Biological Monitoring of Benzene Exposure for Process Operators during Ordinary Activity in the Upstream Petroleum Industry

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This study characterized the exposure of crude oil process operators to benzene and related aromatics during ordinary activity and investigated whether the operators take up benzene at this level of exposure. We performed the study on a fixed, integrated oil and gas production facility on Norway’s continental shelf. The study population included 12 operators and 9 referents. We measured personal exposure to benzene, toluene, ethylbenzene and xylene during three consecutive 12-h work shifts using organic vapour passive dosimeter badges. We sampled blood and urine before departure to the production facility (pre-shift), immediately after the work shift on Day 13 of the work period (post-shift) and immediately before the following work shift (pre-next shift). We also measured the exposure to hydrocarbons during short-term tasks by active sampling using Tenax tubes. The arithmetic mean exposure over the 3 days was 0.042 ppm for benzene (range <0.001–0.69 ppm), 0.05 ppm for toluene, 0.02 ppm for ethylbenzene and 0.03 ppm for xylene. Full-shift personal exposure was significantly higher when the process operators performed flotation work during the shift versus other tasks. Work in the flotation area was associated with short-term (6–15 min) arithmetic mean exposure to benzene of 1.06 ppm (range 0.09–2.33 ppm). The concentrations of benzene in blood and urine did not differ between operators and referents at any time point. When we adjusted for current smoking in regression analysis, benzene exposure was significantly associated with the post-shift concentration of benzene in blood \( (P = 0.01) \) and urine \( (P = 0.03) \), respectively. Although these operators perform tasks with relatively high short-term exposure to benzene, the full-shift mean exposure is low during ordinary activity. Some evidence indicates benzene uptake within this range of exposure.

Keywords: benzene exposure; biological monitoring; ordinary activity; process operators

INTRODUCTION

Offshore petroleum production platforms separate crude oil into oil, gas, water and solids. The water produced in this process contains a variety of chemicals, including hydrocarbons from the geological formation of the reservoir. Thus, process operators in the petroleum industry on offshore installations are potentially exposed to a mixture of hydrocarbons from crude oil, condensate from natural gas production and produced water. During ordinary operation, the processes take place in closed systems, which are opened only briefly for such purposes as sampling crude oil and the water produced, maintenance work and inspecting and cleaning pipelines and process equipment.

The upstream hydrocarbons include such aromatics as benzene, toluene, ethylbenzene and xylene. Although benzene is a known carcinogen (International Agency for Research on Cancer, 1987; Schnatter et al., 2005) and a haematotoxic agent (Lan et al., 2004), data on past and present exposure to benzene in the upstream petroleum industry are not extensive. Some authors (Runion, 1988; Verma et al., 2000; Steinsvåg et al., 2007) have summarized common occupational exposure data from oil
companies obtained to document compliance with recommended limit values and have concluded that long-term mean benzene exposure is low for process operators. During routine offshore oil and gas production, full-shift mean exposure to toluene, ethylbenzene and xylene as well as to benzene is also reported to be low compared with occupational exposure limits (HSE, 1999). However, the wide ranges of exposure values indicate that some workers occasionally experience exposure exceeding the occupational exposure limit during ordinary activity (Verma et al., 2000; Steinsvåg et al., 2007). Previous exposure studies during ordinary activity have not provided exposure data for specific tasks expected to be associated with short-term exposure to hydrocarbons (Gardner, 2003) and have not examined whether such exposure explains some of the variability in full-shift exposure.

Full-shift benzene exposure for operators on a floating crude oil production vessel was lower during ordinary activity than during maintenance work in a cleaned crude oil tank (Kirkeleit et al., 2006a). However, despite relatively low benzene exposure during maintenance work in the oil tanks (arithmetic mean 0.23 ppm), the workers had a significantly higher benzene concentration in blood and urine and acute reduction in circulating immunoglobulin M (IgM), IgA and CD4 T cells compared with referents (Kirkeleit et al., 2006b,c). The internal concentration of benzene was higher than expected at the measured exposure levels, which might be related to the physically demanding 12-h work shifts for tank workers and insufficient use of respiratory protective equipment (Kirkeleit et al., 2006b). Thus, benzene was absorbed and had biological effects even at exposure below the recommended limit value of 0.6 ppm and possibly within the range of exposure levels representative for ordinary activity.

