Correlations Between Metallic Lubricant Additive Species in the Ring Pack and Ash Emissions and Their Dependence on Crankcase Oil Properties

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Motivation

- Lubricant-related ash adversely affects exhaust aftertreatment devices, but inorganic compounds in the oil protect the engine.
- Must find optimal concentrations of additives in the oil for adequate protection while minimizing impact on aftertreatment systems.

GOAL: Develop understanding (via data and modeling) of the characteristics of the lubricant (ash species, composition, and changes) in the critical regions of the engine and exhaust stream.

Ash Emissions vs. Oil Consumption

- Masses of ash elements collected in DPFs are less than expected based on total oil consumption and crankcase oil composition
- Additional fates for lubricant ash-related compounds:
  - Retained in crankcase oil
  - Flow through DPF
  - Deposit on surfaces
  - Anti-wear film formation

Mass Balance Recovery Rates for Elements With 95% Confidence Limits (APBF-DEC, 2004)

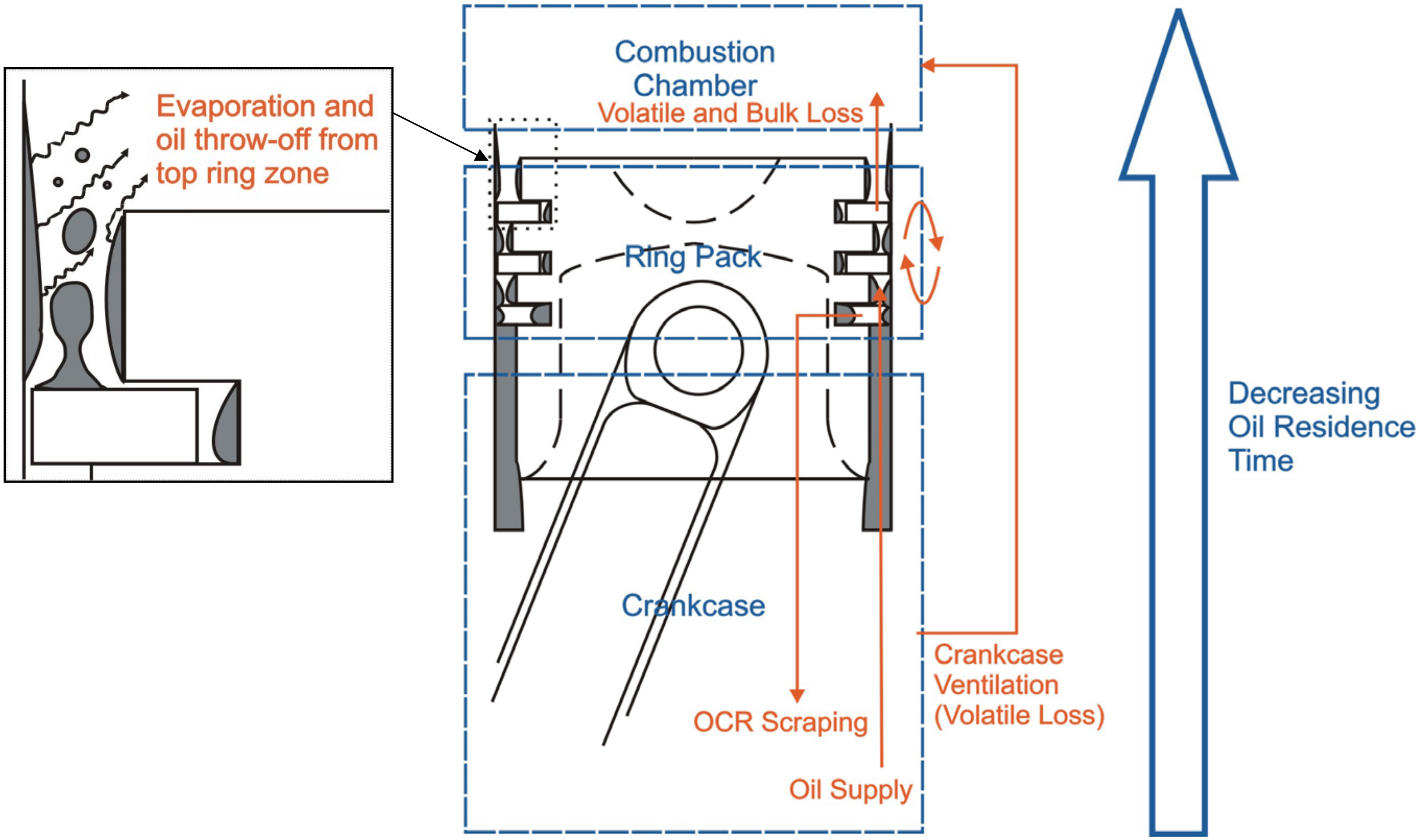
Element	Recovery Rate
S	127% (122%, 132%)
Ca	42% (40%, 43%)
Zn	42% (30%, 55%) @ 0.34 mg/bhp-hr
P	86% (82%, 90%)
Mo	28% (21%, 35%) @ 0.05 mg/bhp-hr
Mg	27% (0%, 55%) @ 0.3 mg/bhp-hr

