National Institute for Public Health
and the Environment
Ministry of Health, Welfare and Sport

Exposure and potential health effects associated with the use of PX-10 in the Dutch Armed Forces

RIVM Report 609037002/2011

Colophon

Schram-Bijkerk, D. (ed.)[1]
Tongeren, M. van[2]
Vermeulen, R.C.H.[3]

Contact:
Dieneke Schram-Bijkerk
Centre for Environmental Health
Dieneke.Schram@rivm.nl

Contributors:
Heederik, D.J.[3]
Portengen, L.[3]
Vlaanderen, J.[3]
Robertson, A.[2]
Schmid, K.[2]
Cherrie, J.W.[2]
MacCalman, L.[2]

Reviewed by:
Stayner, L.T.[4]
Schneider, T.[5]

[1] National Institute for Public Health and the Environment, Bilthoven, The Netherlands
[2] Institute of Occupational Medicine, Edinburgh, United Kingdom
[3] Institute for Risk Assessment Sciences/Utrecht University, Utrecht, The Netherlands
[4] University of Illinois, Chicago, United States
[5] Formerly at National Institute of Occupational Health, Copenhagen, Denmark

This investigation has been performed by order and for the account of the Dutch Ministry of Defence, within the framework of Gezondheidsonderzoek PX-10 (E/609037).

Abstract

Exposure and potential health effects associated with the use of PX-10 in the Dutch Armed Forces

The possibility that members of the Dutch Armed Forces developed acute myeloid leukaemia (AML) or other forms of hematopoietic cancer due to exposure to PX-10 while cleaning and maintaining weapons can be essentially excluded. Until 1970, PX-10 contained small amounts (0.1%) of benzene, a known carcinogen; thereafter, the concentrations of benzene in PX-10 fell sharply. Consequently, the total cumulative exposure of military personnel to benzene over the years was low.

This is the conclusion of a study into the effects and health risks of working with PX-10. The study was commissioned by the Dutch Ministry of Defence in 2008 after liability claims were filed against it related to serious health complaints due to activities involving exposure to PX-10.

Three to four per 1,000 Dutch men develop AML during their lifetime without having had any contact with PX-10. The additional risk of developing AML among military personnel who worked with PX-10 intensively for many years was determined to be 0.03 *extra* cases per 1,000 men. Therefore, it is highly unlikely that additional cases of AML developed, even if a few thousand military personnel were intensively exposed to PX-10.

The exposure to benzene by inhalation and dermal contact varied by time period and working situation. The yearly average concentrations were 0.5 ppm, which is below the currently established occupational exposure limit of 1 ppm during an eight-hour period. PX-10 also contained other volatile components that can have neurological effects. The study determined that the yearly average concentrations of volatile organic compounds (VOCs) were 2–100 ppm, depending on the working situation. As dose-response associations have not been established for VOCs, the risk of developing neurological disorders from exposure to the VOCs in PX-10 could not be calculated.

Keywords:
soldiers, PX-10, volatile organic compounds, cleaning and maintaining weapons, health effects

Rapport in het kort

Blootstelling en mogelijke gezondheidseffecten door het gebruik van PX-10 in de Nederlandse krijgsmacht

Het is praktisch uitgesloten dat defensiepersoneel acute myeloïde leukemie, of aanverwante vormen van kanker heeft ontwikkeld door te werken met het wapenonderhoudsmiddel PX-10. Dit middel bevatte tot 1970 lage concentraties (0,1 procent) van de kankerverwekkende stof benzeen. Daarna daalden de concentraties van deze stof in het product sterk, waardoor de totale blootstelling voor Defensiepersoneel gering was.

Dit blijkt uit berekeningen van de blootstelling aan en de gezondheidseffecten van werken met PX-10. Het Ministerie van Defensie heeft dit onderzoek uitgezet, nadat het in 2008 aansprakelijk was gesteld voor gezondheidsschade door werkzaamheden met PX-10.

Drie tot vier van elke 1.000 Nederlandse mannen krijgen AML, zonder dat ze ooit met PX-10 gewerkt hebben. Onder defensiepersoneel, dat vele jaren dagelijks intensief met PX-10 werkte, is er volgens de berekeningen sprake van 0,03 *extra* gevallen per 1.000 mannen. Het is daarom onwaarschijnlijk dat er daadwerkelijk extra gevallen van AML zijn opgetreden, zelfs als een paar duizend werknemers in hoge mate zijn blootgesteld aan PX-10.

Hoeveel benzeen het defensiepersoneel inademde of opnam via de huid is afhankelijk van de periode waarin de werkzaamheden plaatsvonden en het type werkzaamheden met PX-10. Het jaarlijks gemiddelde per persoon was maximaal 0,5 parts per million (ppm), wat onder de huidige norm ligt van gemiddeld 1 ppm per werkdag. PX-10 bevat ook andere oplosmiddelen die effecten kunnen hebben op het zenuwstelsel. Uit dit onderzoek blijkt dat de blootstelling aan de totale hoeveelheid van deze oplosmiddelen gemiddeld tussen de 2 en 100 ppm lag, afhankelijk van het type werkzaamheden. Het is echter niet mogelijk aan te geven wat de effecten hiervan zijn op de gezondheid, omdat de precieze relatie tussen blootstelling en gezondheidseffecten niet bekend is.

Trefwoorden:
militairen, PX-10, vluchtige organische componenten (VOC's), wapenonderhoudsmiddel, gezondheidseffecten

Contents

Summary

Background

In 2008, liability claims were filed against the Ministry of Defence (MoD) related to serious health complaints due to activities involving exposure to PX-10. PX-10 is a water displacing substance that has been used for cleaning and maintaining steel surfaces of weapons until 1995. It contained 0.1% of the carcinogen benzene till 1970. In response, the MoD commissioned the Dutch National Institute for Public Health and the Environment (RIVM) to quantify the exposure to toxic substances and potential health effects associated with the use of PX-10. RIVM coordinated this study, which was performed by the Dutch Institute for Risk Assessment Sciences (IRAS) of Utrecht University and the Institute of Occupational Medicine in Edinburgh, United Kingdom (IOM). Results of the first part of this study – an independent review of a report from MoD – have been published previously (1). It was concluded that the report was accurate in that benzene exposure is associated with acute myeloid leukaemia (AML), but that there is also (limited) evidence for an association with other leukaemia's and lymphoma (1).

Objectives

The aim of this study was to estimate the exposure to benzene and VOCs from use of PX-10 and to quantify potential health effects associated with the benzene resulting from past PX-10 use. Although VOCs exposures have been linked to neurological effects, no consistent information on the specific constituents causing these effects, nor dose-response relationships were available. Therefore, it was not possible to quantify the health risks due to exposure to VOCs.

Methods

A workplace exposure model was developed and used to estimate the past inhalation and dermal exposure to volatile organic compounds (VOCs) and, in particular, to benzene from PX-10 use. Six representative use scenarios of PX-10 were defined in focus group meetings with former employees/members of the Navy who had used PX-10, i.e.:

- Onshore cleaning of small arms;
- Cleaning of small arms on board;
- Onshore small arms workshop in large room;
- Onshore small arms workshop in small room;
- Onshore washing room for cleaning of torpedo parts;
- Onshore torpedo workshop.

Employees from other branches of military service also had been invited for the focus groups, but did not participate. Estimates of the emission rates were obtained from experiments using a white spirit mixture, similar to PX-10. The information from the focus group meetings and laboratory experiments was used to model the yearly average exposure to benzene and VOCs for each of the six use scenarios. Subsequently, two careers were defined to quantify the risk of developing leukaemia and its subtypes and lymphoma due to exposure to benzene (see box 1). These careers included two exposure scenarios with relatively high average exposures (cleaning small arms in weapon rooms and on board of ships) and a civilian who worked many years with PX-10. Therefore, these careers represent worst-case scenarios. Subsequently, the risk of developing leukaemia in general, acute myeloid leukaemia (AML), acute lymphocytic leukaemia

(ALL), chronic lymphocytic leukaemia (CLL), non-Hodgkin lymphoma (NHL) and multiple myeloma (MM) was modelled. The risks were estimated based on life table analysis of hypothetical cohorts of 100,000 exposed workers in the two defined careers, as it is not exactly known how many people worked in these careers and when. Three weighting functions were applied in the life table analysis, addressing different assumptions regarding the reduction in risk with time since last exposure. In addition, different types of risk models (multiplicative model vs. additive model) and exposure-response models (spline vs. linear model) were used. The main reason to present the outcomes of multiple models is that there is no model that is universally better. As such these different models represent the uncertainty in estimated additional cases. Conclusions were based on the median of the different estimates.

Table S1: Careers used in the quantification of health effects.

Career 1 ‘military personnel of the Navy’		**Career 2 ‘civilian’**	
Cleaning small arms in weapon rooms and on ships		*Cleaning small arms in small workshops*	
Duration career:	38 yrs (age 18-55)	Duration career:	48 yrs (age 18-65)
Start career:	1964	Start career:	1945
		Exposure:	8 hours/day
Rotation land-ship:	3 yrs		
Phase 1 (Seaman)		Full duration of career at the same workplace	
Duration:	6 yrs		
Exposure:	4-8 hours/day		
Phase 2 (Corporal)			
Duration:	9 yrs		
Exposure:	1-4 hours/day		
Phase 3 (Sergeant)			
Duration:	until end of career		
Exposure:	several hours/month		

Results

The experiments showed that benzene would have rapidly evaporated from an open bath with PX-10. A half-life of 2 hours was estimated for the benzene content in a PX-10 bath, meaning that the benzene emission rate from an open bath of PX-10 would have reduced rapidly in the first hours and would have been negligible at the beginning of the next day. Therefore, the long-term exposure to benzene was, to a large extent, determined by the frequency and amount of topping–up of the bath (approximately once a week) and the frequency of completely changing the bath with fresh PX-10 in the scenarios using an open bath (approximately once a month).

Estimates of average yearly benzene exposure ranged for the different use scenarios between 0.009 to 0.4 ppm before 1970, 0.004 to 0.2 ppm between 1970 and 1980, and between 0.001 and 0.04 ppm after 1980. In addition to the inhalable route, exposure via the dermal route would also have contributed to overall systemic exposure. Due to the manual nature of the cleaning procedures this exposure route could have been substantial. Modelling of the dermal exposure route showed that this route resulted in yearly inhalation equivalents below 0.2 ppm but was still the main exposure route in certain operations like for instance in the maintenance of torpedoes onshore. Nevertheless, the inhalation exposure to benzene was the main contribution in most of the tasks. Combining the dermal and inhalation route resulted in exposure estimates that were on a yearly average base maximally 0.5 ppm, see Figure S1. VOCs exposure yearly average levels varied from 2 to 100 ppm depending on the working situation.

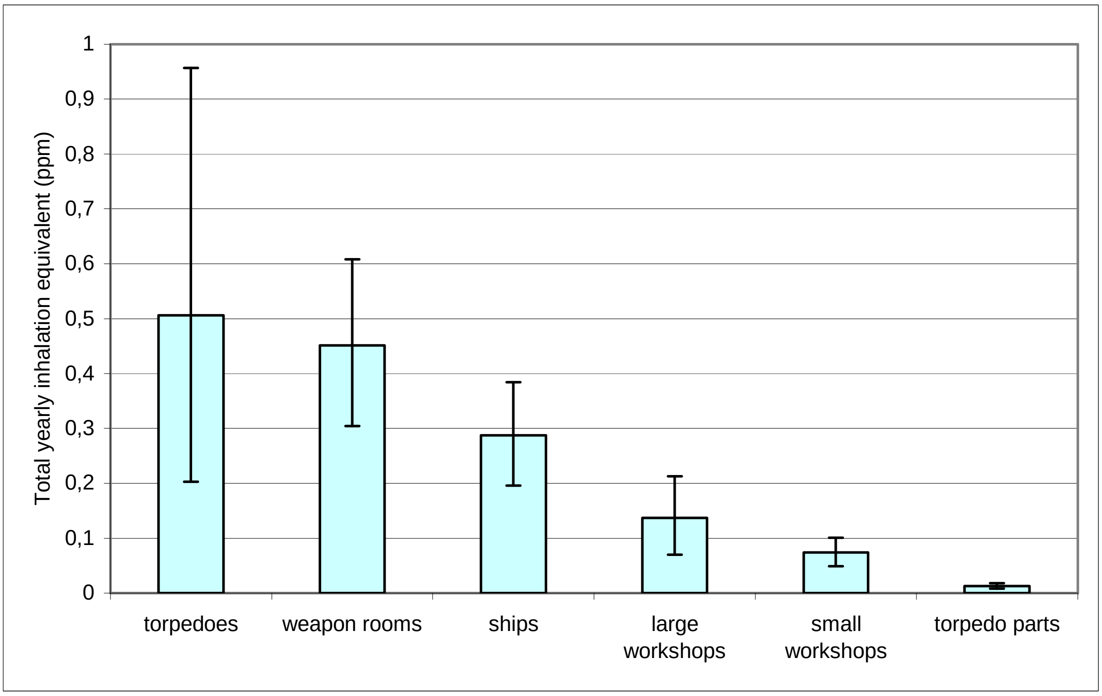

Figure S1: Total yearly benzene exposure before 1970, with error bars indicating the 5th and 95th percentiles of the estimation intervals.

Despite the differences between the two hypothetical careers, the cumulative exposure was similar, i.e. 2.42 ppm-years in career 1 and 2.25 ppm-years in career 2. For career 1 (Cleaning small arms in weapon rooms and on ships) the estimated additional number of cases per 100,000 exposed individuals ranged for leukaemia from 3.9 to 26.3 (median 6.5); for AML from 1.4 to 15.0 (median 3.3); for ALL it was 0.3; for CLL it ranged from 1.7 to 2.9; for NHL from 4.7 to 7.1; and for MM from 7.3 to 11.7.

For career 2 (Cleaning small arms in workshops by civilians) the estimated additional number of cases per 100,000 exposed individuals ranged for leukaemia from 2.6 to 30.3 (median 6.4); for AML from 0.9 to 21.0 (median 2.7); for ALL it was 0.4; for CLL it ranged from 0.9 to 3.2; for NHL from 2.8 to 8.1; and for MM from 4.0 to 13.2.

In summary, the additional risk of developing AML, for which the evidence of a causal association with benzene exposure is most evident, was around 3 cases per 100,000 exposed people, or 0.03 per 1,000 people in both careers. This number is however time-dependent and should not be interpreted as an individual risk. The additional risk and subsequent cases for other leukaemia's and lymphoma was estimated to be similarly low.

Conclusion

It can be concluded that exposure to benzene did occur while using PX-10 and that these exposures on a yearly average would be likely less than the current occupational exposure limit of 1 ppm. Yearly average exposure to VOCs was up to 100 ppm, which equals the (non-legal) current white-spirit 8-hour threshold value.

Based on the yearly average concentrations and two realistic high-risk careers, it was estimated that the additional risk of AML is 0.03 per 1,000 subjects exposed to these exposure scenarios. The additional risk for the other leukaemia subtypes and lymphoma was comparable to the risk of AML. MoD estimated that the number of exposed subjects in these high-risk careers is likely to be in the low thousands. Therefore, the possibility that members of the Dutch Armed Forces developed acute myeloid leukaemia (AML) or other forms of hematopoietic cancer due to exposure to PX-10 while cleaning and maintaining weapons can be essentially excluded. It should be noted that both the exposure estimates and risk estimates have considerable uncertainties. As such the estimated number of additional cases should be interpreted with some caution.

VOCs have been linked with some adverse health outcomes, most notably neurological symptoms and disorders. As no dose-response relations exist for VOCs or specific components with regard to these disorders, no calculation could be made of the potential health impact. Cases of neurological disorders among subjects that worked with PX10 should therefore probably be referred to specialized ‘solvent teams’ for more specific follow-up.

1 Introduction

1.1 Background

In 2008, liability claims were filed against the Ministry of Defence (MoD) related to serious health complaints due to activities involving exposure to PX-10. PX-10 is a water displacing substance that has been widely used for cleaning and maintaining steel surfaces of weapons. Subsequently, this claim has received attention by the national government, the military union and the media. As PX-10, at least for part of the time, contained benzene and other organic solvents, the suggestion has been that the MoD, although aware of the potential health effects, has not acted adequately in eliminating or reducing the exposure or in providing appropriate personal protection to their employees. In response, the MoD has agreed to further investigate the use of PX-10, its contents and the potential associated health effects with the goal to objectively assess the potential health risks that (ex-) military personnel might have been exposed to due to the historical use of PX-10.

