COMBUSTION RESEARCH FACILITY

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Engine Combustion Research: Overview and Research Priorities

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Combustion Research Needs for Everyday Life
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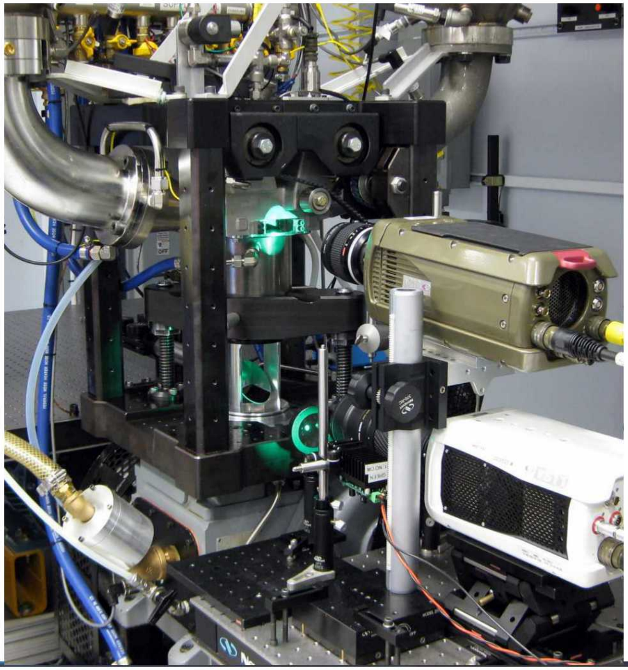
Sandia National Laboratories

Mission

- Provide the combustion and emission knowledge-base needed by industry to develop high-efficiency, clean internal combustion engines adapted to future fuels -- research spans needs from 5 to 20+ years out

- >30 staff, technologists, post docs, and visiting researchers
  - world experts, selected for strong fundamentals
  - staff deeply engaged in leadership roles in the field



The Sandia program has had significant impacts on engine technology over the last 40 years

Energy crisis of the early 70s

DOE ECUT begins engine research.

Light-duty engine working groups with industry/ national labs /universities (DISC, DHC, Knock)

Congress establishes DOE's Tech Transfer Initiative. Many CRADAs with industry established over next decade (e.g., GM, Ford, Caterpillar, Cummins, ...)

Heavy-duty diesel working group

Sandia led Advanced Engine Combustion MOU – 21 industry and national lab partners

Industry engages CRF in WFOs

Engine Combustion Network - Global collaboration and leveraging

Retrospective study – $70 billion return

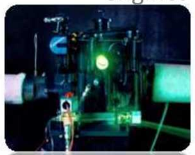
1975	1985	1995	2005	2015

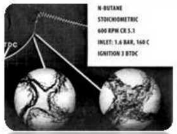
Laser diagnostic development and application in engines begins

Combustion Research Facility (CRF) opens to researchers

Alternative fuels research begins

Introduction of realistic optical engines

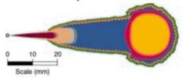




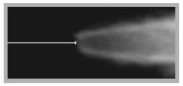
New understanding of SI engine processes developed (knock and flame propagation)

New conceptual model developed and mixing physics clarified for heavy-duty diesel combustion

Conceptual model

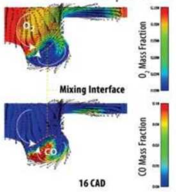


Flame lift-off

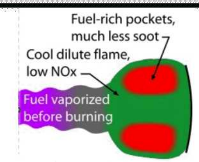


High-efficiency, clean Low- Temperature Combustion (LTC) research initiated

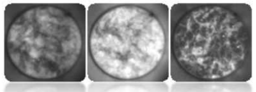
Comprehensive understanding of light-duty diesel combustion developed



