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Dynamic Delivery –
America's Evolving Oil and Natural Gas Transportation Infrastructure
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Topic Paper #4-9

RECIPROCATING COMPRESSORS AND METHANE SLIP

Prepared for the

Technology Advancement and Deployment Task Group

On December 12, 2019 the National Petroleum Council (NPC) in approving its report, *Dynamic Delivery – America's Evolving Oil and Natural Gas Transportation Infrastructure*, also approved the making available of certain materials used in the study process, including detailed, specific subject matter papers prepared or used by the study's Permitting, Siting, and Community Engagement for Infrastructure Development Task Group. These Topic Papers were working documents that were part of the analyses that led to development of the summary results presented in the report's Executive Summary and Chapters.

These Topic Papers represent the views and conclusions of the authors. The National Petroleum Council has not endorsed or approved the statements and conclusions contained in these documents, but approved the publication of these materials as part of the study process.

The NPC believes that these papers will be of interest to the readers of the report and will help them better understand the results. These materials are being made available in the interest of transparency.

The attached paper is one of 26 such working documents used in the study analyses. Appendix C of the final NPC report provides a complete list of the 26 Topic Papers. The full papers can be viewed and downloaded from the report section of the NPC website (www.npc.org).

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Topic Paper

(Prepared for the National Petroleum Council Study on Oil and Natural Gas Transportation Infrastructure)

4-9	**Reciprocating Compressors and Methane Slip**
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SUMMARY

As natural gas reciprocating engines run leaner to minimize criteria pollutant emissions, uncombusted hydrocarbons (including methane) in the emissions increase. The uncombusted hydrocarbons are referred to as methane slip. This topic papers proposes funding of a computational fluid dynamic (CFD) investigation to isolate the relative effects of temperature, partially reacted chemical species (a.k.a. radicals), and turbulent jet mixing on ignition performance. The topic paper also addresses the need for cost effective methods for field quantification of methane in the exhaust.

I. Pipeline and Legacy Engines in the United States

Background

The United States natural gas pipeline industry operates about 5,600 spark-ignited gaseous fueled engine-compressors generating around 9,150,000 BHP (over 6,800 MW). The majority of these engines (~3,600) are unique two-stroke cycle (2SC) and four-stroke cycle (4SC) "legacy" units, which are between 30 and 60 years old (Figure 1).

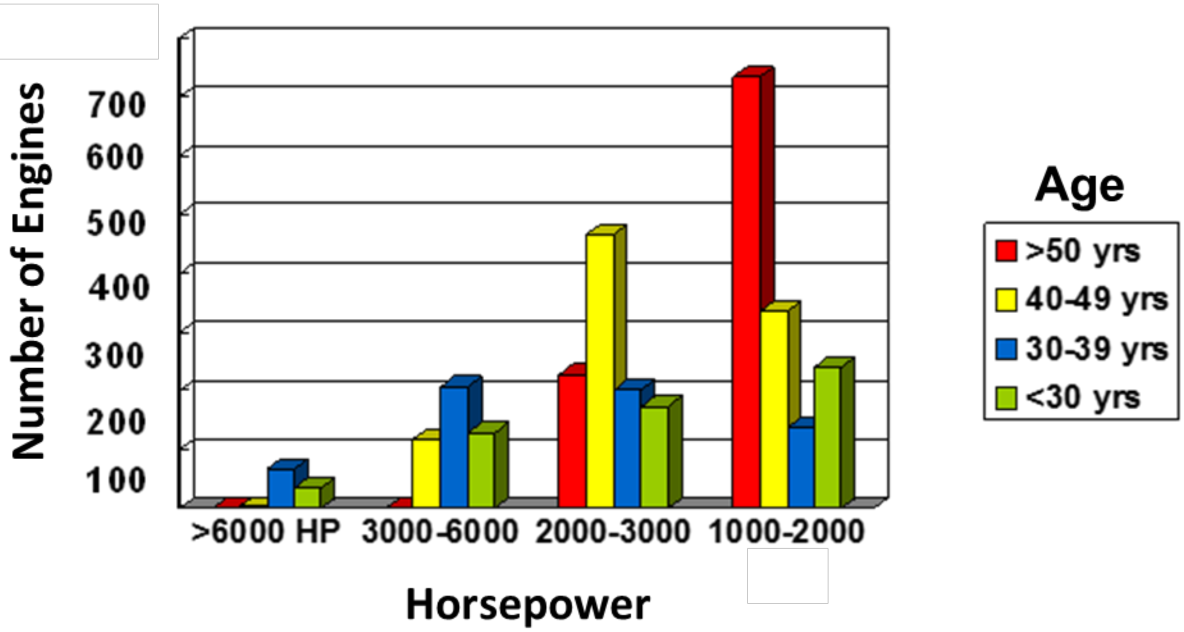
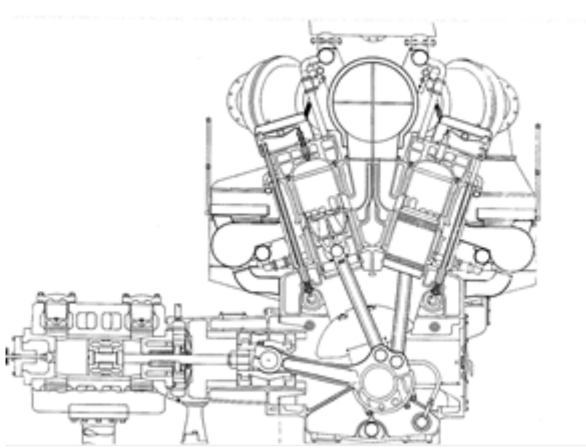


