SAND2018-5588PE

In-Cylinder Diagnostics to Overcome Efficiency Barriers in Natural Gas Engines

Presentation to Cummins
May 22, 2018

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Sandia National Laboratories

Motivation: Drivers for natural gas (NG) in heavy-duty engines = US energy goals, economics, and environment

DOE research support

"The U.S. Department of Energy's Vehicle Technologies Office supports research, development (R&D), and deployment of efficient and sustainable transportation technologies that will improve energy efficiency, fuel economy, and enable America to use less petroleum. These technologies, which include … advanced combustion engines, alternative fuels … will increase America's energy security, economic vitality, and quality of life."

Medium-duty NG engines already achieve NOx emissions 90% below EPA standards

Provides solution today to air quality issues in difficult urban districts, e.g. strict California ARB emissions targets for Los Angeles basin

http://www.cumminswestport.com/

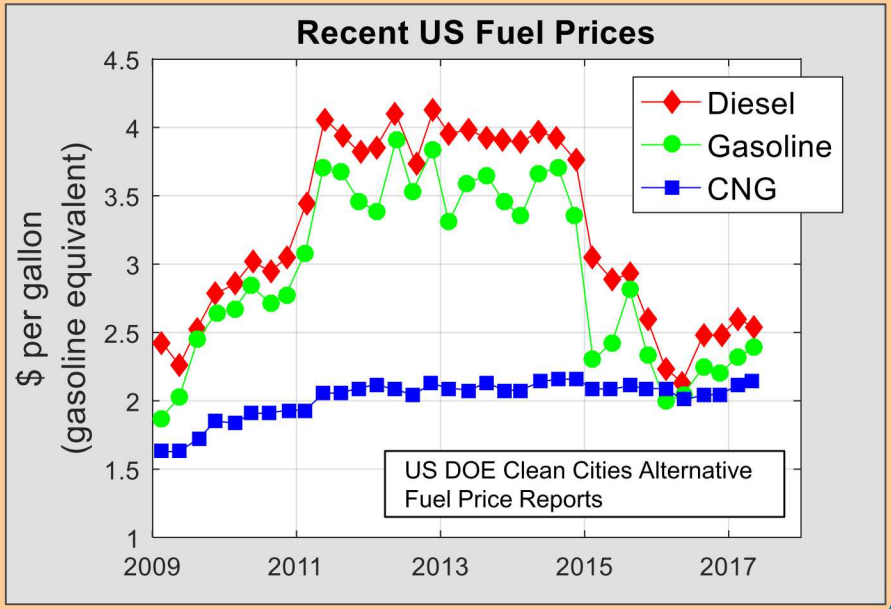
Environmental impact

Per unit energy, methane produces 20-30% less CO_2 than petroleum based fuels:

CH_4 *versus* $C_{10\text{-}20}H_x$

Fuel price differential is past (&future?) driver

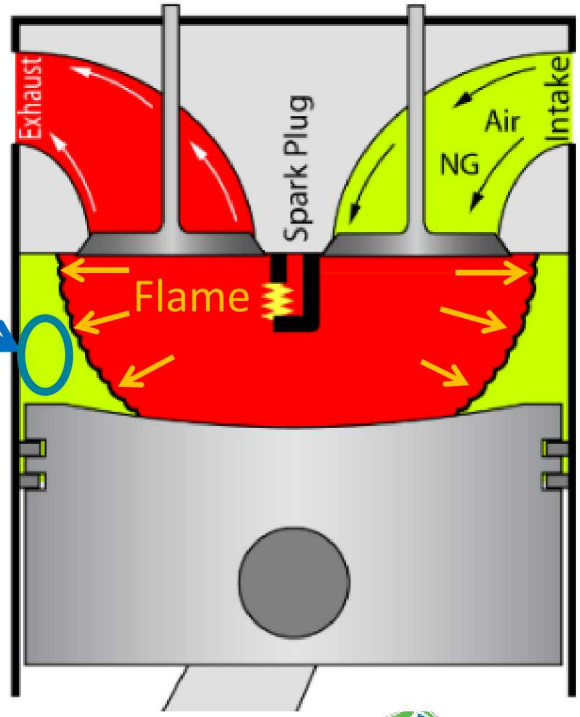
- Sustained +50% gasoline-equivalent fuel savings in recent years; may return again
- NG price less volatile, aids business planning



Problem: NG engine efficiency differential relative to diesel is primary barrier to important heavy-duty market

- Fuel costs drive heavy-duty market to highest efficiency engines (diesel, at 45%+)
- Current NG engines (spark-ignition, SI) have lower efficiency (~36%)
- The primary SI-NG efficiency barrier is destructive end-gas autoignition, a.k.a. "knock," which limits the engine compression ratio, and hence efficiency

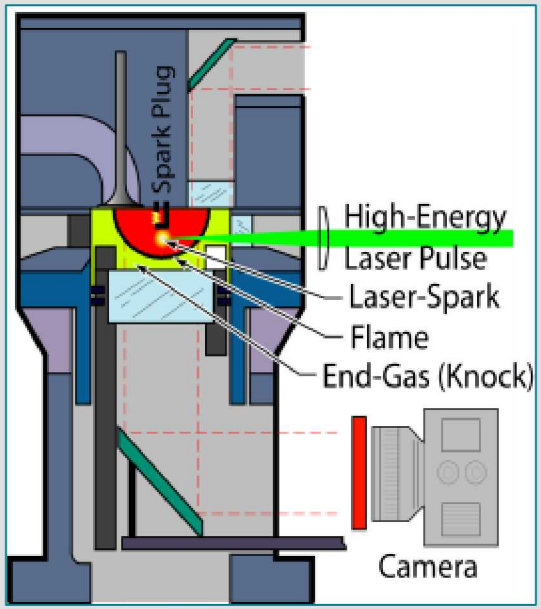
End-gas is compressed by the expanding flame, driving the fuel-air mixture to knock.



Industry Consensus:
Knock modeling lacks predictive accuracy

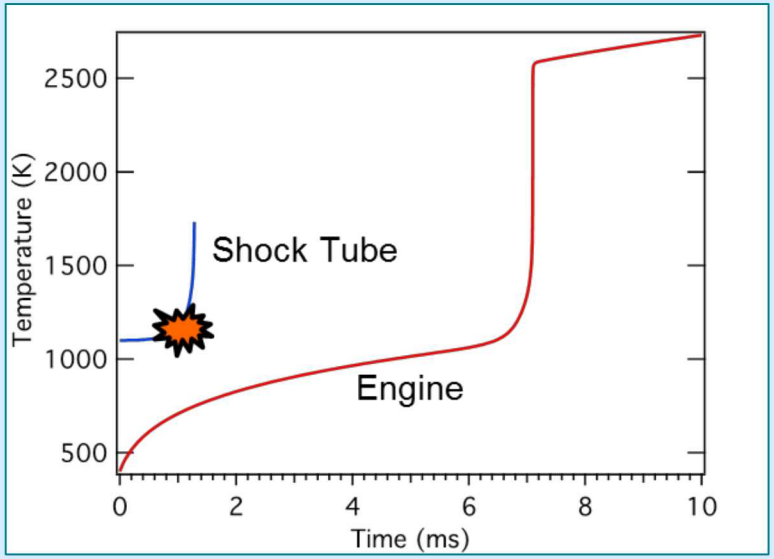
This limits the ability for computer-modeling tools to guide design of more efficient, knock-tolerant engines

Technical Approach: Use optical engine experiments and 0-D chemical kinetics to understand knock and improve models



Optical access engine experiment

- 30+ years of foundational diesel research
- Now adapting engine for natural gas
- Ignite with spark or laser (similar physics)
- Measure cylinder pressure (input to the 0-D kinetics model)
- Image combustion and knock to verify and/or adjust model assumptions
- Quantify in-cylinder mixing effects using fuel-tracer laser-induced fluorescence



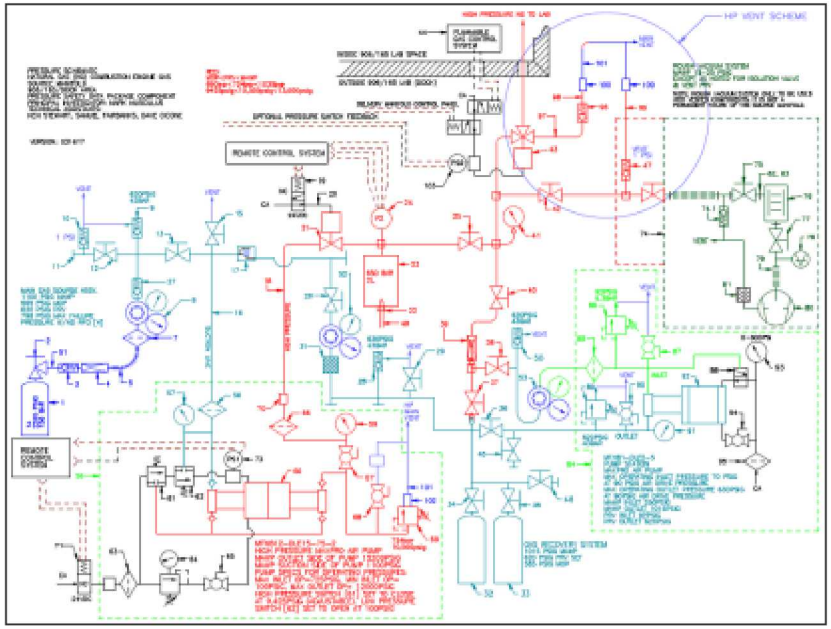
0-D Model: Miller et al. C_0-C_3 mechanism

