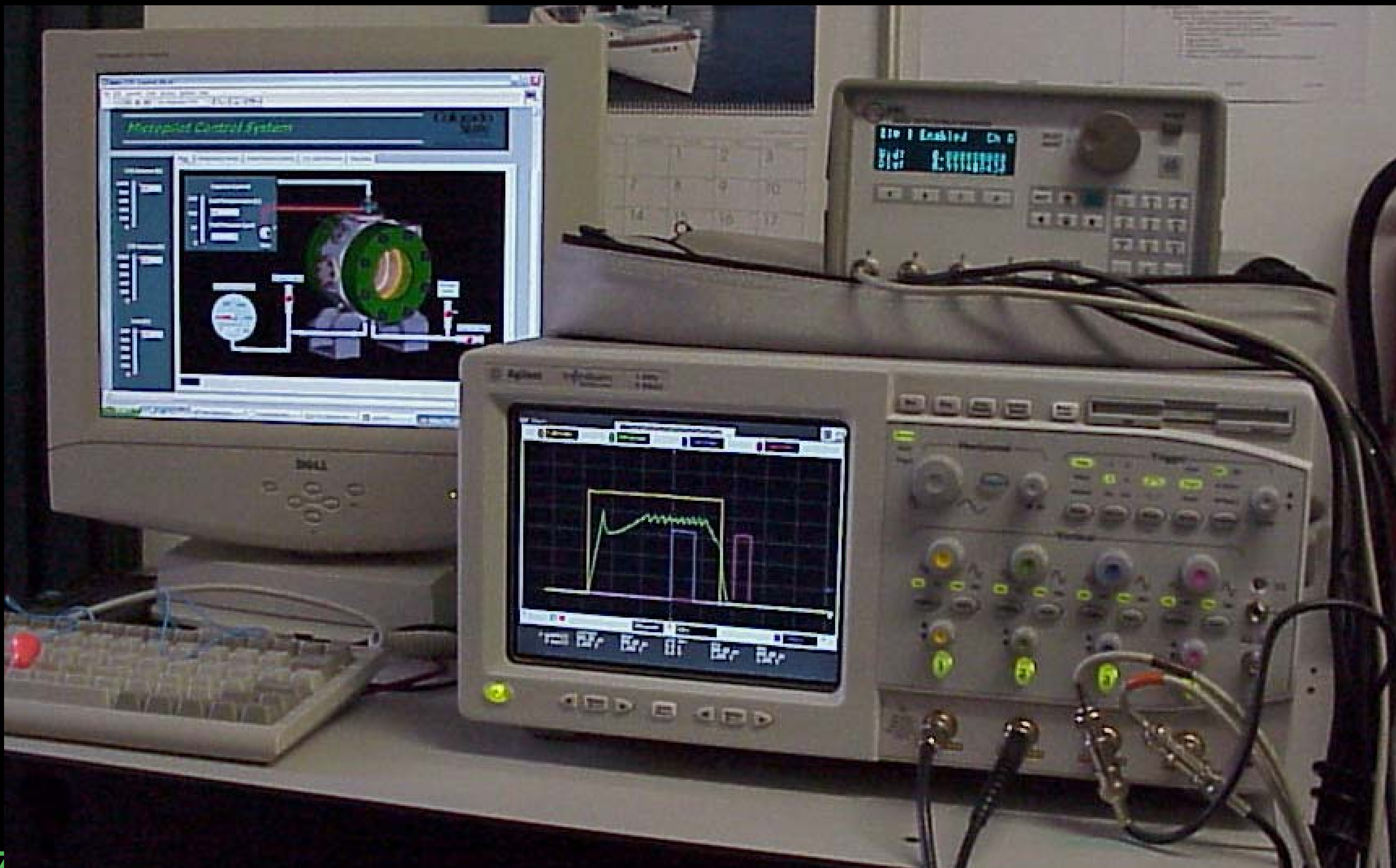
CTC Hardware
Micropilot Project

Drawn by: Morgan Defoort
Revision: 2
Date:12/10/01

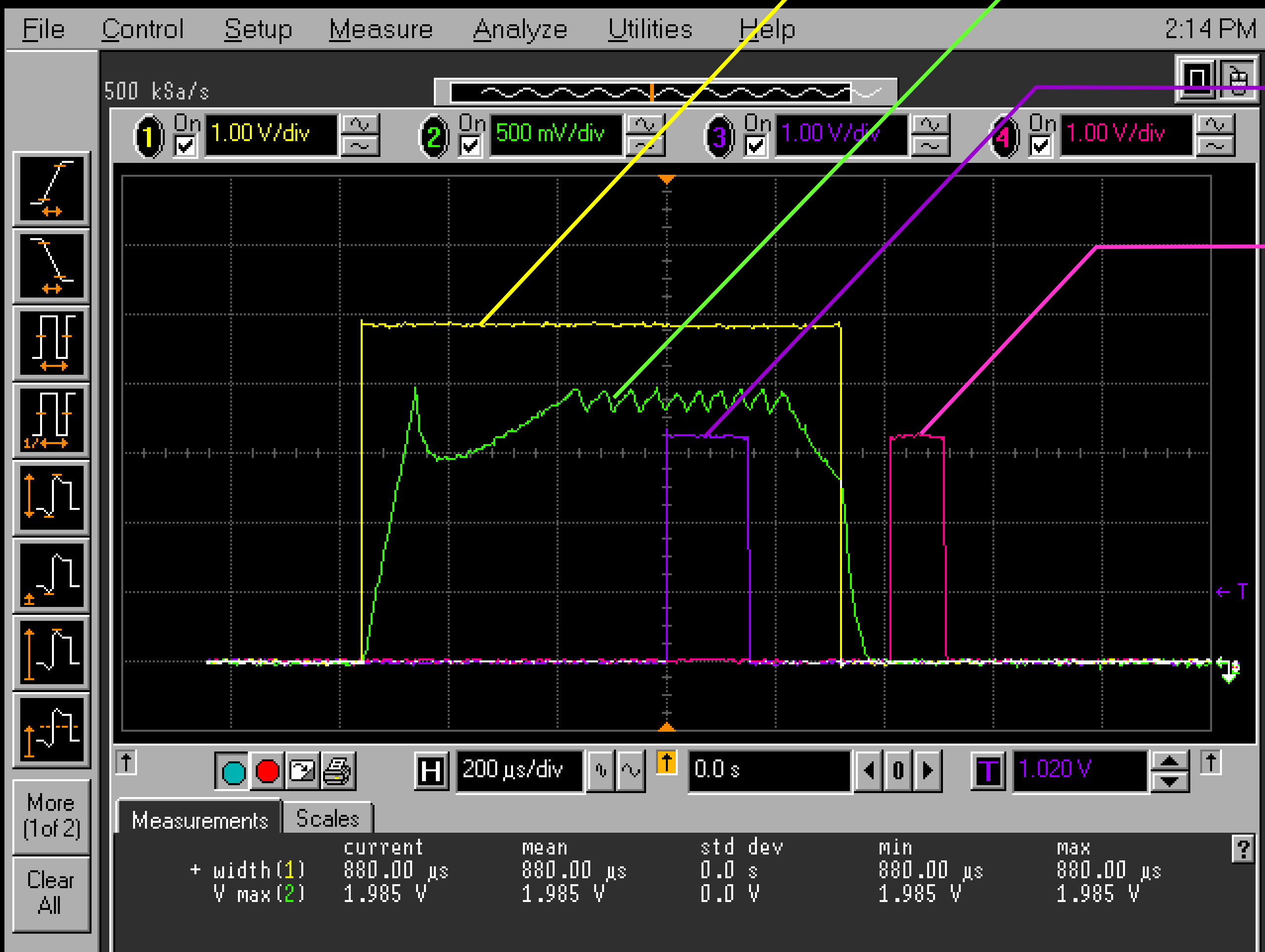
CTC Controls



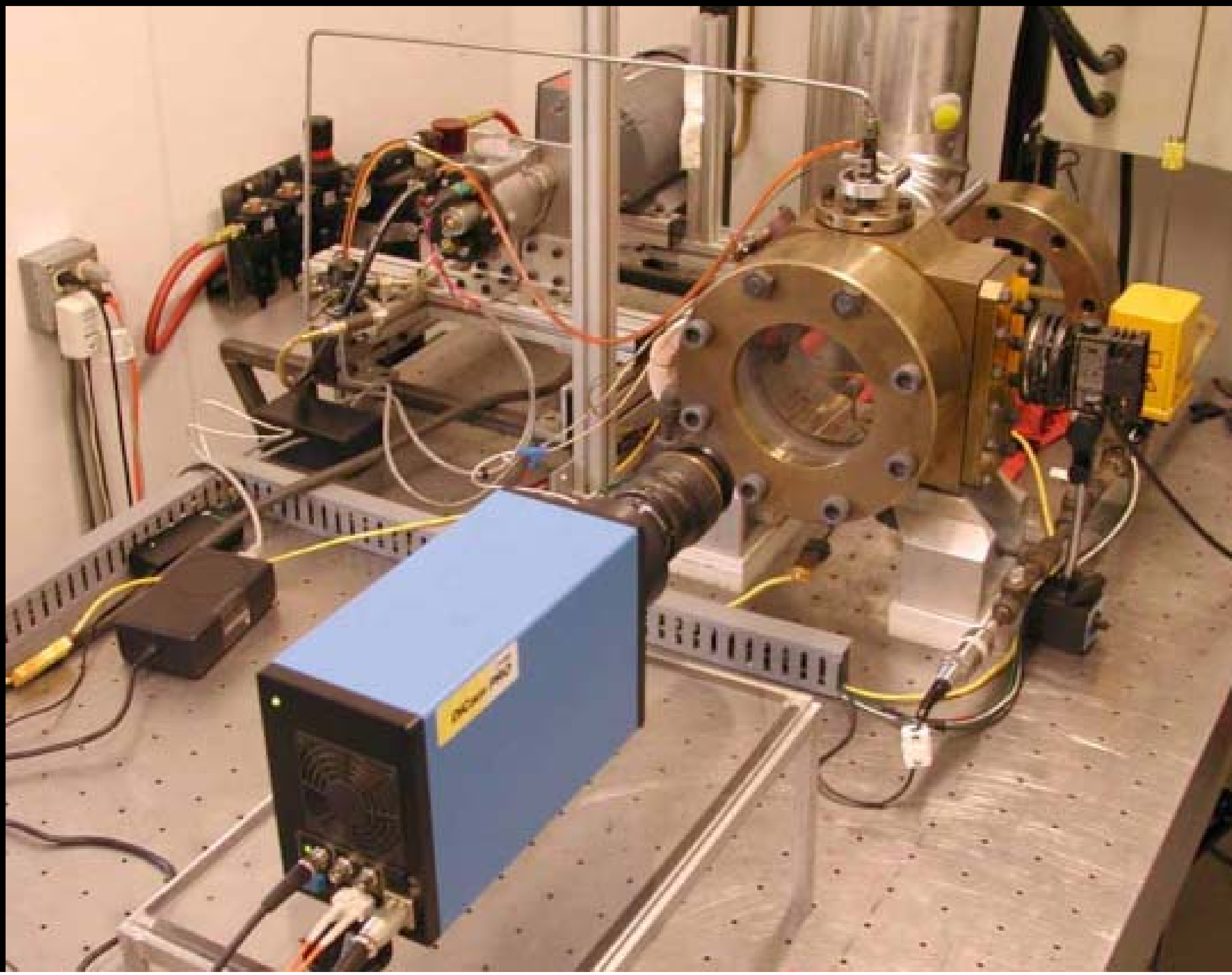
Injector Controls / Diagnostics



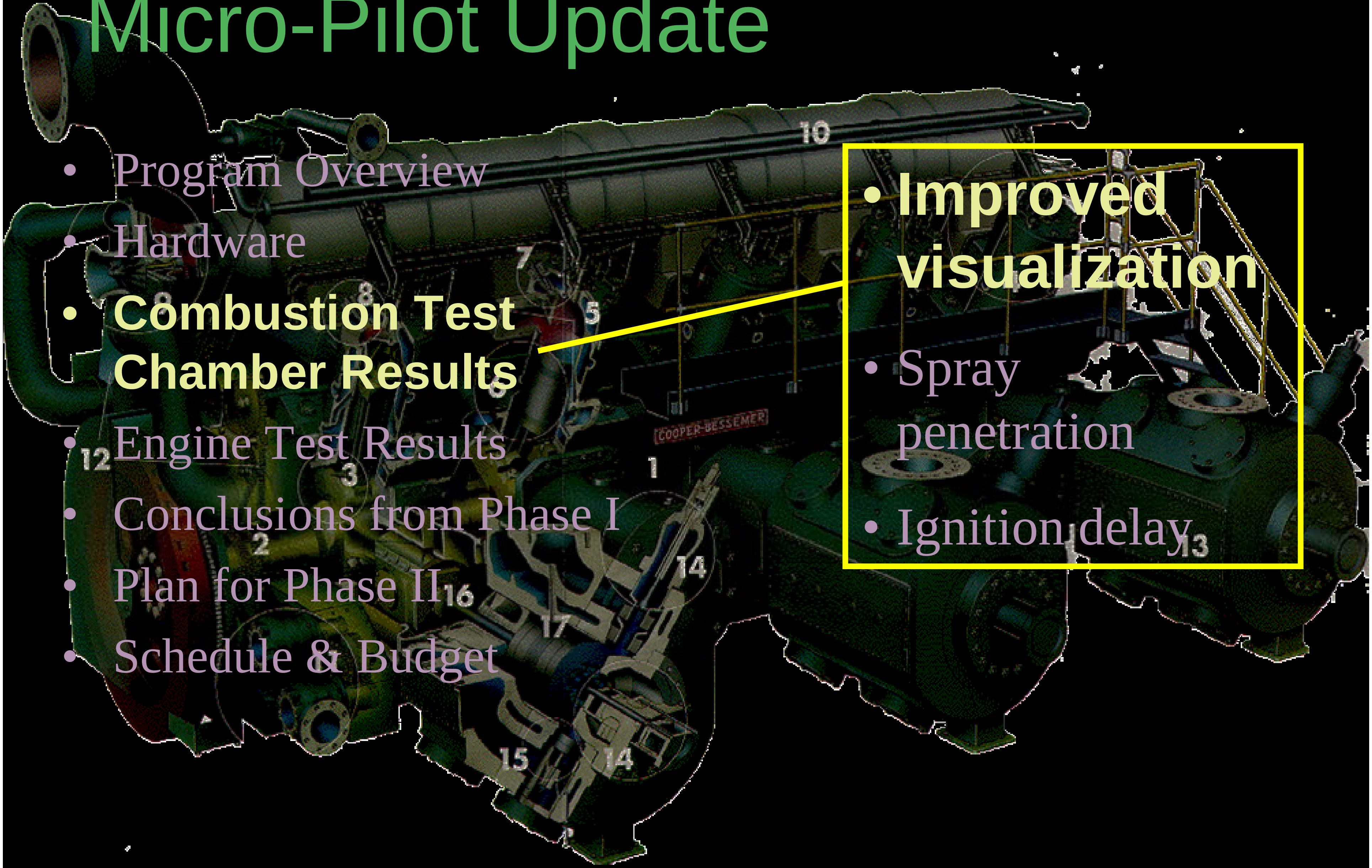
Injector Signals



DiCam Setup for CTC



Micro-Pilot Update