This study characterized the exposure of crude oil process operators to benzene and related aromatics during ordinary activity and investigated the relationship between the individual concentrations of benzene in the breathing zone and the concentrations of unmetabolized benzene in blood and urine in these workers.

METHODS

Study site

We performed the study in October 2005 during ordinary activity in the processing unit on a fixed, integrated oil and gas production facility on Norway’s continental shelf. The process operators worked 12-h shifts and surveyed the upstream processes comprising a closed system in which the effluent was separated into gas, oil, water and solid waste. They carried out this surveillance via computers in the control room and by inspection in the process areas. They also had practical tasks such as sampling and analysing oil and the water produced, fault-finding and repairing.

Sampling strategy

Study population. The study population originally included 10 process operators (seven men and three women) potentially exposed to benzene in the processing area and 9 referents (six men and three women) not expected to be exposed to benzene above the background concentration in the indoor environment. During the study period, two process workers were unexpectedly relocated from the cellar deck, where exposure was expected to be relatively high. To account for this relocation, we enrolled two new process operators in the study during the study period. Thus, the total number of process operators was 12. Seven referents were recruited from the catering section on the same facility, and two referents were process operators located in the central control room. We invited all eligible process workers on the selected day or night shifts and catering personnel with a shift schedule matching that of the process operators to participate. All agreed to participate.

The participants completed a self-administered questionnaire including questions on age, sex and whether they were smokers during the study period. In addition, the process operators maintained a logbook where they recorded their job tasks and use of personal protective equipment during the respective shifts.

We obtained informed written consent from all participants. We informed all subjects about their own results. The Western Norway Regional Committee for Medical Research Ethics and the Norwegian Social Science Data Services approved the study protocol. The Ministry of Health and Care Services gave permission to establish a biobank and to transfer the biological material abroad for analysis.

Personal full-shift exposure to airborne hydrocarbons. We monitored the process operators (n = 12) for personal exposure to benzene, toluene, ethylbenzene and xylene during three consecutive day or night shifts (Days 11, 12 and 13 of the 2-week offshore period) each 12 h (0700–1900 or 1900–0700) using organic vapour passive dosimeter badges (3M™ 3500) attached to the worker’s collar. Prior to laboratory analysis, we visually inspected the sampling badges and rejected one dosimeter due to splashes with oil-contaminated water. The arithmetic mean sampling time for the remaining 35 measurements was 657 min (range 450–730). We did not measure the personal exposure to benzene for referents.

Biological monitoring. The original 10 process operators monitored also provided three samples of blood and urine for analysis of benzene. We collected the first sample in the morning at the heliport before departure to the oil production facility (pre-shift) and considered this the baseline measurement. We...
collected the second exposure sample immediately after the work shift on Day 13 of the offshore work period (post-shift) and a third sample immediately before the work shift on the following day or night (pre-next shift). We only obtained two urine samples (post-shift and pre-next shift) from the two process operators enrolled during the study period. We obtained blood and urine samples from the nine referents on the same days following the same protocol. Due to unsuccessful blood draw, we failed to collect the pre-next shift blood sample from one of the referents. Except for the two process operators enrolled in the study later, all the participants provided urine samples pre-shift, post-shift and pre-next shift.

Exposure measurement during specific work tasks

In separate exposure measurement, we performed personal sampling of hydrocarbons during specific tasks using Tenax tubes connected to pumps (Casella-EEx) at a flow rate of 0.05–0.1 l min

The Tenax tubes were attached to the worker’s collar, and the sampling time (arithmetic mean 16.4 min, range 3–76 min) depended on the duration of the task.

In preliminary exposure assessment, we had identified four work tasks expected to be associated with relatively high short-term exposure to hydrocarbons: (i) inspection and work on the flotation package, (ii) sampling and analysis of crude oil, condensate and produced water, (iii) sending and receiving pipeline cleaning pigs and (iv) jetting of separators. The operators informed the researcher before performing these work tasks during the study period to facilitate short-term exposure measurement. Operators did not jet separators during this period.