A preliminary evaluation of the composition, use and potential health effects of PX-10 was made by the Military Medical Service Agency of the Netherlands (2). MoD commissioned the Dutch National Institute for Public Health and the Environment (RIVM) to independently review this evaluation. Results of this literature review have been published previously (1). In addition, MoD commissioned RIVM to estimate the exposure to toxic substances in PX-10 and to quantify potential health effects associated with these exposures (this report). This study was coordinated by RIVM and performed by the Dutch Institute for Risk Assessment Sciences (IRAS) of Utrecht University and the Institute of Occupational Medicine in the United Kingdom (IOM).

In our previous report (1), it was concluded that:

- The main constituents of PX-10 were white spirit (including aromatics such as toluene and benzene), mineral oils and some additives. Of these exposures benzene was identified as being the most important constituent in relation to possible health effects.
- The concentrations of benzene in PX-10 in the preliminary estimates of MoD (2) were based on a worst-case scenario; we concluded that 10 times lower concentrations were more realistic. The benzene level in PX-10 was reduced from 0.1% before 1970 to 0.03% between 1970 and 1980 and 0.01% after 1980. After 1995 PX-10 was not used anymore.
- Next to acute myeloid leukaemia (AML), there is evidence that benzene exposure is related to acute lymphocytic leukaemia (ALL), chronic lymphocytic leukaemia (CLL), non-Hodgkin lymphoma (NHL), and multiple myeloma (MM).
- In addition to benzene, exposures to other volatile organic compounds (VOCs) will have occurred, among which toluene and xylene. Although VOCs exposures have been linked to neurological effects, the scientific literature is not consistent.

1.2 Objectives

The aim of this study was to estimate the exposure to benzene and VOCs from use of PX-10 and to quantify potential health effects associated with the benzene resulting from past PX-10 use. Although VOCs exposures have been linked to neurological effects, no consistent information on the specific constituents causing these effects, nor dose-response relationships were available. Therefore, it was not possible to quantify the health risks due to exposure to VOCs.

1.3 Organization of the report

The report consists of the following elements:

- Use of PX-10: definition of scenarios (chapter 2).
- Exposure assessment of benzene and VOCs based on the identified scenarios of PX-10 use (chapter 3 and 4).
- Quantification of health effects due to exposure to benzene (chapter 5).
- Discussion (chapter 6)

2 Use of PX-10: Definition of scenarios

As no detailed descriptions on the past use of PX-10 were directly available, it was decided to obtain such information through focus group meetings with (former) long-serving employees of the Dutch Armed Forces. The main aim of the focus group meetings was to define representative scenarios for the use of PX-10 in the Dutch MoD as well as to understand how PX-10 was used within these scenarios. The 23 focus group members, including both civilians and military personnel, were asked to provide information on sizes of rooms, amounts of PX-10 used and type of ventilation, etc. Two focus group meetings were organized, one for exposure scenarios during cleaning and handling of small arms, and one for scenarios during cleaning of large arms. The members of the focus groups, which included current and retired military and civilian personnel, represented only the Dutch Navy; there was no representation from other areas of the Dutch Armed Forces despite the efforts from MoD to include employees from other branches of services.

As a result of the discussion with the focus groups six different exposure scenarios were identified. These six scenarios are described briefly below and represent the most important and frequent past usage of PX-10 in the Dutch Navy.

1. Onshore cleaning of small arms (military personnel): Cleaning of small arms was carried out in a small workshop in the onshore armoury (where handguns were stored). These armouries were well-protected and enclosed rooms below or above ground with little ventilation. There were typically three baths in the workshop, each containing about 200 litres of PX-10. Small arms (guns, pistols) were dismantled; the individual parts soaked in the baths, cleaned with a brush and often dried using compressed air;
2. Cleaning of small arms onboard (military personnel): Constables were responsible for cleaning of all small arms onboard. The baths for the cleaning of small arms with PX-10 onboard ships were generally smaller than in the armoury and typically contained about 20 litres of PX-10. The workspaces were of variable dimensions, but were generally smaller than the onshore facilities;
3. Onshore small arms workshop (civilian staff) in small room: Large numbers of arms were delivered to the workshop where full maintenance was performed. Large baths with hundreds of litres of PX-10 were used for the cleaning of the weapons;
4. Onshore small arms workshop (civilian staff) in large room: Large numbers of arms were delivered to the workshop where full maintenance was performed. Large baths with hundreds of litres of PX-10 were used for the cleaning of the weapons;
5. Onshore washing room: Smaller parts of the torpedoes were cleaned by soaking and washing in large open baths filled with PX-10. This room was adjacent to the torpedo hall;
6. Onshore torpedo workshop: The main body of the torpedoes were manually cleaned by wiping with a cloth soaked in PX-10. This was carried out in a large hall (torpedo hall).

Following the focus group discussions the exposure scenarios were described in as much detail as was available and distributed to the participants together with a list of further follow-up questions. This was done to help refine the scenario descriptions, in particular for information on essential parameters that were required for estimation of exposure (e.g. specific sizes of rooms described in the scenarios etc.). Besides the consensus on the parameter estimates the range was also recorded and subsequently used in the sensitivity analyses (4.2.4.). There were two additional scenarios, for which there was not enough information available to sensibly describe the exposure determinants:

- Onshore Ammunition Maintenance: Ammunition was dismantled and cleaned by hand in a bath with PX-10. For the manual cleaning of the large parts of the ammunition there was a pump dispenser for PX-10, which was applied directly onto a towel; and
- Onshore Maintenance of Large Arms (non-torpedo): No former personnel from the large arms armoury hall were available for the focus group. The work was carried out mainly by civilians and continued until the late 1980s. However, the use of PX-10 was less intense compared with use of PX-10 in the torpedo hall.

Based on the information that was obtained from the focus group it seems that the exposure to benzene can be assumed to be similar or lower than in the other scenarios with PX-10 baths.

The six scenarios have been divided into two different exposure types:

a) Usage of PX-10 in open baths, with continuous evaporation of PX-10 (scenario 1-5). The tasks that were performed at such workplaces consisted of cleaning metal pieces with PX-10. These tasks have been reported to be similar to household dish cleaning with a brush and were performed with completely submerged hands and part of the forearms in the PX-10 liquid; and

b) Treatment of metal surfaces with a cloth soaked in PX-10 (scenario 6). The skin contact with the PX-10 was reported to be less extensive than in the bath tasks, as the hands were not permanently submerged. In most cases the contact with PX-10 was limited to the inner side of one hand and forearm.

3 Methods of exposure assessment

As no measurement data are available for benzene exposure during activities involving PX-10, it was necessary to develop a model to estimate the past exposures. This Chapter describes the methodology used for estimating the past exposure to benzene and total VOCs from use of PX-10.

3.1 Benzene and VOCs content of PX-10

As described previously (1), the main constituents of PX-10 were white spirit (including aromatics such as toluene and benzene), mineral oils and some additives. Tables 3-1 and 3-2. present the best estimates of the content of benzene and VOCs respectively, which were described in our previous report and which were used in the quantification of exposure.

Table 3-1: Best estimates of historical benzene in white spirit.

Period	**% Benzene in white spirit**	
	Best estimate	**Upper limit**
before 1970	0.1	0.2
1970-1980	0.03	0.1
1980 onwards	0.01	0.03

Table 3-2: Reported proportions of toluene and xylene in white spirit (in % volume[1]).

Solvent	**% by volume**		
	Northern Europe	**Russia**	**USA**
Toluene	0.005	0.2	0.4
Xylene (o,p & m)	1.1	4.14	1.4[2]

[1] Source: http://www.inchem.org/documents/ehc/ehc/ehc187.htm#SectionNumber:2.2, visited October 26, 2011.

[2] C_8 aromatics, includes ethyl benzene.

3.2 Modelling approach

To predict the inhalation benzene exposure we adapted a deterministic two-compartment mass-balance model originally developed by Cherrie and Schneider (3). The model consists of two ‘boxes’; a small near-field comprising a virtual cube of 2 metre sides centred on the workers head (8 m^3) and a large far-field describing the rest of the room. Each field is assumed to be perfectly mixed but exchanging air with the other field at a defined rate. This simplification makes it possible to calculate two components of the exposure, i.e. exposures originating from near-field sources (e.g. due to a worker’s task) and exposures originating in the far-field (e.g. due to activities by other workers or other process-related emissions).

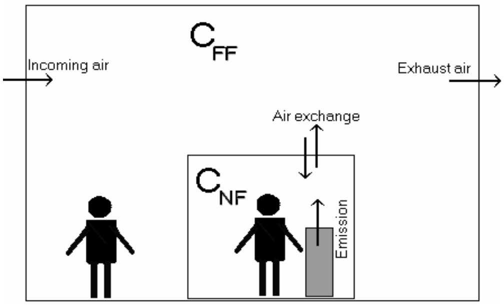

Figure 3-1: Schematic description of the two compartment model at a workplace (C_{FF}: concentration in the far-field, C_{NF}: concentration in the near-field).

The basic model is described by two simultaneous differential equations representing the exchange of contaminant mass between the compartments, including mass lost from the system by air exchange with the external environment.

$$V_{NF}\frac{dC_{NF}}{dt} = \varepsilon N_T - C_{NF}.Q_{NF} + C_{FF}.Q_{NF} \quad \text{[equation 1]}$$

$$V_{FF}\frac{dC_{FF}}{dt} = \varepsilon F_T + C_{NF}.Q_{NF} - C_{FF}.Q_{NF} - C_{FF}.Q_{FF} \quad \text{[equation 2]}$$

The volume airflow into and out of the near-field (Q_{NF}) defines the exchange between the two compartments (defined by their respective near-field and far-field volumes, V_{NF} and V_{FF}), while Q_{FF} defines the volume airflow from the far-field out to the external environment (e.g. external ventilation). The mass emission rate into the near-field (εN_T) or into the far-field (εF_T) are used to calculate the near- and far-field concentration of a contaminant. These differential equations can be solved simultaneously over time and allow an iterative calculation of the concentration in each of the compartments.

To be able to implement this model to estimate benzene exposure for a range of PX-10 exposure scenarios, a number of input parameters were required, including emission rates, room sizes, ventilation rates, bath sizes, working hours, amounts of replaced PX-10 and the frequency of such replacement (see Appendix 1: Scenario description and input parameters for exposure modelling). The benzene emission rates were based on experiments carried out at the laboratory of the IOM (see section 3.3 of this report). The other input parameters were based on information provided by the focus groups or from information provided by the Dutch MoD. The airflow between the near- and far-field compartments (Q_{NF}) was arbitrarily set at 10 m^3/min, which was based on an estimate of the airflow arising from convection and some bulk air movement, and was the mid-value chosen by Cherrie (1999) (4). To account for the uncertainties in these input parameters the model was implemented as a probabilistic model using Monte Carlo simulations.

3.3 Laboratory experiments

A series of laboratory experiments were carried out at the IOM to estimate the evaporation rate of benzene from PX-10 and to assess the effect of several factors. In particular the experiments investigated the following:

- the 'passive' evaporation rate of benzene for PX-10 with different levels of benzene;

- the impact of composition of PX-10 such as mineral oil, fatty ester acid on the benzene evaporation rate;
- the change in evaporation rate over time;
- the impact of carrying out cleaning activities (i.e. agitating the cleaning solution) on the evaporation rates;
- the impact of the air speed over the evaporation surface on the evaporation rate; and
- the impact of the surface area/volume ratio of the container on the evaporation rate.

As production has been discontinued no PX-10 was available for the experiments and therefore, a mixture of white spirit, mineral oils and fatty acids was prepared for the experiments. The composition was based on the information obtained from the review of the report of the Dutch MoD and based on the old material data sheets (1). Benzene was added for most of the experiments, although for some experiments simulating cleaning activities, benzene was replaced by toluene to minimise potential risk for the staff undertaking the experiments.

The experiments were carried out within a fully enclosed box (31.5 x 31 x 34 cm) inside a ventilated fume cupboard (Figure 3-2). A container with PX-10 with a volume of 8 cm³ and a surface area of 6.4 cm² was placed inside the box. The airflow in and out of the box was kept at a constant rate and mixing of the air was ensured by an internal fan. A carbon filter was used to remove any volatile agents from the air flowing into the box.

The concentration of total VOCs was continuously measured with a direct reading detector (Phocheck photo ionisation detector, model 1000, ION Science Ltd., Cambs UK) placed in the box. In addition, benzene in air was sampled with coconut charcoal sorbent tubes which were analysed for benzene according to NIOSH method 1501.

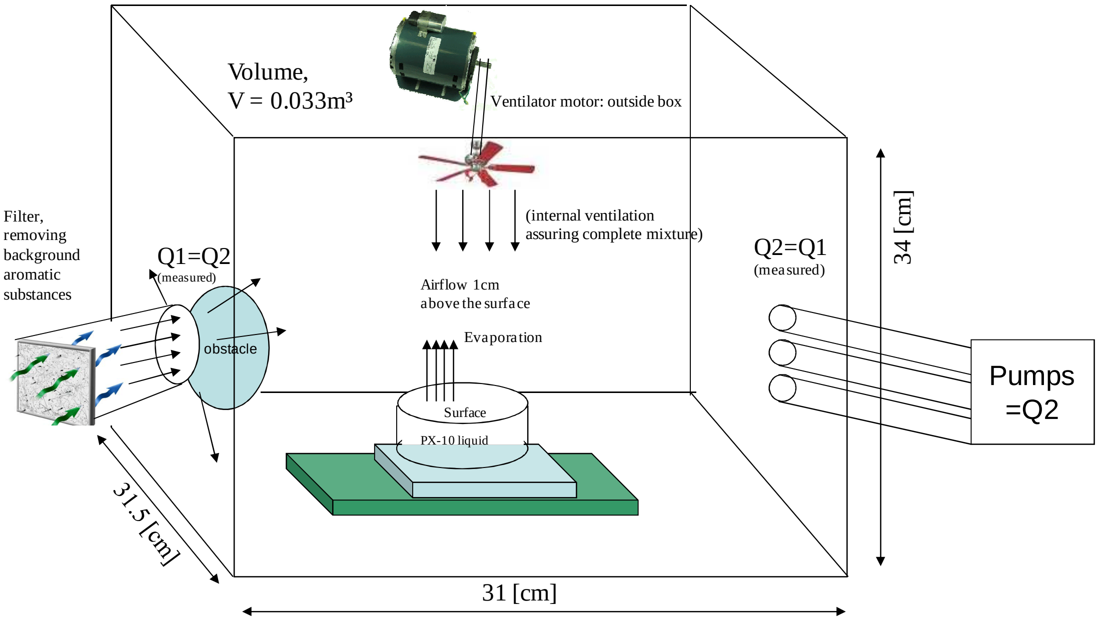

Figure 3-2: Experimental set up for the determination of the benzene evaporation rate (Q=flow through box [m³/min]).

A series of experiments were carried out to test whether the benzene emission rates increased linearly with the benzene concentration using white spirit mixtures with benzene contents ranging from 0 to 5%.

3.4 Emission rates of benzene and VOCs

The emission rate from the container with PX-10 was calculated from the air concentration assuming a steady state condition. Under steady-state condition, the concentration can be associated with the evaporation rate according to the formula [equation 3].

$$C_{ss} = \frac{G}{Q} \qquad \text{[equation 3]}$$

Where: Css = Steady state concentration [mg/m³], G = evaporation rate [mg/min], and Q = Flow through box [m³/min]

The steady state, with stable concentrations of all fractions, could not be maintained as the benzene concentration rapidly declined in the box. Nevertheless the approach allowed the determination of an initial emission rate and the speed of the emission decrease over time. The benzene emission rates in the workplaces were estimated using this information on benzene concentration in PX-10 over time and the experimentally determined emission rates. By varying the benzene concentration in the PX-10 simulation, the relationship between benzene content in PX-10 and emission rate was established. This approach simulated a passive evaporation only. To adjust for active manipulation of PX-10, for example brush cleaning of items, a test procedure was set up investigating the impact of active handling of the materials.

The estimation of the benzene emission from the work with soaked PX-10 cloths was based on the total mass of benzene in the amount of PX-10 that was stated to be used per day and which was assumed to have evaporated during this day. The emission rate was calculated as average over the day.

To estimate exposure to total VOCs, it was assumed that white spirit comprised of a small, highly volatile fraction and a large fraction of medium to low volatile liquids. The highly volatile part of the aromatic fraction was assumed to consist mainly of benzene and toluene, while the aliphatic fraction was assumed to consist of hexane and heptane isomers. The evaporation rate of the medium to low volatile components of PX was essentially constant for the duration of the experiments.