Cummins develops first computationally designed engine



Conceptual model for diesel-LTC developed



Pathway to full load range gasoline LTC revealed

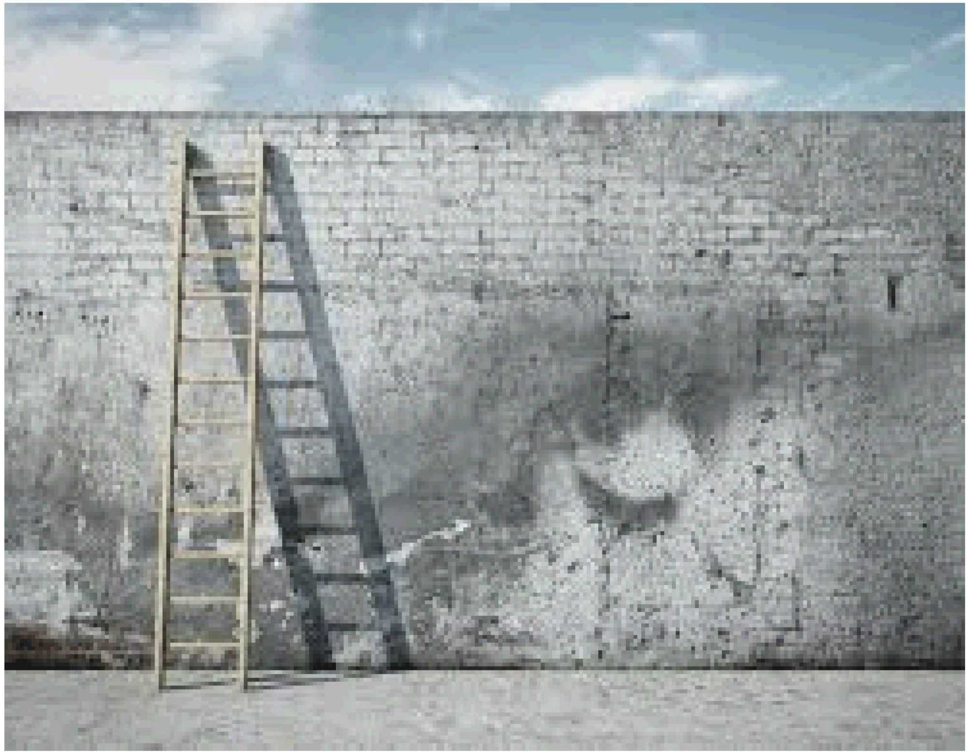
Combustion Research Computation and Visualization (CRCV) opens

Electrification of the transport sector is a desirable long term goal …

… but IC Engines are and will remain the ***environmentally preferred*** propulsion technology for much of the world beyond mid-century

