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COMBUSTION
RESEARCH
FACILITY

Sandia-Toyota EGR Knock Project Highlights with connections to DOE Project

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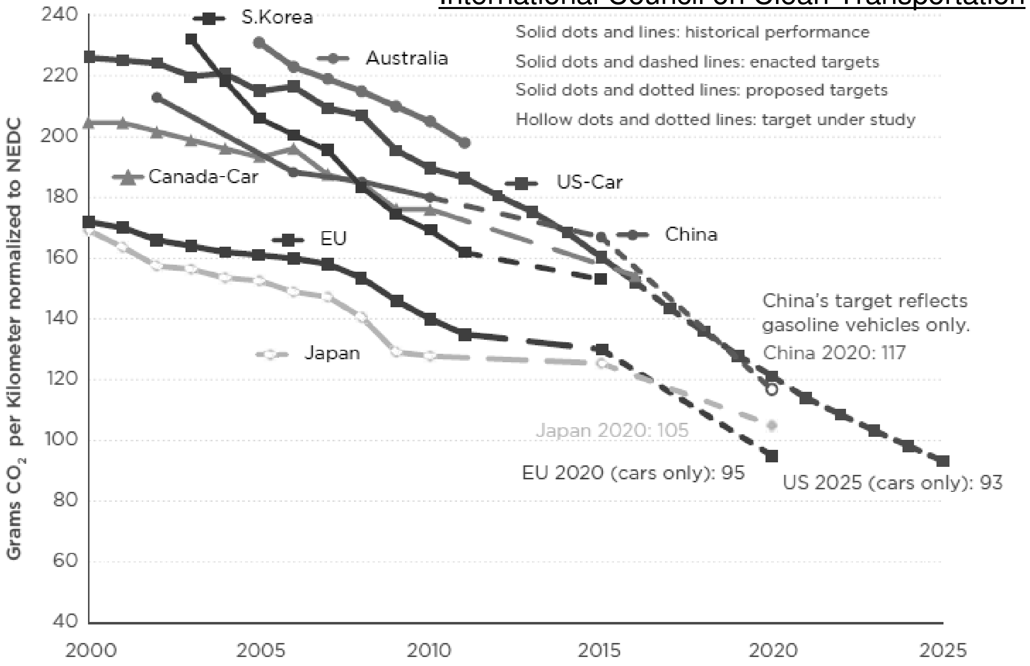
U.S. DEPARTMENT OF
ENERGY

Introduction

- Strong pressure to reduce CO_2 emissions.
- Improved engine efficiency is one key factor.
- Stoichiometric SI operation is standard for gasoline-type engines.



International Council on Clean Transportation

- Knock limited operation often limits engine efficiency.
- What is the optimal SI engine fuel that users are willing to pay for? (DOE Co-Optima project)
- How can EGR be used optimally to suppress knock? (Toyota project)

Research Objectives for Toyota Project

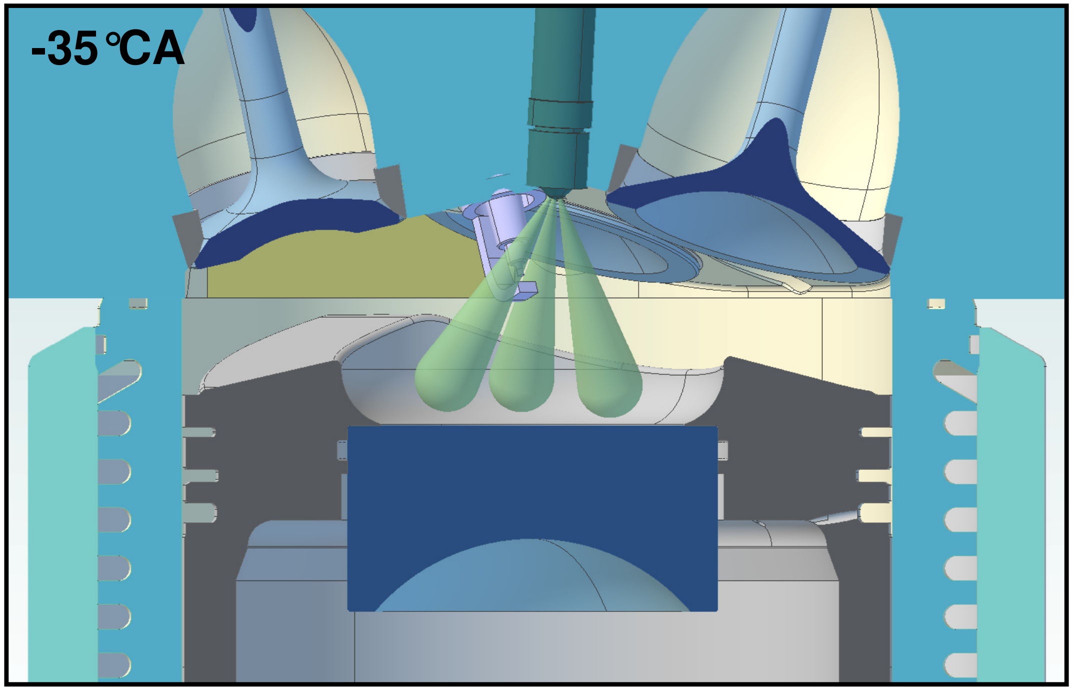
- Clarify the physical, thermodynamic, and chemical factors responsible for the observed response of both deflagration rates and endgas autoignition when EGR is applied.
  - Include fuel effects of gasoline/ethanol blends in the E0 – E30 range.

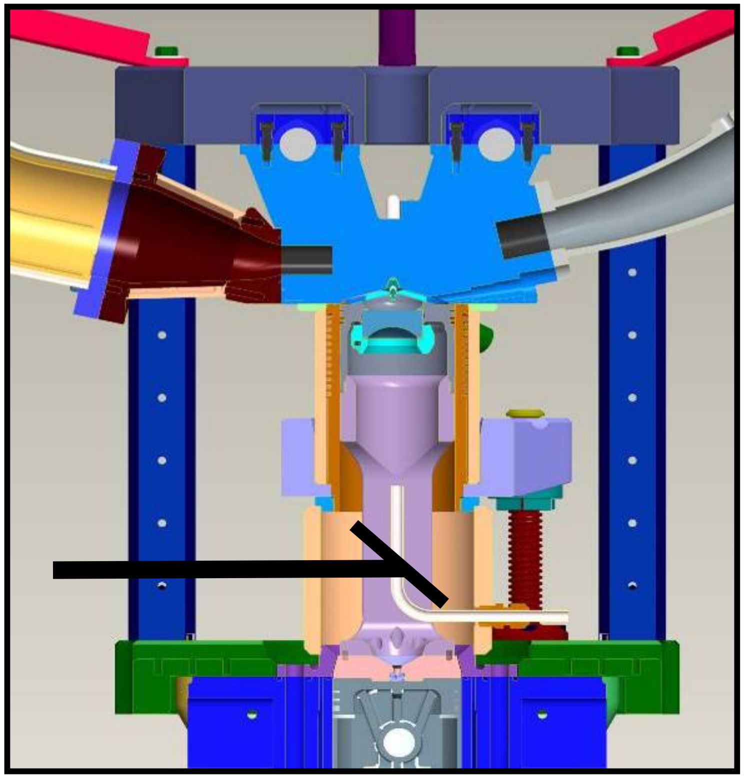
Means:

- Carefully conducted experiments
  - Develop and use knock and autoignition metrics.
  - Parametric studies of ϕ, EGR, and EGR constituents.
- GT-Power.
  - Engine air and EGR flows.
- CHEMKIN
  - Endgas autoignition.

Research Engine

- Drop-down single-cylinder engine.
- Automotive size. 0.55 liter swept volume.
- Identical geometry for **All-metal** and **Optical.**
- Designed for spray-guided stratified-charge operation ⇒ Piston bowl.
- Injections during intake stroke ⇒ well-mixed charge (relatively).