- Fundamental mechanism, with no empirical tuning (as yet unpublished)
- Validated: accurate flame speed and shock tube ignition prediction
- Rigorous 100-bar (engine-knock relevant) pressure dependence
- Match fuel composition of experiment for direct chemical kinetic simulation
- Optical data aid model improvement by identifying any missing phenomena

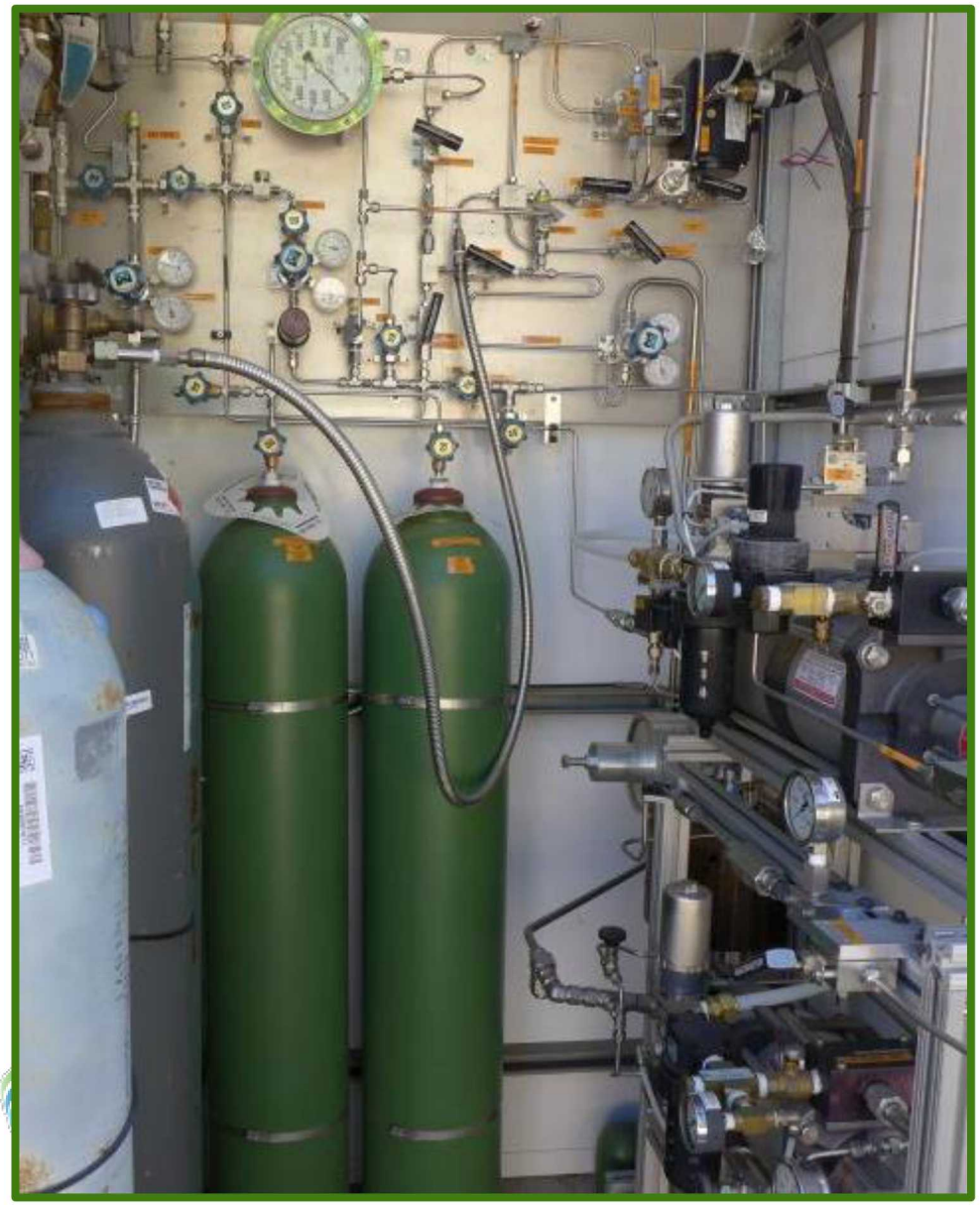
Primary Objectives: Develop the fundamental science base to support engineering design for high-efficiency NG engines

- Provide in-cylinder data relevant to NG engine knock
  - Multi-spectral imaging of ignition, flame development, and onset of knock
  - Quantitative fuel-air mixing data correlated to imaging of knock processes
  - Based on precise, scientific-grade fuels for reliable, reproducible results
- High-fidelity chemical-kinetic model minimizes reaction uncertainty so that other factors affecting knock can be identified and quantified
  - Chemistry of knock is dictated by minor constituents (e.g., ethane, propane), but physical effects (mixing, geometry, flame shape, etc.) are also important
    - With experiments using precise natural gas fuel mixtures with minor species identical to our chemical-kinetic mechanism, departures from expected chemical behavior will reveal how mixing/geometric/combustion mechanisms affect knock
  - With confidence in the chemical-kinetics part of the problem, the new science base of in-cylinder processes affecting knock will guide development of improved simulation tools for engineering design of NG engines

Progress – New Laboratory Capabilities: Natural gas storage, pressurization, and recovery system (100+ components)



Completed, inspected, leak-checked, and EH&S approved for use



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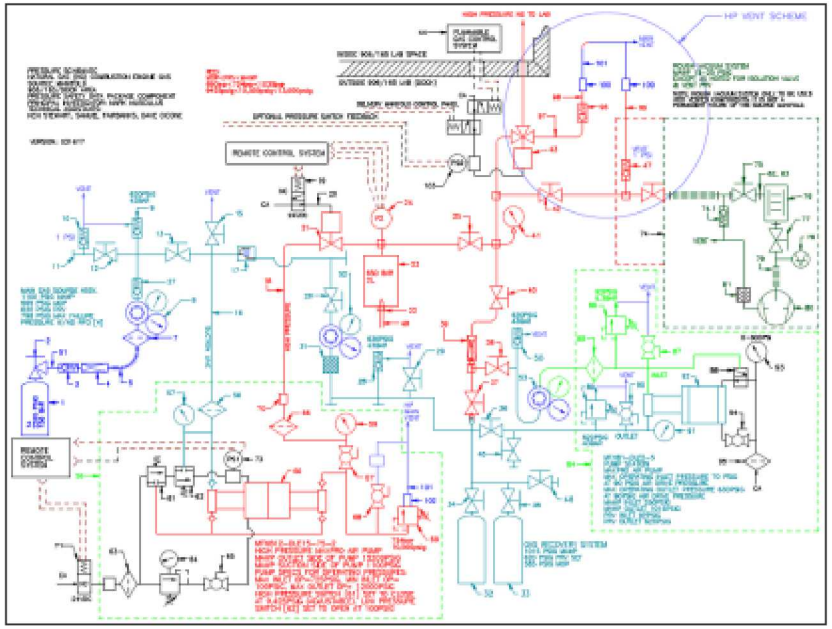
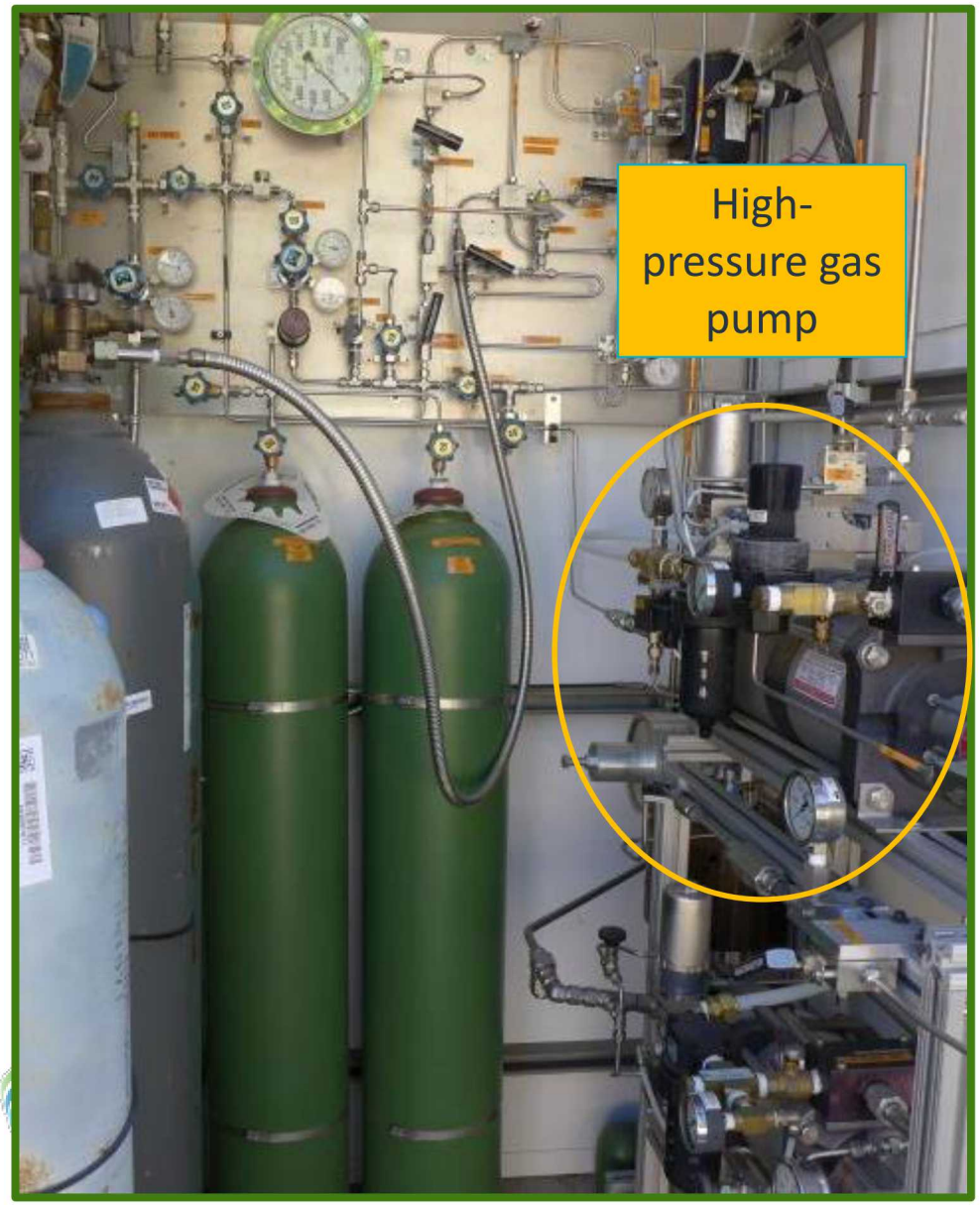