An approximate estimation of the VOCs emission rate was made, assuming that the information on the evaporation behaviour of benzene in PX-10 (that was determined in the experimental setup) was the same as that for all other highly volatile components in PX-10.

3.5 Monte Carlo simulation

To take into account some of the uncertainty in the model parameters, a probabilistic approach was used to estimate benzene and total VOCs exposure. For each model parameter a distribution was provided based on the available information, and a value picked at random for each run of the model. For each scenario the model was run 500 times. The results are provided as the average and standard deviation over all the runs. The probabilistic model was programmed in Matlab (Version 7, MathWorks, Natick, Massachusetts, USA).

While running the model for the exposure calculation the input variables for the model were simulated from triangular distributions, using three defined values:

minimum, maximum and mid-point. To determine the sensitivity of the overall model outcome on changes in the individual input parameters, an additional sensitivity analysis was performed.
The analysis consisted of the following steps:

- the mid-points of all the parameters were taken as input parameters for the model and the resulting exposure estimate was defined as baseline;
- the model was re-run modifying individually each parameter in the range from minimum to maximum; and
- the influence of the individual parameter modification on the outcome of the model was compared with the baseline value.

3.6 Dermal exposure

Due to the extensive use of PX-10 in the absence of any effective personal protective equipment, the contribution of dermal exposure was considered to be potentially significant in some of the PX-10 scenarios. Basically two types of dermal exposure patterns were described for the work with PX-10. The first involved completely submerging the hands in PX-10 for extensive periods. The second involved manual cleaning of surfaces with a cloth soaked with PX-10. Both application methods resulted in intense skin contact, although for the latter the skin surface in contact with PX-10 was smaller (inside palm of only one hand). Note that the dermal exposure was only estimated for benzene but not for VOCs as for the latter there were no dermal uptake estimates available.

Reported benzene uptake rates, partially derived from animal toxicological experiments, vary considerably depending on the experimental model used, the species chosen, the level of benzene applied, length of application, duration of the contact etc. As a consequence the estimated benzene flux through the skin varies to a high extent. The dermal contact of the workers with PX-10 was reported to be very intense and there is anecdotal evidence of widespread skin complaints amongst the former users of PX-10. Therefore, the higher reported uptake values were considered most appropriate for this population. Based on the literature review of Nies et al. (5) as well as Nies and Korinth (6) the benzene uptake rates could range from 1 mg/cm²/h for short-term contact to 2 mg/cm²/h for long-term contact with benzene. This value for benzene uptake rate of 2 mg/cm²/h is furthermore supported by Adami et al. (7) and Sheehan et al. (8). For the purpose of this study the dermal uptake rate was assumed to be, on average, 1.5 mg/cm²/h, ranging from 1 to 2 mg/cm²/h.

The internal benzene exposure, resulting from dermal uptake of benzene, was subsequently converted to equivalent inhalation exposure, based on a model provided by Nies et al., as well as Nies and Korinth (5, 6):

$$EIU = \frac{Uptake}{BR \cdot B \cdot CF} \qquad \text{[equation 4]}$$

Where: EIU is the equivalent inhalation unit [ppm];
Uptake is the daily dose of dermal exposure [mg/d];
BR is the breathing rate [m³/8-h d], defined as 10 m³ per shift of 8 h;
B is the inhalation bioavailability factor (no units), defined as 50%; and
CF is the factor to convert concentration to mass per unit volume [mg/m³], i.e. 1 ppm ≈ 3.2 mg/m³ of benzene.

4 Results of exposure assessment

4.1 Laboratory experiments

4.1.1 Evaluating the effect of benzene content in PX-10 on the 'passive' evaporation rate

A series of experiments were carried out to test whether the benzene emission rates increased linearly with benzene content in the mixture, ranging from 0 to 5%. The evaporation rate from the container was estimated under the assumption of steady state conditions. Figure 4-1 shows the measured emission rate in relation to the level of benzene (%) in the liquid. In experiments without benzene added, the resulting air levels were all below the limit of detection. The results seem to support a linear relationship between the (initial) evaporation rate of benzene and the concentration of benzene added to the PX-10 surrogate.

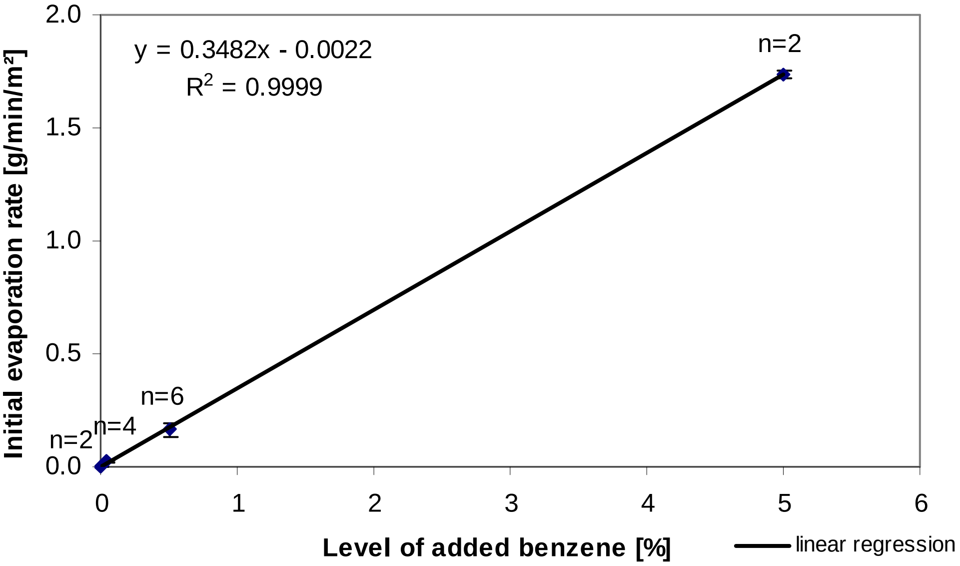

Figure 4-1: Estimated passive initial benzene emission rate by benzene content level in PX-10.

The measurement results were extrapolated linearly from the laboratory experiments to provide a benzene emission rate of PX-10 for a bath with a surface area of 1 m^2 using the following linear regression equation:

$$G = 0.3482 * BC - 0.0022 \quad \text{[equation 5]}$$

Where: G is the evaporation rate (in g/min/m²) and BC is the benzene content in PX-10 (volume %).

Using this equation and estimates of past benzene levels in PX-10, the benzene emission rates were estimated for different time periods (Table 4-1).

Table 4-1: Estimated benzene emission rates by time period based on benzene content of PX-10 as estimated previously (1).

Year	**Emission rate (g/min/m²)**		
	Average	**Minimum**	**Maximum**
<1970	0.03	0.00	0.07
1970-1980	0.01	0.00	0.03
>1980	0.00	0.00	0.01

4.1.2 *Effects of other components in PX-10 on benzene emission rates*

Experiments were carried out to determine the effect of mineral oil and fatty ester acid on the benzene evaporation rate. However, the results suggested that above components did not have any impact on the benzene emission rate from the PX-10 surrogate (results not shown).

4.1.3 *Stability of emission rate over time*

Experiments were carried out to determine the stability of the benzene and total VOCs emission rates over time. The total VOCs concentration in the box remained relatively constant over time at 100 ppm when no benzene was added to the white spirit mixture, suggesting a stable VOCs emission rate (horizontal grey line in Figure 4-2). When 5% benzene was added to the white spirit mixture, the total VOCs levels initially increased dramatically (blue line in Figure 4-2), suggesting the total air VOCs concentration in this situation was dominated by the benzene levels. However, the total VOCs concentration decreased rapidly over time because of a decrease in the benzene emission rate. This finding was confirmed by the results of three 10 minute charcoal tube samples, collected at different time periods during the experiment. The implication of the decreasing emission rate over time was that the benzene content in the PX-10 mixture was rapidly decreasing, i.e. the mixture is being depleted of benzene.

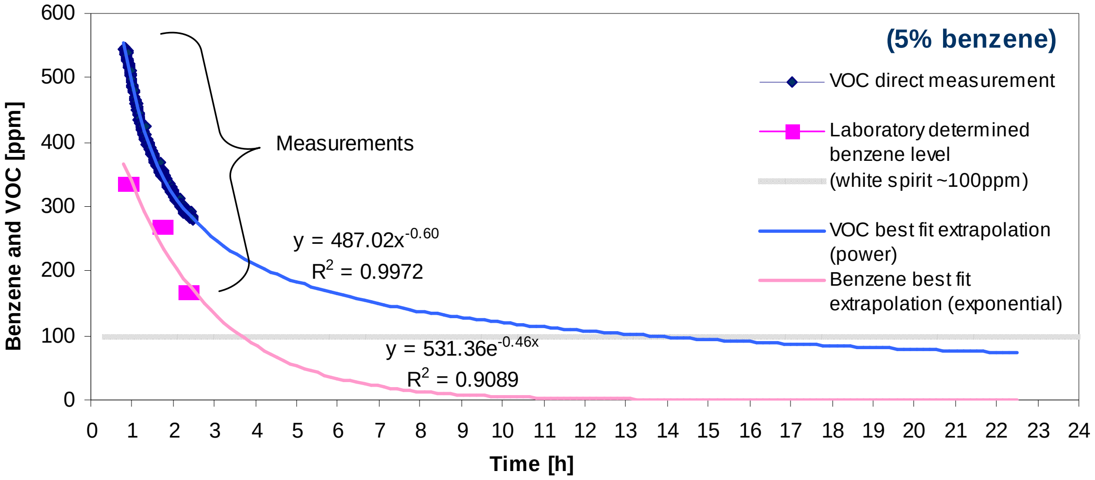

Figure 4-2: Total VOCs and benzene concentration over time in the box (measured with 5% benzene in the white spirit mixture). Note the different types of extrapolation for VOCs (approaching 100 ppm) and benzene (approaching 0 ppm).

Based on these results a half-life of 2 hours was estimated for the benzene content in the PX-10 mixture, which is comparable to results by Nicas et al. (9) who estimated a half-life of benzene in a petroleum distillates solvent of 3 to 5 hours.

Based on the experimental results the emission rate (G) was assumed to decrease exponentially over time according to the following equation:

$$G_t = e^{-\alpha \cdot t}$$ [equation 6]

With α as evaporation constant (defining the speed of decrease) and t for time. In the experiments the α was observed to range from 0.21 to 0.71, the ratio of the volume to surface area that was used in the experimental set up. In addition, other factors such as sampling and analytical error, as well as any differences in degree of mixing of benzene in the white spirit solution, may also have played a role. These influences are, however, expected to be minor.

The implication of the exponentially decreasing benzene emission rate over time was that within a day of filling an open bath with fresh PX-10, the benzene content of the mixture would have been negligible. The long-term average emission rates of benzene from the PX-10 bath depended therefore on the frequency and volume of topping up of the bath with fresh PX-10 and on the frequency of complete replacement of a bath with fresh PX-10. According to the focus groups, the complete replacement of the baths only occurred occasionally (~ once per month), although topping up of the bath with relatively small amounts of fresh PX-10 occurred more regularly (~ once per week).

4.1.4 *Impact of cleaning activities on the benzene evaporation rate*

The emission rates will have been affected by agitation of the liquid in the bath. Two separate experiments were carried out to simulate the effect of washing activity on the benzene emission rate. In particular, it was investigated whether the additional exposure as a result of washing could be thought of as an additional surface equivalent, i.e. passive emission from a notional additional area.

A steel bowl in a fully closed standard laboratory fume hood without ventilation was used to simulate a washing procedure. The fume hood was transformed into a glove box (closed lid with inert plastic and gloves to manipulate things inside the fume hood). Two baths were serially used for this experiment, with surface areas that differed by a factor 4. For both baths the evaporation rates were compared between a still bath (no activity) and cleaning activity. The cleaning activity was simulated by scrubbing a metal piece with a brush dipped every few seconds in the bowl containing simulated PX-10. To minimise the potential risk to the person conducting the work, these experiments were carried out with added toluene instead of benzene. Previous experiments had indicated that the toluene emission rates were comparable to the benzene emission rates.

The results showed an increased emission rate due to the activity of washing metal parts. This increase was best described as additional evaporation surface, not as multiplying factor. An approximation to the added emission was achieved by calculating the additional surface area for the bath when estimating the total emission rate of a bath with activity. The additional equivalent bath surface area required to explain the emission in the experimental setup was estimated to be 800 cm^2 (uncertainty range 724 cm^2 to 893 cm^2), which corresponded broadly to the total surface area of the gloves, metal piece, etc. that were in contact with PX-10. Based on this observation, the influence of the agitation of the passive bath was assumed to be best estimated with the surface that was brought into contact with PX-10 while carrying out the task. With the help of the task description this additional evaporation surface was estimated to be around 0.25 m^2 for each bath (8% of the average batch surface area of 3.2m^2). This equivalent surface area due to the cleaning activity was added in the model to the surface area of the baths to address additional evaporation.

This was a single exploratory experiment in a fume hood, and needed verification before being used in the box model, especially because the results depended on a manual interaction of a person. The setup of the former experiments for the still bath in the box was modified allowing a small metal piece with a known surface area dipping automatically and repeatedly into the evaporation container for a PX-10 with 1% benzene. The VOCs emission during this procedure was approximately 9% higher than VOCs emission without the dipper. This dipping disturbed the surface of the PX-10 and added a known wet surface to the surface of the evaporation container. A linear correlation was found between additional evaporation surface 'x' and the additional VOCs concentration (VOCs ppm = 20*x cm² - 2E-13, $R^2 = 0.990$). Based on this correlation, the influence of the disturbed surface was estimated by the surface of the dipper that was in contact with the mixture. The wet part of the dipper was measured to be around 7.5% which is comparable to the additional solvent emission of 9%.

Both approaches, the up-scaled toluene and the miniature VOCs/benzene, although only explorative, supported the assumption that the emission rates during washing activities could be approximated by simply adding the estimated equivalent evaporation surface area to the surface area of the bath.

4.1.5 *Effect of air speed over evaporation surface on evaporation rate*

The air speed over the surface in the box experiment was measured to be 0.24 m/s for the main experiments. To determine the impact of the internal air speed over the surface, the evaporation was monitored during steady state at the standard flow rate, the internal ventilation was then increased by having the fan directly pointing towards the liquid, doubling the air speed over the surface. This increase approximately doubled the VOCs concentration (Figure 4-3).

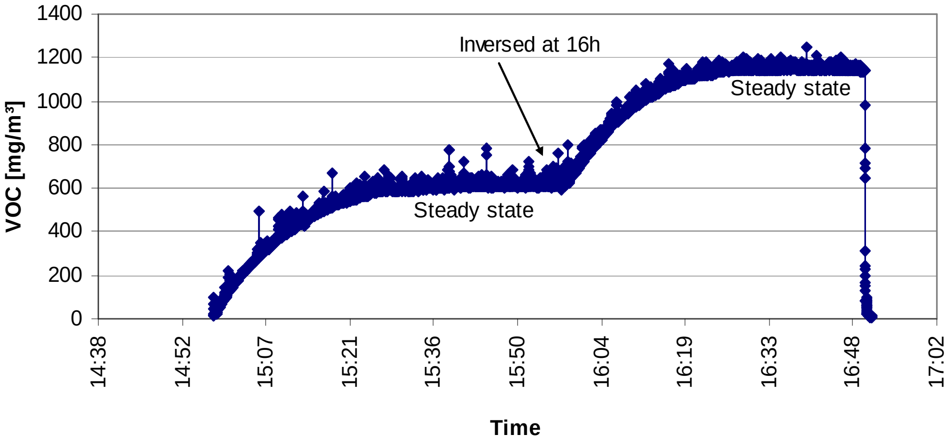

Figure 4-3: Effect of increasing air speed (double due to ventilation inversion) over the evaporation surface on the emission rate.

Although there is a clear effect of air speed on the evaporation rate, it was not clear whether this has any important implications for the estimated long-term benzene exposure levels in the PX-10 exposure scenarios. Most of the PX-10 baths were positioned in rooms with little ventilation and the wind speed over the actual surface was probably low, because the liquid surface would be somewhat below the edge of the bath. Therefore the data collected at 0.24 m/s might be quite high according to the typical workplace air speed data described by Baldwin and Maynard (10). On the other hand, use of compressed air was reported to dry the metal components. Clearly this would have resulted in much higher air speeds and consequently higher evaporation rates. Varying levels of wind speed over the evaporating surface would result in changes in the half-life of the benzene content in the PX-10 mixture. While affecting the pattern of exposure, these changes will have little influence on the long-term average exposure to benzene. The baseline VOCs emission, however, will have been influenced by the air speed, which might have led to higher estimates for the VOCs emission rate. Therefore, the model conditions were assumed to follow the 'worst case' conditions with rather high wind speed.

