

# Relevance of RON and MON, and Role of LTHR, for Knock Limits in a High-Compression Ratio DISI Engine Operated with Compositionally Dissimilar Gasoline Fuels

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U.S. DEPARTMENT OF  
**ENERGY**



Co-Optimization of  
Fuels & Engines

## Abstract:

Spark-ignition (SI) engine efficiency is typically limited by fuel auto-ignition resistance, which is in practice described by the Research Octane Number (RON) and the Motor Octane Number (MON). This paper assesses the auto-ignition resistance (as measured in a modern directly injected spark ignition (DISI) engine) of three compositionally dissimilar gasoline-like fuels with identical RON values and varying or non-varying MON values. The three gasolines are an alkylate blend (RON=98, MON=97), a blend with high aromatic content (RON=98, MON=88), and a blend of 30% ethanol by volume with a gasoline BOB – see Appendix 1 for details – resulting in RON=98, MON=87. All tests were run at 1400 RPM with a compression ratio of 12:1.

The goal of this work is to assess whether fuel properties, in this case RON, MON, and heat of vaporization, are sufficient to describe the anti-knock behavior of varying gasoline formulations in modern engines. The preliminary findings of this work are that RON and MON, when coupled with latent heat of vaporization information, are sufficient to describe the auto-ignition resistance of a fuel to a degree such that knock-limited combustion phasing shows no measurable differences.

While the tested fuels yielded no inconsistencies between their ratings – RON and MON – and properties – latent heat of vaporization – and their performance in a DISI engine, measurable differences were found among the three tested fuels. Specifically, the manner in which the fuels obtained knock-resistance varied, be it through thermal tolerance, charge cooling, or lack of charge-heating Low-Temperature Heat Release (LTHR). In addition, the fuels' knock-limited combustion phasing responses to variations in intake pressure and intake temperature varied with their thermal tolerance and tendency towards LTHR. Yet these dissimilar behaviors combine to produce similar anti-knock qualities and engine performance for naturally aspirated operation.

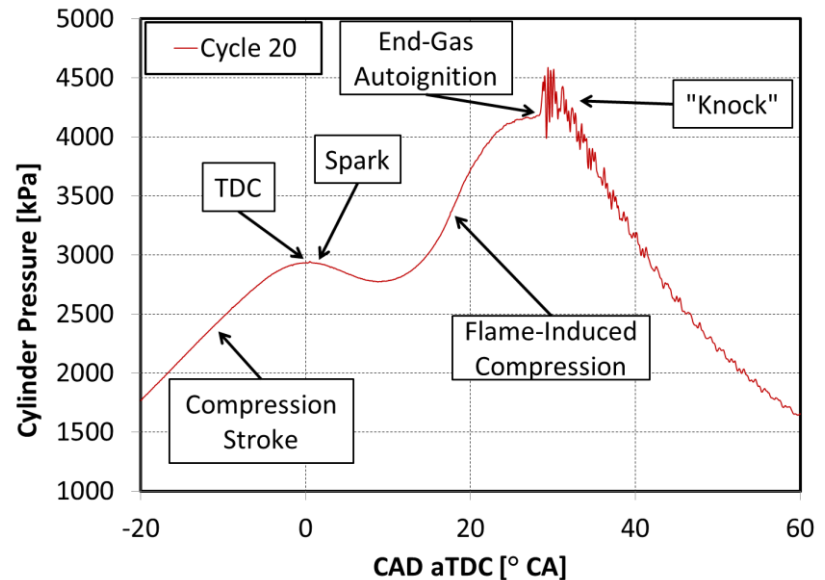
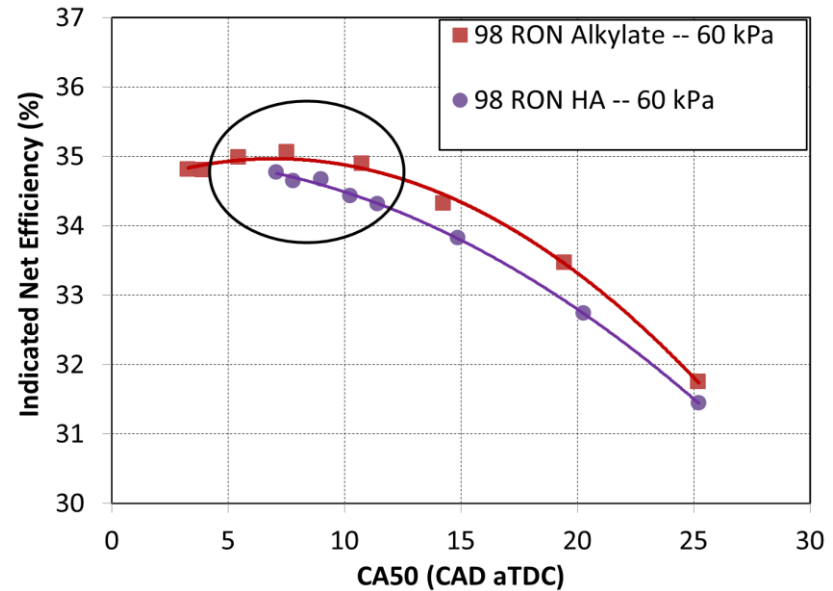


# Outline

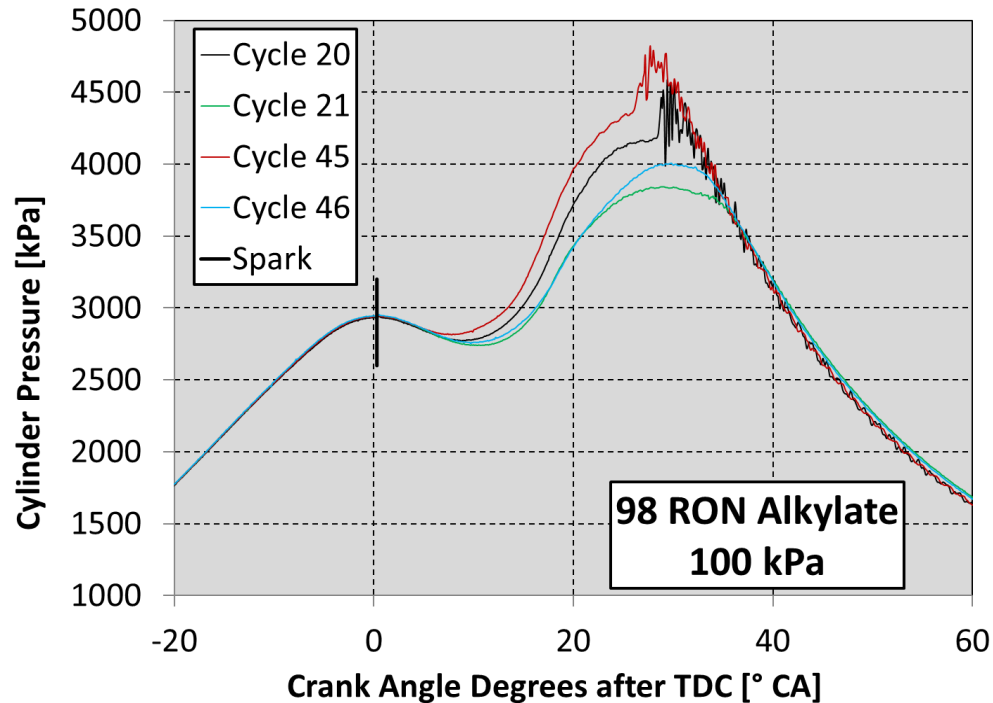
- 1. Motivation, Methods, and Fuel Properties**
- 2. Knock-Limited (KL) Combustion Phasing (CA50) variation with intake pressure**
- 3. KL-CA50 variation with intake temperature**
- 4. Interplay of Heat of Vaporization, Spark-Timing, Low-Temperature Heat Release, and Thermal Autoignition resistance in determining KL-CA50**
- 5. Conclusions and plans for Future Work**

