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Review

The history, genotoxicity, and carcinogenicity of carbon-based fuels and their emissions. Part 2: Solid fuels

Larry D. Claxton *

LDC Scientific Services, 6012 Brass Lantern Court, Raleigh, NC 27606, United States

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ABSTRACT

The combustion of solid fuels (like wood, animal dung, and coal) usually involves elevated temperatures and altered pressures and genotoxicants (e.g., PAHs) are likely to form. These substances are carcinogenic in experimental animals, and epidemiological studies implicate these fuels (especially their emissions) as carcinogens in man. Globally, ~50% of all households and ~90% of all rural households use solid fuels for cooking or heating and these fuels often are burnt in simple stoves with very incomplete combustion. Exposed women and children often exhibit low birth weight, increased infant and perinatal mortality, head and neck cancer, and lung cancer although few studies have measured exposure directly. Today, households that cannot meet the expense of fuels like kerosene, liquefied petroleum gas, and electricity resort to collecting wood, agricultural residue, and animal dung to use as household fuels. In the more developed countries, solid fuels are often used for electric power generation providing more than half of the electricity generated in the United States. The world's coal reserves, which equal approximately one exagram, equal ~1 trillion barrels of crude oil (comparable to all the world's known oil reserves) and could last for 600 years. Studies show that the PAHs that are identified in solid fuel emissions react with NO_2 to form direct-acting mutagens. In summary, many of the measured genotoxicants found in both the indoor and electricity-generating combustors are the same; therefore, the severity of the health effects vary with exposure and with the health status of the exposed population.

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* Tel.: +1 919 839 8978.
E-mail addresses: ldcss@gmx.com, bettyandlarry@yahoo.com

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1. Introduction

Solid fuels have been used for hundreds of years. Before the first use of petroleum, solid fuels like wood, animal dung, and coal were used for heating and cooking. Therefore, populations used solid fuels as countries developed, and most air pollution was from the use of solid fuels. Today, the sources of air pollution depend upon whether air sampling is done in developing countries or in developed populations. For people in developing societies, the majority of indoor exposures are due to solid fuel emissions, which continue for most people throughout their life. In developed countries, the highest indoor pollution levels occur when combustion processes associated with cooking, heating, and/or tobacco smoking are coupled with poor ventilation. When tobacco smoke adds toxicants to other biomass smoke, health concerns are magnified. In both developed and developing countries, pollution exposures indoors may be higher than those outdoors. Desai et al. [1] in a WHO document said, "Although outdoor sources often dominate air pollution *emissions*, indoor sources frequently dominate air pollution *exposures*. Exposure is a function of both the pollutant concentration in an environment, and the person-time spent in the environment. Since most people spend the majority of their time in homes, schools and workplaces, human exposure to air pollution is largely a function of pollutant levels in indoor settings (which can arise from outdoor sources and vice versa)." On a global basis, most indoor air pollution results from the burning of solid fuels for household cooking and heating [1]. Approximately 50% of all households and 90% of all rural households, worldwide, use solid fuels for cooking or heating [2]. These populations use stoves that have high emission factors, exposing occupants of residences to high levels of air pollutants. Cooking, a potential problem for people in both developed and developing countries can produce very high concentrations of emissions. In many locations, solid fuels are burnt in inefficient simple stoves under poorly ventilated conditions. In these situations, solid fuel emissions expose individuals to many health-damaging pollutants (e.g., respirable particulates, carbon monoxide, and other toxic compounds) from high levels of indoor air pollution exposures. Therefore, the severity of the health effects will vary with both the intensity and the duration of exposure and with the health status of the exposed population [3]. Investigators are and will continue to use the data of developing societies to identify and understand the health effects of the emissions of solid fuels.

