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Development of a screening tool to prioritize testing for the carcinogenic hazard of residual aromatic extracts and related petroleum streams

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HIGHLIGHTS

- The carcinogenic activity of petroleum-derived residual aromatic extracts (RAE) is proposed to be determined by distillation properties.
- The carcinogenic moieties that may be present, polycyclic aromatic hydrocarbons, distill in the front-end (lower-boiling) fractions of RAE.
- Gas chromatographic distillation provides an effective method to measure the distillation of RAE and screen for potential carcinogenicity.
- RAE should be non-carcinogenic if their 5% distillation point is equal to or greater than 479 °C.

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ABSTRACT

Residual aromatic extracts (RAE) are petroleum substances with variable composition predominantly containing aromatic hydrocarbons with carbon numbers greater than C25. Because of the high boiling nature of RAEs, the aromatics present are high molecular weight, with most above the range of carcinogenic polycyclic aromatic hydrocarbons (PAHs). However, refinery distillations are imperfect; some PAHs and their heteroatom-containing analogs (collectively referred to as polycyclic aromatic content or PAC) may remain in the parent stream and be extracted into the RAE, and overall PAC content is related to the carcinogenic potential of an RAE. We describe here a real-time analytical chemistry-based tool to assess the carcinogenic hazard of RAE *via* the development of a functional relationship between carcinogenicity and boiling point. Samples representative of steps along the RAE manufacturing process were obtained from five refineries to evaluate relationships between mutagenicity index (MI), PAC ring content and gas chromatographic distillation (GCD) curves. As expected, a positive linear relationship between MI and PAC ring content occurred, most specifically for 3–6 ring PAC ($R^2 = 0.68$). A negative correlation was found between MI and temperature at 5% vaporization by GCD ($R^2 = 0.72$), indicating that samples with greater amounts of lower boiling constituents were more likely to be carcinogenic. The inverse relationship between boiling range and carcinogenicity was further demonstrated by fractionation of select RAE samples (MI = 0.50 + 0.07; PAC = 1.70 + 0.51 wt%; n = 5) into low and high boiling fractions, where lower boiling fractions were both more carcinogenic than the higher boiling fractions (MI = 2.36 ± 0.55 and 0.17 ± 0.11, respectively) and enriched in 3–6 ring PACs (5.20 + 0.70 wt% and 0.97 + 0.35 wt%, respectively). The criteria defining carcinogenicity was established as 479 °C for the 5% vaporization points by GCD, with an approximate 95% probability of a future sample having an MI below the recommended limit of 0.4 for RAEs. Overall, these results provide a cost-efficient and real-time tool by which the carcinogenic potential of RAEs can be assessed at the refinery level, ultimately providing a means to readily monitor and minimize the carcinogenic potential of RAEs.

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1. Introduction

Residual aromatic extracts (RAE) are produced during the lubricating base oil manufacturing process. Substances at each step of this manufacturing process have distinct compositional and toxicological properties. An early step of base oil manufacture produces raw vacuum tower distillates (Fig. 1), which have been shown to be highly carcinogenic in animal studies (Bingham et al., 1979; Chasey and McKee, 1993; Kane et al., 1984), producing tumors in more than two animals as early as 14 weeks after the initiation of repeated dermal application, often in greater than 50% of animals (Mackerer et al., 2003; McKee et al., 1989b). Solvent extraction of distillates produces two substances (Fig. 1): (1) raffinates that are highly depleted of aromatic content and have no demonstrated carcinogenic potential and (2) aromatic extracts that are enriched for polycyclic aromatic hydrocarbons (PAHs) and can be potent carcinogens (Bingham et al., 1979; Blackburn et al., 1996; Dalbey et al., 2014; Gradiski et al., 1983; Mackerer et al., 2003; Smith et al., 1951). The carcinogenic potency of these petroleum substances is dependent upon the relative amount of 4–6 ring PAH and heteroatom-homologues, collectively referred to as polycylic aromatic content (PAC) (Blackburn et al., 1996; Chasey and McKee, 1993). As an example, McKee et al. (1989a) showed that "heavier" distillates, *i.e.*, those distilling at a higher temperature range (389–566 °C, in this example), are less potent as measured by median tumor latency (approx. 34 months) and prevalence of tumor bearing animals (approx. 5%) when compared to "lighter" distillates (288–432 °C; 17 month median latency; 50% tumor bearing animals), consistent with the overall lower 4–6 ring PAH content in the heavier vs lighter distillates (14–27 ppm vs 26–82 ppm).