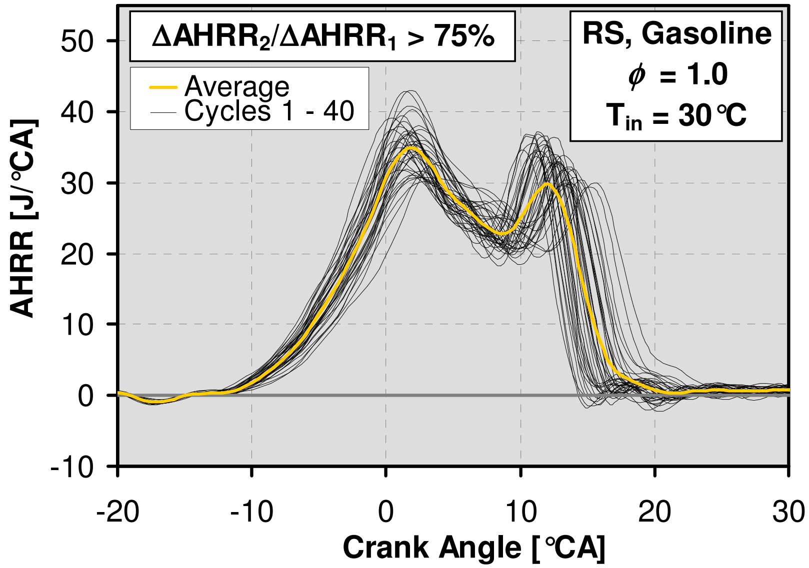


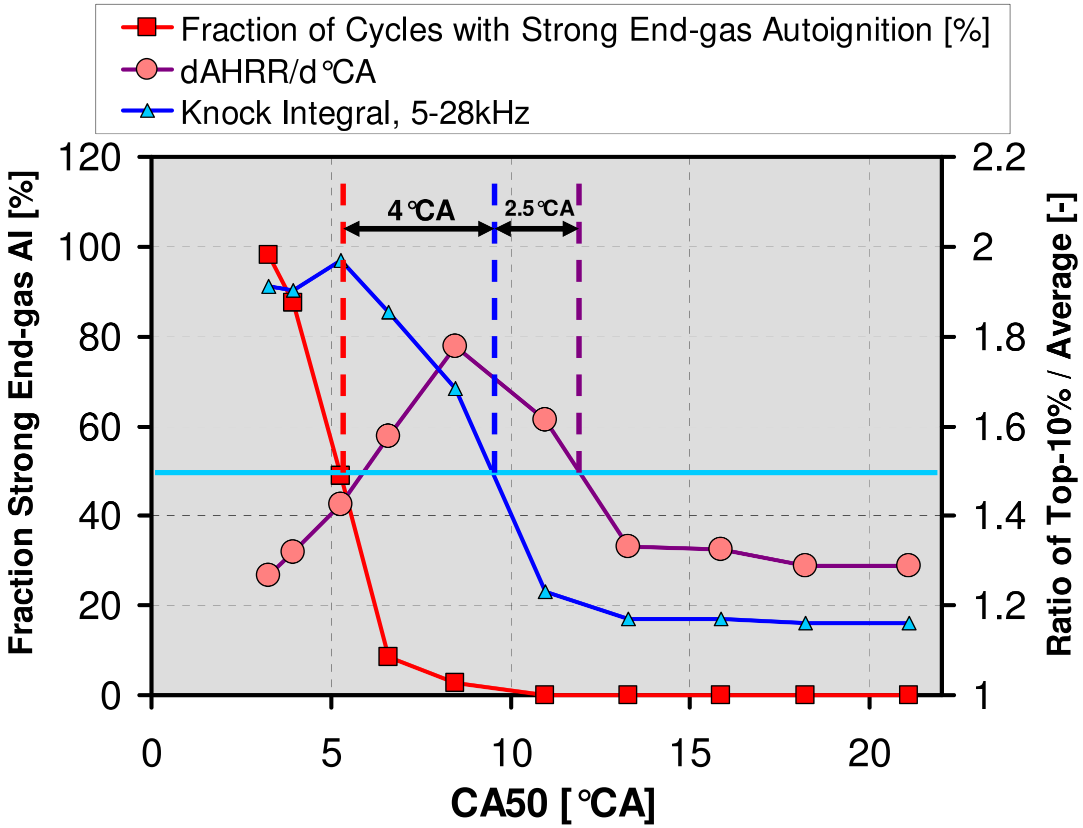
Knock Metrics

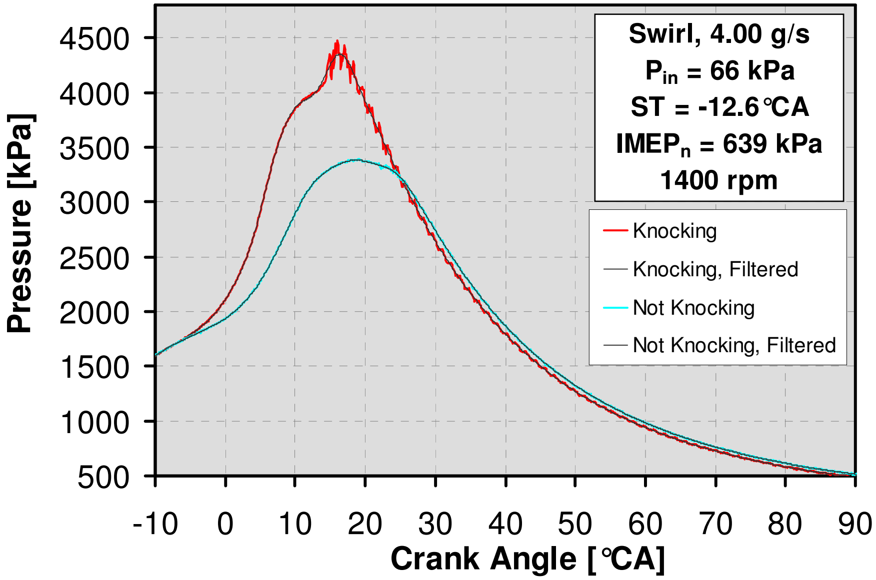
1. **High-frequency analysis of in-cylinder pressure trace – Knock Intensity.**
   - 5-28 kHz energy in 0 – 80°CA range.
   - Used for Co-Optima study.
2. Accelerometer data from cylinder head.
   - Similar to in-cylinder pressure based metric. No observed advantage relative to KI.
3. **Statistical analysis of endgas AHRR for individual cycles.**
   - For a given KI, fraction of cycles with strong end-gas autoignition varies widely with fuel. Unclear what this means.
4. Average AHRR trace.
   - Useful for operating points with very repeatable AHRR. Generally not applicable for combinations of late CA50 and high EGR rates.
5. Combustion Noise Level
   - Increases with end-gas autoignition, but does not provide distinct knock detection.
6. Ringing Intensity
   - Not really applicable for SI knock studies.
7. **AHRR decrease rate at the end of combustion = dAHRR/d°CA**
   - Most sensitive metric. Fundamentally tied to transition from deflagration to autoignition.

Comparison of Selected Knock Metrics

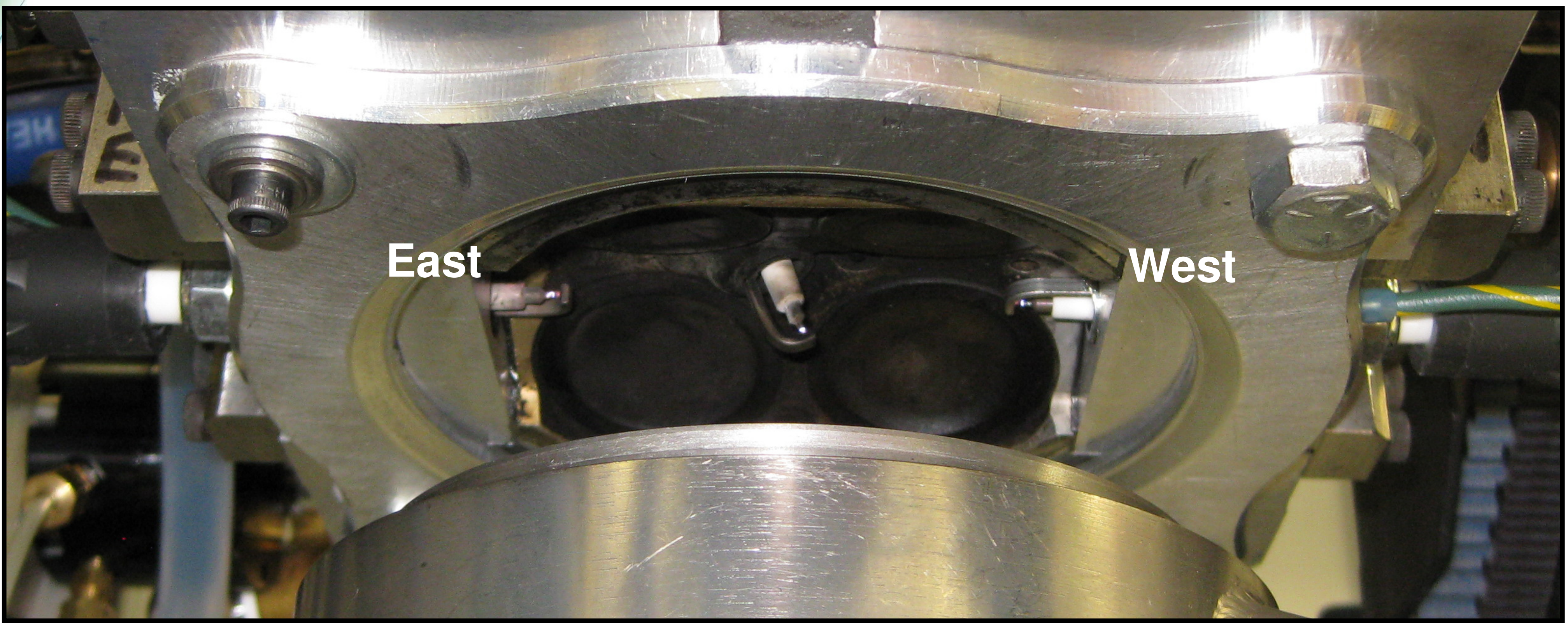
- Having a strong second peak makes data interpretation intuitive.
- Statistical processing of pressure oscillations is 4°CA more sensitive, but direct coupling to autoignition is lost.
- Examination of AHRR trace during burn-out is 6.5°CA more sensitive, and it is tied to end-gas autoignition. (Best option!)