Indoor air pollution can be traced to prehistoric times when humans first moved to temperate climates and it became necessary to construct shelters and use fire inside the shelters for cooking, warmth, and light [2,4]. Fire caused exposure to high levels of pollution, as evidenced by the soot found in prehistoric caves [2]. Today, households that cannot afford fuels that are higher on the "energy ladder" (i.e., kerosene, liquefied petroleum gas (LPG) and electricity) often opt for collecting wood, agricultural residue, and animal dung as the household fuels. Po et al. [5] reported that in today's world the source of energy for cooking and heating is solid biomass fuels for ~2.4 billion people. About 0.6 billion people use coal. Therefore, up to 90% of rural households in developing countries still rely on unprocessed biomass fuels [2,6]. These unprocessed fuels typically are burnt indoors in open fires or poorly functioning stoves [4]. As a result, there are high levels of air pollution to individuals responsible for cooking and caring for their young children (i.e., usually women) [4,6]. Solid biomass fuels (typically wood, charcoal, dried animal dung) and agricultural residues (such as straw and sticks) have low combustion efficiency. This incomplete combustion discharges smoke with fine particulate matter, which fills the kitchen and/or living area. In biomass-burning households, PM_{10} or $PM_{2.5}$ concentration levels often exceed international guidelines [5].

Barnes et al. [7] in a report of the Energy Sector Management Assistance Program (ESMAP) of the World Bank say, "For people in developed countries, burning fuelwood in an open hearth evokes nostalgia and romance. But in developing countries, the harsh reality is that several billion people, mainly women and children, face long hours collecting fuelwood, which is burned inefficiently in traditional biomass stoves. The smoke emitted into their homes exposes them to pollution levels 10–20 times higher than the maximum standards considered safe in developed countries. And the problem is not out of the ordinary. The majority of people in developing countries at present cannot afford the transition to modern fuels. Today, close to one half of the world's people still depend on biomass energy to meet their cooking and heating needs." A number of publications [4,8–22] give information on the indoor use of coal and other solid fuels in developing countries. Although these publications do not give information on the genotoxicology of emissions, they are instructive.

2. Coal as fuel

Achten and Hofmann [23] noted "Numerous environmental polycyclic aromatic hydrocarbon (PAH) sources have been reported in literature, however, unburnt hard coal/bituminous coal is considered only rarely." The review of these authors tell us that land plants are buried and converted to coal by prolonged exposure to elevated temperatures and pressures in the subsurface. The physico-chemical changes are complex, with resistant plant biopolymers (e.g., lignin) converted into a highly aromatic, three-dimensional, networked matrix with the order of increasing maturity being: peat → lignite → sub-bituminous coal → bituminous coal → anthracite coal → graphite. Ether or methylene bridges and aliphatic side chains mainly consisting of methyl groups commonly link aromatic structures. The average number of aromatic rings per structural unit in most coals is 3–5 with some individual units having up to 10 rings. Therefore, a typical hard coal is characterized by 2–6 PAHs linked by methylene bridges with additional aliphatic side chains and phenol functional groups. In addition to the network structure, a multitude of small molecules (known as the "mobile phase") is present within the network. Because these molecules can be released from the coal network, this mobile phrase is of particular environmental interest. The type of a coal influences the concentration and composition of the mobile phase. This extractable phase may be released to the aquatic environment, be available to organisms, and thus be an important PAH source. During coal heating at manufactured gas plant sites, the linkages between some of the carbon units are cleaved, thereby releasing the conjugated aromatic rings into the mobile fraction (gas and coal tar). Therefore, coal can exhibit native PAH concentrations up to hundreds, in some cases, thousands of mg/kg. PAH concentrations and patterns in coals depend on the original organic matter type, as well as temperature and pressure conditions during coalification. The environmental impact of native unburnt coal-bound PAH in soils and sediments is not well studied. The presence of unburnt coal particles has been reported in some marine sediments, freshwater sediments, and soils. For example, during and after the cleanup of the Exxon Valdez oil spill in Alaska, U.S.A., there were detailed discussions whether the PAHs in sediments of Prince William Sound originated from the spill or from naturally outcroppings of coal seams near the shore [24,25].

2.1. Indoor use of coal

In 1775, Pott [26] was the first to describe a cancer caused by the soot of coal burning, when he determined that this soot caused cancer of the scrotum of chimney-sweeps. Thus, the first