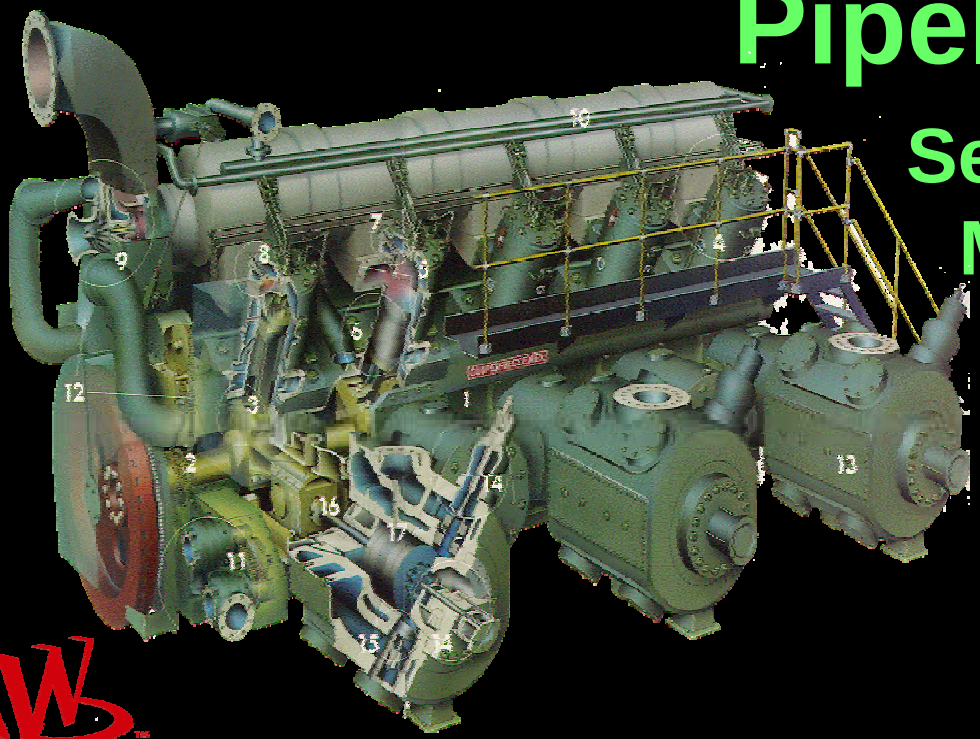
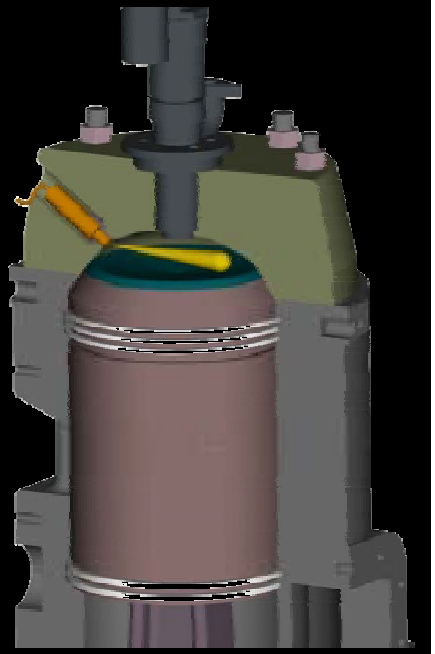
Retro-Fit Micropilot Ignition for Pipeline Engines

September 16, 2002
Morgantown, W.V.





WOODWARD

PRCI

Technology for Energy Pipelines

DEPARTMENT OF ENERGY · UNITED STATES OF AMERICA ·

Colorado State University

Knowledge to Go Places

Micro-Pilot Update

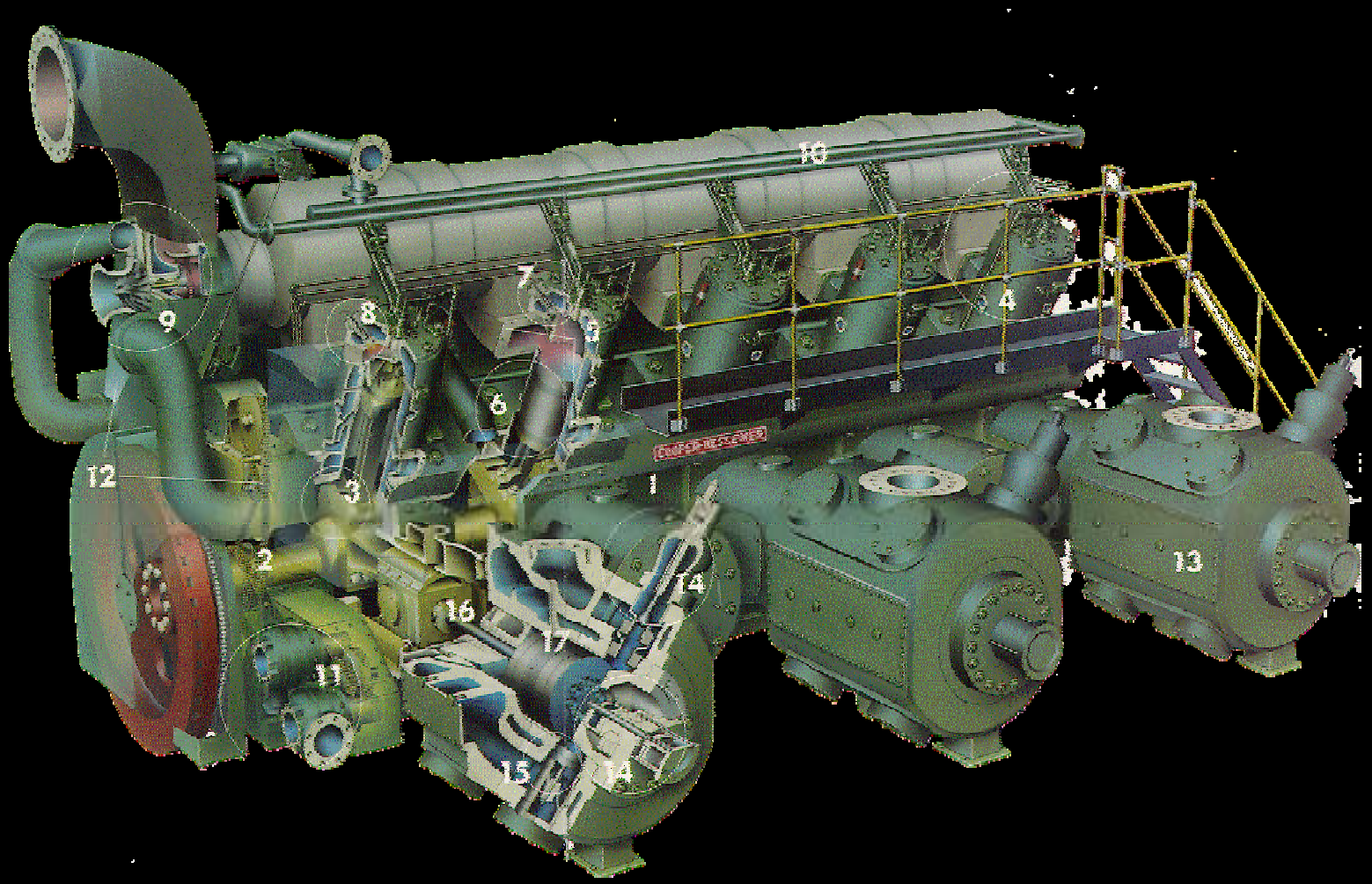
- **Program Objective**
- Background
- Numerical Modeling
- Combustion Test Chamber - Results
- Preparations for Engine Test
- Project Status

Typical Field Engines Used for Gas Compression

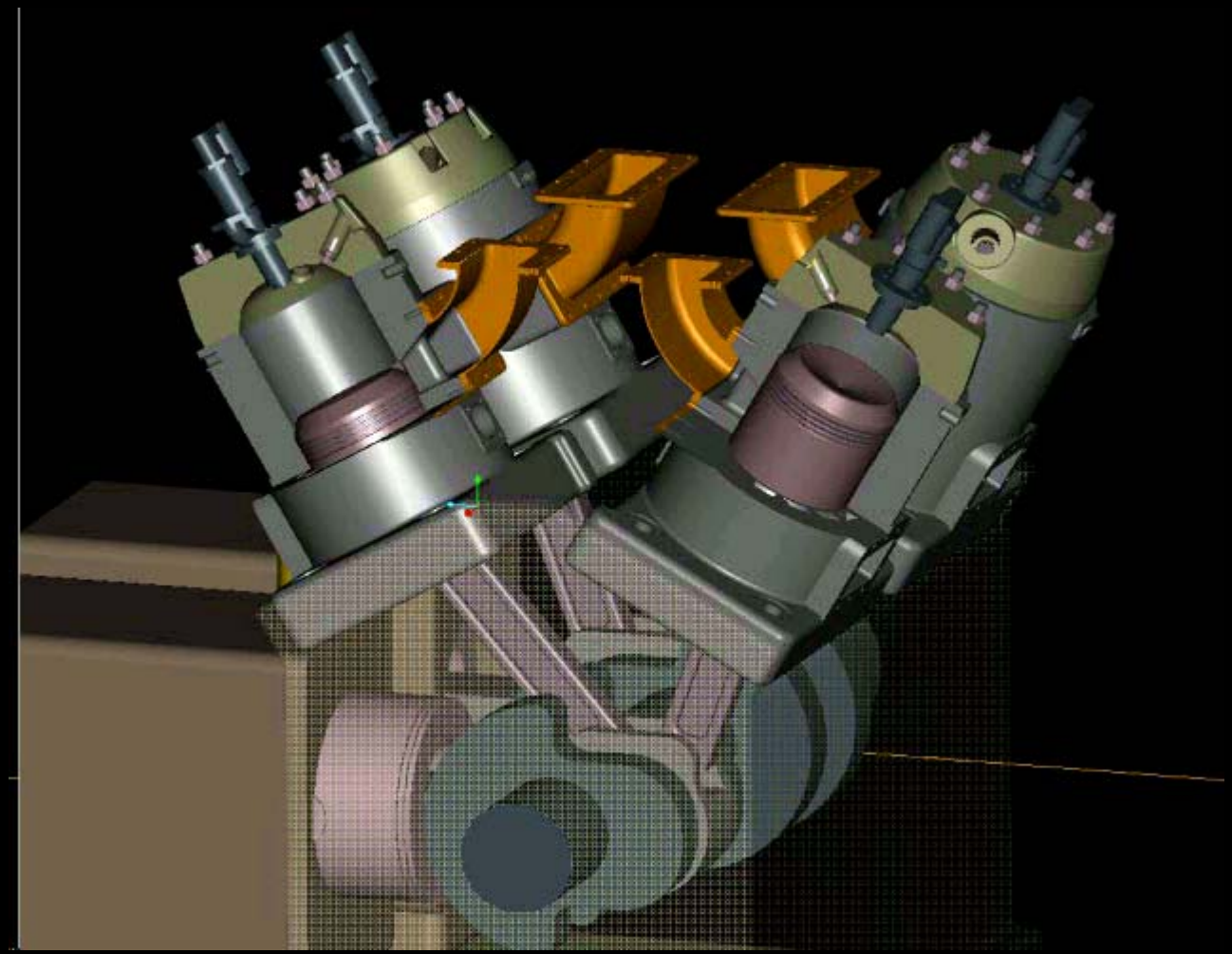
8 Cylinder
Cooper V-275

12 Cylinder Cooper GMV

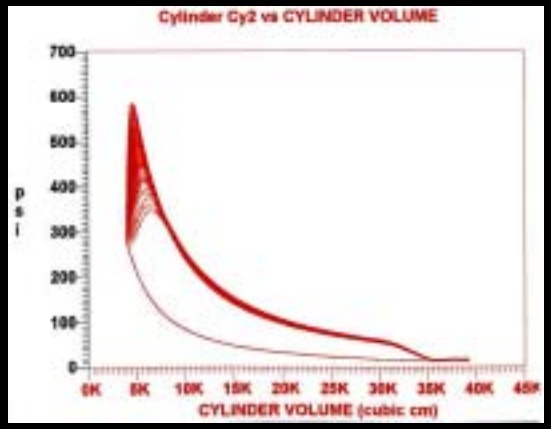
Typical 2-Stroke Gas Engine: Cooper-Bessemer GMVH



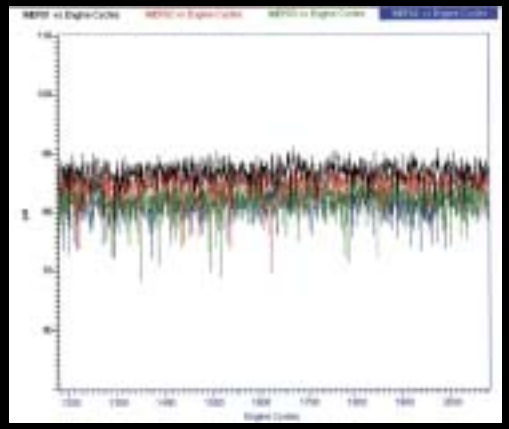
Typical 2-Stroke Gas Engine: Cooper-Bessemer GMV



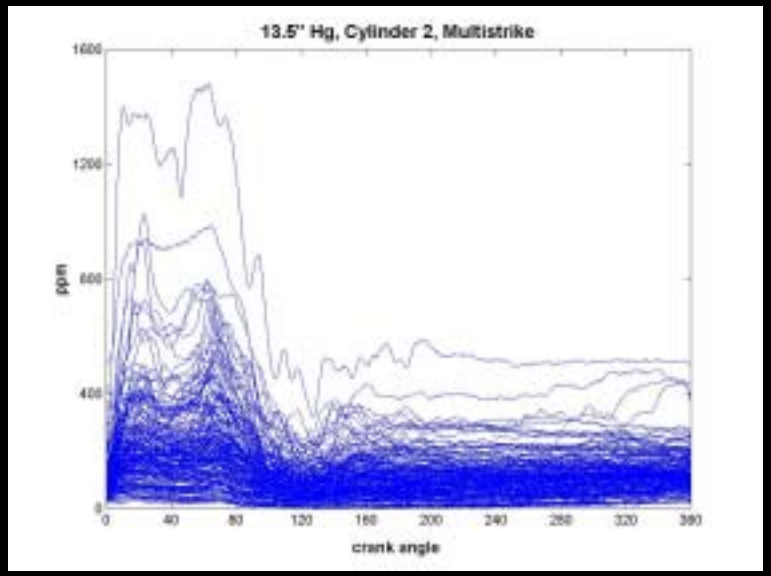
Motivation: Increased Reliability & Stability

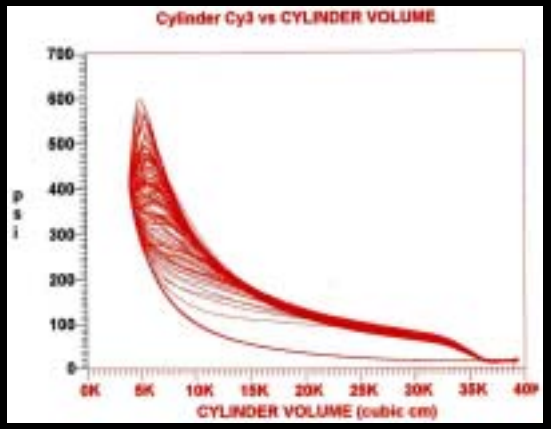


PV Diagrams
Stable Combustion

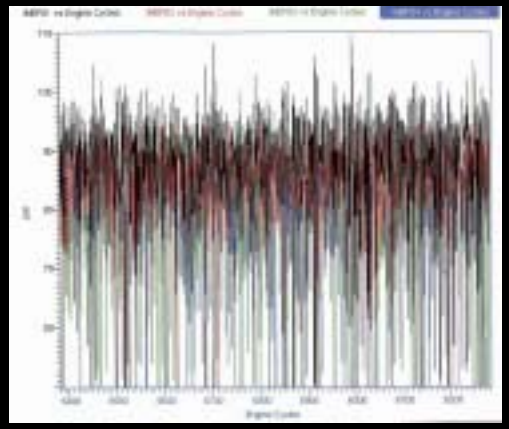


IMEP
Stable Combustion

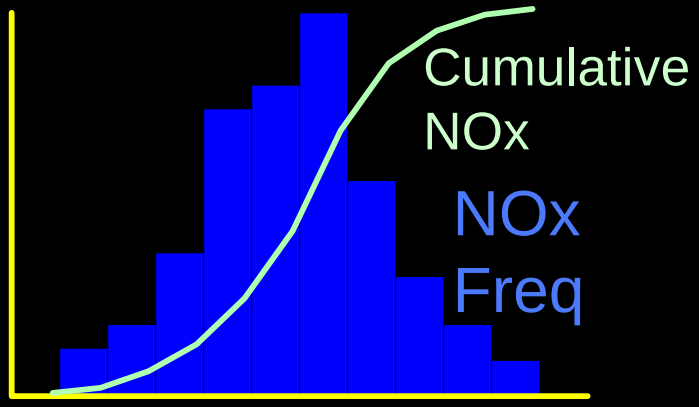




PV Diagrams
Near Lean Limit



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

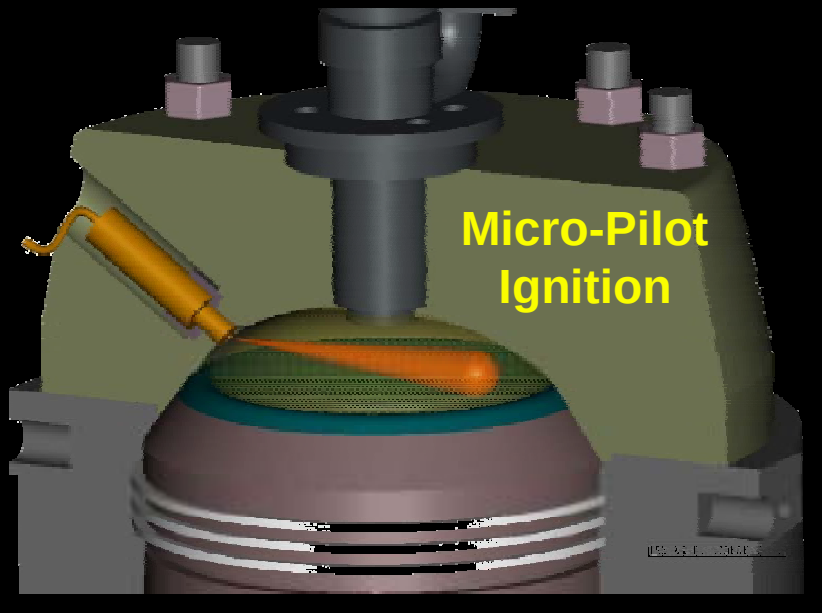
Typically, 1 µL-10 µL (1 mm^3 -10 $mm^{3)}$

Pilot fuel(s):

Diesel fuel

Lube oil

On-board fuel, i.e. dimethyl ether



DOE Micropilot Program

Program Objective: Increase the reliability of the U.S. natural gas pipeline infrastructure

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

Prime Contractor: CSU Engines & Energy Conversion Laboratory

Project Funding: DOE, Gas Technology Institute, Pipeline Research Council International, Woodward Governor

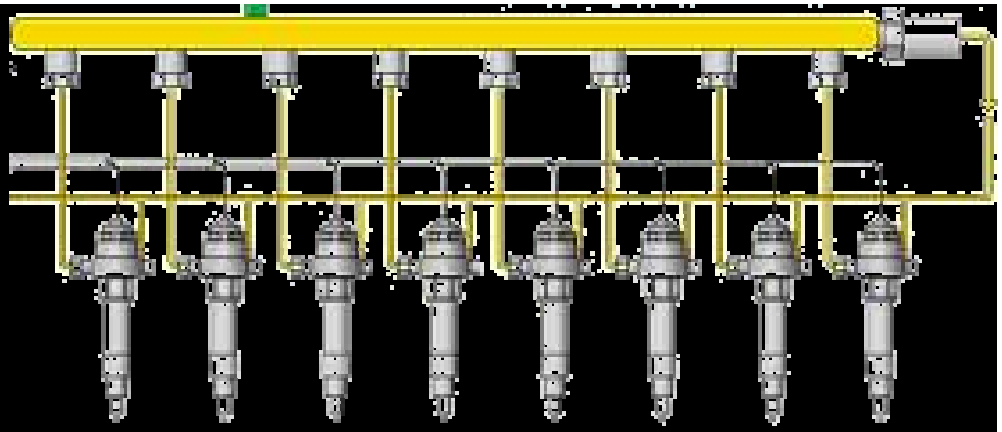
"By 2020 Americans will be consuming 50 percent more natural gas than today."

