

## Mass Absorption Cross-Section of Fresh Flare-Generated Black Carbon: Sensitivity to Gas Composition and Flaring Conditions and Development of a Predictive Phenomenological Model

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Atmospheric black carbon (BC, the carbonaceous component of combustion-generated soot) is an efficient absorber of solar radiation and is thought to be the second most potent radiative climate forcer after carbon dioxide (e.g., Ramanathan and Carmichael, 2008). Anthropogenic BC concentrations in earth's atmosphere are driven by myriad sources including transportation, shipping, and biomass burning. One other industrial source of atmospheric BC is gas flaring within the global oil and gas (O&G) industry. Gas flaring is a common practice where O&G producers choose to dispose of unwanted gases through open to atmosphere combustion, typically from a vertically-raised pipe stack. While BC emissions from flaring are relatively small in a global context, flare-emitted BC has been identified as having an accentuated impact on the arctic climate (e.g., Stohl et al., 2013) due in part to the location of regions with high O&G activity.

As a strong light-absorber with a single-scatter albedo on the order of 20%, the direct radiative forcing efficiency of atmospheric BC is most sensitive to the BC particle's mass-normalized absorption cross-section (MAC, units of area per mass). With the exception of flares, measurements of MAC of freshly-emitted BC exist for the majority of important anthropogenic sources. These were comprehensively summarized in the literature review of Bond and Bergstrom (2006), who concluded that a consistent value of BC MAC likely exists based on the observation that variability between literature data was typically dominated by measurement uncertainties. Unfortunately, the source data available to Bond and Bergstrom were largely from laboratory flames, diesel engines, and other small flames burning generally high molecular weight fuels. In terms of combustion chemistry and aerodynamics, these sources are markedly different from gas flares, which combust lighter fuels and are much larger in scale. This raises the important question of whether the conclusions of Bond and Bergstrom (2006) are applicable to gas flare-emitted BC.

This work presents measurements of BC MAC from large-scale laboratory flames representative of O&G flaring. Experiments were performed at the Carleton University Flare Facility in Ottawa, Canada, where flares of up to 3 m in length burning gas compositions representative of the global O&G industry are created from stacks of up to 3" in diameter. Flare emissions are captured and forwarded to a three-wavelength photoacoustic spectrometer and thermal-optical organic/elemental carbon mass analyzer to directly quantify fresh BC MAC, with uncertainties computed via a Monte Carlo method. Variability of BC MAC beyond measurement uncertainties and as a function of flare gas composition and flow rate was observed —contrary to Bond and Bergstrom's (2006) notion of a consistent BC MAC for all sources. A predictive phenomenological model of BC MAC as a function of readily-available flare metrics is derived and implications with respect to radiative forcing are discussed.