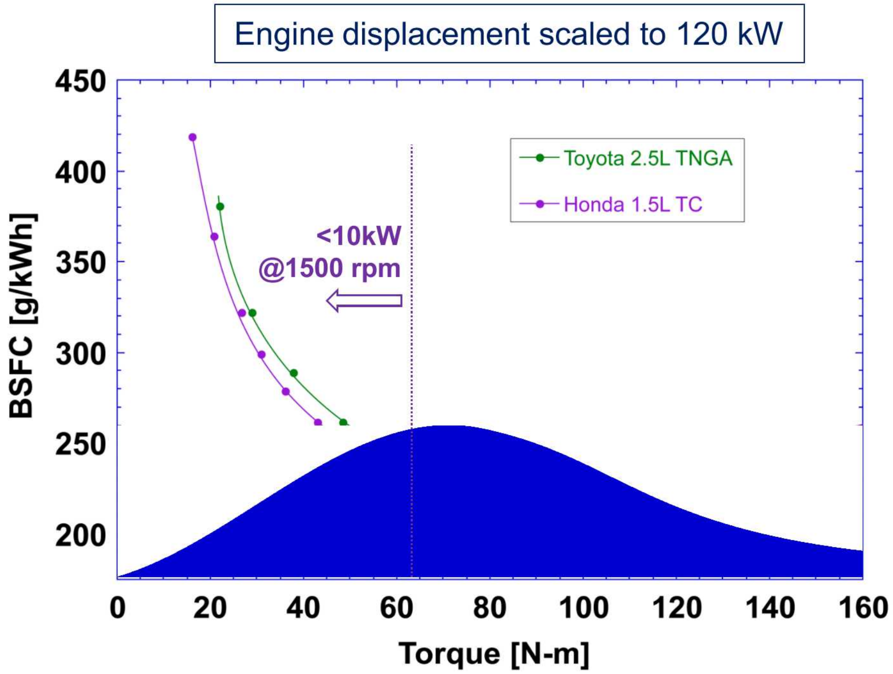
Barriers

What research is needed to achieve the full potential of IC engines?



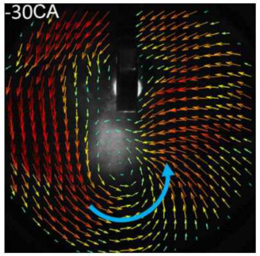
Knock mitigation is key for SI technologies

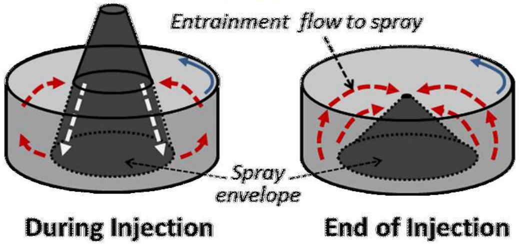
- Hybridization and cylinder deactivation will de-emphasize low-load region — emphasis on increasing mid-to-high load efficiency
- Knock mitigation remains critical for increasing efficiency at mid-to-high loads
  - Knock-resistant fuels
  - Fast-burn combustion systems
    - Understanding impacts of VVL/VVT on in-cylinder flows (tumble/turbulence & scavenging / residual mixing)
  - Controlled mixture distribution
  - Surface temperature control



Lean combustion technologies will also be important

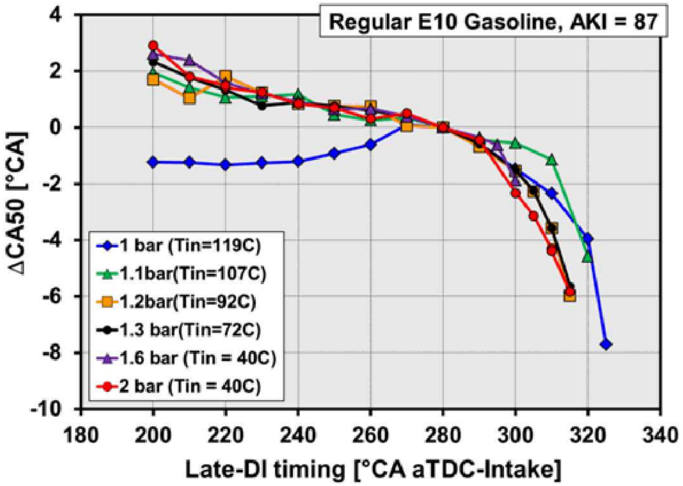
- Stabilization of lean, stratified SI combustion
  - Key flow features causing cyclic variability
  - Understanding of stabilizing flow/spray interactions (effects of multiple injections)
  - Strategies to reduce particulate