Scope and Objectives of Current Work

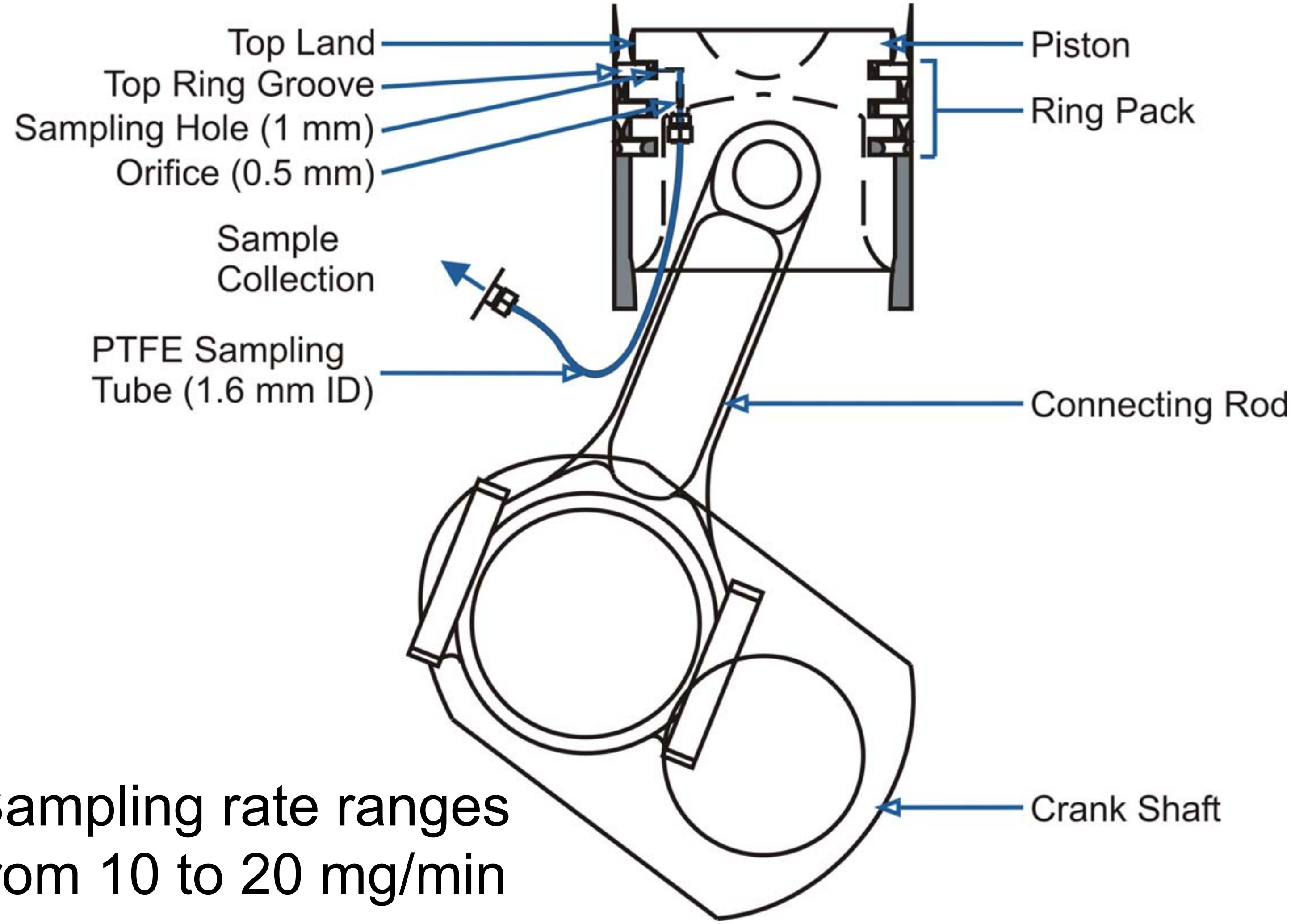
- Initial focus on power cylinder as it is the major source of oil consumption and emitted ash
  - Oil in this region is subjected to the largest contamination due to particulates, gaseous emissions and fuel dilution

- This study examines:
  - Lubricant-species compositional variations in engine (distribution)
  - Transport of these compounds in engine and to exhaust
  - ☞ **How each form of oil consumption in the cylinder affects exhaust ash emissions**