4.1.6 *Effect of container dimensions on the benzene evaporation rate*

The dimensions of the evaporation container in the experimental box were chosen to approximately reflect the miniaturised dimensions of a bath in a workplace environment of an average room. An additional experiment was carried out to determine the impact of the shape of the evaporation container on the benzene emission. A container with double the volume (19 cm^3) but the same surface area of 6.4 cm^2 was used to obtain an extreme value for the long term emission rate. With such a container, a half-life value of 13 hours was measured compared to 2 hours in the used container.

A sensitivity analysis was undertaken to assess the impact of different decrease rates, comparing the model outcomes. The daily average for the exposure to benzene did not change very much using either of the decrease rates. A 2 hour half-life was therefore applied in the main modelling assuming that the chosen dimensions are closer to the up-scaled bath dimensions.

4.1.7 *Cleaning torpedoes*

It was assumed that the emission rate for situations like the washing of torpedoes with a cloth was best described as a repeated total evaporation of a certain amount of PX-10. The situation is similar to the situation described by Nicas et al. (9) for the liquid wrench (a cleaning, lubricant agent). However, it was very difficult to determine the correct surface area for PX-10 in this task. The calculation of a surface evaporation was therefore omitted and the exposure to benzene and total VOCs for this scenario was estimated by the daily amount of PX-10 used for this activity as estimated by the focus groups. It was assumed that all of the benzene evaporated quickly from the thin layer when applied with a cloth to a metal surface. For the estimation of the daily exposure to benzene in the model a total evaporation in the near-field of a worker of all benzene (estimated by the amount of PX-10 used per day) was therefore assumed.

4.1.8 *Summary of laboratory experiments*

The main conclusion from the laboratory experiments was that the emission rate for benzene from PX-10 was not constant but decreased rapidly over time because of its higher vapour pressure compared to white spirit. This observation had significant implications for the predicted benzene exposure level for the exposure scenarios where metal parts were cleaned in an open bath (scenario 1-5). In contrast, this observation has limited or no impact on the exposure during the scenario that involved cleaning metal surfaces with a cloth soaked in PX-10 (scenario 6), as it was assumed that this activity will have always been carried out with fresh PX-10.

4.2 Model estimates for benzene exposure

To account for the uncertainties in the various input parameters a deterministic model was implemented using probabilistic techniques. There was uncertainty in the emission rate, room size, air change rate and the parameters associated with the likely dermal uptake.

Table 4-2 lists the input parameters used with triangular distribution and the sources on which they were based (see Appendix 1 for detailed information on the ranges used in each of the scenarios). For each scenario the outcomes of the model are presented as average and standard deviation of the simulations. The values are presented as inhalation exposure (in ppm) and as dermal uptake, the latter expressed as inhalation-equivalent (in ppm-eq.), according to the model by Nies et al. (5, 6) and Williams et al. (11).

The emission rates in the model were either based on the results of the experiments (for cleaning parts within a bath, scenario 1-5) or based on the total amount of (fresh) PX-10 used (for cleaning of the torpedo tube, scenario 6). The latter was calculated, given the amount used per day and the assumption that all benzene contained within the fresh PX-10 evaporated during eight hours.

The percentage of benzene content in PX-10 during various time periods was based on information obtained from the literature and expert review, and are lower than were originally estimated by the Dutch MoD (1). For the exposure scenarios where metal parts were cleaned in an open bath, two events occurred with certain regularity in the scenarios: a) the weekly top-up of PX-10 in a bath and b) much less frequently, a complete renewal of the bath.

Table 4-2: List of input parameters for the modelling (see Appendix 1 for more details).

Parameter	**Source the parameter is based on**
Scenarios	Obtained from focus group discussions
Emission Rate	1) Experiments 2) Amount of PX-10 used daily 3) Benzene level of PX-10 for specified time periods, as estimated previously (1)
Emission decrease rate	Experiments
Air change rate	Focus groups
Room Volume	Focus groups
Hours worked	Focus groups
Percentage of time spent in NF & FF	Focus groups
Local ventilation	Focus groups
Dermal uptake rate	Literature
Fraction of benzene in solution	Benzene level of PX-10 for specified time periods, as estimated previously (1)
Exposure duration	Focus groups
Surface area	Literature
Breathing rate	Literature
Inhalation bioavailability factor	Literature
Conversion factor (from mg/m^3 to ppm)	Literature

4.2.1 *Benzene exposure after top-up of PX-10 baths*

The probabilistic model was run for the different time periods, scenarios and the two exposure routes (inhalation and dermal). Due to the rapid evaporation of benzene from the open bath of PX-10, the actual benzene content in the bath would have been negligible within a day of topping up a bath with fresh PX-10. Note that the added amount of benzene following a top-up was rather limited compared to the size of the bath. In general this was assumed to have occurred once a week. Information on the frequency and the amount of PX-10 top-up was obtained from the focus groups. The evaporation rate was calculated for the bath scenarios by calculating the concentration of benzene in the bath given the amount of added PX-10 and dividing it by the volume of the bath.

$$C_{bath} = C_{PX-10} \cdot \frac{Volume_{top-up}}{Volume_{bath}}$$

[equation 7]

In the case of replacement of all PX-10 in the bath, the whole volume of added PX-10 was considered to have the benzene concentration as estimated previously (1).

4.2.2 *Average daily benzene exposure from near-field and far-field sources*

Tables 4-3 and 4-4 show the 8 hour-Time Weighted Average (TWA) predicted inhalation, dermal and combined benzene exposures for working with a source in the near-field (NF) only (Table 4-3) and for working with a source in the far-field (FF) only (Table 4-4).

The frequencies with which the baths of PX-10 were completely replaced substantially influenced the exposure to benzene. For each scenario the frequency of total PX-10 replacement has been estimated using information obtained during the focus groups:

- Armouries: from 12/year to 2-3/year;
- Ships: from 12/year to 4/year;
- Workshops: 12/year (one response only); and
- Washing room: 40/year (one response only). This last statement has been ignored, as, firstly, it contradicts the focus group discussion where a less frequent ‘topping up’ was stated.

Weekly average exposures were estimated for weeks with 1) a complete bath replacement and 2) PX-10 top-up. The top-ups and full bath replacements were assumed to occur at the start of the week. The weekly average exposures were estimated based on the declining exposure levels during the week, with relatively high exposures on the day of full PX-10 replacements and top-ups. The yearly average exposure was calculated based on the information obtained from the focus groups on the frequencies of bath replacements and top-ups. Exposure was assumed to occur only during week days; no holiday breaks were included for the calculation of annual average exposure.

$$Exposure_{year}\O = \alpha \cdot Exposure_{top-up}\O + \beta \cdot Exposure_{full-replacement}\O$$

[equation 8]

Where: Exposure$_{top-up}$ is the exposure during top-up and Exposure$_{full-replacement}$ is the exposure during full replacement of the bath. Appendix 1 provides the values for the ranges for the top-up and PX-10 replacement frequencies for each scenario.

Table 4-3 shows the average benzene exposure based on 8 hour work shifts that are exclusively spent with a source in the near-field, i.e. next to a bath or working with the soaked cloth. These results do not reflect the actual work hours. Results are presented for the inhalation exposure and the dermal exposure as well as the combined exposure. The combined exposures show values in the range of 0.02 to 0.9 ppm for the highest exposure estimates (i.e. years before 1970). The dermal exposure was much lower than the inhalation exposure for scenarios 1 to 5. However, for scenario 6 the (inhalation equivalent) exposure by the dermal route was similar as the inhalation exposure. This was due to intense dermal contact with fresh PX10, increasing the dermal exposure, and the large size of the torpedo hall, which resulted in a reduction of the inhalation exposure compared with similar activities in a small room.

Table 4-4 shows the average benzene exposure based on the weekly average of 8 hour work shifts that are exclusively spent with a source in the far-field but not in the near-field. Due to the small dimensions of some of the rooms and the low ventilation rates, the inhalation exposure levels for far-field sources are similar to the near-field values except for the large torpedo halls. No dermal exposure was calculated for these situations, because a far-field source would not lead to dermal exposure (Table 4-5).

Table 4-3: Yearly average benzene exposure based on weekly average of 8 hour work ONLY in the near-field (NF).

No	**Description**	**Year**	**Yearly 8h NF inhalation**			**Yearly 8h dermal estimation (inhalation equivalent)**			**Total (inhalation and dermal) yearly 8h NF inhalation equivalent**		
			Mean	**5th**	**95th**	**Mean**	**5th**	**95th**	**Mean**	**5th**	**95th**
			[ppm]	[ppm]	[ppm]	[ppm eq.]	[ppm eq.]	[ppm eq.]	[ppm eq.]	[ppm eq.]	[ppm eq.]
1	**Cleaning small arms in weapon rooms**	Before 1970	0.505	0.213	0.914	0.011	0.004	0.021	0.516	0.218	0.935
		1970-1980	0.225	0.089	0.406	0.005	0.002	0.010	0.231	0.091	0.416
		After 1980	0.049	0.019	0.087	0.002	0.001	0.003	0.051	0.020	0.090
2	**Cleaning small arms onboard of ships**	Before 1970	0.272	0.104	0.472	0.011	0.003	0.022	0.283	0.107	0.494
		1970-1980	0.114	0.041	0.208	0.005	0.002	0.010	0.119	0.043	0.218
		After 1980	0.026	0.010	0.048	0.002	0.001	0.003	0.028	0.010	0.051
3	**Cleaning small arms in small workshops**	Before 1970	0.071	0.027	0.125	0.011	0.004	0.021	0.082	0.031	0.146
		1970-1980	0.029	0.011	0.054	0.005	0.002	0.010	0.034	0.013	0.063
		After 1980	0.005	0.002	0.009	0.002	0.001	0.003	0.006	0.002	0.012
4	**Cleaning small arms in large workshops**	Before 1970	0.014	0.005	0.025	0.011	0.004	0.020	0.025	0.010	0.045
		1970-1980	0.006	0.002	0.011	0.005	0.002	0.010	0.011	0.004	0.021
		After 1980	0.001	0.001	0.003	0.001	0.001	0.003	0.003	0.001	0.005
5	**Washing of torpedo parts in the adjacent room**	Before 1970	0.174	0.057	0.331	0.011	0.004	0.021	0.185	0.061	0.352
		1970-1980	0.080	0.025	0.154	0.005	0.002	0.010	0.085	0.027	0.163
		After 1980	0.026	0.008	0.054	0.002	0.001	0.003	0.028	0.009	0.057
6	**Maintenance torpedoes onshore**	Before 1970	0.528	0.202	0.875	0.368	0.102	0.672	0.896	0.304	1.547
		1970-1980	0.233	0.074	0.415	0.159	0.048	0.314	0.392	0.122	0.729
		After 1980	0.072	0.024	0.132	0.050	0.013	0.097	0.122	0.037	0.230

Note that these numbers are NOT the peak exposure values after a top-up or full replacement – the values of this table take into consideration the decrease over the week.

The values are shown with a resolution of three digits after the decimal separator, be aware that this high resolution is provided to avoid zero values.

Table 4-4: Yearly average benzene exposure based on 8 hour work ONLY in the far-field (FF).

No	**Description**	**Year**	**Yearly FF inhalation**			**Yearly dermal estimation**	**Total (inhalation and dermal) yearly FF inhalation equivalent**		
			Mean	**5th**	**95th**	**No dermal exposure**	**Mean**	**5th**	**95th**
			[ppm]	[ppm]	[ppm]		[ppm eq.]	[ppm eq.]	[ppm eq.]
1	**Cleaning small arms in weapon rooms**	Before 1970	0.511	0.208	0.933	No dermal exposure was assumed to occur as this is the far-field of a working person	0.511	0.208	0.933
		1970-1980	0.223	0.088	0.397		0.223	0.088	0.397
		After 1980	0.049	0.020	0.090		0.049	0.020	0.090
2	**Cleaning small arms onboard of ships**	Before 1970	0.273	0.104	0.476		0.273	0.104	0.476
		1970-1980	0.113	0.043	0.208		0.113	0.043	0.208
		After 1980	0.026	0.011	0.049		0.026	0.011	0.049
3	**Cleaning small arms in small workshops**	Before 1970	0.066	0.024	0.119		0.066	0.024	0.119
		1970-1980	0.026	0.010	0.048		0.026	0.010	0.048
		After 1980	0.005	0.002	0.009		0.005	0.002	0.009
4	**Cleaning small arms in large workshops**	Before 1970	0.007	0.003	0.013		0.007	0.003	0.013
		1970-1980	0.003	0.001	0.005		0.003	0.001	0.005
		After 1980	0.001	0.000	0.001		0.001	0.000	0.001
5	**Washing of torpedo parts in the adjacent room**	Before 1970	0.170	0.057	0.330		0.170	0.057	0.330
		1970-1980	0.078	0.026	0.152		0.078	0.026	0.152
		After 1980	0.026	0.008	0.051		0.026	0.008	0.051
6	**Maintenance torpedoes onshore**	Before 1970	0.041	0.016	0.081		0.041	0.016	0.081
		1970-1980	0.019	0.006	0.040		0.019	0.006	0.040
		After 1980	0.005	0.002	0.011		0.005	0.002	0.011

Note that the far-field inhalation exposure for the scenario ‘washing of torpedo parts in the annexed room to the torpedo hall’ is based on the FF of the ‘maintenance torpedoes in the torpedo hall’ and therefore based on the less accurate total mass-approach. Note furthermore that these numbers are NOT the peak exposure values after a top-up or full replacement – the values of this table take into consideration the decrease over the week. The values are shown with a resolution of three digits after the decimal separator, be aware that this high resolution is provided to avoid zero values.

4.2.3 *Average daily benzene exposure from near-field and far-field sources adjusted for reported daily working hours at the PX-10 task*

Using the average work hours that were reported by the focus group members for the PX-10 activities, the yearly exposure estimates were adjusted using the following procedure:

- The time spent on working with PX-10 (NF source) was introduced in the probabilistic modelling, using the range described by the focus group members; and
- The total working time on a day was assumed to be 8 hours. If the time spend on the activity was less than 8 hours, then the remainder of the 8 hours was taken to be the time spent elsewhere. The remainder of the time was selected to be in the far-field for this PX-10 activity, in the far-field for another PX-10 task or in a non-exposed area, depending on the scenario description (see Appendix 1).

Based on these calculations an estimated average exposure for a worker was calculated for each scenario. Table 4-5 presents the results for the inhalation exposure and the dermal exposure as well as the combined exposure. The combined results show values in the range of 0.01 to 0.5 ppm for the highest exposure estimates (years before 1970). These average values were only slightly lower than the estimated 8 hour values, which can be explained by the fact that for many tasks the focus group stated long working hours – either in the near-field or in the far-field, but only little time at another places.

Table 4-5: Yearly average benzene exposure based on the reported work hours spent in the near- and far-field (NF&FF) respectively.