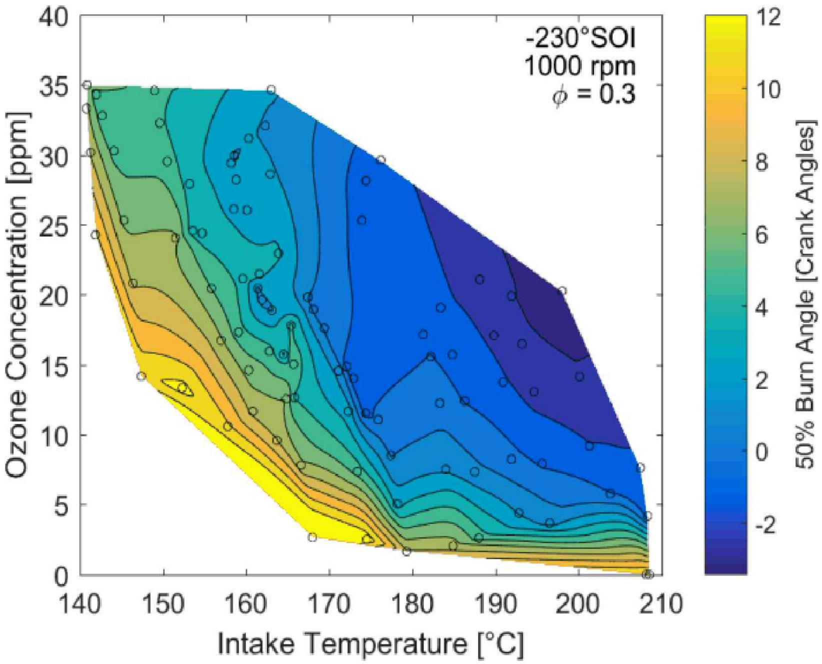
- Further development of spark-assisted CI phasing control techniques
  - Fuel effects
  - Fundamental understanding of impact of boost/T_{in}/EGR etc., interactions with ϕ

- CI combustion phasing control using mixture stratification → synergies with SACI



Enhanced ignition systems will be an enabler for lean combustion technologies

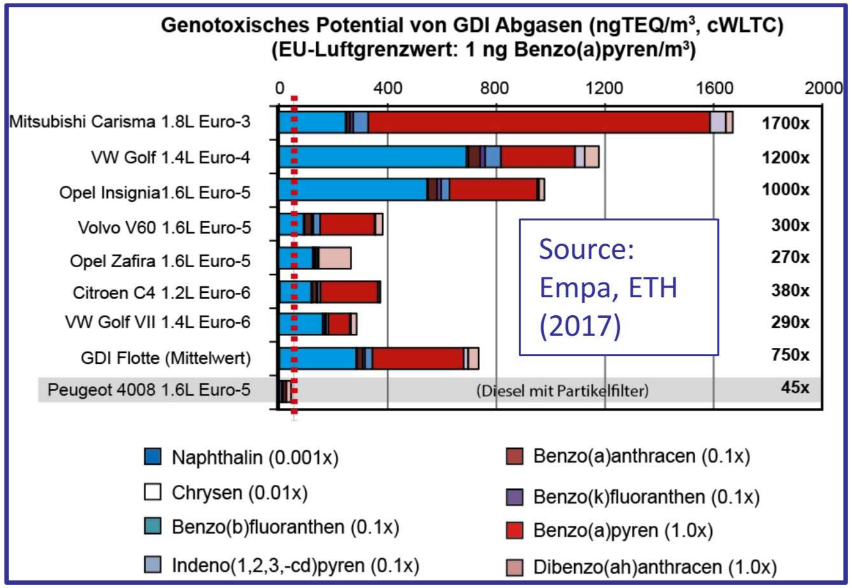
- Low-temperature plasma systems have potential to support multiple combustion strategies using the same hardware
  - More robust ignition for ultra-lean or high-EGR SI operation
  - Improved tolerance to high flow velocities
  - Control and/or reduced intake temperature requirements for inherently low NO_x/PM HCCI-like strategies
- Turbulent jet ignition systems have a similar broad application range, improving both lean and stoichiometric combustion