Power Cylinder Oil Consumption



Ring Pack Sampling System

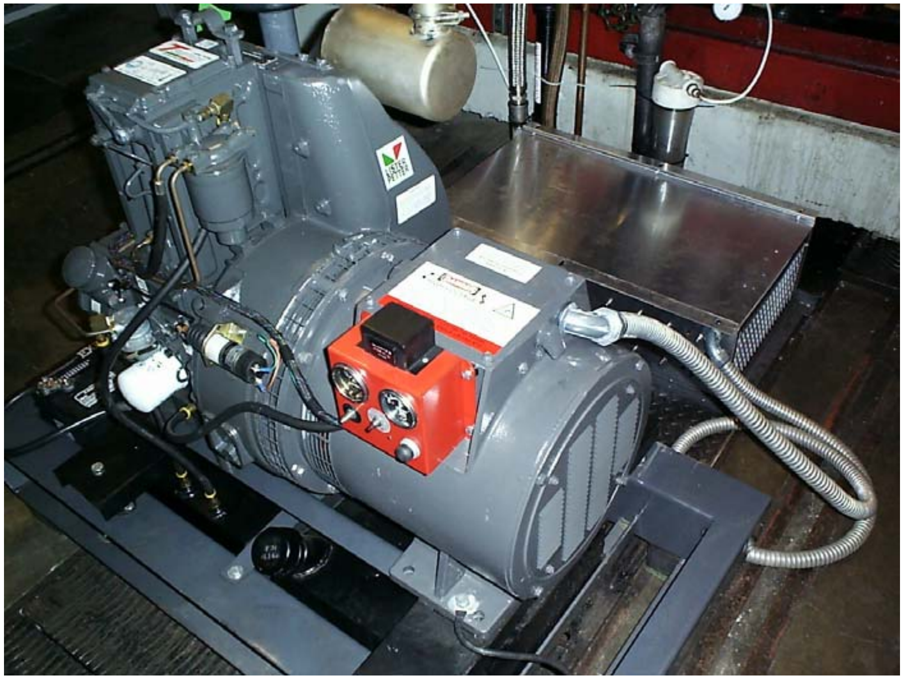


- Sampling rate ranges from 10 to 20 mg/min

Test Engine

Lister Petter TR1 Generator Set

- Specifications:
  - Single Cylinder
  - Naturally Aspirated
  - Maximum Power 5.5 kW
  - Direct Fuel Injection
  - Displacement 0.773 L
  - Compression Ratio 15.5:1
  - Three Ring Pack
  - Sump Capacity 2.4 L
  - Utilizes Closed Crankcase Ventilation with a separator



Lubricant Properties

Lubricant Properties:

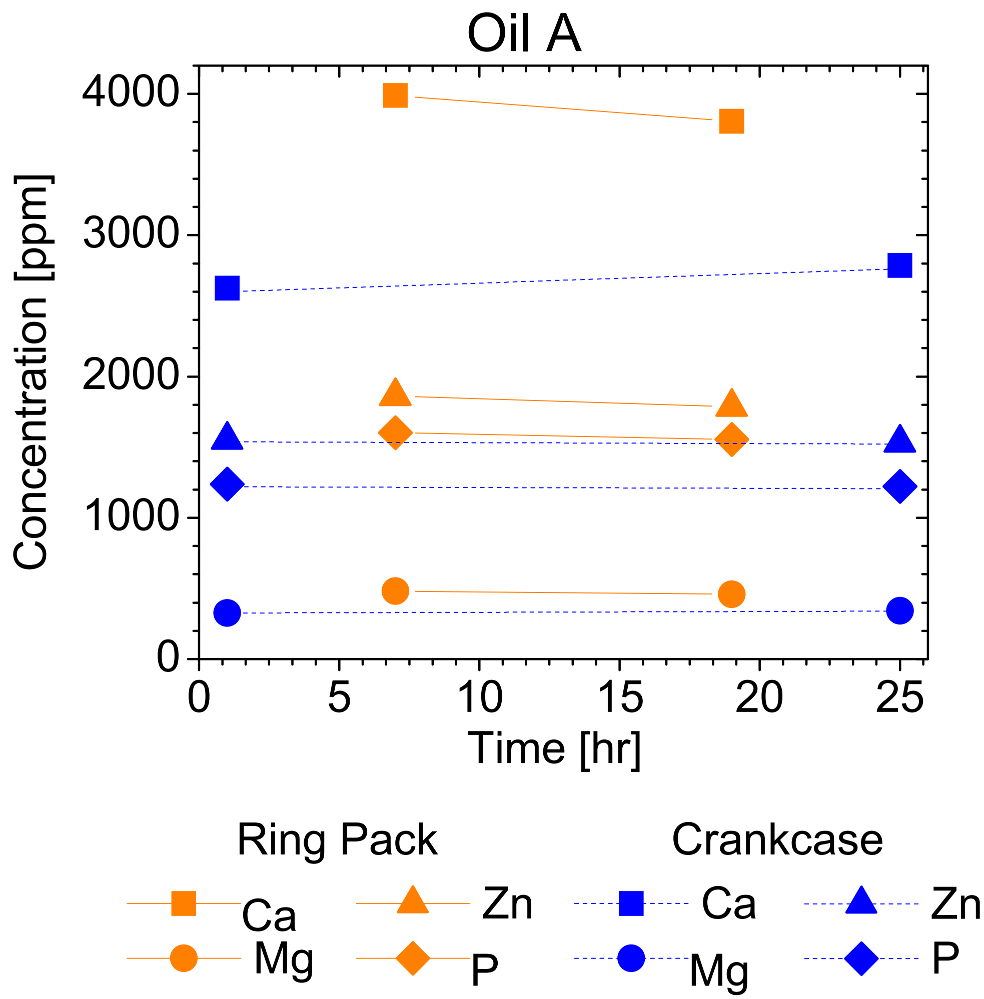
Property	Oil A	Oil B	Oil C
SAE Grade	15W40	30W	40W
Sulfated Ash [%]	1.0	1.0	1.0
Viscosity @100°C [cSt]	14.1	10.9	14.4
Total Base Number [mg/g]	10	7.3	7.3

