The Environmental Occurrence and Health Aspects of Polycyclic Aromatic Hydrocarbons

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THE ENVIRONMENTAL OCCURRENCE AND HEALTH ASPECTS OF POLYCYCLIC AROMATIC HYDROCARBONS

by

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ABSTRACT

Uthe, J.F. 1979. The environmental occurrence and health aspects of polycyclic aromatic hydrocarbons. Fish. Mar. Serv. Tech. Rep. 914, iii + 30 p.

This paper reviews the formation, environmental and foodstuff occurrence, and health effects of polycyclic aromatic hydrocarbons (PAHs). PAHs are derived from the combustion and the use of petroleum and coal products. Coal tar products (e.g. creosote, pitch) and coal liquification products contain substantial amounts of PAH. Major PAH exposures for man (other than direct contact with the above-mentioned materials) result from ingestion of smoked foods, notably meat and fish. Shellfish, notably lobsters which have been exposed to creosoted timbers, have extremely high tissue levels of PAHs compared to other foodstuffs. Degradation of PAHs involves photoxidation or biological oxidation via aryl hydrocarbon hydroxylases, a group of enzymes, which results in oxidized forms of the parent PAH compound. One or more of these oxidized products is believed to be the carcinogenic form of the parent PAH. Changes in the biological oxidative enzyme pathways brought about by other compounds, e.g. other PAH compounds, make prediction of the carcinogenic potential of an individual PAH difficult. The association of PAH exposure and cancer has been demonstrated. It is expected that tolerance levels for PAHs in foodstuffs will be set at the highest level of PAHs naturally found in foodstuffs. That level is generally believed to be about 100 µg total PAH/kg food or about 1 µg benzo(a)pyrene/kg food.

RÉSUMÉ

Uthe, J.F. 1979. La présence dans l'environnement des hydrocarbures aromatiques polycycliques et les aspects concerant la sante. Fish. Mar. Serv. Tech. Rep. 914 , iii + 30 p.

L'auteur a étudié la formation des hydrocarbures aromatiques polycycliques (HAP), leur présence dans l'environnement et les aliments, et leurs effets sur la santé. Ces hydrocarbures, qui proviennent surtout de la combustion et de l'exploitation des produits pétroliers et houillers, sont particulièrement concentres dans les produits du goudron de houille. L'homme y est exposé non seulement quant il entre en contact direct avec les substances susmentionnees mais aussi quant il fume et ingère des aliments fumés, comme la viande et le poisson surtout. Les crustacés, notamment le homard qui a été exposé à des boid de créosote ont des taux extrêmement élèves des HAP quant on les compare à d'autres aliments. Leur dégradation se fait par photoxidation ou oxydation biologique sous l'effet d'hydroxylases des hydrocarbures aryle, groupe complexe d'enzymes qui transforment les composés d'hydrocarbures d'origine en de nombreuses formes oxydées, dont une ou plusieurs seraient cancérigènes. Il est tres difficile de prédire le pouvoir cancérigène d'un HAP donné en raison des différentes voies d'oxydation enzymatique qui peuvent être empruntées en présence de composés hydrocarburés analogues. La relation entre l'exposition à ces hydrocarbures et l'apparition d'un cancer ne faisant plus de doute, il faut espérer que pour fixer les quantités tolérées dans la nourriture, on se fondera sur la concentration la plus élévée trouvée dans les aliments de consommation et jugée auparavant sans danger. On la situe en général à peu près à 100 µg d'HAP/kg d'aliment ou à 1 µg de benzo(a)pyrène/kg d'aliment.

INTRODUCTION

Polycyclic or polynuclear aromatic hydrocarbons (PAHs) are organic compounds having a nucleus composed of three or more fused aromatic carbon rings. Nitrogen, sulfur and oxygen can be readily substituted for carbon atoms within the aromaticized structure to form "heteroaromatic" compounds (Blumer 1976; Patterson et al 1960). Once three or more carbon rings are involved, the number of possible isomers increases due to the various positions of alkyl side chains on the polycyclic nucleus, and the differing possible ways of fusing the rings, e.g. anthracene and phenanthrene are isomers of three fused, non- alkylated benzene rings. Analysis of natural substrates for PAHs is complicated by the presence of several individual PAH compounds. In general PAHs have been found everywhere in the biosphere (Laflamme and Hites 1978). This is expected since PAHs result from thermal rearrangement of organic substances (pyrolysis). In this process energy is released and the aromatic products that are formed are more stable than their precursors. PAH formation can occur over long periods of time at relatively low temperature such as in the conversion of organic matter into crude oil (Blumer 1976; Mair 1964) or rapidly, as in combustion (National Academy of Sciences 1972). PAHs in crude oil are characterized by the presence of numerous alkyl side chains on the aromatic nucleus. As the reaction temperature increases, greater and greater amounts of non-alkylated PAHs are formed (Laflamme and Hites 1978; Broddin et al. 1977; Crittenden and Long 1976).

The complex nature of combustion, the general heterogeneity of the combustible material, and many other factors, result in formation of complex PAH mixtures. Biosynthesis leads to rather simple mixtures (Blumer 1976), but this input to the environment does not appear significant compared with the thermal and geochemical routes.

This review is not intended to cover all aspects of PAH formation, environmental occurrence, biodynamics, metabolism, biological effects, carcinogencity, etc., but to set the stage for a rational view towards the dangers for man posed by marine fishery products containing trace levels of various PAHs.

POLYCYCLIC AROMATIC HYDROCARBON ANALYSIS

The major processes contributing PAHs to the environment lead to complicated end products. The chemist is faced with analytical difficulties in that PAHs must be separated from a heterogeneous matrix prior to qualitative and quantitative analysis. This has led to a divergence in methodology in that some analysts are interested in characterization of all PAHs present in a mixture while others are interested in certain individual PAHs (Lankmayr and Muller 1979), e.g. those which are believed to be carcinogenic in man. Often only benzo(a)pyrene is determined (e.g. Dunn 1976). This makes comparison of data from different investigators difficult. In addition, few intercalibration studies have been carried out among laboratories analyzing PAHs. Haenni (1978) showed that most laboratories could yield similar quantitative results when employing the same methodology. Problems, when encountered, were mainly due to inaccurate preparation of standards.

Hilpert et al. (1978) reported an inter-laboratory comparison of determination of PAHs in natural sediment samples containing µg/kg levels of individual PAHs. Two laboratories identified methylpyrenes as the most abundant, large (4 rings and larger) PAH. Another identified methyl-fluoranthenes and methylpyrenes. One laboratory identified methylchrysenes as well. Total PAH levels (4 rings and larger) values were reported to be 9.3, 40 and 74 µg/kg sediments. Obviously, comparisons of levels determined by different laboratories must be used cautiously.

Studies of PAHs involve isolation, generally by saponification (Sikorski 1965) and solvent extraction, partitioning and chromatography to yield a PAH-enriched fraction which is then analyzed by one of two methods, either UV absorption or fluorescence of individual PAHs or through gas-chromatography-mass spectrometry (Snook et al. 1976; Severson et al. 1976; Lee et al. 1976; Giger and Blumer 1974). Colucci and Begeman (1971) pointed out that early (pre-1971) UV determinations of benzo(a)pyrene levels are probably too high because of inclusion of benzo(k)fluoranthene or benzo(ghi)perylene. Giger and Blumer (1974) believed that analytical resolution of natural samples (sediments) for PAHs is not possible and that only the most abundant PAHs could be determined with any degree of accuracy. Since various investigators have determined various numbers of different PAHs it is difficult to quote total PAH concentrations or percentages of individual PAH components. In more recent years a greater number of individual PAHs have been determined. In the discussions below, a total PAH figure will be given, calculated from the individual PAH levels stated in the reference. Also the number of PAHs determined will be stated. Where possible an absolute and percentage figure for benzo(a)pyrene will be given since it is the most active non-alkylated carcinogenic PAH known to date (National Academy of Sciences 1972).

SOURCES OF POLYCYCLIC AROMATIC HYDROCARBONS

Combustion of organic fuels probably represents the greatest input of PAHs to the environment (National Academy of Sciences 1972; Suess 1976). These inputs are characterized by the presence of relatively large amounts of non-alkylated PAHs (Herlan 1978; Badger et al. 1964). Thirteen major non-alkylated PAHs were identified and quantified by Davies et al. (1976) in a study of garbage incineration at a furnace temperature of 800-1090°C. Oxyacetylene flames (Crittenden and Long 1976), even under carefully controlled conditions, yield mixtures of PAHs and different results were obtained by different investigators. A study of chimney soot (Tausch and Stehlik 1977) separated at least forty-one different PAHs.

It is estimated (Suess 1976; National Academy of Sciences 1972) that 1200 tonnes of benzo(a)pyrene are injected into the atmosphere in the USA annually. Equivalent figures for world wide production give a world total release of benzo(a)pyrene of approximately 5000 tonnes. Benzo(a)pyrene is a minor constituent of the PAH complex injected into the atmosphere (Tausch and Stehlik 1977; Davies et al. 1976; Nielsen 1979; Lankmayr and Muller 1979; Fishbein 1973), ranging from 5 to 10% of the total. The total amount of PAH that is released to the atmosphere is probably at least twenty times the estimated tonnage of benzo-(a)pyrene, i.e. approximately 25,000 tonnes of the

U.S. and a world total of 100,000 tonnes (Herlan 1978).

Natusch (1978) discussed PAH emissions from fossil-fuelled power plants. Most are non-alkylated. Total PAH emissions are quite low (~1 tonne of benzo(a)pyrene for all major coal-fired power plants in the USA in 1972) as long as efficient combustion conditions are maintained. Hand-stoked operations give rise to much higher emmissions of PAHs (up to 10,000 x higher) due to inefficient combustion. Economic and other factors have led generally to the abandonment of such inefficient heating plants (Environmental Protection Agency 1974).

Open and refuse burning were once potent PAH sources but recent controls have drastically reduced such sources. Apartment and home incinerators may still produce various PAH emissions. The recent popularity of tightly-closed wood burning stoves as home heating units remains to be assessed for PAH output. A recent study by Butcher and Sorenson (1979) showed such stoves emit 1-24g particulate matter/kg fuel of which 2-34% is a benzene soluble neutral fraction which would contain PAHs. Use of wood as a heat source was estimated by Suess (1976) to produce 220 tonnes of the benzo(a)pyrene released annually but this would not include increased production by air-limiting stoves (Butcher and Sorenson 1979).

Internal combustion engines also release PAHs into the atmosphere (Mohr 1978; Nielsen 1979). The type of engine, its geometry, combustion temperature, mixture richness, etc., influence the final PAH composition of the exhaust. For example, Mohr (1978) determined that gasoline engine exhaust contained benzo(a)pyrene, benzo(a)anthracene and chrysene at a total concentration of 1030 µg/g, of which 33% was benzo(a)pyrene. Studies on these three compounds by the World Health Organization (International Agency for Research on Cancer 1973) found the total concentration of these three PAHs in gasoline engine exhaust to be 268 µg/g of which 11% was benzo(a)pyrene. Grimmer et al. (1977) studied the PAH emmissions from twenty different car models. He reported that gasoline engines emit a characteristic PAH profile. Levels of benzo(a)pyrene varied from 5 - 268 µg per Europa drive cycle and represented about 2-5% of the total PAH determined (11 different ones). A number of methylated PAH were also identified. Grimmer (1977) estimated known carcinogenic PAHs accounted for only 10-15% of the carcinogenic activity of exhaust condensate and that methylated PAHs accounted for the predominant part of the carcinogenic effect of motor vehicle exhaust. As an engine wears, more lubricating oil is burnt increasing the level of PAHS in the exhaust (National Academy of Sciences 1972). Two-cycle engines, which operate on oil/gasoline mixtures (typically 1/30), produce elevated benzo(a)pyrene emissions (2,000 µg/L of fuel) compared with 40 µg/L for four-cycle engines (Guerin 1978) and may represent a major PAH input into recreational freshwater lakes.

Diesel engines are reported (Lucas 1971; Guerin 1978) to produce somewhat greater amounts of PAHs in their exhaust than gasoline engines but the opposite is also reported (National Academy of Sciences 1972). This ambiguity may result from load characteristics of the engine since Bricklemyer and Spindt (1978) have shown that benzo(a)pyrene emissions from diesel engines increase at full loads. In general PAHs present in fuel are burnt and the exhaust PAHs are formed during fuel combustion (Grimmer 1977).