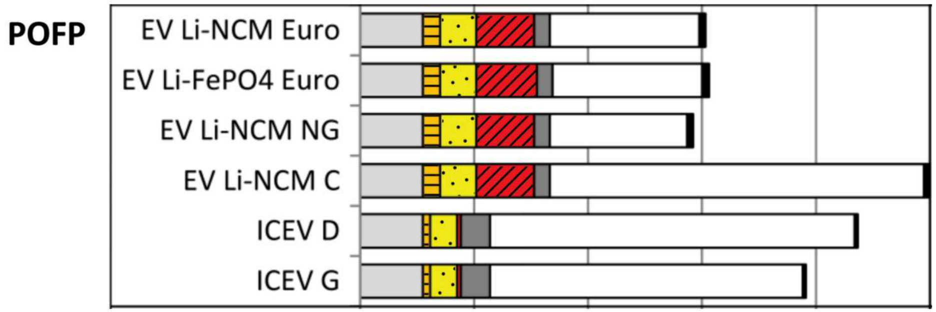
Combustion phasing control and intake temperature requirements can be significantly impacted by O_3

Improved emissions will continue to be key

- Particulate/PAH emission control will be key to future ICE acceptance
  - GPFs increase residuals and back-pressure, impacting FE through knock & pumping losses
  - PM dominated by cold-start
  - Current modeling tools and under-standing of fuel effects inadequate



EU limit for benzopyrene is 1 ng/m3

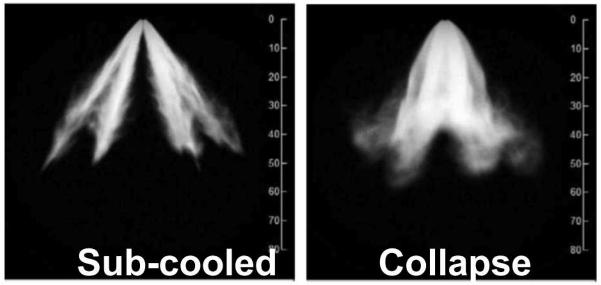


Source: J. Ind. Eco. 17: 53-64 (2013)

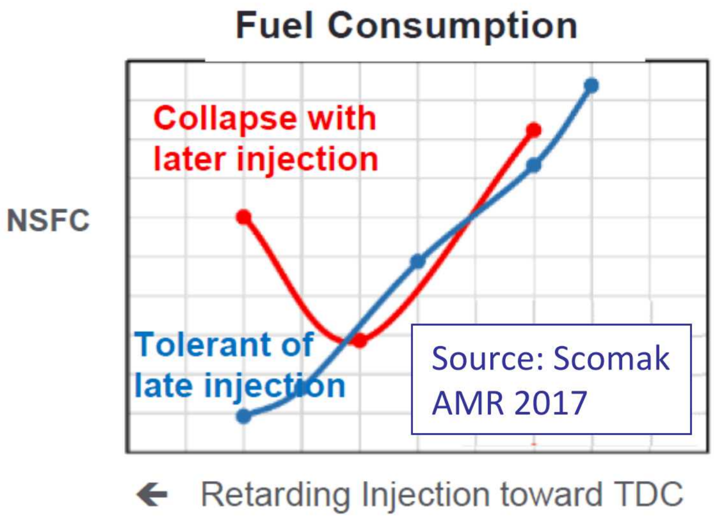
- IC engines can be worse than BEVs for photo-chemical oxidation potential (POFP)
  - Reduced engine-out NOx and HC emissions will be essential
  - Improved, low-temperature lean NO_x aftertreatment technologies