Fresh Oil Composition:

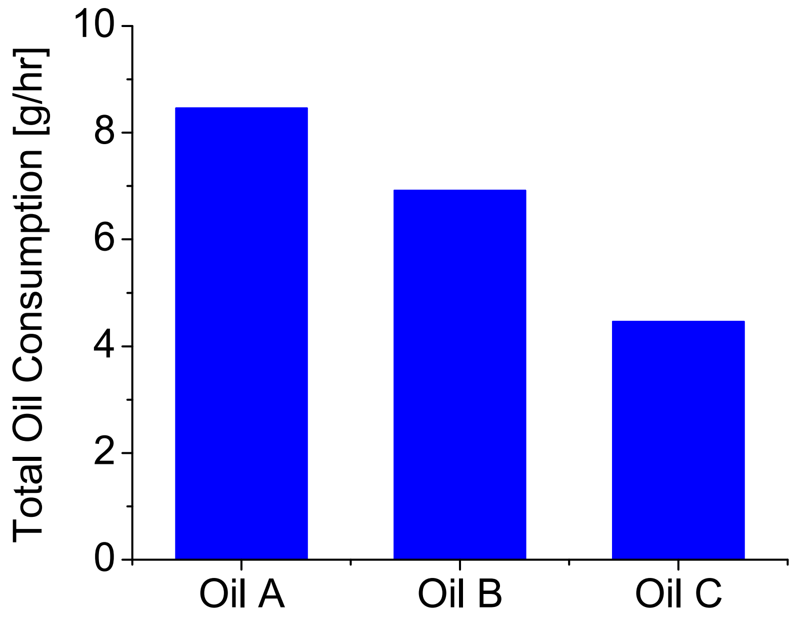
Element [ppm]	Oil A	Oil B	Oil C
Ca	2644	2397	2442
Mg	310	--	--
Zn	1494	1103	1137
P	1201	929	940

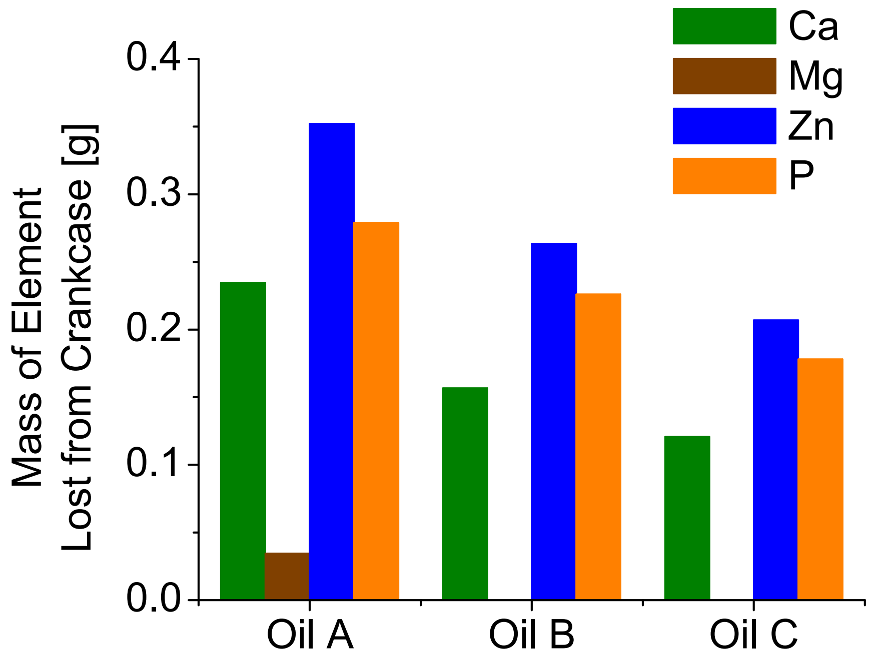
Ring Pack Sampling Experiments

- Load: 75%FP
- Speed: 1800 rpm
- Ring pack sample duration is 1 hr
- Samples are analyzed with ICP