Correlations between mutagenicity, carcinogenicity, and aromatic content are well established for lubricating base oils and related streams. Using 94 oils, high concordance in the carcinogenicity decision was demonstrated between animal bioassays and short term assays measuring either mutagenicity by the Modified Ames assay (ASTM, 2010) or aromatic content by IP346 (Institute of Petroleum, 2004; Chasey and McKee, 1993). Modern carcinogenicity hazard assessment of certain petroleum streams relies on the strength of these correlations, thus providing a practical and cost-effective method for hazard assessment. However, even if such methods are greatly simplified relative to skin painting studies, they are only practical for periodic use, as the global capacity for the conduct of such tests, the test cost and turnaround time limit their wider use. Therefore, the development of even more time and cost-efficient approaches to prioritize testing by such short term assays is desirable.

For substances derived from vacuum residuum (also referred to as vacuum "resid" or the bottom of the vacuum distillation tower, Fig. 1), there is some evidence to suggest that the relationship between mutagenicity, carcinogenicity, and aromatic content may be quantitatively different than that established for substances derived from the lighter distillates derived from lower boiling range cuts from the distillation tower, despite similar processing. Vacuum residual material is first deasphalted through the removal of bulky asphaltene molecules *via* solvent extraction followed by entry of the deasphalted oil into the typical lube oil manufacturing process described above (Fig. 1). For residuum-derived raffinates (with approximate initial boiling points >570 °C), the regulatory criteria for the IP346 assay resulted in false positive calls, indicating that these oils have high DMSO-extractable content despite no evidence of carcinogenic activity in animal bioassays (Blackburn et al., 1996; Chasey and McKee, 1993; Roy et al., 1988). Residual aromatic extracts have had mixed results in animal studies (CONCAWE, 2005), possibly related to the wide distribution in aromatic content reported in RAEs, ranging from 0.7% to 6% (Brandt et al., 1999). A comparison of animal bioassay and modified Ames assay results suggests that the threshold to distinguish oils likely to be carcinogenic for RAEs (mutagenicity index (MI) < 0.4) should be lower than that used for distillate-derived oils (MI < 1) (Blackburn et al., 1996; CONCAWE, 2012). Further, the correlation between mutagenicity and PAH content is shallower for vacuum residuum-derived streams (slope < 1) compared to vacuum distillate-derived

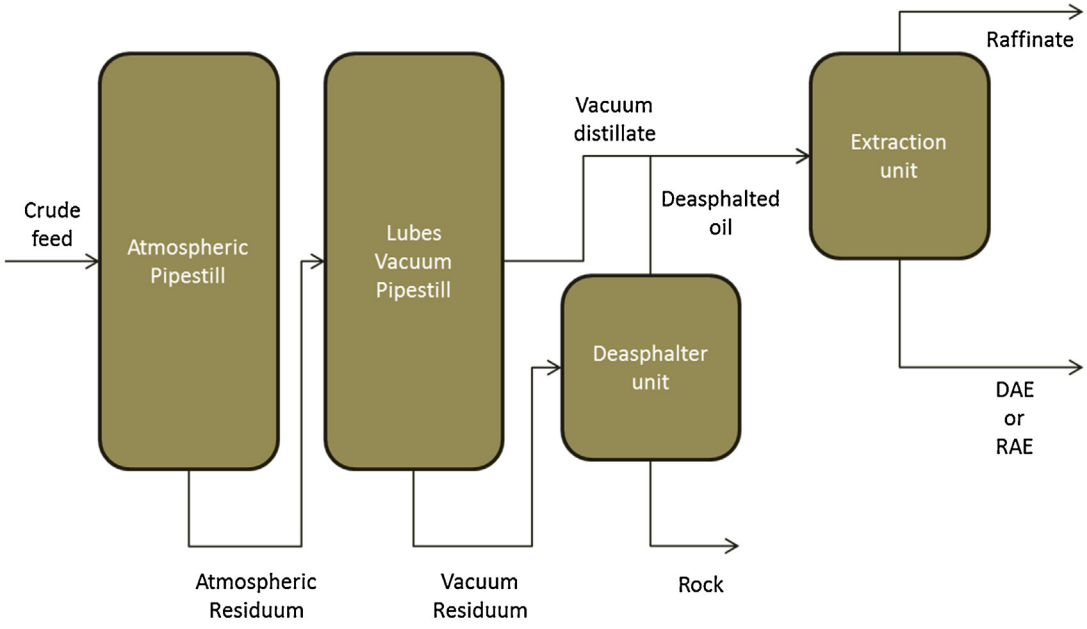

Fig. 1. Feed to the extraction unit is typically alternated between vacuum distillate directly from the lubes vacuum distillation tower and deasphalted oil (DAO) derived from vacuum residuum (*i.e.*, vacuum tower bottoms). Raffinates derived from either vacuum distillate feed or DAO feed have similar toxicological properties, and are thus considered as belonging to the same chemical category for hazard identification purposes. DAE and RAE can have different mutagenic and carcinogenic potential and thus are considered as two unique chemical categories.