- Program Overview
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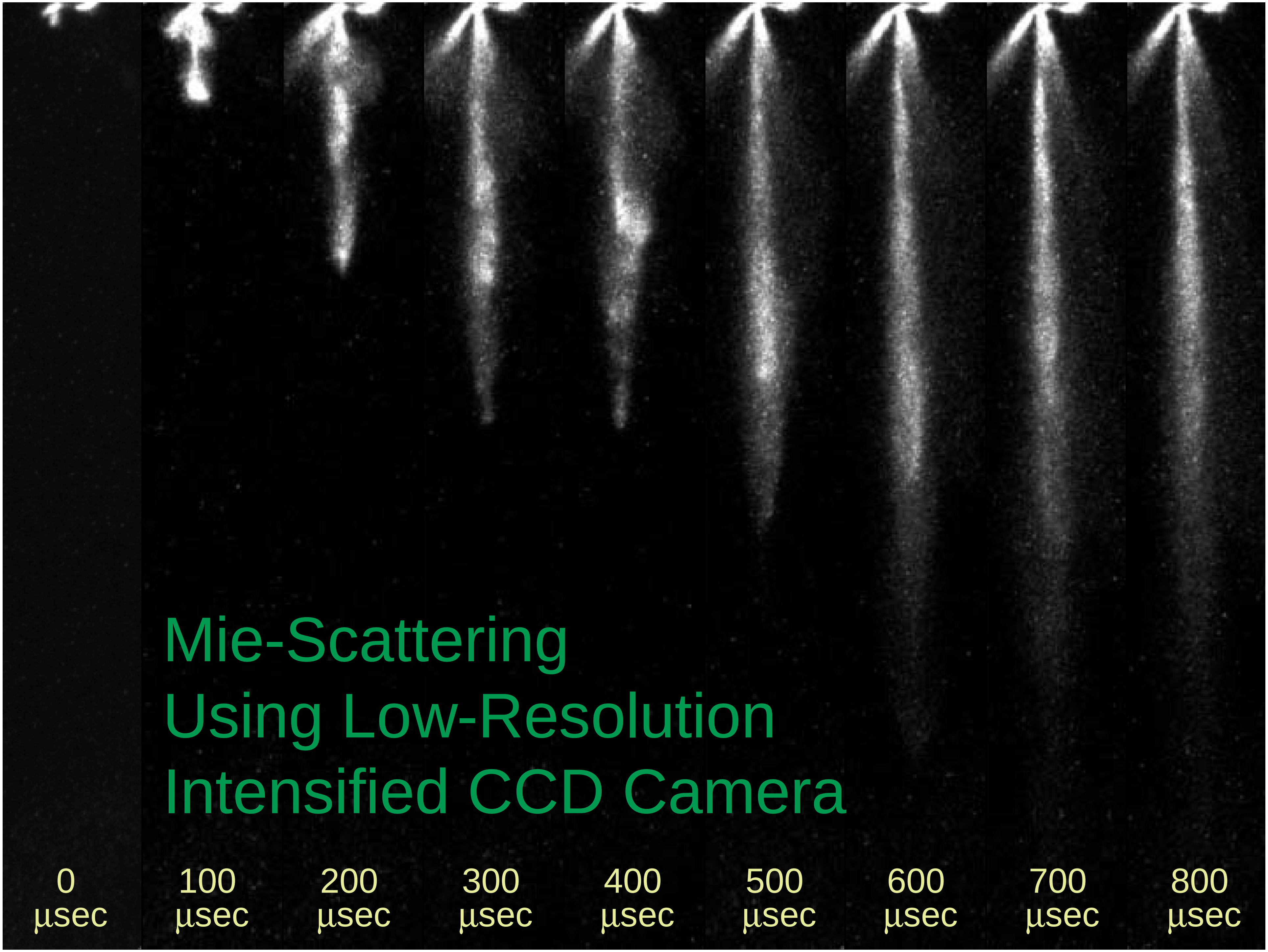
- **Improved visualization**
- Spray penetration
- Ignition delay



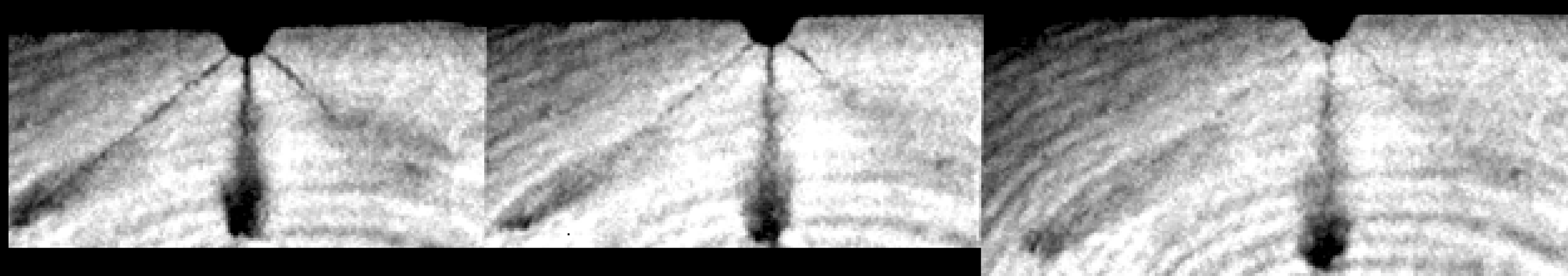
Mie-Scattering
Using Low-Resolution
Intensified CCD Camera
0 µsec
100 µsec
200 µsec
300 µsec
400 µsec
500 µsec
600 µsec
700 µsec
800 µsec