-Energy Secretary Abraham

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

Micro-Pilot Ignition Research



Challenges

- Sparsely studied spray regime
- Poor understanding of early ignition physics
- Low fuel quantities
  - Penetration
  - Tip cooling
- Need for precise delivery of small fuel quantities
  - High pressure
  - Short duration injection

Enabling Technology

- Automotive common rail technology provides potential technical solution
- High speed capabilities developed for split injection
- Project will evaluate application on large natural gas engines

Micro-Pilot Update

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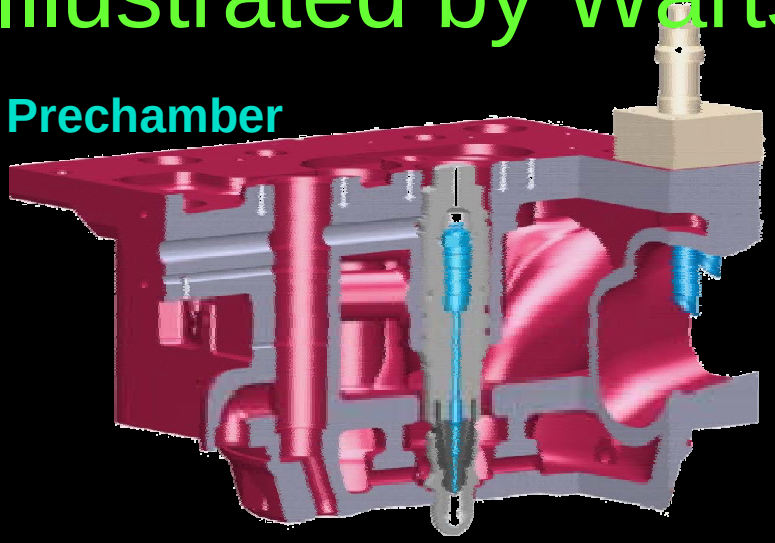
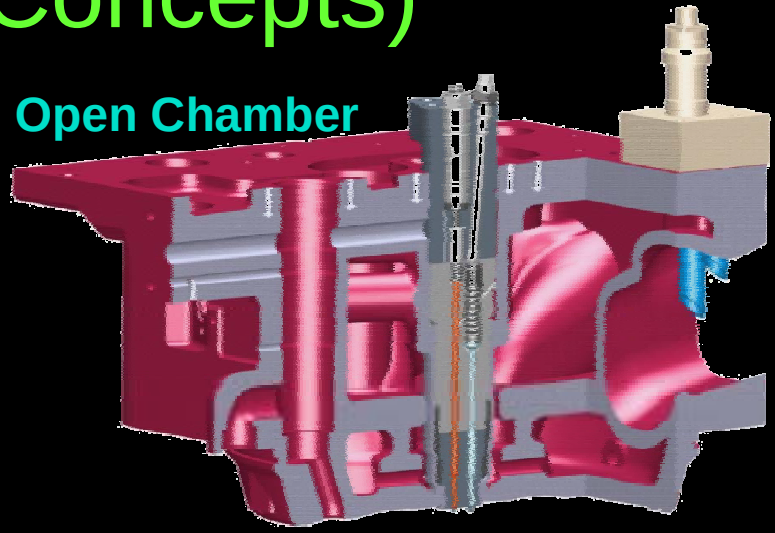
Alternative Approaches
(Illustrated by Wärtsilä Concepts)

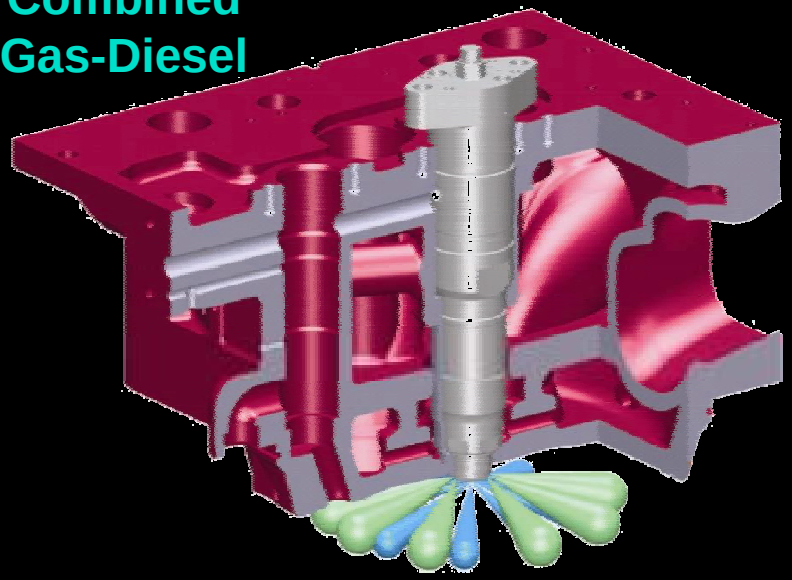
Prechamber



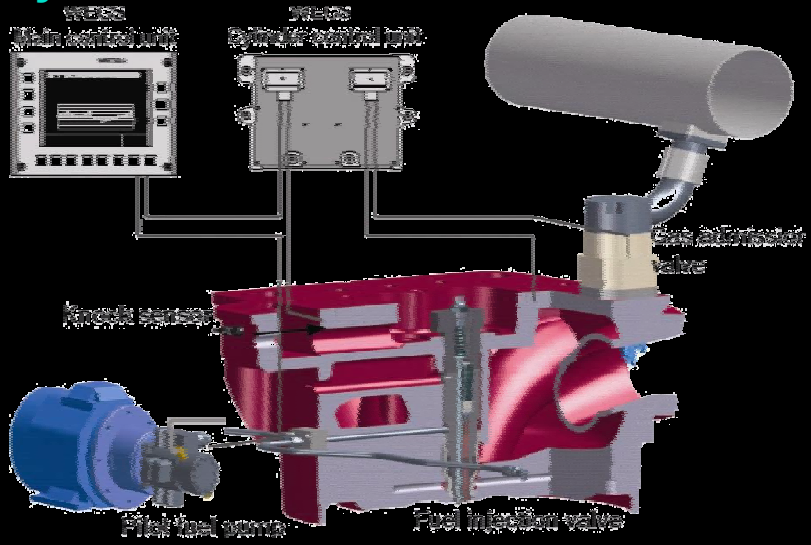
Open Chamber



Combined Gas-Diesel

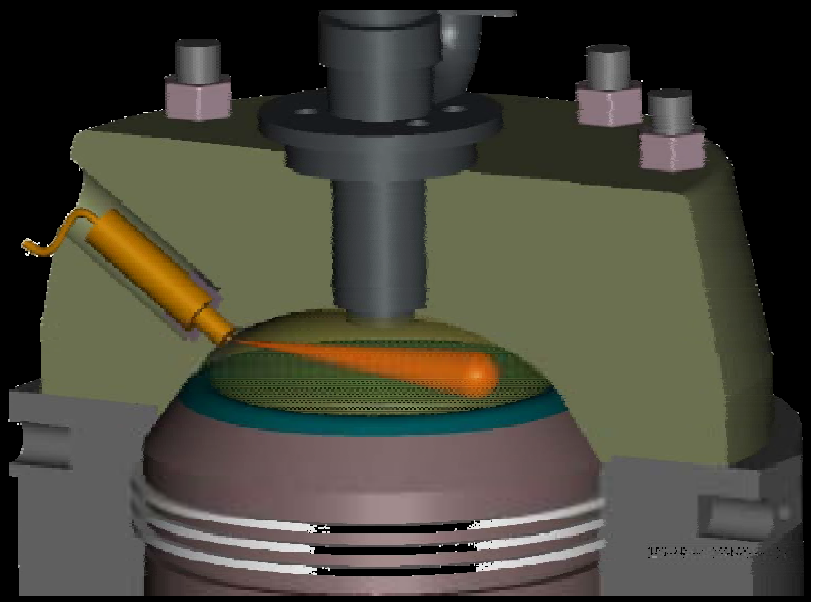


System

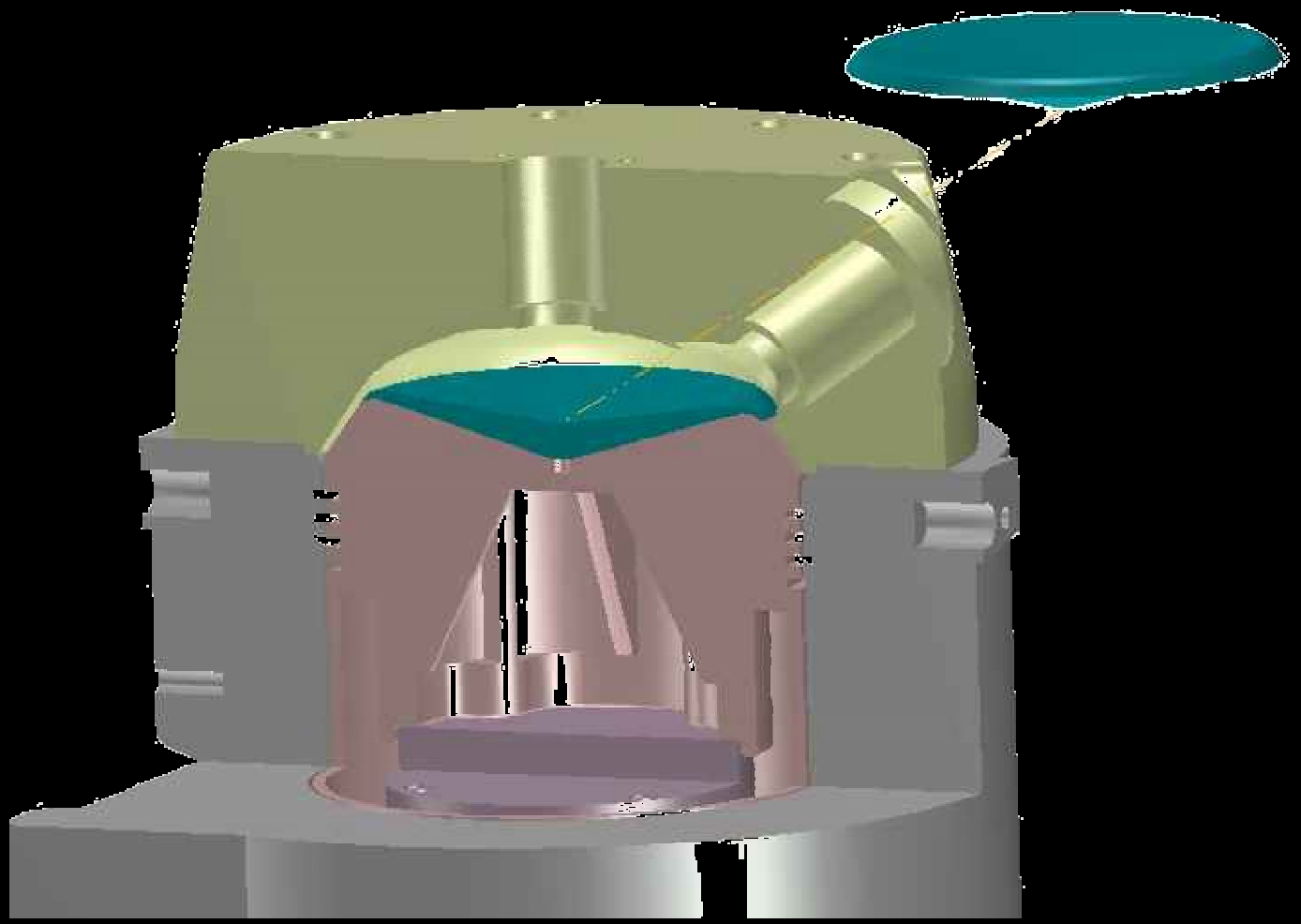


CSU Micro-Pilot Approach

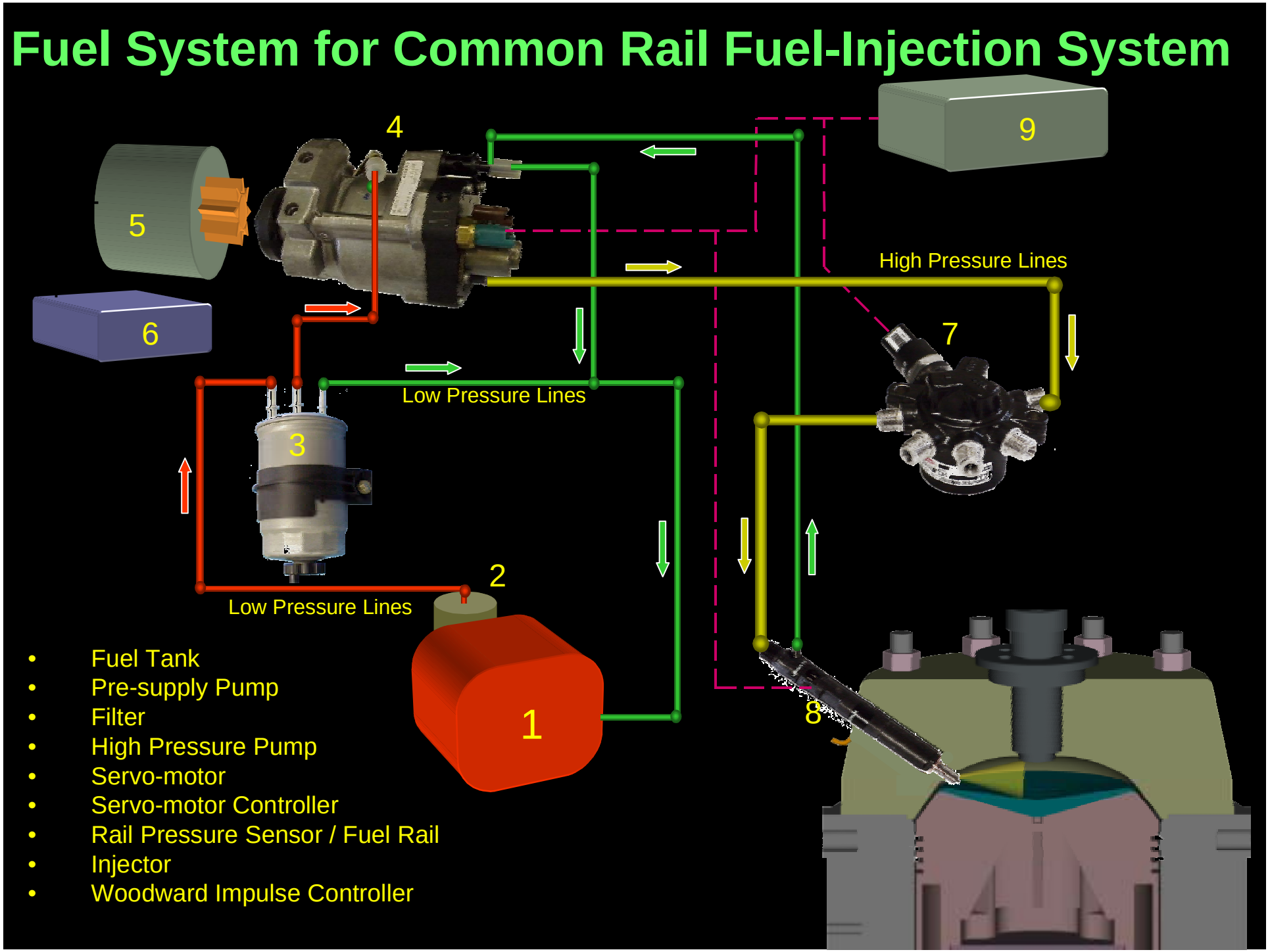
- Open chamber
- Common rail
- Injector mounting through spark plug
- Spark ignition for cold start
- Diesel pilot in Phase 1 – other fuels considered in Phase 2
- Standard compression ratio in Phase 1 – increased CR considered in Phase 2



Piston Mod. for Phase II Compression Ratio Study



Fuel System for Common Rail Fuel-Injection System



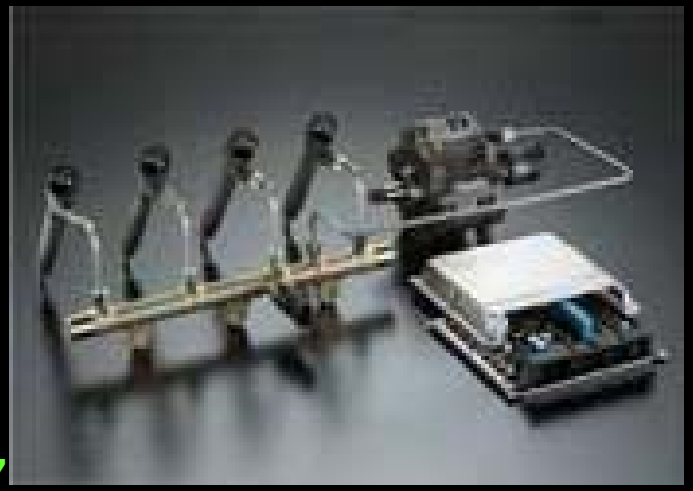
- Fuel Tank
- Pre-supply Pump
- Filter
- High Pressure Pump
- Servo-motor
- Servo-motor Controller
- Rail Pressure Sensor / Fuel Rail
- Injector
- Woodward Impulse Controller

System Specifications

- Modeling used to establish preliminary injection parameters
- Injection parameters incorporated into a system specification
- Specification sent to all suppliers of common rail systems