Loss of Crankcase Oil Species



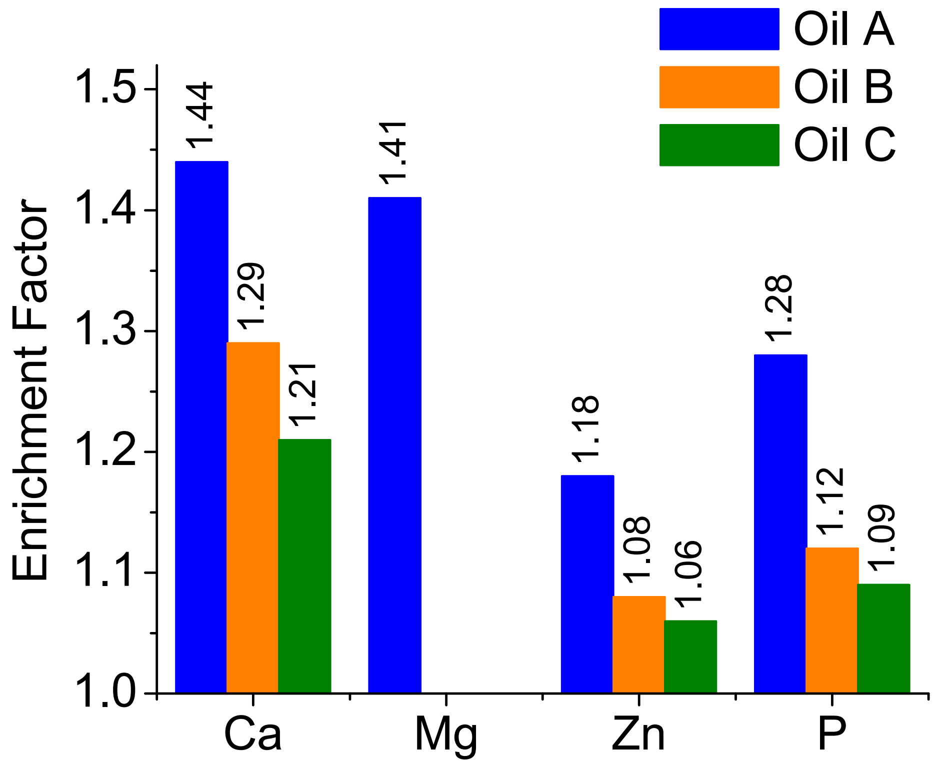


- Fewer additive metals are lost from the crankcase for less volatile/higher viscosity oils

Top Ring Zone Enrichment

- All metals are concentrated in the top ring zone samples
- Degree of enrichment is different for each element
- Lowest enrichment found for ZDDP elements

Enrichment Factor = Concentration of element relative to concentration of element in sump