Inspection and work on the flotation package. The water produced containing dispersed oil was treated in the flotation package, where oil was skimmed off the upper layer of the two-phase water–oil mixture. Under normal conditions, the process operators do not have to inspect the flotation package regularly. During the study period, the operators inspected the flotation package twice per shift since the content of oil in the water produced exceeded the legal limit set by Norway’s authorities for discharge to the sea. The operators opened the trap doors and, when necessary, adjusted the separation level. At times they also used a swab to push the oil phase over the separation edge.

Sampling and analysis of petroleum streams (crude oil, condensate and water produced). During the night shift, operators sampled crude oil through a short-cut loop and brought it to the laboratory for analysis of water content and specific weight. During the day shift, operators manually sampled condensate and water produced in small bottles from taps in the production process and then analysed the oil concentration of the water produced in the laboratory.

Sending and receiving pipeline cleaning pigs. The operators used a pipeline cleaning pig to remove solid or semisolid deposits or debris from the walls of the pipelines. The operators normally sent or received a pig at least once every third night shift. When inserting and launching the cleaning pig, the operators depressurized the launcher, opened the trap door and installed the pig into the launcher before locking and securing the door. When the operators received the cleaning pig from other installations, they normally left the pig within the lock for ~24 h to reduce potential hydrocarbon exposure due to evaporation caused by high temperature in the pipeline. When the operators were ready to remove the pig from the receiver, they depressurized the system and opened the trap closure. They manually pulled the pig out of the receiver and removed thick oil and wax from the pig by manual shovelling. Before they closed the trap, they cleaned and lubricated the trap closure seal.

Other tasks with possible short-term exposure. Before operators did maintenance work on the processing equipment, they had to open, change and close blind flanges and valves. This could imply risk hydrocarbon exposure. Although process operators occasionally open process equipment, the mechanics mainly perform these tasks.

Laboratory analysis

We stored the dosimeter badges and the Tenax tubes at −4°C before transporting them to X-lab AS in Bergen for analysis. X-lab AS desorbed the collected hydrocarbons on the dosimeter badges using CS2 and desorbed the Tenax tubes thermically. Benzene, toluene, ethylbenzene and xylene (all isomers) were analysed quantitatively and qualitatively by gas chromatography with mass spectrometry (NIOSH, 2003). The levels of detection were 0.001 ppm for benzene and 0.01 ppm for toluene, ethylbenzene and xylene.

Kirkeleit et al. (2006b) described methods for sampling, storing, transporting and analysing blood and urine samples in detail. We analysed the concentration of benzene in blood using a headspace sampler (Perkin Elmer Headspace sampler HS40) and a gas chromatograph (Perkin Elmer Autosystem Gas Chromatograph) using photoionization detection according to the method described by Pekari et al. (1989, 1992). We analysed the urinary concentration of benzene using a solid-phase microextraction–gas chromatograph–mass spectrometer/ion-trap detection method (SPME-GC-MS/ITD method). The limit of quantification for benzene in both blood and urine was 1 nmol l

Occupational exposure limits

Norway’s recommended occupational exposure limits are averaged over an 8-h workday. In the guidelines to the Activity Regulations, the Petroleum Safety Authority Norway (2006) recommends a safety factor of 0.6 to correct for a 12-h shift, which
is relevant for the offshore installations. Thus, the recommended occupational exposure limits corrected for 12-h shifts are 0.6 ppm for benzene, 15 ppm for toluene and xylene and 3 ppm for ethylbenzene. The short-term occupational exposure limits (for periods up to 15 min) are 3 ppm for benzene, 37.5 ppm for toluene and xylene and 10 ppm for ethylbenzene.