## Goals:

- Assess anti-knock quality of the core fuels for the Co-Optima program in a Directly Injected Spark Ignition (DISI) engine
- Determine if fuel properties (RON, MON, Heat of Vaporization) are sufficient to predict anti-knock behavior in modern DISI engines
- Assess the effects of fuel sensitivity and Heat of Vaporization (HoV) on knocking tendencies



# Pressure Traces for $KI_{avg} \sim 70$

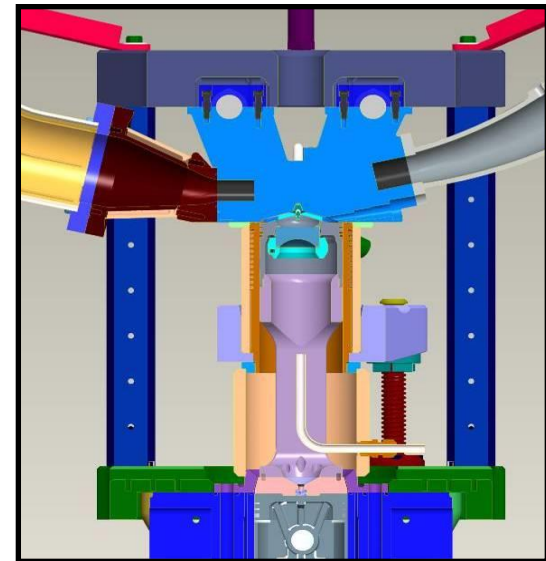
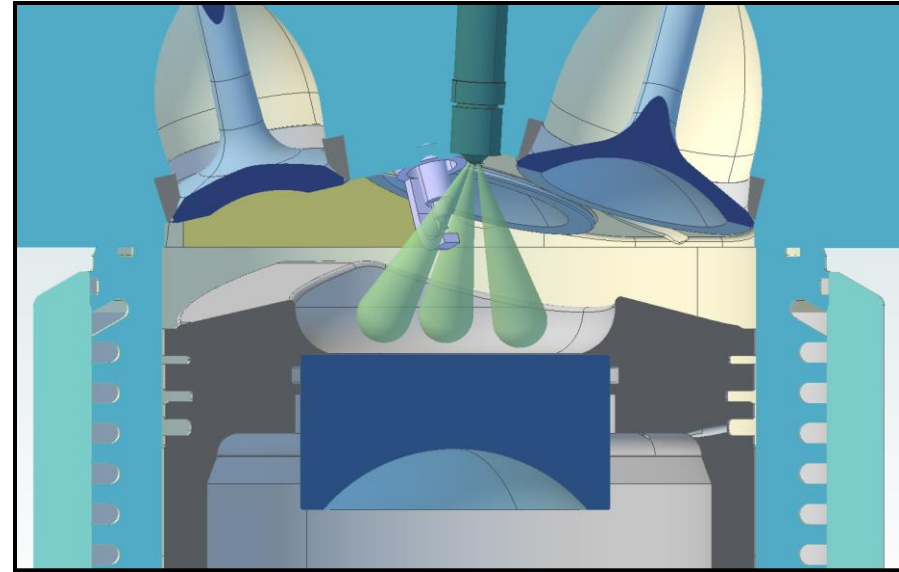


- Combustion behavior ranges from heavy-knocking to non-knocking
- Typical levels of SI engine cycle-to-cycle variation
- Caused by (small) cycle-to-cycle variability of inflammation process.
- COV of IMEP is typically  $\approx 1\%$ .

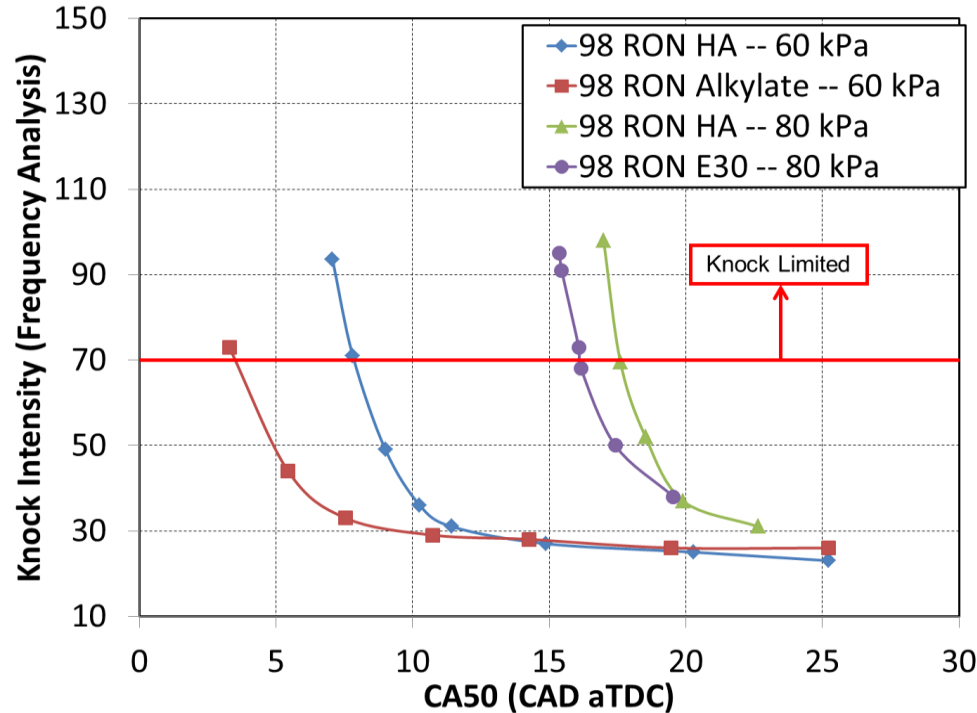


# Research Engine Characteristics

- DISI
- CR = 12:1
- 0.55 L displacement
- High-swirl operation
  - Single intake valve
- Low residuals
  - No valve overlap
- KL-CA50 measured at 1400 RPM
- Conventional High-Energy Ignition System used
- Well-mixed charge operation
  - 3-injection strategy for low PM emissions.