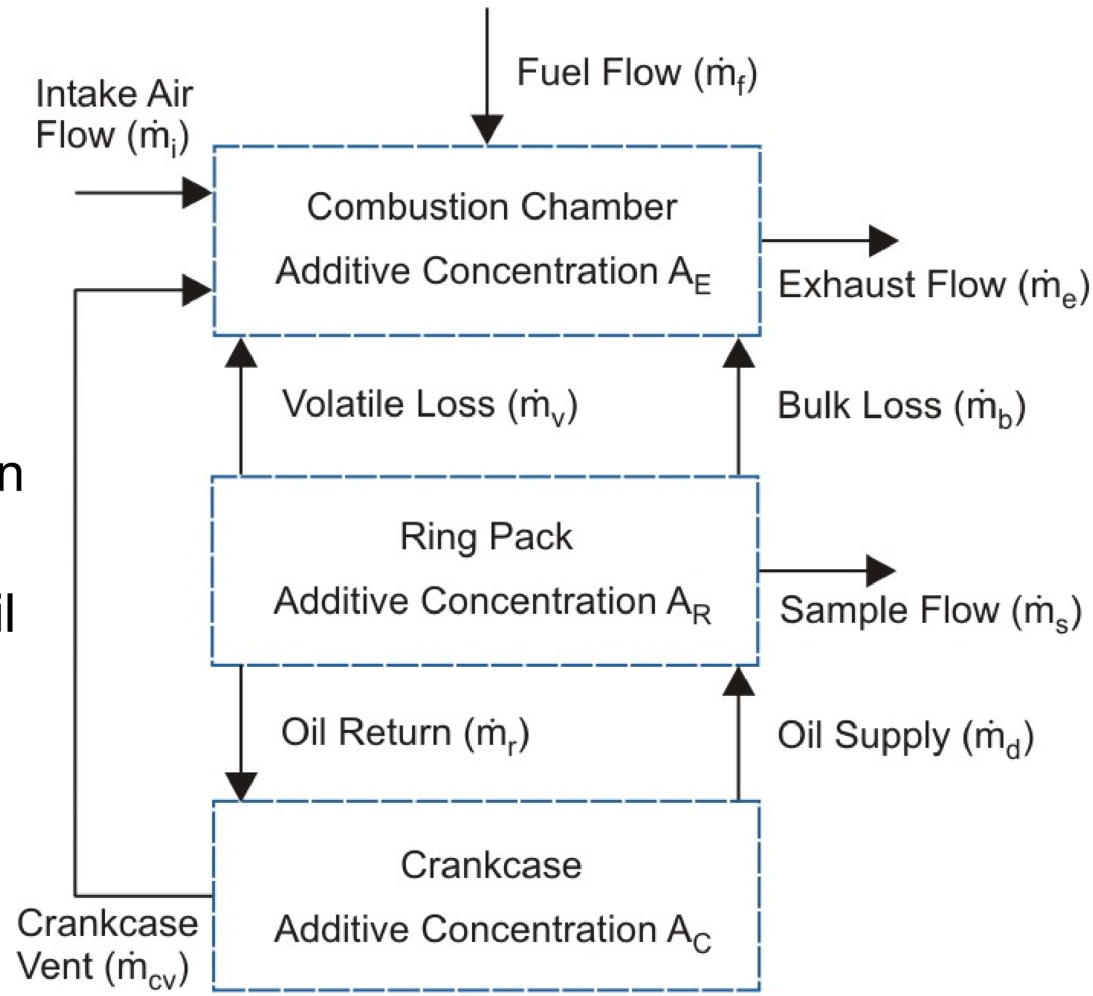
Top Ring Zone Enrichment

- Variations arise from:
  - Stability of the additives, or their degradation products
  - Tendency of element to form deposits

- At high piston temperatures ZDDP possibly degrades into forms that can be carried to exhaust stream via phase change or as part of liquid oil consumption
- Piston deposits rich in Zn and P

Power Cylinder Mass Balance

- Model Assumptions:
  - Average flows
  - Uniform concentration in each zone
  - Constant ring pack oil mass
  - Deposition neglected



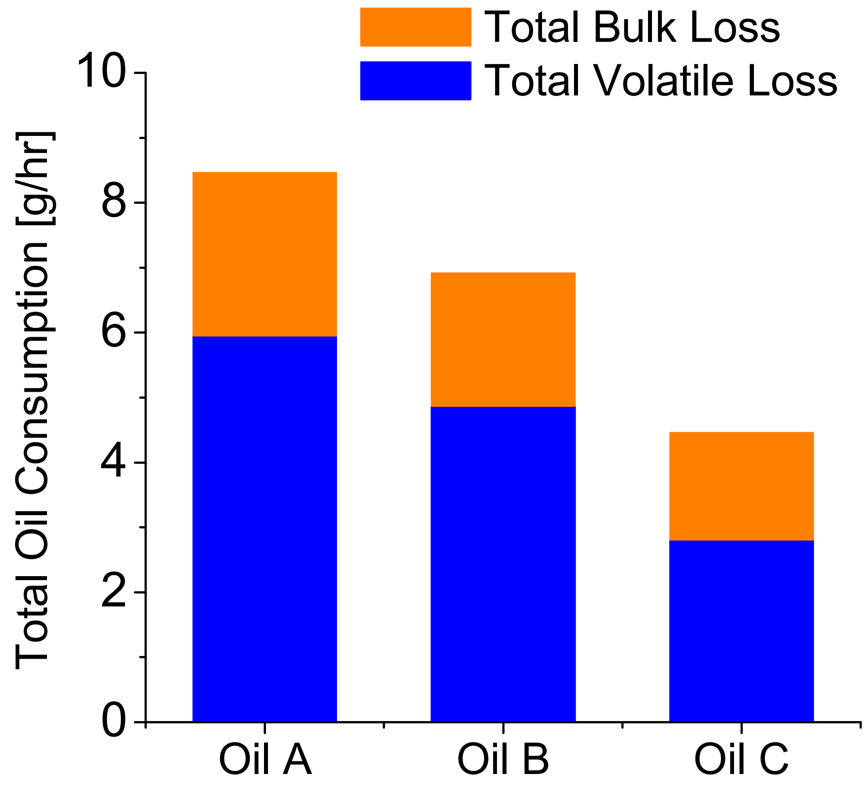
Total Bulk & Volatile Oil Consumption

- For the concentration of an additive in the system assumed to stay in the liquid