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

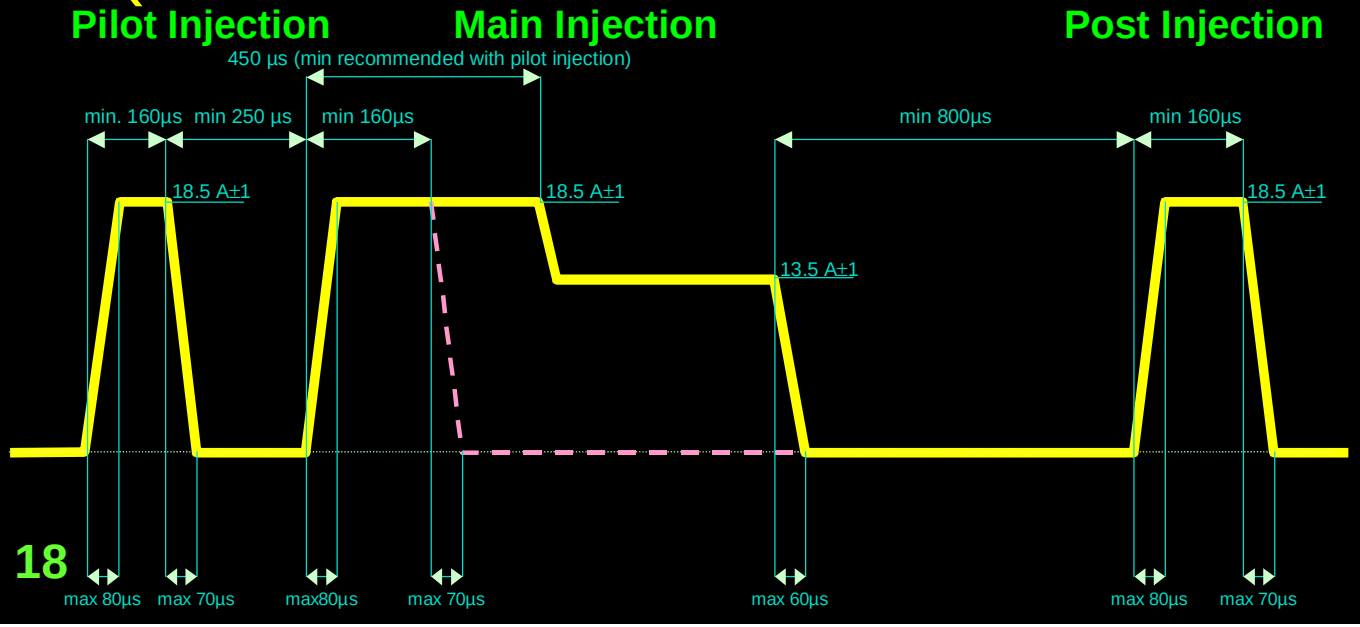


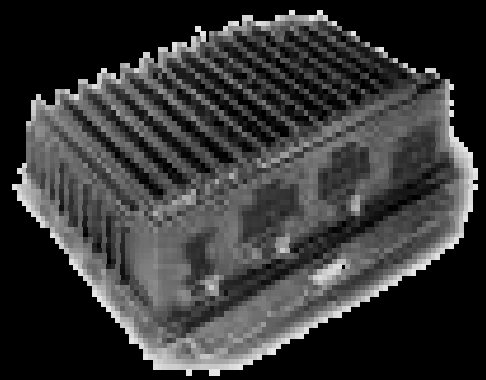
Bosch

Delphi

Electronic Driver

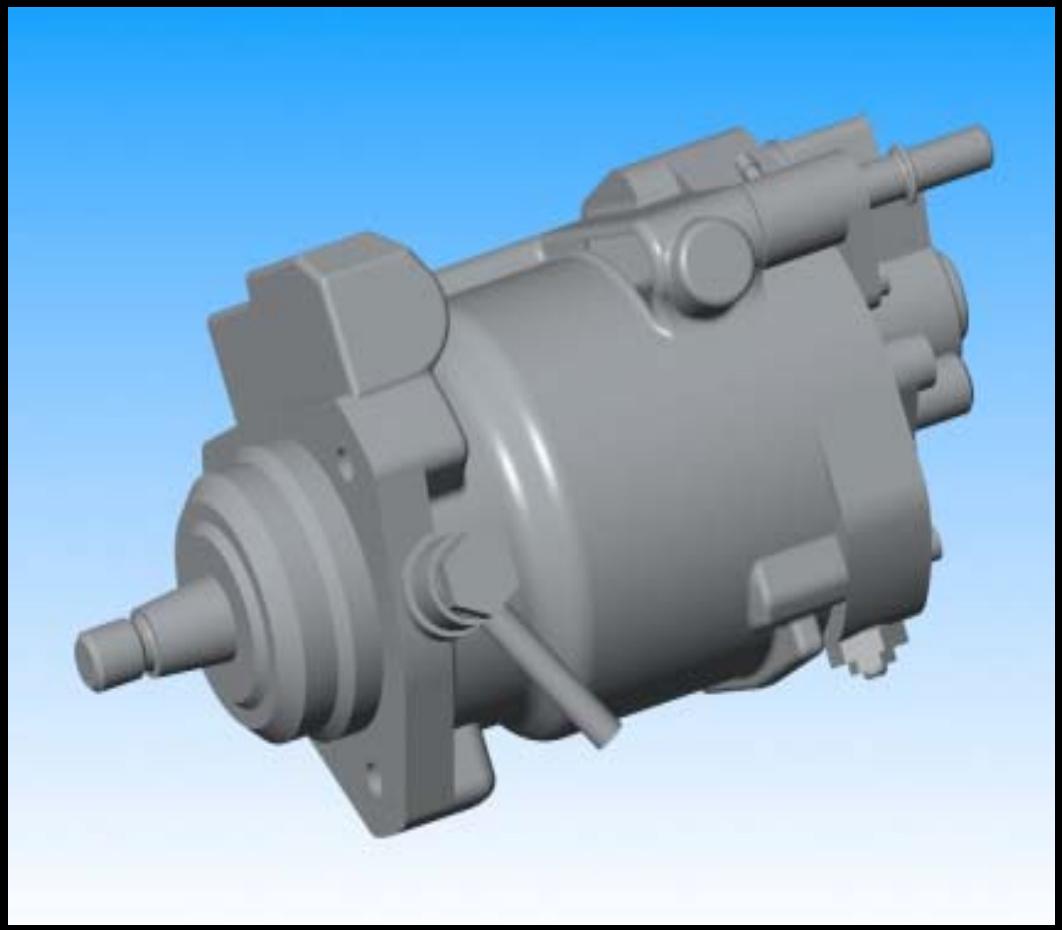
- Delphi controller specialized for automotive applications – difficulties with prototype applications
- Woodward will support with In-Pulse driver (same controller used on AutoBalance / HPFI)



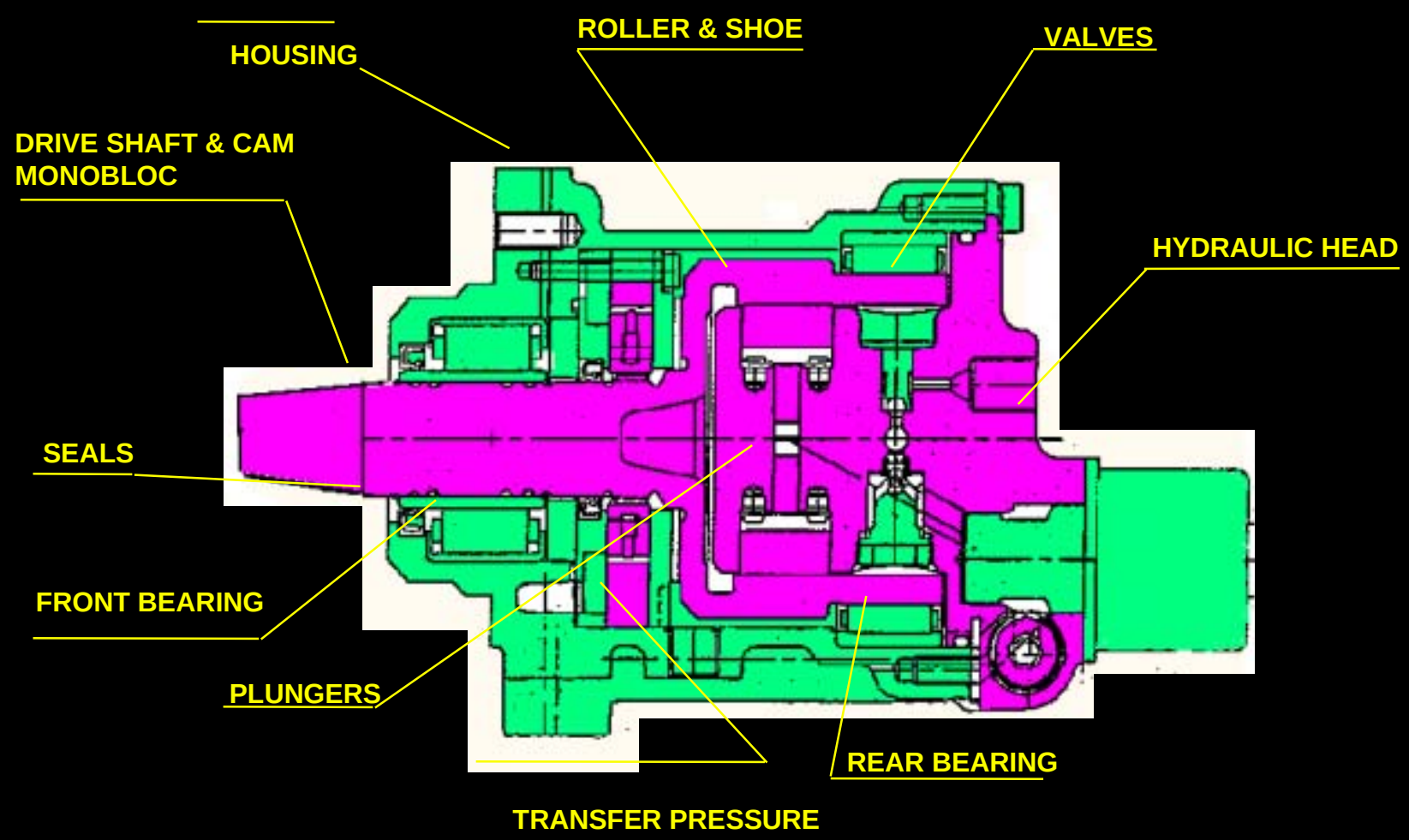


System Components

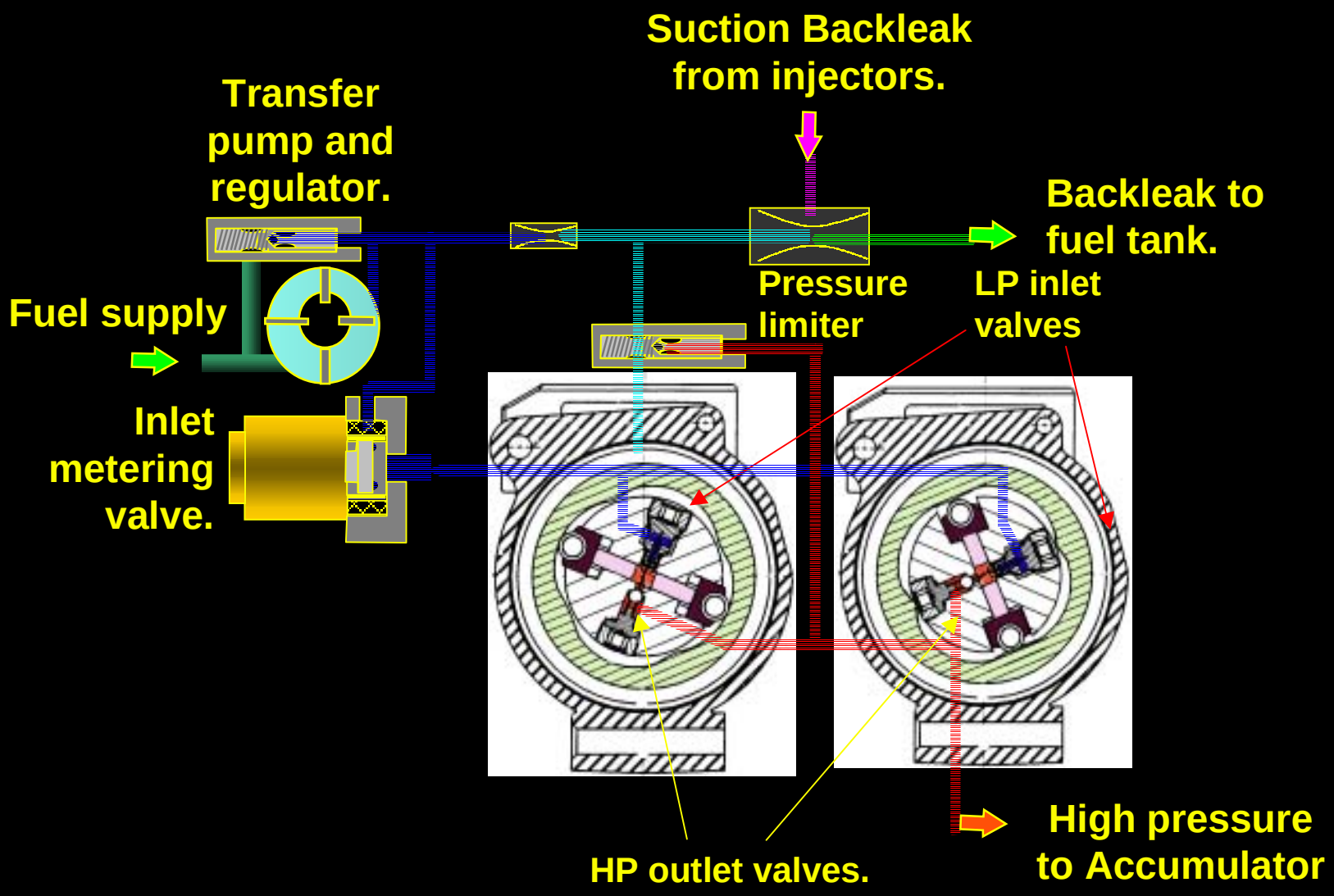
- **High Pressure Pump**
- Fuel Injector
- Injector Driver



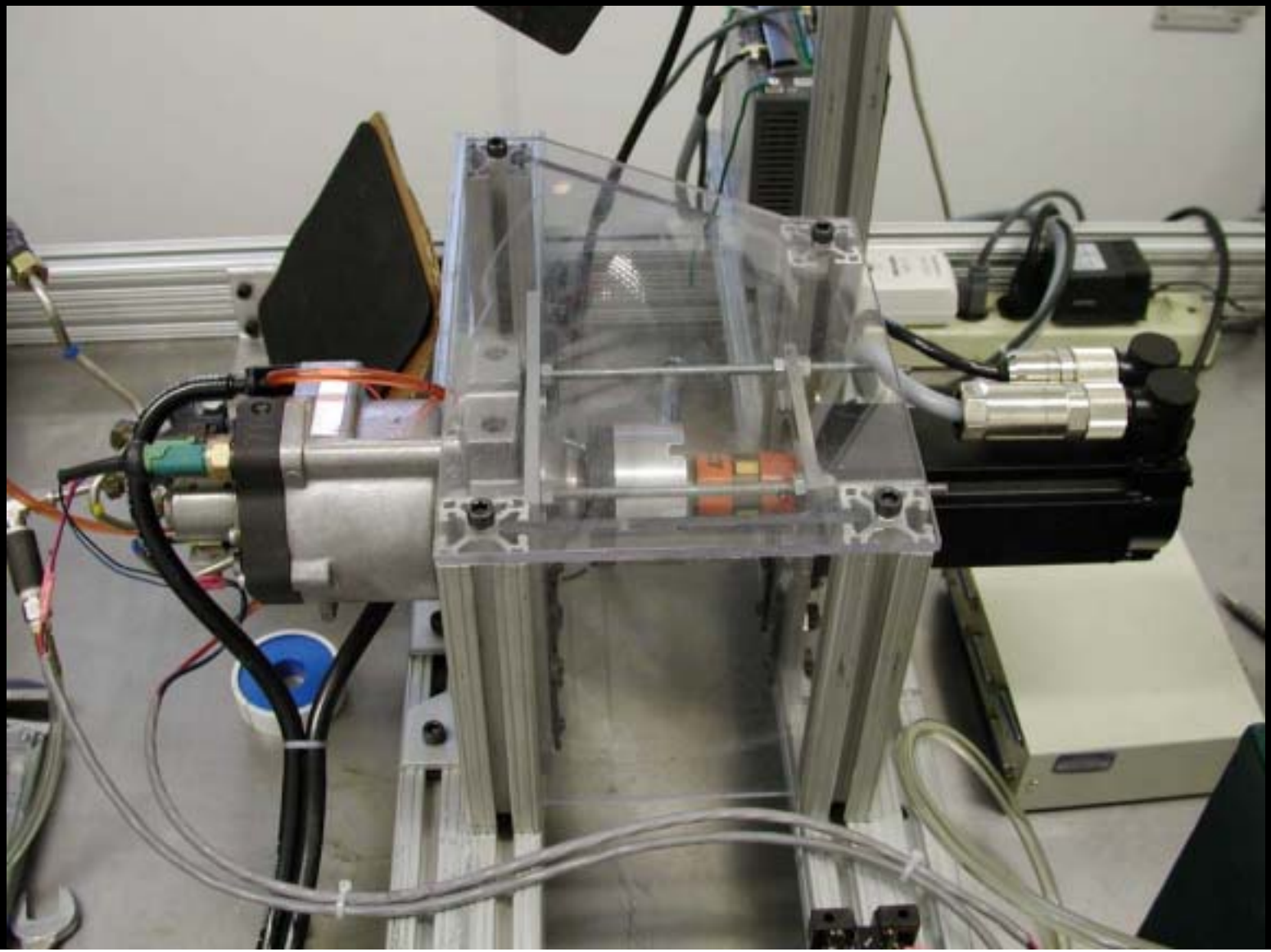
Pump Design


HOUSING
ROLLER & SHOE
VALVES
DRIVE SHAFT & CAM
MONOBLOC
HYDRAULIC HEAD
SEALS
FRONT BEARING
PLUNGERS
REAR BEARING
TRANSFER PRESSURE