# Knock Intensity Increases with Advancing CA50



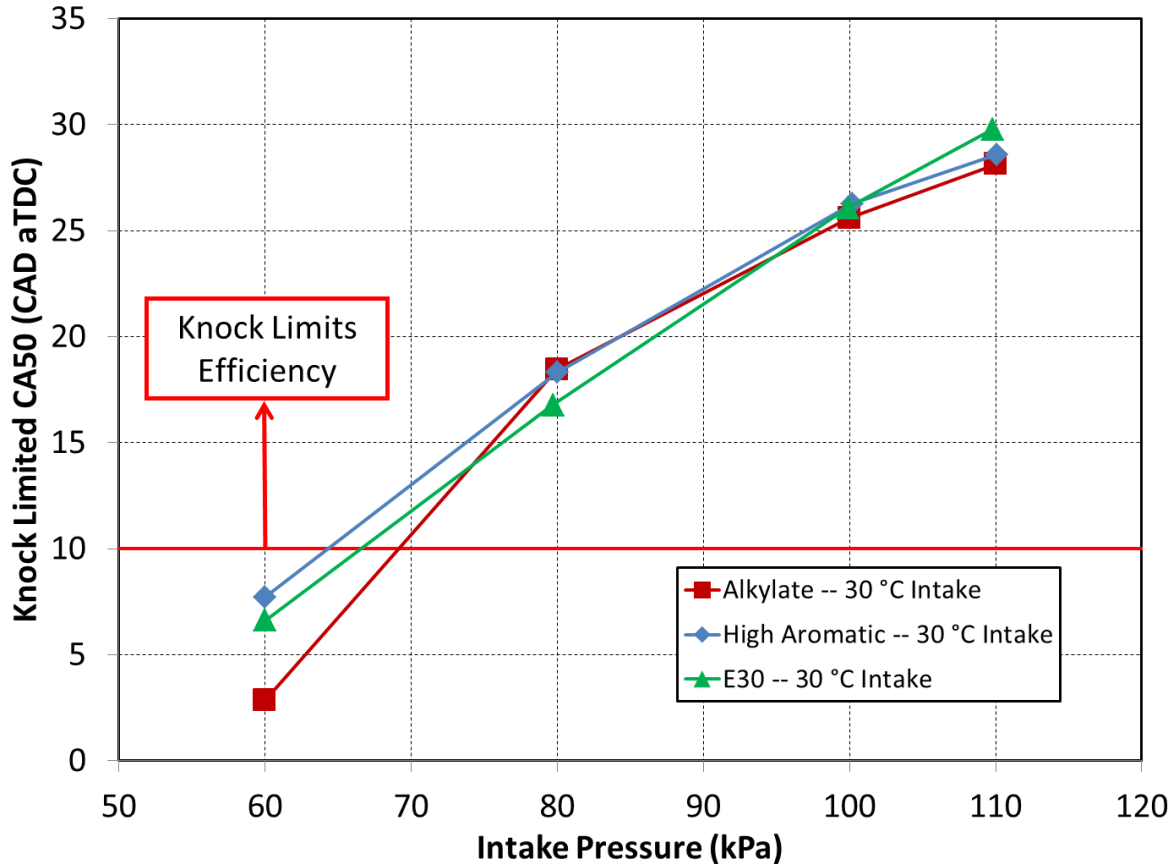
- Fourier decomposition used to quantify knock intensity (KI) by summing contributions in the 5 – 28 kHz range
- Knock-Limited (KL) combustion phasing (CA50) defined as the CA50 resulting in KI = 70
- KI = 70 yields sufficiently steep slope for accurately determining KL-CA50 to within 1 CAD

# Fuel Properties



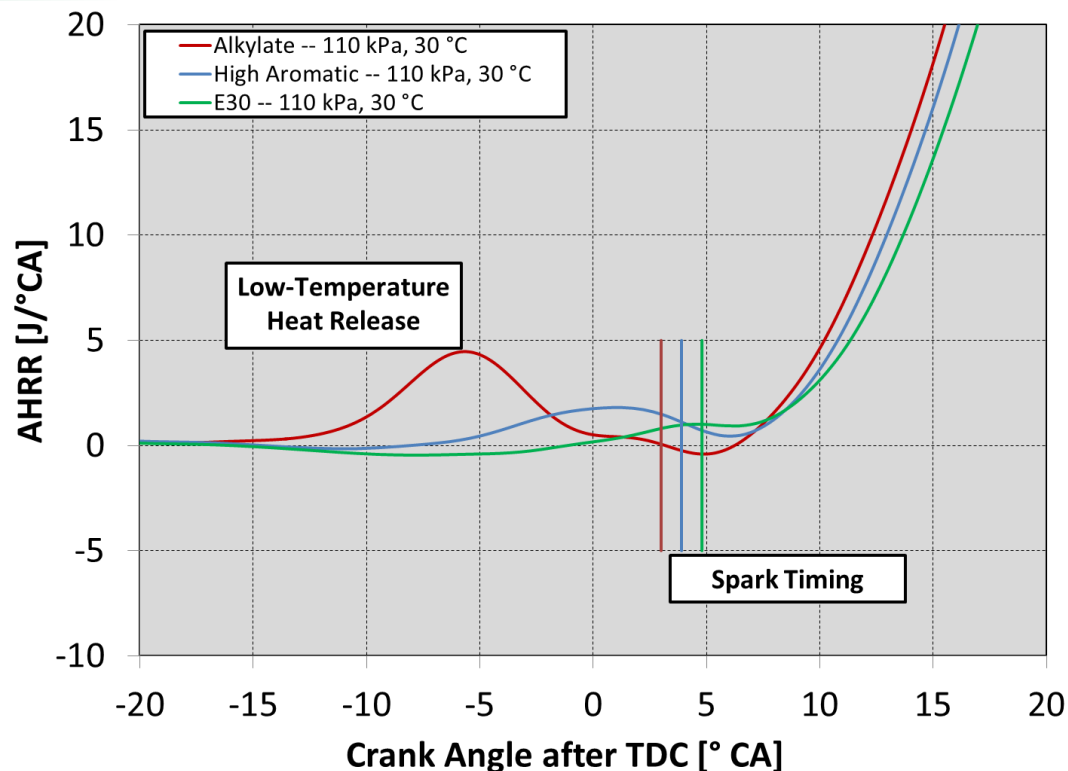
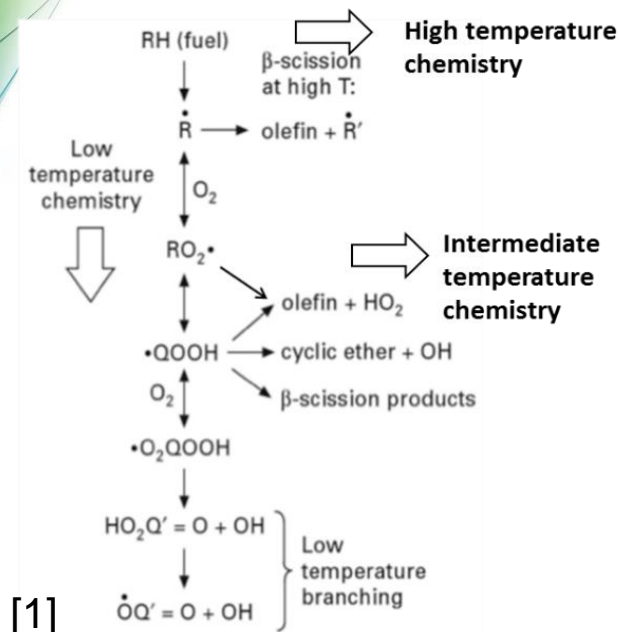
	<i>Alkylate</i>	<i>E30</i>	<i>High Aromatic</i>
<b>RON</b>	98	98	98
<b>MON</b>	97	88	87
<b>AKI (R+M)/2</b>	97	93	93
<b>Sensitivity (RON - MON)</b>	1	10	11
<b>T10 (°C)</b>	93	61	59
<b>T50 (°C)</b>	100	74	108
<b>T90 (°C)</b>	106	155	158
<b>TF (°C)</b>	161	204	204
<b>Aromatics (Vol. %)</b>	0	8	31
<b>Olefins (Vol. %)</b>	0	5	4
<b>Parafins (Vol. %)</b>	100	57	65
<b>Ethanol (Vol. %)</b>	0	30	0
<b>Net Heat of Combustion (MJ/kg)</b>	44.5	38.2	43.0
<b>Average Molecular Formula</b>	C: 7.76 H: 17.45	C: 4.49 H: 9.87 O: 0.5	C: 6.92 H: 12.41