$$\dot{m}_{Bulk} = -\frac{1}{A_{i,R}} \frac{d\left(m_C A_{i,C}\right)}{dt}$$

$$\dot{m}_{Volatile} = \dot{m}_{OC} - \dot{m}_{Bulk}$$

- Assumed detergents, and stable ZDDP compounds consumed only in liquid form



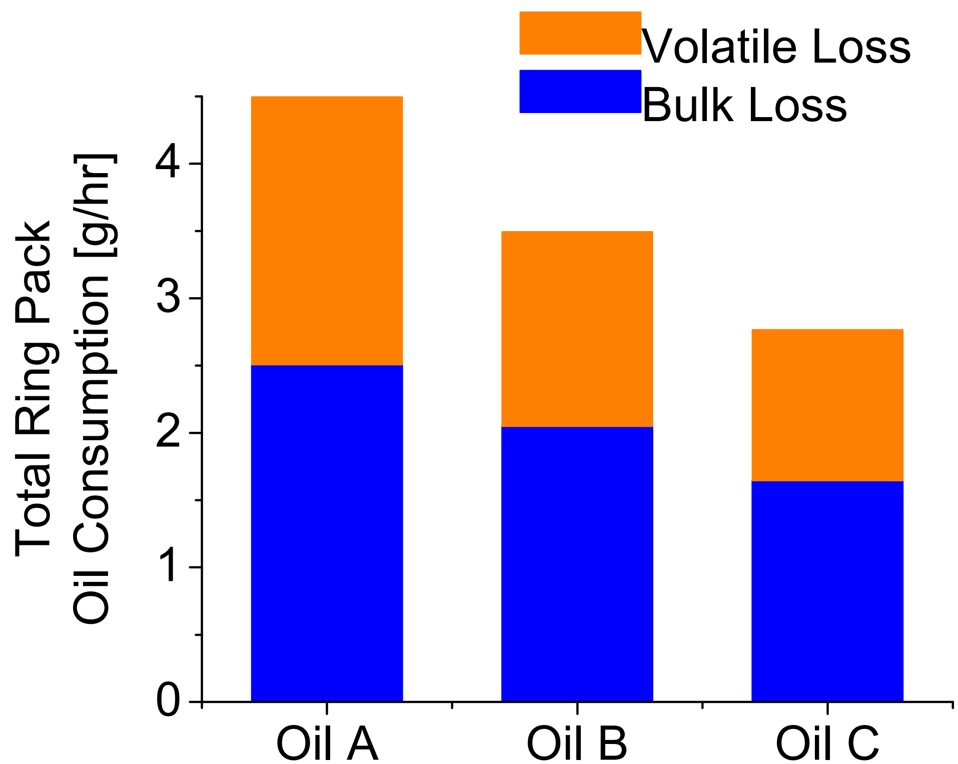
Ring Pack Oil Consumption

- For constant crankcase composition during the sampling period:

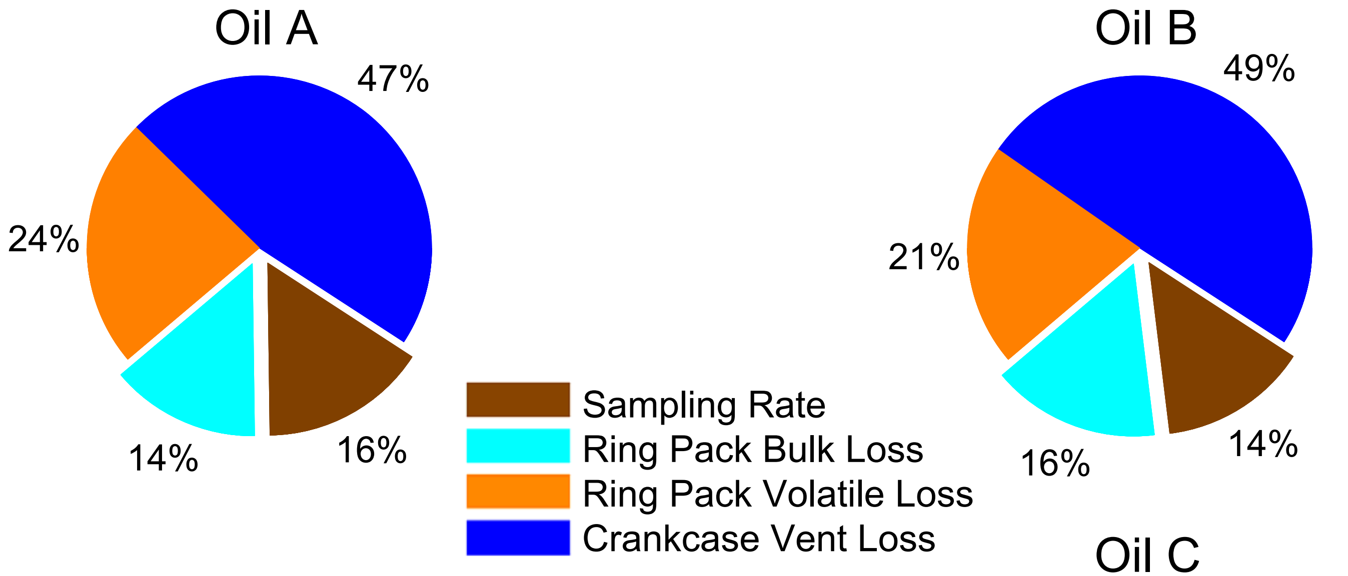
$$\dot{m}_v = \left(1 - \frac{1}{\varsigma_i}\right)\dot{m}_d$$