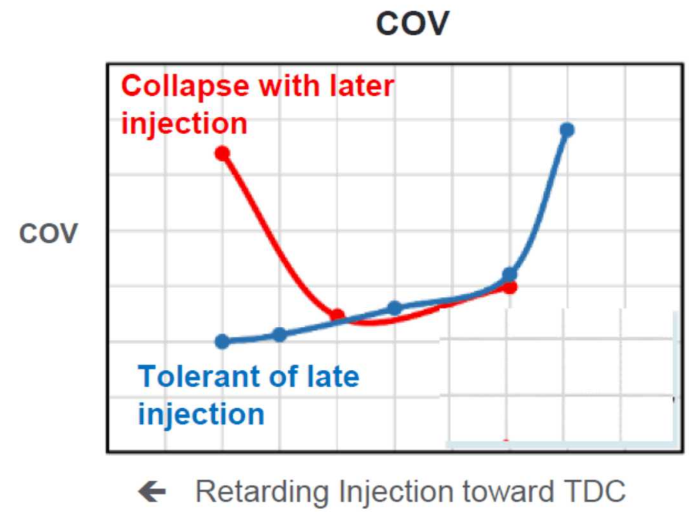
Sprays and mixture formation are foundational to ***all*** high-efficiency, low-emissions combustion strategies

- SI boosted engine knock & emissions sensitive to mixture formation
- Sprays are key to cold-start soot/HC emissions
- DI stratified fuel consumption and COV highly sensitive to spray structure
- Advanced strategies (*e.g.,* Mazda's SPCCI) rely on precise control of mixture formation
- Improved modeling capabilities will be essential → especially multi-phase (enabled by ECN)



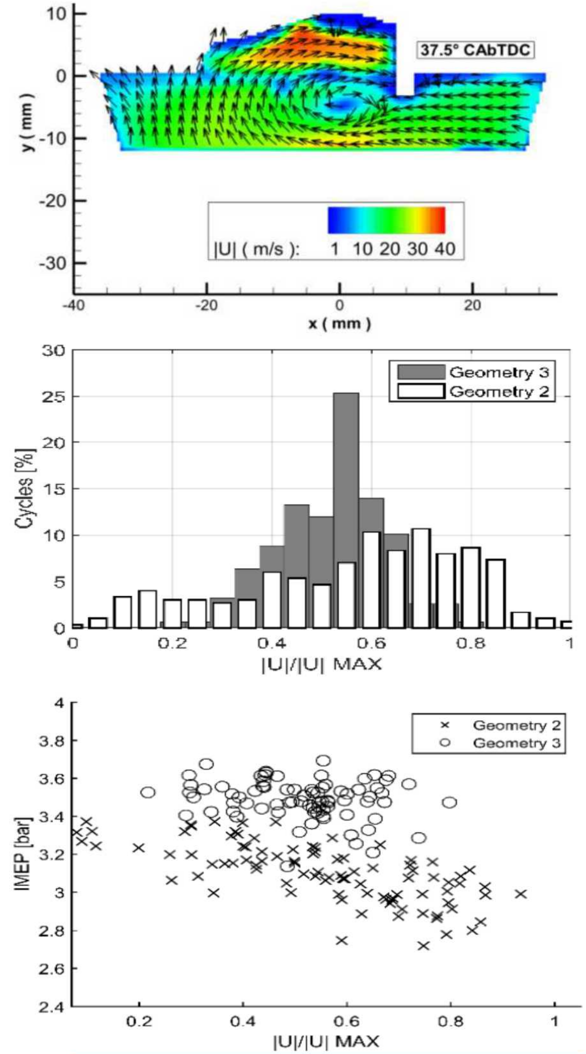
Fuel 183:322–334 (2016)





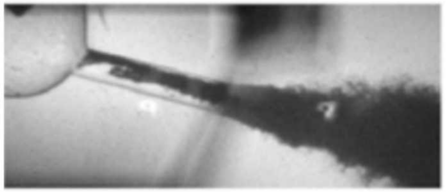
In-cylinder flow control also cross-cuts across multiple technologies

- Key to fast-burn (high tumble) combustion systems – need to understand impact of VVT/VVL
- Reduced cyclic variability
  - More robust ignition and flame kernel growth in lean/dilute systems
  - Mixture formation variability in stratified systems
- Optimal scavenging and mixing of residuals for improved:
  - Knock control in boosted SI engines
  - Auto-ignition control in HCCI-like system