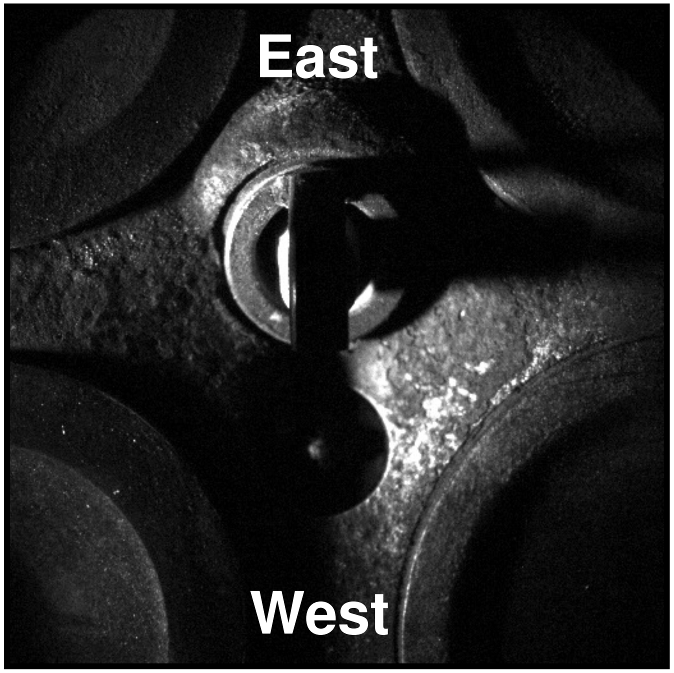
Initial Spark-Plug Study for DOE

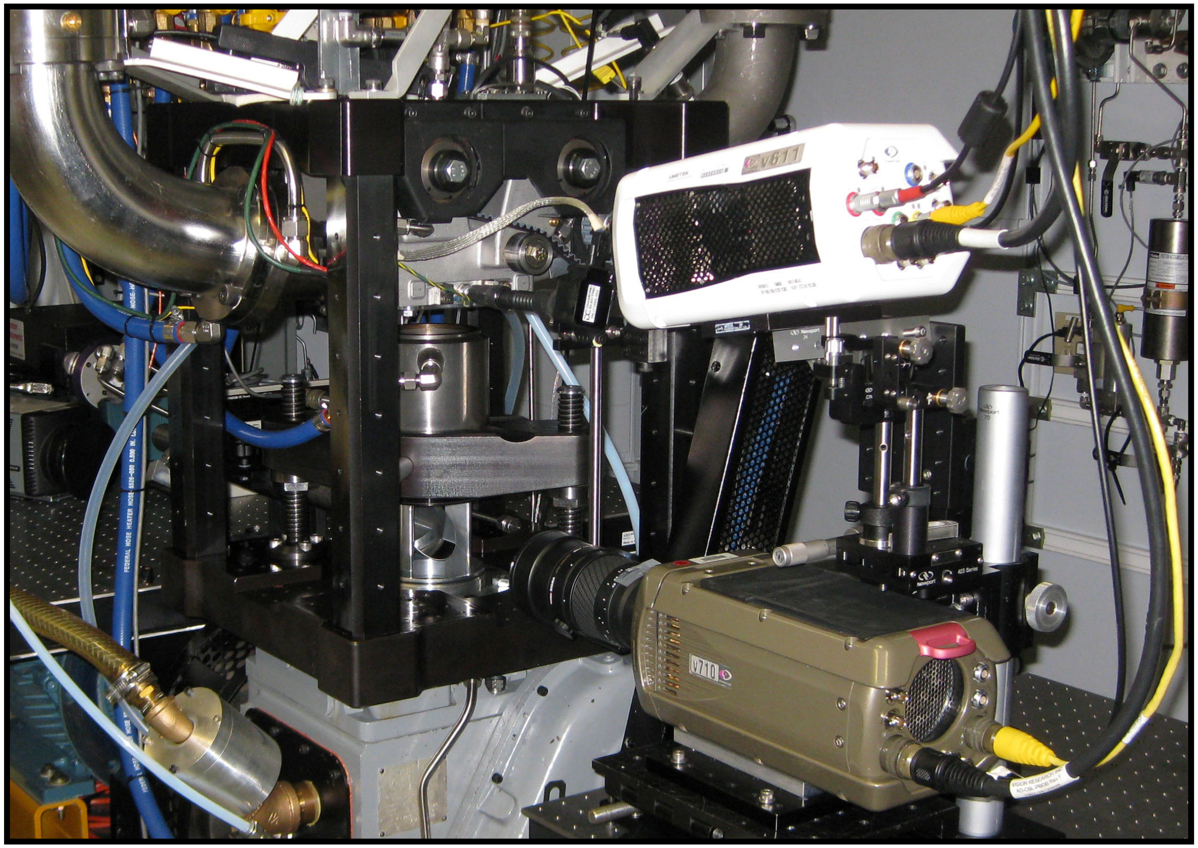


- Three spark plugs allow multiple ignition scenarios.
- Here, study effect of East-West spark scenarios on AHRR and flame spread.

Imaging Study

- Use only Phantom v710, operated at 20 kHz = 0.3 °CA with 512 x 512 pixels.
- 48 μs exposure. f-stop = 2.8.
- Reference image at -25 °CA.
- Illumination from north.