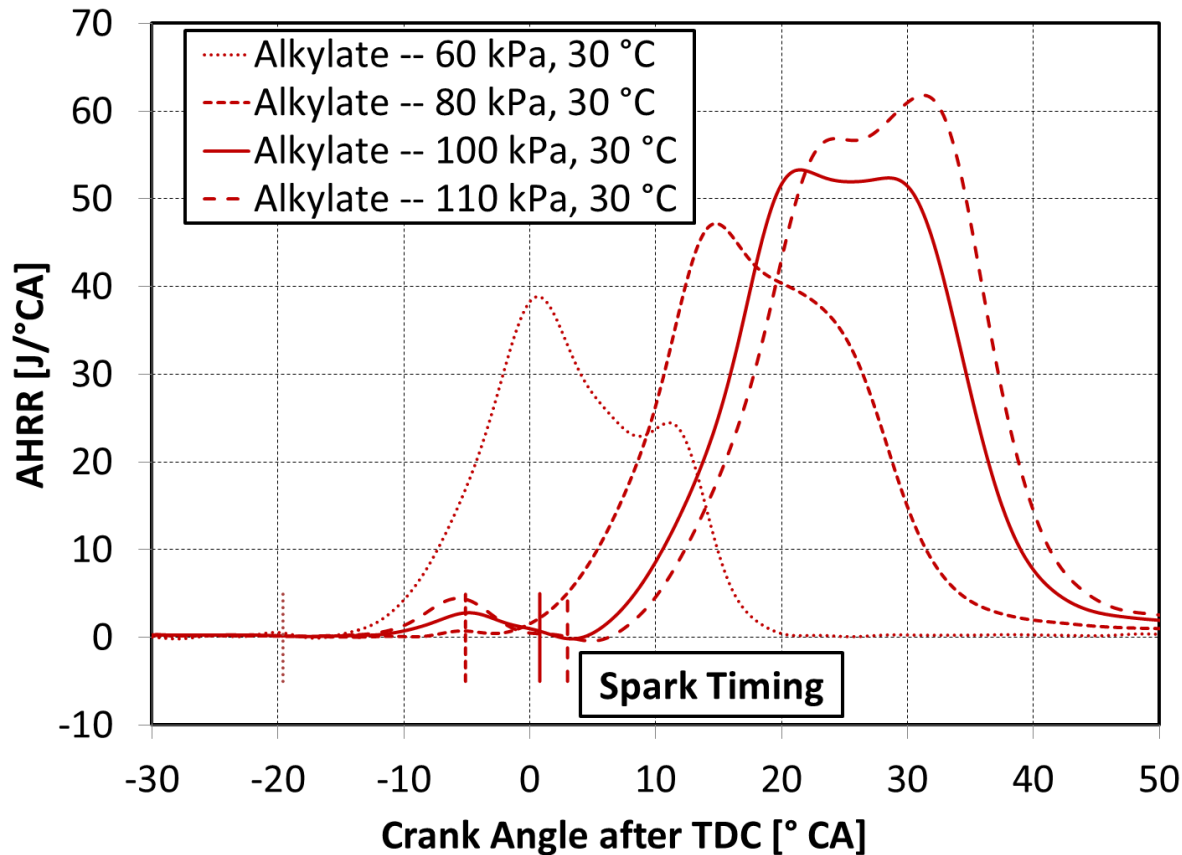
- Similar behavior across fuels
- Alkylate shows benefit at low intake pressures
- Consistent with RON and MON ratings (with appropriate K values)

# Apparent Heat Release Rates

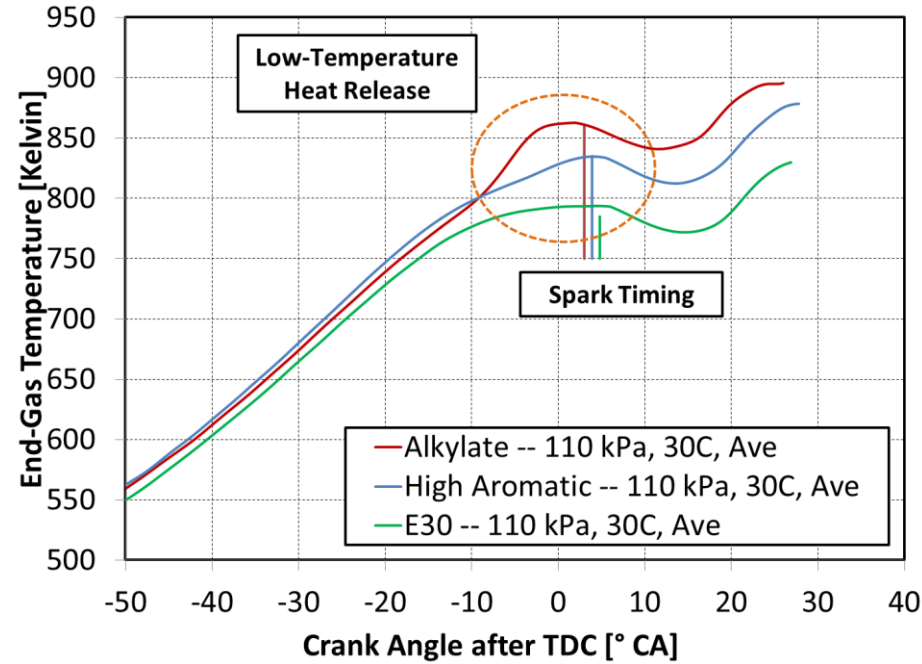
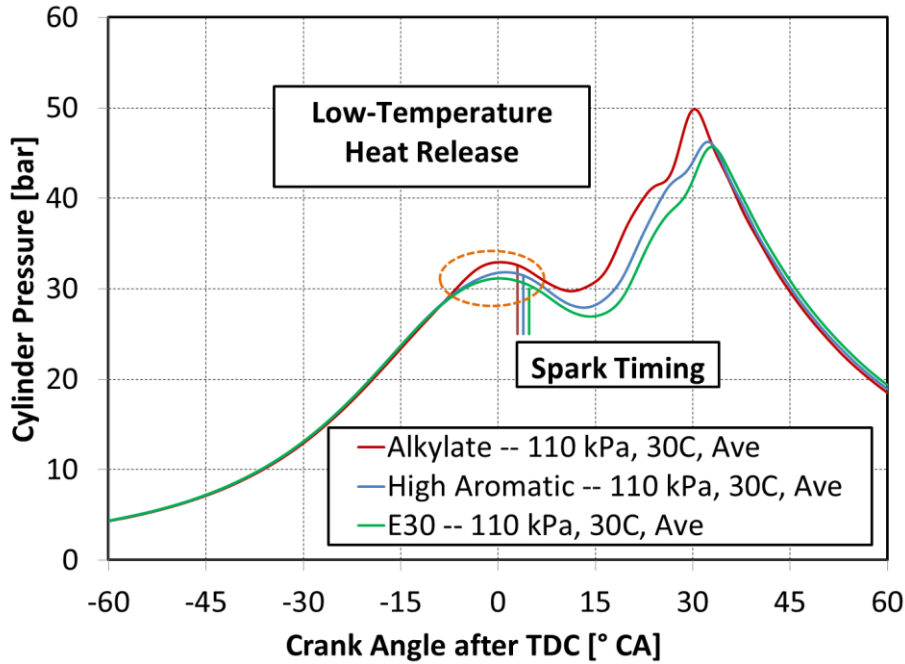