Most aerial PAH emissions are particulate in nature. Broddin et al. (1977) found that over 90% of the PAHs in an aerosol were on particles smaller than 3 µm. Mueller et al. (1964) indicated that most particles emitted from autos were smaller than 0.3 µm, and it was reported (National Academy of Sciences 1972) that PAHs in air are largely associated with particles less than 5 µm in diameter. Katz and Pierce (1976) found two distinct size fractions containing benzo(a)pyrene in dust collected near highspeed highways, small (1.0 µm, 38% of total benzo(a)pyrene; and large (2.0-7.0 µm, 52% of total benzo(a)pyrene). They believed the source of the small particles was engine exhaust. The large particles were thought to be from processes such as tire and highway wear.

Crude oil processing and use involve large amounts of PAHs (Guerin 1978) although it is estimated that benzo(a)pyrene emission in the USA from petroleum usage is only 3.2% (i.e. 27 tonnes) of the annual benzo(a)pyrene emmissions (Environmental Protection Agency 1974). However the total addition of PAHs to the environment is much higher. Crude oil contains about 1-3% by weight of PAHs. The U.S. petroleum industry handles approximately 80 million tonnes (MT) of PAHs and 800 tonnes of benzo(a)pyrene a year in crude oils. If the estimates of Travers and Luney (1976) are reasonable, the annual introduction of 44 MT of crude oils and product into the oceans would contribute 1.1 MT of PAHs to the oceans (8.2 tonnes of benzo(a)pyrene). High boiling distillates tend to concentrate the PAHs from the crude although some remains in the pot residue (asphalt). Catalytic cracking and upgrading result in increased PAH levels in products and regeneration of catalyst through burning off of coke entrained on the catalyst produces PAHs in stack gases. In general, petroleum distillate products contain PAH levels up to 63 µg/g. Used motor oils, are extremely enriched in PAHs (Graf and Winter 1968) and it is estimated that up to 8 MT of benzo(a)pyrene enter the environment (much into sewers) from their discard. Petroleum pitch, a cracked product resulting from pyrolysis of gas oil or fuel oil tars (Trosset et al. 1978), is heavily enriched with PAH (Grienke and Lewis 1975), the level of PAH ranging up to 2.5% by weight (benzo(a)pyrene; 8% of the total PAH present). Asphalt, the residue obtained from the straight distillation of crude oil, contains from 2 - 3 µgPAH/g (10 isomers, benzo(a)pyrene, 0 to 2.5 µg/g, 0-8%) (Wallcave et al. 1971). About 35 MT of asphalt are produced per year as 209 different products in the USA (1974 figure (Trosset et al. 1978)) of which 78% is utilized in paving and 17% as roofing materials. It is estimated that about 6000 MT of asphalt are currently present on road surfaces in the USA (Trosset et al. 1978).

The PAH release from these surfaces has not been determined. Neukomn et al. (1975) could find no differences in airborne PAHs taken from near either asphalt or concrete roads. Waibel (1976) concluded significant benzo(a)pyrene was released from asphalt-coal tar pitch roads presumably due to high PAH levels in coal tar pitch. Natural gas burners could also produce PAHs, particularly if improperly adjusted. The inefficient burning off of waste gases at oil refineries is another source of PAHs which has not been assessed yet.

Petroleum hydrocarbons are in the process of being mined from the Athabascan tar sands in Alberta, Canada, and the tar shales in Colorado, U.S.A. No information of the PAH content of tar sand products was found but shale oils prepared from high grade shale (U.S.) contain about the same level of benzo(a)pyrene as found in crude oil (3 µg/g).

Cutting oils (e.g. the anthracene oil described below) and other lubricants prepared improperly from coal or petroleum wastes can be highly contaminated with PAHs. Thony et al. (1976) studied anthracene oils. Levels as high as 10 µg/g benzo(a)pyrene were found.

Carbon black, produced through burning under low oxygen conditions, contains PAHs (Gold 1975) and is used as a reinforcing agent in synthetic rubber tires. Wearing of tires can contribute PAHs to the environment.

Coal, the other major fossil fuel, contains PAHs (Woo et al. 1978). The coking of coal represents a major route of entry of PAHs into the environment. In the U.S.A. these operations released about 200 tonnes of benzo(a)pyrene a year (National Academy of Sciences 1972). These plants produce coal tar which contains large amounts of PAHs. Coal tar plant aerosols are extremely rich in PAHs (Lao et al. 1975), representing as much as 54.9% by weight of the aerosol (50 different PAHs; benzo(a+e)pyrene; 13.8 mg/g; 2.5%). The coal tar itself had a PAH concentration of 48.5% by weight (50 different PAHs; benzo(a+e)pyrene; 33.13 mg/g; 6.8%). Lao et al. (1975) identified a total of about 60 different PAHs in coke oven emissions. Qualitative and quantitative differences were found from plant to plant. Benzo(a)pyrene levels were 4.3-9.47% of the emitted PAHs. It has been estimated that as much as 1.8 g of benzo(a)pyrene could be emitted during the coking of one ton of coal (National Academy of Sciences 1972).

The current crude oil shortfall can be expected to lead to increased amounts of coal liquifaction and gasification operations. All plants produce mixtures of products, high levels of PAHs (5-41% by weight) being found in the liquid and tar products (Guerin 1978). As an example, Karr et al. (1977) studied coal liquifaction with a number of catalysts and found PAHs represented 16-20% by weight of the oil produced from bituminous coal, even when catalytically reacted to increase the light oil ends and lower the asphaltene concentration. If U.S.A. plans are carried out for 20-40 plants each processing 25,000 tonnes of coal per day, a considerable amount of PAH enriched fuel as well as tars will be produced.

Coal tar, the basic starting stock for the preparation of creosote, is the primary distillate from the anerobic thermal decomposition of bituminous coal at temperatures ranging from 900-1200°C (Hawley 1977; Encyclopaedia Britannica 1973; Clark 1966; Hey 1966; Powell 1973). Coal tars vary in consistency from a thin, oily liquid to a viscous, pitch-like substance. Yields of coal tar range from 25-125 L per metric ton of coal. Coal tar is generally redistilled but some is utilized as open-hearth furnace fuels in steel plants and a small amount in wood preservation (Mann 1959). While stills and distillation practices vary widely, it is customary to fractionate coal tar into: 1) light oils (containing monocyclic aromatics such as benzene, toluene, etc., up to 200°C) representing approximately 2% of the pot charge; 2) chemical oil (containing phenol, creosols, pyridine and naphthalenes, 200-250°C) representing approximately 15% of the pot charge; 3) creosote oil (containing polynuclear aromatics, phenolics, etc., 250-350°C) representing approximately 21% of the pot charge; 4) pitch (the pot residue) representing approximately 62% of the pot charge. The desired nature of the pitch varies from very soft pitches for protective coatings and fuels (McGannon 1971), felt saturation, and paints through intermediate pitches used for road surface binders, bituminous and macadam bindings, pipe line coatings (Larson 1978), better paints and waterproofing agents (Banfield 1974 Brown 1973) to the hard pitches used for coking and electrode production and in clay pigeons (The British Carbonization Research Association 1975).

Creosote is defined by The American Wood Preserver's Association (Webb 1975) as "a distillate of coal tar produced by high-temperature carbonization of bituminous coal; it consists principally of liquid and solid aromatic hydrocarbons. It is heavier than water and has a continuous boiling range of at least 125°C beginning at about 200°C." In addition to creosote itself, a number of types of creosote-coal tar solutions are used extensively in treatment of railroad crossties, posts, and piles (Graham 1959). Creosote is mainly used for the prevention of the deterioration of wood by fungi, insects and marine animals. A small amount finds use in production of carbon black (Encyclopaedia Britannica 1973) and in antifouling marine concretes (Muraoka and Vind 1975). Treatment of wood can be as simple as painting creosote on the surface but the most effective procedure involves treatment by a combination of vacuum, pressure and hot creosote (Mann 1959). Specifications are given in terms lb/ft^3 or kg/m^3 (based upon extraction of treated product). Final treatment may involve vacuum treatment to remove excess creosote and prevent bleeding. This final procedure may be deleterious in marine applications since the borer (Limnoria lignorum) can creep into small cracks and attack the wood. Pressure treated wood retains most of the creosote throughout its useful life (Webb 1975). What losses are observed occur at a higher rate during the first years of exposure (Gibb 1978). Model studies (Sweeney et al. 1958) utilizing treated panels indicated surface losses of as much as 40% in the first year of seawater exposure. Loss caused by hydrative swelling of wood fibers was believed to be responsible. Such losses have been confirmed by other researchers (Miller 1977; Hochman 1967).

It was reported (Gibb 1978) that U.S.A. use of creosote in 1972 was 520 million kg. In 1975 approximately 843 million lb of creosote and 105 million kg of coal tar were used as a wood preservative in the U.S.A. Pesticidal useage in the U.S.A. in 1975 accounted for approximately 16 million kg of coal tar, 167 million kg of creosote and 1 million kg of coal tar neutral oils.

At least 300 compounds have been positively identified in coal tar and it is estimated that at least 10,000 compounds may be present (Gibb 1978). Borwitzky and Schomburg (1979) recently identified over 140 compounds, including heterocyclics and PAHs in coal tar. Lijinsky et al. (1963) reported that creosote contained 8.7% PAHs by weight (15 individual PAHs). Coal tar contained 6.5% PAHs.

The concentrations of tricyclic and tetracyclic hydrocarbons were higher in creosote than in coal tar, the reverse being true for the pentacyclic hydrocarbons. In addition to the usual PAHs, creosote contains large amounts of naphthalene, mono- and dimethylated naphthalenes and a number of phenols (Osusky 1975) including phenol, all three cresols, all six xylenols and both naphthols.

The PAH composition of creosote varies from source to source. Literature PAH levels in creosote are shown in Table 1. Analyses of coal tar and sludge from a wood treatment plant are also included to give some idea of the composition of the starting material for preparing creosote and the final waste product. Creosote is an enriched product with respect to PAHs compared to coal tar, and sludge analysis shows that PAHs get impregnated into the wood along with the tank liquor rather than precipitating in the sludge. Substantial differences in levels of PAHs in creosote were reported which may represent analytical differences and actual differences in the creosotes examined. Colley (1974) found that after 9.5 yr in a marine environment creosote from creosote-treated wood had essentially the same level of total PAH and individual PAH composition as the impregnating creosote originally used. Stasse (1967) reported similar results. Increasingly dense creosotes showed a tendency towards containing somewhat larger concentrations of PAHs.

Creosote as utilized in protection of wood against Limnoria tripunctata must be essentially free of aliphatics since studies have shown that as little as 2% aliphatics in creosote allows attack by Limnoria tripunctata (Baechler and Roth 1961), while pilings impregnated with 100% aromatic tar/naphthalene creosote were found to be totally resistant (Baechler 1968; Becker 1957).

Much work has been carried out on the use of preservatives other than creosote but creosote or creosote mixtures are the only effective preservatives for wood in a marine environment (Mann 1959; Becker 1959; Graham 1959). Creosote is reported to be upgraded in performance by fortification with up to 40% naphthalene or with coal tar itself (Page 1977; Seesman et al. 1977). Commercial treatment of southern pine poles with creosote containing 2% pentachlorophenol has been utilized since 1953 (Colley 1959). Johnson (1973) reported that pre-creosoting pile treatment with copper-arsenic salts was the best treatment against attack by Limnoria and Teredo. Tin salts such as tributyl tin oxide are more toxic to Limnoria and Teredo but the effectiveness testing of such materials as creosote replacement agents will take a great deal of time since creosote structures have lasted up to almost 100 yr in a hostile environment (Encyclopaedia Britannica 1973). Hochman (1973) studied 786 different chemicals and found that, when normalized to creosote for toxicity to two genera of borers, compounds very toxic to one genus were much less toxic to the other genus and vice versa. Creosote containing 40% naphthalene approaches the ideal marine wood preservative which, according to Page (1977), is fluid at treatment temperatures, solid at ambient temperatures, does not move about in the wood, leach or evaporate. It does not spatter during pile driving nor embrittle the wood.

As described above, the pot residue from coal tar distillation is known as coal tar pitch (Trosset et al. 1978). The chemical composition of pitch is extremely complex and quite variable. Pitch is estimated to contain from 5,000-10,000 compounds (McNeil 1966). Of 126 compounds described in coal tar pitch, the majority are condensed PAHs and their heterocyclic analogues. In general, pitch PAH components are 3-6 fused ring compounds with a molecular weight in the range of 200-500.