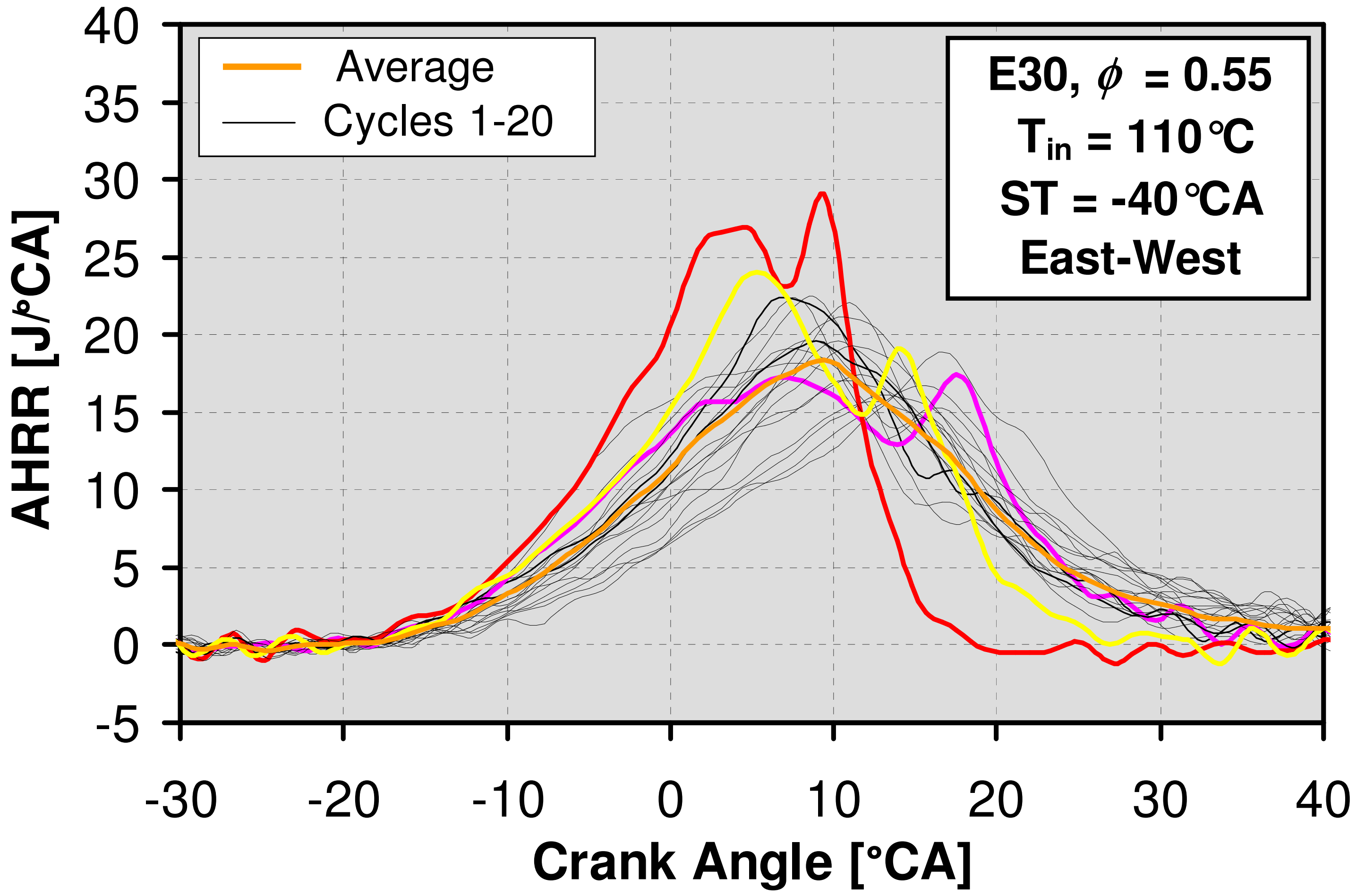


East-West Movie Example

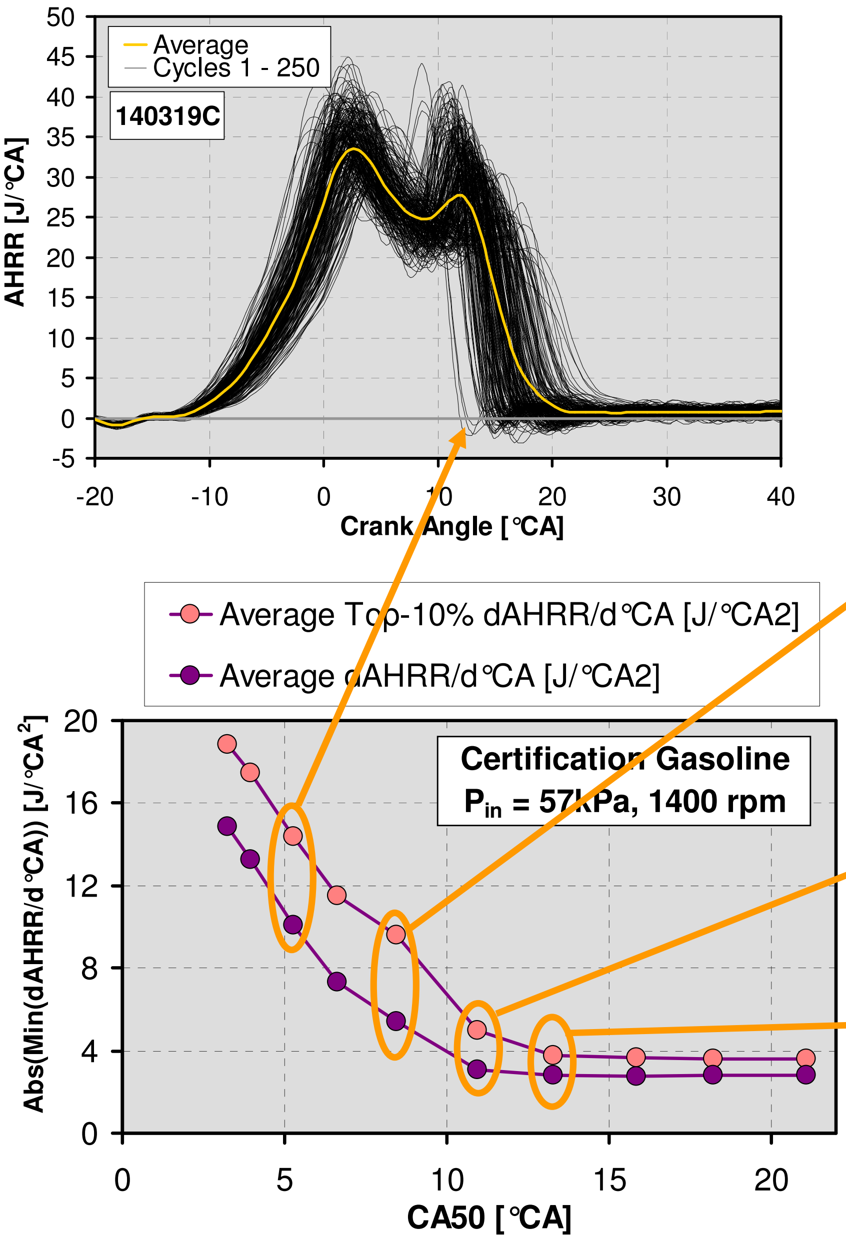
- End-gas autoignition speeds up final combustion stage.
- Beneficial for lean operation, but would be considered “trace-knock”, had stoichiometric charge been used.

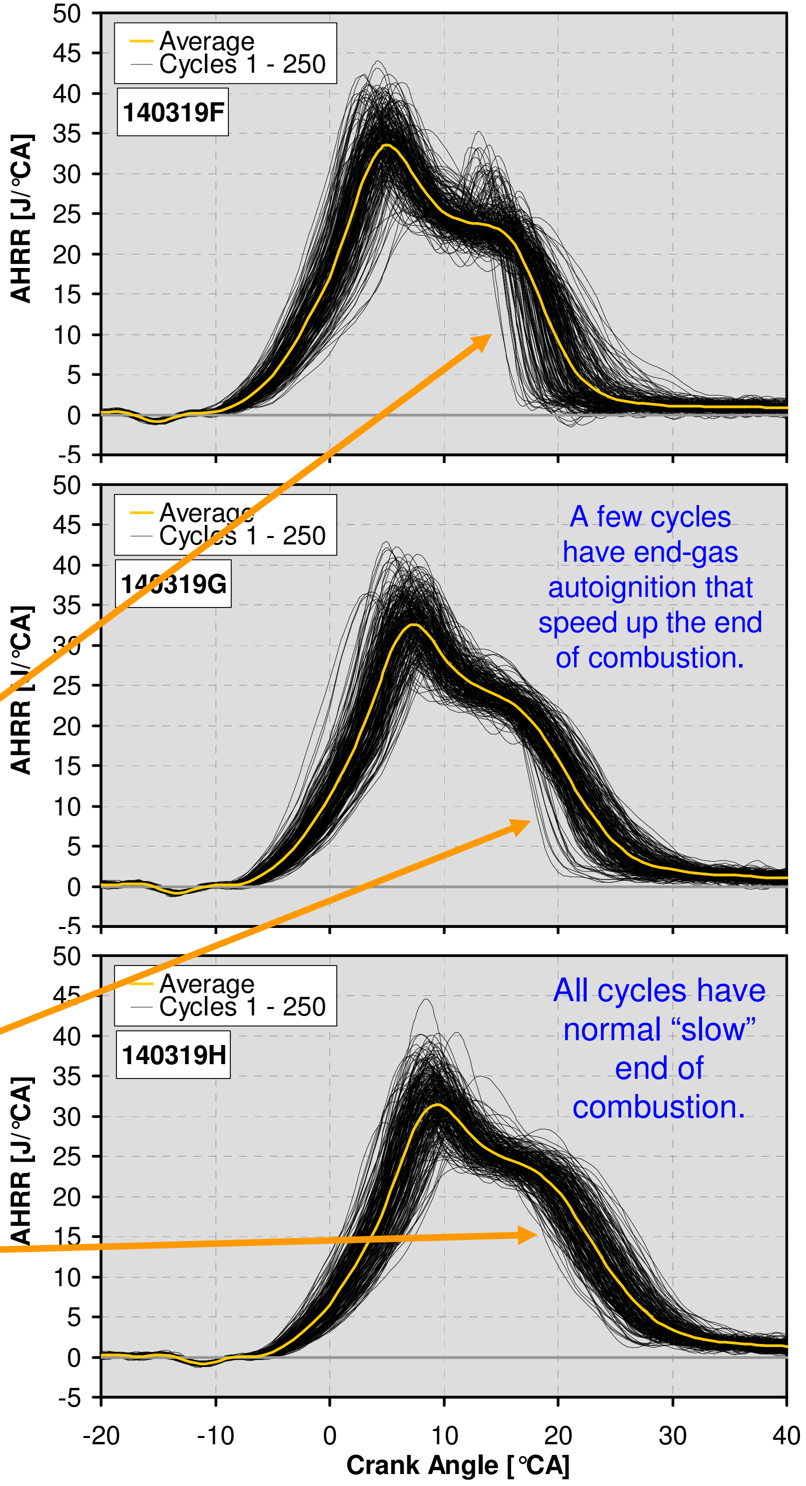
Effect on AHRR for Heated Lean

- Induce end-gas autoignition by heating the intake gas.
- E30 fuel, 1000 rpm, $\phi = 0.55$, T_{in} = 118℃.
- East-West scenario has multiple cycles with mixed-mode combustion.
- Examine “red” cycle, which has the steepest -dAHRR/d℃A at the end of combustion.



- dAHRR/d°CA is our most sensitive metric of end-gas autoignition.



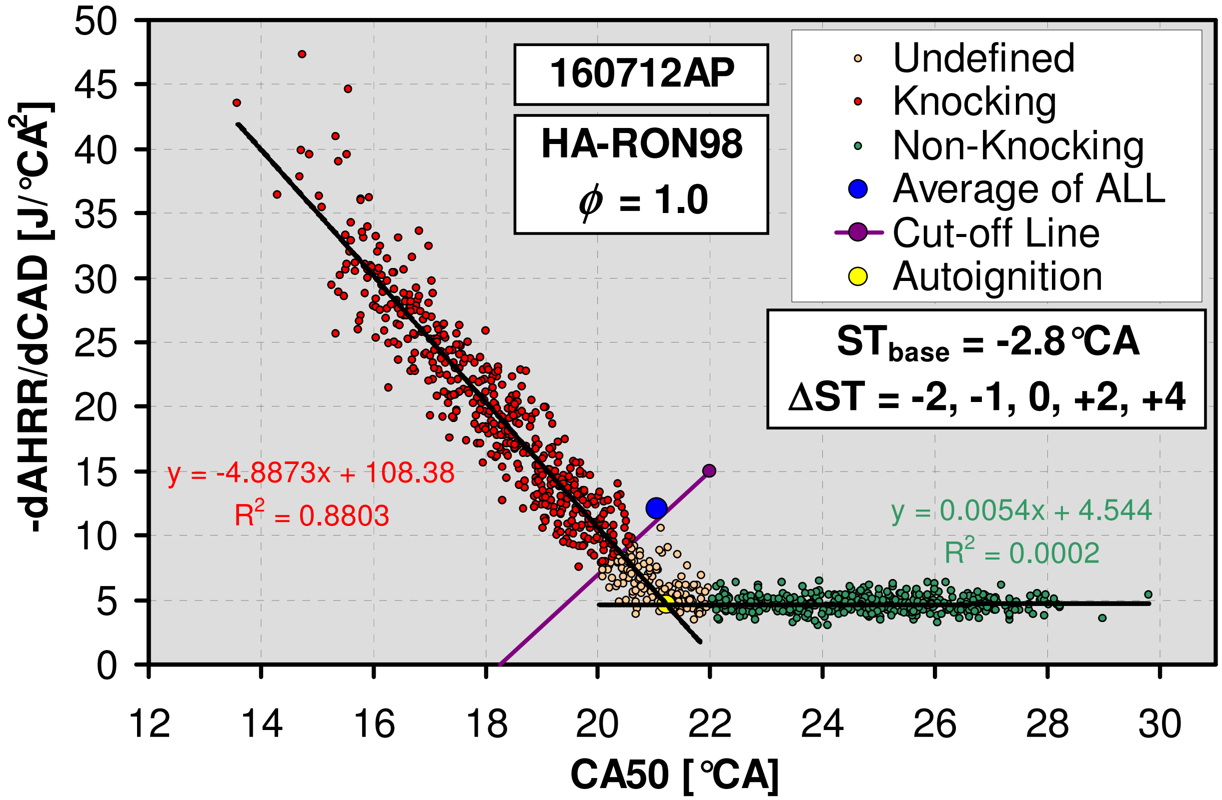


A few cycles have end-gas autoignition that speed up the end of combustion.