Statistical analysis

We display personal exposure to benzene, toluene, ethylbenzene and xylene as arithmetic mean [standard deviation (SD)], geometric mean and range (minimum and maximum). We grouped the results from full-shift exposure measurement according to the logbook recordings of work tasks expected to be associated with short-term exposure to aromatic hydrocarbons. We analysed the differences in the various exposure measures between work tasks and between the process operators and referents using t-tests. We calculated Pearson’s correlation coefficient for studying relationships between the different exposure measures at the various time points. We adjusted these associations for gender, age and being a current smoker by including each of these in separate multiple regression analyses. We also adjusted the associations between personal benzene exposure in the work environment and the benzene concentration in biological media for the corresponding baseline concentrations of benzene in blood and urine, respectively, by including the baseline concentration as a covariate in regression analysis.

All the exposure measurements and the biomarkers of benzene exposure had a skewed distribution, and we therefore log transformed them before statistical analysis (ln). We replaced blood and urinary benzene concentrations and benzene exposure below the limit of quantification and benzene exposure for referents exposure values equal to the level of detection for borne benzene exposure and the concentration of airborne benzene exposure and the concentration of benzene in urine divided by 2. The benzene exposure on the third day of sampling was correlated with the post-shift concentration of benzene immedi-

Results

General characteristics of the study population

The mean age (SD) of the process operators (n = 12) and referents (n = 9) was 42.3 (SD 12.8) and 44.9 (SD 10.7) years, respectively. Three process operators and four referents reported being current smokers. During the study period, the operators always used personal half-mask respirators with filter for organic vapour (brown) during work on the flotation package but not during other work tasks.

Personal full-shift exposure to benzene and related aromatics

Process operators’ arithmetic mean benzene exposure over the 3-day study period was 0.042 ppm (range <0.001–0.69 ppm) (Table 1), which is ~7% of Norway’s occupational exposure limit of 0.6 ppm over a 12-h work shift. The arithmetic mean exposure levels for toluene (0.05 ppm), ethylbenzene (0.02 ppm) and xylene (0.03 ppm) were even lower in relation to the corresponding occupational exposure limits (Table 1). The exposure to benzene was correlated with exposure to toluene (r = 0.72, P < 0.001), ethylbenzene (r = 0.41, P = 0.02) and xylene (r = 0.70, P < 0.001), respectively.

Exposure did not differ significantly between the three consecutive sampling days. For benzene exposure, the arithmetic mean for the first day of sampling was 0.07 ppm (range <0.001–0.69 ppm), for the second day 0.04 ppm (<0.001–0.40 ppm) and for the third day 0.02 ppm (<0.001–0.09 ppm).

Personal exposure to benzene, toluene, ethylbenzene and xylene was significantly higher when flotation work was done during the shift compared with sampling of crude oil and water produced (P < 0.001) or carrying out other tasks (P < 0.001) (Table 1). Exposure levels did not differ when the work shift included sampling of crude oil or produced water compared with other tasks apart from flotation work. Analogous results were found for exposure to toluene, ethylbenzene and xylene (Table 1).

Benzene concentration in blood and urine

The concentration of benzene in blood or urine did not differ significantly between the process operators and referents at any time point (Table 2). This result was found also among the non-smokers. The arithmetic mean concentration of benzene in blood post-shift was 1.8 nmol l⁻¹ for both groups. The arithmetic mean concentration of benzene in urine post-shift was 3.9 nmol l⁻¹ for process operators versus 1.6 nmol l⁻¹ for referents.

When we studied the associations between airborne benzene exposure and the concentration of benzene in blood and urine, we assigned referents exposure values equal to the level of detection for benzene in air divided by 2. The benzene exposure on the third day of sampling was not significantly correlated with the internal concentration of benzene immediately after work hours (post-shift) or prior to the following work shift (pre-next shift), neither in blood (post-shift: r = 0.05, P = 0.83; pre-next shift: r = −0.08, P = 0.77) nor in urine (post-shift: r = 0.04, P = 0.87; pre-next shift: r = −0.19, P = 0.43). When we included only non-smokers in the correlation analysis, benzene exposure on the third day of sampling was correlated with the post-shift concentration of benzene in blood (r = 0.65, P = 0.02). When we adjusted for being a current smoker in multiple linear regression, benzene exposure on the third day of sampling was significantly associated with the post-shift concentrations of benzene in blood (P = 0.01) and urine (P = 0.03), respectively. These
models explained 87 and 79% of the variance in benzene concentration in blood and urine, respectively. Adjusting for other potential confounders such as age, gender and baseline concentrations of benzene in blood or urine did not substantially change the associations between benzene exposure and internal post-shift or pre-next shift benzene concentrations.