Biosynthetic sources of PAHs have been alluded to above. Andelman and Suess (1970) believed that a natural background of 10-20 µgPAH/kg dry organic matter is a realistic estimate of background levels. Several PAHs have been found in areas remote from human habitation (Andelman and Suess 1970). Windsor and Hites (1979) found total PAH levels of 18 µg/kg (dry weight) in deep-ocean sediments (Atlantic Abyssal Plain) and from 1-100 µgPAH/kg (dry weight) in deep Nova Scotia, Canada, soils (20-40 cm). The median total PAH level in Nova Scotia was 50 µg/kg (dry weight) compared to the 100-1000 µg/kg range reported by Andelman and Suess (1970) for the earth's upper layer (soil). Blumer (1961) suggested background levels of PAHs in soils could be due to microbial synthesis but in 1976 he stated that this could only account for a couple of individual PAH compounds. It has been reported that plants (Zobell 1971; Hancock et al. 1970; Graf 1965; Barnett 1976), algae and bacteria (Knorr and Schenk 1968; Niaussat et al. 1969, 1970) can synthesis PAHs including benzo(a)pyrene. Grimner and Duvel (1970) studied PAH synthesis in higher plants under carefully controlled conditions. They found only PAHs up to and including four aromatic rings could be synthesized. Borneff et al. (1968) studied Chlorella vulgaris and reported synthesis of benzo(a)pyrene. Hase and Hites (1976) were unable to demonstrate bacteria synthesis by anaerobic bacteria. This suggests that limited PAH biosynthetic ability exists in the biosphere. Certain biosynthetic chemicals can, during the course of decompositon, yield individual PAHs. For example, perylene is thought to result (Aizenshtat 1973) from the reductive decomposition of terrestrial precursors. Volcanoes have also been suggested as a source of PAHs (Suess 1976).

In addition to exposure resulting from living within the technological/biological environment, man is exposed to major amounts of PAHs from tobacco and marijuana smoke. Tobacco smoke has been the subject of much study regarding its PAH content (Schmeltz and Hoffman 1976) and represents the major general exposure route for man to PAHs (Snook et al. 1976; Severson et al. 1976, 1977; Lee et al. 1976, to name a few). More than 300 PAHs ranging from indene to the dimethylbenzopyrenes have been characterized (Snook et al. 1976) and the authors point out that higher ring systems were not determined. The total amount of PAH in cigarettes averaged 100 µg per 100 cigarettes (Severson et al. 1976). Commercial filters reduced this to less than 40 µg per 100 cigarettes. In a later study Snook et al. (1977) analyzed a higher molecular weight PAH fraction (compounds larger than fluoranthene) from cigarette smoke condensate. Perylenes, indenopyrenes, benzo(ghi)perylenes, anthanthene, and coronenes were identified in this fraction. These were present in amounts of less than 1.0 µg/100 cigarettes. Recently Snook et al. (1978) reported the identification of approximately 1000 PAHs from indene to pentamethylchrysene in cigarette smoke condensate. Lee et al. (1976) analyzed tobacco and marijuana smoke condensates for PAHs. In general, marijauna smoke condensate contained a greater amount of PAHs than tobacco smoke concentrate and the concentration of PAHs of molecular weights greater than that of chrysene were significantly

TABLE I. Polycyclic aromatic hydrocarbon - Composition of creosote, creosote sludge and coal tar. Quantities are expressed in grams/kilogram creosote.

	Lijinsky et al. 1957	Lijinsky et al. 1963	Tarrer et al. 1977	Guin et al. 1977	Prather et al. 1977	Colley 1977 A[2]	Colley 1977 B[2]	Colley 1977 C[2]	Eaton & Zitko 1978	Nestler 1979	Lorenz & Gjovik 1972	Lao et al. 1975 Coal tar	Lao et al. 1975 Wood preservative sludge
Anthracene	6.2	12.1	43	43	18	-	-	-	-	20	15	-[4]	-
Benzo(a)anthracene	2.8	2.8	-	-	-	-	-	-	31	-	-	43[6]	5
Benzo(b)chrysene	-	0.5	-	-	-	-	-	-	-	-	-	23	5
Benzo(j)fluoranthene	-	0.29	-	-	-	-	-	-	-	-	-	1	0.3
Benzo(k)fluoranthene	-	0.20	-	-	-	-	-	-	-	-	-	33[7]	7
Benzo(g,h,i)perylene	-	-	-	-	-	-	-	-	-	-	-	18	-
Benzo(a)pyrene	0.12	0.18	-	-	-	-	-	-	-	-	-	33	3.6
Benzo(e)pyrene	-	0.17	-	-	13	18	38	-	-	-	-	-	2.5
Chrysene	1.3	1.14	-	-	-	-	-	-	-	30	-	-	5[5]
Fluoranthene	7.8	23.5	9.6	5.5	-	39	70	111	70	100	34	54	26
Perylene	0.04	0.04	-	-	-	-	-	-	-	-	-	3	-
Phenanthrene	47.9	36.6	186	186	125[1]	83[3]	155[3]	200[3]	193	210	107	81[3]	15[3]
Pyrene	4.2	8.4	2.6	2.6	-	31	53	81	64	85	22	47	24
Naphthalene	-	-	151	51	93	128	42	28	-	30	158	-	-
2-methylnapthalene	-	-	1.3	1.3	87	53	40	6	-	12	30	-	-
1-methylnapthalene	-	-	3.8	3.8	39	33	31	12	-	9	-	-	-
1,6-dimethylnapthalene	-	-	3.9	3.9	-	15	14	4	-	20	-	-	-
2,3-dimethylnaphthalen	-	-	1.9	1.9	-	-	-	-	-	-	-	-	-
Acenaphthene	-	-	60	60	70	53	83	75	67	90	31	-	-
Dibenzofuran	-	-	67	67	-	40	62	51	-	50	11	-	-
Fluorene	-	-	103	103	53	34	59	56	48	100	31	27	6
9,10-dihydroanthracene	-	-	24	24	-	-	-	-	-	-	-	2	1
3-methylphenanthrene	-	-	9.8	9.8	-	7	13	18	-	30	-	-	8
4,5-methylenephenanthrene	-	-	25	25	-	-	-	-	-	-	-	3[8]	-
2-methylanthracene	-	-	2.4	2.4	-	16	32	39	-	40[8]	-	-	8
9-methylanthracene	-	-	1.2	1.2	-	-	-	-	-	-	-	-	-
2,3,benzfluorene	-	-	-	-	-	13	13	31	-	20[9]	-	20[9]	-

(1) single analysis
(2) Marine creosotes - Specific gravities A-1.070, B-1.092, C-1.108
(3) phenanthrene and anthracene
(4) contains chrysene, triphenylene and all benzanthracenes
(5) contains chrysene and triphenylene
(6) contains benzo(b)chrysene and phenylenepyrene
(7) contains benzo(g,h,i)perylene and anthanthene
(8) contains methyl anthracenes and methylphenanthenes
(9) all benzfluorenes

increased in marijuana smoke condensate.

Another source of PAH exposure to man results from his foodstuffs, especially through certain types of cooking and food preservation treatments (smoking and drying) which elevate PAH levels beyond those normally present. A study of various foodstuffs was carried out by Grimmer and Bohnke (1975). All samples investigated contained more than 100 PAHs. These samples included meats, poultry, smoked fish, yeast, fats and oils. Only 10 major PAHs were quantified. Yeast (unspecified) contained just over 1000 µgPAH/kg (21 individual PAHs) of which benzo-(a)pyrene accounted for far less than 1% (0.28 µg/kg).

Wood smoke, used to enhance flavor and improve storage of many foodstuffs, contains PAHs. The composition of the smoke is very complex. As an example of the PAH content associated with hardwood smoke, Rhee and Bratzler (1968) studied the composition of maple sawdust smoldering around 750-800°C. Whole smoke had 17.4 µg PAH/1.0 kg of wood combusted (0.2 µg/kg benzo(a)pyrene or 1.2%). Haenni (1968) reported that softwoods generally produced higher amounts of benzo(a)pyrene than did hardwoods, and that it was not possible to obtain curing smoke free of carcinogenic hydrocarbons solely by control of temperatures of combustion and smoking. Washing and filtration of smoke have been used to produce acceptable smoked products (Sikorski 1965).

Howard et al. (1966a,b) studied PAHs in smoked and non-smoked fish in the U.S.A. In non-smoked fish (haddock, salted herring and canned salmon) only pyrene and fluorene were detected, both at the 1-2 µg/kg level. Smoking raised the levels of pyrene and fluorene to 2-4 µg/kg. Dried smoked herring had 1.2 µg/kg benzo(a)pyrene out of a total PAH concentration (6 individual PAHs) of 8.5 µg/kg (13%). Malanoski et al. (1968) also determined levels of PAHs in smoked fish. Certain samples of smoked chub, whitefish and kippered cod had benzo(a) pyrene levels of 1-6 µg/kg and benzo(a)pyrene was the major PAH present. Pancirov and Brown (1977) determined PAH levels in marine fish and shellfish from the New York Bight. Benzo(a)pyrene levels were in the range of 1 µg/kg while total PAH levels ranged from the detection level of about 3 up to 94 µg/kg in oysters from Long Island Sound. Levels in specimens from cleaner areas were below detection levels. The authors suggest, since the predominant PAH present is pyrene, combustion was the source of PAHs in this area rather than crude oil but caution that this could also be interpreted as resulting from preferential metabolism of alkylated PAH. Masuda and Kuratsune (1971) studied PAHs in smoked, dried species of fish used as a condiment in Japan. Total levels of PAHs ranged from 517 µg/kg to 5079 µg/kg (7-37 µg benzo(a)pyrene/kg; 0.5-0.7%). In a study on the effect of broiling on horse mackerel (Trachurus japonicus), in which the fresh fish had no detectible level of PAHs, broiling under an electric or gas broiler gave PAH values (benzo(a)-pyrene, %) of 1.6 µg/kg (0 µg/kg, 0%) and 40.3 µg/kg (0.9 µg/kg, 2.2%) respectively, while broiling above (in the smoke) gave values of 30.6 µg/kg (0.3 µg/kg, 0.7%) and 220.6 µg/kg (0.3 µg/kg, 0.01%) (Masuda et al. 1966). Yamazaki et al. (1977) demonstrated similar results but also showed that broiling in aluminum foil resulted in formation of detectable amounts of chrysene only. The formation of PAHs was correlated to the fat content of the fish. The low level of PAHs present in the starting material probably reflects the ability of teleosts to metabolize and excrete benzo(a)pyrene and other PAHs as water soluble products (Lee et al. 1972b). Dunn and Fee (1979) reported that commercial samples of teleosts contained no detectable level of benzo(a)pyrene unless packed in oil. Levels of benzo(a)pyrene in shellfish were generally less than 10 µg/kg wet weight. Lobsters which had been empounded in pounds constructed of creosote treated timber had average benzo(a)pyrene levels of 78 µg/kg in the tail meat. Benzo(a)pyrene levels in unimpounded lobsters averaged 0.6 µg/kg. Benzo(a)pyrene levels in the digestive gland were over 10 times higher than tail meat levels. A number of other PAH compounds were also found in empounded lobster leading the authors to postulate that lobsters accumulate PAH from the creosote-treated wood.

Broiling of other meats besides fish or use of other high temperature cooking processes yielded cooked meats with varying levels of PAHs (Lo and Sandi 1978). Lijinsky and Shubik (1964) determined levels of 15 different PAHs in broiled meats. Following laboratory charcoal broiling the level of PAHs (15 different PAHs) was 87 µg/kg (8 µg/kg benzo(a)pyrene, 9.1%) while under commercial charcoal broiling conditions levels of 123.7 µg/kg (5.8 µg/kg benzo(a)pyrene, 4.7%) were found. Extensive investigations have shown that the presence of PAHs is directly proportional to the treatment temperature (Toth and Blaas 1972b). Contributions from the heat source cannot be ignored since Thorsteinsson and Thordason (1968) have shown the presence of benzo(a)pyrene in sheep and seabirds singed over coal fires. If propane-fed fires were employed no PAHs were detected. Home-smoked meat products represent a potent source of PAHs, especially products that are smoked under poorly controlled conditions, e.g. over open rather than smoldering fires (Lo and Sandi 1978; Barnett 1976; Toth and Blaas 1972b; Howard and Fazio 1969; Thorsteinsson 1969; Fretheim 1976). Thorsteinsson (1969) compared commercial smoked mutton with home-smoked products. Home-smoked products had levels of PAHs (9 individual PAHs) of from 439 µg/kg (3 µg/kg benzo(a)pyrene, 0.6%) to 4492 µg/kg (107 µg/kg benzo(a)pyrene, 2.4%) while commercial production yielded products with total PAH levels between 42 and 260 µg/kg with only trace amounts of benzo(a)pyrene. Sausages and meats enclosed in cotton fabric or cellophane had the lower levels since these materials act as barriers (Hamm 1977).