Pump Function



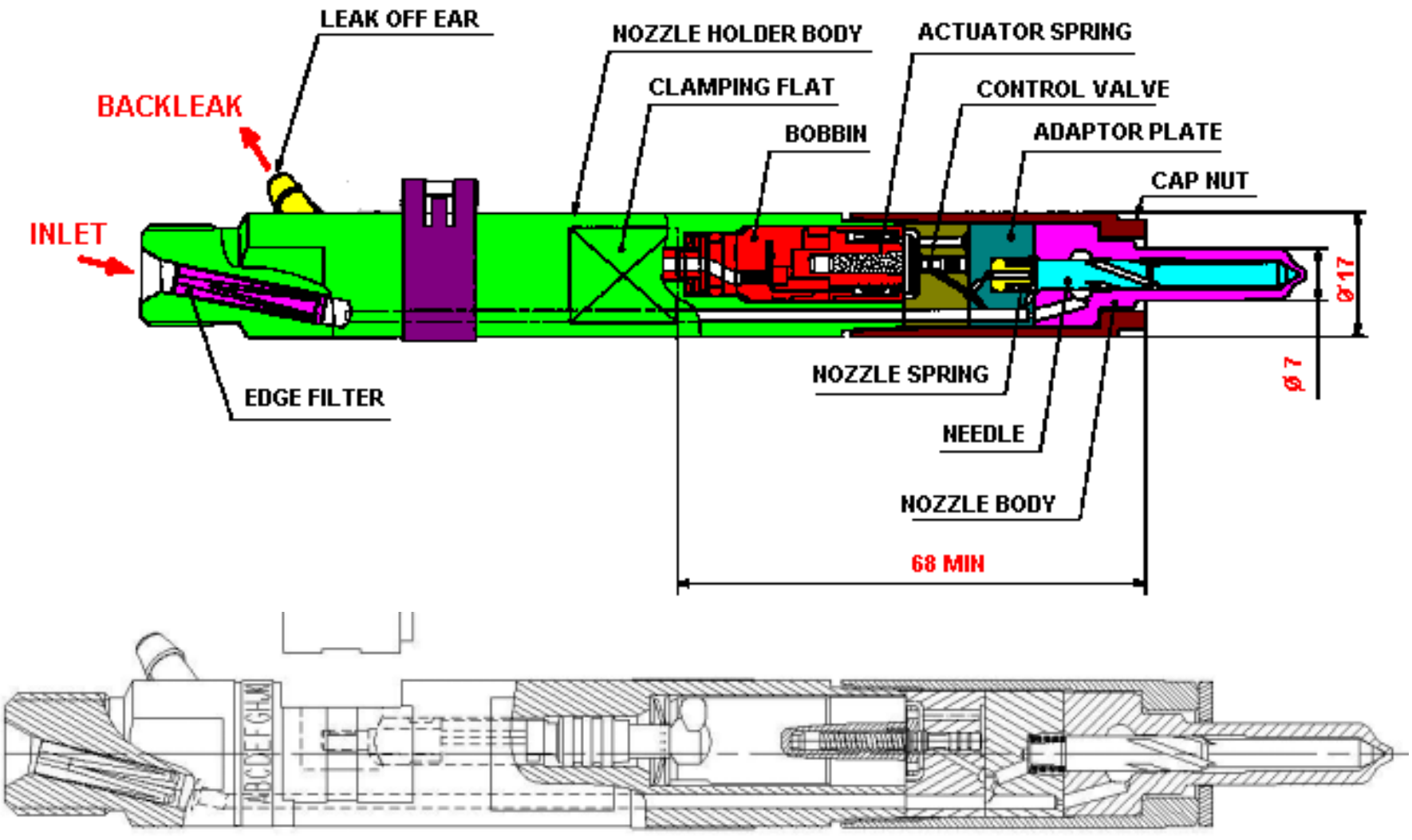
Servo-Motor Pump Drive



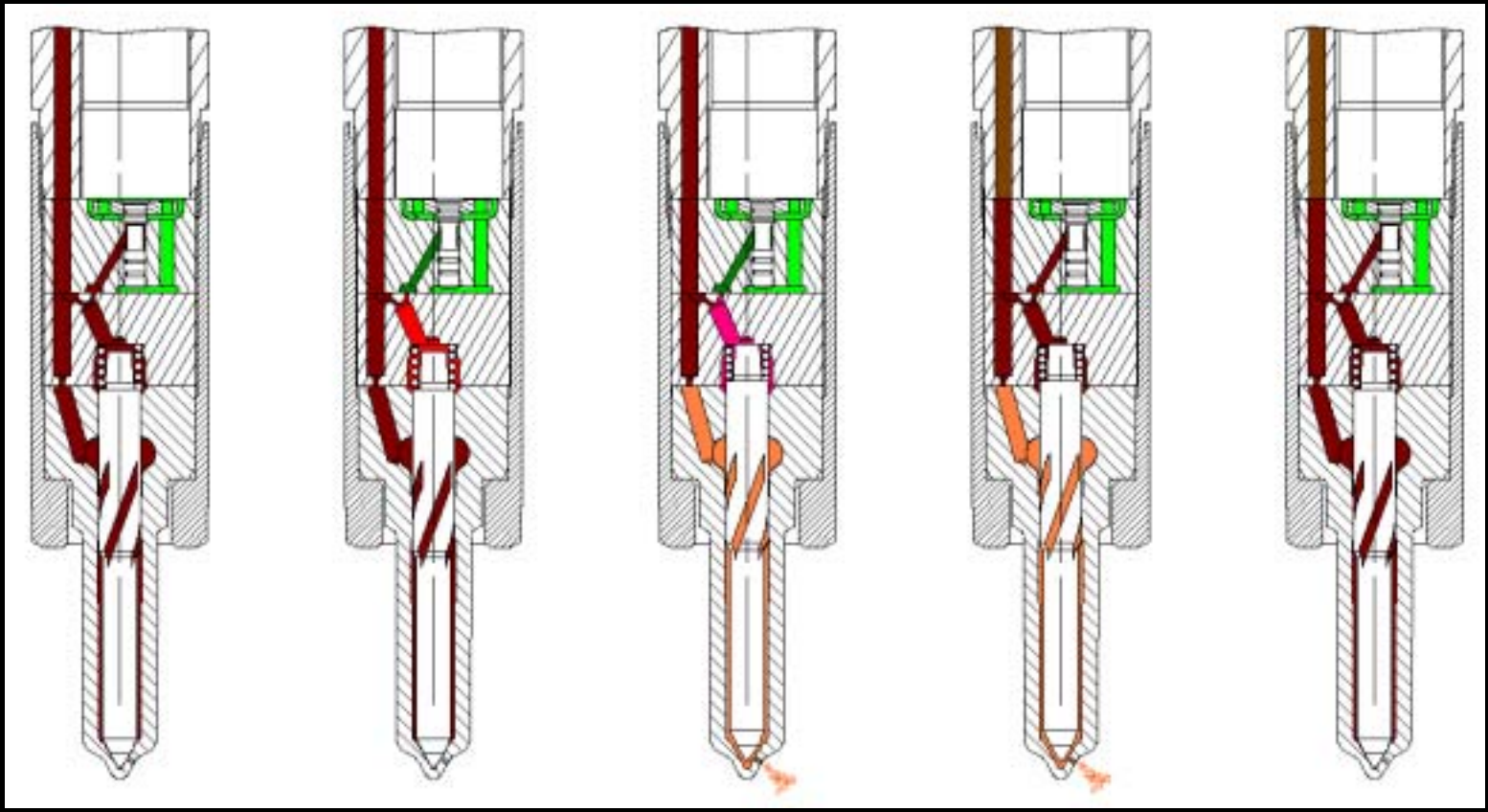
System Components

- High Pressure Pump
- **Fuel Injector**
- Injector Driver

Internal Injector Components



Injector Operation

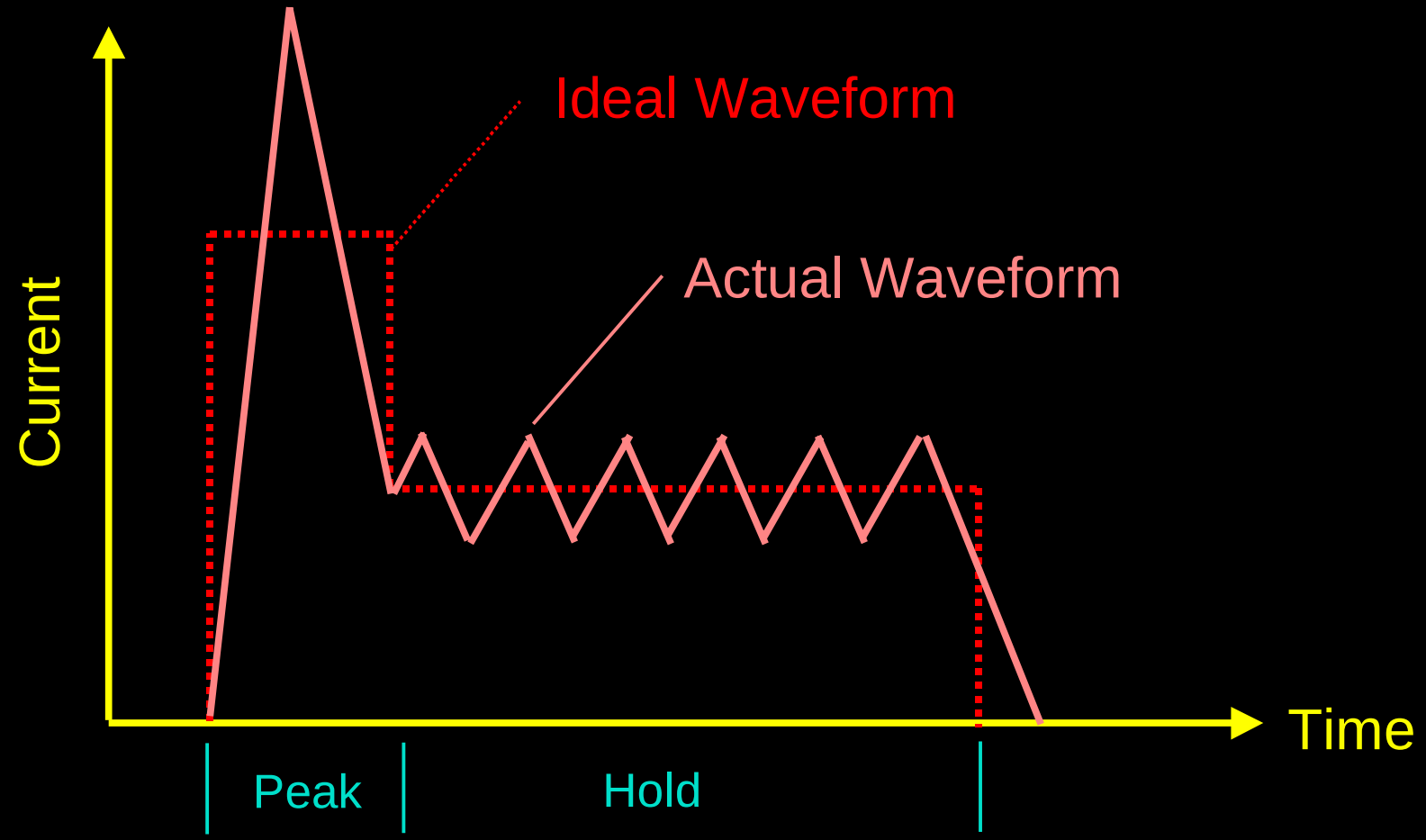


Control valve off	Control valve on	Control valve on	Control valve off	Control valve off
Control pressure above needle at supply pressure	Control pressure reduced	Needle lifts	Control pressure rises to supply pressure	Control pressure at supply pressure
Pressure holds needle closed	Needle begins to rise	Injection begins	Needle beings to close	Needle beings to closed. Injection off

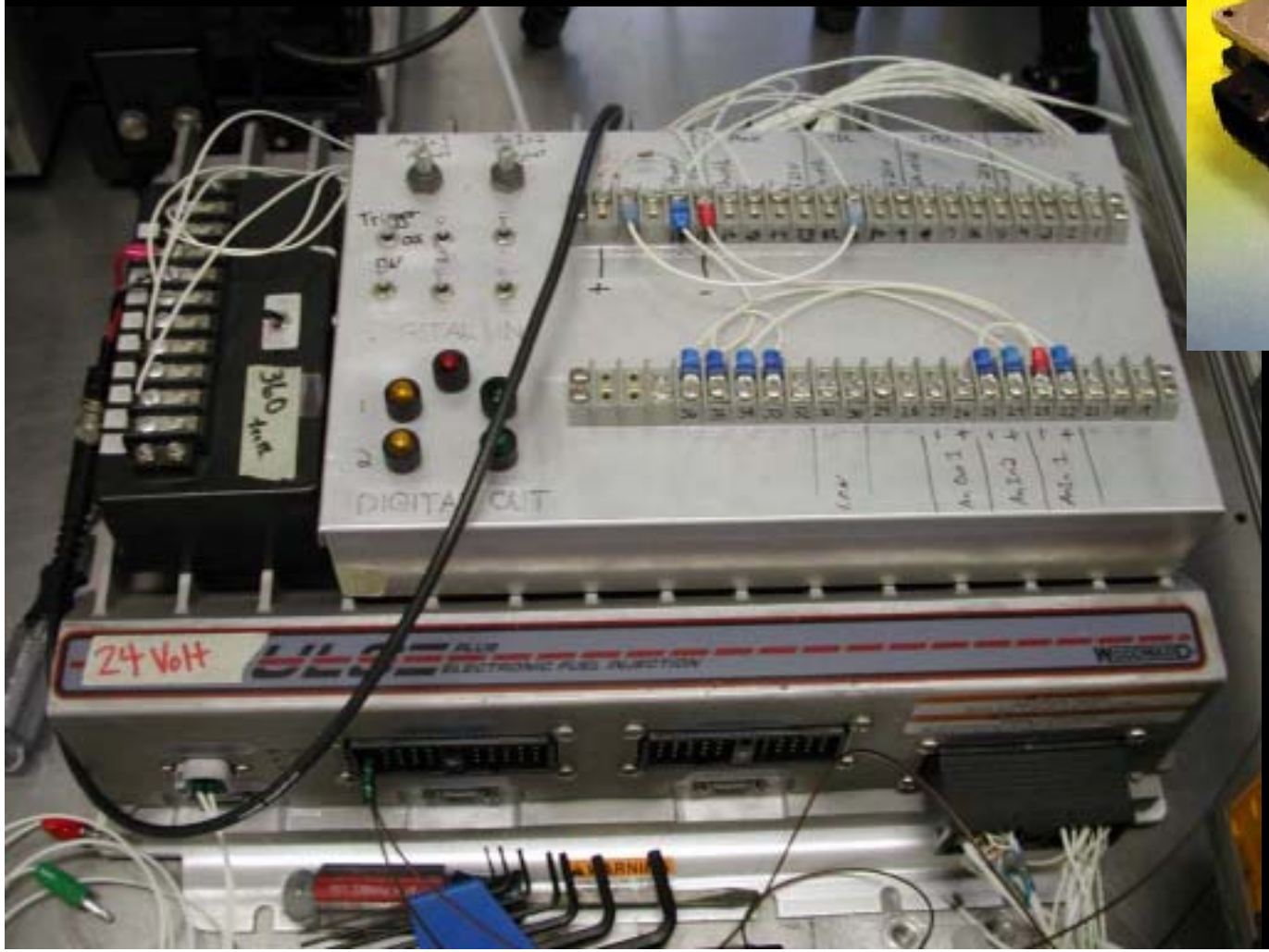
System Components

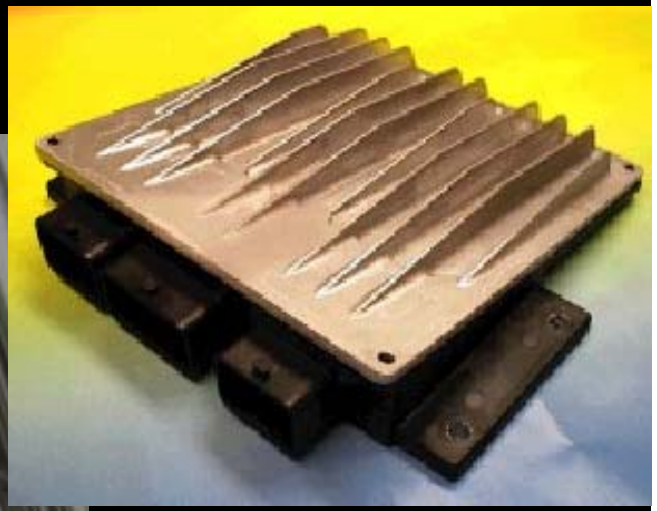
- High Pressure Pump
- Fuel Injector
- **Injector Driver**

Peak and Hold Fuel Injector Driver



Fuel Injector Controller

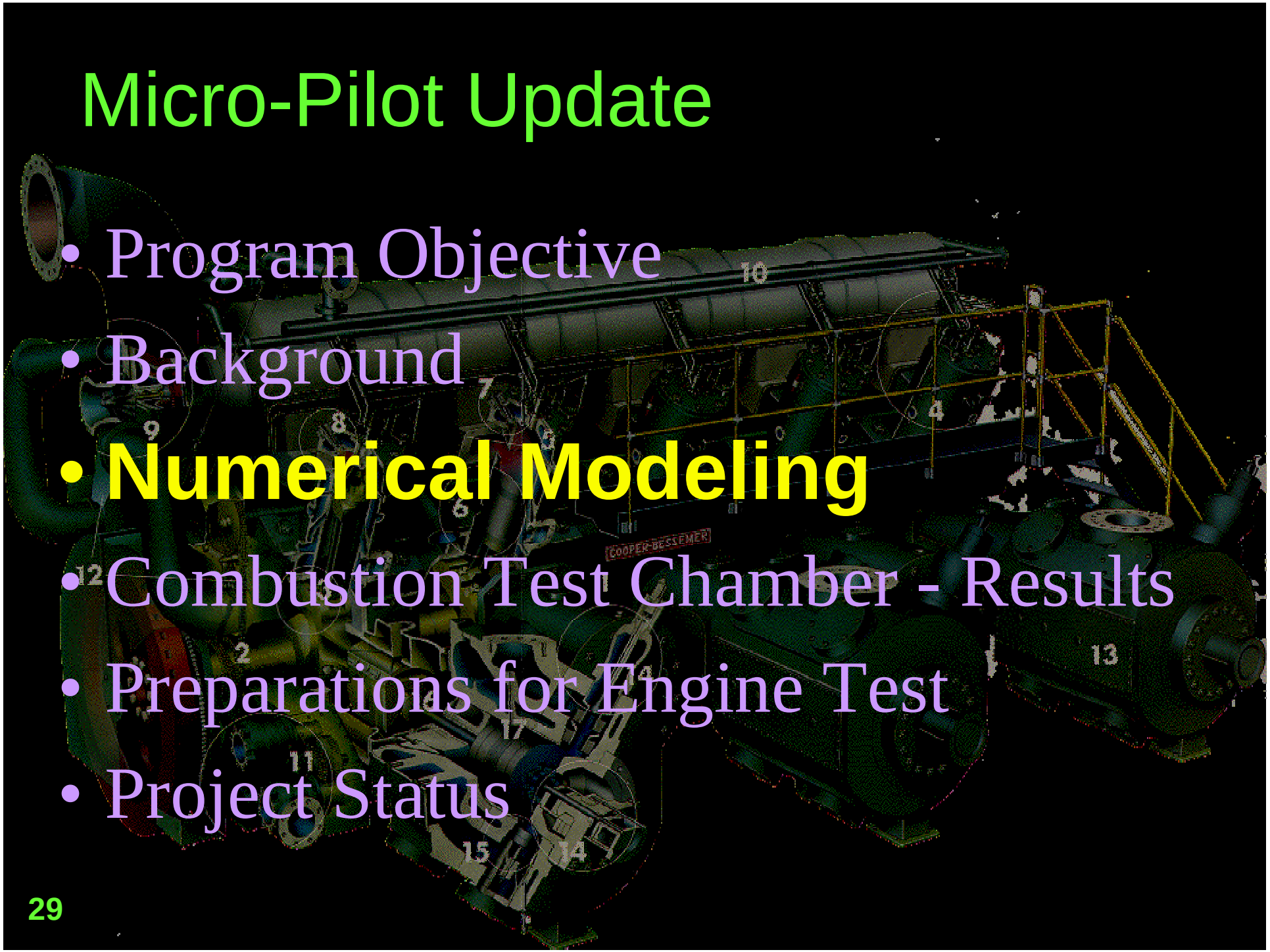




Delphi Automotive Controller

Woodward In-Pulse Injector Controller

Micro-Pilot Update



- Program Objective
- Background
- **Numerical Modeling**
- Combustion Test Chamber - Results
- Preparations for Engine Test
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Modeling Efforts

Modeling performed by:

CSU – For basic design studies

Delphi – For design confirmation

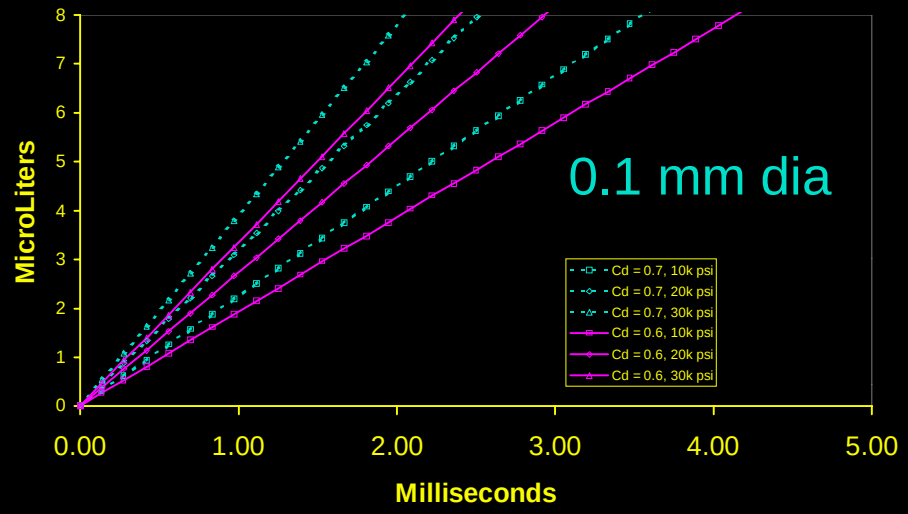
Ricardo Consulting Engineers - (on a separate, but related project) – to extensively explore design strategy