Early Injection Characteristics Using Shadowgraph & Schlieren

0 20 40 60 100 140 170

Times shown in μsec

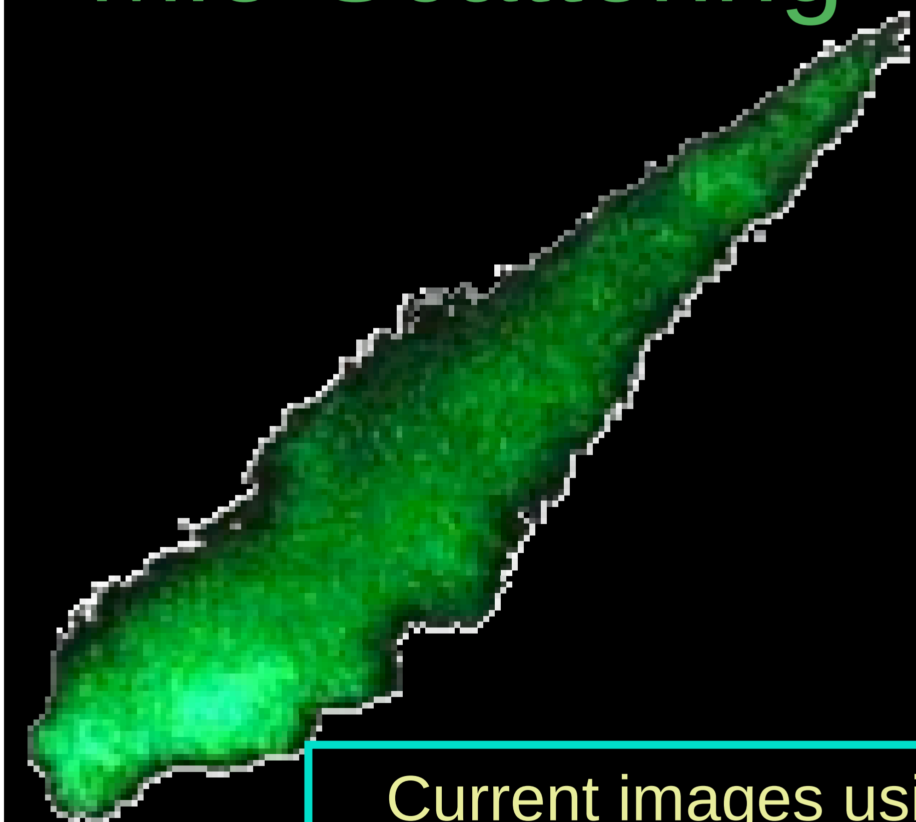
210 250 290

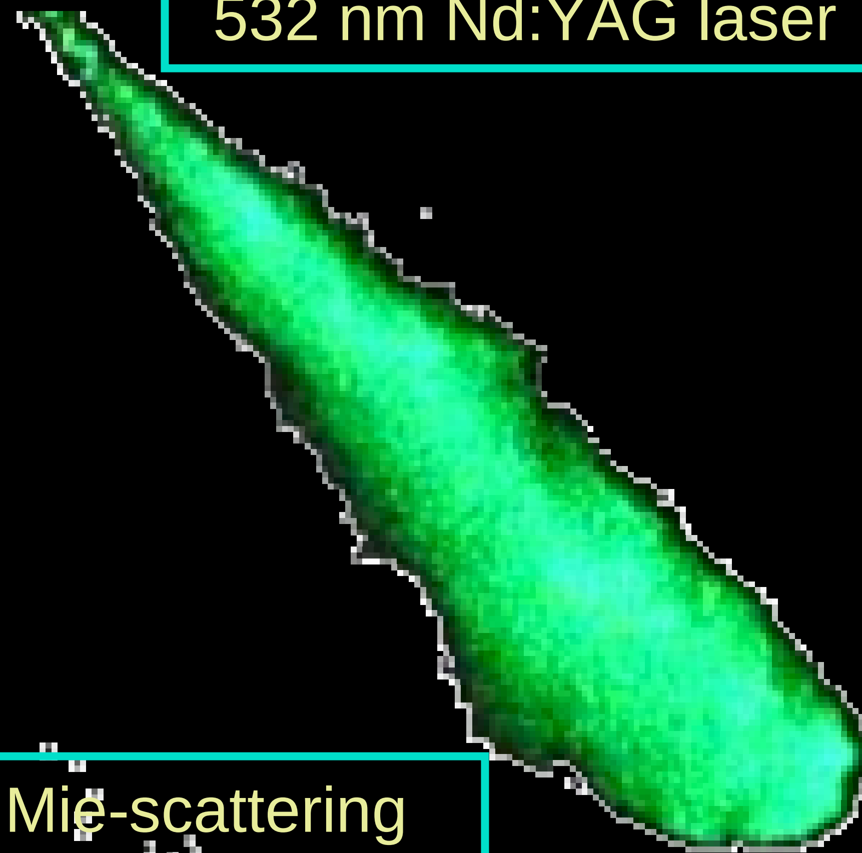


330 370 370+

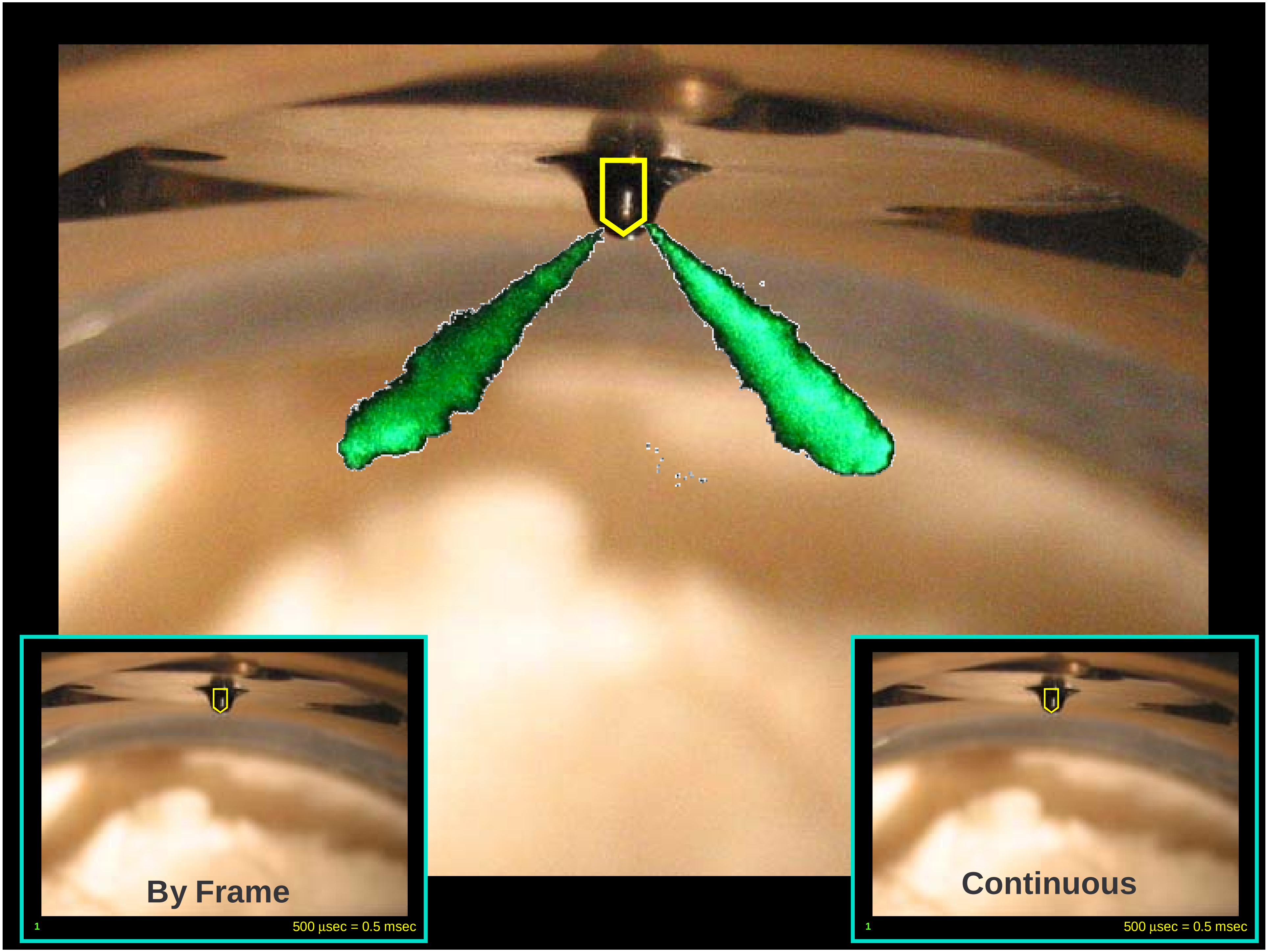
High-Resolution Imaging Using Mie-Scattering

Images appear green due to illumination with 532 nm Nd:YAG laser





Current images using Mie-scattering laser illumination and a 6 megapixel commercial-grade digital camera


By Frame
1
500 µsec = 0.5 msec
Continuous
1
500 µsec = 0.5 msec

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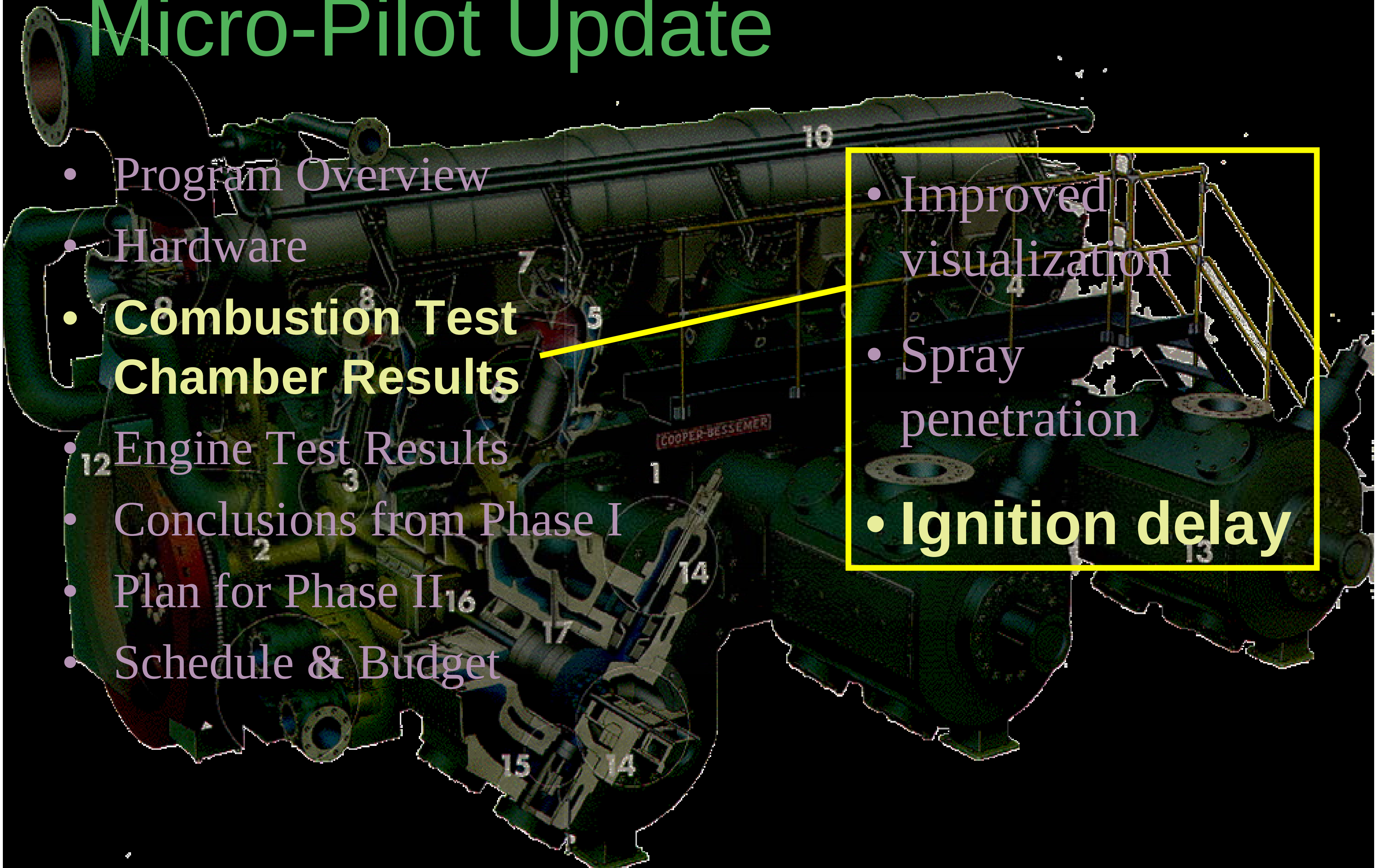
- Improved visualization
- **Spray penetration**
- Ignition delay


CTC Delphi 5 Hole: 1/31/2003
Spray Quantity: 8 μ L
Spray Duration: 550 μsec
Rail Pressure: 5800 psi (400 bar)
CTC Avg. Temp: 700 K
CTC Avg. Press: 275 psi
Injector #: 403DDB20


CTC Delphi 5 Hole
Spray Quantity: 6, 8, & 16 µL
Spray Duration: 496, 550, & 767 µsec
Rail Pressure: 5800 psi (400 bar)
CTC Avg. Temp: 700 K
CTC Avg. Press: 275 psi
Injector #: 403DDB20

Micro-Pilot Update



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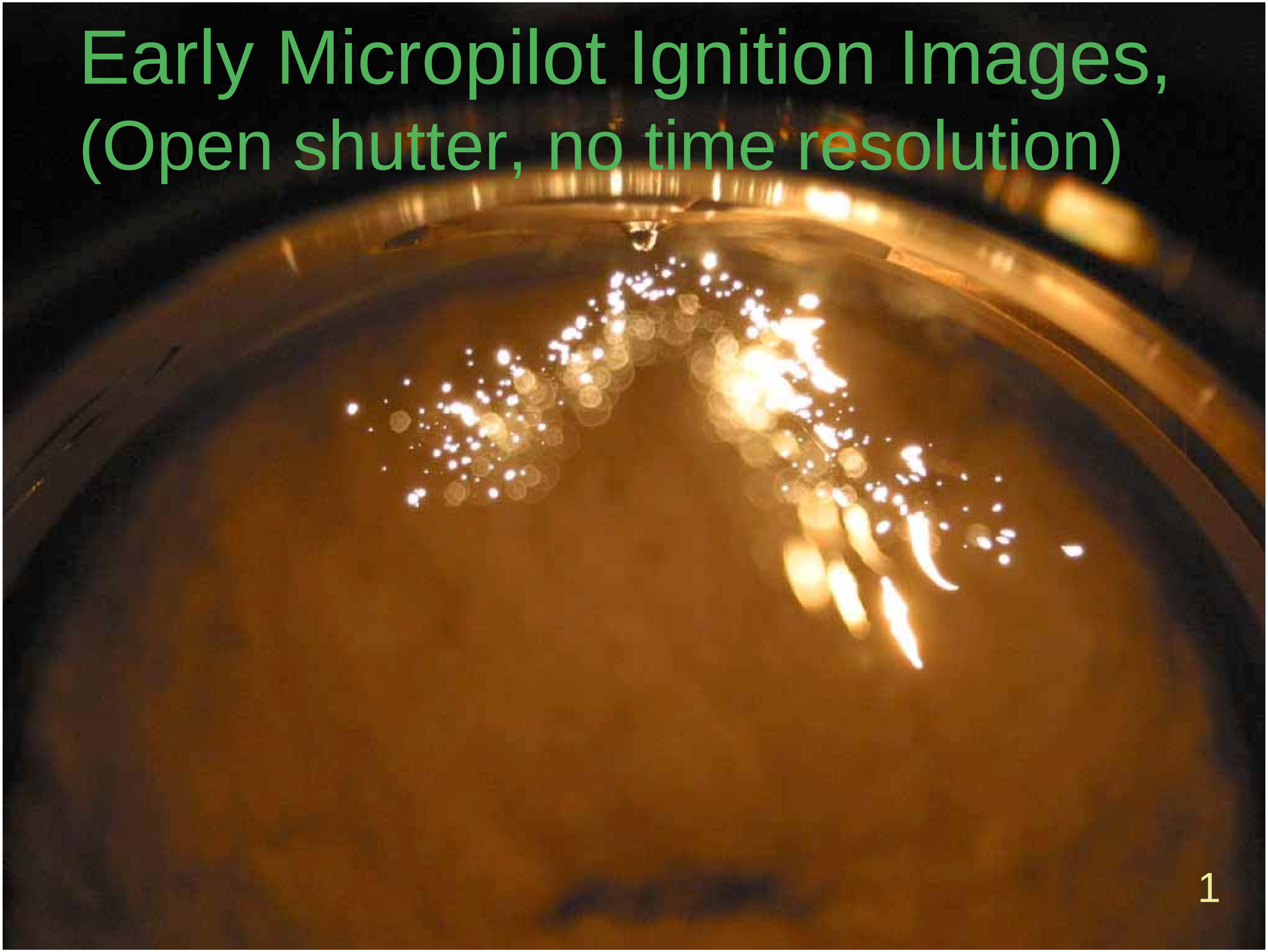
- Improved visualization
- Spray penetration
- **Ignition delay**