No	**Description**	**Year**	**Yearly NF&FF inhalation**			**Yearly dermal estimation (inhalation equivalent)**			**Total (inhalation and dermal) yearly inhalation equivalent**		
			Mean	**5th**	**95th**	**Mean**	**5th**	**95th**	**Mean**	**5th**	**95th**
			[ppm]	[ppm]	[ppm]	[ppm eq.]	[ppm eq.]	[ppm eq.]	[ppm eq.]	[ppm eq.]	[ppm eq.]
1	**Cleaning small arms in weapon rooms**	Before 1970	0.444	0.300	0.598	0.007	0.004	0.010	0.451	0.304	0.608
		1970-1980	0.194	0.127	0.265	0.003	0.002	0.005	0.197	0.129	0.270
		After 1980	0.043	0.029	0.056	0.001	0.001	0.001	0.044	0.029	0.058
2	**Cleaning small arms onboard of ships**	Before 1970	0.284	0.194	0.378	0.004	0.002	0.006	0.287	0.196	0.384
		1970-1980	0.120	0.081	0.163	0.002	0.001	0.003	0.122	0.082	0.165
		After 1980	0.028	0.019	0.038	0.001	0.000	0.001	0.029	0.019	0.039
3	**Cleaning small arms in small workshops**	Before 1970	0.070	0.047	0.096	0.004	0.002	0.006	0.074	0.049	0.101
		1970-1980	0.029	0.019	0.039	0.002	0.001	0.003	0.030	0.020	0.041
		After 1980	0.005	0.003	0.007	0.001	0.000	0.001	0.006	0.003	0.008
4	**Cleaning small arms in large workshops**	Before 1970	0.129	0.066	0.201	0.008	0.004	0.013	0.137	0.070	0.213
		1970-1980	0.059	0.029	0.093	0.004	0.002	0.006	0.062	0.031	0.099
		After 1980	0.020	0.010	0.032	0.001	0.001	0.002	0.021	0.010	0.034
5	**Washing of torpedo parts in the adjacent room**	Before 1970	0.009	0.006	0.013	0.004	0.002	0.005	0.013	0.008	0.018
		1970-1980	0.004	0.003	0.005	0.002	0.001	0.003	0.006	0.004	0.008
		After 1980	0.001	0.001	0.001	0.000	0.000	0.001	0.001	0.001	0.002
6	**Maintenance torpedoes onshore**	Before 1970	0.307	0.160	0.522	0.199	0.043	0.435	0.506	0.203	0.957
		1970-1980	0.136	0.065	0.241	0.086	0.021	0.199	0.222	0.086	0.44
		After 1980	0.044	0.022	0.075	0.027	0.006	0.063	0.071	0.028	0.138

The values are shown with a resolution of three digits after the decimal separator, be aware that this high resolution is provided to avoid zero values.

4.2.4 *Sensitivity analysis*

Sensitivity analyses were carried out to test whether one of the main input variables dominated the results. The calculations used only the deterministic model with average parameter values and the outcome of the individual modifications of the parameters ‘air exchange rate’, ‘room volume’ and the two emission rates in the near- and far-field using the minimum and maximum value of their range. The subsequent input variables influenced the model similarly in all scenarios which suggested that none of them dominated the results.

Table 4-6: Sensitivity analysis of the parameters used in the Monte Carlo model. The influence on the outcome was expressed relative to the average outcome.

		Scenario 1	**Scenario 2**	**Scenario 3**	**Scenario 4**	**Scenario 5**	**Scenario 6**
Air exchange rate	Minimum	2.49	1.43	2.73	2.06	2.43	1.57
	Maximum	1.11	1.11	1.1	1.06	4.26	1.04
Room volume	Minimum	0.91	0.91	0.92	0.95	0.51	0.97
	Maximum	1.52	1.61	1.56	2.98	1.78	1.93
NF emission rate	Minimum	0.35	0.44	0.39	0.6	0.58	0.71
	Maximum	2.49	1.43	2.73	2.06	2.43	1.57
FF emission rate	Minimum	0.63	0.77	0.65	0.78	0.64	0.88
	Maximum	0.91	0.91	0.92	0.95	0.51	0.97
Half-life *	Minimum	1.56	1.56	1.56	1.56	1.56	1.56
	Maximum	0.83	0.83	0.83	0.83	0.83	0.83

Scenario 1: Weapon room maintenance (military): small arms
Scenario 2: Onboard maintenance (military): small arms
Scenario 3: Workshop in small room (civilians): small arms
Scenario 4: Workshop in large room (civilians): small arms
Scenario 5: Washing room: small parts of torpedoes in bath
Scenario 6: Torpedo hall: the main body of the torpedoes
*) Calculation based on the values of α ranging from 0.6 - 2.3. No estimation for the scenario d without a bath was calculated.

As expected of a multiplicative model that depends equally on the emission rate, size of room and rate of air exchange, the outcome of the sensitivity analysis did not show a dominating variable.

A sensitivity analysis for different emission rate decreases (expressed as the evaporation constant: α) were carried out. The half-life time of 1.2 hour (alpha 0.6) was used to calculate the baseline of the model and other half-lifes were compared to it. The initial emission rate was adjusted to account for the change in the decrease rate so that the same total amount of benzene was emitted over time, regardless of the half-life. As would be expected the shorter half-life (α =1.2) resulted in most of the benzene being emitted during the first 8 hours (workday). The slower decrease rate (α = 0.3) resulted in lower exposures during the first 8 hours, and as the remainder of the benzene would have been emitted overnight when no operators were present, the overall average exposure would have also been lower.

Table 4-7: Sensitivity analysis for the half-life of the benzene emission rate used in the Monte Carlo model.

Approximated half-life [h]	**0.6**	**1.2**	**2.3**	**4.6**	**9.2**	**18.5**
α [h^{-1}]	1.2	0.6	0.3	0.15	0.075	0.0375
Exposure relative to α=0.6	1.56	1.00	0.83	0.76	0.73	0.70

α = the evaporation constant (see equation [6])

4.3 Model estimates for VOCs exposure

The total VOCs emission rate from fresh PX-10 was initially dominated by the highly volatile components of the mixture. In addition to benzene, other highly volatile agents would have been present in PX-10, both aromatic (e.g. benzene, toluene) and aliphatic hydrocarbons (e.g. hexane and heptane). This approach of distinction between a highly and a lower evaporative fraction is supported by Kopstein (12). The total highly volatile fraction in the PX-10 was unknown and had therefore to be estimated using the following assumptions:

1. the highly volatile fraction was the same for the aromatic and aliphatic fraction in PX-10;
2. PX-10 consisted of 80% aliphatic and 20% aromatic hydrocarbons. This is based on the safety data sheet information on the composition of PX-10 over time which suggests that the aromatic content was around 20% until approximately 1987, after which time PX-10 was no longer used in large quantities (1); and
3. the highly volatile components in the aromatic fraction consisted of benzene and toluene in equal quantities (see Table 3-2).

Table 4-8 provides the estimates of the total highly volatile faction of PX-10 for three different time periods.

Table 4-8: Estimation for the composition of the total highly volatile fraction of PX-10.

	Before 1970		**1970-1980**		**After 1980**	
	Average	Upper limit	Average	Upper limit	Average	Upper limit
Total aromatic	**20%**	**20%**	**20%**	**20%**	**20%**	**20%**
Benzene total	0.10%	0.20%	0.03%	0.10%	0.01%	0.03%
Toluene total	0.10%	0.20%	0.03%	0.10%	0.01%	0.03%
Total highly volatile aromatic	0.20%	0.40%	0.06%	0.20%	0.02%	0.06%
Total aliphatic	**80%**	**80%**	**80%**	**80%**	**80%**	**80%**
Hexane total	0.40%	0.80%	0.12%	0.40%	0.04%	0.12%
n-Heptane total	0.40%	0.80%	0.12%	0.40%	0.04%	0.12%
Total highly volatile aliphatic	0.80%	1.60%	0.24%	0.80%	0.08%	0.24%
Total highly evaporative	**1.0%**	**2.0%**	**0.3%**	**1.0%**	**0.1%**	**0.3%**

To estimate the emission rate for the highly volatile components of PX-10 it was assumed that they all evaporated at the same rate as benzene. After the highly volatile fraction was evaporated, VOCs continued to be emitted from the mixture at a constant rate. This constant emission rate was estimated based on the experimentally determined evaporation rate of modern white spirit, which has a very small highly volatile fraction.

In the experimental box, the baseline of white spirit was measured to be 100 ppm (under the given box properties and flow rates). This was extrapolated to a 1 m² bath (by analogy with the benzene rate, a flow of 2 L/min and a surface of 6.4 cm² but with the weight conversion for white spirit of 1 ppm = 5.5 mg/m³ (13)). This corresponded to a constant VOCs emission rate of 100 ppm or 1.7 g/min/m² of modern white spirit and provided the estimation for the constant baseline VOCs emission of PX-10. Sizes of the baths were also adjusted to account for active washing of equipment in the VOCs emission modelling.

Figure 4-4 shows the resulting VOCs emission rate for fresh PX-10 before 1970, when the total highly volatile fraction of PX-10 was assumed to be 1%. The highly volatile fraction rapidly evaporated out of the bath, leading to elevated VOCs concentrations, followed by a decrease in VOCs emission, until the system reached the baseline emission rate.

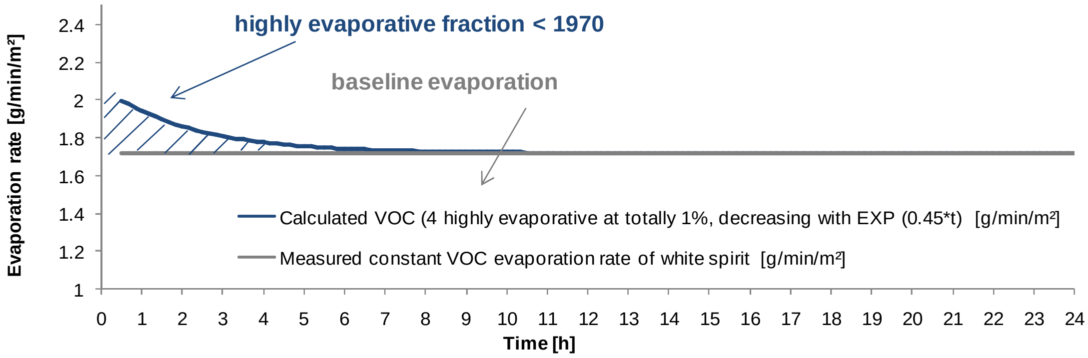

Figure 4-4: Estimated VOCs emission rate over time of PX-10 – example of new PX-10 bath.

According to equation [5] the highly volatile fraction in PX-10 had an initial emission rate of 0.346 g/min/m², assuming that all the highly volatile components evaporated at the same rate as benzene.

Based on this decreasing emission rate, which approximates the baseline after about 6 hours, the probabilistic exposure model was used as described for the benzene concentration modelling. The subsequent tables show the results for total VOCs exposure. They are presented in the same manner as above, however, only for inhalation exposure due to badly defined dermal uptake of VOCs:

- Long-term average exposure from near-field activities assuming the activity takes up the entire working day (Table 4-9);
- Long-term average exposure from far-field activities, assuming the activity takes up the entire working day (Table 4-10); and
- Long-term average exposure, based on the reported actual duration of exposure to VOCs from near-field and far-field sources (Table 4-11).

It is apparent in the subsequent three tables that the highly volatile fraction was a minor part of the average yearly exposure to VOC.

Table 4-9: Yearly average VOCs exposure based on 8 hour work ONLY in near-field (NF).

No	**Description**	**Year**	**Yearly 8h NF inhalation**		
			mean	**5th**	**95th**
			[ppm]	[ppm]	[ppm]
1	**Cleaning small arms in weapon rooms**	Before 1970	96	76	118
		1970-1980	92	72	113
		After 1980	95	74	118
2	**Cleaning small arms onboard of ships**	Before 1970	55	48	63
		1970-1980	54	46	62
		After 1980	53	46	61
3	**Cleaning small arms in small workshops**	Before 1970	14	11	17
		1970-1980	14	10	17
		After 1980	13	10	17
4	**Cleaning small arms in large workshops**	Before 1970	3	2	3
		1970-1980	3	2	3
		After 1980	3	2	3
5	**Washing of torpedo parts in the adjacent room**	Before 1970	33	23	45
		1970-1980	34	22	47
		After 1980	34	23	48
6	**Maintenance torpedoes on-shore**	Before 1970	168	152	183
		1970-1980	153	138	168
		After 1980	149	134	163

Note that these numbers are NOT the peak exposure values after a top-up or full replacement – the values of this table take into consideration the decrease over the week.

Table 4-10: Yearly average VOCs exposure based on 8 hour work ONLY in far-field (FF).

No	**Description**	**Year**	**Yearly 8h FF inhalation**		
			mean	**5th**	**95th**
			[ppm]	[ppm]	[ppm]
1	**Cleaning small arms in weapon rooms**	Before 1970	95	75	118
		1970-1980	91	72	112
		After 1980	93	71	119
2	**Cleaning small arms onboard of ships**	Before 1970	55	47	62
		1970-1980	53	46	61
		After 1980	52	45	60
3	**Cleaning small arms in small workshops**	Before 1970	12	9	16
		1970-1980	12	9	16
		After 1980	12	9	16
4	**Cleaning small arms in large workshops**	Before 1970	1	1	2
		1970-1980	1	1	2
		After 1980	1	1	2
5	**Washing of torpedo parts in the adjacent room**	Before 1970	32	21	43
		1970-1980	33	21	46
		After 1980	33	21	46
6	**Maintenance torpedoes on-shore**	Before 1970	16	12	22
		1970-1980	15	11	19
		After 1980	14	10	19

Note that the far-field inhalation exposure for the Scenario 'washing of torpedo parts in the annexed room to the torpedo hall' is based on the FF of the 'maintenance torpedoes in the torpedo hall' and therefore based on the less accurate total mass-approach. Note furthermore that these numbers are NOT the peak exposure values after a top-up or full replacement – the values of this table take into consideration the decrease over the week.

Table 4-11: Yearly average VOCs exposure based on the reported work hours spent in the near- and far-field respectively.

No	**Description**	**Year**	**Yearly NF&FF inhalation accounted for work hours and location**		
			mean	**5th**	**95th**
			[ppm]	[ppm]	[ppm]
1	**Cleaning small arms in weapon rooms**	Before 1970	78	69	88
		1970-1980	75	65	84
		After 1980	77	68	88
2	**Cleaning small arms onboard of ships**	Before 1970	54	50	58
		1970-1980	53	49	57
		After 1980	53	49	56
3	**Cleaning small arms in small workshops**	Before 1970	13	11	14
		1970-1980	12	11	14
		After 1980	12	11	14
4	**Cleaning small arms in large workshops**	Before 1970	2	2	2
		1970-1980	2	2	2
		After 1980	2	2	2
5	**Washing of torpedo parts in the adjacent room**	Before 1970	27	20	43
		1970-1980	27	19	46
		After 1980	27	20	46
6	**Maintenance torpedoes on-shore**	Before 1970	97	60	148
		1970-1980	88	53	132
		After 1980	86	51	128

Note that the far-field inhalation exposure for the Scenario 'washing of torpedo parts in the annexed room to the torpedo hall' is based on the FF of the 'maintenance torpedoes in the torpedo hall' and therefore based on the less accurate total mass-approach. Note furthermore that these numbers are NOT the peak exposure values after a top-up.

5 Quantification of potential health effects

5.1 Methods: life table analysis

In life table analysis a hypothetical cohort of subjects is followed from birth through death. For each age (year) the following aspects are calculated: the size of the population at risk, the number of cases of a specific health outcome that arises in an unexposed population, the (cumulative) exposure for exposed individuals in the populations, and the number of cases of a specific health outcome in the exposed population. By combining this information the Excess Risk (ER) (the number of additional cases per 100.000 exposed individuals) can be expressed as a function of age. The steps in the life table analysis are illustrated in Figure 5-1.

Estimate the size of the population at risk (Figure 5-1A)

Data from Statistics Netherlands (CBS) were used to estimate the population at risk for each age (in years) between the ages 0 to 100 years. The population at risk is defined as the percentage of the population at age 0 that is still capable of developing health effects associated to benzene exposure. In case of death individuals leave the population at risk. Between the ages 0 and 100 years the population at risk decreases from 100% (at age 0) to <1% (at age 100).

Number of cases in the unexposed population (Figure 5-1B; 5-1C; Table 5-1)

Data from the Comprehensive Cancer Centre (IKC) were used (1989-2008) to estimate age-specific incidence rates for the relevant diseases in a population that is not occupationally exposed to benzene. The age-specific incidence rates are combined with the age-specific size of the population at risk to calculate the number of incident cases in the unexposed population at risk.

Table 5-1: Expected number of cases in unexposed population (100,000) till the age of 120 (source: Comprehensive Cancer Centre).

	# Cases
Total Leukaemia	1121
Acute Myeloid Leukaemia (AML)	334
Acute Lymphocytic Leukaemia (ALL)	118
Chronic Lymphocytic Leukaemia (CLL)	496
Non-Hodgkin Lymphoma (NHL)	1769
Multiple Myeloma (MM)	1446

Exposure (Figure 5-1D)

In life table analyses of chronic exposures, cumulative exposure is generally used as exposure metric. Cumulative exposure is the product of intensity and duration of exposure. It is a standard exposure metric used in many occupational studies of chronic health effects as index of the target tissue dose. Here we generate cumulative exposure estimates for two hypothetical individuals based on two realistic exposure scenarios and the yearly average benzene exposure estimates incorporating the inhalation and dermal route of exposure (Table

4-5). These scenarios (one military and one civilian) were chosen as they are two 'high' exposed scenarios as provided by MoD. The career scenarios are presented in Table 5-2. The exposure scenarios are presented in Tables 5-3 and 5-4.