- All fuels exhibit measurable Low-Temperature Heat Release with 110 kPa intake pressure, 30 °C intake temperature
  - LTHR is the result of a well-known low-temperature chain-branching oxidation pathway present in many hydrocarbon fuels, characterized by oxygen addition to fuel radicals
  - See Curran *et. al.* 1998 [1], and Westbrook *et. al.* 2016: <http://dx.doi.org/10.1016/j.combustflame.2016.05.022>
- Alkylate yields highest magnitude

# LTHR is sensitive to Intake Pressure

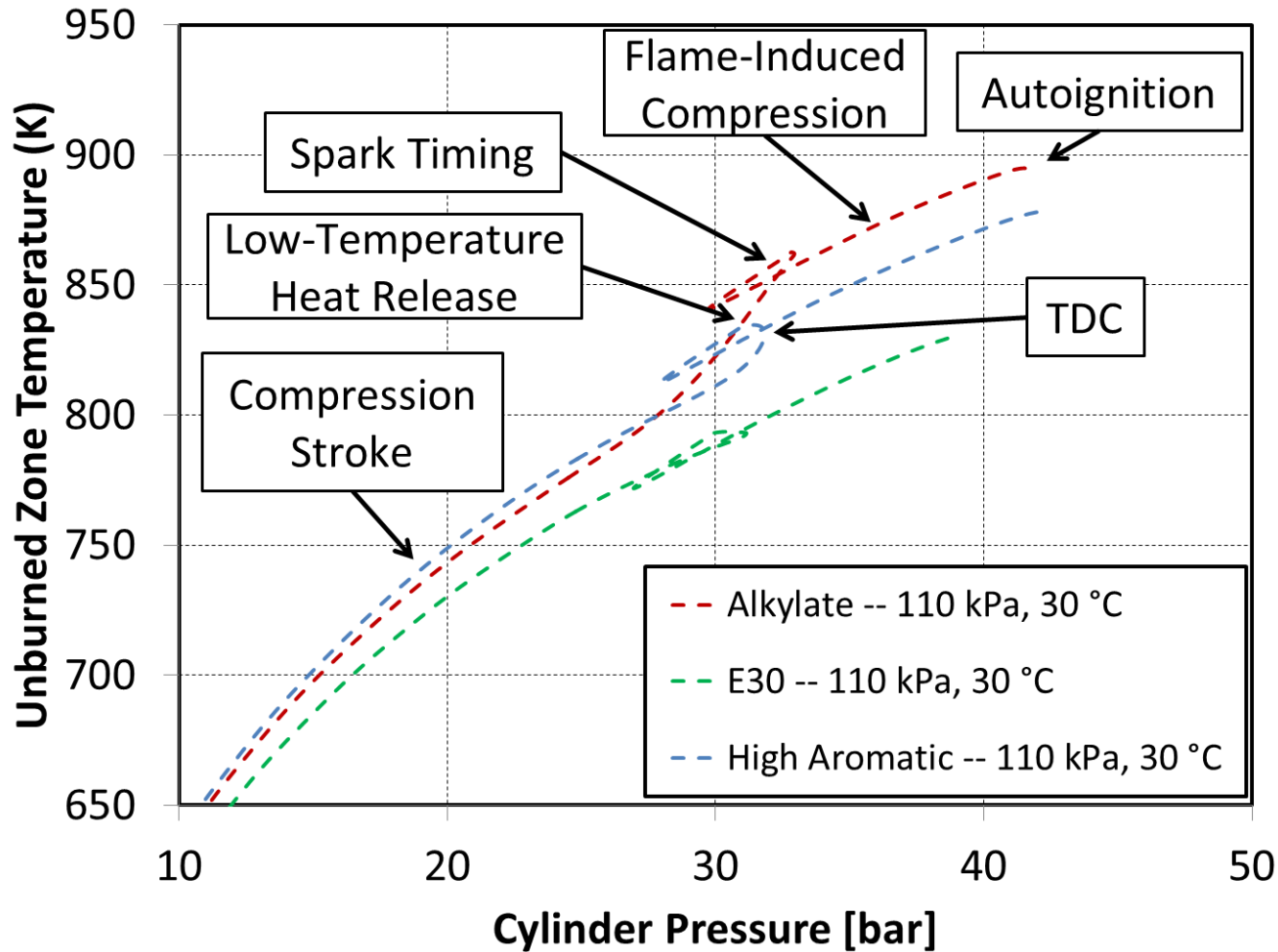


- LTHR disappears at low intake pressures
  - Similar to observed behavior in HCCI engines