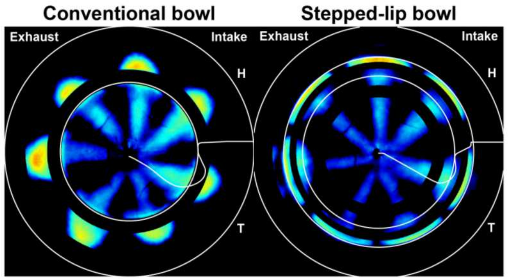


Source: Daimler, THIESEL 2016

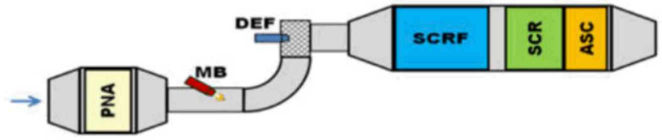
Mixing is key for diesel efficiency improvement



Volvo wave piston



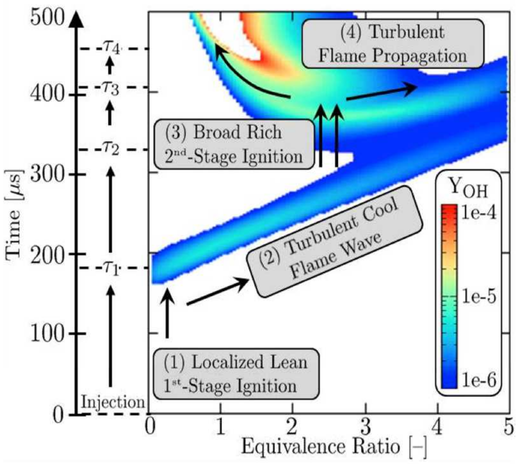
- Shortening/advancing the heat release rate is the mainstream strategy being pursued by the US OEMs. Implementation barriers include:
  - Cavitation – erosion issues
  - Maintaining high late-cycle mixing rates (bowl shape effects)
  - Optimized multiple injection approaches [Understanding both physical & chemical interactions between injection events]
  - Maintaining or reducing NO_x emissions [Complex aftertreatment systems are expected to incur an ~2% FE penalty]

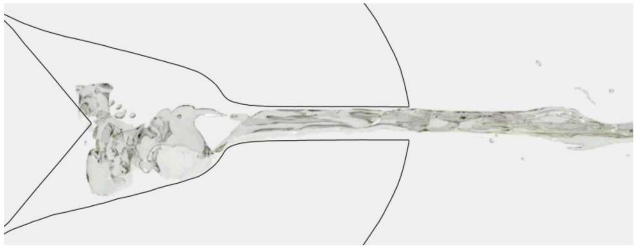


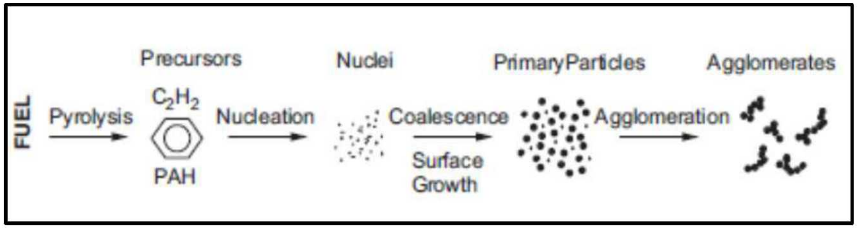
Source: Dieselnet.com/news/2016/09sae.php

Improved models will continue to be essential for engine design and optimization

- Turbulence-chemistry interactions
  - Predictions of ignition delay change by an order of magnitude
  - SI flame kernel can either extinguish or double growth rate depending on conditions
- Two-phase flow and atomization models, including cavitation-turbulence interactions
  - Fuel dependent impact on spray structure, impacting wall-wetting, emissions, and efficiency
- Ignition interactions for multiple injection events
- Improved soot formation models (particle inception)
- Plasma kinetics