- High-pressure gas pump delivers required flow rate for engine operation using pressurized accumulated volume



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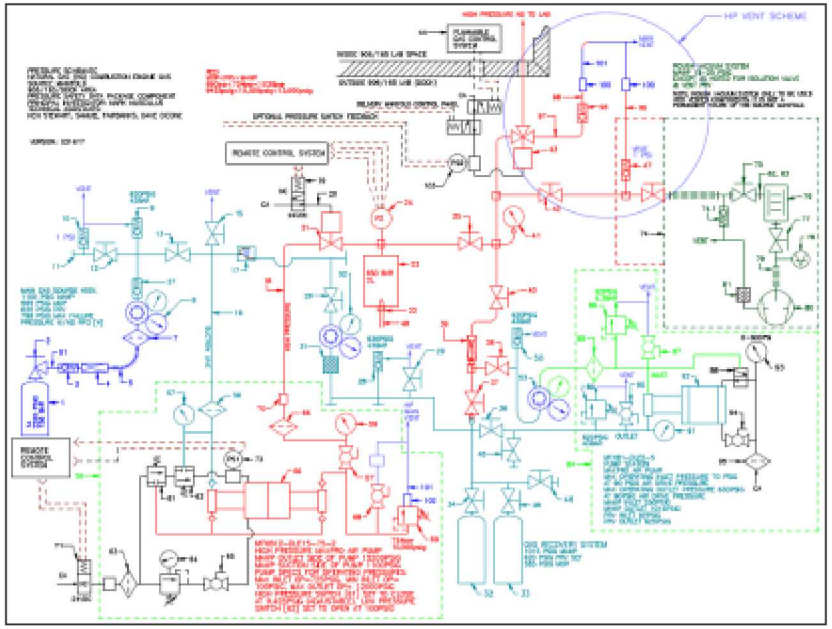
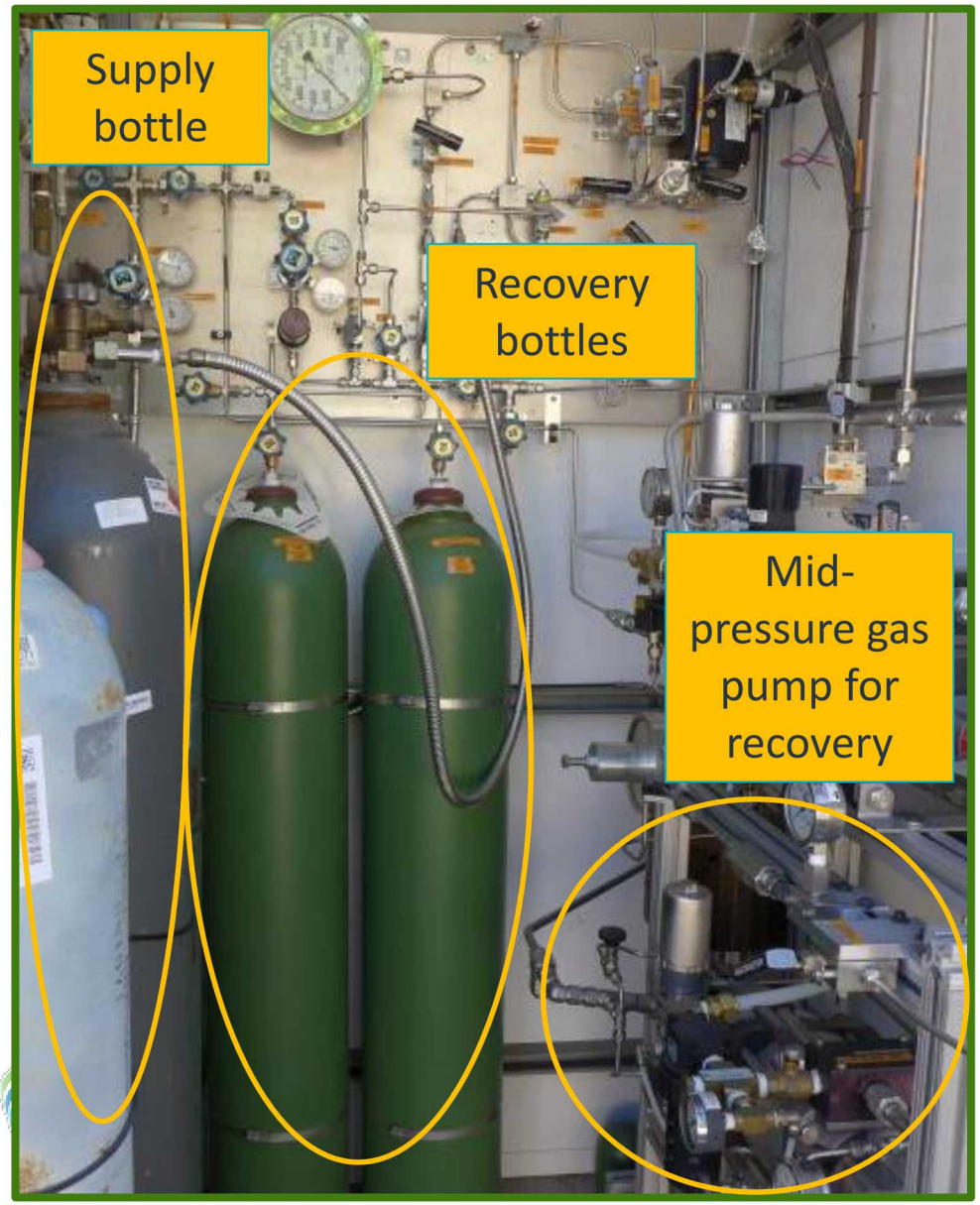
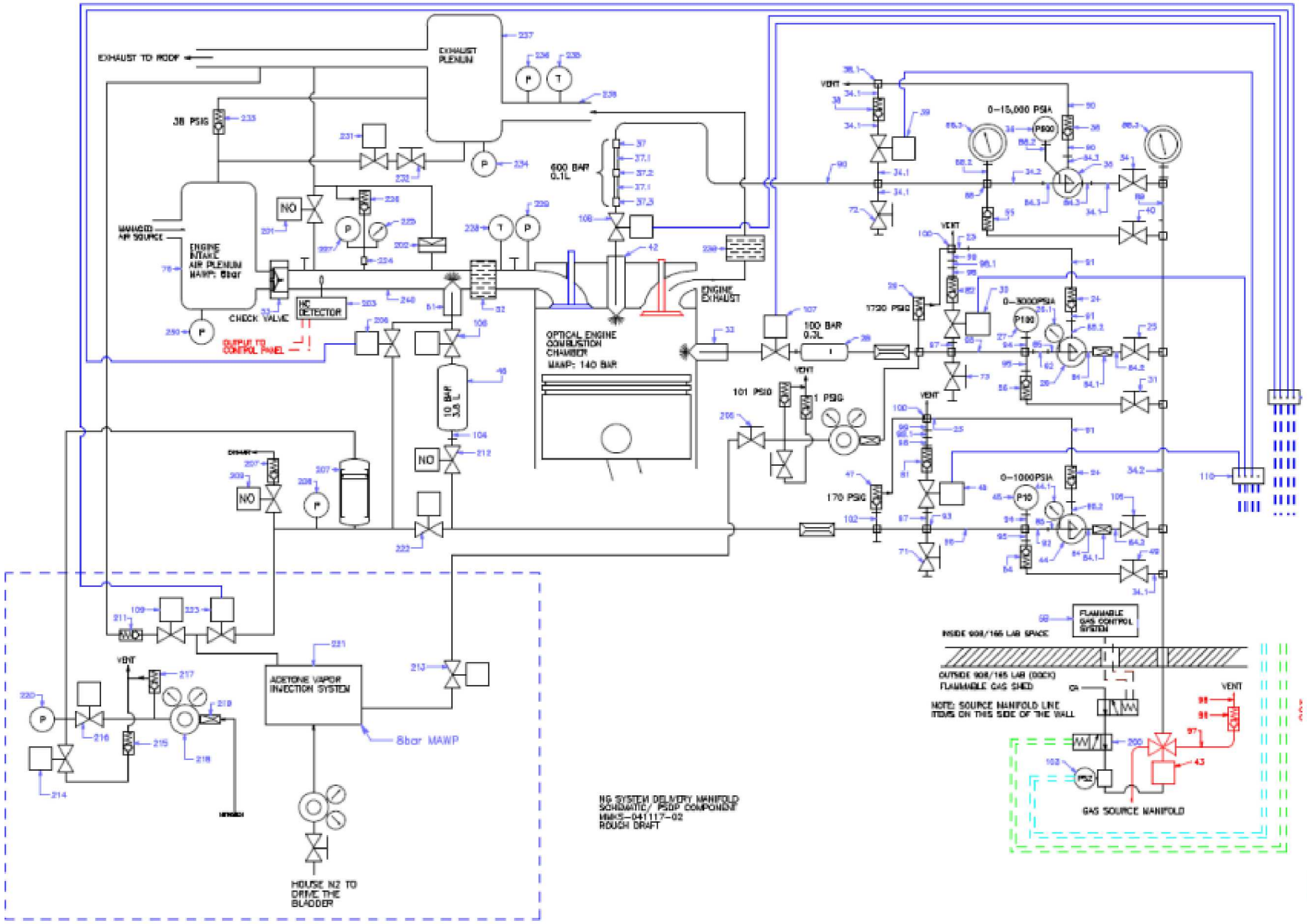