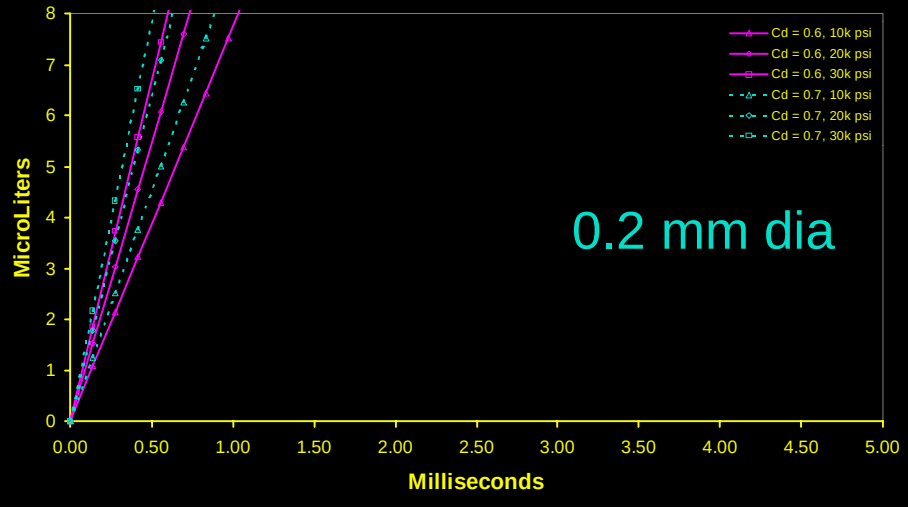
Calculated Mass Flow Rate

- Injection duration varies with orifice size & pressure

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

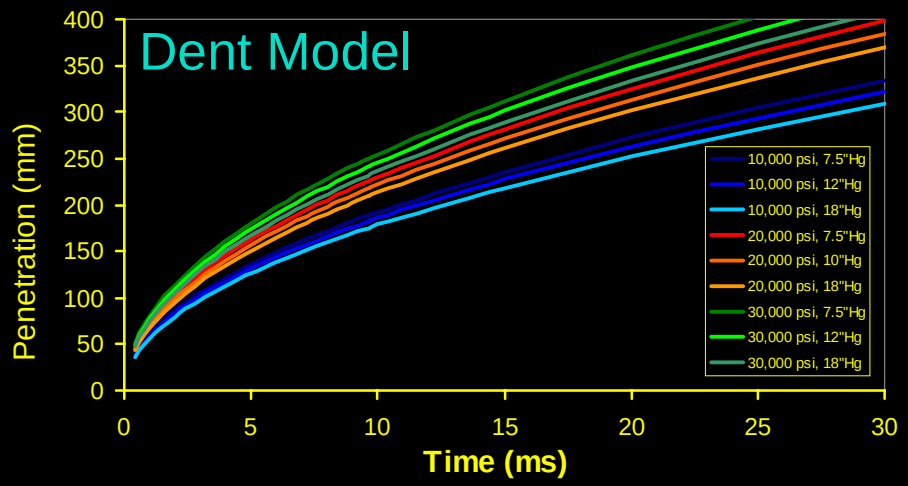
High: 4 msec @ 10,000 psi w/ 0.1 mm

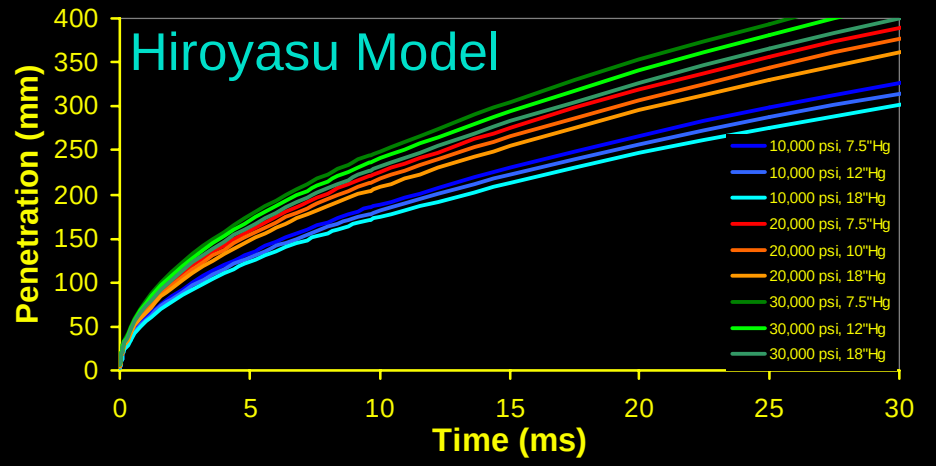




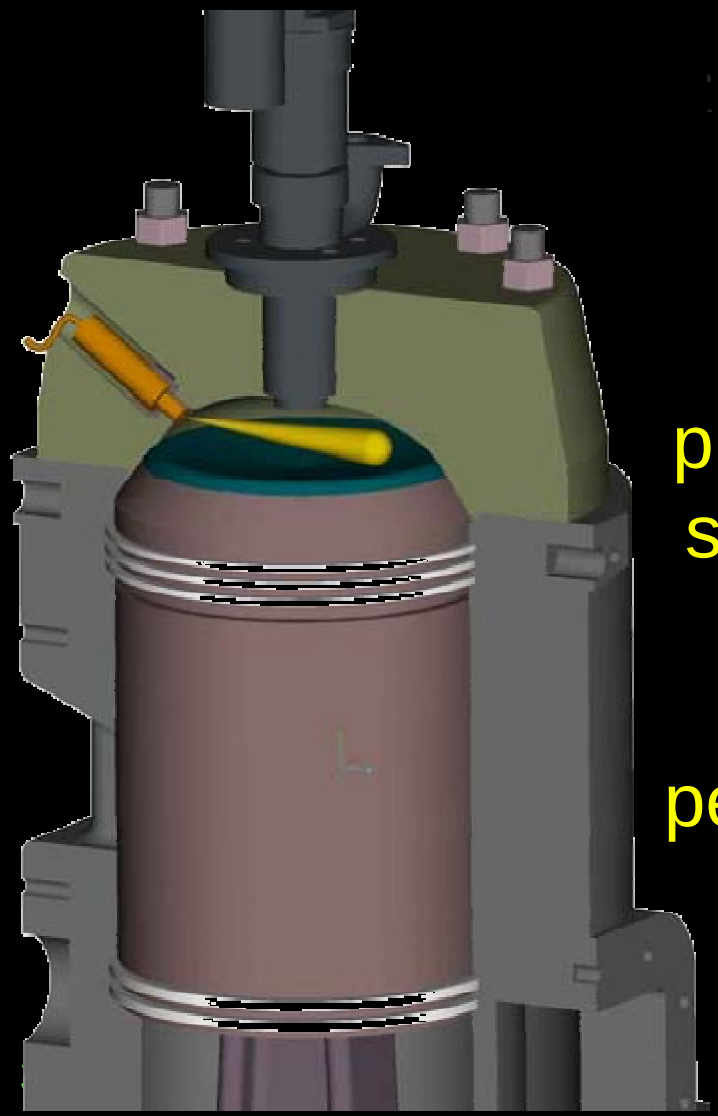
Spray Penetration

- 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

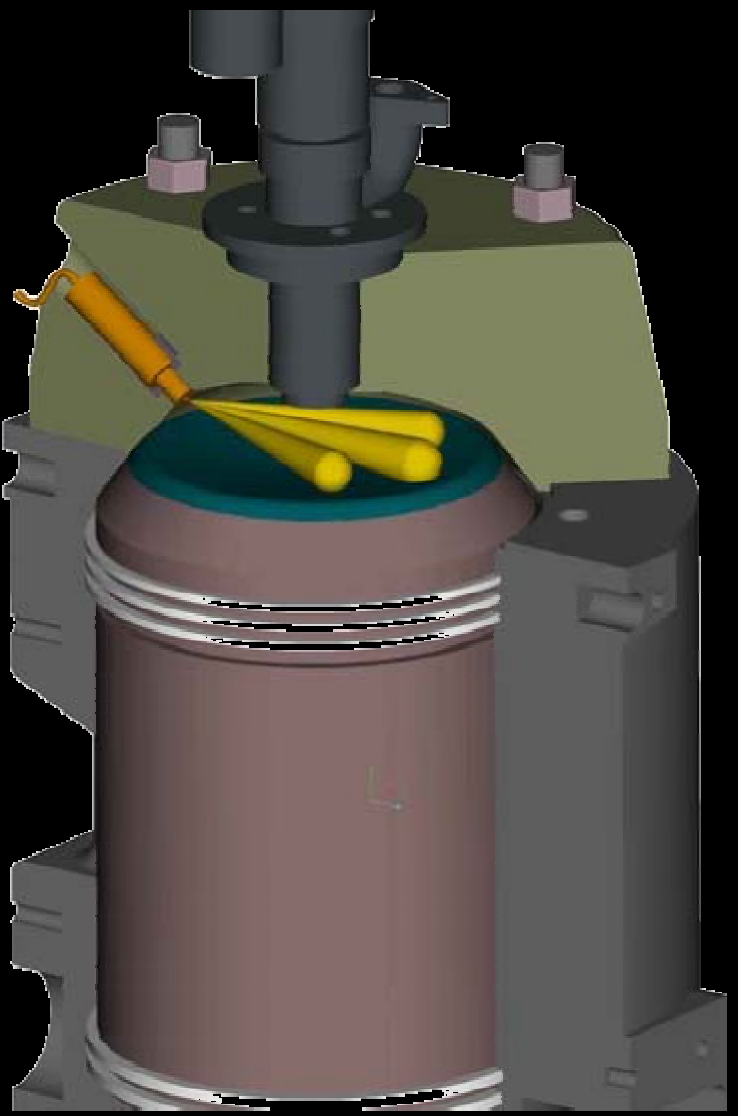




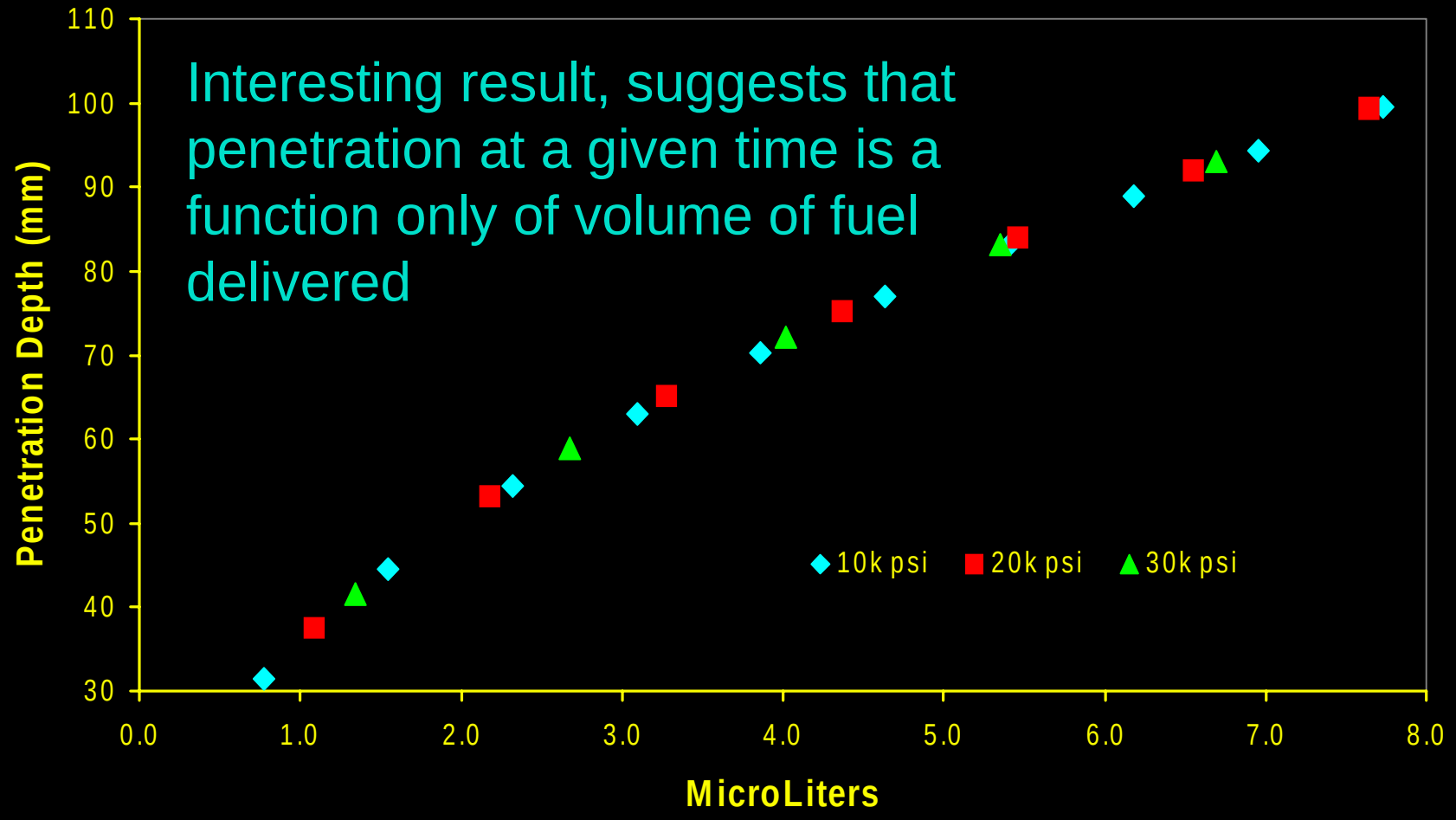
Number of Holes



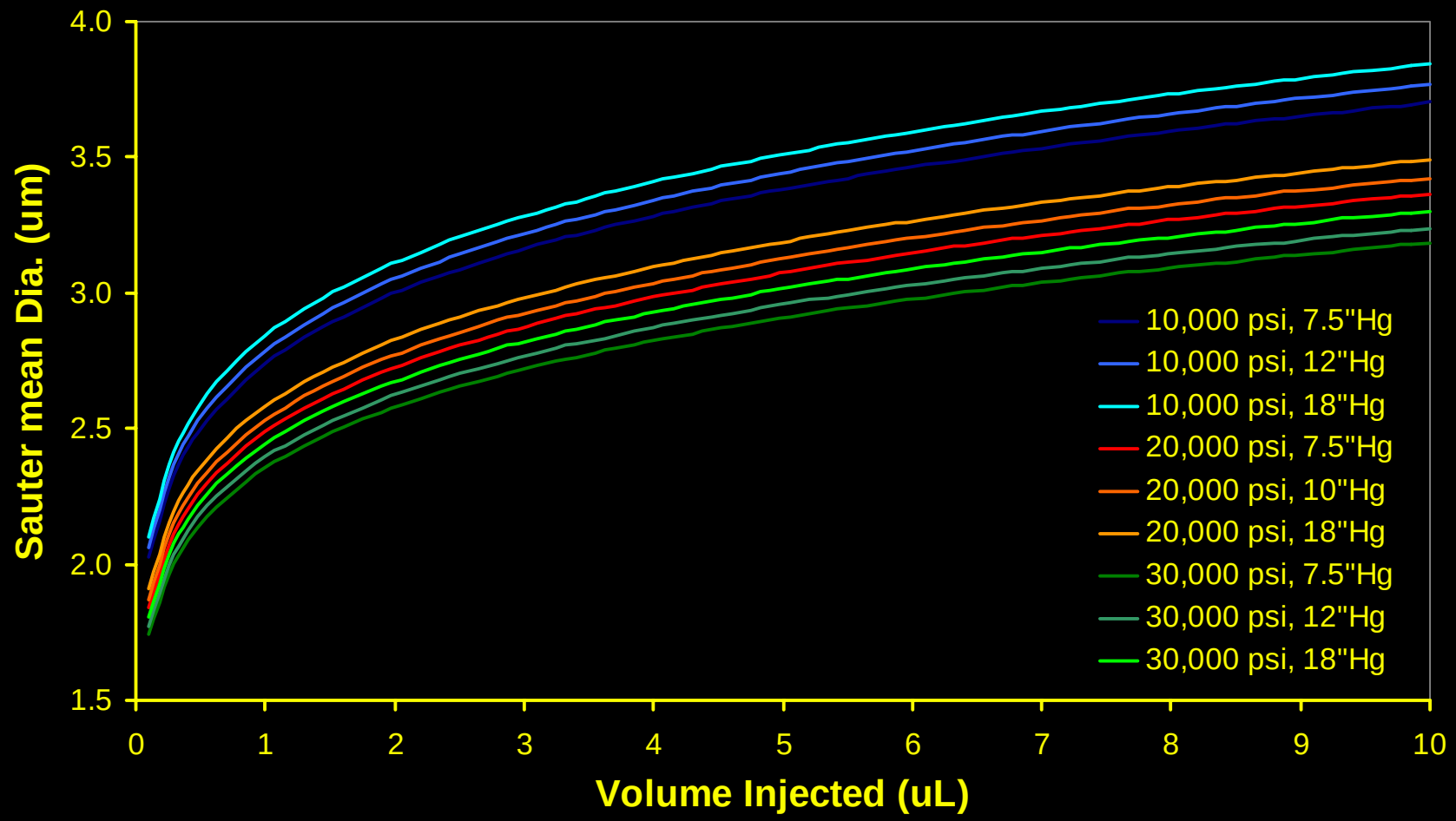
Modeling indicates preference for single hole to provide greatest penetration for given fuel volume