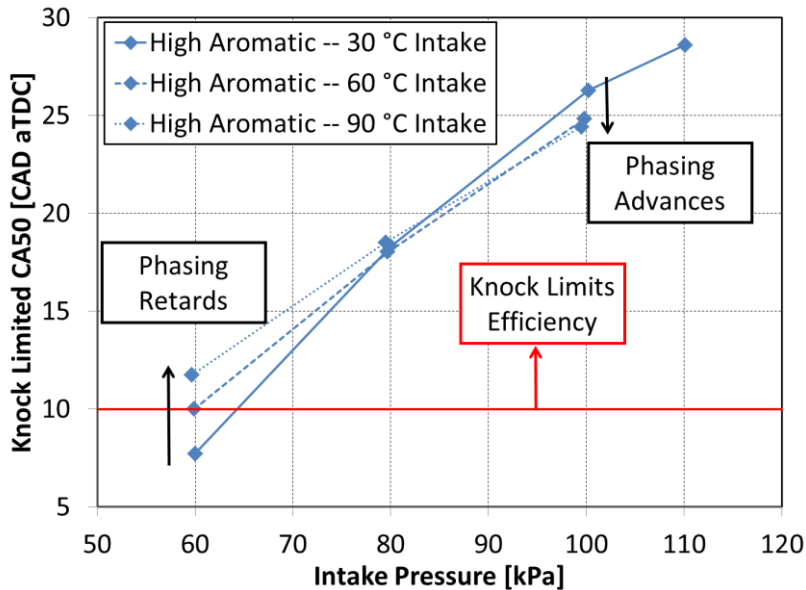
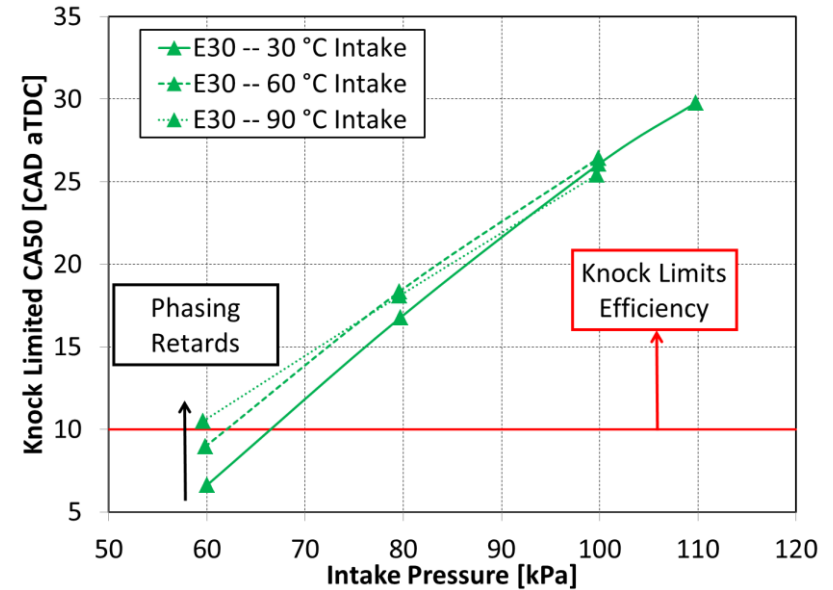
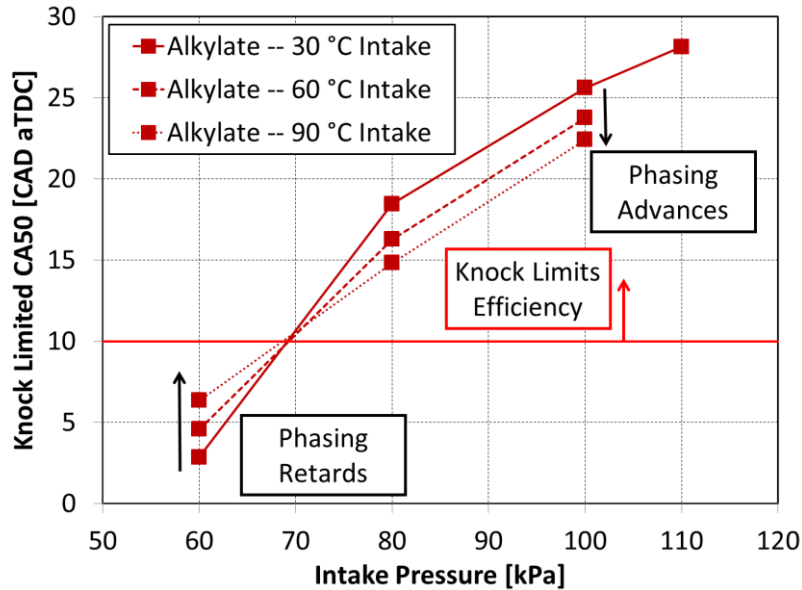
- LTHR raises end-gas temperature and pressure
- Compression Ratio and Flame-Induced Compression effects are of larger magnitude, but similar among these fuels/engine