Table 5-2: Assumptions exposure scenarios.

Career 1 'military personnel of the Navy'	**Career 2 'civilian'**
Cleaning small arms in weapon rooms and on ships	*Cleaning small arms in small workshops*
Duration career: 38 yrs (age 18-55) Start career: 1964 Rotation land-ship: 3 yrs	Duration career: 48 yrs (age 18-65) Start career: 1945 Exposure: 8 hours/day Full duration of career at the same workplace
Phase 1 (Seaman) Duration: 6 yrs Exposure: 4-8 hours/day	
Phase 2 (Corporal) Duration: 9 yrs Exposure: 1-4 hours/day	
Phase 3 (Sergeant) Duration: until end of career Exposure: several hours/month	

Table 5-3: Scenario 'Cleaning small arms in weapon rooms and on ships'.

Year start	*Year end*	*Age start*	*Age end*	*Duration (years)*	*Work location*	*Rank*	*Hrs/day*	*Cumulative exposure (ppm-yr)*
1964	1966	18	20	3	weapon room	Seaman	6	1.16
1967	1969	21	23	3	ship	Seaman	6	1.78
1970	1972	24	26	3	weapon room	Corporal	2.5	2.00
1973	1975	27	29	3	ship	Corporal	2.5	2.11
1976	1978	30	32	3	weapon room	Corporal	2.5	2.32
1979	1980	33	34	2	ship	Sergeant	1	2.35
1981	1981	35	35	1	ship	Sergeant	1	2.35
1982	1984	36	38	3	weapon room	Sergeant	1	2.37
1985	1987	39	41	3	ship	Sergeant	1	2.38
1988	1990	42	44	3	weapon room	Sergeant	1	2.40
1991	1993	45	47	3	ship	Sergeant	1	2.41
1994	1996	48	50	3	weapon room	Sergeant	1	2.42
1997	1999	51	53	3	ship	Sergeant	1	2.42
2000	2001	54	55	2	weapon room	Sergeant	1	2.42

Table 5-4: Scenario ‘Cleaning small arms in workshops’.

Year start	*Year end*	*Age start*	*Age end*	*Duration (years)*	*Hrs/day*	*Cumulative exposure (ppm-yr)4*
1945	1947	18	20	3	8	0.22
1948	1950	21	23	3	8	0.44
1951	1953	24	26	3	8	0.67
1954	1956	27	29	3	8	0.89
1957	1959	30	32	3	8	1.11
1960	1962	33	35	3	8	1.33
1963	1965	36	38	3	8	1.55
1966	1968	39	41	3	8	1.78
1969	1969	42	42	1	8	1.85
1970	1971	43	44	2	8	1.91
1972	1974	45	47	3	8	2.00
1975	1977	48	50	3	8	2.09
1978	1980	51	53	3	8	2.18
1981	1983	54	56	3	8	2.20
1984	1986	57	59	3	8	2.22
1987	1989	60	62	3	8	2.23
1990	1992	63	65	3	8	2.25

The cumulative exposure was derived from the exposure estimates described in chapter 4.

Risk function (Figure 5-1E)

A risk function (dose-response relation) is needed in life table analysis to quantify the relation between cumulative exposure to benzene and the relative risk of developing an adverse health effect. In the life table analysis multiplicative relative risk functions were derived from meta-regressions of studies on humans occupationally exposed to benzene, see Table 5-5. A multiplicative relative risk model assumes that benzene increases the background incidence rate by a multiplicative factor that depends on prior benzene exposure (14). Multiplicative linear models were fitted for all endpoints (15). In addition, nonlinear models were fitted for leukaemia and AML (15). These were fitted with and without an intercept. The intercept in the regression model represents the difference between the background disease rate in the study population as compared to the referent population. In the life table analysis this difference in background rate was addressed by subtracting the intercept from all predictions (effectively lowering the predicted (increased) risks for benzene at each exposure level). In addition to the multiplicative models a set of additive models published by the US Environmental Protection Agency (U.S. EPA) (16) for leukaemia and AML were applied in the life table analysis. An additive risk model assumes that benzene increases the background mortality rate by an additive amount that depends on prior benzene exposure. In Table 5-5 the general form and parameter estimates for the risk functions used in the life table analyses for leukaemia, AML, MM, and NHL are presented. Because of the relative high uncertainty in the risk estimates for CLL and ALL we used the risk function estimate of total leukaemia.

Table 5-5: Risk functions used in the life table analysis.

Health outcome	Multiplicative Spline Intercept[a,b]	Multiplicative Spline No intercept[b,c]	Multiplicative Linear No intercept[d]	Additive Linear No intercept[e,f]
Leukaemia[e]	$\beta_0 = 0.288$ $\beta_1 = 0.013$ $\beta 2 = -0.024$	$\beta_1 = 0.012$ $\beta 2 = -0.04$	$\beta_1 = 0.005$	$\beta_1 = 1.9e-6$
AML[f]	$\beta_0 = 0.273$ $\beta_1 = 0.018$ $\beta 2 = -0.115$	$\beta_1 = 0.023$ $\beta 2 = -0.148$	$\beta_1 = 0.005$	$\beta_1 = 2e-6$
ALL			$\beta_1 = 0.005$[g]	
CLL			$\beta_1 = 0.005$[g]	
MM			$\beta_1 = 0.006$	
NHL			$\beta_1 = 0.003$	

Risk functions used in the life table analysis

[a] General form of a multiplicative model based on a natural spline with intercept: $\mathrm{Ln(RR)} = \beta_0 + \beta_1 (X) + \beta_2 [X - \xi_1]_+^3 + \beta_3 [X - \xi_2]_+^3$ (16)

[b] For the leukaemia spline knots were located at 2.9, 22.7, and 125.5 ppm-yr. For the AML spline knots were located at 4.3, 17.4, 247.1 ppm-yr. (16)

[c] General form of a multiplicative model based on a natural spline without intercept: $\mathrm{Ln(RR)} = \beta_1 (X) + \beta_2 [X - \xi_1]_+^3 + \beta_3 [X - \xi_2]_+^3$ (16)

[d] General form of a linear multiplicative model without intercept: $\mathrm{Ln(RR)} = \beta_1 \ln(X)$ (16)

[e] General form of a linear additive model without intercept: $AR = \beta_1 * X$ (16)

[f] Additive models originally published by the U.S. EPA (15)

[g] Risk function of leukaemia

Temporal variation in the association between benzene and adverse health outcomes (Figure 5-1F; 5-1G)

Multistage cancer models predict that the effect of an increment of exposure on cancer risk may vary with time since (last) exposure. Several studies have shown that the effect of benzene exposure on leukaemia appears to diminish with time since exposure (17, 18). Richardson estimated that the relative risk of leukaemia as the result of exposure to benzene was reduced by 50% every ten years after effective exposure (17). However, this observation is not unique for benzene and leukaemia but has also been observed for other exposure-cancer associations. For example, Hornung et al. (19) showed that in a study of radon exposure and lung cancer in uranium miners the relative risk for a given cumulative exposure was reduced by 50%, 15 years after effective exposure, compared to current miners and those within 5 years of last exposure. Therefore there was an exponential decay in relative risk with a half-life of age-specific relative risk of approximately 15 years.

Three weighting functions were applied in the life table analysis to address reduction in risk with time since last exposure.

1. No weighting function was applied. Additional number of cases were calculated up to 75 years of age. This is the standard procedure used in the calculations of additional cases by the Dutch Health Council.
2. The effect of benzene exposure on the health outcome decreased exponentially with a half-life of 10 years. Additional number of cases calculated at 120 years of age (age at which the full cohort is deceased).
3. The effect of benzene exposure on the health outcome decreased exponentially with a half-life of 15 years. Additional number of cases calculated at 120 years of age (age at which the full cohort is deceased).

Excess risk (Figure 5-1H; 5-1I)

By combining information on the size of the population at risk, the number of cases in the unexposed population, the cumulative exposure, the risk function, and the temporal variation in the association between benzene and adverse health outcomes, the Excess Risk (ER) (the number of additional cases per 100,000 exposed individuals) is expressed as a function of age.

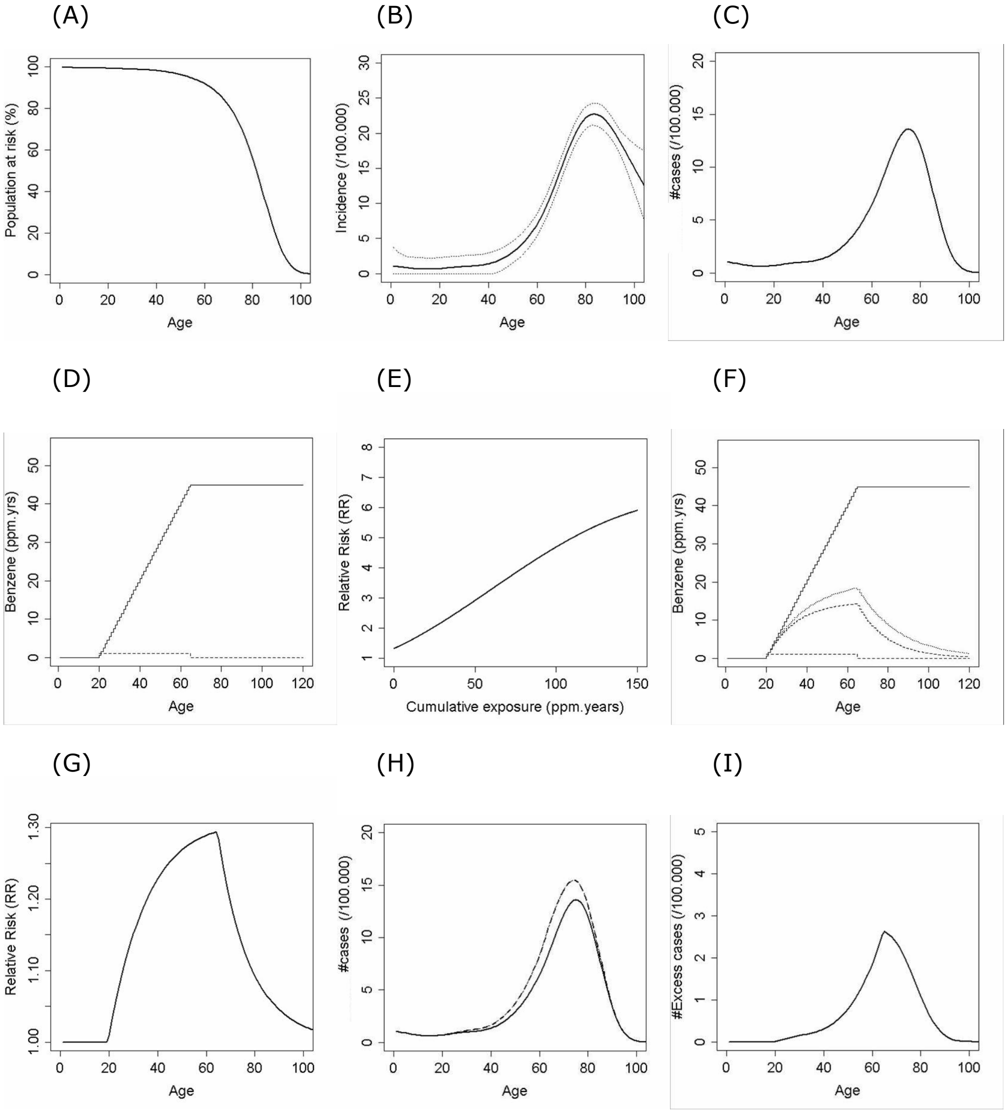

Figure 5-1: Illustration of the steps in a life table analysis; demonstrated for health outcome Acute Myeloid Leukemia (AML) and an exposure of 45 years at 1 ppm.

- *(A) Estimate of the size of the population at risk. Line indicates the percentage of the population that is still capable of developing health effects associated to benzene exposure.*
- *(B) Estimate of the incidence in the unexposed population. Dotted lines are 95% confidence intervals for the estimate.*
- *(C) Estimate of the absolute number of cases in the unexposed population*
- *(D) Cumulative exposure scenario. Continuous line indicates cumulative exposure. Dotted line is the average intensity of exposure.*

(E) Relative risk function
(F) Weighting function. Three types of weighting functions are illustrated. From top to bottom: No weighting, the effect of benzene exposure on the health outcome decreased exponentially with a half-life of 15 years, the effect of benzene exposure on the health outcome decreased exponentially with a half-life of 10 years.
(G) Relative risk function with application of the weighting function
(H) Estimate of the absolute number of cases in the exposed and unexposed population. Continuous line represents the unexposed population. Dotted line is the exposed population.
(I) Estimate of the absolute number of excess cases in the population due to exposure to benzene.

5.2 Results

In Tables 5-6 and 5-7 the outcomes of the life table analysis are presented. The outcomes are based on a combination of the type of risk model (multiplicative model vs. additive model), the type of exposure response model (spline vs. linear model), whether an intercept is allowed in the exposure response model (yes vs. no), and three different approaches to address the temporal variation in the association between benzene and adverse health outcomes. The main reason to present the outcomes of multiple models is that there is no model that is universally better. As such these different models represent the uncertainty in estimated additional cases.

For scenario ‘Cleaning small arms in weapon rooms and on ships’ the additional number of cases per 100,000 exposed individuals ranges for leukaemia from 3.9 to 26.3 (median 6.5); for AML from 1.4 to 15.0 (median 3.3); for ALL 0.3; for CLL from 1.7 to 2.9; for NHL from 4.7 to 7.1; and for MM from 7.3 to 11.7.

Table 5-6: Additional number of cases of hematopoietic cancer per 100,000 individuals exposed to benzene according to exposure scenario ‘Cleaning small arms in weapon rooms and on ships’.

	Multiplicative Spline Intercept			**Multiplicative Spline No intercept**			**Multiplicative Linear No intercept**			**Additive Linear No intercept**[a]		
	1	2	3	1	2	3	1	2	3	1	2	3
Leukaemia	17.7	4.1	7.0	26.3	6.1	10.4	6.0	3.9	4.8	14.1	5.1	6.9
AML	7.5	1.8	3.0	9.5	2.2	3.8	2.1	1.4	1.7	15.0	5.5	7.4
ALL							0.3	0.3	0.3			
CLL							2.9	1.7	2.2			
NHL							7.1	4.7	5.6			
MM							11.7	7.3	9.0			

[a] Additive model originally published by the U.S. EPA (15)

Where;

1. No weighting function applied to address the temporal variation in the association between benzene and the health outcome. Additional number of cases calculated at 75 years of age.
2. Effect of benzene exposure on the health outcome decreases exponentially with a half-life of 10 years. Additional number of cases calculated at 120 years of age (age at which the full cohort is deceased).
3. Effect of benzene exposure on the health outcome decreases exponentially with a half-life of 15 years. Additional number of cases calculated at 120 years of age (age at which the full cohort is deceased).

Table 5-7: Additional number of cases of hematopoietic cancer per 100,000 individuals exposed to benzene according to exposure scenario 'Cleaning small arms in small workshops'.

	Multiplicative Spline Intercept			**Multiplicative Spline No intercept**			**Multiplicative Linear No intercept**			**Additive Linear No intercept**[a]		
	1	2	3	1	2	3	1	2	3	1	2	3
Leukaemia	20.3	2.6	5.2	30.3	3.9	7.8	6.9	2.6	3.6	19.8	6.0	8.2
AML	8.7	1.2	2.3	11.0	1.5	2.9	2.4	0.9	1.3	21.0	6.4	8.8
ALL							0.4	0.4	0.4			
CLL							3.2	0.9	1.5			
NHL							8.1	2.8	4.1			
MM							13.2	4.0	6.2			

[a] Additive model originally published by the U.S. EPA (15). For explanation of 1 -3, see Table 5-6.

For scenario 'Cleaning small arms in workshops' the additional number of cases per 100,000 exposed individuals ranges for leukaemia from 2.6 to 30.3 (median 6.4); for AML from 0.9 to 21.0 (median 2.7); for ALL 0.4; for CLL from 0.9 to 3.2; for NHL from 2.8 to 8.1; and for MM from 4.0 to 13.2.