Early Micropilot Ignition Images, (Open shutter, no time resolution)



Determination of Ignition Delay

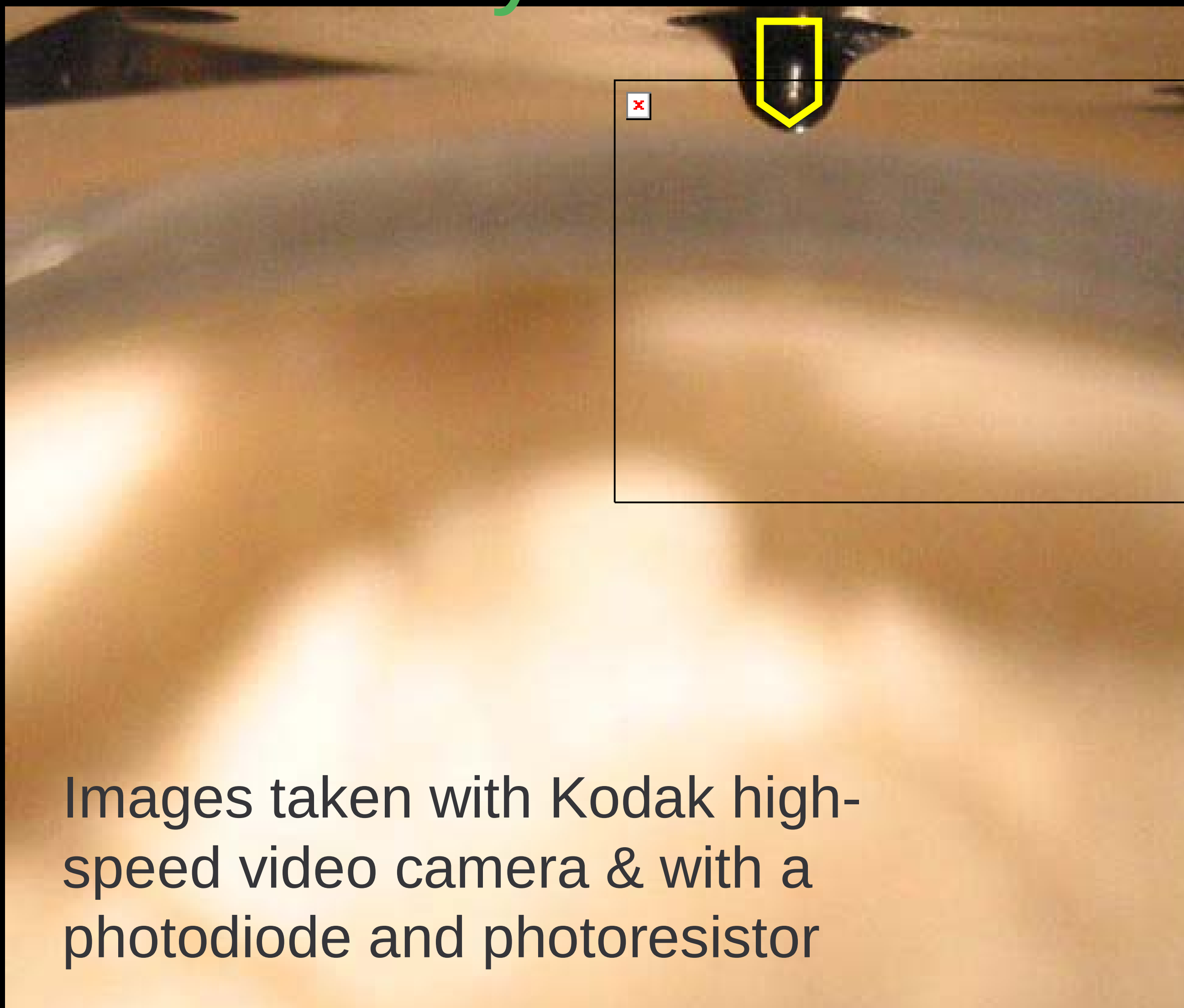
Difficult to determine the start of combustion, the "time after start of injection" (TASI):

Combustion Pressure: unsuccessful in air due to the very low pressure rise with small (≈1μliter) pilot quantities

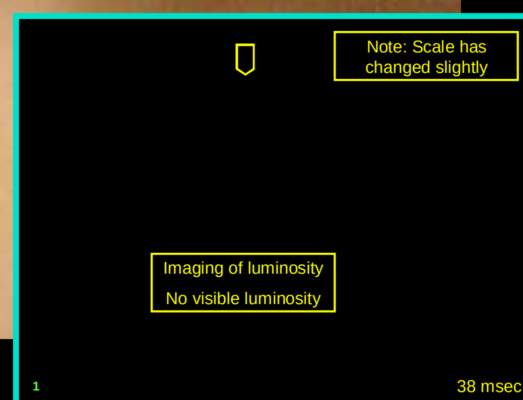
Optical Indication, standard: Visible luminosity measurement undetectable until late soot-formation stage

Optical Indication, PMT: Currently, a photomultiplier (PMT) is used to determine early "cool flame" luminosity by the technique of Higgins & Siebers (Sandia, SAE 2000-01-0940)

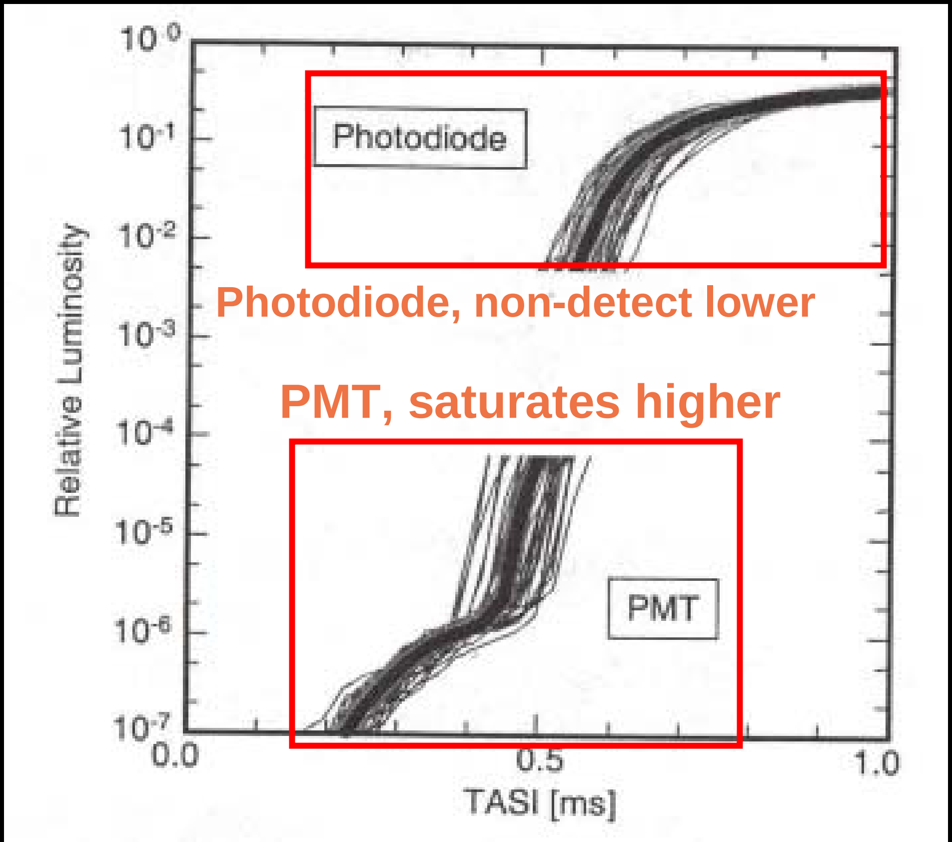
Time-Resolved Visible Luminosity Measurement

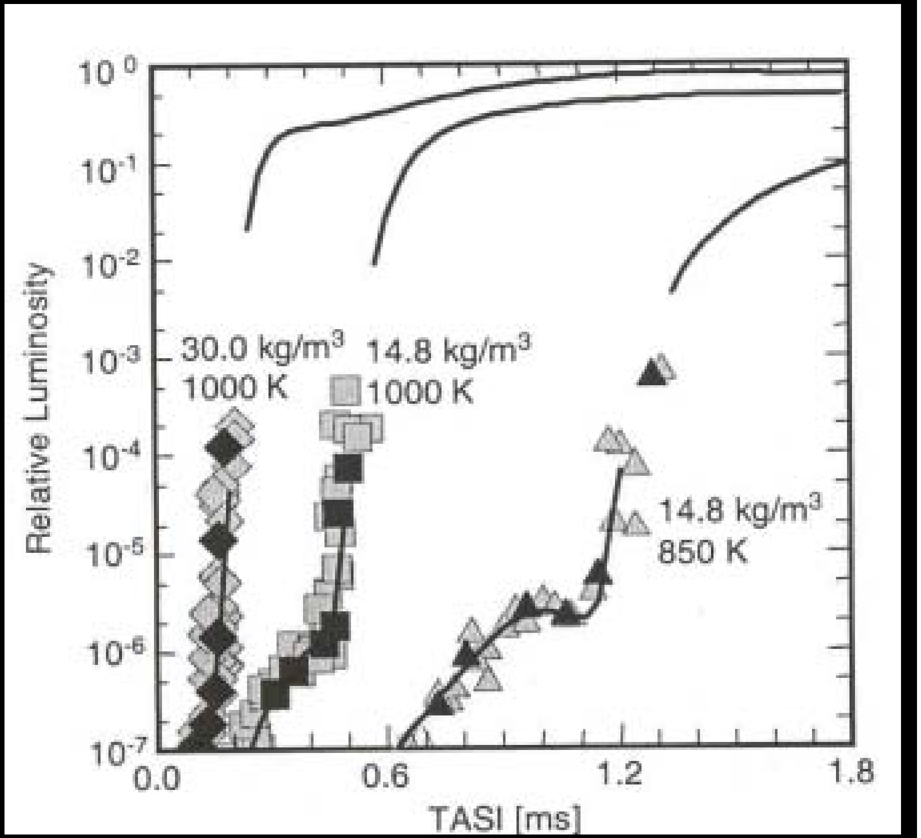


Images taken with Kodak high-speed video camera & with a photodiode and photoresistor