PAHs from smoke mainly penetrate only the external surfaces of the product (Rhee and Bratzler 1970). Similar studies of smoked meats from different European countries yielded similar values (Filipovic and Toth 1971; Toth and Blass 1972a; Fretheim 1976; Soos and Hajdu 1974). Substitution of liquid smoke flavors for preparation of smoked products does not necessarily result in lower levels of PAHs in the final product (White et al. 1971) unless care is taken in the selection of the liquid smoke preparation. Soos and Hajdu (1974) suggested the high level of PAHs found in home-prepared smoked meat products in the Wendish inhabitants of Hungary may be connected with the increased incidence of stomach cancer in these individuals. This has also been suggested in the increased incidence of stomach cancers found in Iceland and Baltic inhabitants

(Haenni 1968).

PAHs have also been studied in plant products and, in general, low concentrations have been found (Lo and Sandi 1978; Barnett 1976). The only groups of edible plant products which have been found to have appreciable PAH concentrations are leafy vegetables such as cabbage, lettuce, kale (1-24 µg benzo(a)pyrene/kg) (Walker 1977; International Agency for Research on Cancer 1973), and coconut oil Grasso and O'Hare 1976). Since these vegetables are high surface area products, the source of PAH is likely fallout. Further evidence for the fallout source comes from Soos (1973) who found higher PAH levels (2-4 times) in cereals grown in the vicinity of highways and industrial centers as compared to cereals from agricultural regions. No explanation of the elevated PAH levels in coconut oil was found although the meat is exposed during the preparation of copra.

Root crops, while not directly affected by aerial fallout, can reflect PAH concentrations in the surrounding soil (Lo and Sandi 1978). This is of particular importance in those areas where municipal waste composts are used.

Due to the hydrophobic nature of PAHs it would not be surprising to find these compounds in edible oil products especially those vegetable oils prepared by extraction with petroleum-based solvents which by themselves could contain PAHs. Howard et al. (1966b) studied PAHs in processed vegetable oils. Total PAH levels (up to a maximum of 6) ranged from undetectable in safflower oil to 8.6 µg/kg in peanut oil (up to 1.6 µg benzo(a)pyrene/kg). Preliminary analyses indicated that the processing solvents were not responsible for the contamination. Preparation of margarines from these oils could be expected to result in partial or total removal of PAHs during the deodorization and other processing steps in a manner similar to removal of organochlorine residues (Addison et al. 1978). No carcinogenic PAHs were detected in food-grade hexanes although 9 of 15 batches contained amounts (~35 µg/kg) of other PAHs (Howard et al. 1968). Lijinsky and Raha (1961) reported the presence of PAHs in commercial solvents including hexanes, but these may have not been food grade solvents. "Dairy wax" (paraffin) prepared from petroleum is utilized in food packaging and coatings and has been intensively studied (Haenni 1968). Only 6 of 209 waxes investigated contained traces of identifiable PAHs at or above 0.1 µg/kg and none of these were established carcinogens.

It is also possible for components of food processing equipment to add trace amounts of PAHs to foodstuffs. Medvedev (1973) showed that food grade carbon black filled rubber tubing would yield a number of PAHs including benzopyrene (isomer unspecified).

Joe et al. (1979) carried out a survey of PAHs present in market basket commodities in the U.S.A.. Benzo(a)pyrene was detected in only 1 of 24 products, at a level of 3 µg/kg. That product was soft-shell clams. These authors reported that generally levels and types of PAHs in American foodstuffs had not changed significantly over the past 10 yr.

DEGRADATION OF POLYCYCLIC AROMATIC HYDROCARBONS

PAHs are destroyed in the environment through a variety of chemical and biochemical mechanisms, both involving oxidation. Photooxidation is probably quantitatively the most important degradative pathway (Suess 1976). Particulate benzo(a)-anthracene and benzo(a)pyrene decomposed under ultraviolet light to their respective quinones which, under certain circumstances, prevent further oxidation of the interior of the PAH particle (McGinnes and Snoeyink 1974). Decomposition in water was found to follow first order kinetics and was relatively unaffected by water chemistry. The quinone protection layer is not so effective in water. Volatilization from water to air does not appear to be a very important process in removing PAHs (Southworth 1979). In addition to photo-oxidation, PAHs are susceptible to oxidation by ozone, peroxides, nitrogen oxides and sulfur dioxide (National Academy of Science 1972). Alkylated PAHs are generally more susceptible to oxidation than the corresponding non-alkylated PAH. The temperature dependence of these reactions show that PAH oxidation will drastically decrease in winter (Radding et al. 1976), an important fact with regard to the fate of PAHs produced by two-cycle outboard engines in cold water lakes. Chlorination also chemically alters PAHs (Radding et al. 1976) but the nature of the products was not reported. Lee et al. (1978) studied the fate of PAHs in a controlled ecosystem enclosure. The disappearance of PAHs from the water columns was ascribed to evaporation, sedimentation, microbial action and photooxidation. Photooxidation was judged to occur in the upper 5 m of water.

Microbial degradation is a major biochemical route in the metabolism of PAHs in the environment (Suess 1976; Radding et al. 1976). Some bacteria (Pseudomonas aeruginosa, Escherischia coli) show enhanced growth and increased protein levels when grown on benzo(a)pyrene (Lorbacher et al. 1971; Groenewegen and Stolp 1976). Other bacteria species and strains have been reported to accumulate PAHs but metabolize them only slowly (Gibson 1976; Malaney et al. 1976; Moore and Harrison 1965). Caution in interpreting microbial metabolism is warranted since Herbes and Schwall (1978) pointed out that four and five ring PAHs may persist even in sediments that receive chronic PAH inputs and that support microbial populations capable of transforming two and three ring PAHs. Radding et al. (1976) reported that aquatic microorganisms are generally less efficient in metabolizing PAHs than soil microorganisms. Lower animals are also capable of metabolizing PAHs. This will be discussed below.

ENVIRONMENTAL LEVELS OF POLYCYCLIC ARMOATIC HYDROCARBONS

Since PAHs are formed in large quantities, are relatively stable materials, are relatively water-insoluble and lipophilic, it is not surprising that PAHs have been found in essentially all compartments of the biosphere (Fishbein 1973). Fishbein's review (1973) reported air levels for 13 different PAHs, 7 of which have demonstrated carcinogenic properties. Average U.S.A. urban atmospheric levels of total PAH

(13 individual PAHs) of 58 ng/m^3 (5.7 ng/m^3 benzo(a)pyrene, 10%) were reported. Colucci and Begeman (1971) ascribed the higher benzo(a)pyrene levels in European cities to the use of coal for space heating. Due to imposed controls, atmospheric levels of benzo(a)pyrene and presumably other PAHs have fallen over recent years (Environmental Protection Agency 1974). This has been especially true for those cities with coke ovens where average benzo(a)pyrene levels of approximately 5 ng/m^3 dropped to about 2 ng/m^3. Radding et al. (1976) has reviewed air levels of PAHs and included seasonal data showing PAH levels higher in winter than in summer. Air emmissions of PAHs are generally particulate in nature (Nielsen 1979; Natusch 1978 and Davies et al. 1976). Some amount of PAHs falls out of the atmosphere rather close to the source (Lankmayr and Muller 1979). Lunde et al. (1977) studied PAHs in rainfall from various sites in Norway. Higher levels of PAHs were found only in samples from southern Norway and were associated with use of fuels and meteorological trajectories transversing England or the European continent. The bulk of PAHs in rainfall was associated with the particulate matter. Benzo(a)pyrene, fluoranthene and benzofluoranthene were the most common PAHs. Levels of 50-300 ng/L of rainfall of benzo(a)pyrene were found.

Drinking water contains PAH but levels do not appear to pose a danger. Processing of raw water to drinking water generally lowers PAH levels. Sediments, both marine and terrestial, contain PAH. Studies of the distribution of non-alkylated and alkylated PAHs indicate an anthropomorphic source for these PAHs. Concern has been expressed about man's exposure through drinking water. Shabad and Il'nitskii (1970) however, pointed out that the amount of PAHs a man may consume from polluted water is only 0.1% of the total amount of PAH which a man consumes. Analysis of raw water in the U.S.A. (Basu and Saxena 1978) showed PAH levels (6 individual PAHs) of 4.7 to 632 ng/L (0.3 to 60 ng benzo(a)pyrene/L; 6-10 %); levels in treated waters ranged from 0.9 to 14.9 ng/L (0.2-0.3 ng benzo(a)pyrene/L; 2-20%). Domestic sewage effluents contain significant levels of PAHs (Andelman and Suess 1970). Total PAH levels ranged from 800-87500 ng/L (1-1840 ng benzo(a)pyrene/L; 1-2%). Dried humus from Leningrad had 3 µg benzo(a)pyrene/g. Andelman and Suess (1970) identified industrial sources of benzo(a)pyrene to waters. Oil, chemical, coal and coking industries had selected effluent levels of benzo(a)pyrene of from 0 (after treatment) to 1,000,000 ng/L. Jungclaus et al. (1978) studied the effluent and downstream sediments associated with an organic chemical production plant. At least 22 different PAHs were identified in the sediments and tarry deposits. Individual PAH levels of as high as 120 µg/g sediment were found. Griest and Herbes (1978) tentatively identified more than 170 PAHs in effluent sediment and water from a coal coking plant, many with alkyl side chains (133 out of 173). These authors believed that the identified PAHs in the sediment represent 74% of the total three to six ring PAHs present. These authors estimated that about 50% of the identified PAHs are accounted for by eight "bioactive" PAHs. Benzo(a)pyrene represented about 10% of these eight PAHs. Marine sediments from the New England region have been shown to contain a very complex mixture of PAHs (Blumer 1976; Herbes et al. 1976; Blumer and Youngblood 1975; Hites and Bieman 1975; Youngblood and Blumer 1975; Giger and Blumer 1974; Speers and Whitehead 1969).

Sediment from the Charles River Basin (Boston, MA) contained PAHs with at least eleven different aromatic ring structures. Non-alkylated and abundantly alkylated derivatives of these PAHs were also present, in some cases containing up to fifteen carbon atoms in the alkyl groups (Hites and Bieman 1975). Laflamme and Hites (1978) report that the qualitative PAH composition of these sediments is characteristic of marine sediments in general. There is general agreement that combustion is the major source of sediment PAHs but disagreement over the type of combustion (coal, wood, internal combustion, forest fires, etc.) and the amount of PAH originating from other sources such as biosynthesis. Blumer and Youngblood (1975) maintained that it is possible through a study of the PAH alkyl homologue distribution in sediments to obtain information on the formation temperature of these compounds. They suggested, from their study of the relative abundances of alkylated PAHs in sediments, that the bulk of these must have originated from forest fires because of considerable differences in relative homologue abundance between air particulates from cities and sediment samples. This, according to Laflamme and Hites (1978), did not take into account the possibility of subsequent modification, e.g. selective metabolism or photooxidation and, in particular, differential water solubility of the alkyl homologues versus the unsubstituted species. They suggest that solubility differences enrich the higher alkylated homologues within the sediments and that fossil fuel use is the predominant PAH source. A study of PAHs in Charles River waters and sediments and Boston's air particulate showed that the water is enriched in the lower homologues while the sediment is enriched in the higher homologues relative to the air particulate PAHs (Hase and Hites 1976). Windsor and Hites (1979) suggested that large airborne PAH particulates rapidly settle out near the source and are washed into the immediate watershed from whence they are transported via the usual particulate transfer mechanisms. Long-range transport of PAHs is suggested as the explanation of the rather uniform low PAH levels found in soils and sediments far removed from PAH sources.

Most world wide samples showed about the same qualitative distribution of unalkylated PAHs. The fluroranthene/pyrene ratio is near 1.0 and most samples have a relative abundance of phenanthrene of about 12%, fluoranthene about 16%, pyrene about 15%, $C_{18}H_{12}$ species (including chrysene, triphenylene) about 23% and $C_{20}H_{12}$ species (included benzofluorenes, benzopyrenes and perylene) about 35%. Evidence was offered that two PAHs present in some sediments originate from biological sources; retene, which is suggested to have originated from abietic acid and perylene, possibly from erythroaphin pigments. The occurrence of PAH in plankton was studied by de Lima Zanghi (1968). Much higher levels were found in plankton from coastal areas than from offshore samples. This further supports the belief that the majority of environmental PAHs are of terrestrial and anthropogenic origin.

