

Mercury arising from oil and gas production in the United Kingdom and UK continental shelf



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Executive Summary

Integrating Knowledge to Inform Mercury Policy (IKIMP) is a UK knowledge exchange initiative created to ensure that the scientific and technical knowledge base is used to inform and guide public policy relating to mercury (see www.mercurynetwork.org.uk). A recognised knowledge gap hindering the construction of mercury budgets is the release of mercury into the environment from the activities of the oil and gas industry. Consequently, the IKIMP initiative has produced this report to synthesise the knowledge available in the public domain to inform UK policy makers and regulators, and other stakeholders.

The report considers:

- the quantities of mercury associated with the activities of the oil and gas industry in the UK, where it emerges in the chain of extraction, processing and use, and the species involved;
- how the UK mercury content of oil and gas compares to that elsewhere in the world, including any reasons for observed differences; and
- the significance of the mercury burden from the oil and gas industry in the UK for mercury emissions and management more generally.

A key, overarching conclusion of the study is that the paucity of data available in the public domain means that there are large uncertainties in the quantities of mercury contained in the oil and gas processed and used in the UK, and in consequent releases to the environment. These difficulties of estimation are exacerbated by substantial variations in the mercury contents of oil and gas derived from different sources, ranging globally from 0.1 to 20,000 µg/kg in crude oil and 0.05 to 5000 µg/Nm³ in natural gas. The mercury is believed to largely accumulate through secondary geological processes, with high concentrations the result of exceptional geological conditions.

Around 200 kg of mercury is estimated to be released annually to the environment from the production of oil and gas in the UK sector of the North Sea, primarily associated with discharges of produced water. Published data suggest that around 70 kg of mercury per year is contained in UK-sourced **crude oil** refined in the UK, but in addition, up to 750 kg of mercury per year arrives with imported crude oil which is refined in the UK. This latter figure is dominated by the mercury associated with crude oil imported from Norway, for which the mercury content is particularly uncertain (and is a priority for further investigation). Process variations between refineries impose further uncertainties on the releases of mercury from UK refineries. Annual atmospheric releases of 162 to 530 kg mercury may be the main pathway, but releases with wastewater and as solid wastes are not negligible.

The mercury contents of **natural gas** refined and used in the UK are even less well-constrained. While around 50 kg of mercury per year is estimated to be associated with natural gas sourced from UK fields, 1380 to 1720 kg of mercury per year is estimated to be annually contained in imports, mainly from the mercury rich Groningen gas field of the Netherlands. It may be that a substantial fraction of this mercury is removed in gas treatment plants before transportation to the UK by pipeline as natural gas (where there may be further reductions in mercury content), or as LNG (where mercury may otherwise cause problems on liquefaction). The existence, location and efficiency of these treatment plants is a key area of uncertainty, having a major impact on the UK's mercury budget, and is a priority area for any future study.

Losses from natural gas during processing and use are entirely dependent on whether and where mercury removal units are installed. It is considered likely that all natural gas has mercury removed prior to, or during, processing. Within the processing plant this may be before or after acid gas scrubbing and drying.

These two processes release up to 80% of the mercury present in the natural gas to the atmosphere, consequently atmospheric mercury releases from natural gas processing are estimated to range from less than 1 to 1416 kg of mercury per year. The quantification of releases of mercury from natural gas processing in the UK requires the existence and positions of mercury removal units to be disclosed.

The National Atmospheric Emissions Inventory estimates a total atmospheric release of mercury of 6220 kg in 2008. Atmospheric releases from oil and gas are estimated to make up 3 to 31 % of this total. Further work is necessary to constrain this important, poorly understood and under studied, proportion of the total UK mercury budget.

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Annual fluxes refer to 2009 production and usage, chosen as a compromise between data availability and presenting an up-to-date picture, unless otherwise stated. Concentration measurements are from a range of years.

1. Introduction

Integrating Knowledge to Inform Mercury Policy (IKIMP) is a UK knowledge exchange initiative created to ensure that the scientific and technical knowledge base is used to inform and guide public policy relating to mercury (see www.mercurynetwork.org.uk). A recognised knowledge gap hindering the construction of mercury budgets is the release of mercury into the environment from the activities of the oil and gas industry. While extensive research has been carried out on mercury release from coal burning in the UK and worldwide (reviewed in 1), relatively little has been published on mercury inventories and impacts from the oil and gas industries. Consequently, the IKIMP initiative has produced this report to synthesise the knowledge available in the public domain to inform UK policymakers and regulators, and other stakeholders. This report sets out to address:

- the quantities of mercury associated with the activities of the oil and gas industry in the UK, where it emerges in the chain of extraction, processing and use, and the species involved;
- how the UK mercury content of oil and gas compares to that elsewhere in the world, including any reasons for observed differences; and
- the significance of the mercury burden from the oil and gas industry in the UK for mercury emissions and management more generally.

As discussed in the subsequent sections of the report, the limited data available in the published literature reviewed in this report reveal high levels of uncertainties in the quantities of mercury contained in oil and gas extracted, processed, and used in the UK. It is hoped that publication of the report will stimulate discussion and potentially lead to the identification and publication of additional data that will enable uncertainties to be reduced. In particular, it is anticipated that the oil and gas industry may have access to information that could substantially improve the quality of estimates of mercury releases at the different stages of extraction, processing and use of oil and gas.

Mercury (Hg) is a highly volatile transition metal found in the environment in trace quantities in both elemental form and as highly toxic organo-mercury compounds (2). The speciation of mercury in crude oil has been comprehensively reviewed elsewhere (3). In brief, the complex variety of mercury species in oil can be separated into 3 broad categories: volatile mercury (including elemental mercury and dialkylmercury⁽¹⁾), insoluble mercury (of uncertain chemical identity), and dissolved forms (including elemental mercury, dialkylmercury, mono-alkylmercury and loosely complexed ionic mercury). Whereas crude oil contains a complex array of mercury species, most of the mercury in natural gas is elemental mercury (4, 5). Trace quantities of inorganic (including HgCl₂), organic (including dimethylmercury and diethylmercury) and organo-ionic compounds have been detected, although it is possible these are measurement artefacts (5).

Bioaccumulation in the food chain may concentrate trace amounts of organo-mercury up to 10⁴ to 10⁵ times, and the primary route into the human diet is through seafood consumption, especially the consumption of large predatory fish (4). The dangers of this were vividly demonstrated at Minimata Bay, Japan in the 1950's and 1960's when fishermen were found to be suffering from mercury poisoning originating from factory effluent. Linked to this incident are 1,784 fatalities, and over 10,000 people have consequently been compensated for their exposure by the Chisso Corporation (6). Furthermore, there are also more localised dangers within the petroleum industry, as demonstrated by the catastrophic failure of aluminium heat exchangers at the Skikda plant in Algeria in 1973. In this incident the mercury that collected during the cryogenic stages of liquefied natural gas (LNG) production subsequently amalgamated with the aluminium of the heat exchangers. This weakened the metal resulting in a catastrophic failure and an explosion causing 30 fatalities (7).

⁽¹⁾ Refers to organic mercury compounds which consist of two alkyl groups (single-bonded hydrogen and carbon molecules, e.g. CH₃- [methyl group]), and the element mercury.

2. Origin of mercury

While no comprehensive, wide-ranging research has been published on the origin of mercury in oil and gas, it appears that the bulk of the mercury is the product of secondary geological processes mobilising mercury into the reservoir as discussed below. Differences between local geological conditions are thought to explain the range of mercury concentrations reported.

One possibility is that atmospheric mercury deposition, taken up in organic material prior to burial and hydrocarbon formation, may account for some of the mercury found within crude oil and natural gas (4). However, measured concentrations vary by many orders of magnitude between different deposits, from 0.1 to 2×10^4 $\mu\text{g}/\text{kg}$ in crude oil (8) and from <0.01 to 5×10^3 $\mu\text{g}/\text{Nm}^3$ ⁽²⁾ in natural gas (9). Atmospheric deposition may be able to explain the prevalence of mercury across all hydrocarbon deposits but not the orders of magnitude range in concentrations (4).

Enhanced mercury concentrations are thus likely to be caused by secondary geological processes, including interaction with metal rich fluids and formation waters (10). The exact nature of the processes may vary depending on local geology. For example, the high mercury content of the Rotliegend sandstone natural gas reservoirs of Europe (including Groningen and North Germany) is interpreted as originating in underlying volcanic units (11); while the exceptionally high mercury concentrations in gas from the Gulf of Thailand are attributed to nearby coal and carbonaceous shale (12). In both of these cases secondary geological processes are thought to transfer mercury from the source and redeposit it within the petroleum reservoir.

Evidence for secondary geological processes mobilising mercury into a reservoir has been found at the Cymric Field in California where the highest global crude oil mercury concentrations have been reported. This field is associated with cinnabar deposits containing bituminous nodules and inclusions suggesting high mercury concentrations in the oil may be due to the interaction of organic matter and metalliferous fluids (10). Enhanced mercury concentrations have also been measured in deposits associated with deep fault zones such as the Russian Karpinsky lineament, and the presence of mercury in this reservoir is attributed to mantle degassing (13).

An assumption commonly made in mercury analysis is that that any individual petroleum/natural gas reservoir is likely to be well mixed, and consequently it is argued that the variation seen in mercury content is attributable to inter-reservoir differences each with distinct mercury concentrations. However, studies in Russia and Ukraine have demonstrated that the concentration of mercury within even a single deposit can be highly variable, with measurements at the Mirnenskoye gas deposit, Russia, for example, varying from 0.05 to 40 $\mu\text{g}/\text{Nm}^3$ (13). Furthermore, research has shown both short-term (days) variations of 10-80%, possibly caused by changing pressure affecting the distribution of mercury between solid and liquid phases, and long-term (annual) variations of 160 to 1700 % in mercury concentrations in individual natural gas deposits. Consequently, the variation seen at a single well can be larger than that across a deposit as a whole (14), although the reason for this warrants further investigation.

Concentrations of trace metals in crude oil (e.g. nickel and vanadium) are often proportional to the dense asphaltene concentration (10) and given that much of the mercury in crude oil is held in this fraction (3) a similar proportionality might be expected. However, this relationship has not been established (15), although alternative properties including reservoir CO_2 content may allow prediction of mercury levels (16). That asphaltene composition and mercury concentration of crude oil are not related is additional evidence that secondary geological processes play a dominant role in mobilising mercury into the reservoir.

⁽²⁾ Nm^3 = Normal cubic meter: unit of mass for gases equal to the mass of 1 cubic meter at a pressure of 1 atmosphere and at standard temperature.