- Certified gas mixtures are expensive + long lead time (~$1500 + 1-2 mo./cylinder)
- A recovery system is in place to collect pressurized gas for future use (instead of venting)



Progress – New Laboratory Capabilities: NG fueling and safety system upgrades to existing heavy-duty optical diesel engine



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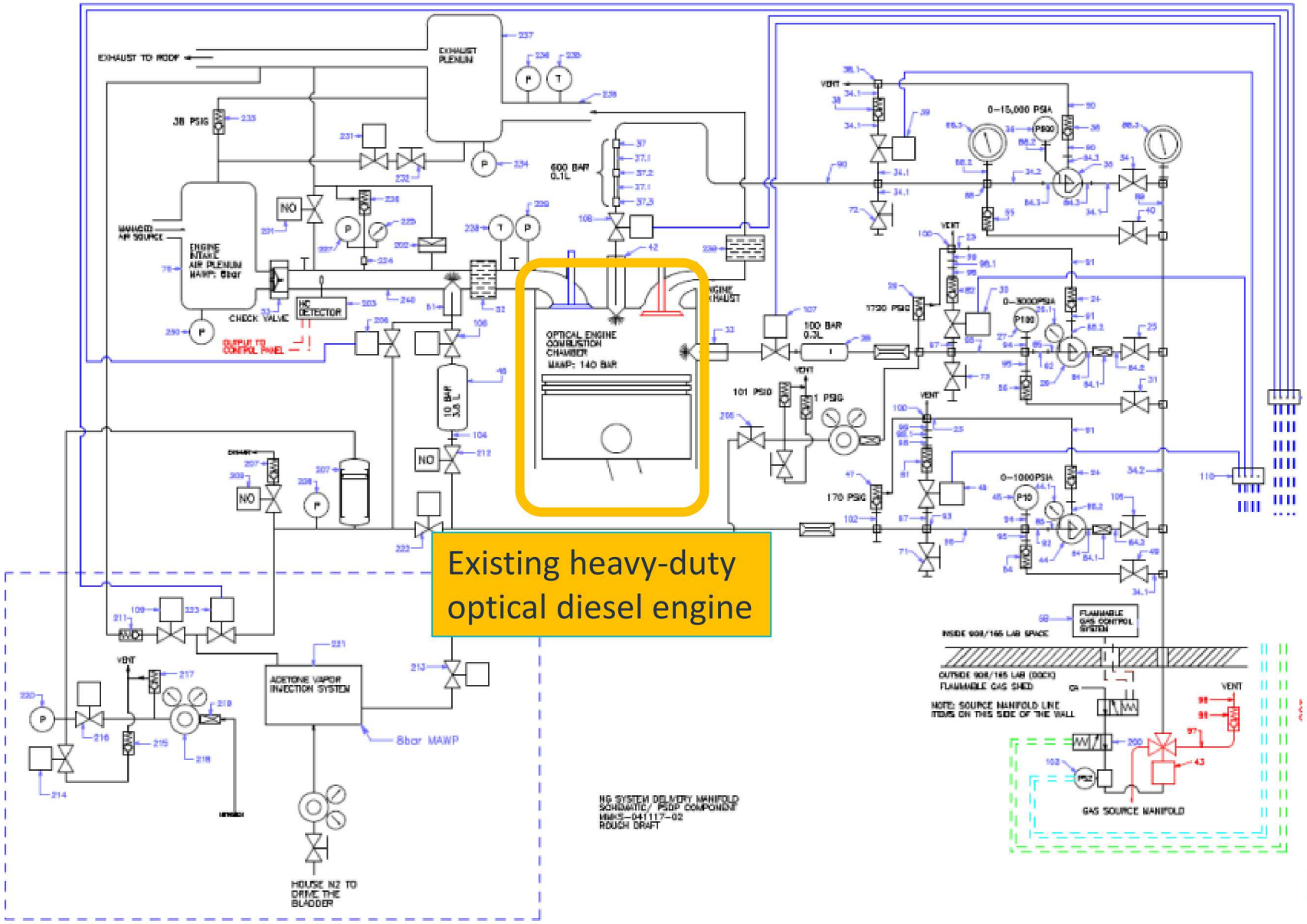