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

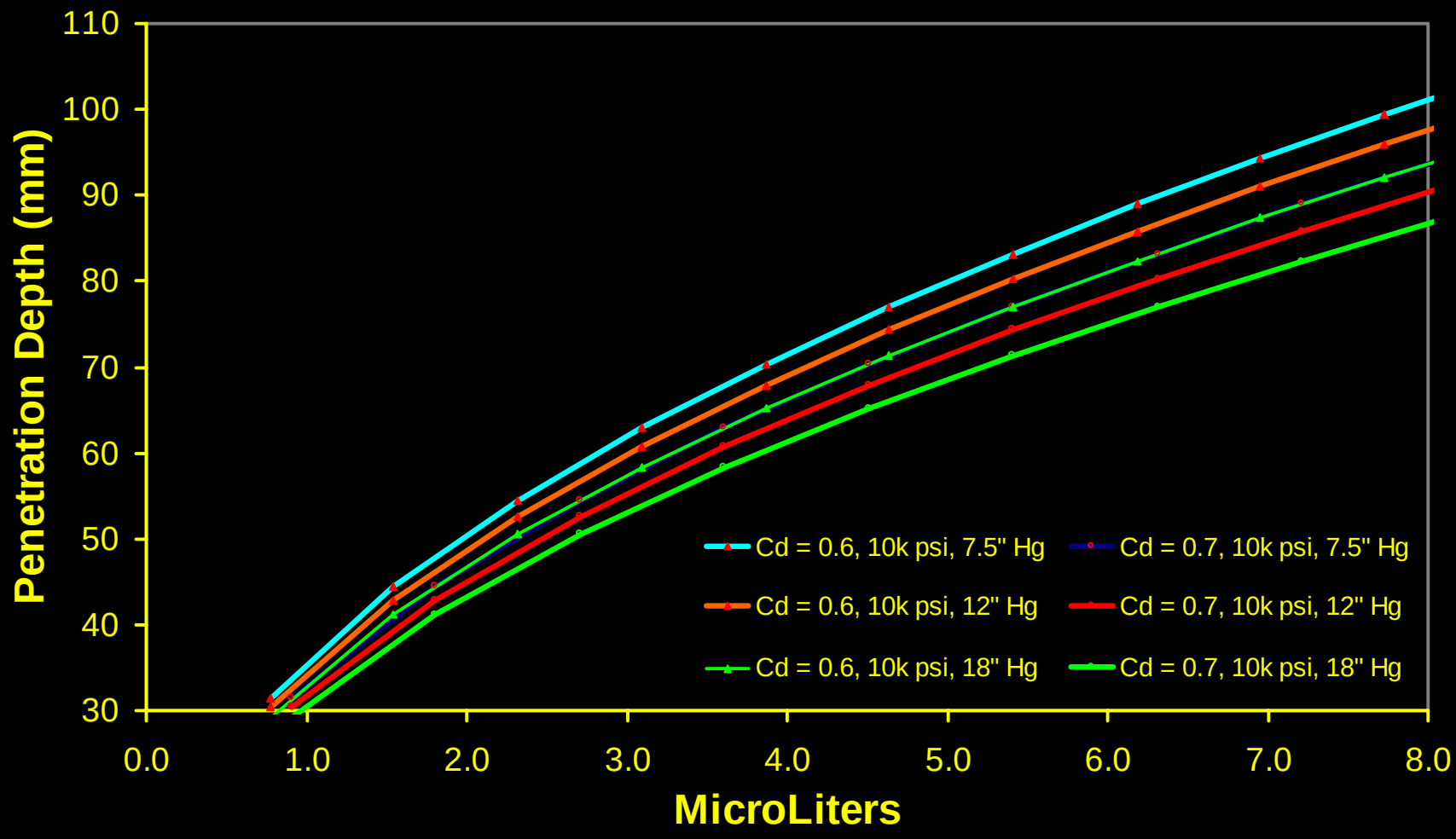


Sauter Mean Diameter

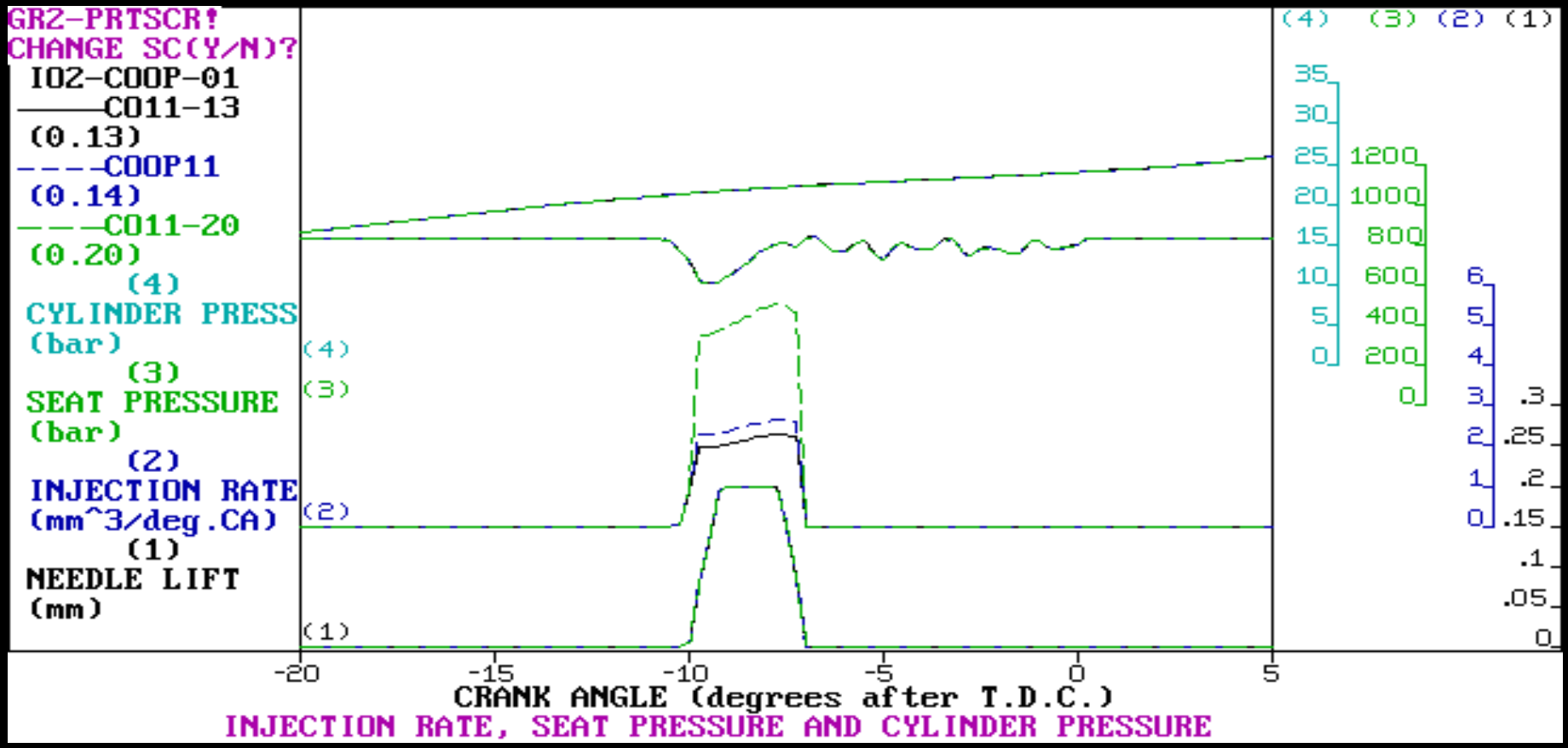


Normally, higher pressure preferred for finer atomization, but larger droplets penetrate farther. Tradeoff to be explored experimentally.

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



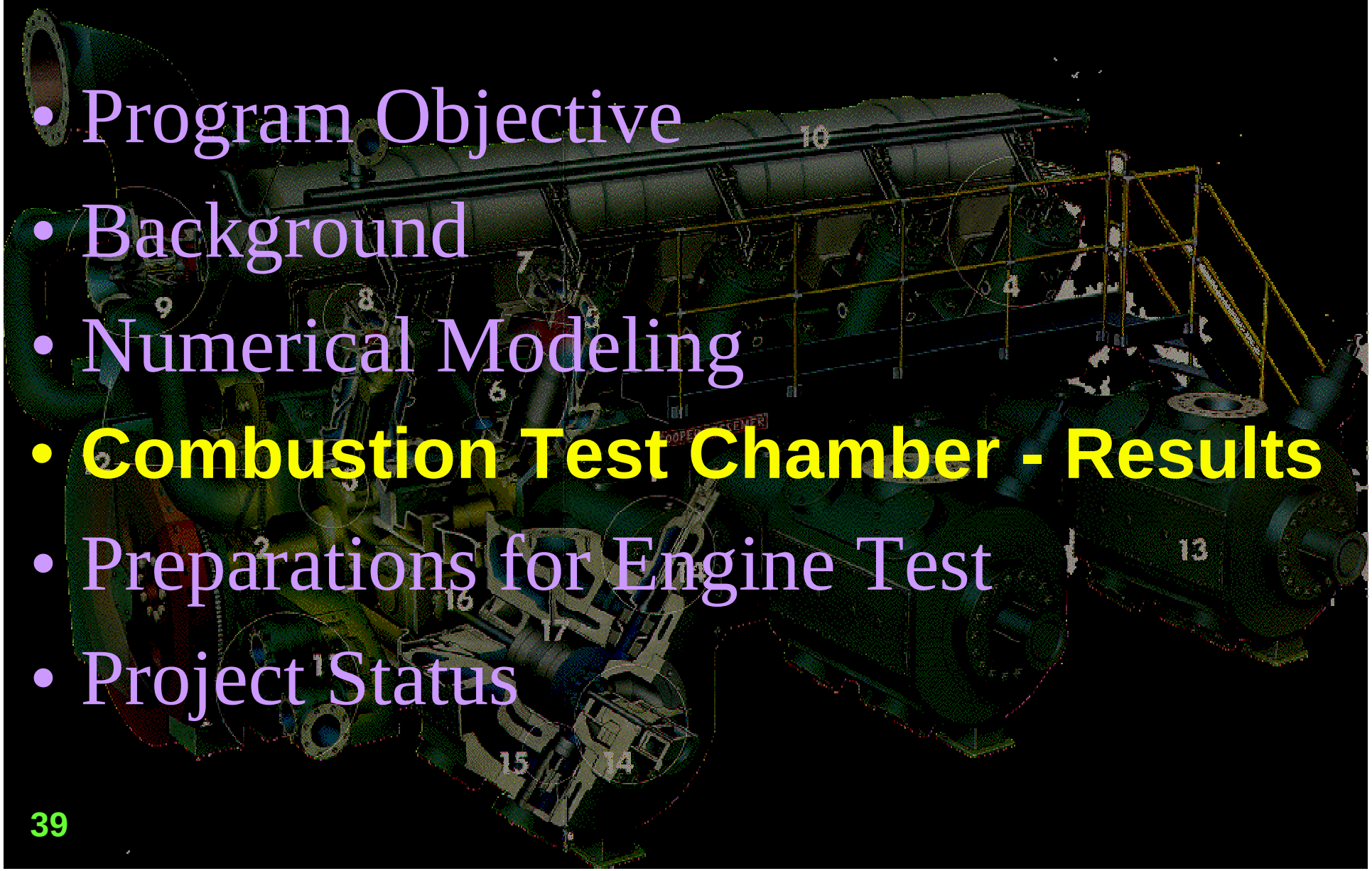
Delphi Modeling Results



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 Objective
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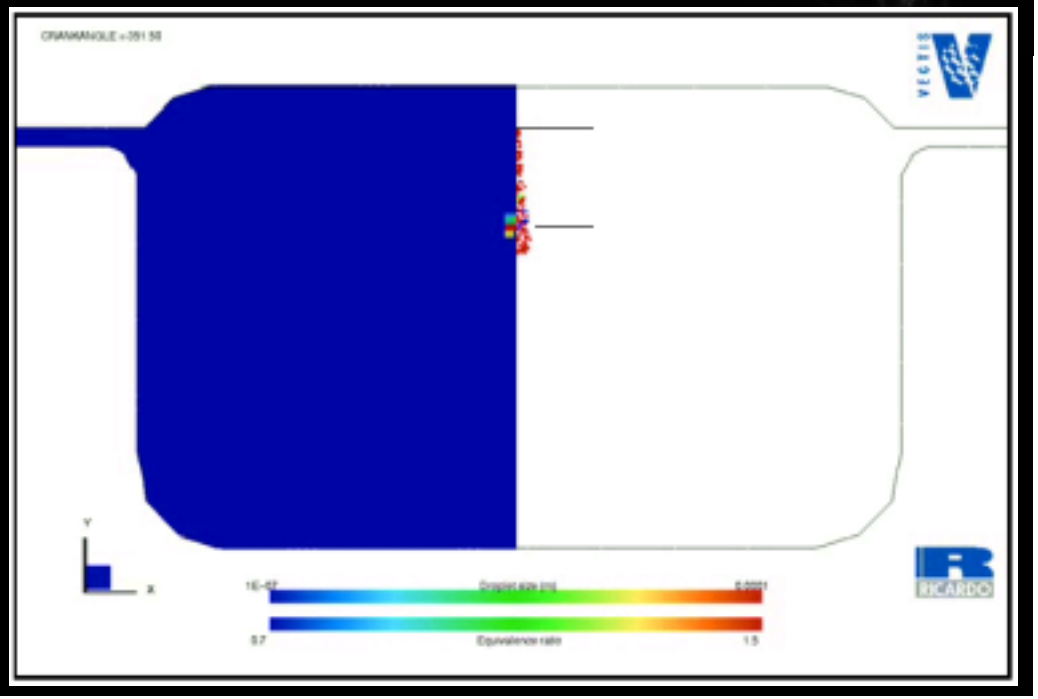
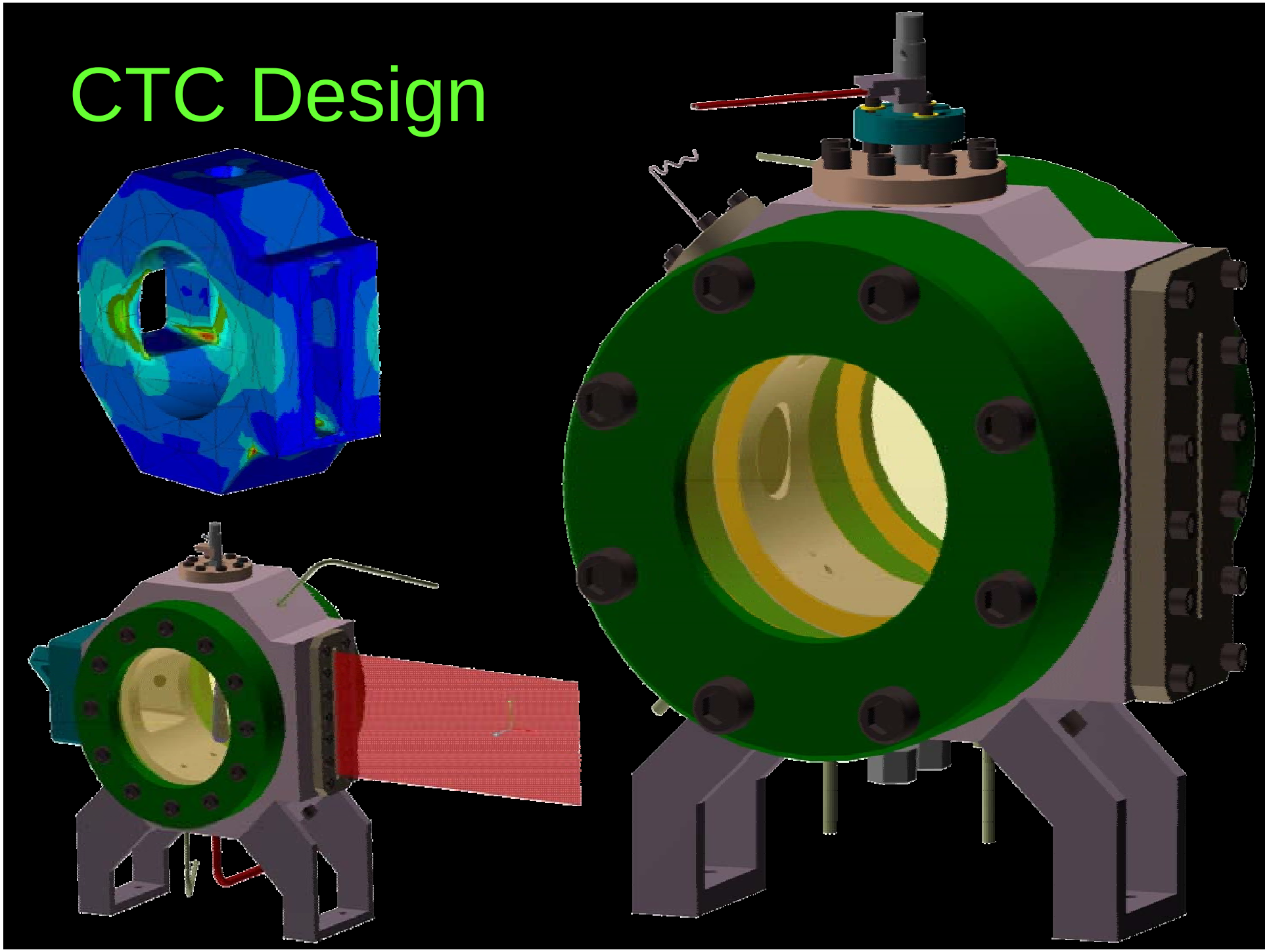
CTC Program Objectives

- Provide validation for CFD modeling
- Provide insight into physical processes:
  - Sray penetration
  - Vaporization
  - Spray angle
  - Droplet size
  - Ignition
  - Flame Propagation