Soils show similar patterns to marine sediments (Youngblood and Blumer 1975), not unexpectedly, if combustion is the major source of such PAHs. Laflamme and Hites (1978) confirmed the overall similarity of sediment and soil PAH profiles.

Over the last 125 yr the distribution of PAHs

in dated sediment cores has been quantitatively constant with respect to the distribution of alkyl homologues and percent composition. The total amount of PAH has increased over this time period, suggesting an increasing source between 1850 and 1900 (Hites et al. 1977). Prior to this date PAH levels were lower and compositions different. The results are consistent with the use of fossil fuels over the period, not with forest fire data.

Marine biota, in particular those living in and on the sediments, can be contaminated with PAHs (Sammut and Nickless 1978). Marine molluscs exposed to sublethal concentrations of petroleum accumulate PAHs in their lipid pools (Cahnmann and Kuratsune 1957; Teal 1976; Blumer et al. 1970; Guerrero et al. 1976). Andelman and Suess (1970) reviewed benzo(a)-pyrene levels found in marine fauna. Greenland samples of mollusc, sea cucumber and cod had levels of benzo(a)pyrene of 60, none detected and 55 µg/kg dry weight, respectively. Various shellfish from the Mediterranean and European Atlantic had benzo-(a)pyrene levels ranging from 1-100 µg/kg dry weight, suggesting that as of the 1960's severe PAH contamination of shellfish was not occurring generally. Pancirov and Brown (1977) reported benzo(a)-pyrene levels in cod, clams and oysters from the New York Bight of 0.5, 1.0 and 0.2-2.0 µg/kg wet weight. The much higher levels presented in the review by Andelman and Suess (1970) compared with Pancirov and Brown (1977) demonstrate the severity of analytical problems associated with PAH determination. Zobell (1971) reviewed benzo(a)pyrene levels in marine animals; levels ranged from nil to about 2000 µg/kg dry weight. Interestingly, the sea cucumber was the species spanning this range but individual species were not identified. Mix et al. (1977) reported benzo(a)pyrene levels ranging from detectable to 715 µg/kg in clams, mussels and oysters from bays in Oregon. Cahnmann and Kuratsune (1957) reported that oysters from Virginia contained 2-60 µg benzo(a)-pyrene/kg wet weight and 2000 µgPAH/kg (8 individual PAHs). Baseline benzo(a)pyrene levels in southern California mussels (Mytilus californianus, Mytilus edulis) were estimated to be less than 0.5 µg/kg wet weight by Dunn and Young (1976). Higher (0.5-2.3 µg/kg wet weight) levels were associated with areas of human activities and a mussel sample collected off pilings had 8.2 µg/kg wet weight (Dunn and Stich 1975). Bravo et al. (1978) reported total PAH levels (25 individual PAHs including naphthalenes) in oyster (Crassostrea virginica)taken from the Mexican coast of the Gulf of Mexico ranged from 2120-9160 µg/kg wet weight. They suggested the petroleum industry as the source of such high levels. Guerrero et al. (1976) showed shellfish (unidentified species) from an oil spill area had elevated benzo(a)pyrene and benzo(ghi)perylene levels. Samples associated with marinas were also higher than controls but lower than those from oil spills. Control levels were below the detection limit (0.01 µg/g). The association of higher PAH levels with marinas, pilings, etc. was investigated by Zitko (1975) who showed mussels (Mytilus edulis), periwinkles (Littorina littorea), and whelks (various species) had PAH patterns closely resembling those of creosote. The creosote treated pilings present within the collection area were believed to be the source of the PAHs. Dunn and Stich (1976b) report similar findings in Mytilus edulis based upon gas chromatographic profiles of cleaned up extracts from Mytilus edulis and wood from pilings. In addition, these investigators found benzo(a)pyrene levels in Mytilus edulis decreased with increasing distance from the pilings. Benzo(a)pyrene levels were considerably lower in summer than winter. The high PAH levels found in lobster after impoundment in pounds constructed of creosoted timbers (Dunn and Fee 1979) has been mentioned above. Dunn and Fee (1979) reported that levels of benzo(a)pyrene in crab and shrimp were generally below 0.5 µg/kg.

Differential depuration of oil compounds from oysters (Crassostrea virginica) (Lee et al. 1978; Anderson et al. 1974; Stegeman and Teal 1973), clams (various species) (Roesijadi et al. 1978) and mussels (Mytilus edulis) (Lee et al. 1972a) results in faster removal of smaller PAHs. For example, in a study utilizing oysters the depuration half-lives for naphthalenes, anthracene, fluoranthene, benzo(a) anthracene and benzo(a)pyrene were 2,3,5,9 and 18 d respectively. Dunn and Stich (1976a) found that mussels (Mytilus edulis) exposed to creosote treated timbers depurated benzo(a)pyrene in clean water with a half-life of 16 d at 7-9°C. DiSalvo et al. (1975) calculated a half-life of 4 - 5 wk for depuration of PAHs from mussels. Neff and Anderson (1975) found that the clam (Rangia cuneata) took 30-60 d to depurate benzo(a)pyrene which had been taken up in 24 h. Lee (1976) has reviewed depuration by bivalves. Teal (1976) cautioned against simple interpretation of depuration based on total ^{14}C retention since metabolism of PAHs to significantly different materials occurs. Teleosts rapidly metabolize benzo(a)pyrene to hydroxy derivatives (Bend et al. 1977; Lee et al. 1972b). Excretion from the animal of radioactive label from benzo(a)pyrene-^{3}H was slower than excretion of the label from ^{14}C-naphthalene but 96 h after exposure to benzo(a)pyrene only 10 % of the original benzo(a)pyrene remained. The rapid conversion of benzo(a)pyrene by teleosts is similar to mammals. Daniel et al. (1967) fed rats radioactively labelled dibenzo(a,h)anthracene, 7,12- dimethylbenzo(a)-anthracene and dibenzo(a,c) anthracene. All were rapidly absorbed and later excreted in the feces and urine. A small residual amount of PAHs could be detected in adrenals, ovaries and body fat after 8 d.

METABOLISM OF POLYCYCLIC AROMATIC HYDROCARBONS

Aryl hydrocarbon hydroxylase is an inducible enzyme found in teleosts and higher animals (Payne 1977) which oxidizes aromatic compounds via epoxidation of the aromatic nucleus (Creaven et al. 1965). This group of enzymes is located on the microsomes and is associated with the cytochrome P-450-mediated microsomal mixed function oxidases system. This multienzyme system is marked by a surprising degree of diversity not unlike the immune system (Fox 1979). Entire families of enzymes are known, e.g. those based upon cytochrome P-450 and those based upon P-448 (the numerical designation indicating the absorption maximum of the cytochrome-carbon monoxide complex). Induction of aryl hydrocarbon hydroxylase occurs during exposure to various PAHs including benzo(a)pyrene and in varying degrees by oxygenated and other metabolites of benzo(a)pyrene (Itsu et al. 1977). No metabolite is a more potent inducer of hydroxylase activity than benzo(a)pyrene suggesting the the parent PAH compound is the primary inducing agent. Inducible mixed function oxidase enzymes were originally believed to fall into two classes: (1) those induced by phenobarbital-like drugs, and (2) those induced by methylcholanthrene-like chemicals (Fox 1979). This division is arbitrary

and overlap occurs (Fox 1979). Negishi and Nebert (1979) have shown that 3-methylcholanthrene administration to mice activates at least five structural genes and results in the formation of monooxygenases of differing degrees of substrate specificity. Yang et al. (1978) describe, for example, six forms of cytochrome P-450 enzymes which hydroxylate different substrates at different positions. The complex nature of the mixed function oxidase system leads to an array of sterospecific and positional isomeric oxidized products even from a single substrate such as benzo(a)pyrene. This mixed-product response depends upon species, strain, tissue studied, age of the animal, genetics, nutritional status, presence of other inducers in the animal's environment, the presence of inhibitors such as lead, and finally the nature of the inducing chemicals. Aryl hydrocarbon hydroxylases in human lymphocytes have been reviewed by Paigen et al. (1978) who showed that aryl hydrocarbon hydroxylase inducibility is influenced by: (1) age, aryl hydrocarbon hydroxylase being induced at higher levels before 30 y of age than afterwards; (2) genetics; since inducibility was widely variable, an observation confirmed by studying monozygotic twins; and (3) season of the year, with lower values of basal and inducible activity being observed in summer than winter. No relationship with tobacco use was found. Pelkonen et al. (1973) demonstrated that fetal levels of aryl hydrocarbon hydroxylase are only a few percent of the adult human liver level, first becoming detectible at 6-7 wk. The nature and specificity of fetal liver are also different from the adult (Pelkonen et al. 1973).

Nebert et al. (1978) separate out those P-450 cytochromes which rise and fall with rise and fall of induced aryl hydrocarbon hydroxylase activity as P_1-450 but others such as Coon and Vatsis (1978) use a different nomenclature (e.g. $P\text{-}450_{LM2}$ is that cytochrome inducible by benzo(a)pyrene). Nebert et al. (1978) have studied the Ah (aryl hydrocarbon hydrocylase) locus in mice. This locus was originally thought to be a simple genetic system controlling synthesis of a subset of P-450 mediated enzymes but now the locus appears to include multiple groups of both P_1-450 and P-448 enzymes. At least 14 monoxygenases and associated P_1-450 and P-448 cytochromes have been identified which are under the control of this locus and inducible by PAHs. P_1-450 induction is associated with aryl hydrocarbon hydroxylase activity while P-448 induction is associated with N-acetylarylamine N-hydroxylase activity. Increases in both cytochromes occur after PAH treatment and the induction is accompanied by de novo protein synthesis. A PAH receptor protein that tightly binds PAHs has been discovered. The receptor site can be activated not only in liver but also in lung, kidney, bowel, skin, lymph node, retina, bone marrow, ovary, testis, and mammary gland. The inducible aryl hydrocarbon hydroxylase response appears to be dominantly inherited since heterozygotes are inducible. Non-responsive animals can be bred by appropriate crosses and, compared with responsive animals, they are much less affected by the topical application of 7,12-dimethylbenzo(a)anthracene, methylcholanthene and benzo(a)pyrene with respect to induced subcutaneous sarcomas and methyl-cholanthrene-induced lung tumors and other PAH lesions such as leukemia, skin inflammation, cataracts, birth defects, stillborns, resorption, and decreased birth weight. Although the Ah locus was not found to be linked in the mouse, Nebert and Jensen (1979) postulate at least one major regulatory gene and temporal gene control. Induction leads to increased levels of other enzymes including UDP-glucuronyl transferase, oxidoreductase and ornithine decarboxylase in addition to monooxygenase. The usual environmental exposures of an animal are to mixtures of PAHs. In general, exposure to PAH mixtures leads to elevations in tissue activities of aryl hydrocarbon hydroxylases, e.g. coal tar (Bickers and Kappas 1978), and cigarette smoke condensate (Akin et al. 1975). The situation becomes complex in man where use of drugs and other preparations such as tobacco and marijuana markedly affects the overall collage of monoxygenases present and other detoxifying enzymes in various tissues (Alvares 1978). The overall activities of the monoxygenases, hydroxylases, conjugating enzymes, etc. are important in the toxicological activity of a PAH such as benzo(a)pyrene which is believed to exert its carcinogenicity through its metabolites rather than directly (Fox 1979; Nebert et al. 1978; Brooks 1977; Heidelberger 1975). Whether enzyme heterogeneity results from modification of a single enxyme complex or through synthesis of multiple enzymes is still being investigated. Negishi and Nebert (1979) have shown that the Ah locus produces at least two structural gene products.

The initial step in the metabolism of benzo(a)-pyrene is binding to a cytosolic receptor protein (Nebert et al. 1978), followed by oxygenation by aryl hydrocarbon hydroxylase, hydration of the initial expoxide to the dihydrol, further oxidation to diol expoxide and again hydration of the epoxide to yield a terahydroxide derivative.

Conjugating enzymes are involved in conversion of the benzo(a)pyrene oxygenated intermediates to water soluble conjugates. Benzo(a)pyrene 4,5-epoxide is conjugated by glutathione-S-epoxide transferase and at least seven different forms, each with a unique specificity for the 4,5-epoxide, have been isolated. These enzymes also conjugate a variety of substrates including halide and oxide compounds (Nemato and Gelboin 1976; Habig et al. 1974).