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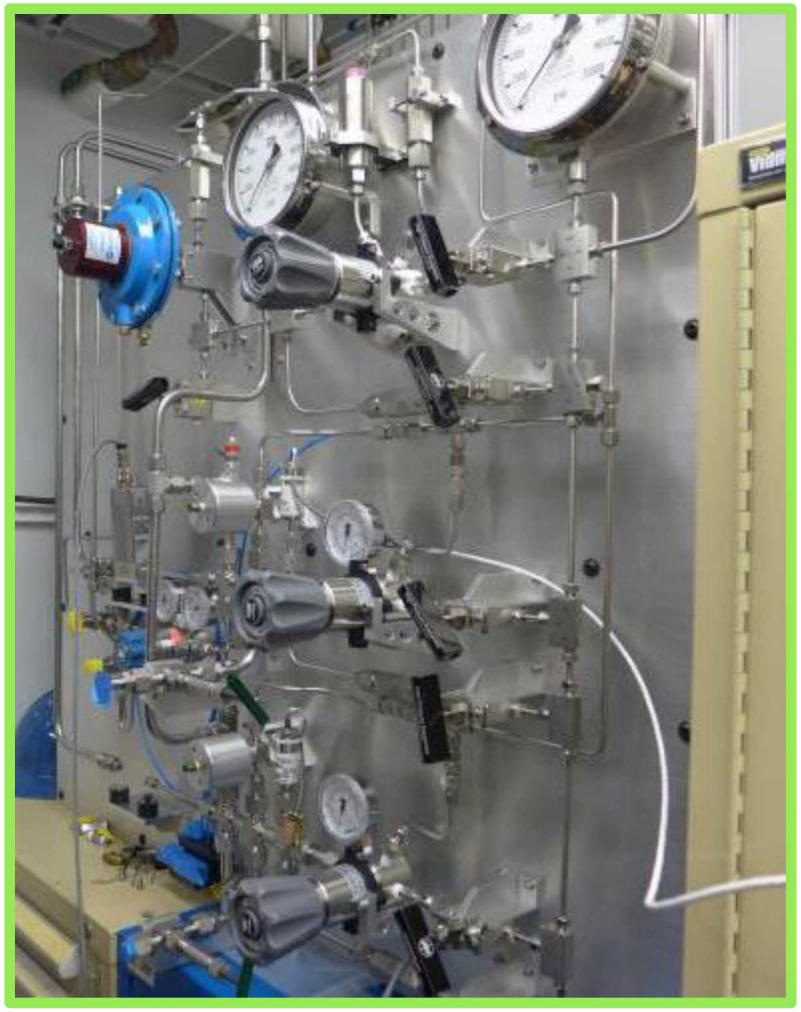
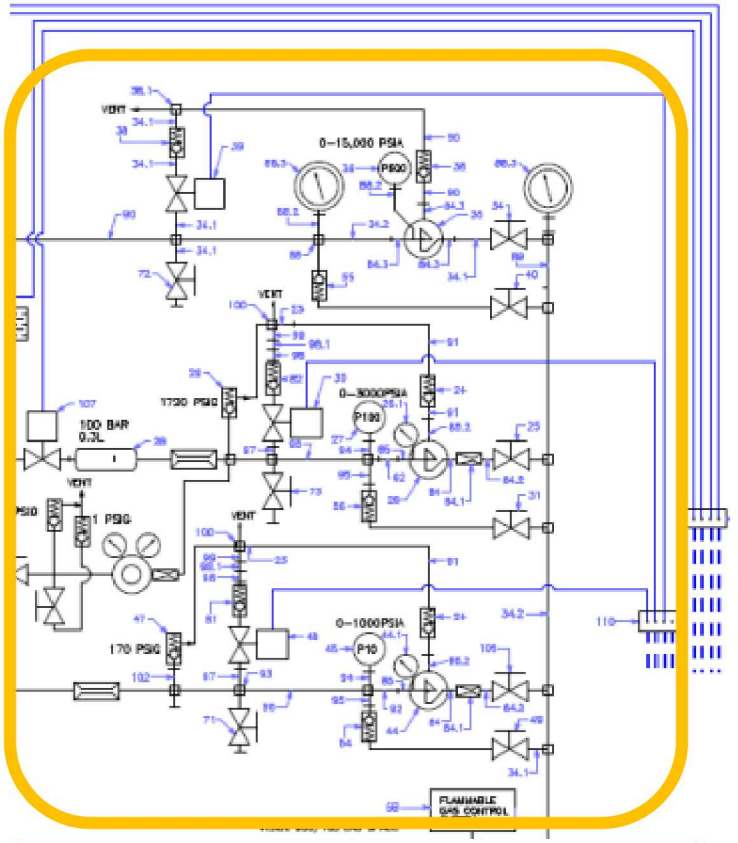
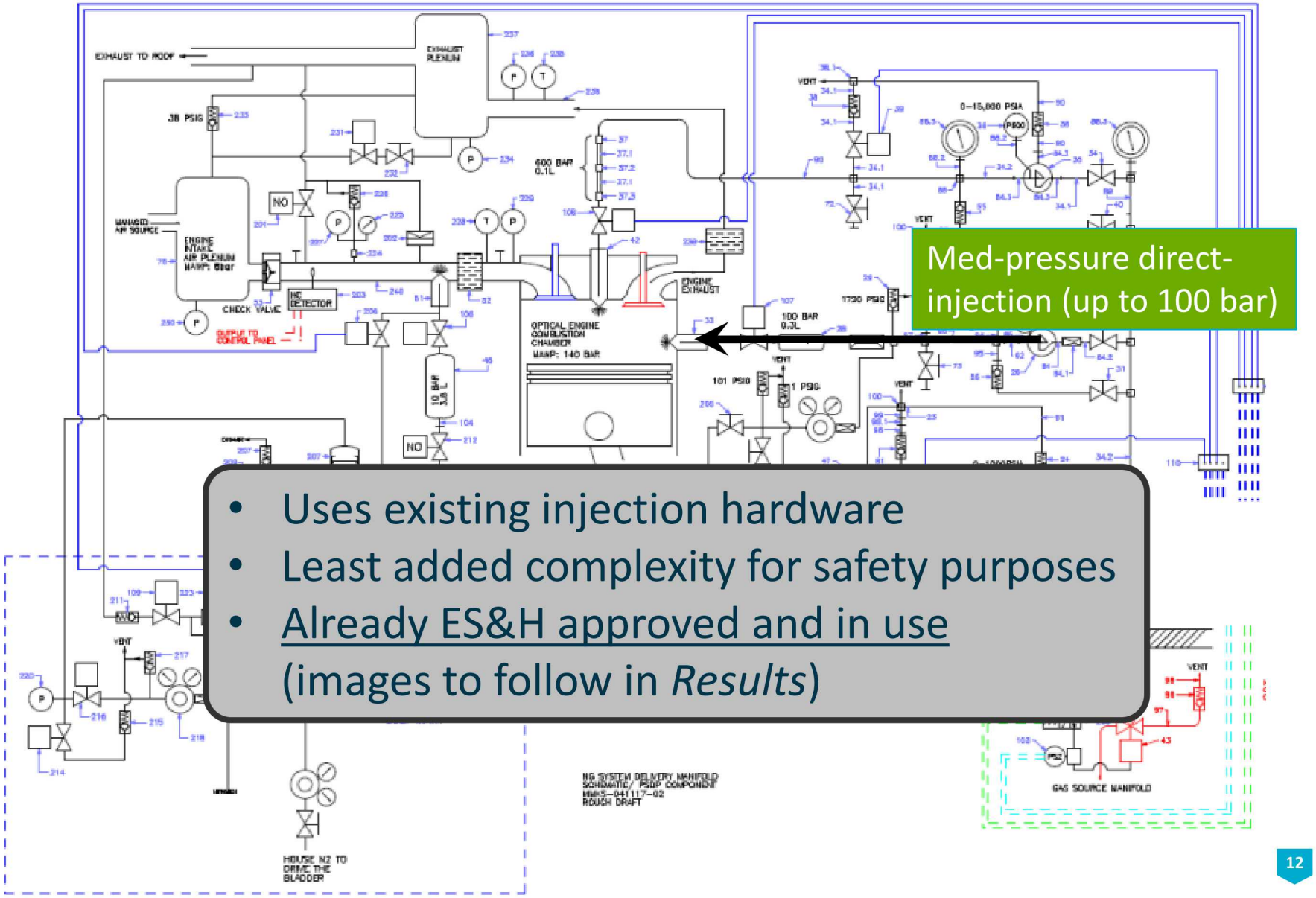




3-leg gas-control and safety manifold capable of both low-pressure premixed intake injection (10 bar) and medium- / high-pressure direct in-cylinder injection (100 and 600 bar)

Progress – New Laboratory Capabilities: NG fueling and safety system upgrades to existing heavy-duty optical diesel engine