All cycles have normal "slow" end of combustion.

Detecting Onset of Autoignition

- For each data point, a spark-timing (ST) sweep was conducted.
  - For this example: ΔST = -2, -1, 0, 2, 4°CA.
- 200 cycles for each ST, for a total of 1000 cycles. (Using ST-variability pattern.)
- dAHRR/d°CA plotted against CA50 creates very well behaved correlation.
- Use intersection of two linear fits to determine CA50 for borderline autoignition.



Fuel Properties

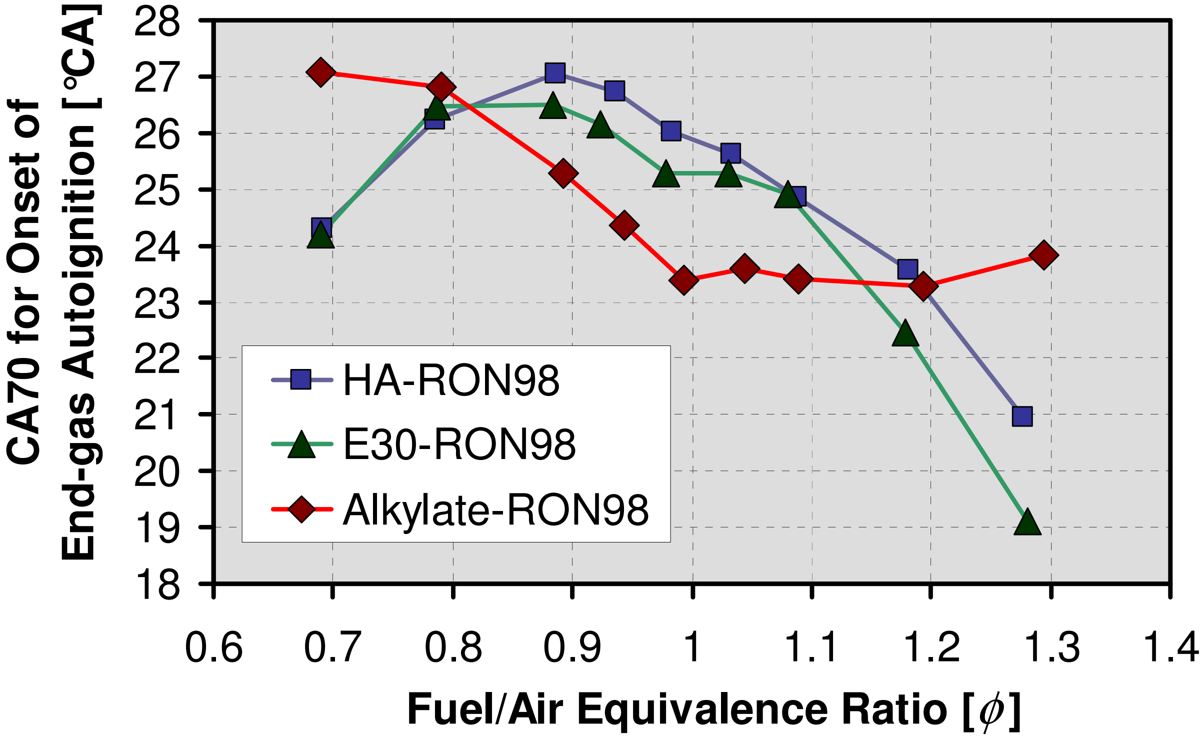
- Newly acquired fuels all have RON98, which makes it easier to compare them for identical operating points.
- First, compare and understand basic equivalence ratio effects.

Co-Optima Core Fuels

	RD3-87	**Certification Gasoline**	**⇒ E30**	**Alkylate**	**New E30**	**High Aromatic**
S	8.3	7.9	13	1.2	10.7	10.7
RON	91.0	96.6	105	97.9	98.3	98.0
MON	82.7	88.7	91	96.7	87.6	87.3
Ethanol [vol.%]	0	0	30	0	30	0
Aromatics [vol.%]	24.5	32.7	22.9	0	8.1	30.8
T90 [℃]	147	158	?	106	155	166

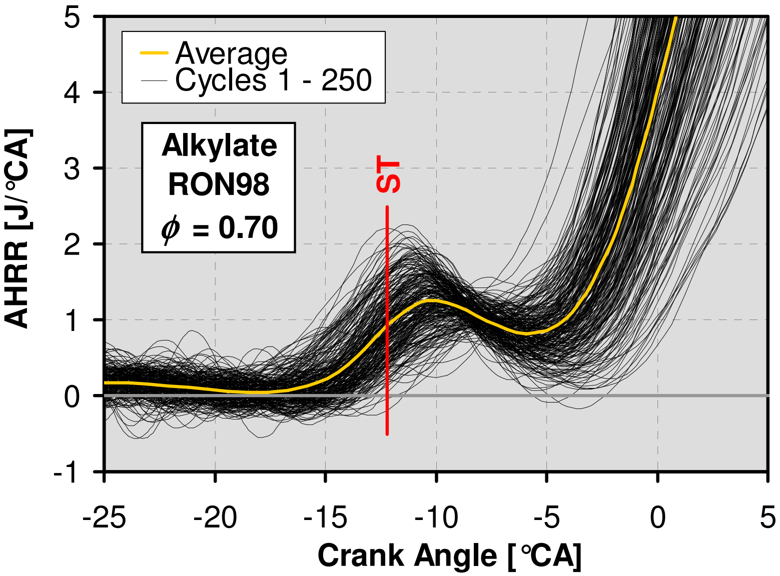
Autoignition Comparison

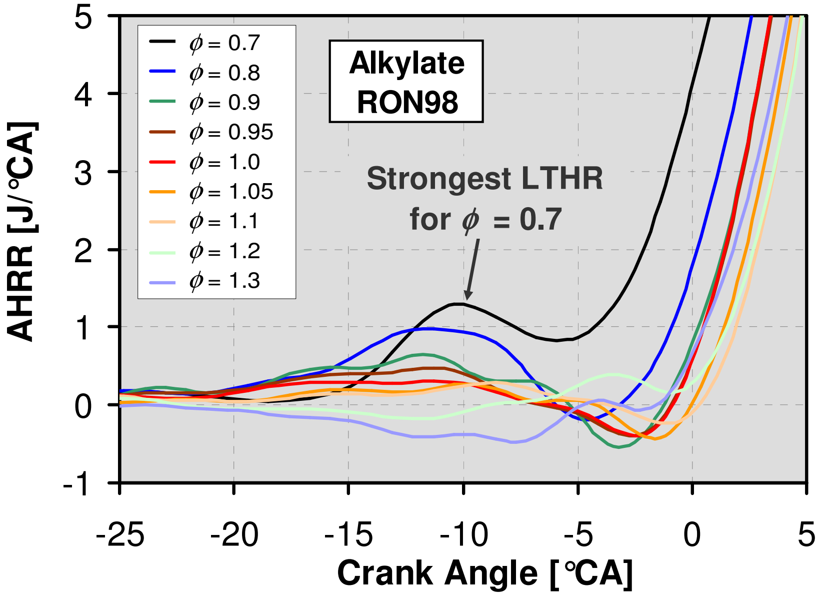
- Despite equal RON ratings, CA70 for “trace autoignition” differ by up to 2.5°CA for stoichiometric operation with $P_{in} \approx 85$ kPa and $T_{in} = 60$°C.
- Alkylate shows no benefit of enrichment.
- Low (RON-MON) sensitive fuel benefits less from charge cooling.
- Lean operation is only detrimental for Alkylate. Increases LTHR.

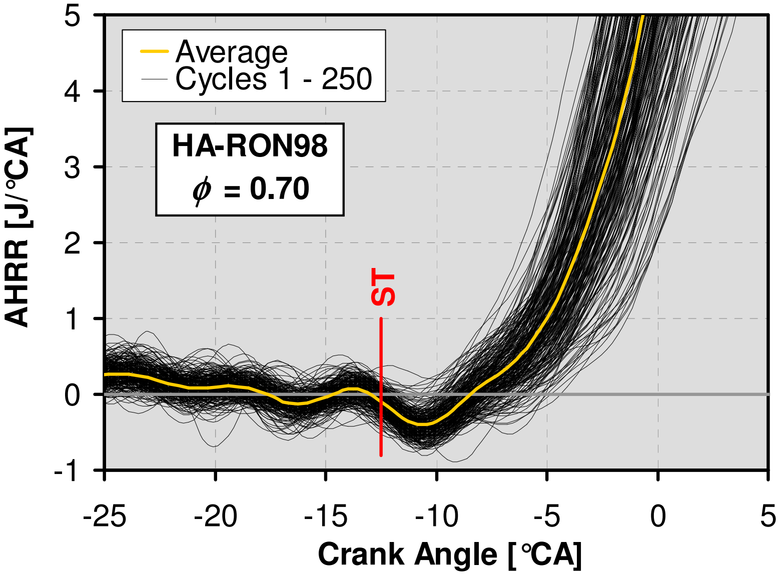


Cycle-to-cycle Variability of LTHR

- LTHR starts before ST, so should not be confused with deflagration-based AHRR.
- LTHR exhibits strong cycle-to-cycle variability.
- High-aromatics fuel shows no LTHR, and exemplifies normal variability of pre-flame AHRR.
  - Heat-transfer variability, measurement noise, etc.