3. Quantities of mercury

An upper limit on total mercury release by the UK oil and gas industry may be obtained by constructing a budget of the total amount of mercury present in crude oil and natural gas processed in the UK. Since the UK Department for Energy and Climate Change (DECC) does not monitor mercury levels in produced hydrocarbons or inputs to UK refineries, it is necessary to extrapolate from the limited available data in order to estimate UK releases. The variations in mercury concentrations in crude oil and natural gas, together with the absence of correlations between mercury concentrations and hydrocarbon properties, limit the accuracy of the estimates that can be made.

The input into a gas processing plant or oil refinery is a mixture of natural gas/crude oil from various fields in the North Sea, and imports from abroad. The net result of the temporal and spatial variations in hydrocarbon mercury concentration is fluctuating inputs of mercury into a refinery.

3.1 In crude oil

A study initiated by the United States Environmental Protection Agency on crude oil imported to the USA provides the only systematic, volume weighted, data on worldwide mercury concentrations in crude oil (8).

The results of this study are included in Annex 1, and indicate an average mercury concentration of 3.6 µg/kg in crude oil imported to the USA from the UK. This may represent a severe under-sampling of UK production, since this average is produced by weighting measurements on individual crude oils to the proportion of U.S imports, rather than UK production. One possible conclusion to be drawn from the data in Annex 1 is that crude oil from Norway has a mean mercury concentration of 19.5 µg/kg; 5 times greater than the UK average. An alternative estimate puts the mercury concentration of North Sea crude oils at 2.5-9.3 µg/kg⁽³⁾ (17).

A histogram of the distribution of concentrations across the globe, excluding an extreme outlier from Thailand, suggests that most global sources of crude oil have low (0-5 µg/kg) mercury concentrations, with the reported ranges skewed by outliers (Figure 1). This statistical distribution is consistent with theories of crude oil accumulating mercury with very high concentrations under exceptional geological conditions.

⁽³⁾ Reported as 2.5-9.3 ppb. If by mass this converts to 2.5-9.3 µg/kg.

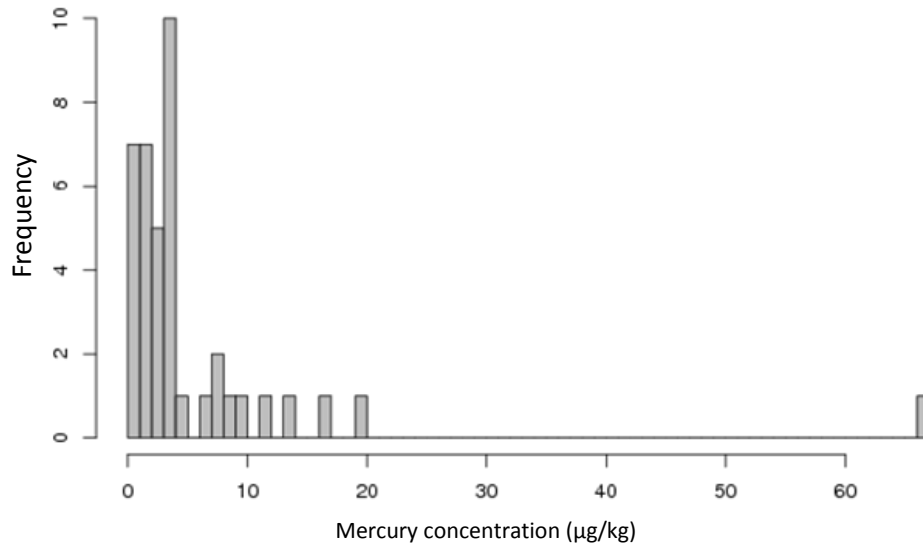


Figure 1: Histogram of crude oil mercury concentrations reported by country showing the statistical distribution of mercury concentrations. The extreme outlier of 593 µg/kg mercury in Thailand crude oil is provided to illustrate how ranges can be skewed by outliers. (Data from 8)

Using a mercury concentration of 3.6 µg/kg for the UK (8), it is calculated that 230 kg of mercury was present in the 62.8 million tonnes of crude oil produced in the UK in 2009 (18). Of this, 19.4 million tonnes (31 %) was processed in the UK which, if used as annual production, yields an estimated 70 kg of mercury per year (kg Hg/yr) to UK refineries. Assuming that the concentrations reported in (8) characterise imports to the UK, a flux of 750 kg Hg/yr is estimated for the 50.7 million tonnes of crude oil imported to the UK annually (Annex 2.a). This estimate is dominated by the contribution of Norwegian crude oil for which the US Environmental Protection Agency estimates of mercury content (at 5 times UK concentrations) have been questioned above.

If Norwegian crude oil had the same 3.6 µg/kg mercury concentration as UK crude oil (8), within the range given by (17), this would reduce the total mercury budget of imported crude oil to 200 kg Hg/yr. Using the 200-750 kg Hg/yr range in imported crude oil provides a total UK mercury budget in crude oil (imported and produced) of 270-820 kg Hg/yr. The geometric mean concentration is 3.9-12 µg/kg (Annex 2.b).

3.2 In natural gas

Like crude oil, natural gas deposits can have a high variation in mercury concentration across a range of spatial scales (summarised in Annex 3). The study revealed no reported mercury concentrations for UK gas fields, and only one reported measurement for the Norwegian sector, for the Albatross & Askeland gas fields. While extensive variation in mercury content across the North Sea cannot be ruled out, the low concentration reported for the Albatross & Askeland gas fields is consistent with the absence of reported mercury related problems in the North Sea. Therefore, assuming that the mercury concentration reported of 1.0 µg/Nm³ (9) holds across the North Sea, there would be a flux of 62.4 kg Hg/yr in the 62.2 billion m³ of natural gas produced in the UK annually; again, the 2009 production value (18) is being used to represent annual production. Of this, 50.1 billion m³ (80%) was processed in the UK, introducing an estimated 50 kg Hg/yr to UK refineries.

Assuming that the concentrations reported in Annex 3 characterise natural gas imported to the UK, a flux of 1380-1720 kg Hg/yr is estimated from the approximately 40.3 billion m³ of natural gas and LNG imported to the UK annually (Annex 4.a). This suggests a total mercury budget of 1430-1770 kg Hg/yr related to natural

gas arriving at UK refineries, with a geometric mean concentration of 16-20 $\mu\text{g}/\text{Nm}^3$ (Annex 4.b). Imports dominate the total.

It must be stressed that this flux range represents the initial mercury of the extracted natural gas and does not include losses during transportation or mercury removal prior to entry to refineries, as discussed further below. In addition, the figures are strongly influenced by imports from the Netherlands, some of which reportedly have high mercury concentrations. The Groningen gas field produces approximately half of the total Dutch production and has high measured mercury concentrations (180-200 $\mu\text{g}/\text{Nm}^3$ [9]), whereas smaller fields, for which the mercury concentration is not reported, account for the remainder of Dutch production (19).

Since serious localised problems caused by mercury contamination can be encountered during natural gas processing, many refineries have installed mercury removal units prior to the raw gas entering the plant. These reduce the mercury concentration of the natural gas to a negligible quantity ($<0.01 \mu\text{g}/\text{Nm}^3$). It is also possible that mercury removal occurs prior to transportation to the refinery. In the case of imports this will prevent mercury from entering into the UK budget. Of note is that LNG plants must have mercury removal units prior to liquefaction (9), meaning that only a negligible amount of the estimated 220-430 kg Hg/yr (Annex 4.a) originally in natural gas imported to the UK as LNG ever enters UK refineries.

An estimated 1130-1260 kg Hg/yr, of the total 1430-1770 kg Hg/yr natural gas mercury flux is contained in mercury rich Dutch natural gas (Annex 4a). NAM (Nederlandse Aardolie Maatschappij BV) – the operator of the Groningen gas field reports that “immediately upon the gas coming to the surface of the earth, it is treated and most of the mercury is removed before the gas is handed over to the Gasunie for transportation etc”(20). The proportion of mercury removed at this stage is, however, not clear and work is necessary to map the process used in more detail. Nonetheless, any significant removal prior to export to the UK will have a large effect on the UK mercury budget.

Assuming complete removal of mercury from all imported natural gas before entry to UK refineries would reduce the natural gas budget to just the 50 kg Hg/yr derived from UK production. The 50-1770 kg Hg mercury budget of UK natural gas is a large range on which further work is necessary.

4. Release of mercury during extraction

Mercury associated with crude oil and natural gas is released to the atmosphere, in wastewater streams and in solid waste streams during extraction, transportation and processing of natural gas and crude oil. That which remains in refined products is released into the atmosphere on combustion (21). For extraction, this report considers mercury releases from operations on the UK continental shelf irrespective of whether the hydrocarbons extracted are exported, while releases from extraction associated with imports are not discussed.

During crude oil and gas extraction mercury is released to the ocean in solid drill cuttings, produced water, and to the atmosphere when natural gas is flared or combusted to produce power. Each by-product of the extraction process will be considered for its contribution to the mercury budget.

4.1 Drilling waste

The mineral barite (BaSO_4) is commonly used in water based drilling muds to regulate the hydrostatic pressure in the well. These muds may contain high concentrations of heavy metals including mercury (22), with published measurements ranging from 400-750 $\mu\text{g}/\text{kg}$ (4, 23).

In 2010 the Scottish Environmental Protection Agency (SEPA) reported that 29,200 tonnes of drilling mud was released into the North Sea (24). Using the 400-750 $\mu\text{g}/\text{kg}$ range of mean mercury concentrations an annual release to North Sea sediments of 12-22 kg Hg/yr can be estimated.

4.2 Produced Water

Produced water is that which is removed on the production platform during the primary separation of hydrocarbons into oil and gas streams. This consists mainly of formation water, naturally present within the reservoir (25), but it must be noted that the volume of produced water increases over time as the reservoir becomes more depleted (22). On the UK Continental Shelf, oil and gas platforms have an obligation to remove hydrocarbons from produced water and to report the quantities that remain⁽⁴⁾. Although there is no obligation to remove mercury, there is an obligation for producers to analyse the concentration, and report measurements to DECC in accordance with the Oil Pollution Prevention and Control Regulations (26). DECC reports 2008 discharges of 91 kg Hg, and 2009 discharges of 186 kg Hg (27). Total produced water discharges in 2008 and 2009 were 198 and 197 million m^3 respectively; with mean mercury concentrations of 0.46 $\mu\text{g}/\text{litre}$ (2008) and 0.94 $\mu\text{g}/\text{litre}$ (2009). The total input is minor compared to natural riverine inputs, estimated at 7000 kg Hg/yr across the North Sea (28).

The mercury release reported by DECC is calculated from measurements at just over 100 facilities in the North Sea, but as it they are based on only two samples per year from each facility these data are likely to be subject to inaccuracies. No explanation is suggested for the 104% increase in total mercury release between 2008 and 2009, a rise despite no significant change in the volume of produced water discharged (29). Measurements from the (Norwegian) North Sea oil platform Brage over just 5 days show a 44 % variation (30), suggesting that natural variability might be the cause.