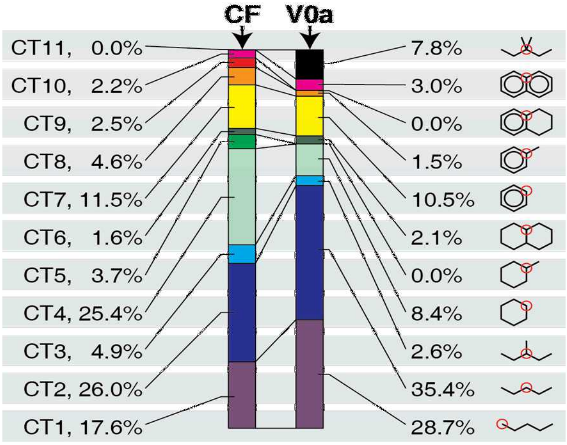


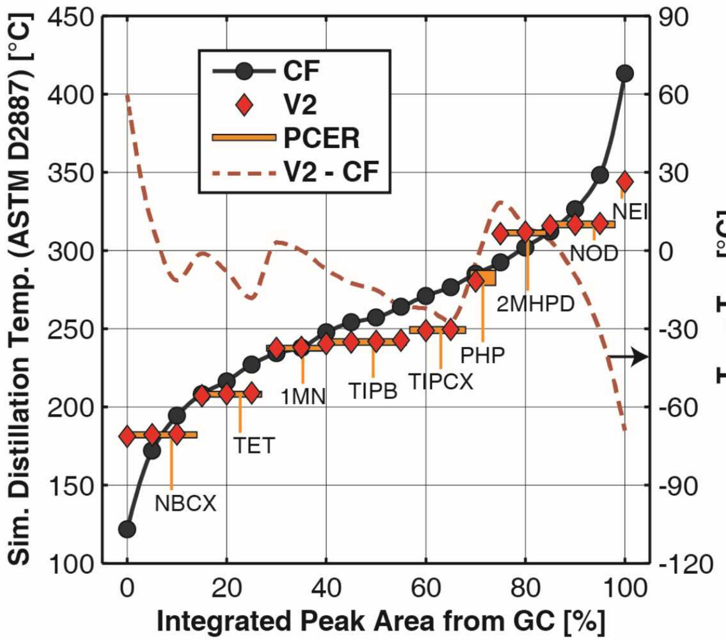




Science-based fuel surrogate formulation

- Realistic surrogate fuels enable coupling of real fuel properties to numerical engine optimization. *How much complexity is required?*
- Approach matches target fuel chemical structure as well as key physical properties (cetane, density, distillation…)
- Optical engine validation of in-cylinder behavior, clarifying and separating PM formation from oxidation, is a necessary project component





Key Challenges Summary

Fuel economy

- SI **knock mitigation** with new fuels, fast-burn combustion systems, controlled mixture/residual distribution, and surface temperature control
- **Robust, low-load** lean operation
  - Reduce COV with advanced ignition, in-cylinder aero, mixture formation control
  - Shorten combustion duration with controlled autoignition, in-cylinder aero
- Advanced diesel, LTC diesel, & high-load GCI
  - Improved **mixture formation** for soot, HC/CO, and high-EGR calibration NOx control
  - More rapid **late-cycle mixing**
- Full-time ACI
  - **Transient control** and **robust low-load** operation through fuels/additives, mixture formation
- All market segments & technology paths – **heat loss reduction**

Key Challenges Summary

Emissions

- **Soot/PAH control** in SI engines through fuel properties, mixture formation control, surface film control
- **In-cylinder NOx control** in mixing-controlled systems through improved mixture formation and late-cycle mixing
- Improved **cold-start/re-start** emissions – intersection of hybridization and advanced combustion strategies