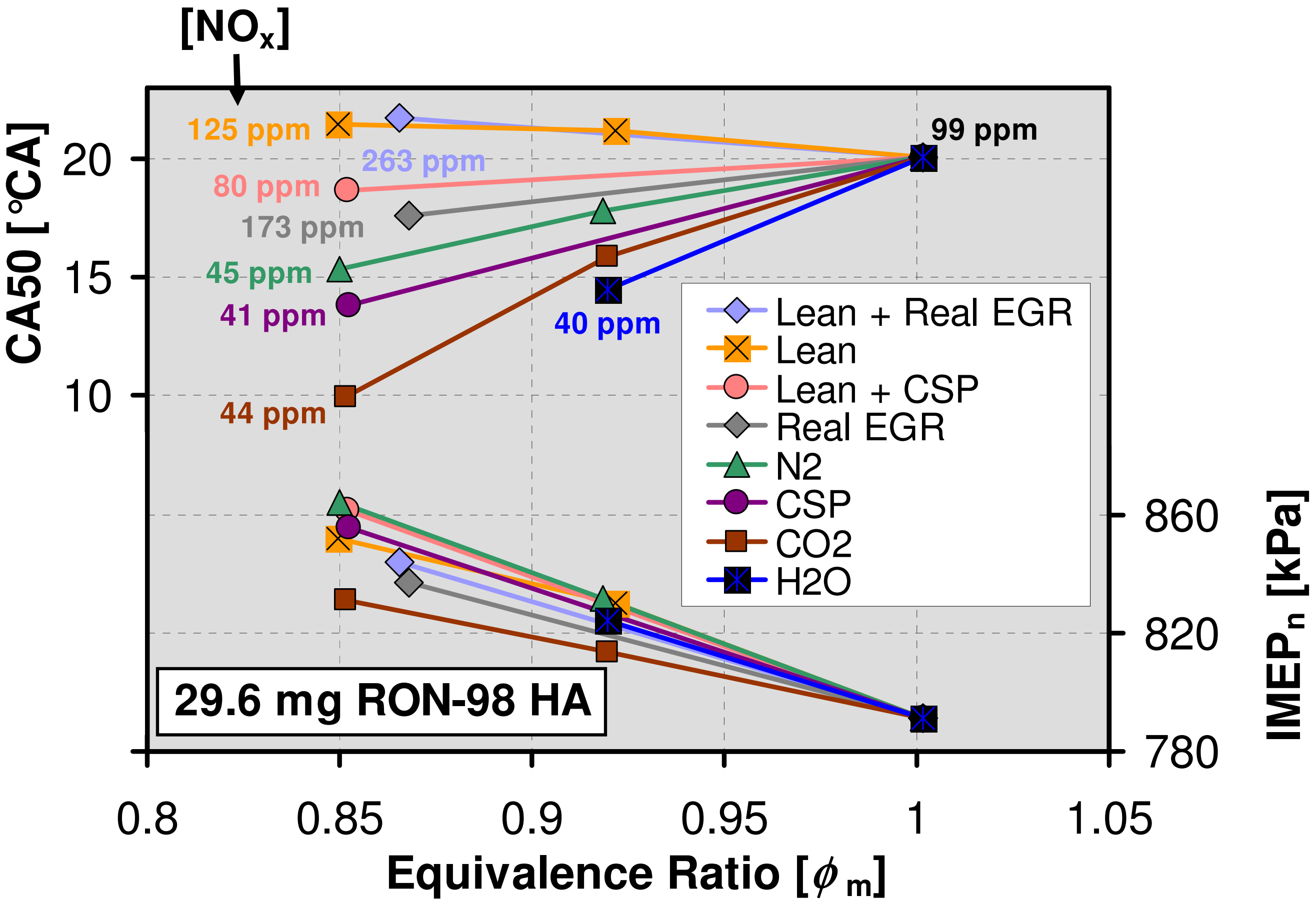






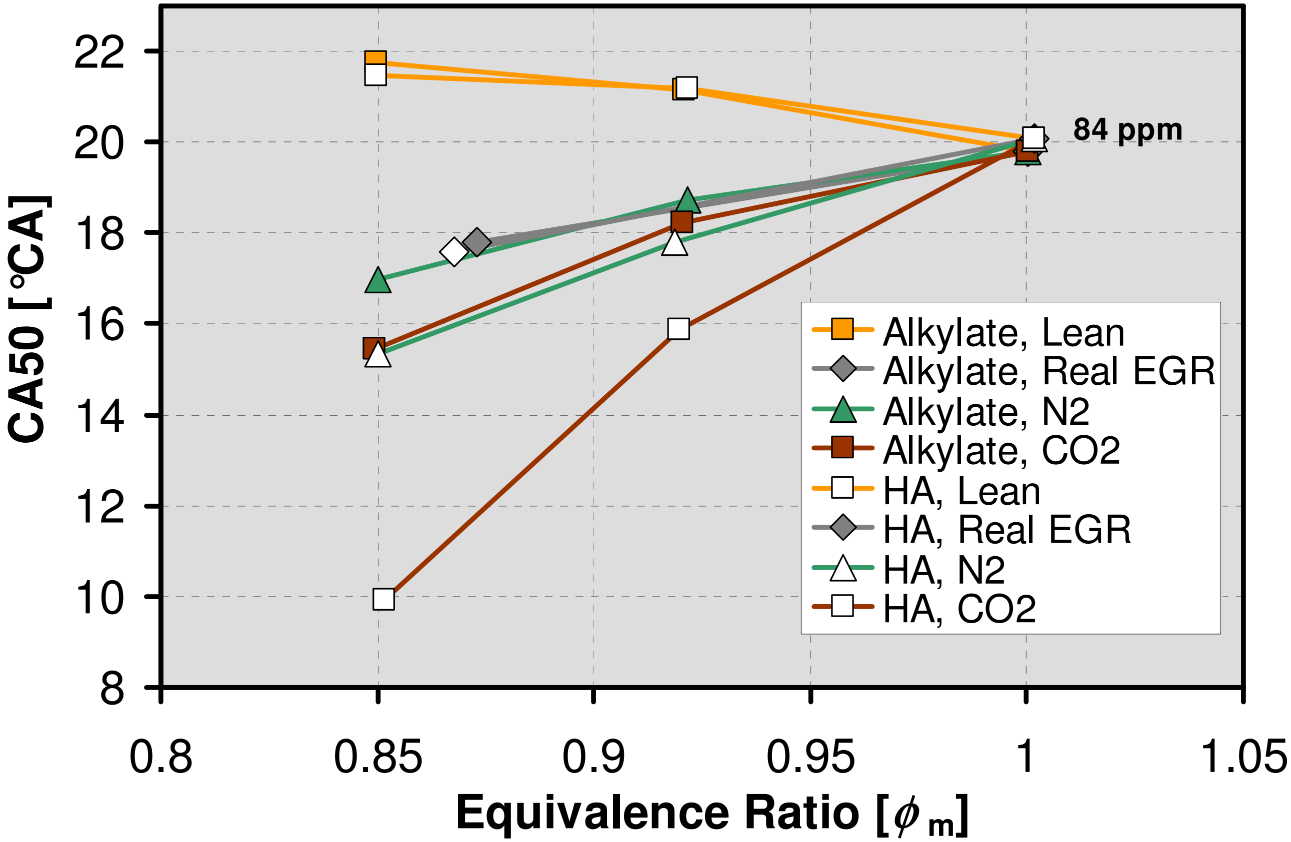
EGR Effects for High-Aromatics RON98

- Largely, knock-suppression trend is consistent with the combined effects of γ, $[NO_x]$, and $[O_2]$.
- Slope of $IMEP_n$ trend indicates combined effect of knock suppression (CA50 advance) and thermodynamics (γ) on changes to thermal efficiency.
- CO_2 and H_2O are detrimental to η_{th}.
- CSP is better than Real EGR also for η_{th}.
  - Chance to reburn HC with pre-catalyst EGR is less important than keeping NO_x low in EGR gases.
- N_2 is overall very good.
  - Illustrating that γ reduction is not required for knock suppression.