Mercury species found in the Gulf of Thailand produced water include elemental mercury, particulate mercury sulphide (HgS), inorganic mercury and (of particular concern) organo-mercury forms (e.g. monomethyl mercury) (31). While the mercury losses from primary separation are relatively low, fractionation occurs at this stage both from gravitational settling of suspended forms into the liquid phase and the partitioning of dissolved and suspended forms into produced water (4). Processes have been

⁽⁴⁾ In 2008 3160 tonnes of dispersed oil was reported to be discharged with produced water in the North Sea (29)

developed to remove mercury from produced water prior to release, and are used to comply with environmental regulations in areas where the natural gas and produced water have exceptionally high mercury concentrations; such as in the Gulf of Thailand (32). Alternatively, produced water may be re-injected into the well, preventing mercury release. For example, in the North Sea in 2009, 40 million m³ of produced water was re-injected while 197 million m³ was discharged (29).

4.3 Effects of drilling waste and produced water on the ecosystem

While little research has been published on the effects of oil and gas production on the ecosystem within the UK sector of the North Sea, the Norwegian sector has been intensively researched, with the Norwegian authorities initiating a water column monitoring programme around oil and gas platforms (28). In the Tampen Region (an area with a high density of production platforms, accounting for 70 % of Norwegian produced water), the produced water is rapidly mixed and diluted by 10²-10⁵ times at 0.5-1.0 km from the platform (28). No study was found of mercury concentrations in North Sea fish near to platforms, but studies on fish tissues in the Gulf of Mexico show no evidence for bioaccumulation of mercury above that of uncontaminated organisms far from production platforms (28).

Although sediments near to offshore platforms may contain enhanced mercury concentrations, mercury in barite-based drilling muds is insoluble and not known to be bioavailable to marine organisms in the water column. Sampling near production platforms in the Gulf of Mexico has provided measurements of 11-92 µg/kg mercury far from production platforms (>3 km) while concentrations of 41-422 µg/kg close to marine platforms (<100 m) have been reported (33). However, there is no evidence of this accumulating in the tissues of organisms (22). Furthermore, no statistically significant increase in highly toxic dimethylmercury (produced by bacteria from inorganic mercury) is observed in the vicinity of production platforms in the Gulf of Mexico (33). This suggests that mercury in drilling mud is unavailable to marine organisms. If these findings hold for the North Sea, then potential impacts on ecosystems due to the release of drilling waste and produced water in the North Sea should not be a major concern.

4.4 Gas Flaring Offshore

Gas flaring is the burning of unwanted gas at the production platform, either to remove waste gas that it is not economical to use/sell, or as a safety measure to reduce pressure. In the UK there is no obligation to measure, record or report to DECC the mercury concentrations in flared gas. There is, however, an obligation to report the quantity of gas flared (34). In 2009, the total quantity of flared gas in the UK was 1.3 billion m³: 2% of all natural gas produced (35). Although no measurements are reported for mercury concentrations in flared gas (due to the difficulty of sampling), it can be expected that the mercury concentration will be higher than in gas reaching the refinery due to losses during transportation (*see section 5*).

The reported concentration (as discussed in section 3.2) of 1 µg/Nm³ mercury in gas from the Albatross & Askeland fields of the North Sea is taken as the concentration in flared gas for the purposes of this study. This allows for an emission of 1.3 kg Hg/yr to be calculated from the estimated 1.3 billion m³ of natural gas flared at production platforms.

4.5 Offshore energy production

Oil and gas production platforms produce their own power, using onboard power stations fuelled by natural gas from the wells. This gas has not been processed and consequently will have higher mercury concentrations than the gas combusted after refining. This mercury will be released directly to the atmosphere when the gas is burnt.

Reported figures for usage of natural gas at production facilities are 5.6 billion m³/yr (36). Taking the 1 µg/Nm³ concentration used above for flared gas gives a total of 5.6 kg Hg/yr released to the atmosphere from gas usage offshore for marine platform power generation.

4.6 Overview

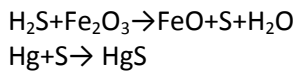
In terms of compiling a mercury budget, Table 1 summarises estimated total annual mercury releases from crude oil and natural gas extraction using publicly available data.

Table 1 - Estimated annual mercury release from crude oil and natural gas extraction prior to processing

	Quantity	Mercury concentration	Total mercury release (kg Hg/yr)	Type of release
Drilling Waste	29,200 tonnes	400-750 µg/kg	12-22	Solid
Produced Water	197 billion litres	0.94 µg/litre	186	Liquid
Offshore Gas Flaring	1.3 billion m ³	1 µg/Nm ³	1.3	Atmospheric
Own Usage at Production platforms	5.6 billion m ³ /yr	1 µg/Nm ³	5.6	Atmospheric

5. Release of mercury during transportation

The mercury content of natural gas is reduced during transportation due to processes such as adsorption onto metal surfaces and volatile losses. Chemisorption occurs as mercury reacts with, and is bound to, metal surfaces such as steel pipelines, container walls and pipes within processing facilities. For example, measurements on natural gas before and after passing through a single 100km pipeline showed the mercury concentration decreasing from ~50 to ~20 µg/Nm³; a 60 % decrease (7). The reaction is catalysed by the presence of H₂S in trace quantities, and driven by the following reactions (7):



In April 2011 there were 15,407 km of pipelines on the UK continental shelf (37), primarily transporting offshore crude oil and natural gas to onshore terminals. Of concern is that mercury is described as being able to penetrate up to 1 mm into pipeline walls (9), and this chemisorbed mercury can be easily remobilised over extended periods of time thereby contributing to the mercury burden of the hydrocarbon being transported (2).

Many smelters set a 2000 µg/kg limit on mercury in scrap steel to avoid damage to the off-gas clean-up filters – with higher concentrations requiring disposal as hazardous waste (9). The difficulties in disposing of material classified as hazardous waste means that some natural gas pipelines set entry specifications that limit mercury content (e.g. the Frigg pipeline, 38). This requires the installation of a mercury removal process prior to gas entering the pipeline, upstream of the refinery process. As an approximate calculation to establish an upper bound on the mercury retained within the pipeline network, if one assumes 2000 µg/kg mercury absorbed up to a 1mm depth across the whole pipeline system, an average pipeline diameter of 0.27 m (37) and density of 8 tonnes/m³, this would suggest that up to 207 kg⁽⁵⁾ of mercury could be absorbed on UK pipeline walls.

Distinct from mercury chemisorbed into pipeline walls is mercury rich sludge which is removed from pipelines via “pigging”; effectively rolling a large ball down the pipeline in the gas stream collecting the sludge that has accumulated. While the waste collected from the “pig” is mercury rich, the quantities are very small and the contribution to national mercury budgets considered negligible (4). The concentrations of mercury, and methods of disposal, associated with “pigging” are unclear.

In addition, vents on oil tanks release methane to the atmosphere during storage and transportation (4). This will contain volatile elemental mercury from the crude oil with which it is in equilibrium, providing another poorly constrained source of mercury to the atmosphere. It is extremely difficult to estimate mercury release from this process. There will also be volatile losses of mercury throughout transport from both natural gas and crude oil. Consequently, many challenges are faced when trying to quantify mercury losses during transport.

⁽⁵⁾ Volume of absorption = approx. (15.407E+06 m)*(1.00E-03 m)*0.84 m = 12941.88 m³
 Mass of pipeline with absorbed mercury = (12941.88 m³)*(8000 kg/m³) = 1.04E+8 kg
 Mass of mercury = (2000 µg/kg)*(1.04E+8 kg) = 2.07E+11 µg

6. Release of mercury during processing

6.1 Crude oil processing

Oil refining consists of two principal initial steps, the primary and vacuum distillations. These separate the crude oil into product streams of different density, which are then treated and cleaned to saleable products. However, the full process is complex and highly variable from refinery to refinery. Unlike gas processing, which simply treats and separates the raw products, oil refining includes molecular transformations to produce saleable products, and to increase the proportions of those most in demand. A typical crude oil refinery process is shown in Figure 2.

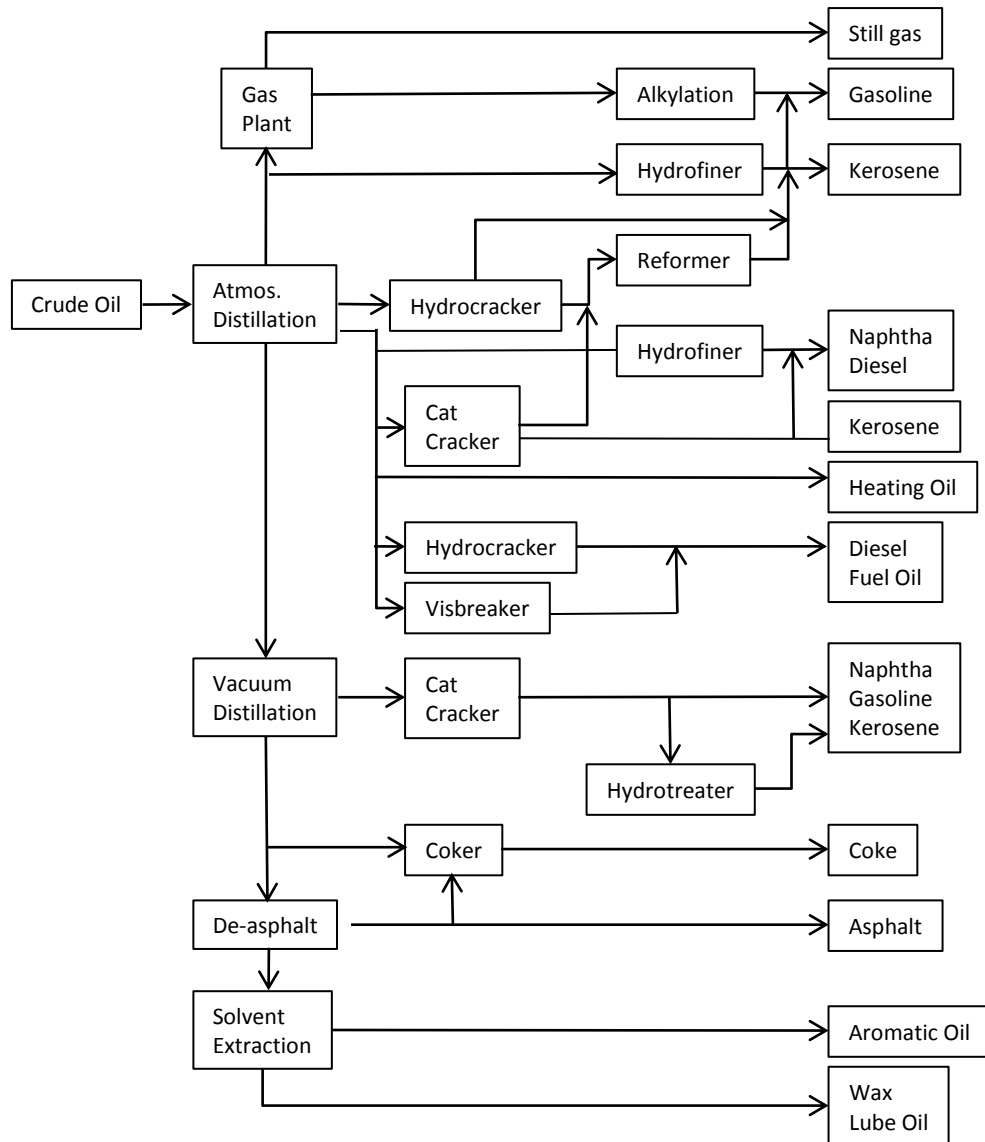


Figure 2: Schematic of a typical crude oil processing plant. Reproduced from (4)

Crude oil refineries produce three waste streams: atmospheric, solid and liquid waste. Atmospheric emissions come from plant processes including fuel use, gas flaring, coke calcining and asphalt blow. Solid wastes include tank bottom sludge, slop oil, spent catalyst and filter cake from treatments. Wastewater associated with the process is discharged to the environment (4). While little data exists on mercury release in the UK from oil refineries, parallels may be drawn with the rest of the world. A comparison of the

distribution of mercury in USA refineries illustrates extensive variation in product and waste stream estimates (Table 2). The extent to which this reflects variations in the refinery process or variations in crude oil composition is not known.