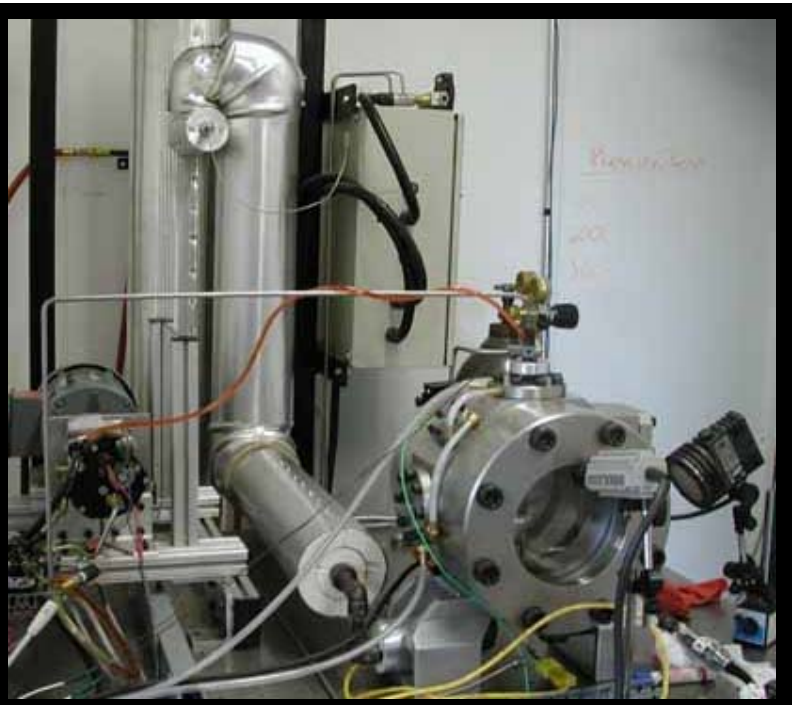


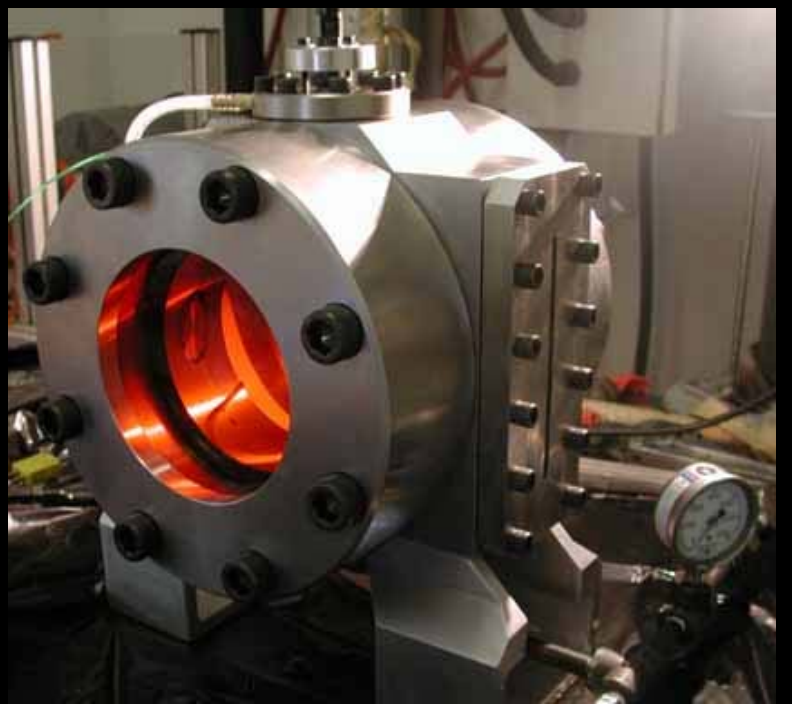
CTC Design



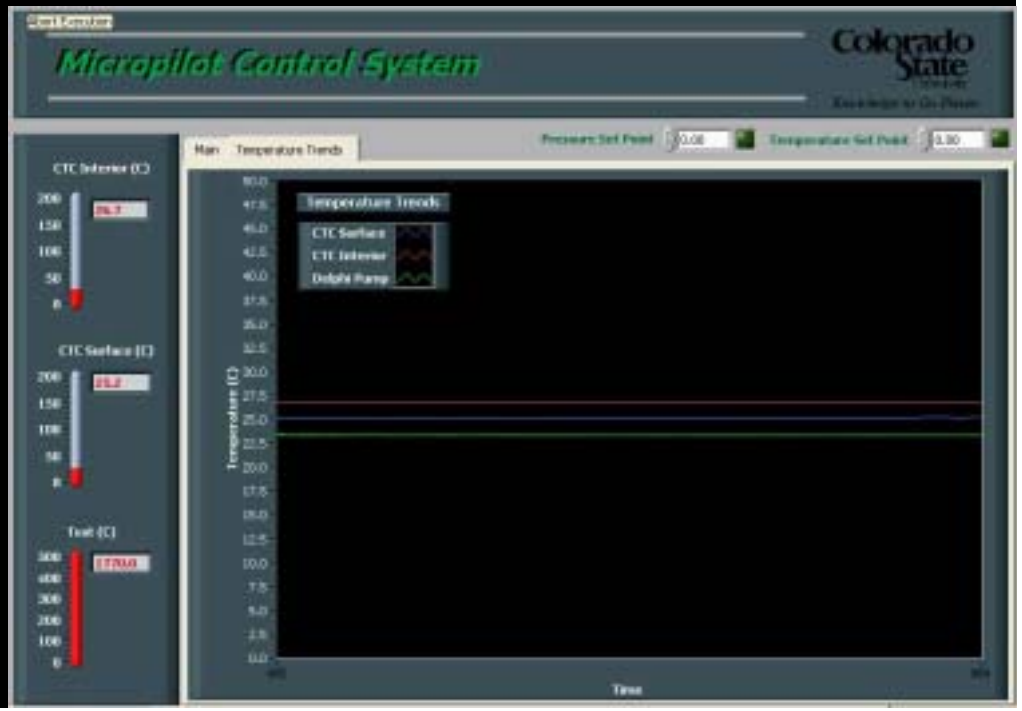
Combustion Test Chamber Capabilities

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

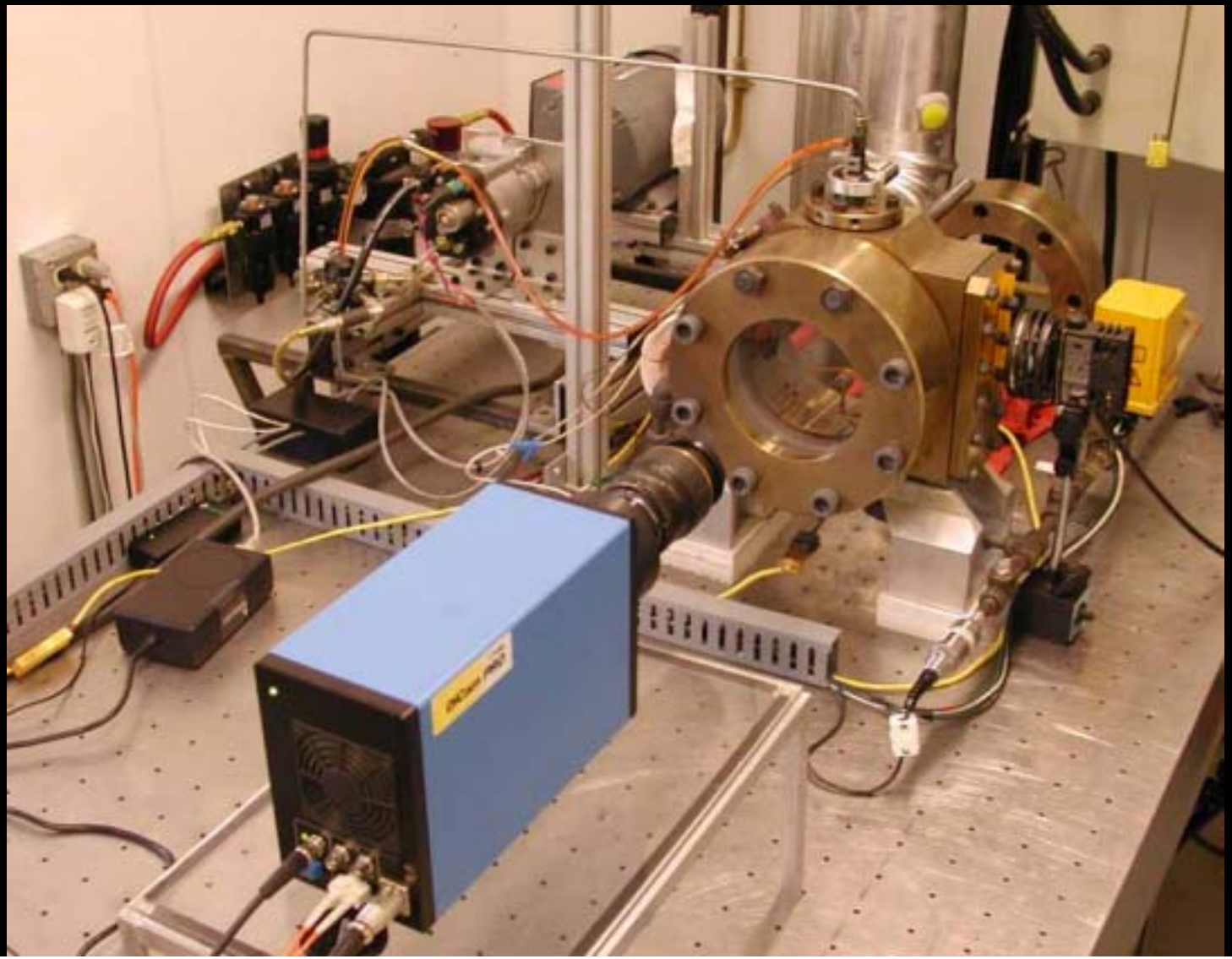




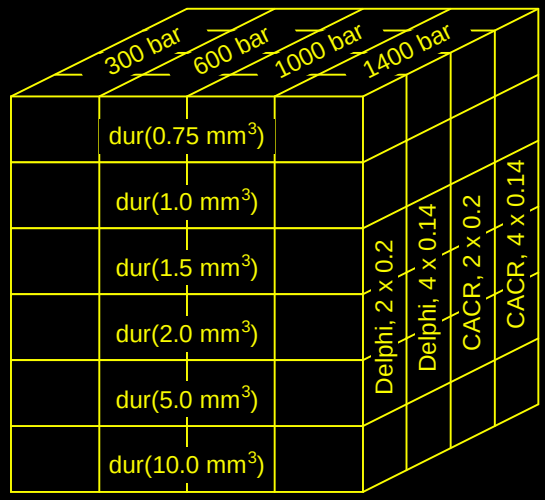
CTC Controls

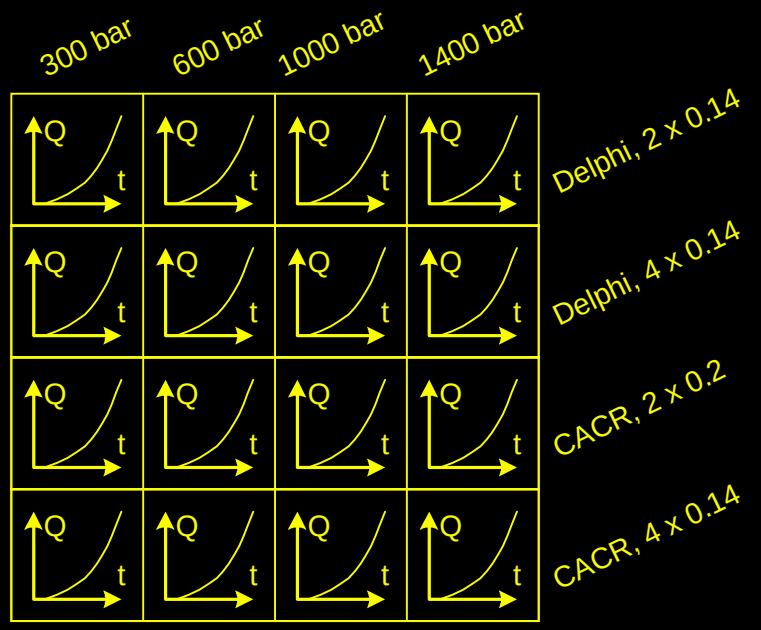


DiCam Setup for CTC



Injector Calibration

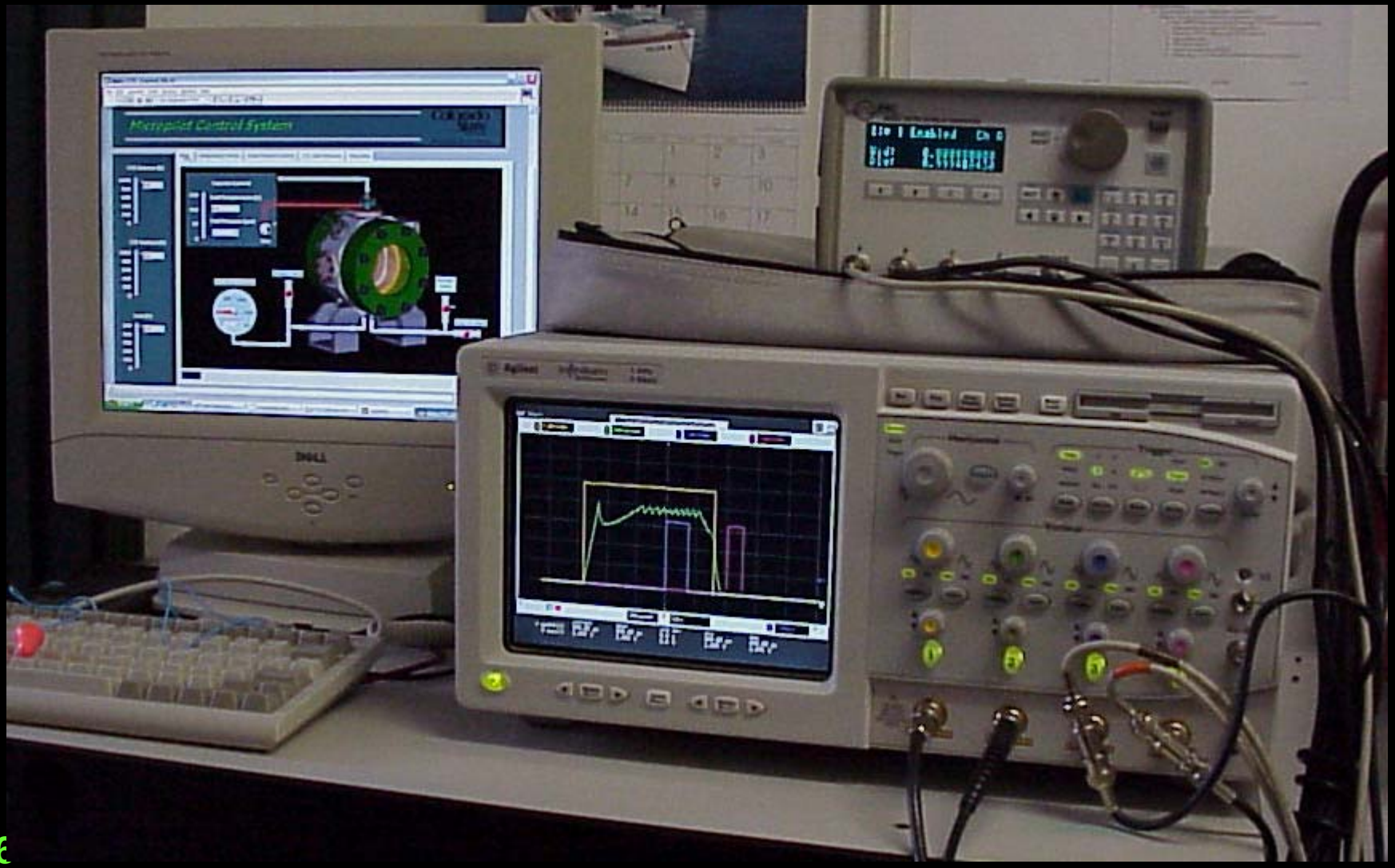




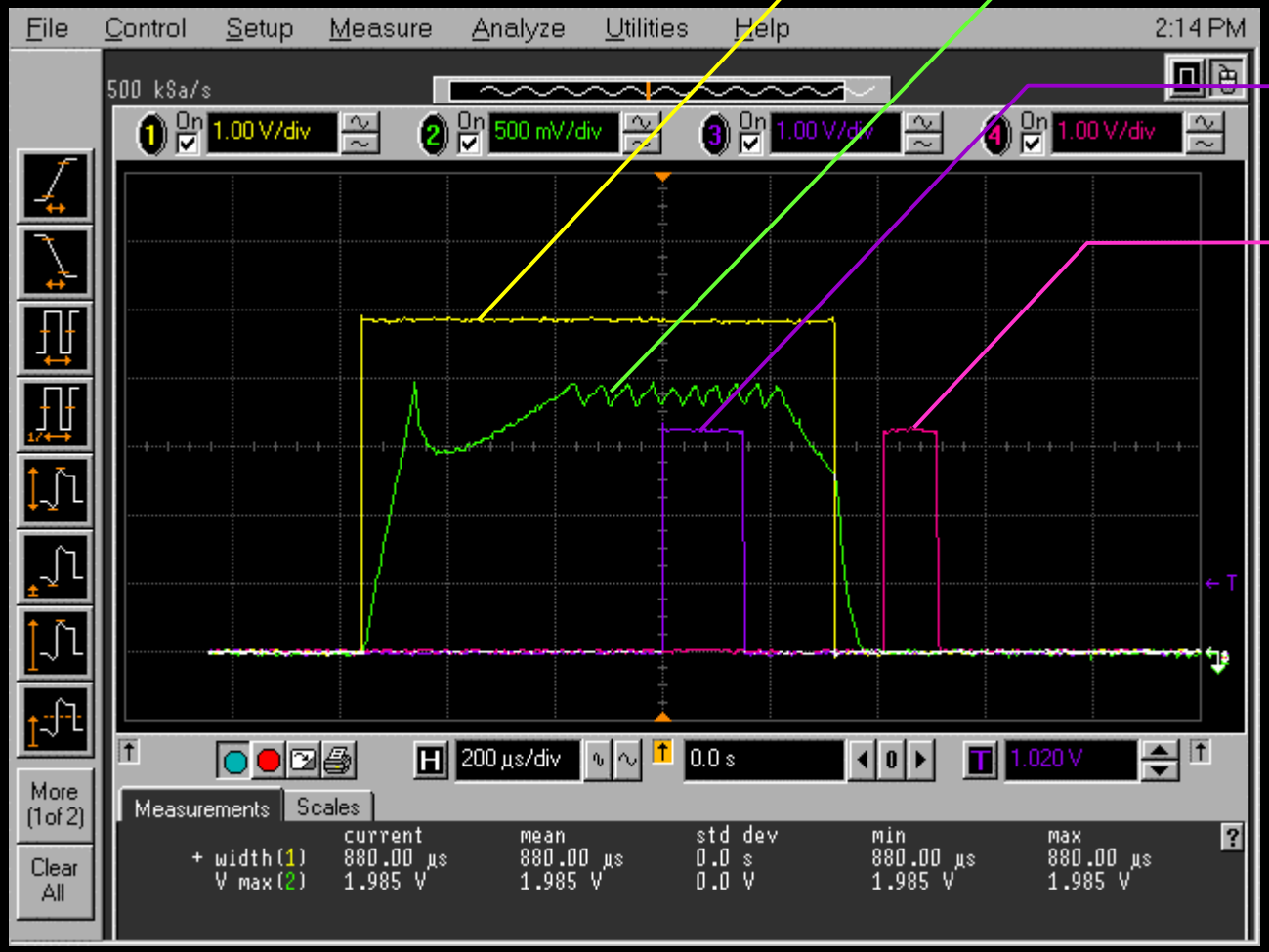
Prioritization:

- Cummins 2 x 0.20
- Cummins 4 x 0.14
- Delphi 2 x 0.20
- Delphi 4 x 0.14
- 3-hole injector also available