Figure 1: Age distribution of pipeline reciprocating compressors in the United States

These engines utilize an "integral" design in which the gas compressors are integrated directly into the engine crankcase (Figure 2). The power cylinders share a common crankshaft with the driven compressor cylinder, often utilizing an articulated connecting rod. The engines are generally port scavenged using a form of Schnürle scavenging. Fuel gas, the same gas flowing through the pipeline, is directly injected by a central fuel valve (either mechanically or electronically controlled) prior to port closure at about 15 to 30 psig. Air-fuel mixing is achieved through a combination of residual air swirl from the scavenging process and impingement of the injected fuel gas into the central bowl of the rising piston.



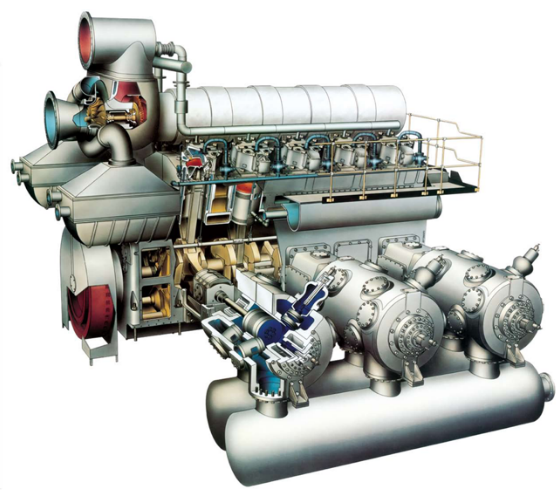


Figure 2: Cross-section and isometric-section views of typical legacy integral compressor engines

Table 1 shows typical power cylinder dimensions and ratings. With their simple yet elegant low speed design and low power outputs these engines have very long lifespans; many of these engines have been in service for over 60 year with expectations to run for at least another 40 years.

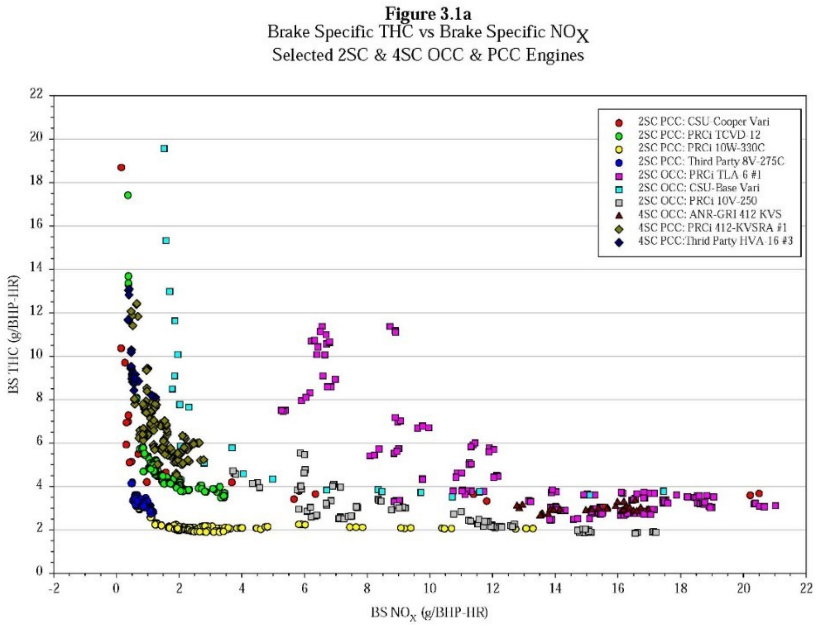
Table 1 - Typical Pipeline Engine Characteristics