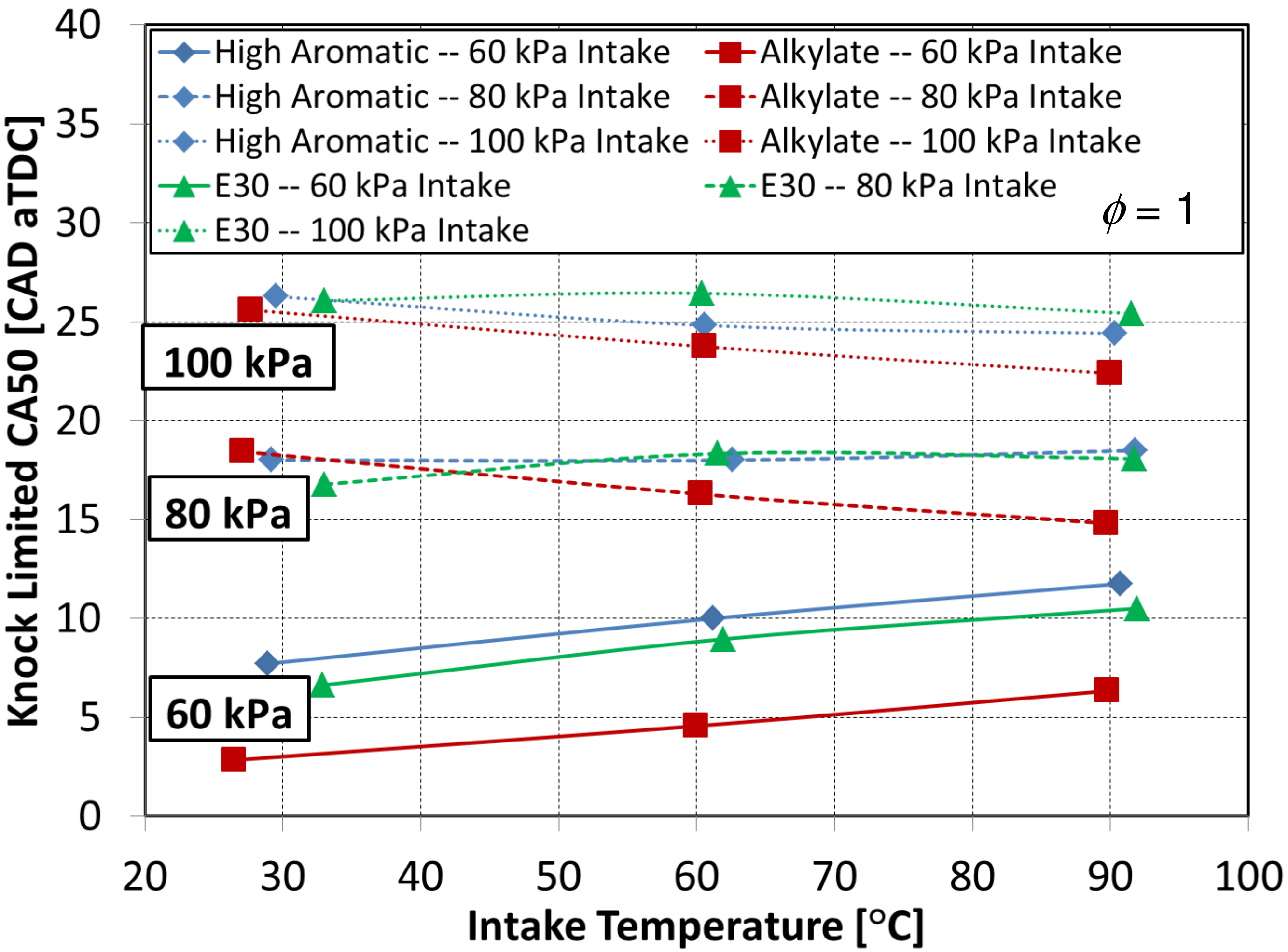


Comparison of EGR Effects on KL-CA50

- Extra air is equally detrimental to KL-CA50 for the two fuels.
- Real EGR effect is virtually identical.
- Benefit of N_2 is greater for HA-RON98 fuel.
- Strong cooling effect of CO_2 provides much less benefit for the alkylate fuel.
  - Increase of LTHR with a reduction of compressed-gas temperature?



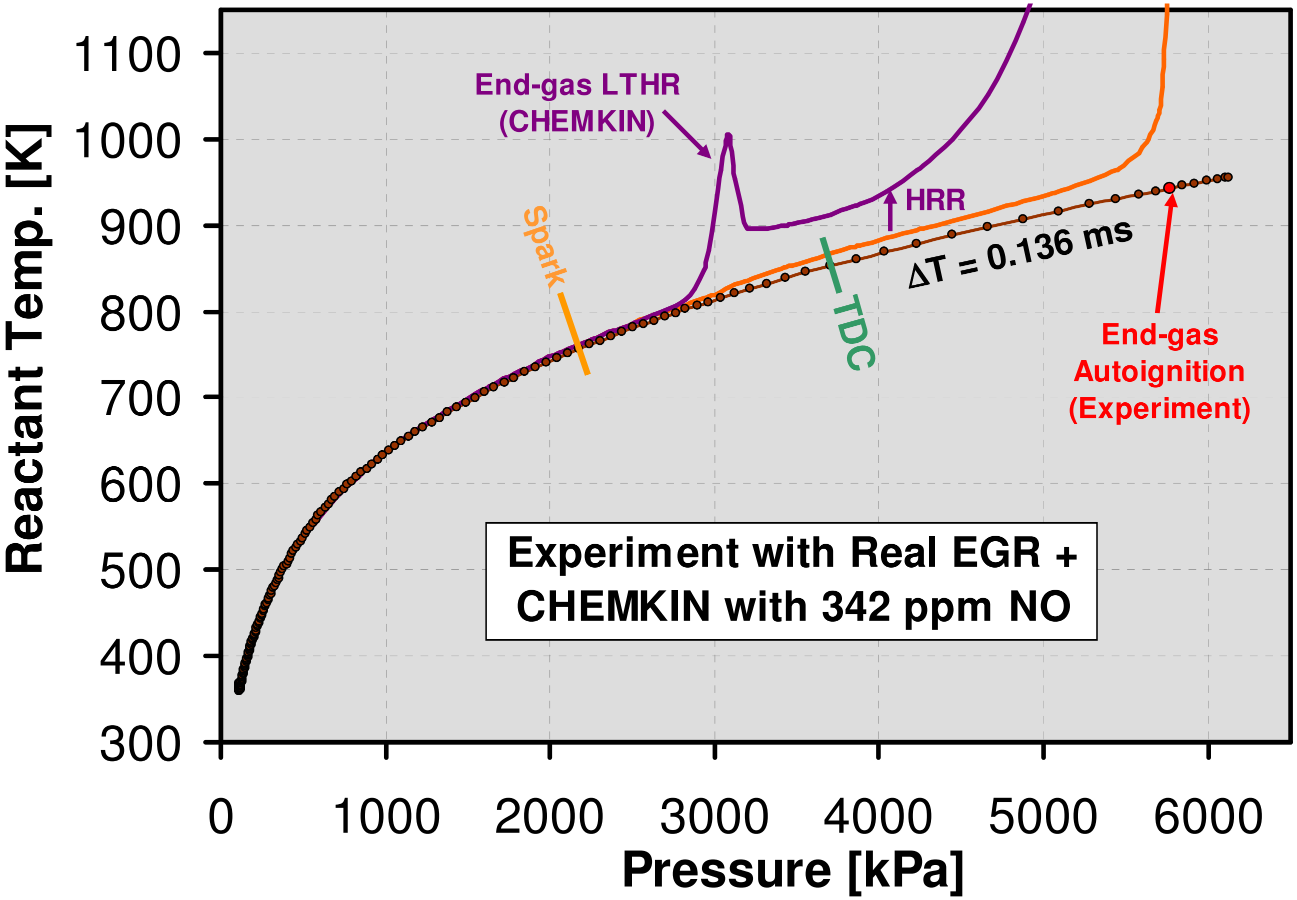
KL-CA50 Trends with Intake Temperature



- KL-CA50 of Alkylate fuel advances with increased intake temperature for higher P_{in}.
- Suppression of LTHR with increasing temperature.
- Also, suggests low temperature sensitivity of autoignition ⇒ poor utilization of thermal stratification in boundary layer ⇒ high AHRR for a given MFB of onset of autoignition.

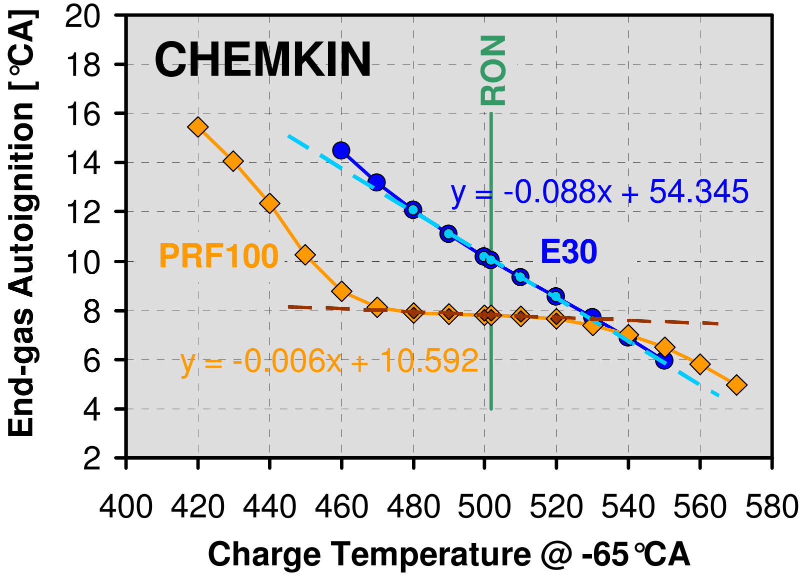
T/P Trajectory for Real EGR

- Example for Certification Gasoline.
- Examine in more detail simulation with 50% higher [NO].
- LTHR is predicted to occur before TDC.
- ITHR in end-gas ramps up quickly during deflagration-based combustion.



Temperature Sensitivities vs. CLR Testing

- At a temperature level corresponding to the “RON”-test, temperature sensitivities are very different for PRF100 and E30.
  - Consistent with high RON-MON sensitivity of E30.
- Two implications:
  - Knock mitigation requires more spark retard for PRF100.
  - For equal autoignition timing, **expect** stronger knocking/ringing for PRF100.
    - Ringing ∝ peak PRR ∝ peak HRR
    - Just like HCCI, peak HRR is determined by thermal stratification in combination with temperature sensitivity of the fuel’s autoignition.
    - The thermal stratification is caused mostly by heat transfer and remains invariable with fuel.
- **Hypothesis** is consistent with observations from CFR octane testing by Swartz *et al.* in SAE Paper 2005-01-2081.