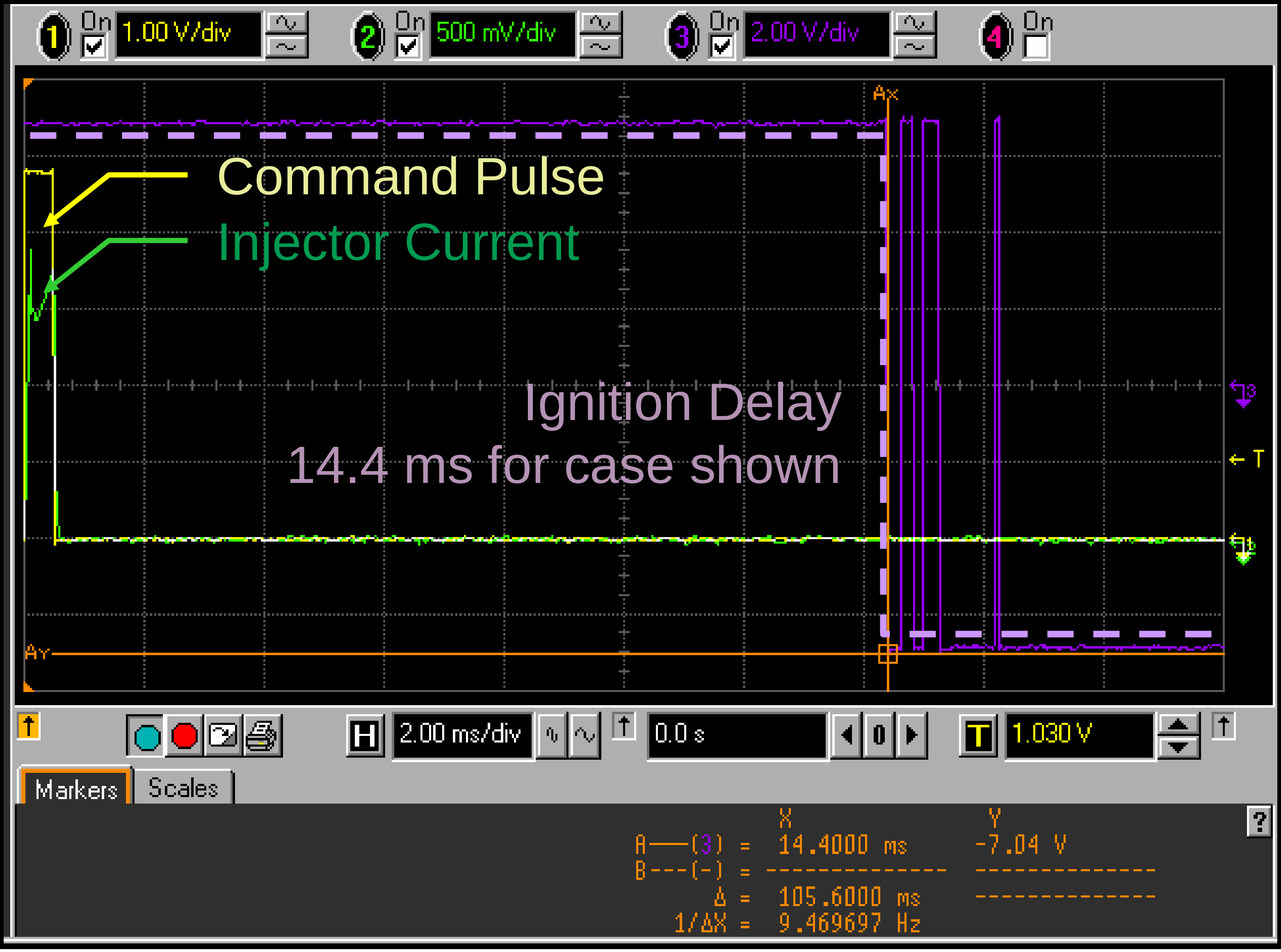
Photomultiplier Images
(from Higgins, Siebers, Aradi: SAE 2000-01-0940)



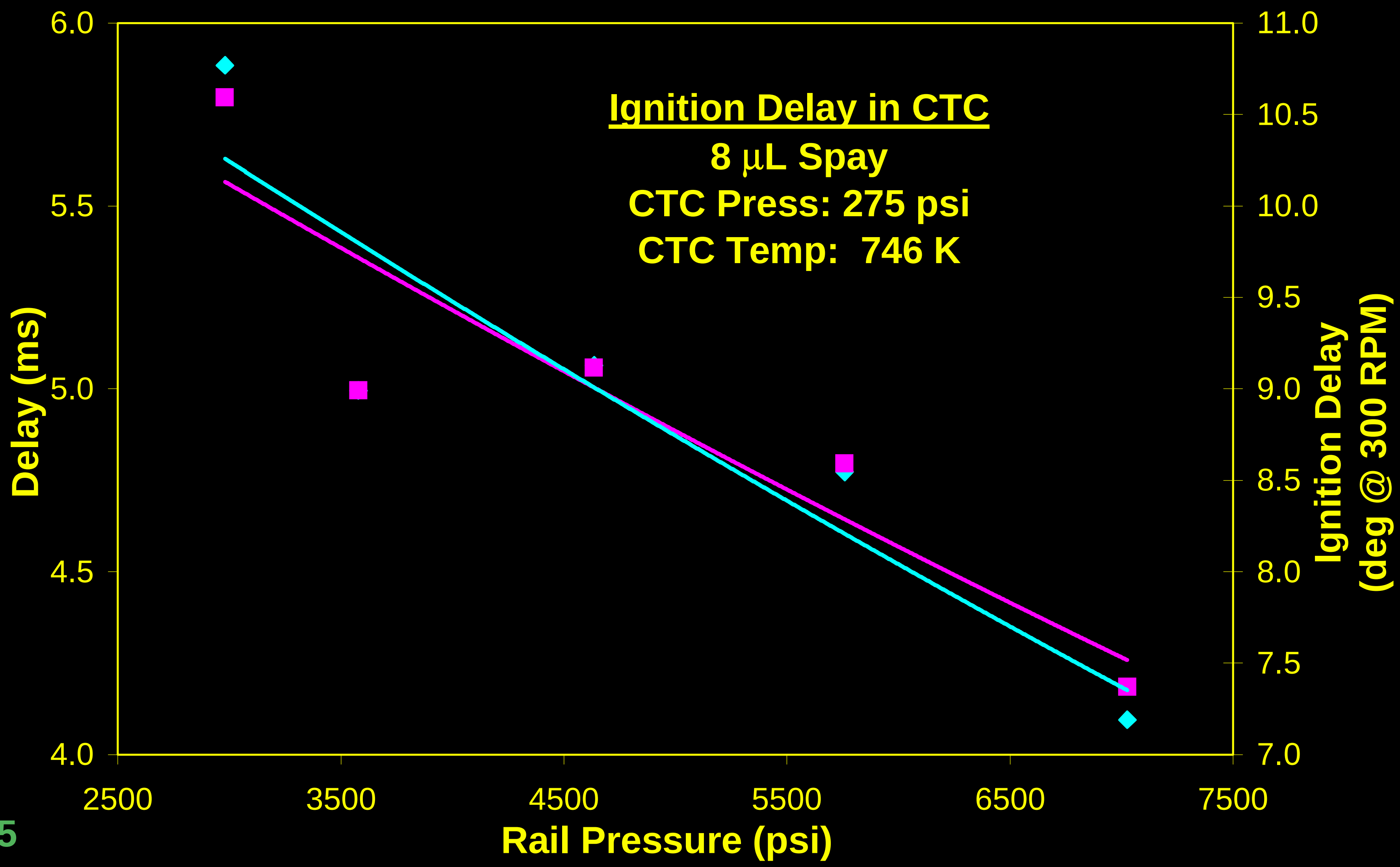


Photomultiplier for Early Optical Detection of Combustion

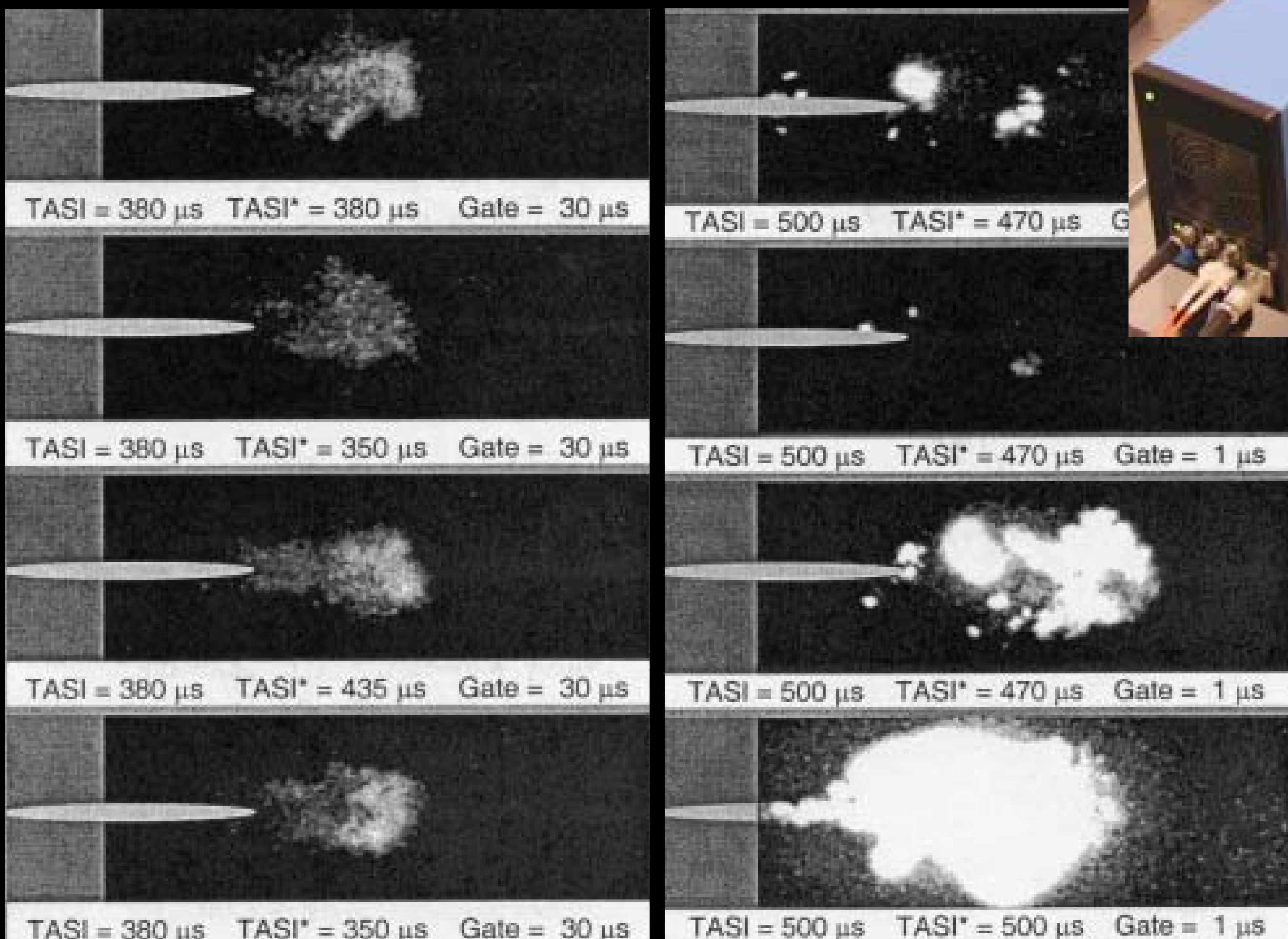
Determination of Ignition Delay using Photomultiplier