Table 2 – Distribution of mercury at USA crude oil refineries from available data sources

	Percentage of total mercury in product or waste stream		
	United States Environmental Protection Agency (USEPA), mass balance of USA refineries (4)	Minnesota Pollution Control Agency, mass balance of Flint Hills Refinery, Minnesota, USA (39) ⁽⁶⁾	Western States Petroleum Association, 5 San Francisco Bay petroleum refineries, USA (40)
Wastewater	3%	N/A	0.4%
Atmospheric emissions	23%	23%	8%
Solid Waste/ Sulphur by-product	15%	24%	79%
Other/Unaccounted	0%	37% ⁽⁷⁾	0%
Refined Products	59%	13%	13%

Using the previous estimate of 270-820 kg /yr for mercury entering UK crude oil refineries, taken together with the data presented in Table 2, allow the fate of mercury during crude oil processing in the UK to be estimated (Table 3).

Table 3 – Estimated mercury in outputs streams from UK crude oil refineries

	Estimated percentage of total mercury in waste/product stream	Estimated total mercury in stream (kg Hg/yr)
Crude Oil Input	-	270-820
Wastewater	0.4-3%	1.1-25
Atmospheric emissions	8-23%	22-190
Solid Waste	15-79%	41-650
Refined Products	13-58%	35-480
Total Waste (atmospheric, solid and water)	42-87%	110-710

Our calculations predict 35-480 kg Hg/yr will remain in refined products, while estimates from published concentrations in these products and UK usage (see section 4.4 and annex 5) predict 140-340 kg Hg/yr to remain in these products. These results are broadly consistent.

In the USA, the mercury concentration of refinery wastewater is estimated to be < 1µg/litre, and is positively correlated to crude oil mercury concentration (4). Most of the mercury in refinery wastewater comes from the desalting process, as the crude oil is bought into contact with water. As in primary separation, suspended and ionic forms of mercury are most likely to enter the water in this process (4). It is suggested that a typical refinery process produces 45-68 litres of wastewater per barrel of oil (159 litres) produced (4). Assuming crude oil to have a density of 0.8 kg/litre, and wastewater a density of 1 kg/litre, the 70.1 million tonnes of crude oil processed in the UK annually fills 0.55 million barrels and is associated with 25 to 37 million litres of

⁽⁶⁾ Percentages sum to 97%, even including the mass described as unaccounted for.

⁽⁷⁾ Author's note: Assumed to be within a waste stream as not in refined products.

wastewater. At a concentration of <1 µg/litre, <37 kg Hg/yr is released directly to the environment in refinery wastewater. This is broadly consistent with the estimate in Table 3.

There are many different methods that may be used to remove mercury from refinery wastewater; for example, precipitation treatments with excess sacrificial ions added to drive the precipitation reaction of the target ions (41). The same system may be used to remove other heavy metals as well as mercury, although under UK regulations there is currently no obligation to do so. The low concentrations of mercury measured in refinery wastewater are explained by ionic mercury species being removed in the desalter, and the mercury is disposed of in the desalter sludge (4). Measurements of desalter sludge mercury concentrations in four U.S refineries provided concentrations ranging from 100-41,000 µg/kg. The variability can be explained by a combination of differing mercury concentrations in the crude oil, and differing refinery processes (4). No data on the mass of desalter sludge produced in the UK are available.

An additional release from the refinery process will come from fuel use at a refinery. Refineries tend to be powered by still gas and petroleum coke, as there is a strong financial incentive to use these since these are products for which there is the least demand. As both of these refined products are rich in mercury it is likely that a high proportion of atmospheric mercury release from the combustion of 'products' occurs at refineries. These emissions will be included within the total for emissions from refined products (see section 7.1). In the U.S.A, in 2000, 54% by mass of the fuel burnt at refineries was still gas, and 41% petroleum coke, providing an estimate of 1500 kg of mercury released in the USA in that year (4).

The UK National Atmospheric Emissions Inventory estimated in 2008 a 500 kg release of mercury to the atmosphere from petroleum refining in the UK, using emission data supplied by the UKPIA (United Kingdom Petroleum Industry Association) (42). It is unclear how this estimate was made, and whether it includes fuel usage at UK refineries. If fuel usage at refineries has not been included then this estimate is inconsistent with that produced in Table 3, being significantly higher than the upper estimate of 190 kg Hg/yr calculated.

The atmospheric mercury release reported in Table 3 is equivalent to 0.31-2.7 kg Hg per million tonnes crude oil, of the same order as the estimated 2.2-8.4 kg Hg per million tonnes crude oil based on reported atmospheric emissions from Australian refineries from 2001-2007 (43).

6.2 Natural gas processing

Gas processing plants do not subject the gas to any molecular transformations, but simply treat and separate the raw material into saleable products. Gas processing may be summarised as follows (4):

- Prior to entering the refinery the gas is treated to remove water using triethyleneglycol (TEG) or molecular sieve absorbents.
- The gas is cleaned through acid gas scrubbers.
- A mercury removal process may be included, in which case it will be deployed upstream of the cryogenic distillation stage.
- Cryogenic distillation involves cooling the gas in an aluminium heat exchanger. The gas is then progressively heated through a number of heat exchangers, allowing the individual products to be boiled off and separated in towers.
- The liquid product streams (condensate) are sent to petrochemical manufacturers or sold as LPG, while the gaseous product streams are sold to users as sales gas.

Mercury release to the atmosphere during natural gas processing occurs during flaring or combustion of natural gas, and through gas cleaning and drying. Additionally, mercury rich solid waste is also produced during processing.

Data from the St Fergus Gas Terminal (Total E&P UK Ltd) in Scotland provides an insight into the inputs and outputs of natural gas processing (Table 4).

Table 4 - St Fergus Gas Terminal inputs and outputs for 2008 (44)

Input		Output stream	
Gas	12.0 million tonnes	Sales Gas	11.6 million tonnes
Electricity	29 Gwh	Natural Gas	
		Liquids	460.9 tonnes
		Condensate	0 tonnes
		Flare Gas	7,740 tonnes
		Venting	7.17 tonnes
		Fuel Gas	18.9 tonnes

Should these figures be extrapolated across all UK gas processing plants to allow an estimate of the volume of gas flared and vented at UK processing plants then, with the St Fergus Terminal accounting for ~20% of UK processing (44), a total of 51,000 m³/yr of natural gas is estimated to be vented at terminals, and 55 million m³/yr flared. Taking the mean concentration of mercury in natural gas entering UK refineries of 16-20 µg/Nm³ (Annex 4.b) for flared and vented gas, one can determine the amount of mercury released to be 0.88-1.1 kg Hg/yr, and likely to be lower if the gas is flared after some degree of processing. These figures assume no mercury removal.

Mercury is highly mobile and bonds to metal surfaces with which it comes into contact. The implication is that any mercury that enters a gas processing plant will be distributed across process and waste streams (Table 5) (2).

Table 5 - Distribution of mercury in a Far Eastern plant lacking a mercury removal unit (2)

Process Stream ⁽⁸⁾	Mercury (kg/yr)	Percentage (%) distribution across streams
Raw Gas	220	-
Acid Removal Vent	22	10 %
Dryer Vent	3	1.4 %
Condensate	45	20.5 %
Sales Gas	150	68 %

Consequently, the most important losses associated with natural gas processing come from dryers and acid gas scrubbers, as most gas will pass through dehydration and acid gas removal stages prior to entering the processing plant itself.

Most commonly, dehydration uses glycol dryers which scrub the gas at line pressure and ambient temperature with mono or triethylene glycol (17). Clean (“rich”) glycol accumulates mercury, water and other trace contaminants as it strips the gas. This dirty (“lean”) glycol is then put through heat exchangers to drive off accumulated impurities, which are either vented or flared. Either way, bound mercury is released directly to the atmosphere (“Glycol vent” or “MS vent” in Figure 3). While the solubility of mercury in glycol is low, high concentrations are found in the vented gas (up to 150 µg/Nm³). A potential explanation is that mercury is in suspension attached to fine sulphur particles, or alternatively that the gas contains hydrocarbon residues (17).

⁽⁸⁾ The plant has a capacity of 0.52 billion m³/yr (0.36 million tonnes/yr). The mercury concentration in the raw gas varied from 0.01-70 µg/Nm³ (2).

When a low water dew point is required, molecular sieves are often used (17). These metal sieves quickly become loaded with mercury (as mercury is absorbed onto metals) and other contaminants. These contaminants are then removed by hot gas pumped through the sieve. This “regeneration gas” may be burnt as fuel or released directly to the atmosphere. Either way the mercury is released to the atmosphere. Stripper gas from acid gas removal units is also incinerated, releasing any contaminants (including mercury) directly to the atmosphere.

There is large variability in the losses of mercury at each stage of natural gas processing as an investigation into the concentration of mercury measured in product and waste streams at six different, unspecified, refineries demonstrated (Figure 3). Since the volumes in the study were not reported it is not possible to convert this figure into a mass balance. However, it is notable that the proportions of mercury removed at various stages and entering the finished product and condensate vary from plant to plant. The variation is large, with the mercury concentration of the sales gas varying from 0.02% (at plant B) to 60% (at plant D) of that of the raw gas. At plant F (the only plant to feature a mercury removal unit) there is still some loss of mercury within the plant, with the sales gas having just 20% of the mercury concentration of the raw gas entering the refinery⁽⁹⁾.