Bore	14	in	356	mm
	20		508	
BMEP	60	psi	4	Bar
	125		9	
Rotative Speed	225			rpm
	460			
Output	1,000			BHP
	18,000			

Due to their longevity and emissions profile, these engines have come under increased regulatory scrutiny since the 1980's to reduce their exhaust emissions, particularly oxides of nitrogen (NO_x) while maintaining relatively low carbon monoxide (CO) emissions. NO_x, defined as the sum of nitric oxide (NO) and nitrogen dioxide (NO_2), are regulated pollutants. NO_x regulatory controls in the United States vary from state to state and even region to region based upon National Ambient Air Quality Standards. Rates for controlled NO_x emissions for legacy engines typically range from 0.5 to 3.0 g/BHP-HR.

Methane in the Exhaust

Typical of all lean burn gas engines, these legacy engines typically have 2 to 10 g/BHP-HR (1,000 to 5,000 ppm) total hydrocarbons (THC) in the exhaust. Moreover, as the engines run leaner to reduce NO_x emissions, the THC in the exhaust increases (Figure 3).



Source: Final Report: Carbon Pollutant Emissions and Engine Performance Trade-Offs vs NOx Emissions for Reciprocating Internal Combustion Engines Utilized in Gas Transmission Service," prepared for the Compressor Research Supervisory Committee of PRC International, prepared by: Advanced Engine Technologies Corporation, Contract No. PR-260-9726, December 1998

Figure 3 – Typical THC vs. NOx emissions from a variety of legacy engines (Beshouri 1998)

This THC does not arise from fuel short circuiting out of the exhaust valves or ports during cylinder fueling. Rather this THC comes from fuel gas, which is trapped in the cylinder during the combustion process but does not actually combust. This unburned fuel comes from crevices, quench zones, and extremely lean pockets. During the expansion stroke, the unburned fuel gas expands into the exhaust. The majority of the unburned THC is methane in the same ratio as the methane in the fuel gas.

The resultant exhaust methane emissions, though significantly lower than CO_2, have a significant impact on carbon dioxide equivalent emissions (CO_{2e}) due to methane's 25:1 global warming potential factor. Depending on the NO_x emissions levels and combustion technologies being utilized, this methane can increase CO_{2e} in the exhaust by 15% to 40% or more over the CO_2 from the combustion process itself.

Oxidation catalyst technology cannot reduce methane emissions at the low exhaust temperatures typical of legacy engines (Lehtoranta). Retrofits with modern ignition and fuel injection technology can somewhat reduce methane in the exhaust by improving mixing and flame propagation. However, these upgrades are usually associated with ultra-lean NO_x reductions and generally result in the same or only slightly reduce CO_{2e} in the exhaust.

It is important to note that modern four-stroke cycle lean burn engines also contain significant fractions of methane in the exhaust (Wang).

Consequently, the need exists to develop new technologies for reducing or eliminating methane in the exhaust. The focus is in-cylinder combustion technologies which can reduce methane in the exhaust without increasing NO_x or other criteria pollutant emissions.

Radical combustion initiates combustion through chemical means by introducing partial combustion products which are rich in highly reactive radicals and intermediate species (molecules) collectively referred to as Radical Species. These Radicals, when sufficiently mixed with the Main Combustion Chamber lean fuel-air charge, rapidly initiate a chain-branching, chemical-decomposition combustion reaction.

The relative contributions of turbulence, temperature and reactive chemical species (radicals) is not clear. The majority of work to date has focused on optimizing the first two factors. However, the success of micropilot dual fuel engines which rely solely on radical induced combustion suggests a strategy which optimizes radical formation may offer unique benefits.

Funding of a Computational Fluid Dynamic (CFD) investigation to isolate the relative effects of temperature, partially reacted chemical species (a.k.a. radicals), and turbulent jet mixing on ignition performance is proposed to better understand the relative importance of these three effects, which will provide insight into how to better optimize precombustion chambers (PCCs).

In addition, cost effective methods for quantifying methane in engine exhaust would be beneficial. Fundamental research of cost-effective field measurement of methane is an excellent opportunity for DOE funded research.