# End-Gas Temperature – Pressure Histories

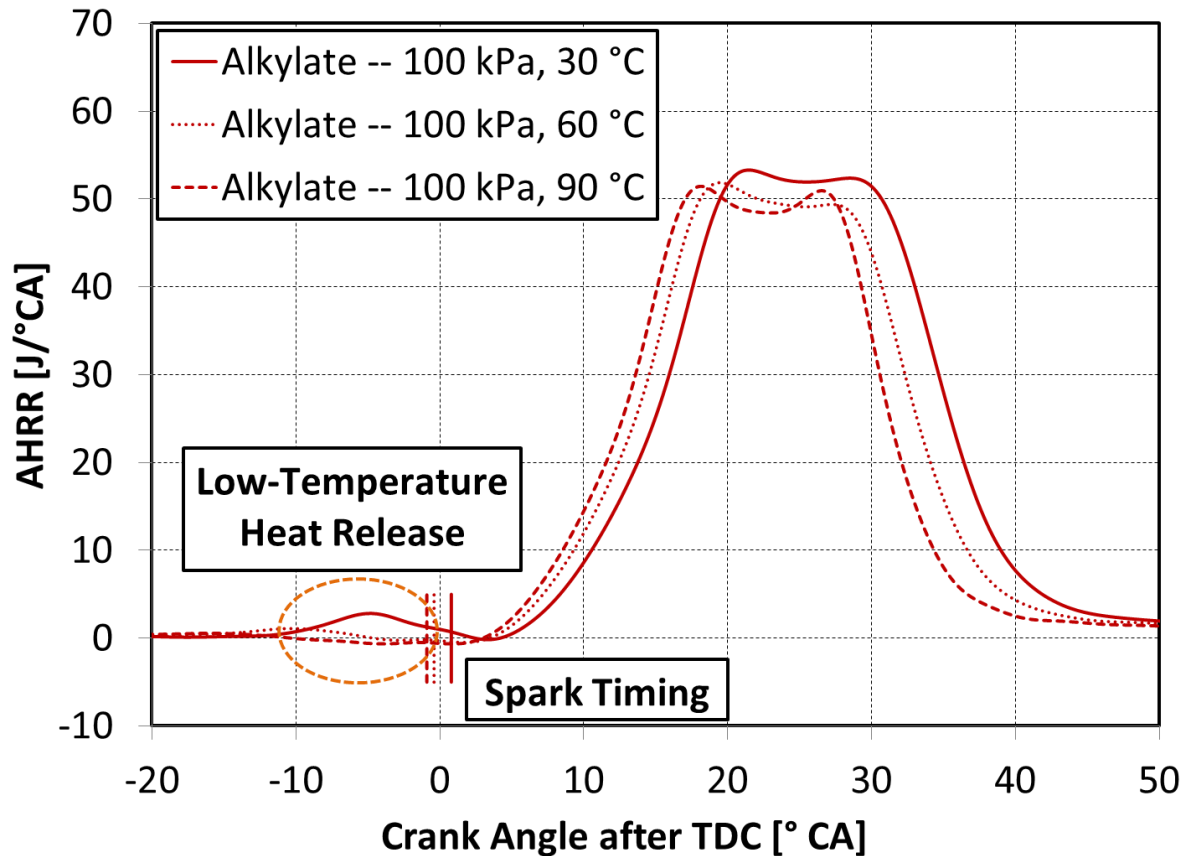


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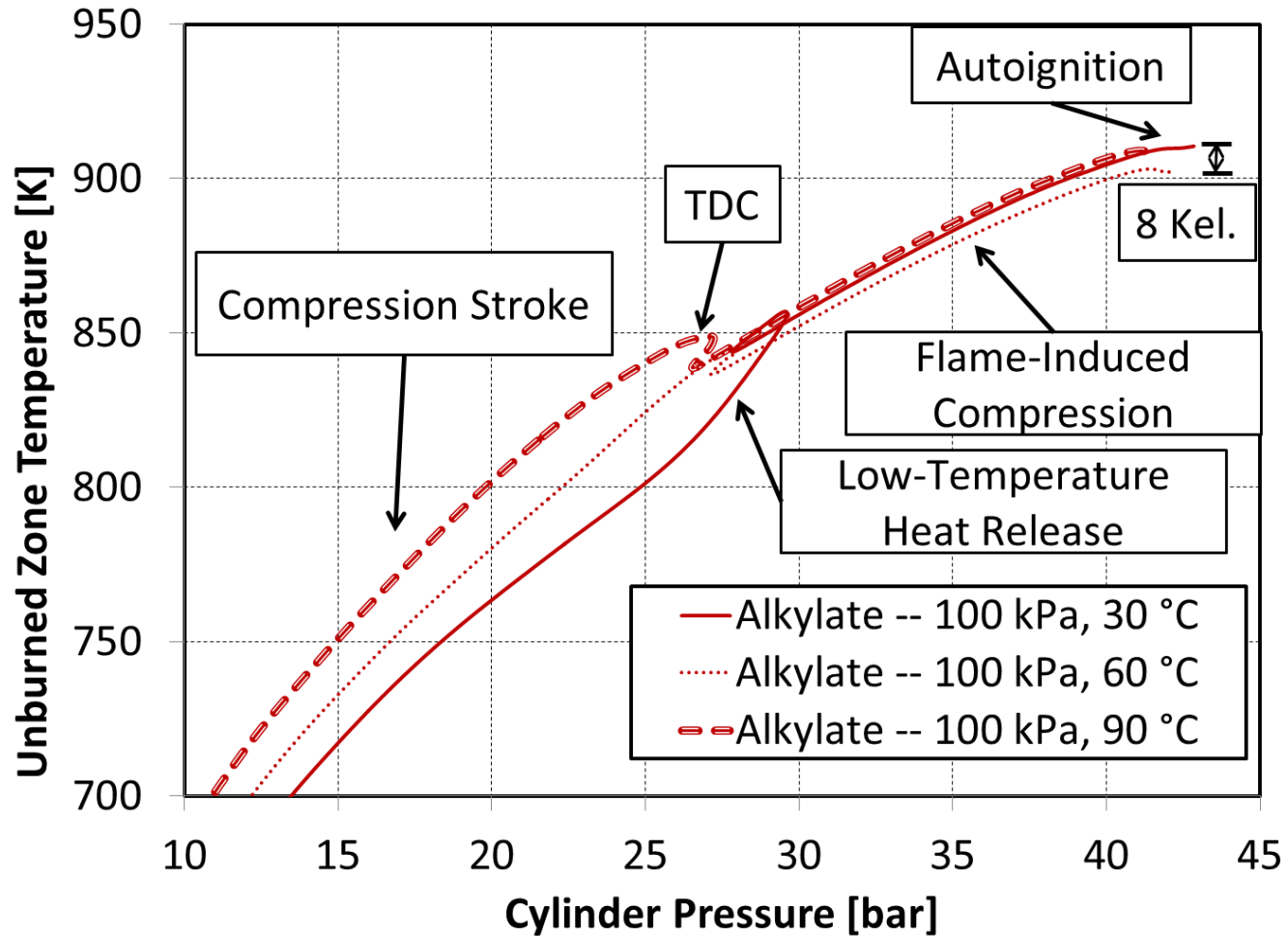
# Effect of Intake Temperature on KL-CA50



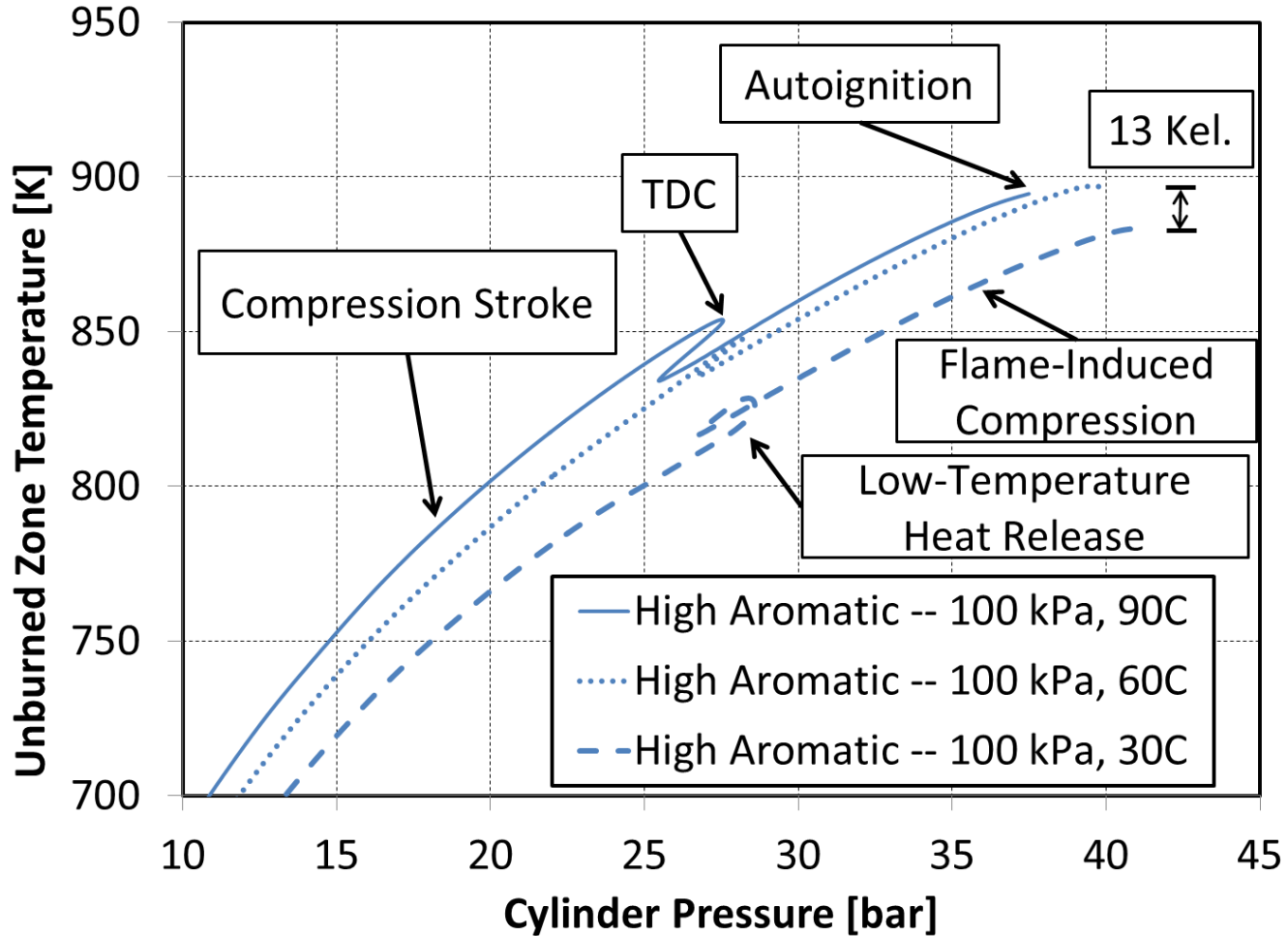
- KL-CA50 alternately advances and retards with intake temperature variation
- Transition point varies across fuels