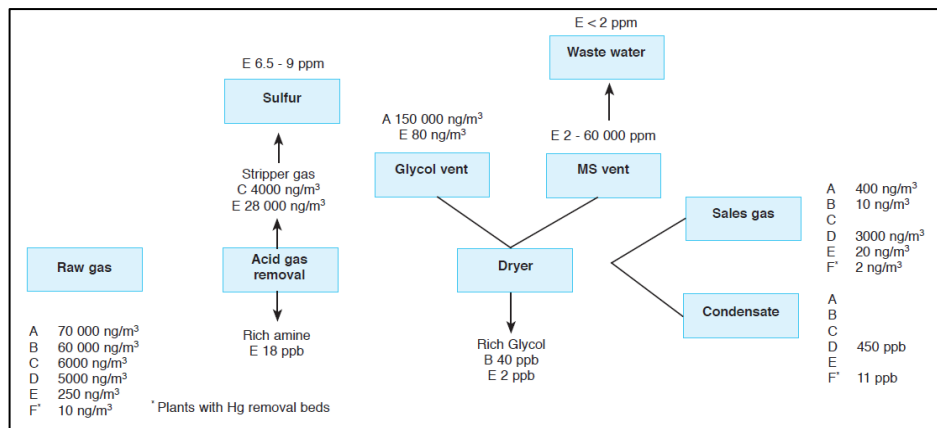


Figure 3: Flow diagram of mercury concentration in production and waste streams from 6 different, unspecified, refineries from the UK, North Africa, the Far East and South America. Reproduced from (2).

Estimates in the literature for the quantity of mercury lost during natural gas processing range from 11% of the total mercury input to the process (as shown in Table 5) to as much as 50-60% of the mercury accumulated at the bottom of the glycol absorbers, and 15-20% removed in acid gas scrubbers (7, 45). Consequently, an estimated 11-80% of the mercury contained in the natural gas entering a processing plant is lost to the atmosphere during processing. Therefore, using the 50-1770 kg Hg/yr mercury budget of UK natural gas (see section 3.2 and Annex 4.b) this suggests atmospheric releases of 5.5-1416 kg Hg/yr. However, this estimated range is dependent on the presence or absence of mercury removal units. The location at a refinery where a mercury removal unit is installed varies; it may be installed before the gas is dried, after the gas is dried, or after both the drying and acid gas removal processes (9). Contaminants in gas cause difficulties for mercury removal units leading to many removal units being positioned after cleaning of the gas – allowing for mercury losses to the atmosphere.

A 2005 UK Department of Trade and Industry report lists the facilities installed at the UK’s major Natural Gas terminals (Table 6). Of the UK’s 7 major natural gas terminals in 2005, only 2 were listed as having mercury removal capabilities. The locations of the mercury removal units are not specified.

⁽⁹⁾ The reported concentration of 0.01 µg/m³ (0.014 µg/kg) in the raw gas suggests the unit to be located prior to the sampling point. The 80% loss during processing is in addition to intentional mercury removal.

Table 6 – Facilities reported as installed at major UK Natural Gas Processing Plants in 2005. Y-present, N-not present. Reproduced from (46).

	Bacton	The'd'pe	Easing'n	Teeside	St. Fergus	Barrow	Pt of Ayr Burton P
No. of Terminals	4	1	2	2	3	2	1
Storage Facility	N	N	Y	N	N	N	N
Dehydration	Y	Y	Y	Y	Y	Y	Y
H/C Dewpointing	Y	Y	Y	Y	Y	Y	Y
NGL recovery	N	N	N	Y	Y	N	N
CO ₂ Removal	N	N	N	N	Y	Y	N
H ₂ S Removal	Y	N	N	Y	Y	Y	Y
RSH Removal	N	N	N	N	N	Y	Y
N ₂ Removal	N	N	N	N	N	Y	Y
Mercury Removal	N	N	N	Y	N	Y	N
N ₂ Ballasting	N	N	N	Y	Y	N	N
LPG Injection	N	N	N	N	Y	N	N

A possible explanation for the lack of mercury removal units at some UK natural gas processing plants is that mercury may be removed upstream to protect pipelines as explained earlier (see section 5). For example, a maximum mercury content of 0.01 µg/Nm³ is set for natural gas entering the Frigg Pipeline to the St Fergus Terminal (38), whereas the North Sea terminal for the Central Area Transmission System (CATS) uses a fixed bed mercury removal unit to remove mercury from several fields prior to transport to the Teeside refinery (47). In 2009 these two pipelines landed 13 billion m³ of natural gas (48), 26% of total UK production processed in the UK (48).

In the event that all UK natural gas undergoes mercury removal prior to all processing then atmospheric mercury releases would be negligible. Therefore, <1-1416 kg Hg/yr can be estimated to be released to the atmosphere from natural gas processing in the UK. The disclosure of the presence or absence, and locations, of mercury removal units in the UK and abroad is necessary to further constrain mercury releases from natural gas processing.

The disposal of mercury collected by a mercury removal system varies depending of the type of system used. Organic methods for removing mercury rely on the use of sulphur-impregnated activated carbon. The spent absorbent is difficult to dispose of as it is classified as hazardous waste and may not be sent to landfills. It must either be stored or be combusted to release the mercury. If the waste is combusted then mercury must be condensed, captured and disposed of. Inorganic methods involve the removal of mercury by amalgamation with a metal sulphide. The spent absorbent is recycled through metal smelters, with the mercury driven off through roasting at high temperatures (2). The mercury may then be condensed, captured and disposed of. Johnson Matthey Catalysts, the manufacturer of most mercury removal units in the UK, dispatches waste to accredited smelters and obtains a certificate of safe disposal on behalf of customers (17). It is thought that waste from natural gas cleaning in the UK is sent to mainland Europe for processing; “probably to the Netherlands” (49). The Netherlands estimated the sludge from natural gas cleaning processes to contain ~2 % mercury, and filtercake ~7 % (49). Where properly disposed of, this mercury should not be released to the environment.

7. Releases from the combustion of refined products

7.1 Crude oil

To estimate mercury releases from the burning of refined products in the UK, measurements of mercury concentrations from a variety of sources, and data from DECC, on the production, import and export of the major refined products have been used (Annex 5). Assuming that all mercury present in the refined product is released to the atmosphere on combustion, a total release of 140-340 kg Hg/yr can be calculated.

Furthermore, Annex 5 brings together measurements from a variety of sources worldwide, and where multiple sources were found for the same product a large range is invariably seen. Evidence for the variability noted is found in the mercury concentrations in gasoline and diesel of various origins (Figure 4). This results, at least in part, from differences in the refinery process and the mercury concentration of the crude oil.

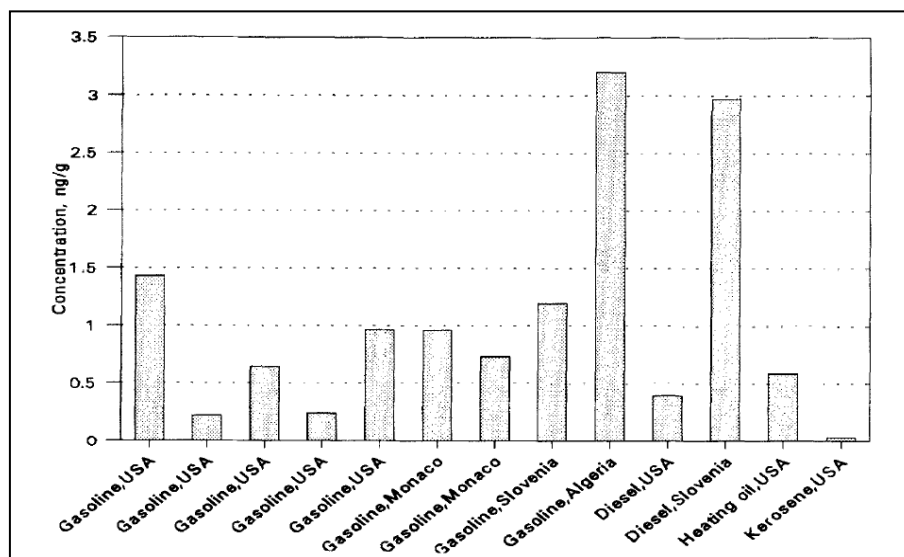


Figure 4: Mercury concentrations in gasoline and diesel of various origins. Reproduced from (50)

A second uncertainty arises from the lack of reported measurements of mercury concentrations in aviation fuels, usually kerosene, but sometimes kerosene/naphtha blends are also used for aviation fuel. Since Kerosene/Naphtha blends are likely to have a higher mercury concentration (Annex 5), the mercury concentration reported for aviation fuels in Annex 5 is potentially an underestimate.

A further assumption is that 100% of the mercury contained in products is released during combustion, but not all petroleum products are burnt (e.g. asphalts, lubricant oils and solvents). However it is possible that the mercury contained within such products is still released. For instance, asphalt is hardened and its melting temperature increased through asphalt blowing, a process which operates at 400-450°C, a high enough temperature to partially volatilise HgS (4). While research into potential losses from non-combusted refined products is lacking, it is likely that they are very low. As these processes will occur at factories acting as point sources, there is potential for accumulation in the local environment. A published map shows an asphalt plant at the centre of a “bull’s-eye” of mercury concentration in soil contours (51).

It is expected that, whatever the form of mercury in crude oil, the bulk in refined products will be elemental mercury as compounds are broken down by high temperatures during the refinery process. This volatile mercury is concentrated in the low-density LPG, gasoline, and naphtha product streams (17). Thermally stable species that resist volatilisation are found predominantly within the asphaltene fraction of crude oil,

concentrated in dense residual products such as petroleum coke and asphalt during refining. Likely species are HgS or HgSe (3).

Liquefied Petroleum Gas (LPG) is produced either as a product of crude oil refining or from the separation of natural gas; and is included in Annex 5 under petroleum gases, irrespective of its origin.

7.2 Natural Gas

It is extremely difficult to estimate the mercury concentration in processed natural gas because the locations and presence/absence of mercury removal units is unclear. Any gas that has passed through a mercury removal unit will have its mercury concentration reduced to $<0.01 \mu\text{g}/\text{Nm}^3$ (34). It is suggested that this is invariably the case (52), although the information to confirm this for the UK is not in the public domain. Assuming a concentration of $<0.01 \mu\text{g}/\text{Nm}^3$ in the 90.4 billion m^3 of natural gas passing through UK refineries each year (Annex 4.b) leads to the conclusion that $<1 \text{ kg Hg}$ is released from the combustion of refined products. If gas is sold and combusted without mercury being removed then this mass will be substantially higher. With 11-80 % of mercury contained in the natural gas lost to the atmosphere during processing, the remainder would be emitted during combustion.