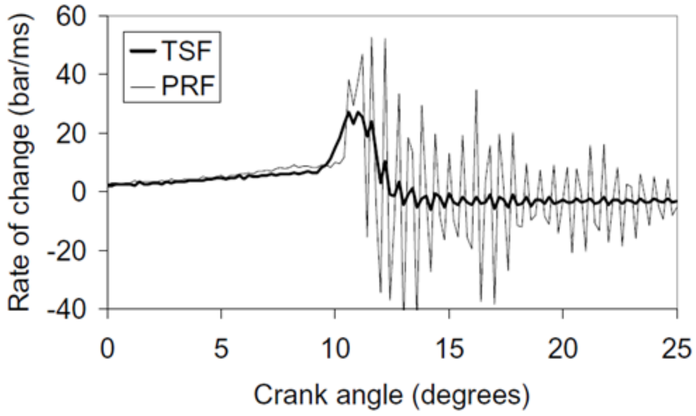


Figure 14: Comparison of the first derivative of pressure between a paraffinic primary reference fuel (PRF) and a toluene standard fuel (TSF). The larger extent of pressure oscillations are evident in the PRF, despite similar octane ratings and replicated conditions.

Imaging of End-gas Autoignition, NS

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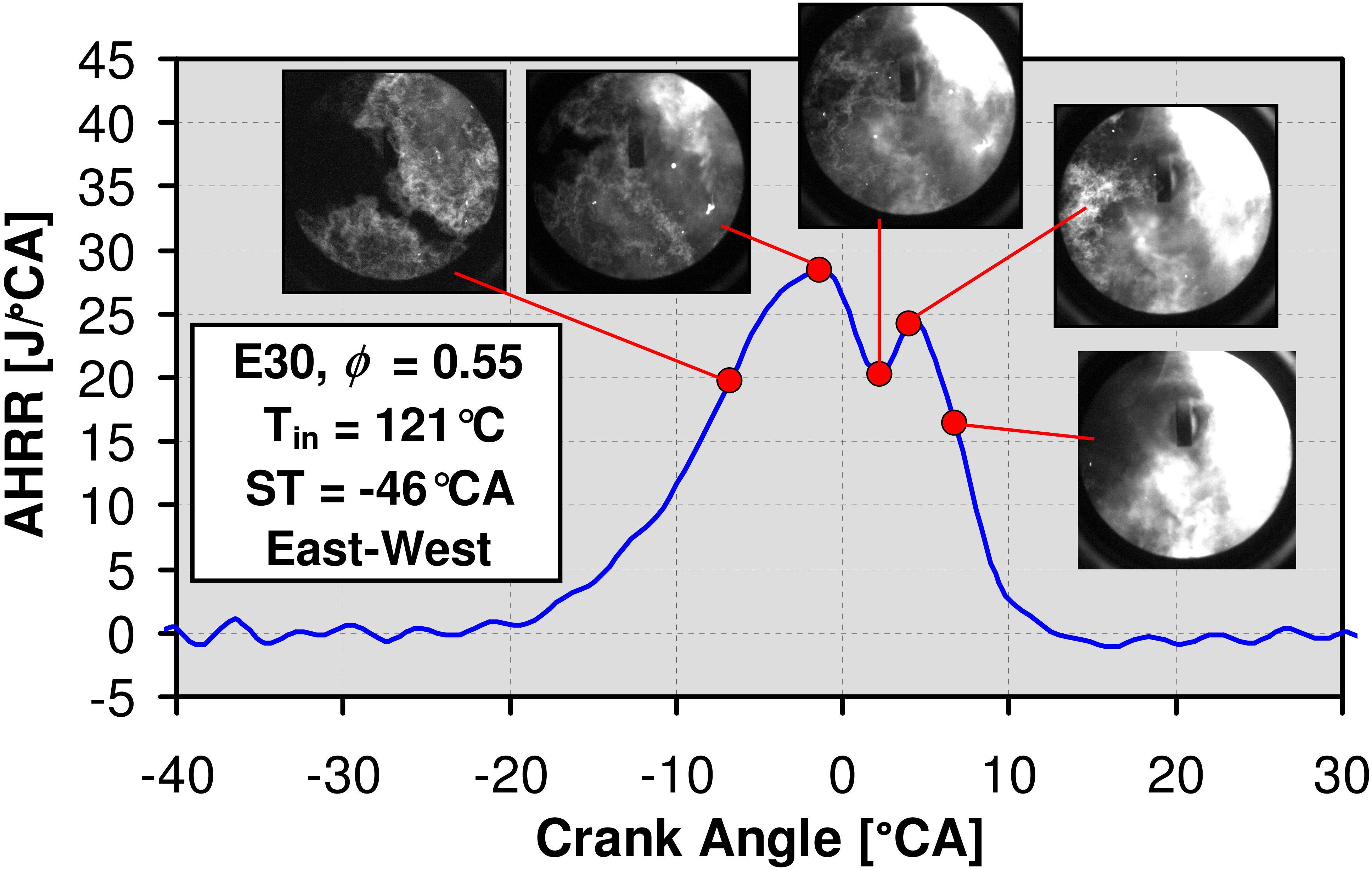
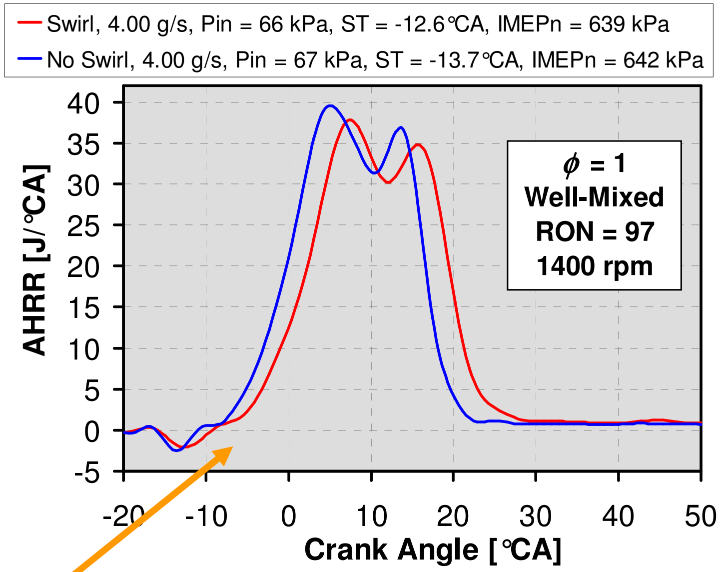
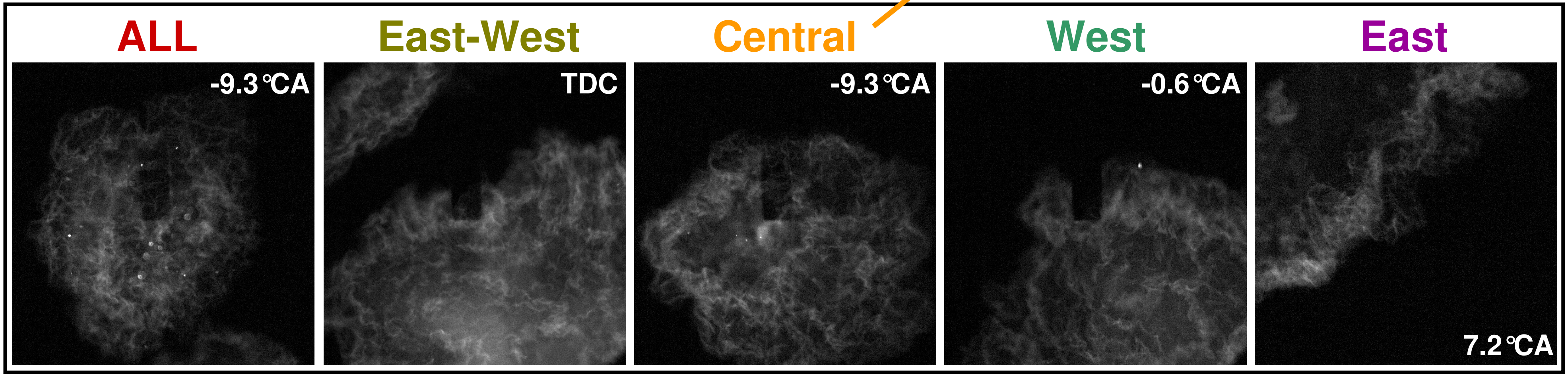


E30, ϕ = 0.55
T_{in} = 121°C
ST = -46°CA
East-West

Swirl Effect on Knock Limits

- Swirl promotes endgas autoignition slightly for stoichiometric operation.
- Flame asymmetry may contribute to higher tendency for knock.





Conclusions

- There is good synergy between the DOE project and the Toyota project.
  - Thank for your support to make this possible!

- The Co-Optima Core Fuels provide opportunities for very insightful knock studies.
- KL-CA70 trends with ϕ are very different for the low-sensitivity alkylate fuel.
- Enhanced LTHR on lean side appears to be one important factor.
  - Here, NO in residual gases seems to play an important role.
- Poor anti-knock performance on rich side for alkylate is consistent with limited thermal sensitivity.
  - LTHR compensates for charge-cooling effects.
- KL-CA70 of E30 benefits from stronger vaporization cooling on rich side.
- Trace autoignition via dAHRR/d°CA appears to be a fundamental metric to build from.
- The response of Alkylate is different for N_2 and CO_2 diluents, indicating fundamentally different roles of $[O_2]$ and charge cooling for this fuel.