Benzo(a)pyrene is capable of producing tumors in a variety of experimental animals, tumors being formed not only at the site of application but also at other sites within the animal (Dipple 1976; National Academy of Science 1972). The carcinogenicity of benzo(a)pyrene is believed to be mediated through the binding of some intermediate benzo(a)pyrene metabolite to nucleic acids (Weinstein et al. 1978). Pre-treatment with other aryl hydrocarbon hydroxylase inducers can often decrease tumor formation subsequently induced by benzo(a)pyrene (Yang et al. 1978). However, other PAHs, including some which are not carcinogenic by themselves (Scribner 1973), can enhance carcinogenicity of benzo(a)pyrene. For example, Pfeiffer (1973) demonstrated synergism between benzo(a)pyrene and dibenz(a,h)anthracene. These effects are not surprising when one considers the multiplicity of induced enzymes, and the role of metabolites of PAHs in cancer initiation. One can postulate circumstances which could lead to increased levels of the active carcinogenic form of benzo(a)pyrene and others which would lead to decreased levels. These effects could all be mediated through the plethora of microsomal enzymes but effects on other systems such as DNA repair cannot be excluded.

The microsomal oxidation of PAH leads to a multitude of diols, quinones, and phenols from benzo(a)pyrene. The initial oxygenation catalyzed by the multiple P_1-450 enzymes results in formation of single epoxides of at least the 4,5-,7,8-, and 9,10 positions of which only the 4,5-epoxide is stable enough for isolation (Yang et al. 1978). The 7,8-diol metabolite binds covalently to DNA about 10 times better than benzo(a)pyrene, suggesting that this diol is closer to the active intermediate involved in binding (Borger et al. 1973). The expoxidation of the 7,8-diol to the 9,10-epoxide yields mainly a trans configuration to the 7-hydroxyl as a major metabolite. The cis epoxide is also found but in lower yield. The trans epoxide is further hydrolyzed stereoselectively at the 10-position to form a major (7,10/8,9) - tetrol and a minor (7/8,9,10) - tetrol. It was suggested (Hulbert 1975; Yang et al. 1978) that such diol epoxides can form C-10 carbonium ion intermediates which can react with DNA. A number of theories have been suggested to account for the carcinogenicity of benzo(a)pyrene and PAHs in general (Jerina et al. 1978). The most popular theory is the "Bay Region" theory which has replaced the "K-region" theory which asserted that a hydrocarbon had to have a highly electron dense "K-region" to be carcinogenic. The occurrence of a reactive "L-region" which results in a quinone rather than an epoxide was thought to decrease carcinogenicity. "K-region" epoxides were believed to be the likely carcinogenic intermediates (Jerina et al. 1978). The "Bay Region" theory simply assumes that an epoxide on a saturated angular benzo-ring which forms part of a "Bay Region" is the critical carcinogenic structure. Examples of "Bay Regions" are the hindered regions between 4- and 5- positions of phenanthrene, the region between the 1- and 12- position of benzo(a)-anthracene and the region between the 10- and 12-positions of benzo(a)pyrene. The "Bay Region" theory is not essentially in conflict with the the "K-region" theory since, as Pullman (1978) has pointed out, that in order for a PAH to have a "Bay Region" the molecule must have a "K-region" and that the "Bay Region" approach is just a different way of perceiving the significance of a "K-region". The evidence supporting the "Bay Region" theory has been reviewed recently by Jerina et al. (1978). The "Bay Region" theory runs into trouble with benzo(e)pyrene, a PAH with two "Bay Regions" (1- and 12-, and 8- and 9-) and is not particularly carcinogenic. Selkirk (Anon. 1979) has suggested that benzo(e)pyrene is not attacked at the "Bay Region" but at a different site as opposed to benzo(a)pyrene.

The product of diol expoxide - DNA interaction has been widely studied (reviewed by Weinstein et al. 1978; Neidle 1976.) In the main, in vitro reaction of (±) 7β, 8α-dihydroxy-9β,β10 -epoxy -7,8,9,10- tetrahydrobenzo(a)pyrene with nucleic acids preferentially forms adducts with the quanine, rather than adenine and then to a lesser extent cytosine nuclei of DNA. In a study of the adducts formed from guanine residues and dimethylbenz(a)-anthracene -5,6-oxide, it was found that the N-2 amino group of quanine was linked to the 5- or 6-position of the PAH with a hydroxyl in either positions 6- or 5- respectively (Weinstein et al. 1978). The number of adducts formed with RNA is much greater than with DNA following incubation utilizing benzo(a)pyrene or diol expoxide derivatives. About 80% of the DNA product involves the 2-amino group of quanine and the 10- position of the PAH. Intact DNA which has covalently bound PAH attached to it is not capable of being used as a template for RNA synthesis (Weinstein et al. 1978). A sample of DNA containing 1.5% benzo(a)pyrene modified bases showed approximately 55% inhibition compared to native DNA under nonreiterating conditions and much greater inhibition under repeating conditions. This should be compared to the one benzo(a)pyrene residue per 10^4 - 10^5 nucleotides observed in vivo. In addition to binding with cellular DNA and to a greater extent RNA, PAHs are bound to protein, at a level far greater than that found for the nucleic acids. The role of RNA and protein binding of PAH and cancer induction remains obscure.

Non-mammalian organisms have been much less studied than mammalian ones, and the detailed studies of the mixed function oxidases in these organisms have yet to be carried out. Most studies merely indicate the presence or absence of benzo(a)-pyrene metabolizing enzymes and whether or not such enzymes are inducible. Sometimes only the presence of cytochrome P-450 is noted.

PAH oxidizing enzymes are present in microbial life forms since PAHs can be utilized as a carbon source (Herbes and Schwall 1978). Gibson (1976) states that certain eucaryotic microorganisms (yeasts and molds) have been shown to contain cytochrome P-450 enzyme systems and that some fungi oxidize naphthalene via the dihydrodiol system. Certain bacteria also oxidize certain aromatic hydrocarbons through the dihydrodiol system (Gibson 1976) but in these cases via a cis-diol system rather than the trans-diol system found in mammals.

No evidence was found to indicate plants have aryl hydrocarbon hydroxylase (Payne 1977; Malins 1977). At low concentrations PAHs, particularly those with relatively high carcinogenic potency, act as growth stimulators in both algae and higher plants (Radding et al. 1976).

Aryl hydrocarbon hydroxylases have been identified in many invertebrates (Khan et al. 1972, 1974). Aryl hydrocarbon hydroxylases were present in house flies, locusts, mosquitoes (Culex and Aedes) (Khan et al. 1974). Crayfish (Cambarus sp.) exhibited expoxidation of benzo(a)pyrene with the digestive gland (hepatopancreas) exhibiting the highest activity. In general, mixed function oxidase activities in aquatic organisms are extremely low when compared to terrestial animals.

The occurrence of aryl hydrocarbon hydroxylase in marine organisms has been reviewed by a number of authors (Malins 1977, 1976; Payne 1977; Philpot et al. 1977). In general, large variations in enzyme activities were found in individuals of the same species collected in the same area. Animals from different areas have different average levels of the enzyme, higher levels being presumably due to the presence of inducers in their environment (Stegeman 1978; Philpot et al. 1977). Table 2 summarizes these studies. Basal aryl hydrocarbon hydroxylase activity is present to a degree in a large number of species. The enzyme is inducible in some species but not in all species exhibiting basal activity of aryl hydrocarbon hydroxylase.

Reports concerning the presence of aryl hydrocarbon hydroxylase in lobster (Homarus americanus) are conflicting. Payne (1977) reports the presence of the enzyme in the digestive gland and that it is not inducible. Elmamlouk et al. (1976, 1974) identified cytochrome P-450 in lobster digestive

Table 2. Presence and inducibility of aryl hydrocarbon hydroxylase in aquatic fauna. (++ - high activity compared to other species studied, + - presence of enzyme based on epoxidation-hydroxylation of aromatic ring; - -no significant activity detected; ? - not studied).

Species	Basal Activity	Inducibility	Reference
Polychaete worm (Capitella capitata)	+	yes	Lee, 1976
Polychaete worm (Nereis succinea)	+	yes	Lee, 1976
Polychaete worm (Nereis virens)	+	yes	Lee, 1976
Sea anemone (Metridium sp.)	-	no	Payne, 1977
Snail (Littorina littorea)	-	no	Payne, 1977
Sea urchin (Strongylocentrotus drobachiensis)	-	no	Payne, 1977, Vandermeulen & Penrose,1978
Sea star (Asterias sp.)	-	no	Payne, 1977
Protochordate (Microcosmos sulcatus)	+	-	Payne, 1977
Blue mussel (Mytilus edulis)	-	no	Kurelec et al., 1977
Scallop (Placopecten sp.)	-	no	Payne, 1977, Vandermeulen & Penrose,1978
Soft-shell clam (Mya arenaria)	-	no	Vandermeulen & Penrose 1978
European oyster (Ostrea edulis)	-	no	Amphipod (Gammarus sp.)
Rock crab (Cancer irroratus)	+	no	Payne, 1977, Philpot et al., 1977
Spider crab (Maia squinado)	-	no	Corner et al., 1973 Malins, 1977
Shrimp (Pandalus platyceros)	+	?	Malins, 1977
Fiddler crab (Uca pugnax)	+	no	Burns, 1976
Lobster (Homarus americanus)	+	no	Philpot & Elmamlouk et al., 1977, Payne, 1977
Squid (Illex illecebrosus)	+	?	Malins, 1977
Spiny lobster (Panolirus argus)	-	?	Philpot et al., 1977
Blue crab (Callinectes sapidus)	-	?	Philpot et al., 1977
Dogfish (Squalus acanthias)	+	?	Philpot et al., 1977
Stingray (Dasyatis sabina)	++	?	Philpot et al., 1977
Large skate (Raja ocellata)	+	?	Philpot et al., 1977
Little skate (Raja erinacea)	+	?	Philpot et al., 1977
Thorny skate (Raja radiata)	+	?	Philpot et al., 1977
Mummichog (Fundulus heteioclitus)	++	yes	Stegeman, 1978, Philpot et al., 1977
Winter flounder (Pseudopleuronectes americanus)	+	?	Philpot et al., 1977 Payne, 1977
Eel (Anguilla rostrata)	+	?	Philpot et al., 1977
King of Norway (Hemitripterus americanus)	+	?	Philpot et al., 1977
Sheepshead (Archosargus probatocephalus)	++	yes	Philpot et al., 1977
Drum (Pogonias cromis)	+	?	Philpot et al., 1977
Mudsucker (Gillichthys mirabilis)	+	?	Lee et al., 1972b
Sculpin (Oligocottus maculosus)	+	?	Lee et al., 1972b
Sand dab (Citharichthys stigmaeus)	+	?	Lee et al., 1972b
Rainbow trout (Salmo gairdneri)	++	?	Ahokas et al., 1975 Payne, 1977
Brown trout (Salmo trutta)	+	yes	Ahokas et al., 1975 Payne, 1977
Brook trout (Salvelinus fontinalis)	+	?	Payne, 1977
Capelin (Mallotos villosus)	+	yes	Payne, 1977
Cunner (Tautogolabrus adspersus)	+	yes	Payne, 1977
Herring (Clupea harengus)	+	?	Payne, 1977
Cod (Gadus morhua)	+	?	Payne, 1977
Sculpin (Myoxocepalus sp.)	+	?	Payne, 1977
Bluegill (Lepomis macrochiros)	+	?	Malins, 1977
Coho Salmon (Oncorhynchus kisutch)	+	?	Malins, 1977
Sardine (Blennius pavo)	+	yes	Kurelec et al., 1977

gland but at very low levels and could not detect mixed function oxidase activity with biphenyl, ethylmorphine or aniline as substrates. Brodie and Maickel (1962) found low levels of mixed function oxidase in lobster digestive gland microsomal preparations when aminopyrene, chlorpromazine, hexobarbital and thiopental were used as substrates. Pohl et al. (1974) and James et al. (1977) were unable to detect mixed function oxidases in lobster digestive gland.