8. Past and future trends

8.1 Overview

Figure 5 (overleaf) summarizes estimated annual mercury releases in the UK from oil and gas extraction, processing and use in 2009

Legend for Figure 5 overleaf

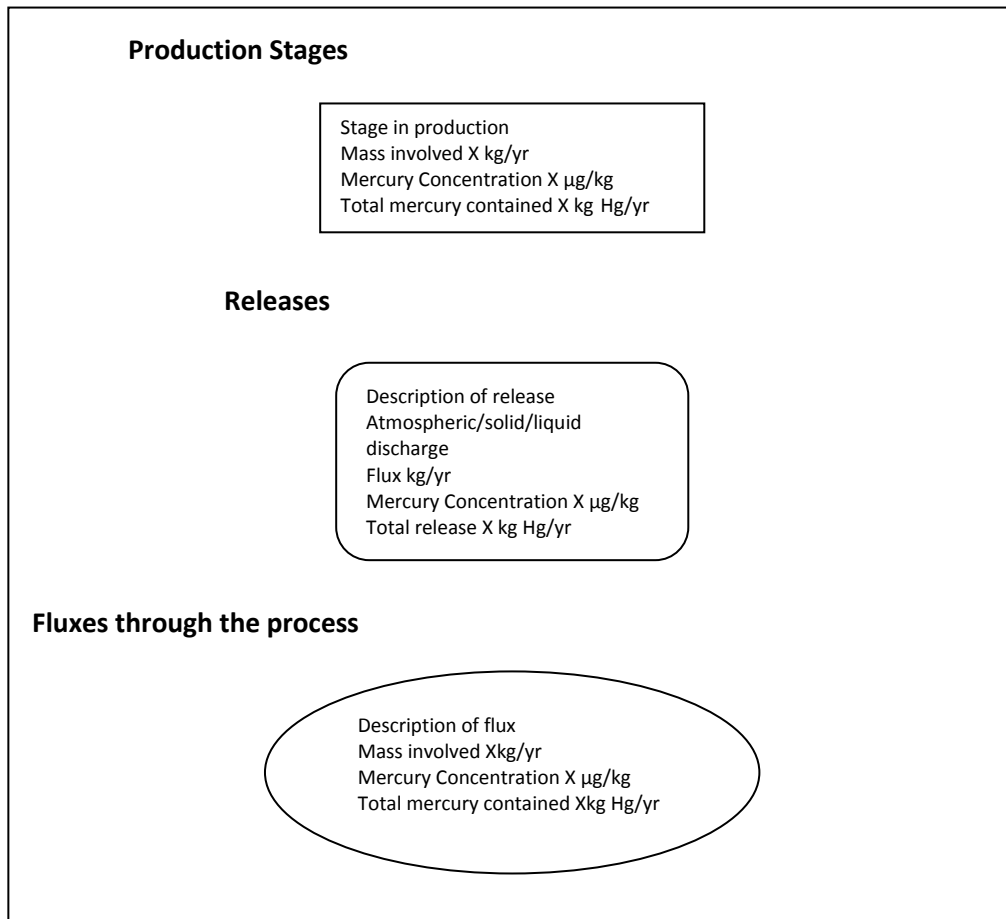
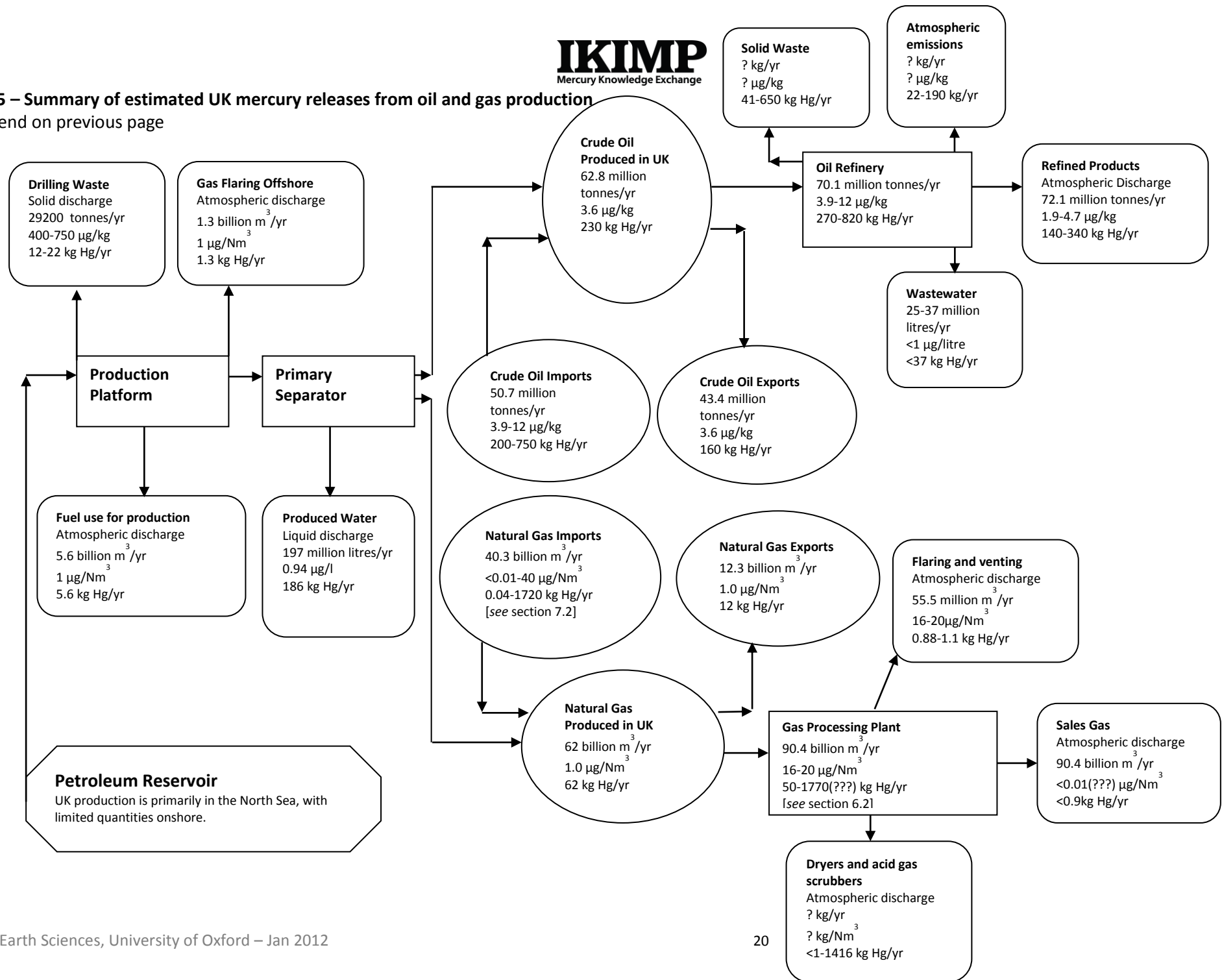


Figure 5 – Summary of estimated UK mercury releases from oil and gas production

See legend on previous page



8.2 Crude Oil

Historical data on UK oil and gas usage and imports are readily available e.g. (53), but estimates of trends in associated mercury releases is complicated by the fact that variations in crude oil mercury content are many times greater than recent variations in UK usage. Changes in provenance therefore dominate changes in usage. Estimates of the UK crude oil mercury budget (defined as total mercury in UK crude oil imports and UK production) since 1950 are given in Annex 6, with Figure 6 presenting these data graphically. The upper and lower bounds represent high and low estimates for Norwegian crude oil as discussed in section 3.2. The recent (post 1970's) increase shown on the graph occurs despite a fall in oil usage, reflecting the move towards higher mercury imports.

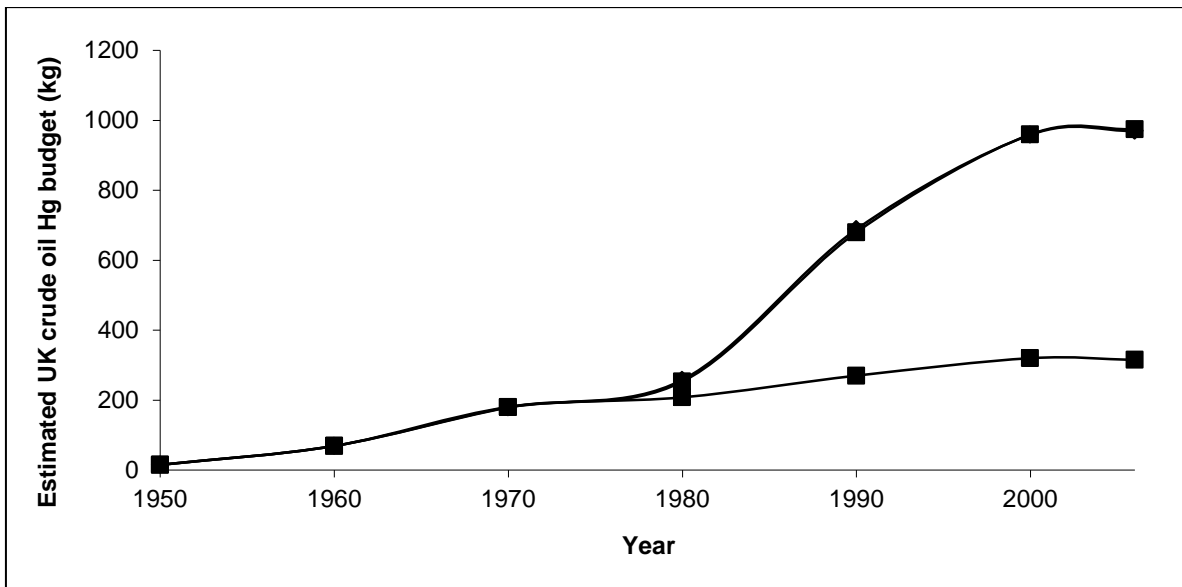


Figure 6: Maximum and minimum estimated mercury budget of crude oil refined in the UK (black lines). See Annex 6 for calculations.

It has been suggested that as North Sea oil reserves are depleted the UK is likely to increase the proportion of crude oil that is imported. Consequently, by 2020 crude oil imports could rise by 45-60% (54). Any future analysis to construct a mercury budget for UK crude oil must take the potential rise in imports into account.

8.3 Natural Gas

Historical UK natural gas consumption figures are shown in Table 7.