Injector Controls / Diagnostics



Injector Signals

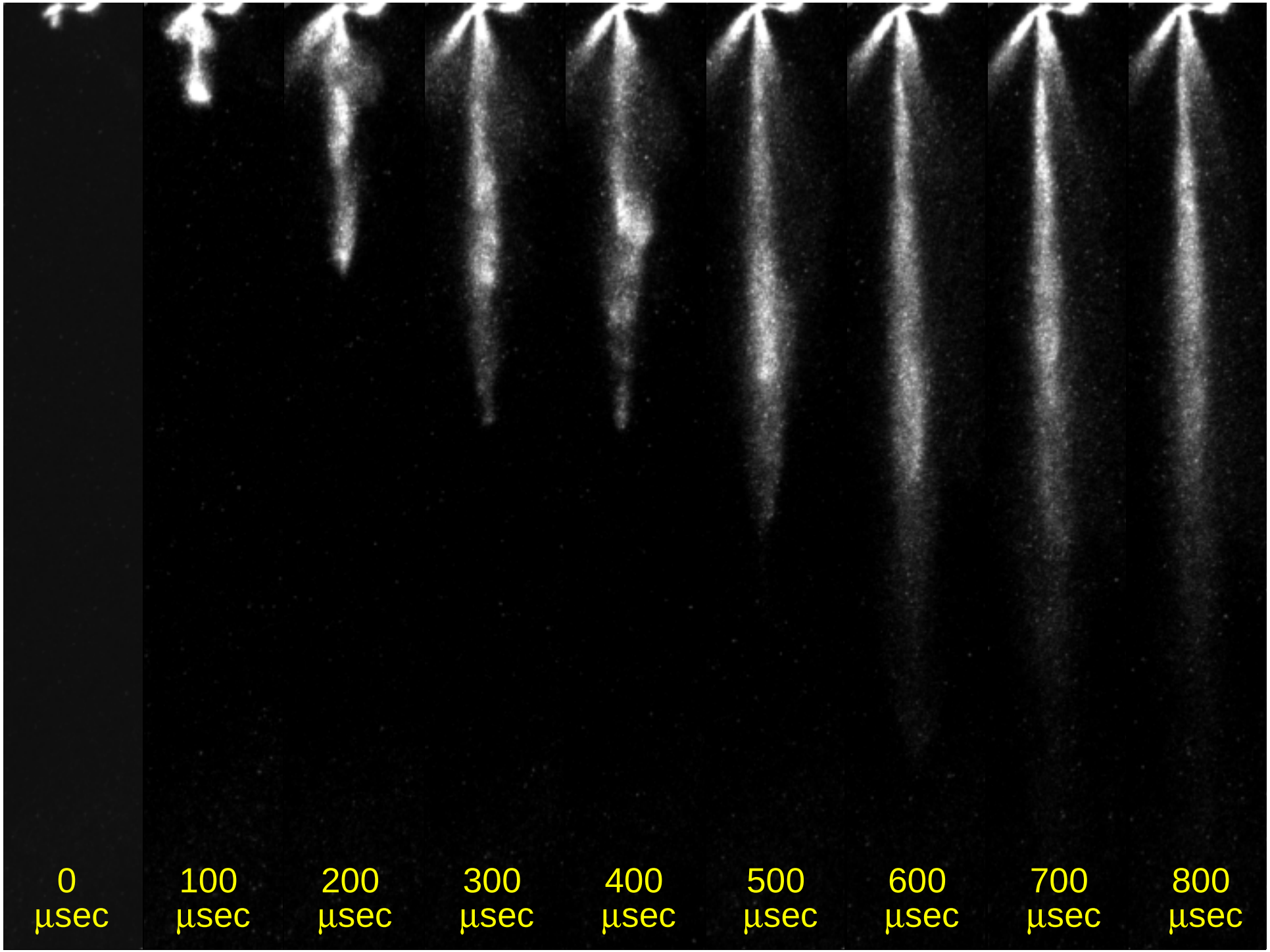


Injector Fire Command

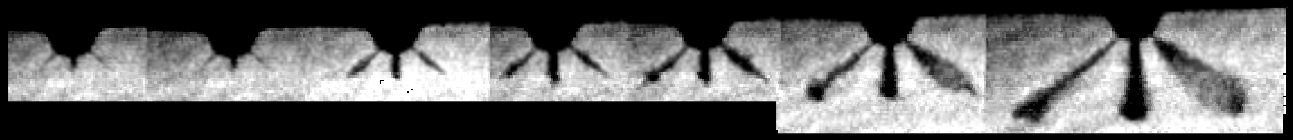
Injector Current

Laser Flash Lamp Fire Command

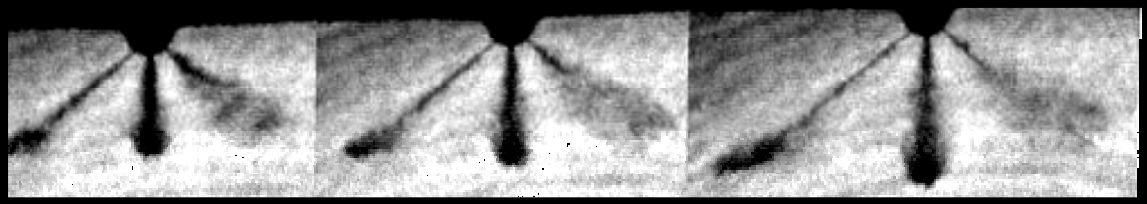
Laser Q-switch Fire Command


0 µsec
100 µsec
200 µsec
300 µsec
400 µsec
500 µsec
600 µsec
700 µsec
800 µsec

Early Injection Characteristics

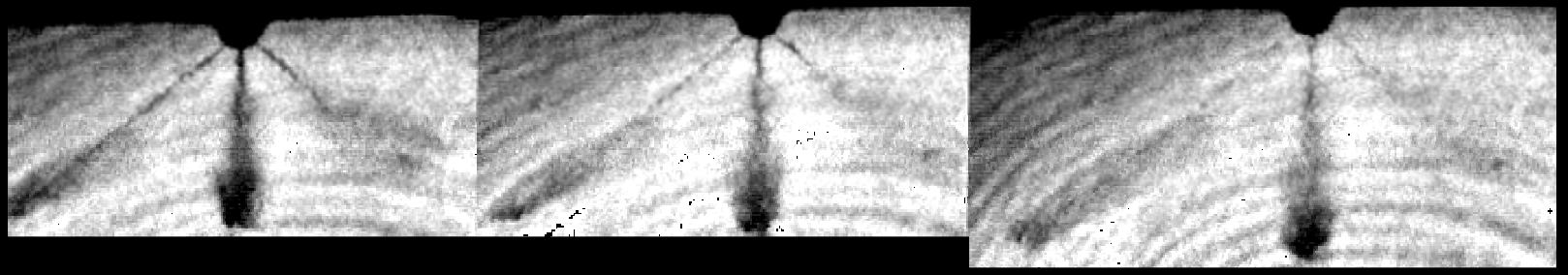


0 20 40 60 100 140 170



210 250 290

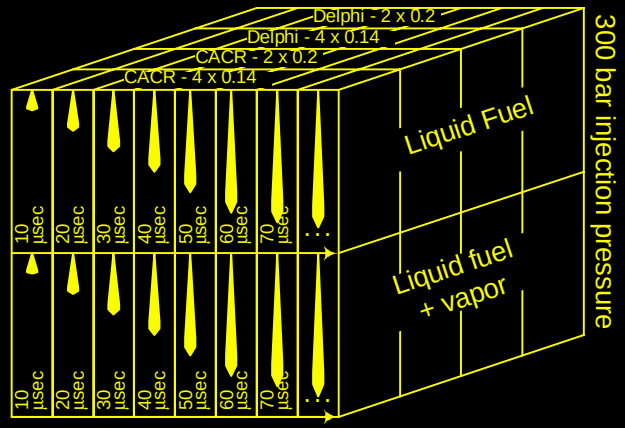
Times shown in μsec

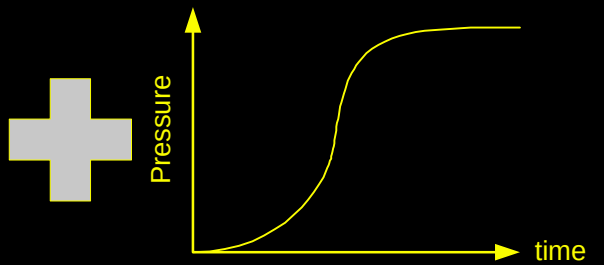


330 370 370+

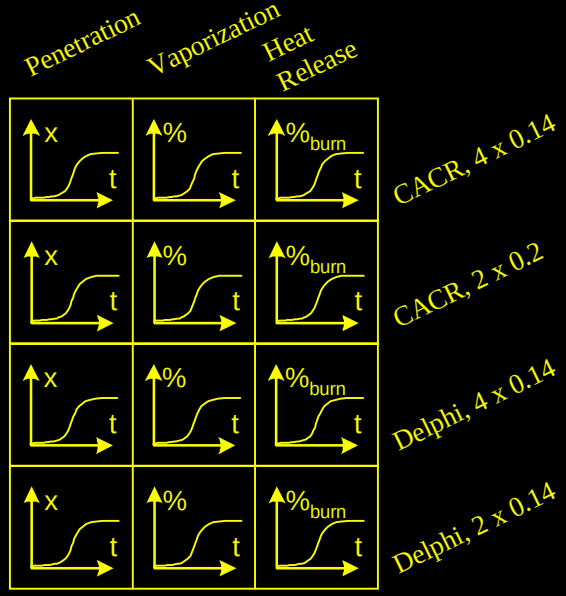
Typical Injector Characteristics

Modeling Validation

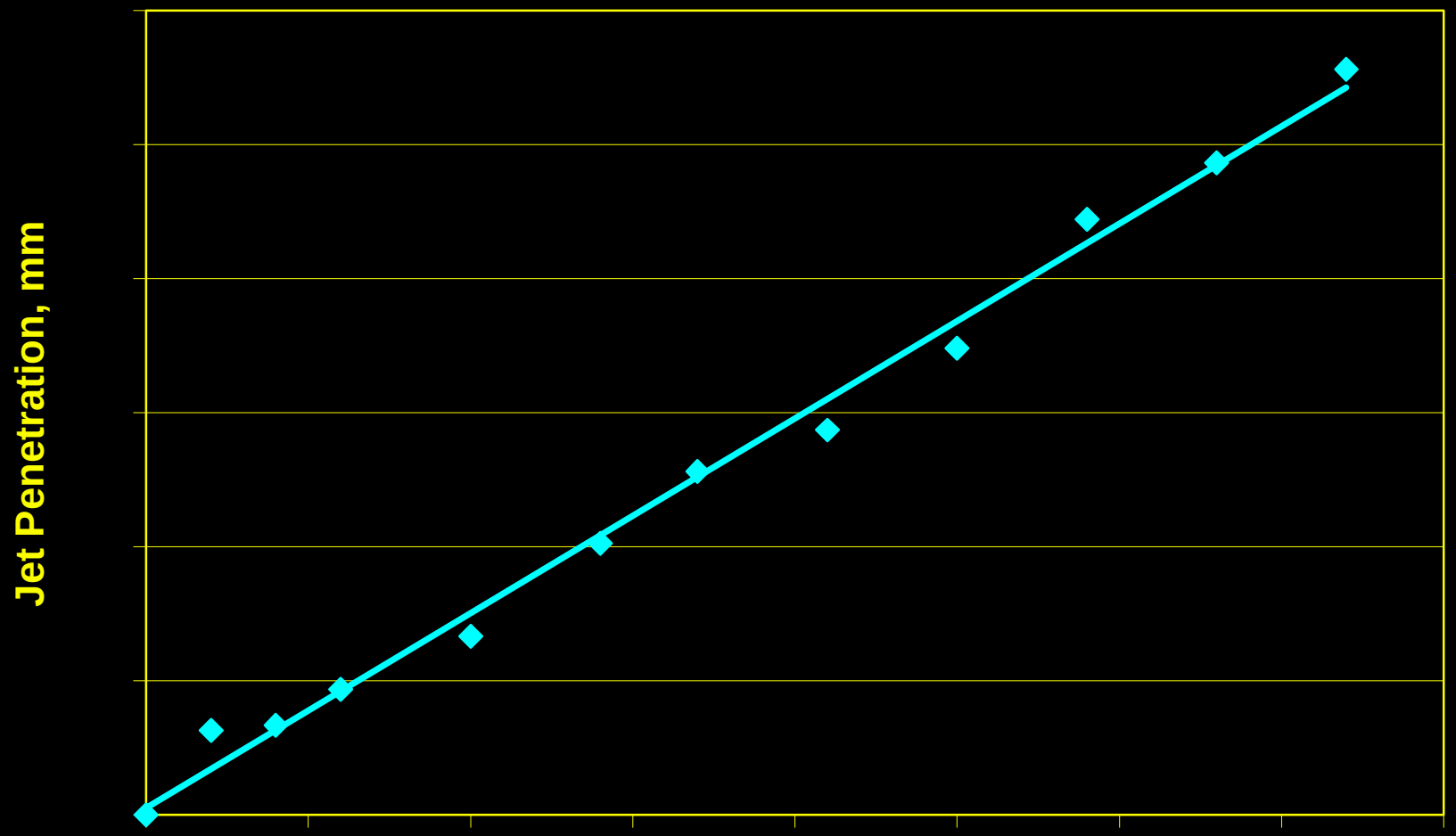




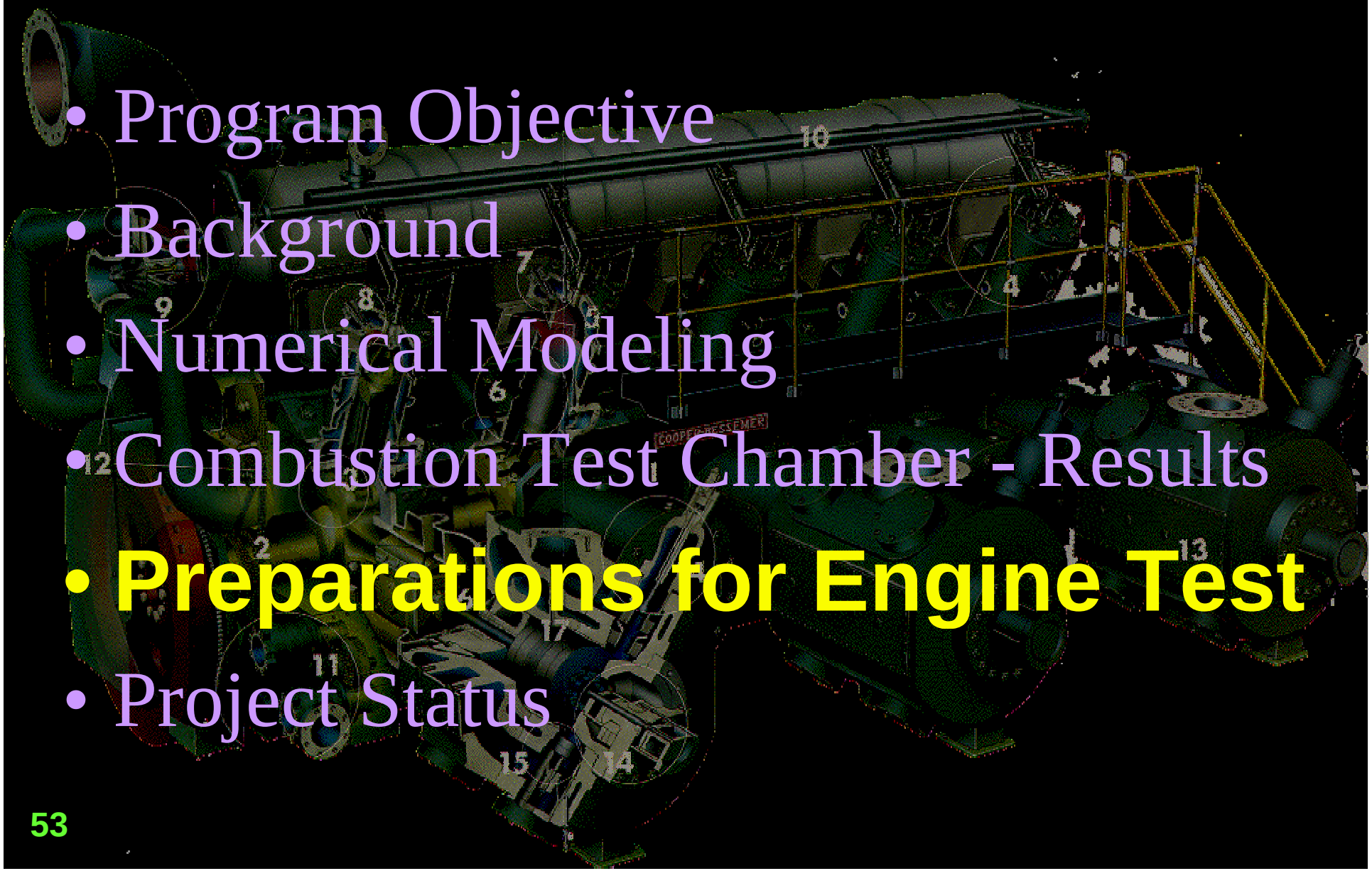
Objective: Generate data for validation of Ricardo injection modeling



Jet Penetration



Micro-Pilot Update

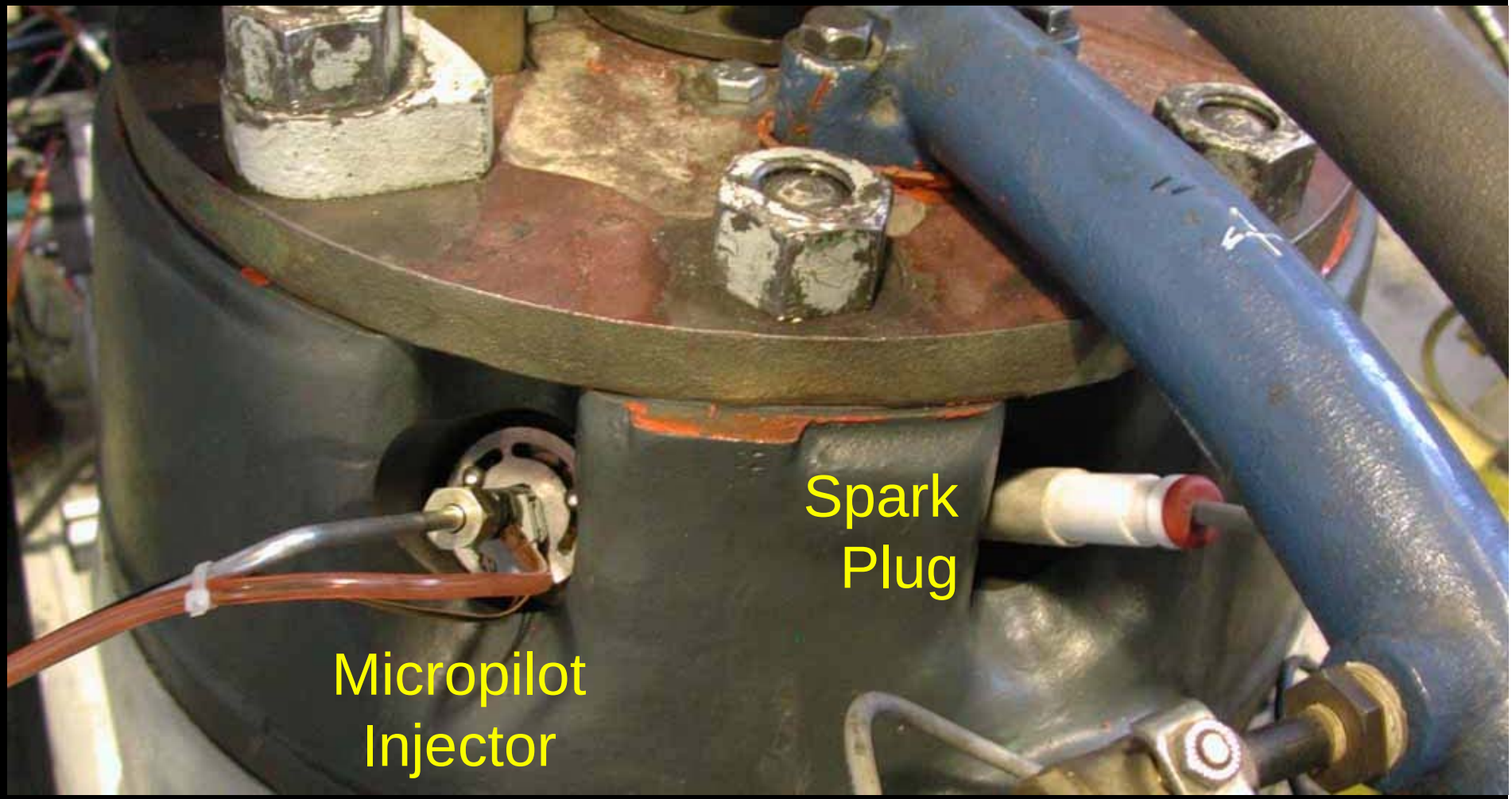


- Program Objective
- Background
- Numerical Modeling
- Combustion Test Chamber - Results
- **Preparations for Engine Test**
- Project Status

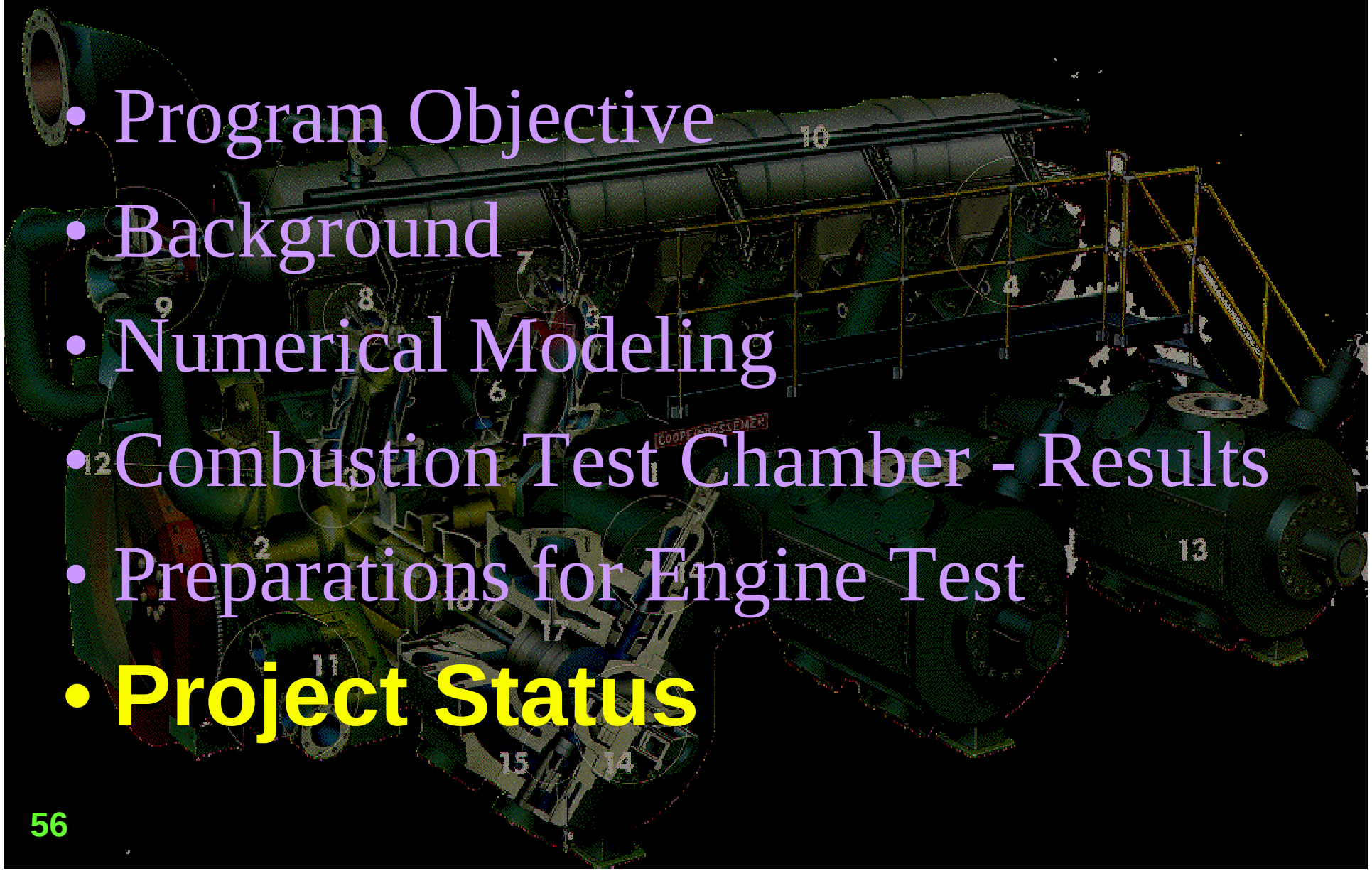
Preparations for On-Engine Testing

- Preparations underway for on-engine test
- Dual plug head
- Initial evaluation on single cylinder
- Spark ignited during cold start
- Micropilot used when warm
- Followed by complete test matrix on all cylinders

Micropilot System on Engine



Micro-Pilot Update



- Program Objective
- Background
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- Combustion Test Chamber - Results
- Preparations for Engine Test
- **Project Status**

Contact Information

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