Short-term exposure during specific work tasks

Work on the flotation package was associated with a short-term arithmetic mean exposure to benzene of 1.06 ppm (range 0.09–2.33 ppm), which is ~35% of Norway’s recommended short-term occupational exposure limit of 3.0 ppm for periods up to 15 min (Table 3). We measured non-statistically significantly lower concentrations of benzene during work with pipeline cleaning pigs (arithmetic mean 0.32 ppm) and when opening process equipment (arithmetic mean 0.24 ppm). The apparent variability in short-term benzene exposure was higher during flotation work than when other short-term tasks were done (Fig. 1). The arithmetic mean sampling time for work in the flotation package was 9 min (range 6–15 min), for sampling of petroleum streams 19 min (3–40 min), for pipeline cleaning operations 28 min (4–76 min) and for opening of process equipment 12 min (8–16 min).

Benzene exposure during sampling of crude oil, condensate and produced water (0.021 ppm) was significantly lower and had low variability compared with other short-term tasks (Table 3, Fig. 1). Differences in exposure between the different work tasks followed a similar pattern for toluene, ethylbenzene and xylene (Table 3).

**DISCUSSION**

During ordinary activity for offshore process operators, full-shift exposure to benzene and related aromatic hydrocarbons was generally low compared with the recommended occupational limits. Work in the flotation area was associated with relatively high short-term exposure to benzene, which contributed considerably to the full-shift exposure. Although the internal concentration of benzene did not differ between process operators and referents, benzene uptake was indicated within the range of exposure representative for ordinary activity on the installation.

In this study, we ascribe the low mean full-shift exposure to benzene at the fixed oil- and gas-producing installation to the closed process systems, which during ordinary activity are opened only briefly. In addition, the processing systems are located in open air, efficiently diluting emissions from process systems.

Our low reported benzene exposure is in accordance with previous studies during ordinary activity in the offshore petroleum industry (Glass et al., 2000;
Table 2. Mean concentration of benzene in blood (nmol l$^{-1}$) and benzene in urine (nmol l$^{-1}$) pre-shift, post-shift and pre-next shift for offshore process operators and referents

<table>
<thead>
<tr>
<th>Marker of benzene exposure</th>
<th>Group</th>
<th>n</th>
<th>AM</th>
<th>GM</th>
<th>Range (minimum–maximum)</th>
<th>&lt;LOQ</th>
</tr>
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<tr>
<td>Blood, pre-shift</td>
<td>Process operators</td>
<td>10</td>
<td>2.1</td>
<td>1.4</td>
<td>0.5–6.0</td>
<td>3</td>
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<tr>
<td></td>
<td>Referents</td>
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<td>2.0</td>
<td>0.5–5.0</td>
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<td>Blood, post-shift</td>
<td>Process operators</td>
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<td>1.8</td>
<td>1.5</td>
<td>1.0–4.0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Referents</td>
<td>9</td>
<td>1.8</td>
<td>1.5</td>
<td>1.0–4.0</td>
<td>0</td>
</tr>
<tr>
<td>Blood, pre-next shift</td>
<td>Process operators</td>
<td>10</td>
<td>2.0</td>
<td>1.6</td>
<td>1.0–5.0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Referents</td>
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<td>1.6</td>
<td>1.5</td>
<td>1.0–3.0</td>
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<tr>
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<td>3.0</td>
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<td>Process operators</td>
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<td>3.9</td>
<td>1.1</td>
<td>0.5–34.0</td>
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<td>1.6</td>
<td>1.1</td>
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<tr>
<td>Urine, pre-next shift</td>
<td>Process operators</td>
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<td>1.7</td>
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<td>0.5–35.0</td>
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AM, arithmetic mean; GM, geometric mean; <LOQ, number of samples below the limit of quantification.