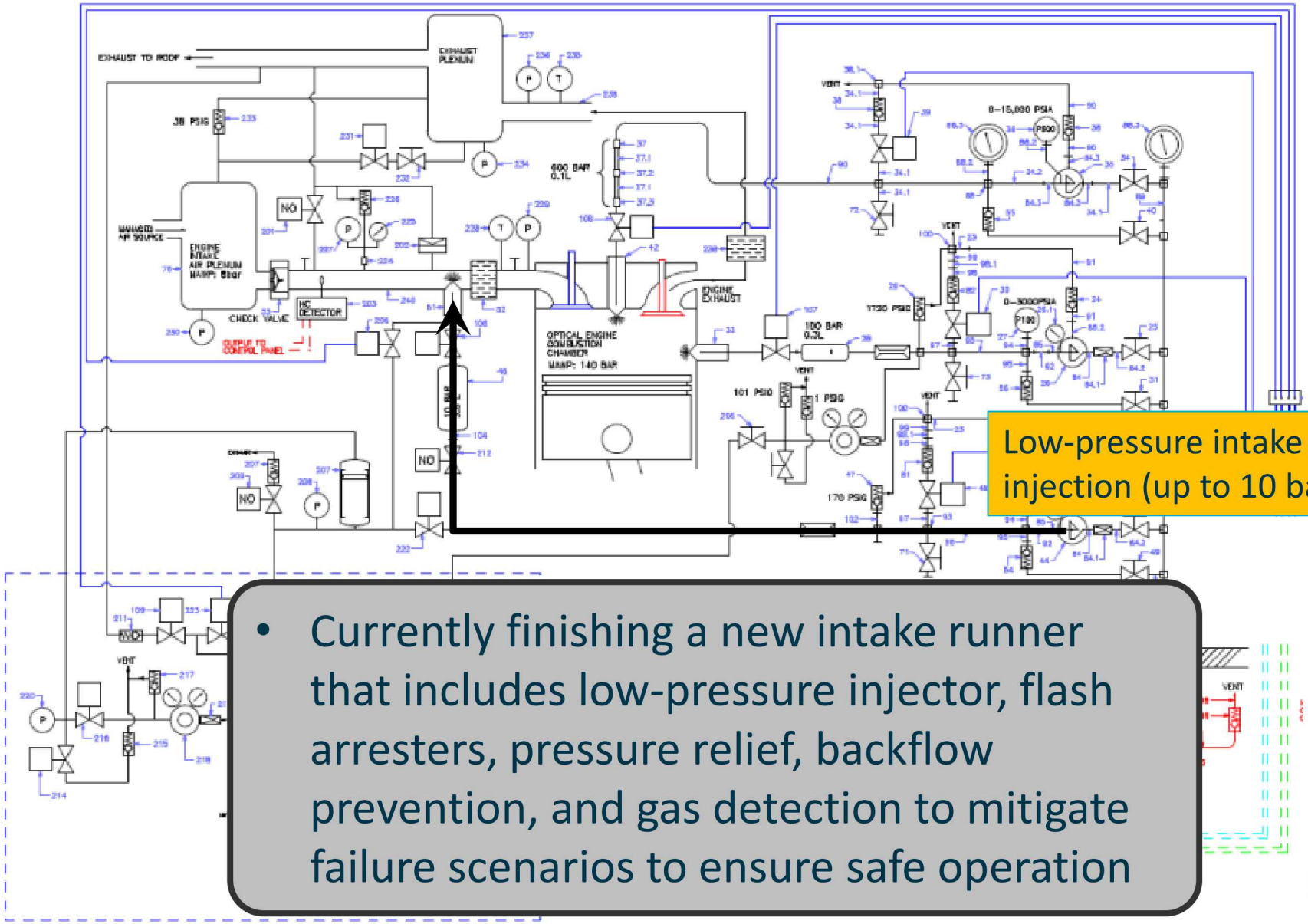


Med-pressure direct-injection (up to 100 bar)

- Uses existing injection hardware
- Least added complexity for safety purposes
- Already ES&H approved and in use

(images to follow in *Results*)

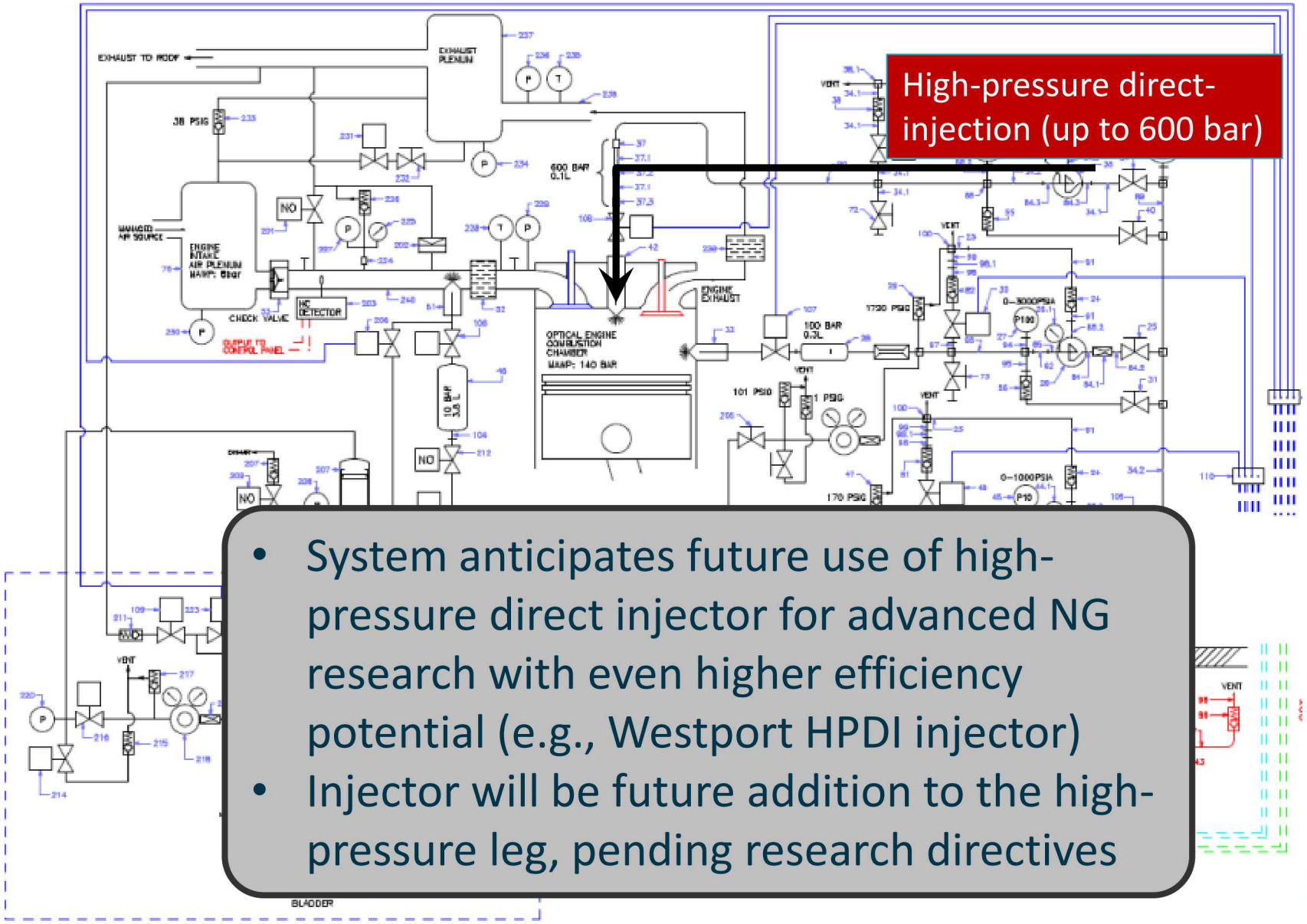
Progress – New Laboratory Capabilities: NG fueling and safety system upgrades to existing heavy-duty optical diesel engine



Low-pressure intake port injection (up to 10 bar)

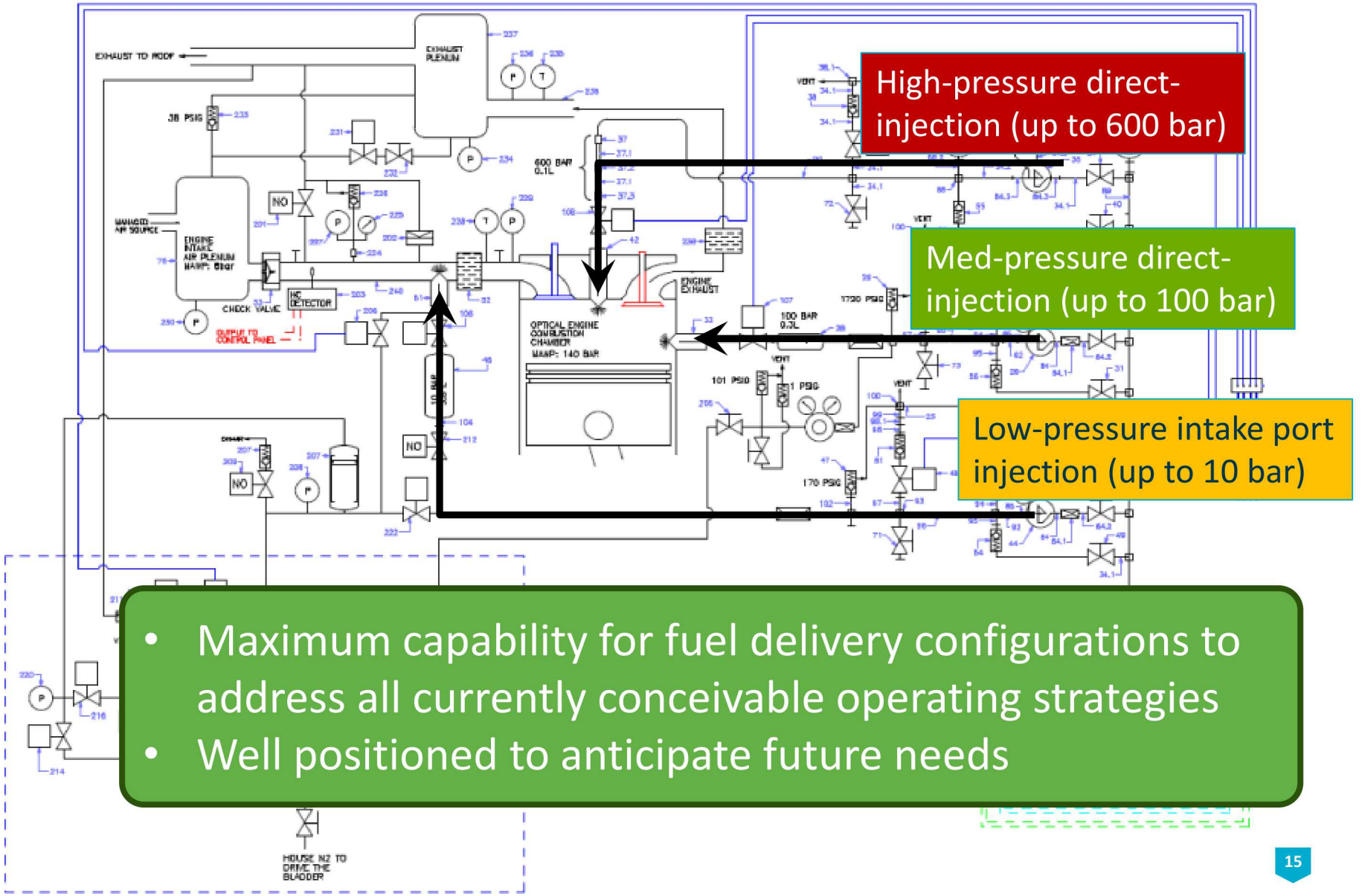
- Currently finishing a new intake runner that includes low-pressure injector, flash arresters, pressure relief, backflow prevention, and gas detection to mitigate failure scenarios to ensure safe operation