Table 7 - Historical UK inland natural gas usage

Year	Gas Usage (billion m ³ /yr) (53)
1970	12
1980	49
1990	56
2000	105
2009	90

Were mercury releases per billion m³ natural gas constant, then total releases would correlate to natural gas consumption and a rapid rise through the 1970's, reaching a peak early this century, would be seen. However, the variation between natural gas reservoirs, and the uncertainty regarding the location of mercury removal units at UK processing plants, impacts significantly on the estimate of the annual release of mercury from natural gas usage. Therefore, recent and on-going changes to the UK natural gas market have implications for future mercury releases which must be considered for future analyses:

1. LNG imports to the UK commenced in 2005, with the opening of the Isle of Grain LNG import facility. Since then there has been a rapid growth in UK LNG imports to a 25% share (by calorific content) of natural gas imports in 2009. In 2009 two new LNG facilities opened, at Milford Haven, South Hook and Dragon. LNG is described by DECC as being "increasingly important in meeting the UK's gas demand" (36). Owing to the need for mercury to be removed from LNG prior to liquefaction the amount of mercury entering the UK in LNG will be negligible.
2. The Balgzand-Bacton Pipeline opened in 2006, and consequently there was a rapid rise in natural gas imports from the Netherlands to ~5.6 billion m³/yr by 2007 (55). While the Netherlands do have some North Sea gas reserves, much Dutch natural gas comes from the adjacent Groningen province (~50%) and smaller onshore fields. As discussed above, gas from the Groningen deposits has been reported as having high mercury concentrations. Using the 180-200 µg/Nm³ range reported (9) results in 1130-1260 kg Hg/yr in natural gas imported from the Netherlands, an order of magnitude greater than that in UK production. However, mercury may be removed from the gas prior to its transportation to the UK: this is a key area of uncertainty that needs to be addressed in further studies
3. The provenance of UK natural gas is likely to continue to change. It is suggested that by 2020 >70% of UK natural gas could be imported (54), and will have an important, but unpredictable, effect on the UK natural gas budget.

9. Contribution to the UK mercury budget

Total Environmental Releases

Table 8 summarises the total estimated annual solid, liquid and atmospheric releases from the oil and gas industry, including the combustion of refined products. Releases on the production platform, prior to the primary separator, are included separately.

Table 8 - Estimated UK total mercury environmental releases from oil and gas production (kg/yr)

Form	Production Platform	Natural Gas	Crude Oil	Total
Solid	12-22	0 ⁽¹⁰⁾	41-650	53-672
Liquid	186	Negligible	<37	223
Atmospheric	7	<1-1416 ⁽¹¹⁾	162-530	170-1954
Total	205-215	<1-1416	240-1217	446-2849

Considering the atmospheric emissions, which dominate at the higher end of the ranges allowed by the reviewed data, mercury as a volatile element achieves a relatively long atmospheric residence time of 0.5 to 2 years, allowing it to mix extensively in the atmosphere and be deposited over a wide area (56). Any attempt to assess the large-scale significance of mercury release to the environment from oil and gas must look at the relative contribution this industry makes to the overall total and anthropogenic mercury emission budgets. The United Nations Environmental Program in 2005 estimated total worldwide anthropogenic mercury release at 1.23-2.89 million kg Hg/yr, of the same order as natural emissions (57). The 446-2849 kg Hg/yr total (Table 8) estimated to be released to the environment from UK oil and gas production is therefore a very small proportion of worldwide release, although still a significant proportion of UK release, as discussed below.

Recent efforts to reduce mercury emissions from coal combustion for power generation have increased the relative contribution of oil and gas to both the UK and global anthropogenic mercury budgets. These measures are expected to be on-going in both the UK and worldwide through anticipated United Nations legislation limiting the use of mercury. Within the UK, estimates of atmospheric emissions of air pollutants are compiled in the national atmospheric emissions inventory (NAEI) (42). It is difficult to judge the extent to which mercury emissions from crude oil and natural gas are included in NAEI estimates, even when broken down by source (Figure 7). Due to recent large reductions, primarily relating to legislative changes, the upper end of the range of atmospheric emissions of mercury from the oil and gas industry estimated in this report is a significant fraction (3-31 %) of the total 6220 kg calculated for 2008.

⁽¹⁰⁾ Solid, mercury containing waste from natural gas purification is primarily that produced by mercury removal units, which is disposed of safely.

⁽¹¹⁾ This value is entirely dependent on the presence, and position, of mercury removal units. In the absence of mercury removal all mercury will be released to the atmosphere during processing and combustion.

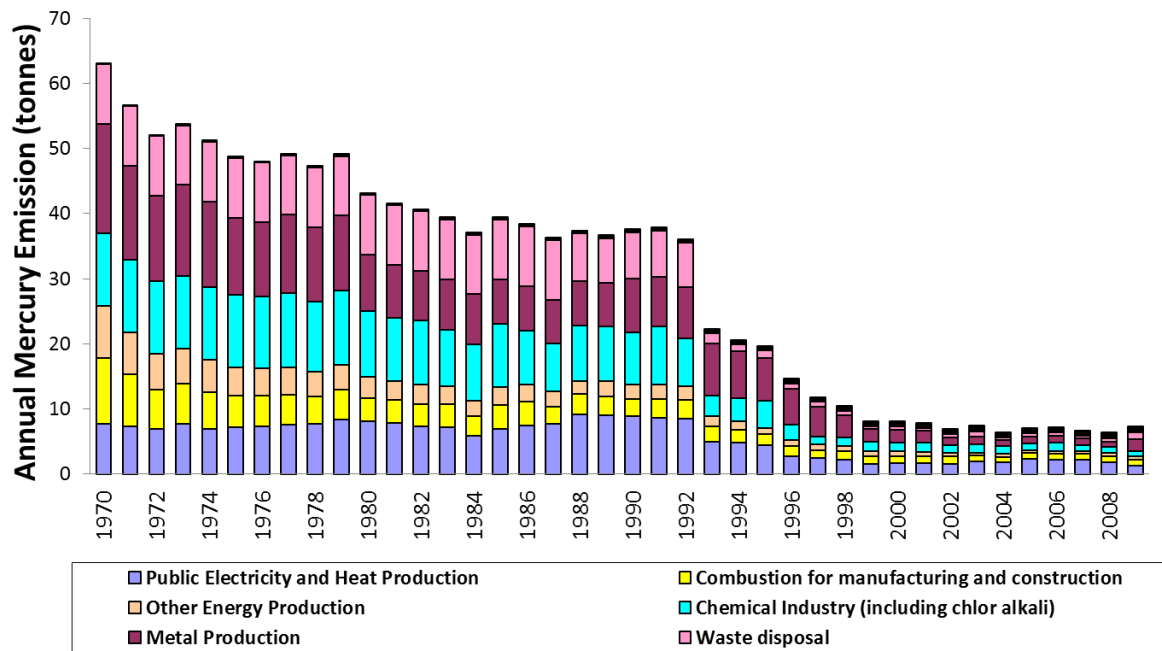


Figure 7: Estimates of total UK mercury released to the atmosphere. (42).

10. Conclusions and recommendations

Reported values of global mercury concentrations range from 0.1-20,000 µg/kg in crude oil and 0.05-5000 µg/Nm³ in natural gas. The mercury is believed to largely accumulate through secondary geological processes, with high concentrations the result of exceptional geological conditions.

Published data for the UK indicate that 205-215 kg/yr of mercury released to the environment is associated with **extraction** of oil and gas in the UK sector of the North Sea, although there are likely to be significant year-on-year variations. Of this estimated release, 186 kg Hg/yr is discharged to the North Sea with produced water and 7 kg Hg/yr is released to the atmosphere from gas flaring and usage at the production platform. Approximately 12-22 kg Hg/yr is discharged to the North Sea in barite based drilling wastes.

There is likely to be loss of mercury during **transportation** of natural gas from well-head to refinery through processes such as chemisorption onto metal pipeline walls. It was not possible to quantify this loss with the information currently publicly available. To better understand the amounts lost would require a study of variations in mercury concentration throughout transport, taking into account temporal changes as processes of sorption and de-sorption of mercury on metal surfaces move towards equilibrium.

Up to 820 kg Hg/yr is estimated to be present in crude oil refined in the UK, of which, 750 kg Hg/yr is imported, primarily from Norway. This estimate is based on extremely limited data, and dominated by a questionable estimate of the mercury content of Norwegian crude oil. Using a lower value for Norwegian oil (equal to that measured for UK oil, and consistent with an independent estimate), would reduce the total mercury budget to 270 kg Hg/yr. A more accurate assessment of this figure would require a volume weighted statistical analysis of mercury concentrations in crude oil arriving at UK refineries, similar to that performed for the USA (see reference 5). In the meantime, a review of the mercury content of Norwegian crude oil would be a useful first step.

The crude oil **refinery process** varies between refineries, making it difficult to accurately constrain mercury releases. Extrapolating from published mass balances suggests that although there are annual UK mercury releases to the environment from wastewater (<37 kg Hg/yr) and solid wastes (41-650 kg Hg/yr), the main emission pathway may be to the atmosphere, both during processing and from the combustion of refined products (total atmospheric flux from crude oil refineries of 162-530 kg Hg/yr). Mercury speciation in crude oil is complex with a variety of species detected. The different species behave differently during refining, with volatile forms partitioning into low-density fractions such as liquefied petroleum gas (LPG), and thermally stable species that resist volatilisation partitioning into high density residual products such as petroleum coke.

Assuming no mercury removal prior to transport of imported natural gas to the UK, 1430-1770 kg Hg/yr is estimated to be present in natural gas refined in the UK in 2009, primarily in elemental form. Of this, 1380-1720 kg Hg/yr was contained in imports, mainly from the mercury rich Groningen gas field of the Netherlands. It may be that a substantial fraction of this mercury is removed in gas treatment plants before transportation by pipeline as natural gas (where there may be further reductions in mercury content), or as LNG (where mercury may otherwise cause problems on liquefaction). The existence and effect of these treatment plants is a key area of uncertainty, having a major impact on the UK's mercury budget, and is a priority area for any future study.

Rapidly growing LNG imports (standing at 25% of UK natural gas imports in 2009) and importation of natural gas from the Groningen field via the Balgzand-Bacton Pipeline which opened in 2006 (and now accounting for 15 % of UK gas imports) have had a significant impact on the UK's mercury budget associated with natural gas. Projections of future mercury budgets need to have particular regard to such imports and their mercury contents.

Losses from natural gas during processing and use are entirely dependent on whether and where mercury removal units are installed. It is considered likely that all natural gas has mercury removed prior to, or during, processing. Within the processing plant this may be before or after acid gas scrubbing and drying. These two processes release up to 80% of the mercury present in the natural gas to the atmosphere, consequently atmospheric mercury releases from natural gas processing range from <1-1416 kg Hg/yr. The quantification of releases of mercury from natural gas processing and use in the UK requires the existence and positions of mercury removal units to be disclosed.

The National Atmospheric Emissions Inventory estimates a total atmospheric release of mercury of 6220 kg in 2008. Atmospheric releases from oil and gas are estimated to make up 3-31 % of this total. Further work is necessary to constrain this important, poorly understood and under studied, proportion of the total UK mercury budget.