The calculated additional cases of total leukaemia, lymphoma and its subtypes per 100,000 benzene exposed subjects according to a certain scenario ranges between 0.3 to a maximum of 30 cases. This ratio is however time-dependent and should not be interpreted as an individual risk. For AML, the median of the estimates for the number of additional cases per 100,000 benzene exposed subjects was 3, or 0.03 per 1,000. How many additional cases can be expected within military and civilian personnel that has worked with PX-10 is difficult to predict as the number of exposed subjects per exposure scenario is not exactly known. However, estimates of MoD are that the number of exposed subjects in these described scenarios is likely to be in the low thousands. Therefore, the possibility that members of the Dutch Armed Forces developed acute myeloid leukaemia (AML) due to exposure to PX-10 while cleaning and maintaining weapons can be essentially excluded. The additional risk and subsequent cases for other leukaemias and lymphoma was estimated to be similarly low. Of note, the risk estimates for lymphoma (ALL, CLL, NHL, MM) should be interpreted with caution because the exposure-response functions used were based on limited quantitative data or extrapolated from total leukaemia.

6 Discussion

This study showed that the estimated average yearly benzene exposure by working with PX-10 ranged between 0.009 to 0.4 ppm before 1970, 0.004 to 0.2 ppm between 1970 and 1980, and between 0.001 and 0.04 ppm after 1980. When exposure by dermal contact was added to these inhalation levels, exposure estimates were maximally 0.5 ppm. These yearly average benzene exposures are below the current eight-hour occupational exposure limit of 1 ppm. VOCs exposure yearly average levels varied from 2 to 100 ppm depending on the working situation. VOCs exposure was rather constant over the years.

Based on the yearly average concentrations and two realistic high-risk careers, it was estimated that the additional risk of AML is around 0.03 per 1,000 PX-10 exposed subjects. The additional risk for the other leukaemia subtypes and lymphoma was comparable to the risk of AML.
MoD estimated that the number of exposed subjects in these high-risk careers is likely to be in the low thousands. Therefore, the possibility that members of the Dutch Armed Forces developed acute myeloid leukaemia (AML) or other forms of hematopoietic cancer due to exposure to PX-10 while cleaning and maintaining weapons can be essentially excluded. The potential health impact of VOCs other than benzene could not be calculated because of the lack of dose-response relations.

6.1 Exposure assessment

6.1.1 *Dealing with uncertainties*

The exposure levels were estimated based on a combination of laboratory experiments, focus group discussions and historical documents as no measurements or detailed records were available regarding important exposure determinants of PX-10. This will inherently have led to uncertainties in the input parameters. However, this has been taken into account by documenting estimated ranges in the input parameters, which were subsequently used in the probabilistic modelling to quantify the likely exposure distributions. The model input parameters (e.g. room sizes, bath sizes, amount of PX-10 used etc.) were used in a multiplicative way and a model sensitivity analysis did not reveal a predominant para-meter.

A two-box exposure model was developed based on the model described by Cherrie and Schneider (3) to estimate past exposure. The application of the two-box model is a simplification of the complex processes around the emission and dispersion of solvents which allows running a Monte Carlo simulation. The emission of benzene from the PX-10 mixture in open baths was assumed to be proportional to the surface area. This was based on experiments carried out in the laboratory under controlled conditions. Clearly, other parameters, such as geometry of the bath and the air velocity over the surface of the bath are other important determinants of the evaporation rate of benzene (20). Although the air velocity over the surface of the bath was expected to have been low for the majority of the time, the use of pressurized air to dry metal parts was also reported, and would have increased for short time the air velocity over the surface and therefore the benzene evaporation rate.

Furthermore, the model assumed perfect mixing of the vapours in the near- and far-fields. This is also a simplification, however, since there may have been distinct and consistent plumes of contaminated air in the near-field, in particular if PX-10 was spilled on clothes (21), which could have led to higher short-term personal exposure levels. Finally, the airflow between the near- and far-field compartments was arbitrarily set at 10 m^3/min, which was the mid-value chosen by Cherrie (1999) (22). The author concluded that within a plausible range of airflow rates from the near-field there was little variation in the magnitude of the difference between near- and far-field concentrations. However, the use of pressurized air would significantly affect the airflow between the near- and far-field.

It needs to be noted that the estimates of the focus group related to the average work circumstances and practices. This does not preclude that PX-10 was used in different ways or in different settings as described in this report. However, the exposure scenarios described in this report cover the largest and most likely uses of PX-10 in the Navy. Unfortunately, it was only possible to collect information for exposure scenarios from the Navy. Although the conditions of use may be slightly different within other sections of the Armed Forces, it was expected that the benzene estimates for the scenarios in the Navy were broadly comparable to the exposure in other branches.

6.1.2 *Evaporation rate of benzene*

The emission rate was estimated based on the result of laboratory experiments and on information collected during focus group meetings. The experiments showed that benzene would have rapidly evaporated from an open bath with PX-10. Based on the experiments, a half-life of 2 hours was estimated for the benzene content in a PX-10 bath, meaning that the benzene emission rate from an open bath of PX-10 would have reduced rapidly in the first hours and have been negligible at the beginning of the next day. Such decrease was also confirmed by Nicas et al. (23), who saw a similar decrease (even though with a longer half-life) of benzene in a mixture of similar solvents. For simplicity reasons the model was run for 24 hours a day with the emission rate for a cleaning activity in the bath, even though the active washing was presumably only performed during work time, which might have lead to a shorter half-life time of the benzene in the PX-10 mixture. However, the level of benzene in PX-10 was also for passive baths rather low at the end of the first working day.

The rapid depletion of benzene from the PX-10 mixture has important implications for the estimates of exposure for the first group of scenarios (using an open bath). The long-term exposure to benzene is, to a large extent, determined by the frequency and amount of topping–up of the bath and the frequency of completely changing the bath with fresh PX-10. Information on the frequency of top-up and the amount used was obtained during the focus group meetings (once per week). With regard to the frequency of replacing all the PX-10 in a bath, the information we obtained pointed to a monthly replacement, although some indications were provided by the focus group members that the PX-10 in the baths was replaced at an irregular frequency.

6.1.3 *Exposure levels in different use scenario's*

For scenarios with open baths of PX-10 the maximum inhalation exposure values were reached in the time before 1970 and ranged from 0.009 ppm for cleaning of torpedo parts in a room next to the torpedo hall up to 0.44 ppm for cleaning of small arms in the weapon room. The difference in the exposure between the two scenarios was mainly due to the room size and the duration of the activities. The annual average inhalation exposure during the cleaning of the torpedo tubes with a soaked PX-10 cloth was estimated to have been 0.307 ppm. The benzene exposure was generally lower in later periods of time, due to the reduction in the benzene content of the PX-10.

Rather similar results were found for the benzene levels in the near-field and the far-field of the scenarios except for the two scenarios in larger facilities. The similarity of the values is explained by the assumed low air exchange values. Cherrie (22) showed that at low air exchange rates the near-field and the far-field levels are rather similar. These similar values can be furthermore explained by the fact that there were also sources of benzene placed in the far-field (i.e. other baths, or part of a bath that was out of the dimension attributed to the near-field: 8 m^3).

The results from the retrospective exposure assessment were compared with workplace benzene exposure assessment levels described in published peer review articles (8, 9, 11, 23-28). It is clear that any comparison with results from other studies is very limited. The large differences in the scenarios studied mean that other studies can only be used as contextual information and not as material to validate our model estimates. Benzene concentrations of <0.007 up to 0.55 ppm have been reported. The studies cover different solvents being used in quantities from a few millilitres up to 100 litres, with benzene content from 0.00001% to 0.01% and cleaning tasks that lasted minutes up to hours, and workplaces from 7 m^3 to 70,000 m^3. These massive differences in exposure affecting factors make it almost impossible to use the studies as validation for the model described here.

One study should be highlighted. It provides estimates for benzene exposure during a task that is very similar to the cleaning with PX-10 by Fedoruk et al. (24). This study describes the measurement of exposure during a simulation of the work with Safety-Kleen 105, a substance similar to PX-10, used for similar purposes of cleaning/de-greasing. The Safety-Kleen 105 was used in a half open degreaser station similar to a PX-10 bath. Benzene was added at two levels to the substance: 0.0009% and 0.0058% by weight (lower than the assumed levels in PX-10). The study reported short-term concentrations measured in the breathing zone of <0.03 ppm and 0.44 ppm, respectively. Note that these results relate to short-term exposure and not long-term exposure and therefore do not take into account any declining emission rates for benzene. These data are fairly similar to predicted benzene exposure levels for the first day exposure at the later periods (with 0.01% benzene in PX-10) after a complete replacement of the baths with fresh PX-10 (data not shown in detail: values from 0.02 to 1.2 ppm were calculated in the different scenarios for the exposure in the near-field).

6.1.4 *Dermal exposure*

Dermal exposure to benzene was estimated using a model by Nies et al. and Williams et al. (5, 6, 11) and expressed as inhalation exposure equivalent. The estimated dermal exposure was relatively low compared to the inhalation exposure. On average, the inhalation exposure was found to be 10-30 times higher than the dermal exposure in the bath scenarios. The relative contribution of dermal exposure was only equivalent to the contribution from inhalation exposure in the very large torpedo hall. Note that similar application with a towel and fresh PX-10 was reported to have occurred onboard ships but in smaller amounts. However, there was insufficient information available to model these situations as independent scenarios.

In addition to the nature of the task and the benzene content in the PX-10, the estimated dermal exposure to benzene depends largely on the assumed uptake rate. There is a wide range in reported dermal uptake values for benzene, based on different experimental approaches. Skin condition is likely to play an important role, with enhanced uptake of benzene where there is damage to the outer layers of the skin, e.g. dermatitis. We have decided to adopt a relatively high dermal uptake rate, as there was anecdotal evidence of widespread dermal symptoms amongst users of PX-10. Despite this assumption, in most cases dermal exposure was not considered to be an important contributor to systemic benzene exposure.

6.1.5 VOCs exposure

VOCs exposure from the open baths or the use of PX-10 on surfaces has been estimated based on the amount of PX-10 used and the experimentally determined VOCs emission rate of white spirit. Additional to this basic level of white spirit emission, it was considered that a fraction of white spirit consisted of the highly evaporative substances benzene, toluene, hexane and heptane isomers. This fraction was estimated to have been around one percent of the PX-10 in the time period before 1970 and was decreased over the years to a very low level after 1985.

As for benzene, the highest modelled levels for VOCs exposure were found before the 1970s, with annual average levels up to 100 ppm in the large torpedo halls. The emission of VOCs was shown to be mainly due to the evaporation of white spirit and was little influenced by the evaporation of the highly evaporative fraction. For the scenarios with open baths these values were therefore only slightly lowered after 1970 when the highly evaporative fraction was lowered in white spirit (benzene, toluene, hexane and heptane). The current Dutch 8 hour threshold value for white spirit is 575 mg/m^3 (about 100 ppm).

6.2 Potential health effects at low levels of exposure

The exposure estimates showed that yearly average levels of benzene were below 1 ppm. There have been numerous studies of benzene-induced haematotoxicity (15), but few have been able to study effects at low levels of exposure. Ward et al. (29) found no evidence of a threshold for haematotoxic effects of benzene and suggested that exposure to <5 ppm benzene could result in haematological suppression. Occupational exposure decreased white blood cells (WBCs) in petrochemical workers exposed to <10 ppm benzene (30), and Qu et al. reported that WBCs and other cell types were decreased in workers exposed to <5 ppm benzene (31). In contrast, Collins et al. (32, 33) and Tsai et al. (34) did not detect decreased blood cell counts based on routine monitoring of workers exposed to low levels of benzene. A study by Lan et al. (35) showed that total WBCs, granulocytes, lymphocytes, B cells and platelets significantly declined with increasing benzene exposure and were lower in workers exposed to benzene at air levels of 1 ppm or less compared to controls. In this study an extensive exposure assessment over a 16-month period was conducted and individual air-monitoring data was linked to the endpoints measured. Although confirmation of these findings in other studies is needed, these data strongly suggest that benzene causes haematological effects at or below 1 ppm. This is in line with our conclusion that working with PX-10 may have been associated with an additional risk of AML, although exposure levels were low.

6.2.1 *Potential confounding factors*

Benzene is not the only exposure that is capable of inducing haemato- and lymphopoietic cancers. However, it is important to realize that for an exposure to confound the association between exposure to benzene and hemato- and lymphopoietic cancer it needs to be correlated to benzene exposure as well. In general, two factors are considered as potential confounding factors: cigarette smoke and ionizing radiation.

Ionizing radiation is the best studied risk factor for hemato- and lymphopoietic cancer and there is convincing evidence that this exposure is indeed causally related to hemato- and lymphopoietic cancer subtypes (36). It is however unlikely that exposure to ionizing radiation was associated with exposure to benzene due to working with PX-10. Primarily because exposure to ionizing radiation above background levels is not expected in the exposure scenarios discussed in this report.

Based on the results of several large cohort studies (37-39), cigarette smoking is associated with an increased risk of leukaemia. The relative risks range from 1.5 to 2.0. The association with leukaemia is primarily thought to be related to exposure to benzene present in cigarette smoke. There are other known or suspected leukemogens present in cigarette smoke, including urethane, 1,3-butadiene, radioactive elements, N-nitrosodi-*n*-butyulamine, and styrene. Benzene is therefore unlikely responsible for all smoking induced-leukaemia. However, based on current knowledge of the leukemogenicity of these compounds and their relative concentrations in tobacco smoke, it seems likely that benzene’s contribution is substantial (40). The evidence for the association between cigarette smoke and other lymphohematopoietic cancers is less convincing (41). Due to the strength of the association between smoking and leukaemia and because it is unlikely that smoking behaviour would be related to occupational benzene exposure it is not likely a potent confounder and would be unlikely to affect the shape of the dose-response relation. However, tobacco smoke is an additional source of benzene. In Table 6-1 estimates of the lifetime cumulative exposure to benzene for an individual only exposed to environmental sources, a light smoker, and a heavy smoker are summarized.

Table 6-1: Estimate of lifetime cumulative exposure to benzene.

Exposure source	**Lifetime exposure (ppm-year)**	**Source**
Background exposure	0.35	(42)*
Light smoker (20 cigarettes/day)	3	(40)
Heavy smoker (40 cigarettes/day)	6	(40)

* Assumed 75 years of exposure to calculate background exposure

6.2.2 *Life-table analysis*

A limitation in the calculations is that only for leukaemia and its subtype AML quantitative exposure response associations (multiplicative and additive models) have been published. Although lymphoma has been linked to benzene exposure no quantitative exposure-response relations have been published. We derived quantitative estimates of the dose-response of MM and NHL by fitting a linear no intercept model to the available risk estimates for which a quantitative exposure estimate was available. These estimates however are rather imprecise and should be interpreted cautiously. For CLL and ALL we used the leukaemia risk estimate to calculate the additional cases that could be expected for CLL and

ALL. We furthermore, used several different models to account for a temporal decrease in risk. These models differ from counting only cases till the age of 75 (standard in calculations of the Dutch Health Council), and two models in which the risk declined after exposure with 50% in 10 or 15 years. These models provide as such a bandwidth of expected additional cases.

As no dose-response relations exist for VOCs or specific components with regard to neurological disorders no calculation could be made of the potential health impact. Subjects with neurological disorders who worked with PX-10 should therefore probably be referred to specialized solvent teams for more specific follow-up.

Acknowledgement

We would like to thank Jurgen van Belle, Nicole Janssen, Ingrid van Kuilenburg, Erik Lebret, Carla van Wiechen and Kees van Luijk (National Institute for Public Health and the Environment) for their contributions to this study. We are grateful to the members of the focus groups for providing information for the exposure assessments.

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Appendix 1: Scenario description and input parameters for exposure modelling

As a result of the discussion with the focus groups six different work scenarios were developed. These were considered to be the jobs that were likely to have endured exposure to vapours of PX-10 and physical contact with the mixture.

Scenarios for small arm maintenance

1) *Armoury (military personnel):* In the armoury store, cleaning of small arms was performed. These armoury stores were generally small, well-protected and enclosed rooms below or above ground with little ventilation. The scenario description was based on a store visited during the day of a focus group meeting. Small arms were kept in racks of relatively large size. PX-10 was used in large stainless steel containers (baths). Sailors/marines stationed at the armoury store took weapons apart and put loose items in the baths to clean them. After a certain time in this bath (often overnight) they were manually cleaned with brushes. During this task hands and arms were often immersed in the PX-10. PX-10 was never sprayed, neither was there a manual dispenser of PX-10. However, the weapons were often dried with compressed air to aid drying, especially in the holes and crevices. The far-field (FF) of this scenario was defined as performing other maintenance task with weapons in the background of the same rooms without direct contact to PX-10.