Progress – New Laboratory Capabilities: NG fueling and safety system upgrades to existing heavy-duty optical diesel engine



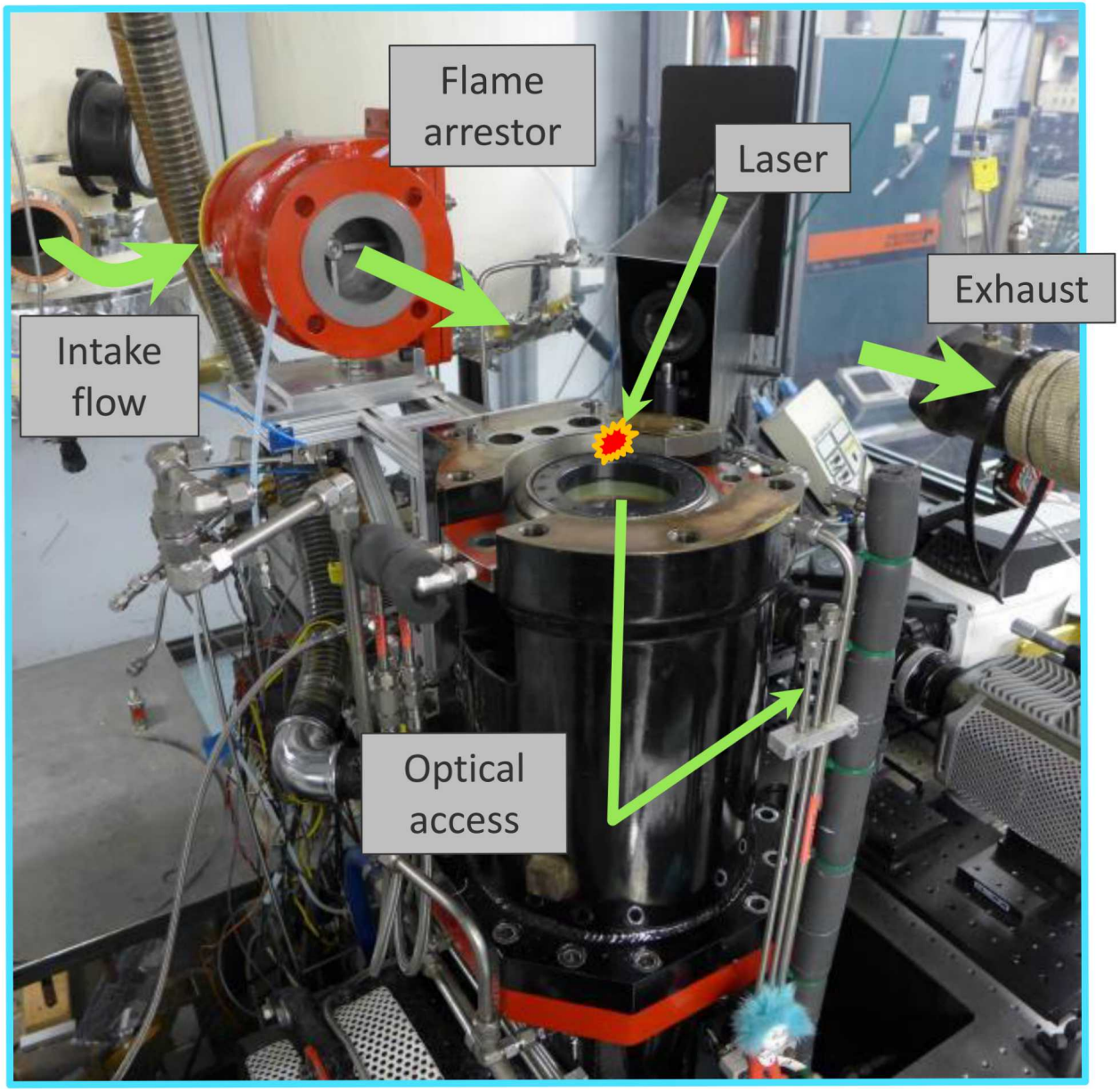
- System anticipates future use of high-pressure direct injector for advanced NG research with even higher efficiency potential (e.g., Westport HPDI injector)
- Injector will be future addition to the high-pressure leg, pending research directives

Progress – New Laboratory Capabilities: NG fueling and safety system upgrades to existing heavy-duty optical diesel engine

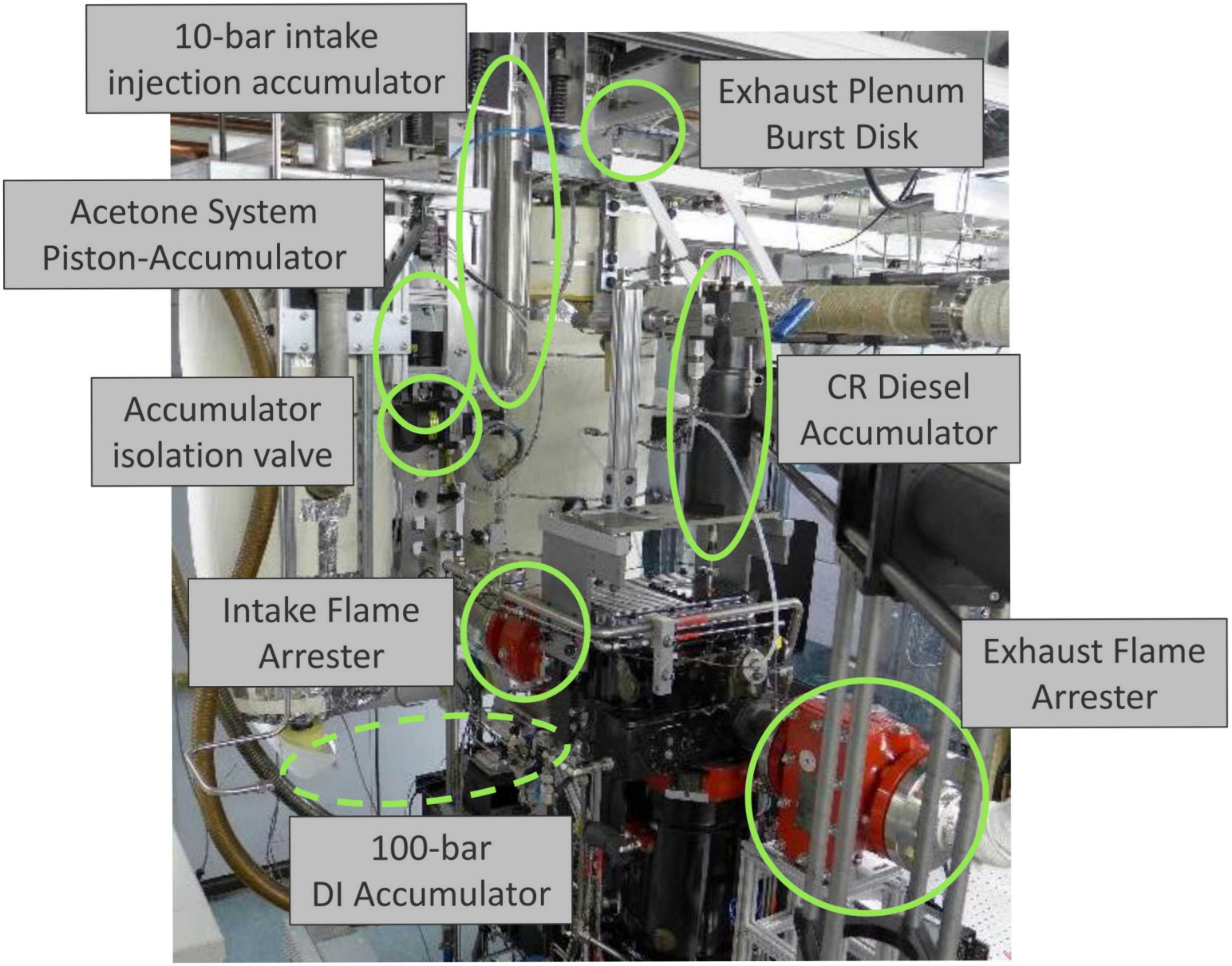


- Maximum capability for fuel delivery configurations to address all currently conceivable operating strategies
- Well positioned to anticipate future needs