- LTHR magnitude declines with temperature
  - LTHR occurs prior to spark: not a ST effect
  - Likely related to pressure, temperature history of the charge

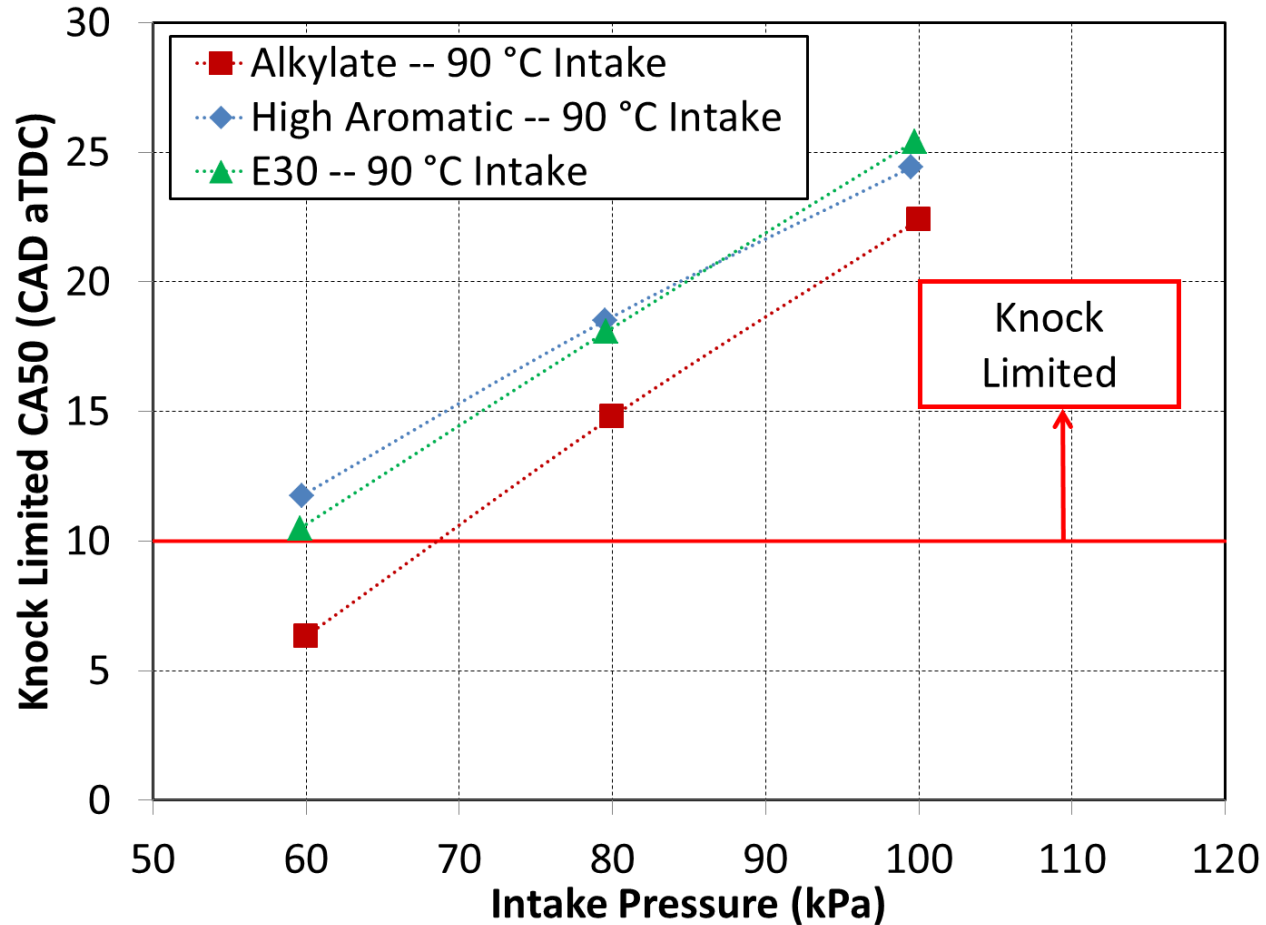


- Regardless of intake temperature, end-gas temperatures are similar at the point of auto-ignition
  - Combined LTHR and spark-timing effects (ITHR is not accounted for in this analysis.)



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  - Combined LTHR and spark-timing effects
  - LTHR less significant for High Aromatic fuel (but ITHR may be more important.)

# KL-CA50 at 90 °C Intake



- Alkylate provides clear advantage at elevated intake temperatures
- E30 and High-Aromatic nearly indistinguishable
- Consistent with RON and MON ratings (with appropriate K values)

- RON and MON, combined with HoV, are sufficient to describe anti-knock qualities over the tested (non-boosted) range of conditions
- The fuels differ in their LTHR behavior
  - LTHR affects the end-gas temperature, pressure history
  - LTHR influences the sensitivity of KL-CA50 to intake temperature and pressure
- All three fuels have same RON = 98, but this is obtained through different combinations of chemical auto-ignition resistance and charge cooling effects



# Future Work

- Use kinetic models of end-gas to assess end-gas heat release during flame-induced compression (when the deflagration heat release masks potential end-gas heat release)
- Investigate knock-limits and fuel-specific auto-ignition behaviors at boosted conditions while using a reduced compression ratio
  - Applicable to boosted SI engines
- Test additional Co-Optima research fuels
  - Most promising new biofuels (still TBD)
  - High Olefins
  - High Napthenes



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