Table A1-1: Parameters of the scenario 'Armoury (military personnel)' that were used in the Monte Carlo model to determine the range of expected exposure to benzene.

Parameter	**Unit**	**Minimum**	**Mode**	**Maximum**	**Distribution**	**Source**
Room size	[m³]	24	27	30	Triangular	Vis / FG
Ventilation	[ACH]	0.2	0.5	0.8	Triangular	Lit / FG
NF Bath surface *)	[m²]		0.6		Fix	FG
NF volume PX-10 in bath	[m³]	0.07	0.08	0.09	Triangular	FG
NF amount PX-10 topped up	[L/week]	6	6.67	7.33	Triangular	FG
FF Bath surface *)	[m²]		1.20		Fix	FG
FF volume PX-10 in bath	[m³]	0.14	0.16	0.18	Triangular	FG
FF amount PX-10 topped up	[L/week]	12	13.33	14.67	Triangular	FG
Daily duration in NF	[h]	4.05	4.50	4.95	Triangular	FG
Daily duration in FF	[h]	1.80	2.00	2.20	Triangular	FG
Daily duration non-exposed	[h]	0.85	1.50	2.15	Triangular	FG
Top-up frequency	[/year]	40	47	52	Triangular	FG
Full bath replacement frequency	[/year]	2	12	24	Triangular	FG
Initial emission rate <1970	[g/min/m²]	0.000	0.033	0.067	Triangular	Exp
Initial emission rate 1970-1980	[g/min/m²]	0.000	0.008	0.033	Triangular	Exp
Initial emission rate >1980	[g/min/m²]	0.000	0.001	0.008	Triangular	Exp
Half-life of benzene in PX-10	[h]	0.5	1.3	3.7	Triangular	Exp
Dermal uptake rate	[mg/cm²/h]	1.0	1.5	2.0	Triangular	Lit
Dermal surface exposed	[cm²]	1179	1525	1872	Triangular	Lit
Dermal exposure time	[h]	4.05	4.50	4.95	Triangular	FG

ACH: Air changes per hour, NF: near-field, FF: far-field. The source of information is provided with the abbreviation FG for focus group, Lit for literature, Vis for visited or estimated from photo. *) Additional 0.25 m² were accounted for the active washing. The exponent α of the decrease rate is provided for the calculation by the formula for exponential decrease: Emission (t) = Initial emission rate * $t^{(-\alpha)}$. The non-exposed working time was calculated subtracting from 8 hours the work in NF plus the work in FF and was set to 0 if NF+FF was more than 8 hours. The values of the initial emission rate were measured experimentally 30 minutes after the start of emission.

2) *Maintenance of small arms on board of ships:* Constables were cleaning all small arms on ships. The main task of these constables was to clean weapons, up to the 3rd step (only main parts disassembled). This task was performed daily for a long time. This weapon maintenance aboard took place in different parts of the boat that had in common that they were much smaller than the armoury on the mainland. The baths for the cleaning of small arms with PX-10 on board of ships were much smaller than the ones in the other scenarios and could be anywhere, e.g. in the corridor or in designated weapon rooms. Usually there was no ventilation used while working with these PX-10 baths. On board of the ships, the baths were not completely filled with PX-10 (to be prepared for a movement of the ship) and the PX-10 was replaced irregularly, depending on dirtiness and missions. The stainless steel containers were additionally closed with lids that when the bath was not in use. Similar to the mainland the weapons were removed after soaking for 10-15

minutes and dry cleaned with compressed air. The manipulation of the weapon cleaning and drying was performed with bare hands.

Table A1-2: Parameters of the scenario 'Maintenance for small arms on board of ships' that were used in the Monte Carlo model to determine the range of expected exposure to benzene.

Parameter	**Unit**	**Minimum**	**Mode**	**Maximum**	**Distribution**	**Source**
Room size	[m³]	7	8	9	Triangular	Vis / FG
Ventilation	[ACH]	0.8	1.2	1.5	Triangular	Lit / FG
NF Bath surface *)	[m²]		0.2		Fix	FG
NF volume PX-10 in bath	[m³]	0.45	0.49	0.54	Triangular	FG
NF amount PX-10 topped up	[L/week]	0.06	0.07	0.08	Triangular	FG
FF Bath surface *)	[m²]		0.25		Fix	FG
FF volume PX-10 in bath	[m³]	0.09	0.10	0.11	Triangular	FG
FF amount PX-10 topped up	[L/week]	0.45	0.51	0.56	Triangular	FG
Daily duration in NF	[h]	2.25	2.50	2.75	Triangular	FG
Daily duration in FF	[h]	5.50	5.50	5.50	Triangular	FG
Daily duration non-exposed	[h]	0.00	0.00	0.25	Triangular	FG
Top-up frequency	[/year]	40	47	52	Triangular	FG
Bath replacement frequency	[/year]	2	12	24	Triangular	FG
Initial emission rate <1970	[g/min/m²]	0.000	0.033	0.067	Triangular	Exp
Initial emission rate 1970-1980	[g/min/m²]	0.000	0.008	0.033	Triangular	Exp
Initial emission rate >1980	[g/min/m²]	0.000	0.001	0.008	Triangular	Exp
Half-life of benzene in PX-10	[h]	0.5	1.3	3.7	Triangular	Exp
Dermal uptake rate	[mg/cm²/h]	1.0	1.5	2.0	Triangular	Lit
Dermal surface exposed	[cm²]	1179	1525	1872	Triangular	Lit
Dermal exposure time	[h]	2.25	2.50	2.75	Triangular	FG

*see explanation Table A1-1.

3) *Civilian workshop (smaller size):* Large numbers of arms were delivered to the workshop where the full maintenance of them was performed. Very large baths with PX-10 were used for the cleaning of the weapons. The parts of the weapons were placed in the bath with PX-10. Small parts were put in a basket, while larger parts were placed individually in the bath. Gun barrels were put vertically above the bath all night. The parts were often left to soak in PX-10 overnight. The next day, the components were manually cleaned with brushes, a task during which the hands were often immersed in PX-10. PX-10 was never sprayed, nor was there any use of a manual dispenser. However, compressed air was often used to aid the drying of the weapons. Different locations were used for full maintenance of the weapons, the main difference between these workplaces was the room size.

Table A1-3: Parameters of the scenario 'Civilian workshop (smaller size)' that were used in the Monte Carlo model to determine the range of expected exposure to benzene.

Parameter	**Unit**	**Minimum**	**Mode**	**Maximum**	**Distribution**	**Source**
Room size	[m^3]	68	75	83	Triangular	Vis / FG
Ventilation	[ACH]	0.8	2.4	4.0	Triangular	Lit / FG
NF Bath surface *)	[m^2]		1.6		Fix	FG
NF volume PX-10 in bath	[m^3]	1.30	1.44	1.58	Triangular	FG
NF amount PX-10 topped up	[L/week]	60	66.67	73.33	Triangular	FG
FF Bath surface *)	[m^2]		3.20		Fix	FG
FF volume PX-10 in bath	[m^3]	2.59	2.88	3.17	Triangular	FG
FF amount PX-10 topped up	[L/week]	120	133.33	146.67	Triangular	FG
Daily duration in NF	[h]	2.25	2.50	2.75	Triangular	FG
Daily duration in FF	[h]	4.95	5.50	6.05	Triangular	FG
Daily duration non-exposed	[h]	0.0	0.0	0.8	Triangular	FG
Top-up frequency	[/year]	40	47	52	Triangular	FG
Full bath replacement frequency	[/year]	2	12	24	Triangular	FG
Initial emission rate <1970	[g/min/m^2]	0.000	0.033	0.067	Triangular	Exp
Initial emission rate 1970-1980	[g/min/m^2]	0.000	0.008	0.033	Triangular	Exp
Initial emission rate >1980	[g/min/m^2]	0.000	0.001	0.008	Triangular	Exp
Half-life of benzene in PX-10	[h]	0.5	1.3	3.7	Triangular	Exp
Dermal uptake rate	[mg/cm^2/h]	1.0	1.5	2.0	Triangular	Lit
Dermal surface exposed	[cm^2]	1179	1525	1872	Triangular	Lit
Dermal exposure time	[h]	2.25	2.50	2.75	Triangular	FG

*see explanation Table A1-1.

4) *Civilian workshop (larger size):* The same task as described for the small workshop was performed in a larger workshop. Large numbers of arms were delivered to the workshop where the full maintenance of them was performed. Large baths with hundreds of litres of PX-10 were used for the cleaning of the weapons. Different locations were used for this full maintenance of the weapons was performed, the main difference between the workplaces was the size of the room. Due to the larger size of the room this location was better designed for tasks that were not related to the bath.

Table A1-4: Parameters of the scenario 'Civilian workshop (larger size)' that were used in the Monte Carlo model to determine the range of expected exposure to benzene.

Parameter	**Unit**	**Minimum**	**Mode**	**Maximum**	**Distribution**	**Source**
Room size	[m³]	900	1000	1100	Triangular	Vis / FG
Ventilation	[ACH]	0.8	2.4	4.0	Triangular	Lit / FG
NF Bath surface *)	[m²]		1.6		Fix	FG
NF volume PX-10 in bath	[m³]	1.30	1.44	1.58	Triangular	FG
NF amount PX-10 topped up	[L/week]	60	66.67	73.33	Triangular	FG
FF Bath surface *)	[m²]		3.20		Fix	FG
FF volume PX-10 in bath	[m³]	2.59	2.88	3.17	Triangular	FG
FF amount PX-10 topped up	[L/week]	120	133.33	146.67	Triangular	FG
Daily duration in NF	[h]	2.25	2.50	2.75	Triangular	FG
Daily duration in FF	[h]	4.95	5.50	6.05	Triangular	FG
Daily duration non-exposed	[h]	0.00	0.00	0.80	Triangular	FG
Top-up frequency	[/year]	40	47	52	Triangular	FG
Bath replacement frequency	[/year]	2	12	24	Triangular	FG
Initial emission rate <1970	[g/min/m²]	0.000	0.033	0.067	Triangular	Exp
Initial emission rate 1970-1980	[g/min/m²]	0.000	0.008	0.033	Triangular	Exp
Initial emission rate >1980	[g/min/m²]	0.000	0.001	0.008	Triangular	Exp
Half-life of benzene in PX-10	[h]	0.5	1.3	3.7	Triangular	Exp
Dermal uptake rate	[mg/cm²/h]	1.0	1.5	2.0	Triangular	Lit
Dermal surface exposed	[cm²]	1179	1525	1872	Triangular	Lit
Dermal exposure time	[h]	2.25	2.50	2.75	Triangular	FG

*see explanation Table A1-1.

Scenarios for heavy arm maintenance

5) *Torpedo parts washing:* In the room where smaller elements were soaked in large baths with PX-10. After disassembly, the single parts of the torpedoes were washed in a PX-10 bath. This was performed in a small cleaning chamber, adjacent to the main torpedo hall, which had a number of PX-10 baths along its walls. Compressed air was used to dry the parts. Due to proximity of the large torpedo hall, it is to assume that the personnel did not perform much work in the FF but rather moved out of the room when not performing cleaning activities. This only influences the interpretation of the model outcome, where the far-field of the activities in the washing room was therefore assumed to be in the far-field of the larger torpedo hall. Note that for the modelling of the washing room far-field concentration, the parameters of Table A1-5 were used to calculate the near-field concentration.

Table A1-5: Parameters of the scenario 'torpedo part washing' that were used in the Monte Carlo model to determine the range of expected exposure to benzene.

Parameter	**Unit**	**Minimum**	**Mode**	**Maximum**	**Distribution**	**Source**
Room size	[m³]	22	95	195	Triangular	Vis / FG
Ventilation	[ACH]	0.2	0.5	0.8	Triangular	Lit / FG
NF Bath surface *)	[m²]		1.5		Fix	FG
NF volume PX-10 in bath	[m³]	1.22	1.35	1.49	Triangular	FG
NF amount PX-10 topped up	[L/week]	31.50	35	38.5	Triangular	FG
FF Bath surface *)	[m²]		0.5		Fix	FG
FF volume PX-10 in bath	[m³]	0.41	0.45	0.50	Triangular	FG
FF amount PX-10 topped up	[L/week]	10.5	11.67	12.83	Triangular	FG
Daily duration in NF	[h]	3.5	5.2	8.0	Triangular	FG
Daily duration in FF	[h]	1.8	2.0	2.2	Triangular	FG
Daily duration non-exposed	[h]	0.0	0.8	2.7	Triangular	FG
Top-up frequency	[/year]	40	47	52	Triangular	FG
Bath replacement frequency	[/year]	2	12	24	Triangular	FG
Initial emission rate <1970	[g/min/m²]	0.000	0.033	0.067	Triangular	Exp
Initial emission rate 1970-1980	[g/min/m²]	0.000	0.008	0.033	Triangular	Exp
Initial emission rate >1980	[g/min/m²]	0.000	0.001	0.008	Triangular	Exp
Half-life of benzene in PX-10	[h]	0.5	1.3	3.7	Triangular	Exp
Dermal uptake rate	[mg/cm²/h]	1.0	1.5	2.0	Triangular	Lit
Dermal surface exposed	[cm²]	1179	1525	1872	Triangular	Lit
Dermal exposure time	[h]	3.5	5.2	8.0	Triangular	FG

*see explanation Table A1-1.

6) *Torpedo hall:* The cleaning and protecting of torpedoes was performed in a large hall. PX-10 was poured from large containers in buckets of 10 litres to be used for cleaning the body of a torpedo. Cleaning of the torpedo body was carried out using cloths soaked with PX-10. One or more such buckets were used per day. There were six teams of torpedo washers. On one side of the hall were large hangar doors. These were open only in summer. PX-10 was used in above described way every day, sometimes during 8 hours a day. Sometimes the job was rotated and a person was not exposed for a whole day. It is to assume that the personnel were mainly using this location to perform the background work of both the scenarios 'torpedo hall' and 'torpedo parts washing'. The far-field concentration of this scenario was therefore used as the far-field exposure for both scenarios.

Table A1-6: Parameters of the scenario 'Torpedo hall' that were used in the Monte Carlo model to determine the range of expected exposure to benzene.

Parameter	Unit	Minimum	Mode	Maximum	Distribution	Source
Room size	[m³]	15750	17500	19250	Triangular	Vis / FG
Ventilation	[ACH]	0.8	2.4	4.0	Triangular	Lit / FG
NF daily amount PX-10	[L/day]	-	10	-	Fix	FG
FF daily amount PX-10	[L/day]	-	50	-	Fix	FG
Daily duration in NF	[h]	1.50	3.25	8.00	Triangular	FG
Daily duration in FF	[h]	0.0	4.75	6.5	Triangular	FG
Daily duration non-exposed	[h]	0.0	0.0	0.0	Triangular	FG
Dermal uptake rate	[mg/cm²/h]	1.0	1.5	2.0	Triangular	Lit
Dermal surface exposed	[cm²]	295	381	468	Triangular	Lit
Dermal exposure time	[h]	1.5	3.25	8.0	Triangular	FG

*see explanation Table A1-1.

Three further scenarios were identified but not modelled

The exposure to benzene was estimated to be lower than in the other scenarios. Based on the information about amounts of PX-10 used, room sizes or ventilation situation etc. However, due to a lack of data the exposure could not be modelled.

1. Large gun workshop.
2. Ammunition was maintained and cleaned with PX-10.
3. Maintenance of torpedoes and other equipment on board of vessels.

Note that due to smaller amounts of PX-10 and slightly better ventilated facilities the first two scenarios are expected to have shown smaller exposure than the scenarios described in detail above, however, the exposure on vessels was reported to have been very variable in task and location. An application of larger amounts of PX-10 in places with limited space and ventilation might have led to high short-term exposure to benzene.

Full bath replacement frequency

The frequency of the total replacement of the PX-10 in a bath (in comparison to topping up the bath with PX-10) was found to predominantly influence the benzene exposure level. The focus group members were therefore specifically asked to estimate the replacement frequency for each scenario.
The answers of the focus group showed a rather large range for the frequencies.

Range of answers:

Small arm maintenance in armouries onshore:	12/year; 2-3/year
Small arm maintenance on board of ships:	12-16/year; 5-6/year; 2-3/year
Small arm maintenance in civil workshops:	12/year
Torpedo parts washing:	more frequent than 2/year
Ammunition maintenance:	12/year

As none of the scenarios was clearly reported to have a much more frequent or much less frequent replacement of the whole PX-10 in the bath, the range was defined as between two weeks and twice a year for all scenarios with PX-10 baths.