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Annexes

Annex 1 –Mercury content in crude oils imported to the U.S.A by country and region in 2004 (8)

Country	Average Mercury ($\mu\text{g}/\text{kg}$)	Number of Samples
Algeria	13.3	2
Angola	1.6	2
Argentina	16.1	1
Australia	0.8	1
Brazil	1.1	2
Canada	2.1	32
Chad	1.2	2
Columbia	3.4	7
Ecuador	1.8	6
Gabon	0.5	1
Guinea	0.3	1
Iraq	0.7	6
Ivory Coast	0.3	1
Kuwait	0.8	4
Mexico	1.3	9
Nigeria	1.8	12
Norway	19.5	2
Russia	3.1	4
Saudi Arabia	0.9	14
Thailand	593.1	1
UK	3.6	3
USA	4.3	42
Venezuela	4.2	12
Viet Nam	66.5	2
Region	Average Mercury ($\mu\text{g}/\text{kg}$)	Number of Samples
Africa	2.7	21
Asia	220.1	4
Europe	8.7	9
Middle East	0.8	24
S. America	5.3	28

Annex 2.a – Estimate of the mercury content of imported crude oil processed in the UK annually. Created by multiplying UK imports by country (55) and estimated Hg concentration by country (8)

Country of origin	Imports to UK (million tonnes) (55)	Mercury concentration (µg/kg) (8)	Total Mercury (kg)
Iran	0.56	Iran concentration unreported.	0.45
Other Middle East	0.24	(Middle East mean 0.8)	0.19
Algeria	1.2	13.3	16
Angola	0.95	1.6	1.5
Libya	1.9	Unreported. (Africa mean 2.7)	5.1
Netherlands	0.038	Unreported. (Europe mean 8.7)	0.33
Nigeria	1.8	1.8	3.2
Norway	35	3.6-19.5 (see section 3.1)	130-680
Russia	4.1	3.1	13
Venezuela	0.96	4.2	4.0
Other (non-Middle East)	3.9	Unknown. (Mean [†] = 5.6)	22
Total/mean	50.7	Geometric Mean = 3.9- 15[‡]	200-750

[†] Taken as the arithmetic mean of European (8.7 µg/kg), African (2.7 µg/kg) and South American (5.4 µg/kg) regional averages as reported in (8).

[‡] 200-750kg/50.7 million tonnes = 3.9-15 µg/kg

Annex 2.b – Estimated mercury concentration in crude oil processed in the UK annually

UK crude oil production (million tonnes) (18)	UK crude oil exports (million tonnes) (55)	Net UK Production (million tonnes)	Mercury budget of net UK crude oil production [using 3.6 µg Hg/kg] (kg) (8)	Crude oil imports (million tonnes) (see Annex 2.a)	UK mercury budget of imports, kg) (see Annex 2.a)	Total crude oil processed at UK refineries – net production and imports (million tonnes)	Total mercury budget of crude oil received at UK refineries (kg)
62.8	43.4	19.4	70	50.7	200-750	70.1	270-820

Geometric mean Hg concentration in crude oil processed in the UK = 270-820 kg / 70.1 million tonnes = 3.9-11.7 µg/kg

Annex 3 –Mercury content in natural gas by field (9) and region (58).

Field[†]	Mercury Concentration ($\mu\text{g}/\text{Nm}^3$)
Albatross & Askeland (Norwegian North Sea)	1
Arun (Indonesia)	250-300
Goodwin, N Rankin & Perseus (Australia)	38
Groningen (Onshore Netherlands)	180-200
Saih Nihayda & Saih Rawl (Oman)	60
Region[‡]	Mercury Concentration ($\mu\text{g}/\text{Nm}^3$)
Algeria	50-80
Eastern Europe	1-2x10 ³
Far East	0.02-193
Germany (Northern)	15-450
Germany (Southern)	<0.1-0.3
Indonesia (Sumatra)	200-300
Middle East	1-9
North America	0.005-40
South America	69-119

[†] Sampling location not specified

[‡] Wellhead concentration

Annex 4.a – Imports of natural gas and LNG to the UK by country. Total mercury estimated by multiplying total UK imports (55) with estimates of mercury content in natural gas by country (58, 9)

	Country	Volume of imports to the UK (billion m ³) [†] (55)	Estimated Hg concentration µg/Nm ³ (58, 9)	Estimated total Hg (kg)
Natural Gas by pipeline	Via Belgium [‡]	0.7	Unreported. (N. Sea concentration of 1 used)	0.7
	Netherlands	6.3	180-200	1130-1260
	Norway	23.3	1	23
LNG Shipped [♠]	Algeria	1.7	50-80	85-140
	Australia	0.1	38	3.8
	Egypt	0.5	Unreported. (Typical Middle East concentration of 1-9 used)	0.5-4.5
	Norway	0.2	1	0.2
	Qatar	5.5	Unreported. (Typical Middle East concentration of 1-9)	5.5-50
	Trinidad and Tobago	1.9	Unreported. (South America: 69-119 used)	130-230
	U.S.A	0.1	North America: 0.005-40	0.0005-4
	Total	40.3	Geometric mean concentration = 32-40 µg/Nm³ [♠]	1380-1720

[†] Values reported in GWh (Gigawatt hours). Converted based on 11.117 kWh/m³. LNG is reported by the volume of natural gas in standard conditions represented – the actual volume will be ~600 times lower.

[‡] Via the Bacton-Zeebrugge Interconnector. Belgium has no natural gas reserves. The primary source of gas imports via Belgium is not reported –North Sea values have been assumed. Eastern European, German or Russian sourced natural gas may make up some of the imports and contain a higher mercury content.

[♠] Volume represented in natural gas.

[♠] Calculated as (1300-1600 kg/40.3 billion m³ = 32.3-39.7 µg/Nm³)

Annex 4.b – Estimated mercury in natural gas processed in the UK annually

UK natural gas production (billion m ³) (36) [†]	UK natural gas exports (billion m ³) (36)	Net UK Production (billion m ³)	Mercury budget of net UK natural gas production [using 1.0 µg/Nm ³] (kg) (9)	UK natural gas imports (billion m ³) (see Annex 4.a)	UK mercury budget of imports (kg) (see Annex 4.a)	Total natural gas processed at UK refineries – net production and imports (billion m ³)	Total mercury budget of natural gas received at UK refineries (kg)
62.4	12.3	50.1	50	40.3	1380-1720	90.4	1430-1770

Geometric mean Hg concentration = 1430-1770 kg/90.4 billion m³ = 16-20 µg/Nm³

[†] Values reported in GWh (Gigawatt hours). Converted based on 11.117 kWh/m³

Annex 5 – Estimates of mercury release from refined products of crude oil. Atmospheric Hg emissions found by multiplying total UK product use (18) with measurements of mercury concentration in refined products (see table for sources).

Fuel	Net demand (million tonnes) (18)	Estimates of Mercury Content ($\mu\text{g}/\text{kg}$)	Range ($\mu\text{g}/\text{kg}$)	Estimate of atmospheric mercury emissions (kg)
Petroleum Gases, LPG (incl. Ethane, Propane, Butane)	7.2	LPG: $2.5 \pm 0.047^\dagger$ (21)	2.5	18
Naphtha	1.0	37 ± 6 (59) $3-60$ (17)	3-60	3.0-60
Motor Spirit	15.8	$0.82 \pm 0.09^\ddagger$ (21) $0.41 \pm 0.15^\phi$ (60) 0.22 \pm 0.02 to 1.43 \pm 0.06 U.S.A (50) 3.2 Algeria (50) 0.6-1.3 $^\psi$ Brazil (61) 0.22-3.2 (17) 0.08-1.4 (62)	0.08-3.2	1.3-51
Aviation Turbine Fuel (ATF-Kerosene)	11.5	No data reported. Blends are Kerosene or Kerosene/Naphtha based. Since, kerosene mercury concentrations used: this may underestimate total releases.	0.04	0.46
Burning Oil (Kerosene or paraffin)	3.7	Kerosene: 0.04 ± 0.004 (50)	0.04	0.15

[†] Reported as 1230.3 \pm 23.5 ng/L. Conversion assumes a density of 0.5 kg/litre.

[‡] Reported as 571.1 \pm 4.5 ng/L. Conversion assumes a density of 0.7 kg/litre.

^ϕ Reported as 284 \pm 108 ng/L. Conversion assumes a density of 0.7 kg/litre.

^ψ Reported as 0.4-0.9 $\mu\text{g}/\text{litre}$. Conversion assumes a density of 0.7 kg/litre.

Gas/Diesel Oil	25.4	0.034±0.026 (63) 0.23±0.0033 ^γ (21) 0.084±0.046 ^κ (60) 0.40±0.03 (50) 0.4-3 (17) 0.05-0.34 (62)	0.034-3	0.86-76
Fuel Oils	2.7	3.5±0.74 (63) 0.67 ^ω (64) 10 (4)	0.67-10	1.8-27
Bitumen	1.4	0.27 ^ρ (64)	0.27	0.38
Petroleum Coke	2.2	50 (4)	50	110
Other	1.2	Unknown	N/A.	N/A
Total	72.1		Geometric Mean: 1.9-4.7[§]	140-340

All values given in (17) are in ppb. It is assumed that this is mass/mass.

^γ Reported as 185.7±2.6 ng/L. Conversion assumes a density of 0.8 g/litre.

^κ Reported as 67±37 ng/L. Conversion assumes a density of 0.8 g/litre.

^ω Standard deviation = 0.96

^ρ Standard deviation = 0.32

[§] Calculated as (140 to 340 kg)/72.1 million tonnes = 1.9 to 4.7 µg/kg

Annex 6 – Estimates of mercury in UK crude oil (produced and refined) through time.

Percentage share of UK crude oil imports (65). Concentrations from (8)

Year	Middle East (0.8 µg/kg)	W. Hemisphere (mean of S & N America = 4.8 µg/kg)	Norway (3.6-19.6 µg/kg)	Africa (2.7 µg/kg)	Others (using 5 µg/kg as a typical concentration; <i>see</i> Annex 2a)	Geometric mean Hg conc. (µg/kg)	UK Imports (million tonnes) (65)	Total Mercury in imports (kg)	UK production processed in the UK (3.6 µg/kg) (65)	Total Mercury in UK production (kg)	Estimated UK crude oil Mercury budget (kg)
2006	2	4	70	7	17	3.8-15	58.5	220-880	26.4	95	315-975
2000	5	4	74	7	10	3.6-15	54.4	200-840	33.3	120	320-960
1990	31	5	49	6	9	2.9-11	52.7	150-560	34.6	120	270-680
1980	81	4	6	2	7	1.5-2.4	46.7	68-113	40.3	140	208-253
1970	59	5	0	33	3	1.8	102.2	180	Negligible	~0.0	180
1960	81	16	0	2	1	1.5	45.4	69	Negligible	~0.0	69
1950	81	18	0	0	1	1.6	9.5	15	Negligible	~0.0	15