TOXICOLOGY OF POLYCYCLIC AROMATIC HYDROCARBONS

Polycyclic aromatic hydrocarbons, particularly those with larger numbers of rings, do not appear to be acutely lethal to fish exposed to water saturated with different PAHs (Payne and May 1979). Rossi and Neff (1978) studied the 96-h toxicity of a variety of PAHs to the polychaete (Neanthes arenaceodentata) Phenanthrene, fluorene and 1-methylphenanthrene, (triaromatics) were toxic at 1.0 µg/L or less while none of the tetra- or pentaaromatics were toxic at 1.0 µg/L except for fluoranthene which exhibited a 96-h TL_m of 0.5 µg/L. Mitchell (1912) found that a layer of coal-gas tar (similar to coal tar but obtained from coal by high temperature (1450°F) steam treatment) had no effect on oysters if maintained in flowing seawater. Up to 1.5 ml of coal gas tar could be instilled into the shell without effect. This tar, in stagnant water, was lethal presumably due to the inability of the oyster to purge itself. Geiger and Buikema (1976) found that the 96-h TL_m for creosote water solubles to Daphnia pulex was 0.8% while McLeese and Metcalfe (1979) found that the 96-h thresholds were 0.02 mg/L for lobster (Homarus americanus) larvae at 20°C, 1.76 mg/L for adults at 10°C, and 0.13 and 0.11 mg/L for Crangon septempspinosa at 10 and 20°C respectively. These observations plus many other reviewed by Radding et al. (1976) suggest that, based upon expected effluent concentrations of 0.1-1 mg/L for coal conversion (Herbes et al. 1976) and the lower levels reported by Andelman and Snodgrass (1974), no acute toxicity problems of a widespread nature should be encountered with PAHs.

PAHs are of major toxicological concern regarding chronic mutagenic and carcinogenic effects. Other chronic and sublethal effects have been found (e.g. photosensitization, enzyme inhibition, growth effects, etc.) (Radding et al. 1976; Brooks 1977) and will not be covered in this review.

The mutagenic properties of PAHs and their metabolites have been reviewed by Brooks (1977). Carr (1947) reported seven variants, including four proven recessive gene mutations, in the offspring of mice treated subcutaneously with dibenzo(a,h)anthracene and suggested that mutagenic effects may occur in humans exposed to the prolonged action of carcinogenic PAHs. The difficulty in proving that such variants were, in fact, true, inheritable mutations was pointed out (Burdette 1955). The advent of mixed system testing procedures enabled Ames et al. (1975; reviewed by Ames 1979) to demonstrate the mutagenicity of benzo(a)pyrene, 3-methylcholanthrene and 7,12 dimethylbenz(a)-anthracene. More sensitive procedures (McCann et al. 1975) showed that of 34 PAHs tested all were mutagenic towards the TA100 strain of (Salmonella typhimurium). Huberman and Sachs (1974), utilizing the Chinese hamster V79 cell line plus irradiated rodent fibroblasts, detected the mutagenicity of carcinogenic PAHs at 0.1 µg/mL. They found 7,12-dimethylbenz(a)anthracene to be highly mutagenic even at 0.01 µg/mL. The non-carcinogenic PAHs such as pyrene, phenanthrene, and chrysene were not mutagenic. Guerin et al. (1978) studied fractions of synthetic coal and shale fuels as well as crude oil and found the neutral fractions containing the PAHs were mutagenic. Mutagenic activity was greater in those fractions containing four and five ring PAHs. Enzymic activation was not necessary for mutagenic action of the fraction but the mutagenicity of the fractions was increased by such activation.

The experimental and epidemiological association between substances containing PAHs and tumor and cancer incidence has been a topic of concern since the original observation of Pott (1775) of increased scrotal cancer incidence in chimney sweeps exposed to coal-burning fireplace soots, and the first induction of skin tumors in rabbits by application of coal tar for 150 d (Yamagiwa and Ichikawa 1916). This latter work was predated by Volkman (1875) who defined the association between skin cancer and workers in coal tar plants. There has been a bewildering array of different chemicals identified as human chemical carcinogens based either upon human exposure (epidemiology) or animal experimentation (Heidelberger 1975). The induction period in human cancers is usually a matter of years, making it difficult epidemiologically to ensure adequate control groups are utilized (Bridbord and French 1978). Induction of tumors in laboratory animals is not a straightforward procedure in defining a human health hazard since, in addition to species differences, questions can be raised regarding dosing level procedures, exacerbating and ameliorating factors, routes of administration and target organs. Another problem is that of determining if the experimentally induced or observed tumor is a cancer, or simple hyperplasia. The concepts of lethality to the organism and tumor progression as formulated by Foulds must be kept in mind (Stewart 1977).

Cancer-inducing chemicals may be divided into a number of activities based upon experimental observations (Sivak 1979; Van Duuren 1976; National Academy of Science 1972): (1) Carcinogenic compounds - those compounds which by themselves can induce cancers, e.g. benzo(a)pyrene, 3-methylcholanthrene. Experiments by Mondal and Heidelberger (1970) have demonstrated that such compounds act by transforming normal cells into cancerous ones rather than by selecting for pre-existing cancer cells. (2) Co-carcinogens - those compounds which in combination with each other induce greater numbers of tumors than the individual agents alone. Huebner and Todaro (1969) have suggested that chemical co-carcinogens act through cancer-causing viruses. (3) Tumor initiators - those compounds which in a single dose, too low to cause cancer by itself, followed by application of another agent, lead to the development of tumors. Benzo(a)pyrene and 7,12-dimethylbenzo(a)anthracene are common initiators (e.g. Akin et al. 1976). The initiating effect can persist in the absence of a promoter for as long as a year (Van Duuren 1969). (4) Tumor promoters - agents such as croton oil which, when applied following dosing with a tumor initiator, lead to development of tumors. The sequential process of induction of tumors by a single dose of a tumor initiator followed by repeated low level exposure to a tumor promoter is referred to as "two stage carcinogenesis". Many chemicals fall into one or more of these groups. In general, tumor-promoting agents by themselves are non-carcinogens or weak

carcinogens. The same is true for tumor initiators, especially at the doses used in initiating experiments. A number of PAHs such as benzo(e)-pyrene, pyrene and fluoranthene are active in a co-carcinogenic manner with benzo(a)pyrene but are not promoters or carcinogenic agents per se (Sivak 1979). These compounds may work through their ability to induce aryl hydrocarbon hydroxylase which could in turn rapidly metabolize benzo(a)pyrene to the active carcinogen mentioned above. Viruses have been shown to act as co-carcinogens for coal tar or 3-methylcholanthrene induced cancers (Sivak 1979). (5) Anti-carcinogenic agents - those agents which, when given in single or multiple doses before, during and after treatment with a carcinogen, partially or completely inhibit tumor induction. They are sometimes carcinogenic but more commonly non-carcinogenic (Kinoshita and Gelborn 1972).

The two-stage carcinogenesis approach is often used by investigators to test various chemicals for their carcinogenicity since experimental times are decreased and lower doses of the test chemicals result in greater numbers of tumors (Akin et al. 1975). Table 3 lists the carcinogenic properties of PAHs gleaned from the literature. Only the non-alkylated parent PAHs and common methylated PAHs are listed. Alkylation, leading to a multitude of isomers and oxygenation, modifies the carcinogenic properties of the parent compound, sometimes abolishing it or enhancing it markedly (Dunning et al. 1968). The reader is referred to a review by Dipple (1976) who discusses the activities of alkylated and substituted PAHs. The carcinogencity of benzo(a)pyrene and its derivatives is described in detail by Levin et al. (1978). It is obvious from the table that a degree of ambiquity surrounds the carcinogenicity of many PAHs. The inhibitory potential of certain PAHs complicates the issue and is relevant to environmental concerns since, for example, Khesina et al. (1977) have shown that briquette soot extracts containing carcinogenic PAHs inhibited the carcinogenicity of benzo(a)pyrene to some degree. One should also realize that there is a lower limit to the carcinogenic properties of even a potent carcinogen such as benzo(a)pyrene since Neudecker (1978) has shown no increase in tumor incidence in a four-generation rat study based on carrots (3.6-5.0kg/rat/year) containing approximately 1 µg/kg benzo(a)pyrene even when this dietary regiem was fortified with 10 µg benzo(a)pyrene/animal/week.

ASSOCIATION BETWEEN CANCERS IN MAN AND EXPOSURE TO SUBSTANCES CONTAINING POLYCYCLIC AROMATIC HYDROCARBONS

With few exceptions, materials known to contain relatively high levels of PAHs are associated with cancer in man. Carbon black contains high levels of PAH but apparently does not lead to cancer in either exposed humans or in animal experiments (Locati et al. 1979), and the suggestion has been made that the PAHs are rendered inert by binding to the carbon matrix. Coal, although causing pneumoconiosis, also does not induce cancer (Freudenthal et al. 1975).

Increased cancer incidence in humans has been reported in individuals exposed to: 1. Tobacco smoke - see reviews by Hoffman et al. (1978); Royal College of Physicians (1971,1962); Falk et al. (1964). The PAHs in tobacco smoke have been implicated in animal studies but they do not appear to be self-sufficient carcinogens at the dosages of cigarette smoke condensates to account for the level of carcinogenesis observed by Hoffman et al. (1978). Snook et al. (1976) and Severson et al. (1978) have shown that the PAH fraction of tobacco smoke is synergistic with certain neutral and acidic fractions of tobacco smoke condensates in skin tumor production in mice. Hoffman et al. (1978) further point out that the reduction of "tar", nicotine and PAHs in commercial cigarettes has lowered the smoker's risk of cancer of the larynx and lung.
2. Combustion smoke. The association between coal-fire soot and scrotal cancer has been mentioned (Pott 1775). In addition to scrotal cancers in chimney sweeps other sites such as the face, ear, penis, jaw and wrist (Falk et al. 1964) were involved. Soot, obtained from food smoke houses utilizing wood, was shown by Sulman and Sulman (1946) to be carcinogenic to rats but Tillmanns (1880) speculated that the lack of cancer in chimney sweeps in Germany prior to 1873 was due to the exclusive use of wood for heating. The lack of cancer associated with carbon black (a specialized soot preparation) has been mentioned above. In addition to binding of PAHs, the variation of PAH concentration in soots should be noted (Kipling and Waldron 1976) since values of benzo(a)pyrene ranged from 0.0-0.2% by weight. Increased evidence for the carcinogenicity of soot (smoke) comes from Africa (Hoffman and Wynder 1976) where there is a high incidence of nasopharyngeal cancer amoung natives inhabiting poorly ventilated huts heated with open wood and cow dung fires.
3. Motor vehicle exhausts. Viadana et al. (1976) observed significant increases in skin and prostate cancers in automotive mechanics and repairmen but this could also have been due to exposure to lubricants since engine lubricants, especially used lubricants, contain PAHs. Brune (1977) reported that automobile exhaust condensates induced squamous cell cancers and papillomas in mice in a dose/response manner. PAH enriched fractions were also carcinogenic. Mohr (1978) induced multiple pulmonary tumors in Golden hamster by intratracheal instillation of automobile exhaust condensate and pointed out that the carcinogenicity of this material more than exceeded that expected from its benzo(a)pyrene content. Lawther and Waller (1976) pointed out that no excess of lung cancer was found among workers in London transport diesel bus garages when compared to other equivalent workers. Blumer et al. (1977) studied the cancer incidence and PAH composition of soils in a Swiss mountain town associated with a highway. PAH concentration and cancer incidence decreased with increasing distance from the highway. PAH profiles in soil resembled automotive exhausts rather than residential soots.
4. Fuel conversions and lubricating and other oils. Coal gasification (water gas) and coking (coal tar) operations have been widely studied to investigate the possibility of occupationally related cancers. Trosset et al. (1978) reviewed a number of studies involving workers in coal gas and coking plants. Generally, cancers of the bladder, skin, lung, and scrotum showed increased incidence in workers and the incidence, especially of lung cancer, was greatly increased by smoking. The co-carcinogenicity of cigarette smoke has been found with uranium and asbestos workers as well (Sivak 1979). Lloyd (1971) found that the incidence of cancer in coking operations increased as the temperature of carbonization increased. Lung cancer deaths were twice as frequent in pensioners of a London gas company than expected (Doll 1958). Lubricating and other high

TABLE 3. Carcinogenic properties of individual PAH compounds: +++ - high activity carcinogen, ++ - moderate activity carcinogen, + - low activity carcinogen, + - possible carcinogen, c - co-carcinogen, p - promoter, i - initiator, in - inhibitor of PAH induced cancer, ? - unknown, - - non-carcinogen.

naphthalene +(1)

fluorene -(7)-(12): benzo(a)fluorene -(7); benzo(b)fluorene-(3),-(7); benxo(c)fluorene-(7); dibenzo(ah) fluorene +(7); dibenzo(ag)fluorene -(7); dibenzo(ac)fluorene + (7).