Ring Pack Enrichment

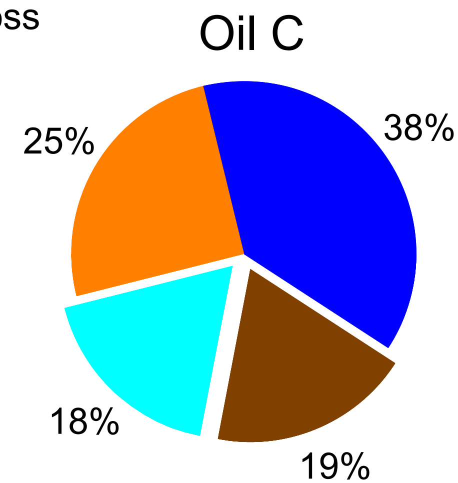
- Volatility increases concentration of metals in the oil transported to the combustion chamber



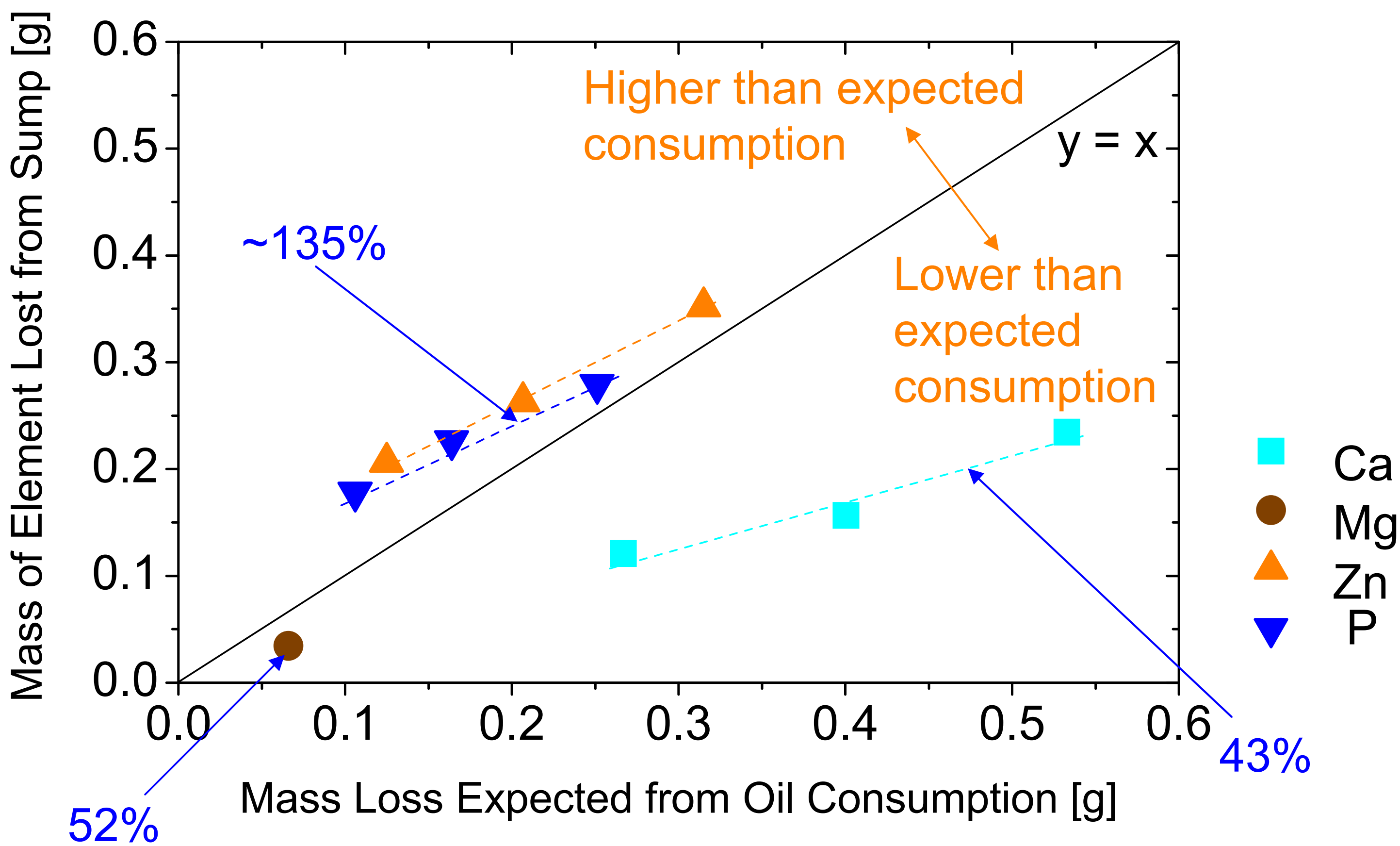
Oil Consumption Breakdown



- The fraction of oil consumed as a liquid is comparable for all three oils (~30-37%)



Correlation with Expected Mass Loss



Conclusions

- All additive metals are concentrated in ring pack samples
- Detergent compounds are concentrated to a higher degree than anti-wear additives
- Detergents and stable ZDDP-related by-products are consumed by bulk oil consumption
- Ring pack volatility increases concentration of metals lost to the combustion chamber as a liquid
- Other sinks for consumption of ZDDP elements include:
  - wear surface formation
  - deposition
  - volatilization of ZDDP thermal degradation products

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