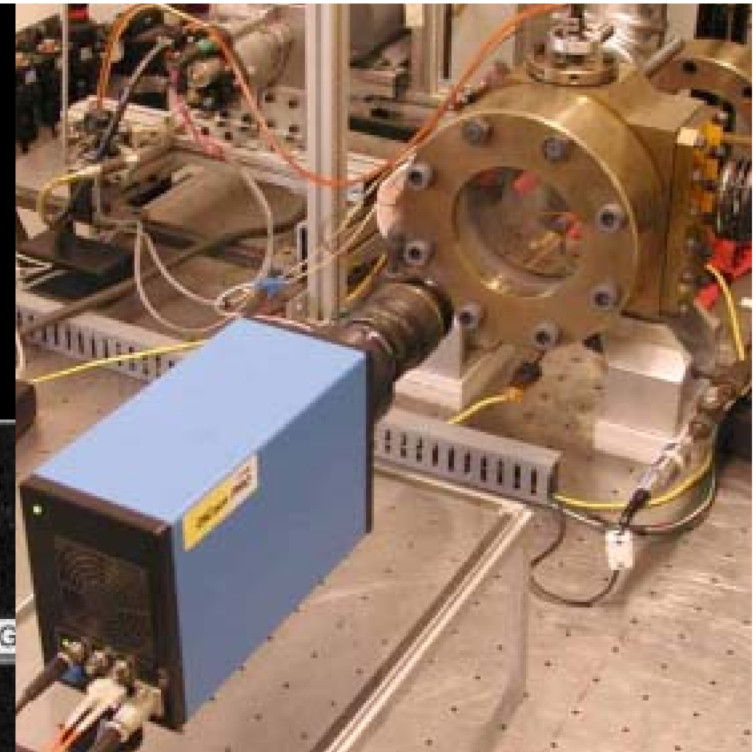


Ignition Delay from CTC Tests



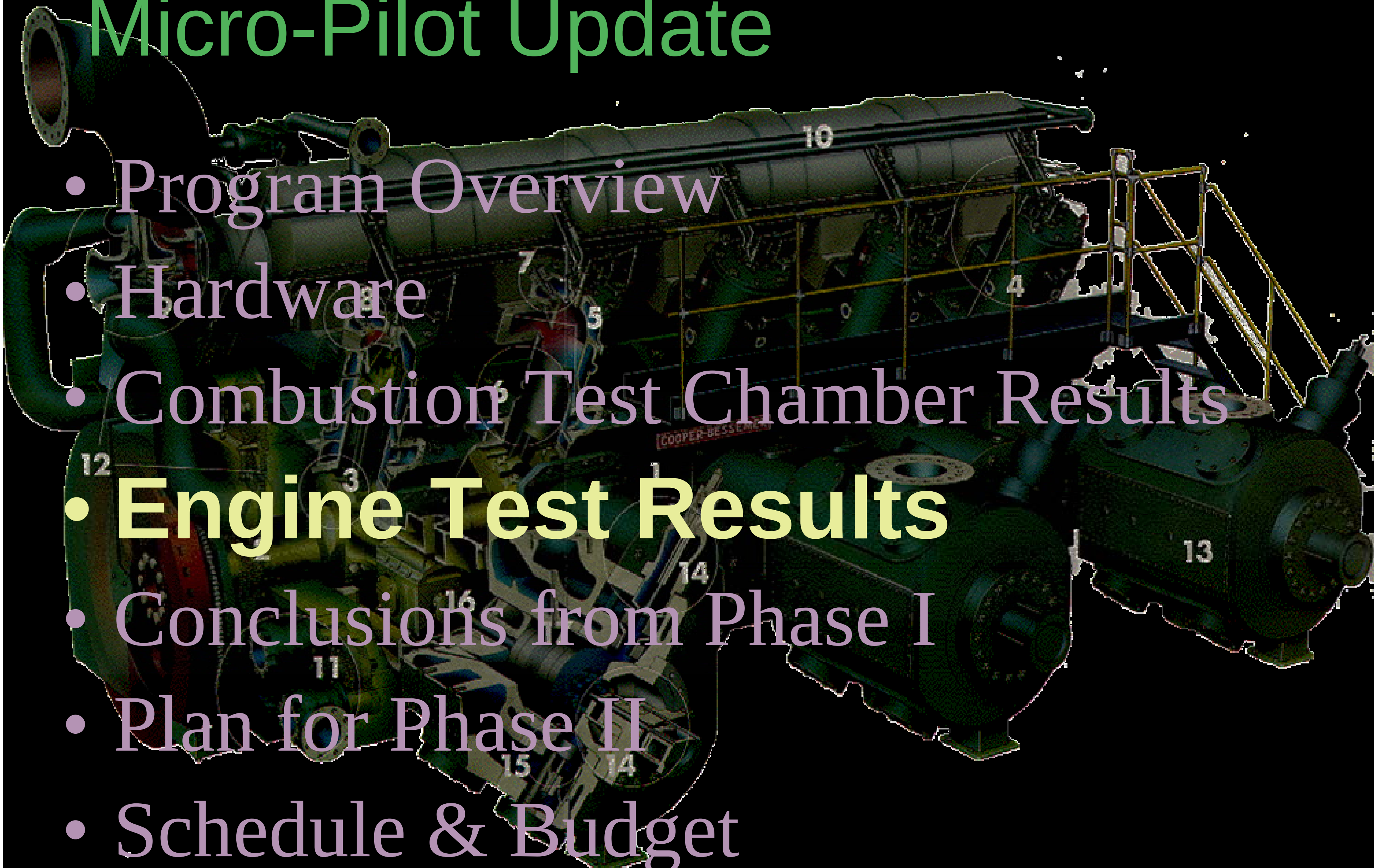
Intensified CCD Imaging of Cool Flame Luminosity
(Under Consideration for CTC)





(from Higgins, Siebers, Aradi: SAE 2000-01-0940)

Micro-Pilot Update



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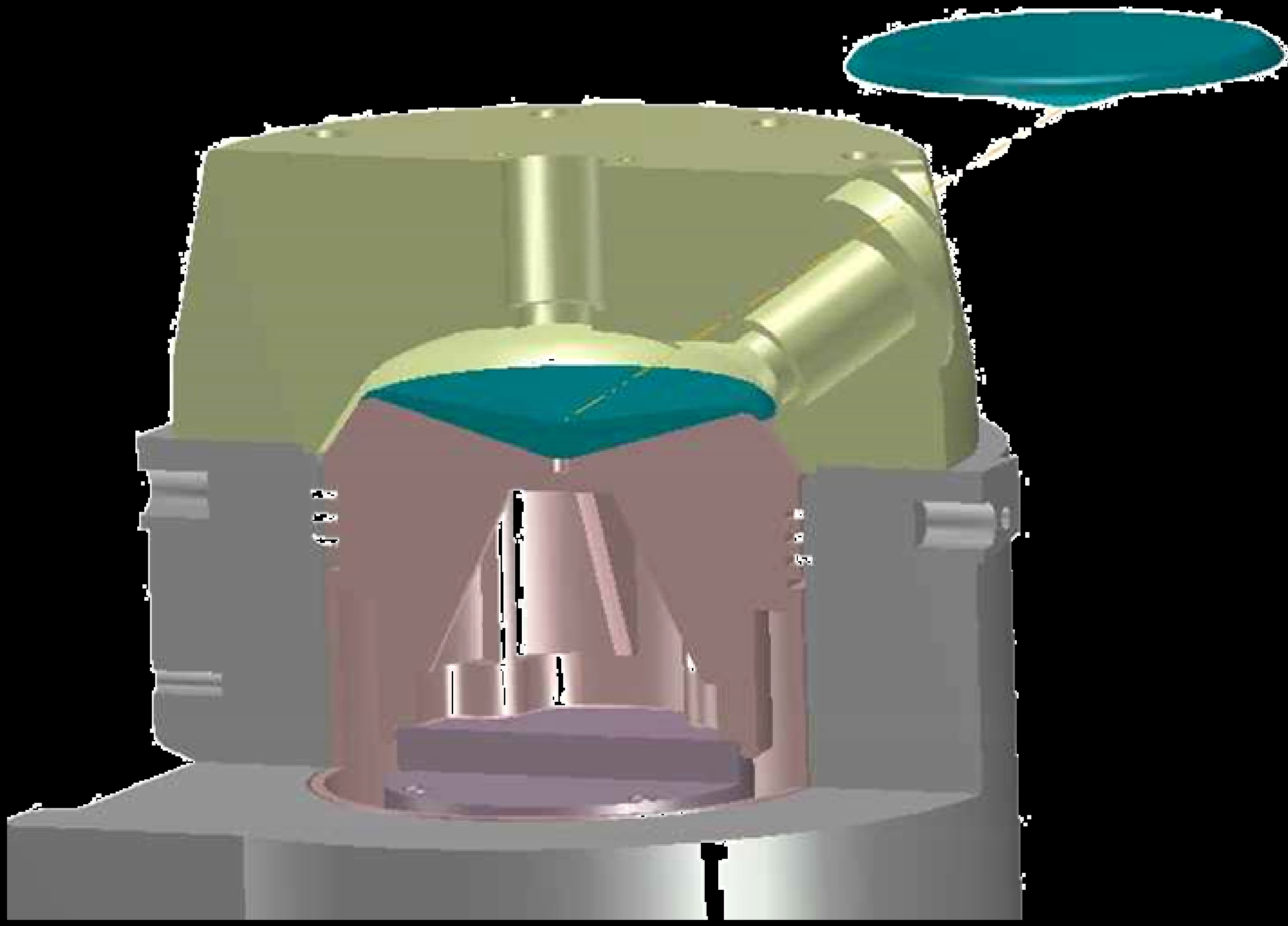
Fuel Quantity

- Nominal operation at 8 μL → ≈0.5%

$$8\frac{\mu\text{L}}{\text{inj}}\frac{300\text{ inj}}{\text{minute}}\frac{60\text{ min}}{\text{hr}}\frac{24\text{ hrs}}{\text{day}}\frac{\text{L}}{1\text{E}6\mu\text{L}}\frac{\text{gal}}{4\text{L}}\approx 1\frac{\text{gal}}{\text{day/cyl}}$$

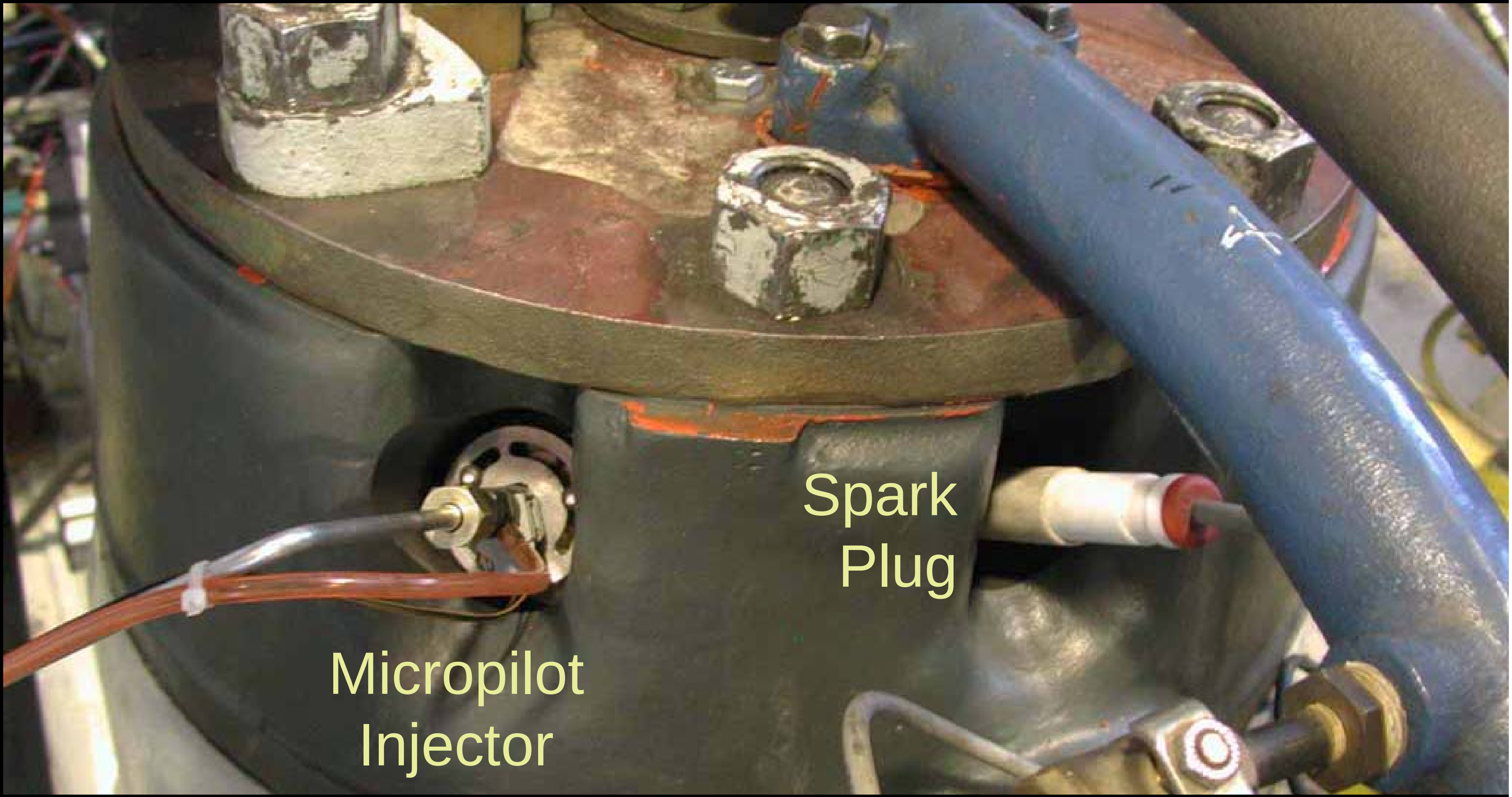
- Thus, on a 10 cylinder engine → 10 gal/day
- At 0.125% (2 μL) → 2.5 gal/day