anthracene +(1),-(7),-(11),i(8), in(10): 7,12-dimethylanthracene+(4),+++(7); benzo(a)anthracene-(1), +(3), +(7), i(8), i(9), p(11); 10-methyl-anthracene+++(11), benzo(a)anthracene+++(3); 7,12-dimethylbenzo(a) anthracene+(2), i(8), dibenzo(ac)anthracene-(1), +(7), i(8); dibenzo(ah)anthracene+(1), +(2), ++(5), ++(7), ++(11), in(10); dibenzo(aj)anthracene+(1), +(7).

phenanthrene +(1), -(7), i(8), in(10), p(11): benzo(c)phenanthrene +(1), ++(7), +++(11), dibenzo(ag)phenanthrene ?(1).

fluoranthene -(2), -(7), c(9): benzo(ghi)fluoranthene-(7), -(11); benzo(a)fluo-ranthene?(1) benzo(b)fluoranthene+(4), +(7), ++(11); benzo(j)anthene +(7), +(10), benzo(k)fluoranthene+(3), -(7), -(11); 3,4-benzofluo-ranthene++(2), ++(11), 10,11-benzofluoranthene ++(2), 4+(11).

pyrene +(1), -(7), -(11), c(8), c(9), in(10): benzo(a)pyrene+++(1), +++(2), +++(7), c(6), c(8); benzo(e)pyrene-7, +(11), c(8)c(9)p(11); dibenzo(ah)pyrene (1), ++(3) +(4), ++(7); dibenzo(el)pyrene ?(1); dibenzo(ai)pyrene ++(1), ++(4), ++(7); dibenzo(al)pyrene ++(1), +(7), +++(11); dibenzo(cd,jk)pyrene-7, i(8); dibenzo(ah)pyrene +++(11).

chresene ?(1), +(3), +(11), i(4), +(7), i(8), i(9), in(10); 5-methylchrysene ++(5); naphthol(1,2,3,4-def)chrysene++(1); benzo(b)chrysene-(1), i(7); benzo(g)chrysene -(1); dibenzo(bk)chrysene-(1).

naphthacene ?(1), -(7): -(11), benzo(a)naphthacene ?(1): dibenzo(ac)naphthacene +(1); dibenzo(aj)naphthacene-(1); dibenzo(de,gr)naphthacene ? (1).

triphenylene ?(1): naphtho(1,2-b)triphenylene-(1).

perylene -(1), -(7), in(10): benzo(ghi)perylene+(1), -(3), -(7), c(9); benzo(a)perylene+(2).

cholanthene +(7): 3-methylcholanthene +++(7), +++(11); 20-methylcholanthene +(2), +(3).

pentaphene ?(1): benzo(b)pentaphene-(1).

picene -(1)i(8).

(1) Dipple (1976)
(2) Graf (1965)
(3) Arcos and Argus (1974)
(4) Kipling and Waldron (1976)
(5) Cavalieri et al. (1978)
(6) Pfeiffer (1973)
(7) National Academy of Sciences (U.S.A.) (1972)
(8) Scribner (1973)
(9) Van Durren (1975)
(10) Crabtree (1946)
(11) Pfeiffer (1977)
(12) Lo and Sandi (1978)

temperature oils (shale oils, mineral oils, anthracene oils) have been associated with cancers in both production and usage (e.g. mule spinners, machine tool operators) (Kipling and Waldron 1976; U.S. National Academy of Sciences 1972; Falk et al 1964).

5. Foodstuffs. Gastric intubation of benzo(a)-pyrene or 20-methylcholanthrene twice weekly induced forestomach and other tumors in mice (Poel 1963). The incidence of stomach cancer in humans is known to vary from country to country. Dungal (1961) studied the problem in Iceland and came to the conclusion that the uneven distribution of stomach cancer in Iceland was related to the uneven distribution observed with the consumption of smoked trout and smoked mutton, the cancer incidence being highest in those areas of highest consumption of these foodstuffs. A high incidence of cancer was noted in one island town (Westman Islands) where consumption of smoked fish and mutton was limited. Heating of houses on this island utilized coal and roof rain runoff was used as drinking water. The presence of soot in the water was noted. Feeding rats with smoked mutton or fish led to forestomach cancers. Levels of benzo(a)pyrene in these foodstuffs were only 1-3 µg/kg but much higher levels of other PAHs (especially acenaphthene, fluorene, phenanthrene, and anthracene were found. Wynder et al. (1963) confirmed the validity of the statistical approach used. In addition, animals were fed with mutton or trout at 40 g/wk for 1 - 2 y and tumor incidences of 4/18 and 6/18 were found for mutton and trout respectively. The higher incidence in trout feeding compared with mutton is interesting as trout contained almost twice the amount of benzo(a)pyrene and about one-half the total PAH level of mutton. The case for cancer related to food ingestion is questioned by certain authors (Grasso and O'Hare 1976).

6. Use of creosote, coal tar and coal tar pitch. Skin cancers have been reported in creosote plant workers (U.S. National Academy of Sciences 1972) but only cases of skin cancers were found. Sall and Shear (1940) and Cabot et al. (1940) found that various fractions of creosote could accelerate or retard the carcinogenic action of benzo(a)pyrene. Anthracene oil, the high boiling fraction of creosote, has been widely associated with cancers in users of such oils (Thony et al. 1976; Falk et al. 1964). Investigation of a wood treating plant utilizing 70% creosote, 30% coal tar and some pentachlorophenol after 1 yr of operation (Markel et al. 1977) showed skin and eye irritations, mil folliculitis and pitch warts. No incidence of cancer was found, not unexpectedly since only 1 yr of exposure was involved. Garett (1975) associated bladder tumors and chronic exposure to cresol and creosote. Coal tar, on the other hand, and coal tar pitch production are widely associated with cancer in workers (National Academy of Sciences 1972; Fisher 1953). The area has been adequately reviewed by Trosset et al. (1978) who report increased frequency of tumors of the bladder, kidney, stomach, pancreas, mouth, phlarynx, esophagus, and lung in workers in coal tar and coal tar pitch industries. Coal tar has been used in the treatment of psoriasis and other skin disorders and skin tumors and cancers have been associated with its use (Urbach 1959; Rook et al. 1956) but, according to Trosset et al. (1978), there is a strong impression amoung dermatologists that the incidence is low or non-existent. One factor in this is the synergistic action of ultraviolet light and coal tar which yields essentially 100% cancers in treated animals (Urbach 1959). These coal tar preparations are mutagenic in vitro (Saperstein and Wheeler 1979). Use of coal tar pitch in electrodes for reduction smelting, briquettes, roofing, and fishing applications have all been associated with increased cancer. Sladden (1928) observed that incidence of skin cancer reached 66% after 10-15 yr exposure to coal tar pitch and 100% after 40 yr. This was confirmed by Fisher (1953). The carcinogenicity of pitch is not unique to pitch obtained from coal tar. Tars obtained from blast furnaces, isoprene, acetylene, cholesterol, yeasts and human skin were shown to be actively carcinogenic (Kennaway 1925) and as a general rule the potency of the tar was greater as the temperature of formation increased (Kipling and Waldron 1976).

In the last few years great interest has developed into the occurrence of neoplasia in aquatic organisms and their relationship to pollution (e.g. Annals of the New York Academy of Sciences, Vol. 298, 1977; Stich et al. 1977; Sonstegard 1977; Brown et al. 1973) but the involvement of PAHs in the etiology of such neoplasms is unclear. Yevich and Barszcz (1977) found tumors in Mya arenaria from oil-impacted sites but could not specifically show oil to be the causative agent.

Invertebrates also respond to PAHs. The earthworm (Lumbriculus terrestuis) developed hyperplasia and incipient tumors upon exposure to benzo(a)pyrene, 3-methylcholanthrene or dimethylbenz(a)anthracene and developed lethal growths upon forced regeneration. Their offspring developed lethal tumors (Foster 1969; Gorsch 1954). Krieg (1970) reported that benzo(a)pyrene caused tumors in snails. Manfred (1970) induced tumors in Rhodeus amarus and Gasterosteus aculeatos, two short-lived fish species, by skin treatment with benzo(a)pyrene and methylcholanthrene (mixed) but not in Cyprinus carpio, a long-lived species. Tumors have been induced in frogs and toads (Matoltsy 1974; Balls 1964; Leone 1953) but not in salamanders (Breedis 1950).

CONCLUSIONS

The data reviewed above, clearly demonstrate that an association exists between PAH-containing substances and the occurrence of cancer. It could be argued that another cancer-inducing material is associated with all of these occurrences but studies with purified PAHs contradict this. Studies by Cottini and Mazzone (1939) using human volunteers whose skin was deliberately painted with benzo(a)-pyrene demonstrated pre-cancerous cellular transformations. The question from a health point of view seems to be one of what level of PAH humans can be exposed to without significantly increasing their likelihood of developing cancer (Lawrence 1976). Cancer theoreticians work from two premises, one which assumes that a threshold exposure level exists for any chemical carcinogen, (Falk 1978; Jones 1978; Rall 1978). The other premise is that no such threshold exists (Peto 1978) and the number of cancers induced is proportional to the dose. In any event, individuals who believe in the threshold theory recognize that a static threshold would only apply to a relatively homogeneous, genetically identical population living under carefully controlled conditions. When one considers the large number of genetic and environmental factors (Vesell and Passanati 1977; Boulos 1978), the role of disease (Boulos 1978), the inherent statistical problems in extrapolating down to low levels, the

role of the "ultimate carcinogen" and the possible variations inherent in its synthesis (e.g. nutrient and drug effects on aryl hydrocarbon hydroxylase (Alvares et al. 1979) and degradation (e.g. via non-carcinogenic pathways) and the diverse nature of human behavior patterns, it is likely that the human situation will mimic a dose/response situation at all dose levels even if a discrete threshold exists in each individual. The research approach to chemical carcinogenesis is difficult. Some authors (see Ames 1979; Carter 1979; and Ts'o 1978) have advocated carcinogenic ranking of chemicals based upon relatively fast and cheap microbial tests but these tests only give an estimate of the potential of these chemicals to cause cancers in humans. Prediction of the cancer inducing potential of PAH contaminated foodstuffs is extremely difficult and until better information is forthcoming the approach would seem to be one of minimum exposure and elimination of unnecessary exposures. The various sources of input to man are difficult to rank but Bridbord et al. (1976) use a method by which exposures are ranked in terms of packages of filter cigarettes per day, i.e. one package of filtered cigarettes per day is equivalent to 0.4 µg benzo(a)pyrene. On this basis workers in coke oven plants were exposed to the equivalent of from 175-450 packages of cigarettes a day and coal tar pitch workers to 1875 packages a day. Since coal tar workers as we have seen above develop cancers like smokers, this approach has some merit.

The question of the effect of ingestion of PAHs and cancer is still more complex. The Iceland studies mentioned above (Dungal 1961) show that increased ingestion of smoked foods is related to increased incidence of gastric cancers but the level of benzo(a)pyrene was quite low (1-2 µg/kg wet weight) suggesting that the presence of other PAHs (acenaphthalene and phenanthrene) in the foodstuffs (smoked mutton and trout) may play an important role.

The high levels of PAHs in edible portions of impounded lobsters (Dunn and Fee 1979) are substantially higher than reported for any other foodstuff. The advisability of continued marketing of lobsters with such high levels of PAHs must be assessed by the various regulatory bodies. It is likely that allowable levels of PAHs if set, will be set at the highest PAH levels naturally encountered in foodstuffs (E. Sandi, personal communication, T. Fazio, personal communication, W. Kraybill, personal communication). This level is thought to be about 100 µg total PAH/kg food or about 1 µg benzo(a)pyrene/kg. Lobster is a foodstuff that is consumed in significant quantity by only a very small portion of the population, most of whom have access to freshly caught lobster which have low levels of PAHs (Dunn and Fee 1979). With regard to future use of impounded lobsters an acceptable course of action would involve: 1) no construction or repair of pounds by using creosote-treated timbers; 2) limiting the duration of lobster holding in pounds constructed with creosote-treated timbers; 3) depuration, if feasible, in pounds constructed of non-creosote-treated materials. Further research is needed to determine: 1) if certain coastal areas (e.g. downstream of plants producing or utilizing creosote or coal-tar) yield contaminated lobster; 2) if lobsters depurate PAHs to acceptable levels in a reasonable length of time 3) if a marked difference in uptake of PAH by impounded lobster exists between summer and winter.

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