Kirkeleit et al., 2006a; Steinsvåg et al., 2007). On a floating production vessel, the arithmetic and geometric mean benzene exposure levels during ordinary activity of the workers were 0.02 and 0.004 ppm, respectively (Kirkeleit et al., 2006a). Steinsvåg et al. (2007) pooled 367 personal full-shift measurements of benzene exposure in processing and drilling areas from 12 installations on Norway’s continental shelf from 1994 to 2003. The benzene exposure ranged from below the limit of detection to 2.6 ppm, with arithmetic and geometric means of 0.037 and 0.0067 ppm, respectively. In retrospective exposure assessment of benzene in Australia’s petroleum industry, Glass et al. (2000) estimated exposure of 0.02 ppm for workers classified as ‘upstream operator offshore’. In the conventional oil and gas sector of the upstream petroleum industry in Canada, 198 personal long-term samples from 1985 to 1996 were within the range of <0.001–2.43 ppm, with an arithmetic mean of 0.064 ppm and a geometric mean of 0.011 ppm (Verma et al., 2000).

In our study, the six full-shift samples with the highest benzene exposure included brief work in the flotation area carried out by two of the 12 process operators. The supplementary short-term measurements indicated high exposure variability for benzene during this task, probably due to many factors such as the actual work done, the position of the operator, the time trap doors were open and the temperature and composition of the oil and water mixture. Several production platforms constructed during the first period of oil production on Norway’s continental shelf used similar flotation package systems, but at present only a few installations have these. Sampling and analysis of crude oil and water produced did not appear to contribute significantly to full-shift exposure, and short-term measurements indicated low exposure within a narrow range for this task. On this installation, the partly automated system for sampling crude oil probably contributed to the low exposure during this task. On most offshore installations, crude oil is mainly sampled manually, which may result in higher exposure than we found. Sending and receiving a cleaning pig was associated with higher short-term exposure. However, this task was not performed during the three consecutive days of full-shift sampling. The exposure to toluene, ethylbenzene and xylene was relatively lower compared with the respective recommended occupational limit values than for benzene, indicating low health risk for these hydrocarbons.

Smoking is a major respiratory source of benzene uptake (Darrall et al., 1998). Although smoking was prohibited in the oil and gas production areas, the living quarters had a few designated smoking rooms. In our study, the internal benzene concentration did not differ between process operators and referents, but benzene in the breathing zone was associated with benzene in blood and urine, respectively, when adjusted for current smoking. Our results indicate that, even at the relatively low exposure levels during ordinary activity, workers seem to take up benzene from the working environment. Since the elimination of internal benzene is time dependent, the time lag between short-term exposure and biological sampling at the end of the work shift might have contributed to reducing the impact of such exposure on benzene uptake. Our study included relatively few workers, and recruiting more workers would have strengthened the indicated association between benzene exposure and the internal concentration of benzene in blood and urine. Our results with strongly overlapping ranges of benzene concentration in biological media between exposed workers and referents seem to depend on both being a current smoker and exposure to benzene in the working environment. Kirkeleit et al. (2006b) showed a significant relationship,
independent of smoking, between benzene exposure and internal benzene for crude oil tank workers at a geometric mean of 0.15 ppm (range 0.01–0.62), which is three times higher than our current results. The arithmetic means of the post-shift concentration of benzene in blood (17.3 nmol l\(^{-1}\)) and urine (59.3 nmol l\(^{-1}\)) of these tank workers were also considerably higher than for process operators in our present study. However, tank work should be considered a specific task, quite different from ordinary process work offshore. The concentrations of benzene measured in blood and urine in our study were in the lower part of the exposure range reported in benzene-exposed tank workers experiencing acute reduction in the circulating immune parameters IgM, IgA and CD4 T cells (Kirkeleit et al., 2006c), indicating a low risk of biological effect.

In conclusion, although offshore process operators have relatively high short-term exposure to benzene during ordinary activity, the full-shift mean exposure is low. Some evidence indicates benzene uptake within this range of exposure.

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