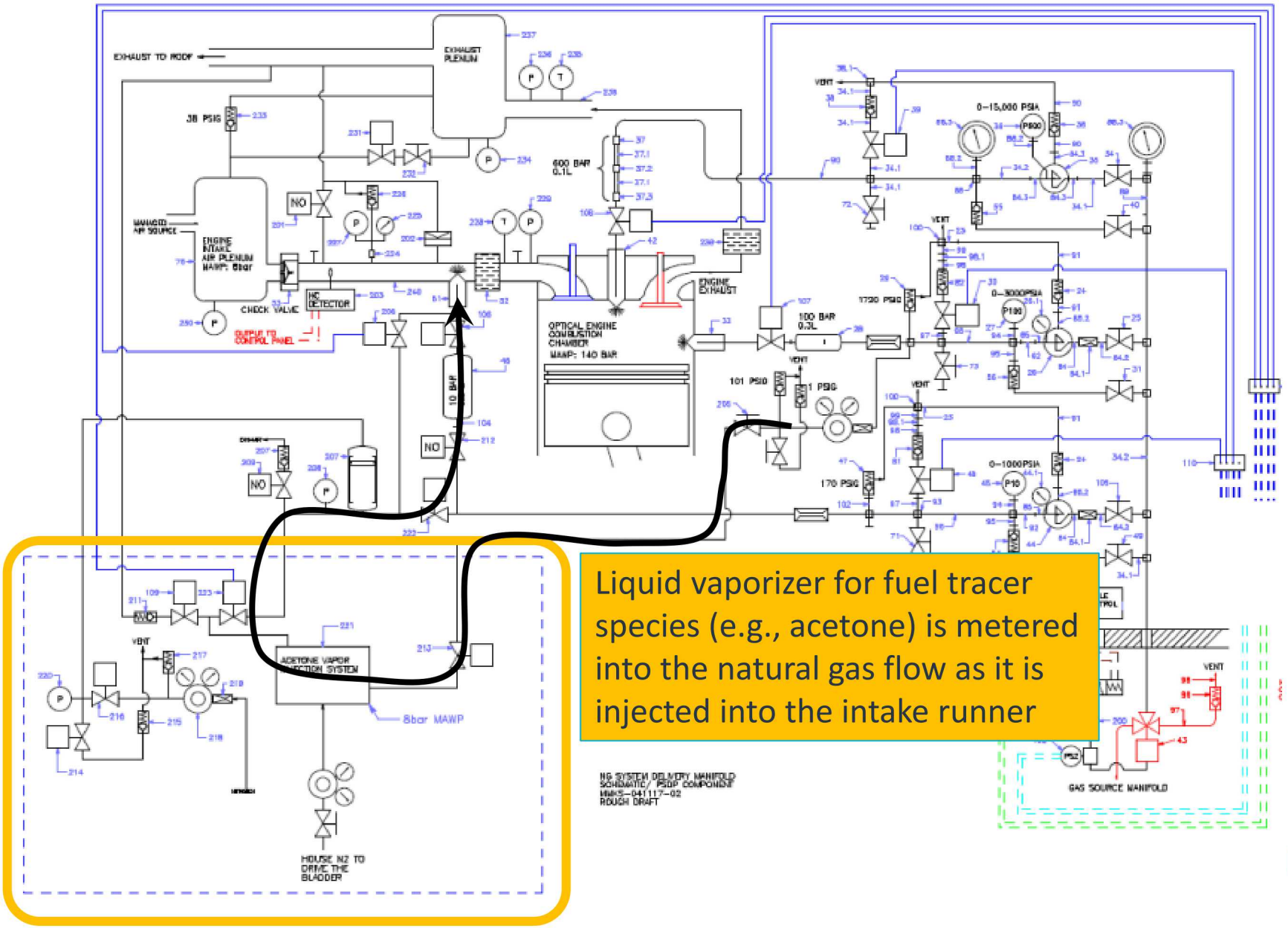
2017 Status – New Laboratory Capabilities: New intake runner with port fuel injector and safety system is in progress



Progress – New Laboratory Capabilities: New intake runner with port fuel injector and safety system is near completion



Progress – New Laboratory Capabilities: a fuel-tracer system is being designed and built to obtain quantitative mixing measurements

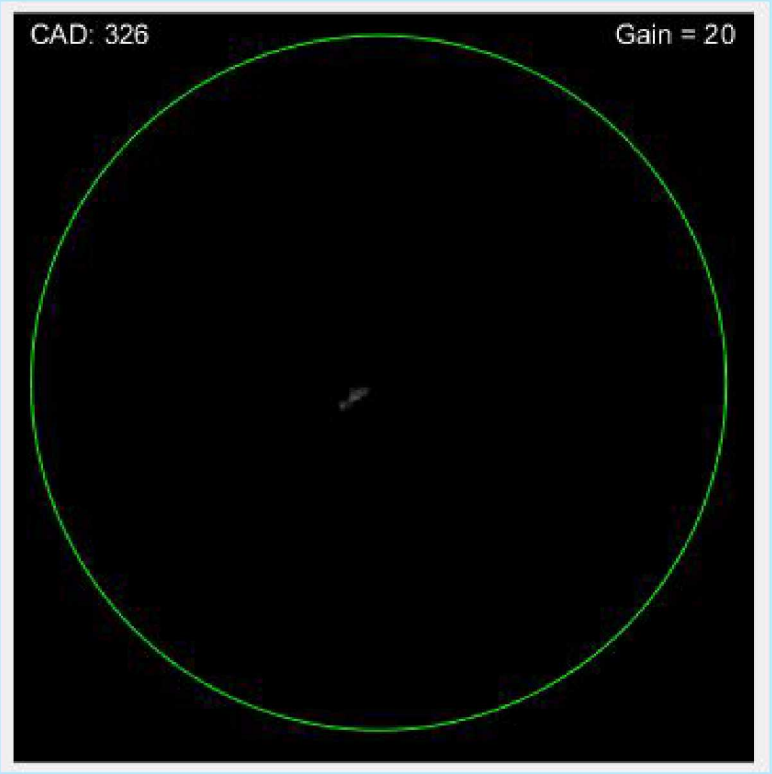


Liquid vaporizer for fuel tracer species (e.g., acetone) is metered into the natural gas flow as it is injected into the intake runner

Results – Engine experiments: demonstrated operation with 100 bar methane (NG surrogate) injection and laser spark

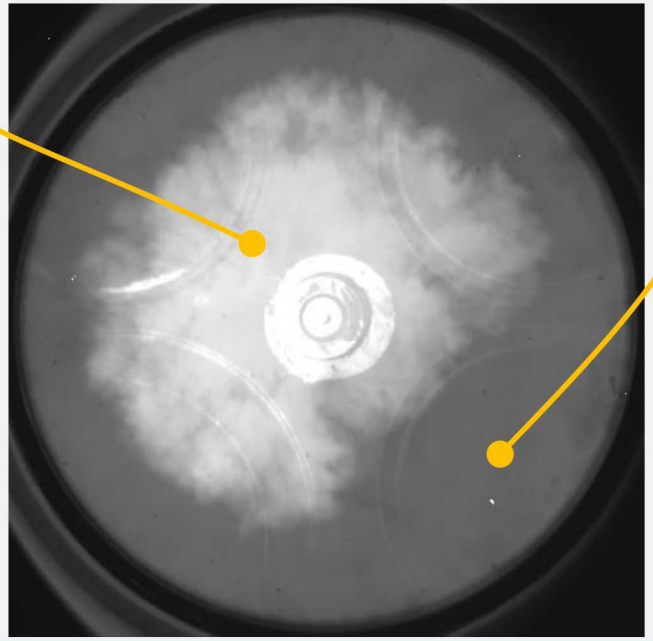
Visible (350 - 600 nm) imaging @ 7kHz

Chemiluminescence from intermediate species generated by the flame



Infrared (3.3 µm) *C-H* stretch emission

- Shows concentration/temperature gradients in compressed unburned fuel mixture that undergoes knock
- Brighter emission from flame zone



These & other diagnostics quantify consistency with model assumptions to understand knock processes