Piston Modification Increased Compression Ratio Study

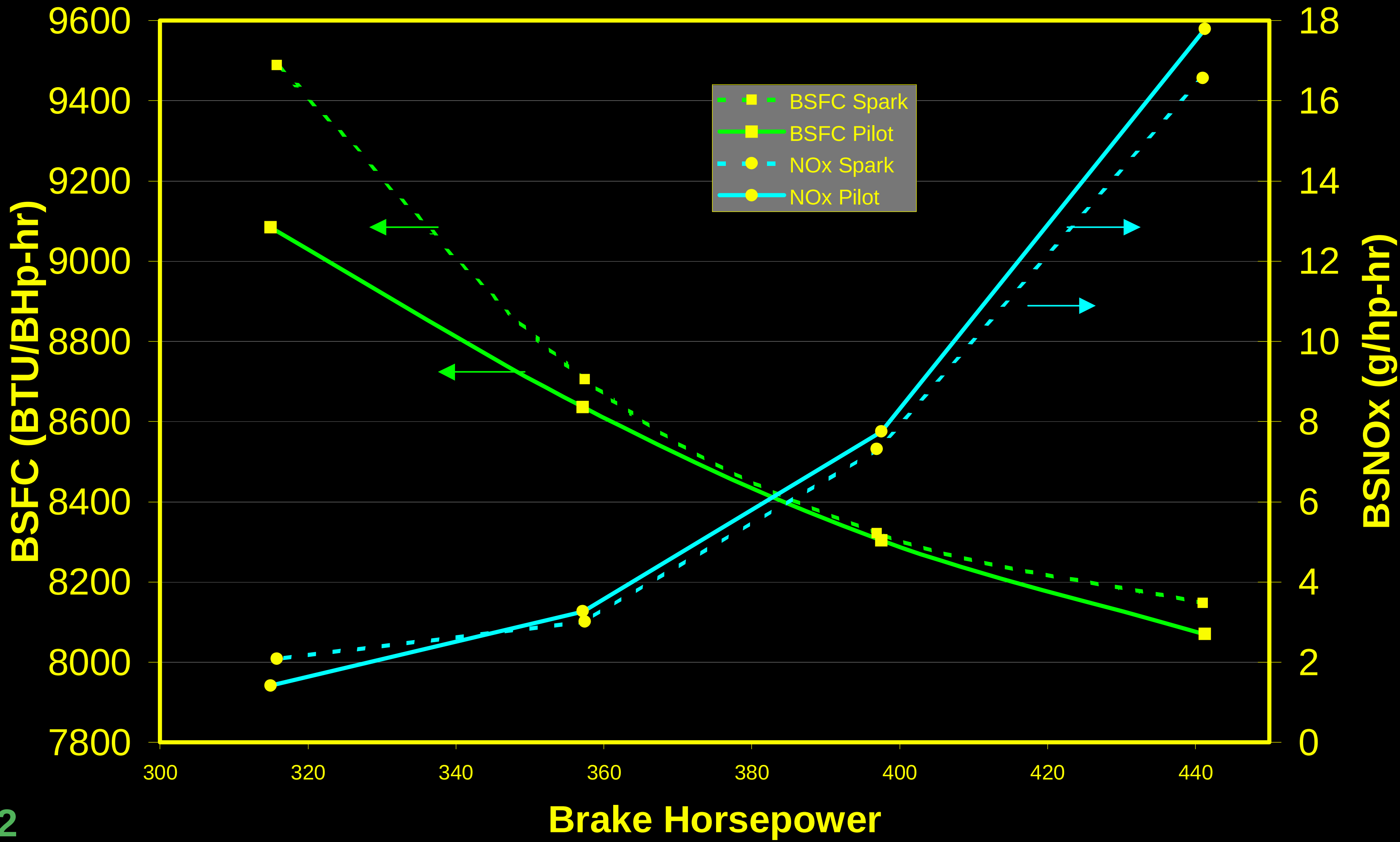


Micropilot Fuel Skid

Micropilot System on Engine

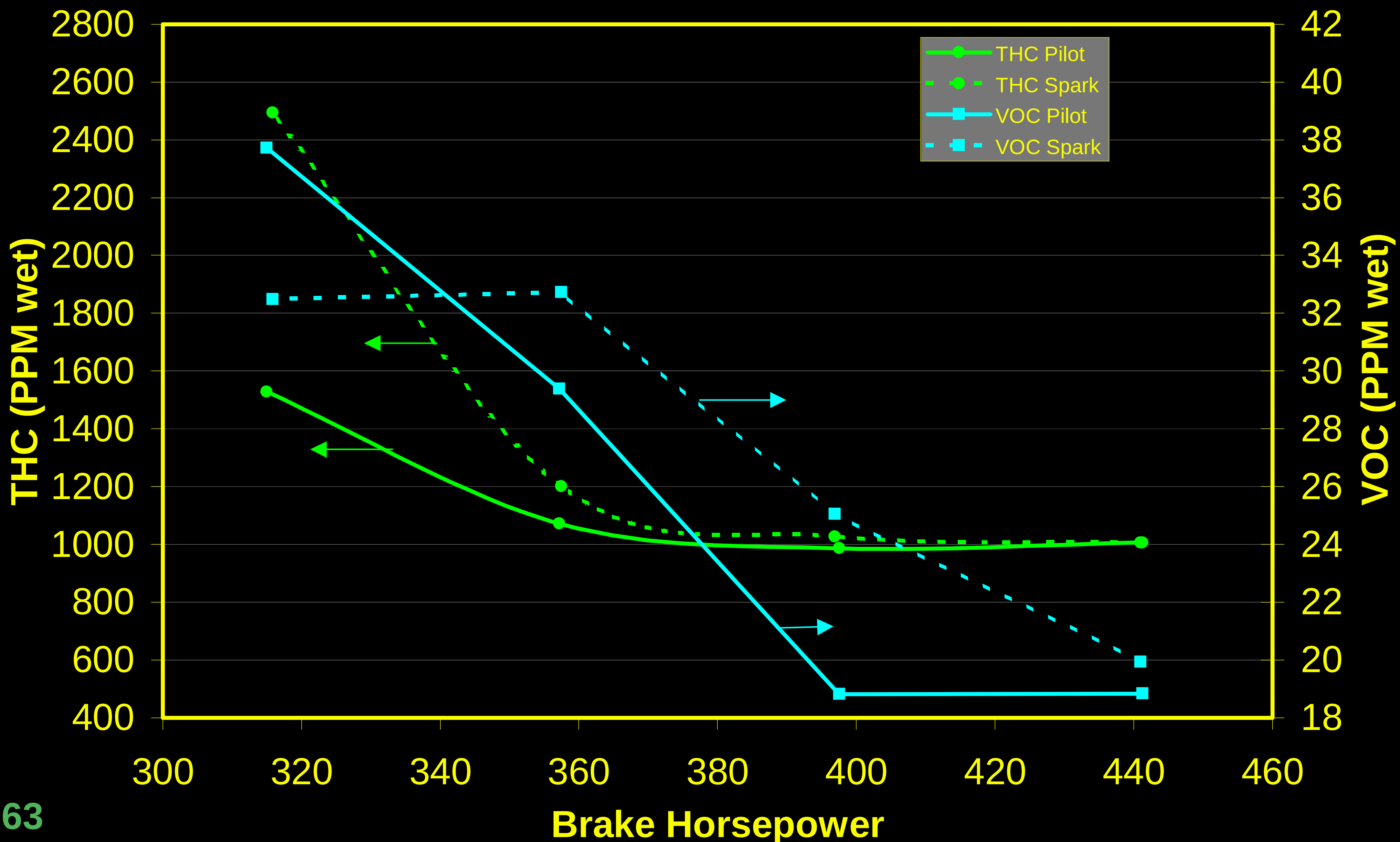


Micropilot Results: NOx & BSFC
8 μL, 5800 psi



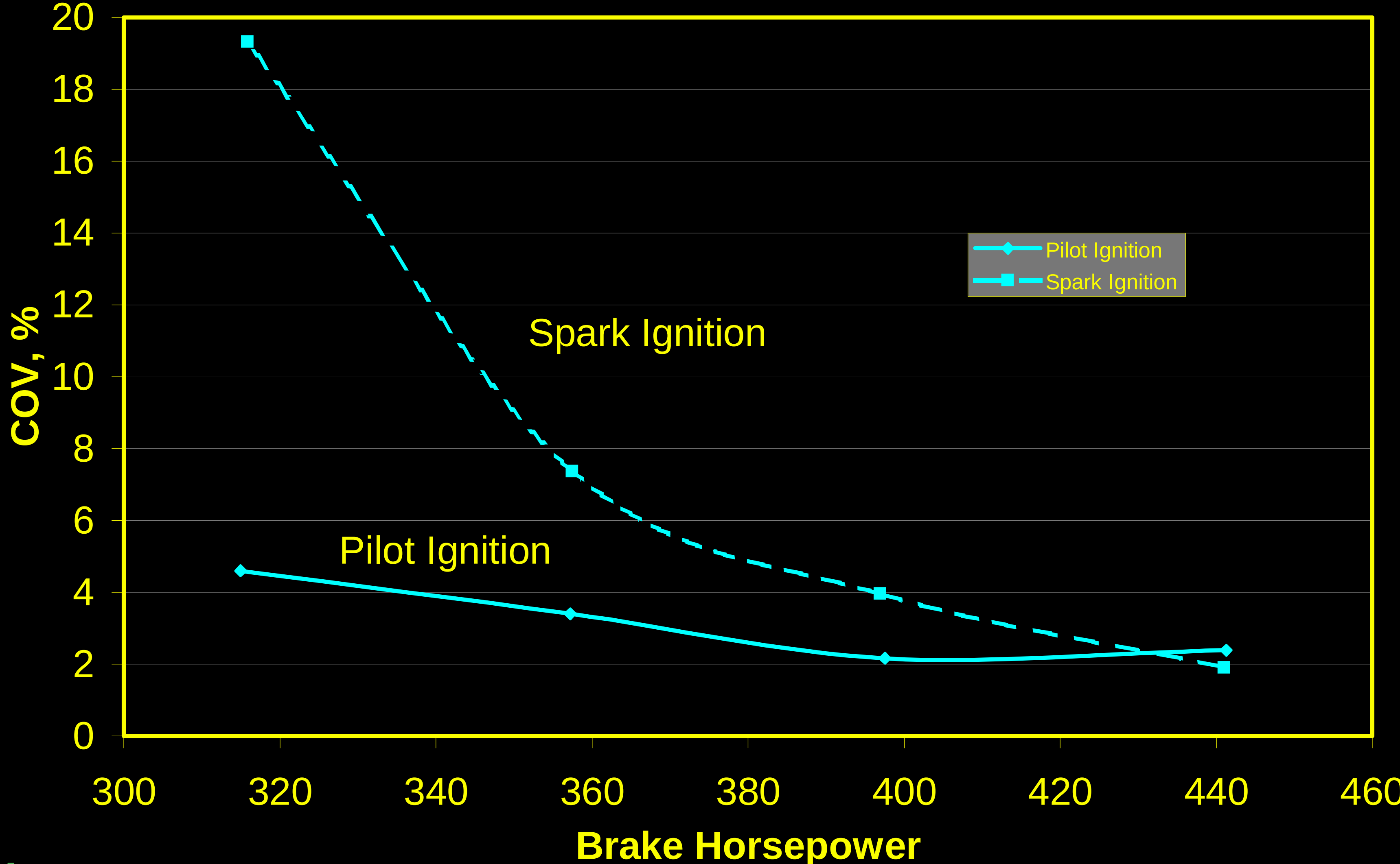
Micropilot Results: THC & VOC

8 μL, 5800 psi

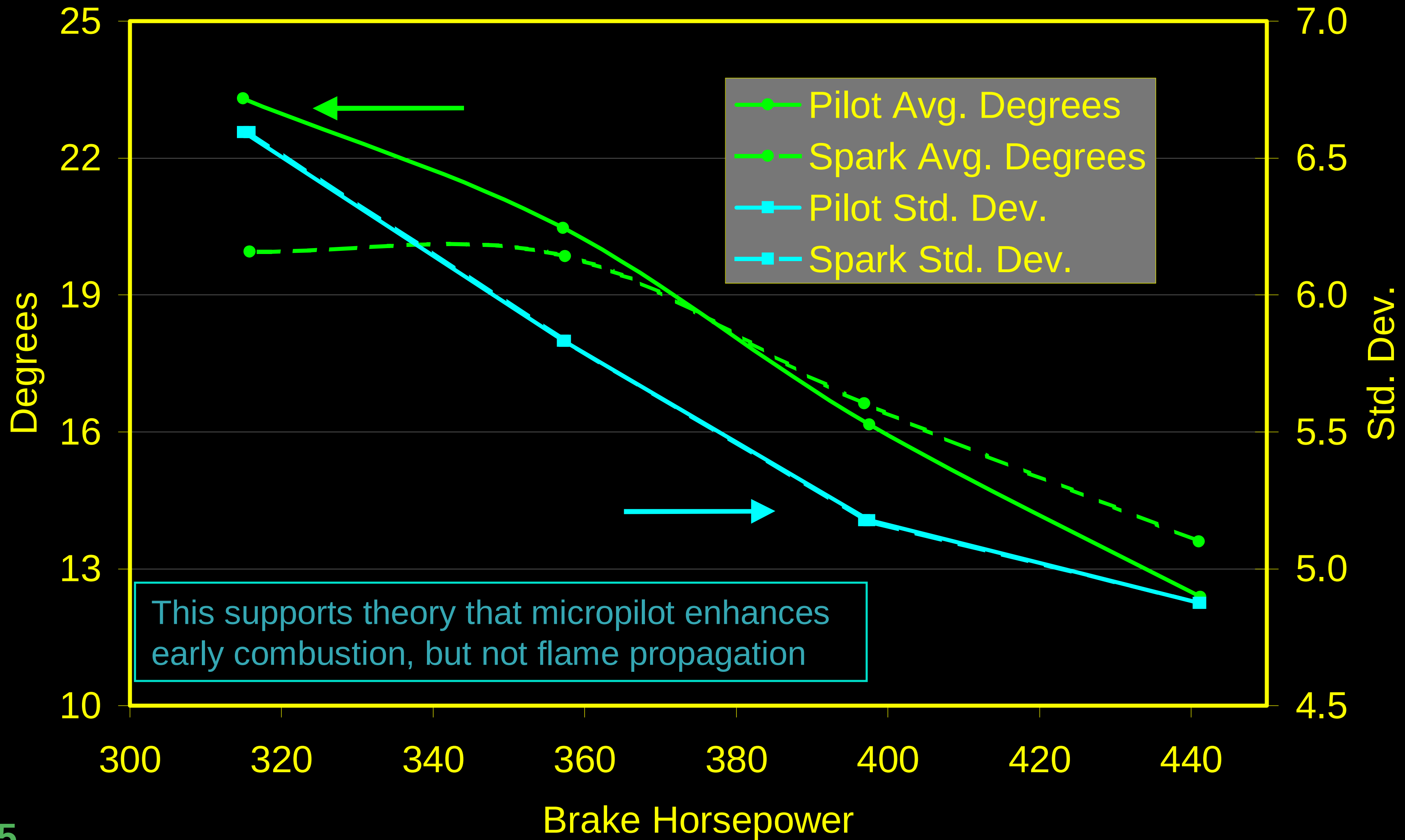


Micropilot Results: Comb. Stability

8 µL, 5800 psi



Micropilot Results: 5%-95% Burn
8 μL, 5800 psi



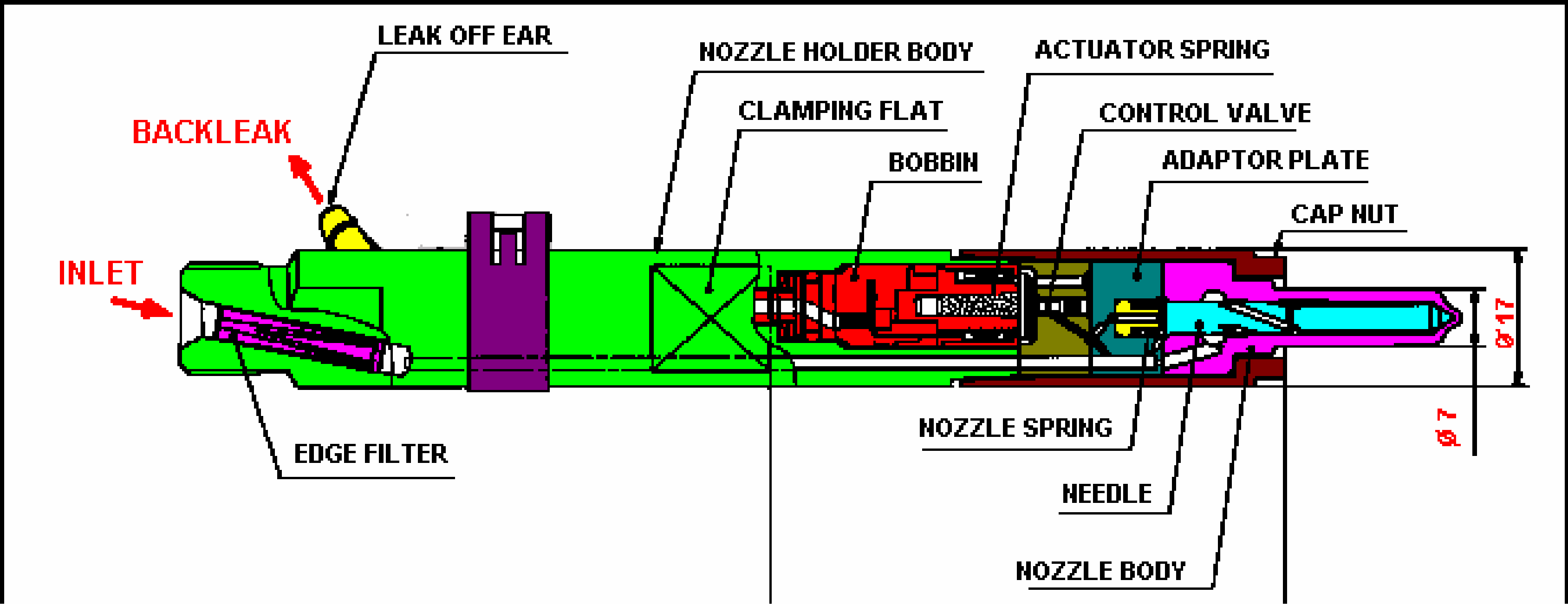
Temperature Effects

- The injectors performed well in the engine tests, but would not operate after cooling down. Heat-induced “varnishing” is suspected.
- Injectors were sent to Delphi for “post-mortem” analysis – awaiting results.
- Water-cooled adapters currently being fabricated to accommodate test schedule.
- High confidence that a non-cooled solution is possible.

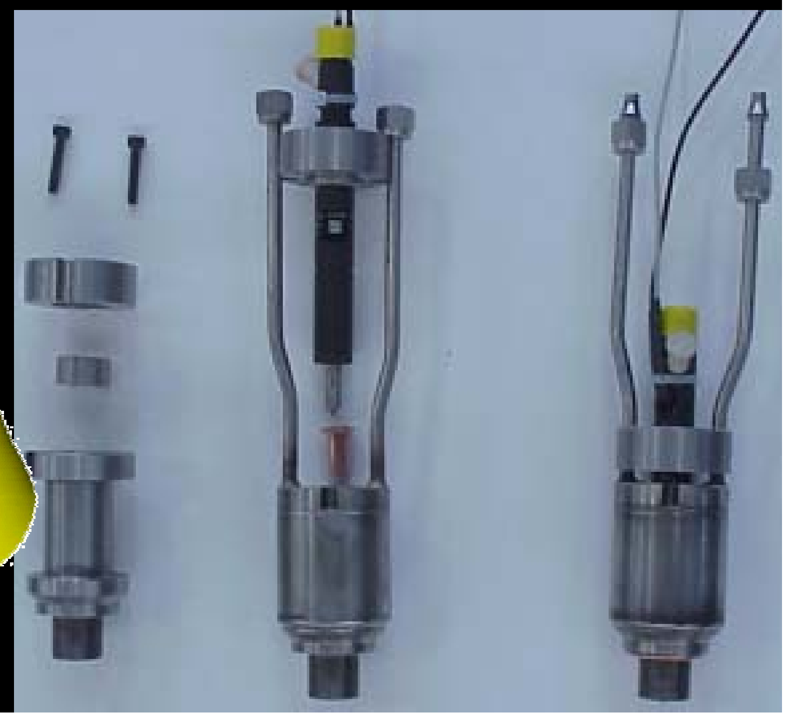
“Post-Mortem” Disassembly

The control valve was “glued” into its housing.

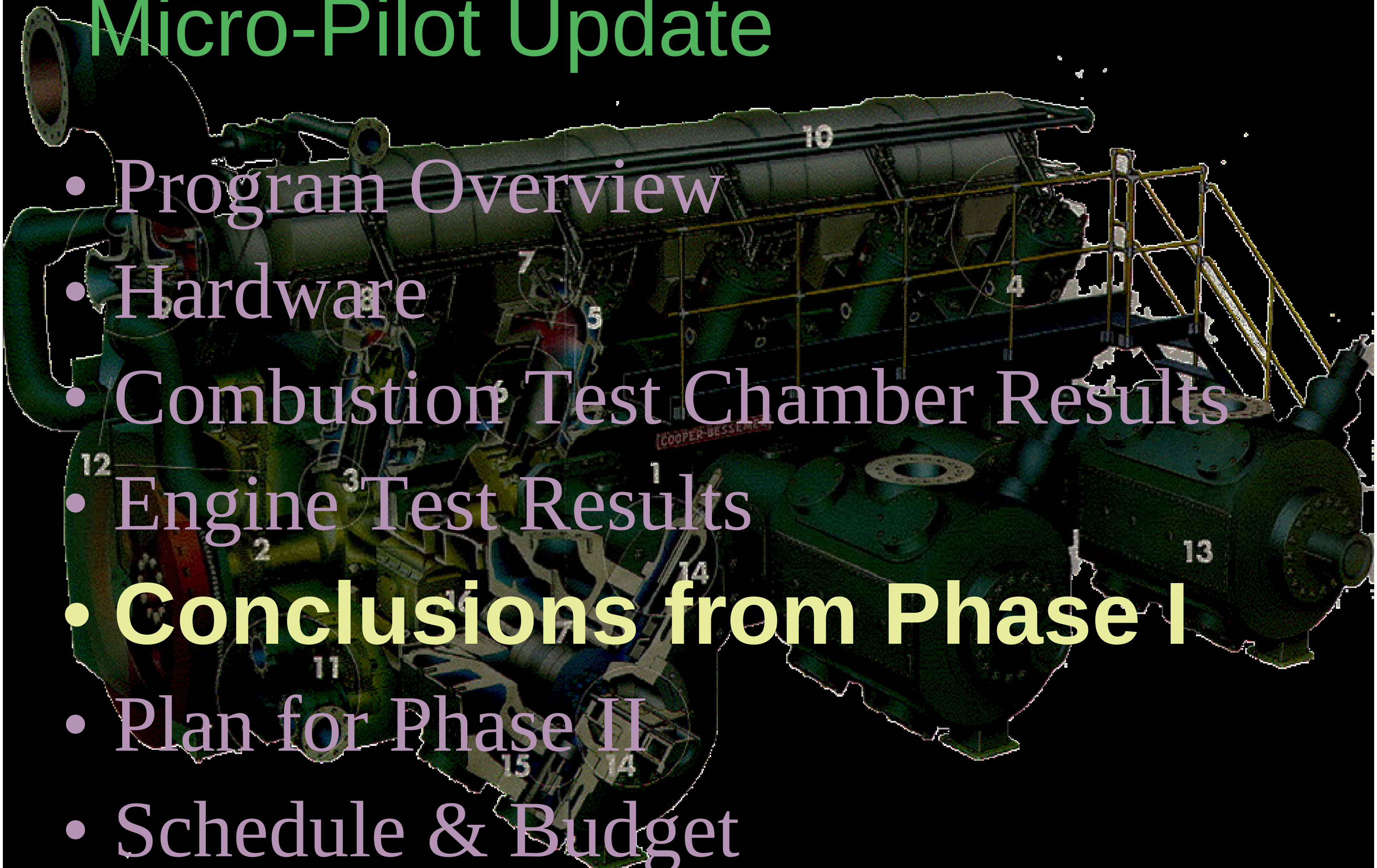
The needle was “glued” into the nozzle body.



Interim Solution: Cooled Injector Housing



Micro-Pilot Update



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Conclusions from Phase I

- Micropilot will work on low-compression ratio pipeline engines
- Injection quantities below 0.5% - believe 0.1% quantity achievable
- Significant industry interest from both pipeline and distributed generation industries
- Initial temperature concerns were confirmed – but experience with other “micro-pilot” engines suggests high confidence in a solution
- Look forward to optimization efforts in Phase II

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Approach for Phase II

- Optimization of 4-cylinder system on LBET
- Explore calibration for off-load operation
- Pursue uncooled heat transfer solution for injectors
- Address effects of compression ratio
- Examine use of engine oil as an alternative pilot fuel
- Work with stakeholders on preparation for field evaluation

Optimization Strategy

- 5 total variables: number of holes, hole area, pressure, quantity, timing
- 3 operational variable (pressure, quantity, timing), vs. only 1 (timing) for spark ignition
- Currently working w/ Operations Research faculty on Design of Experiments approach: will utilize 3-parameter gradient optimization

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Budget Considerations

- 100% of Phase I funds expended
- Phase I report submitted
- 0% of Phase II funds expended
- Execution of Phase II underway

Contact Information

Dr. Bryan Willson
Research Director
Engines & Energy Conversion Laboratory
Colorado State University
Fort Collins, CO 80523

Phone:	**(970)-491-4783**
Mobile:	**(970)-227-5164**
FAX:	**(970)-491-4799**
E-mail:	**Bryan.Willson@colostate.edu**

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