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Workers' exposure to dust and potentially toxic elements during steel cutting in two ship dismantling cases

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ABSTRACT

Ship dismantling is the recommended recycling solution for the end of a ship's life, but the process is not free of occupational risk. Despite proper regulations, there are underlying chemical and physical hazards, mainly due to the cutting of steel parts, which is the core of the recycling process. The overall aim of this research study is to determine, in two case study examples, the ship recycling workers' potential occupational exposure by inhalation of chemical agents generated by the torch cutting process of coated and de-coated steel. This was carried out specifically through (i) monitoring and measuring ship recycling workers' local environment for the inhalable (total dust) and respirable (fine dust) fractions during their working operations, (ii) analysing the heavy metal content of the dust and (iii) calculating and comparing this against occupational exposure limits, (iv) comparing de-coating operations with cutting of coated and de-coated steel. Results of this study show that without further mitigation workers involved in torch cutting processes are at high risk of exposure to heavy metals by inhalation as these are exceeding the norms defined by regulatory bodies.

1. Introduction

When a ship comes to its operational end-of-life (EOL), it requires dismantling to allow the contained steel to be recycled; this process is regulated by the International Maritime Organisation's (International Maritime Organisation, 2009) Hong Kong International Convention for the Safe and Environmentally Sound Recycling of Ships and the European Commission's Ship Recycling Regulation (Regulation (EU), 2013) with a focus on health, safety and environmental compliance. Due to the size, construction method and material used, steel-cutting is an inherent component of ship recycling, but also one which allows for the maximum reuse or recycling of components and steel plate, typically 90–95% of the total mass of EOL ships (Barua et al., 2018), so is in keeping with the principles of the Circular Economy. Cutting options available for the primary and secondary dismantling zones include oxy-acetylene (or oxy-LPG) torch cutting, abrasive waterjet, plasma or lasers (Gunbeyaz et al., 2020). However, ship recycling involves a number of paradoxical sustainability challenges (Dey et al., 2021), in particular through the open-beaching method commonplace in Bangladesh, India and Pakistan, which exposes all spheres of the environment to the release of any hazardous materials which may be present (Barua et al., 2018).

Ships going for dismantling must also have on board an inventory of hazardous materials (IHM); this obligation is applied to all existing ships sailing under the flag of Member States of the Union as well as to ships flying the flag of a third country and calling at an EU port or anchorage from December 31, 2020. Ship recycling is considered to be a high risk operation for the workers and the environment (Kurt et al., 2017), mainly due to the manual operations involved, the nature of materials to be recovered, and the confined spaces in which some operations must take place; therefore, during the recycling process work place regulations such as the occupational exposure to chemicals and the confined spaces regulations are also relevant. Regulations on occupational exposure to chemicals, as well as potential carcinogenic and mutagenic substances set up limits and thresholds of concentrations. Confined space means 'any place including chamber, tank of which, by virtue of its enclosed nature, there arises a reasonably foreseeable specified risk' (UK Statutory Instrument 1713, 1997). However, despite these

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legislative advances there is still a lack of quantitative data to scientifically answer and understand the true extent of the unique occupational health and environmental challenges within ship recycling.

In a life cycle assessment of ship recycling, it was found that the most adverse effects for health and environment inside the yard can be attributed to steel cutting with oxy-acetylene torches (Rahman et al., 2016); this task is among the most common activities in the process of ship decommissioning and recycling. Torch cutting for ship recycling involves cutting steel with multiple layers of paint and coatings (e.g., rust-preventive primers, antifouling agents) with the task performed in a variety of locations, onboard a vessel or on land, in confined or open spaces. The activity is usually conducted in close proximity to other workers, such as the accompanying fire watcher. When steel parts are coated with protective chemicals, such as paints, primers, etc. the torch cutting process can release toxic gases with consequences for the potential exposure by inhalation of those who work directly and indirectly within this job task, including possibly to banned chemicals such as DDT due to the ships' age (Yılmaz et al., 2016).

The overall aim of this study is to determine, in two real case study examples, the ship recycling workers' potential occupational exposure by inhalation of chemical agents generated by the torch cutting process of coated steel, in open, confined, and semi-confined spaces. In this European study, environmental monitoring of inhalable (total dust) and respirable (fine dust) fractions for ship recycling workers who were wearing requisite PPE were monitored and measured during normal working operations. These measurements were then analysed for their heavy metal contents. Finally, exposure values were calculated and compared against occupational exposure limits, providing a worst-case scenario for workers without adequate dust masks and other PPE, as might occur in a poorly regulated ship dismantling facility in developing countries.

To the best of our knowledge, published data on airborne dust monitoring data during live ship-recycling does not currently exist in the academic literature. We strongly believe, therefore, that the findings of this study will contribute significantly to current scientific knowledge, indicate how different locations and working conditions affect dust exposure during ship recycling activities, and thereby contribute to the development of engineering best practice and related environmental policies to improve the ship recycling workers' safety.

2. Materials and methods

Two contrasting European facilities, Facility A and Facility B participated ino this study, one based in the UK and one in Spain, with respectively two different but widely represented ships destined to be recycled, Ship A and Ship B. Commonplace dismantling tasks and typical working practices were selected for observation in each case, including examples in confined, semi-confined and open air conditions. Sampling periods were chosen to correspond to the duration of single tasks representative of those which would be carried out repeatedly by the workers. This study is in line with the guidance of the European Standard EN 689: 'Workplace atmosphere- Guidance for the assessment of exposure by inhalation to chemical agents for comparison with limits values and measurement strategy' (European Standard EN 689, 1996). This Standard is now replaced by its 2018 version, but this study was conducted before 2018.

Personal breathing zone air samples (n = 25) were collected from torch cutting workers and accompanying fire watchers in each of the facilities A and B. During this experimental study, workers used personal protective equipment including a full-face mask and gloves.

2.1. Facility A, ship A

Facility A based in the UK was originally a fully covered dry dock ship building yard; when a redundant moored ship (a former passenger ferry) sank in the nearby river the facility decided to acquire the ship for recycling (Ship A) since it was not engaged in any ship building or repairing activities. Five workers were operating the facility on an 8-h work schedule from Monday to Friday. The work activities for the purposes of the vessel's demolition involved mainly onboard cutting. Three different tasks were selected for estimating the potential exposure levels due to steel cutting from Ship A: Task 1 (T1) cutting coated steel, Task 2 (T2) mechanical de-coating, Task 3 (T3) cutting de-coated plate. These took place inside a former lounge space of approximately 280 m^3 on the 4th deck. Each monitoring procedure was performed on different days, when there was no other activity on board beyond the tasks monitored.

Task 1 (T1): Cutting in coated steel was carried out inside Ship A. In total 30 m of cutting length was achieved using a torch (oxygen and acetylene) and the measurement time was 55 min. This space, in the context of this study, is defined as a confined space without sufficient ventilation to successfully remove the cutting torch fumes and associated dust from the area.

Task 2 (T2): Mechanical de-coating with a grinder was carried out inside Ship A. The grinding area was approximately 1–1.5 m^2 and the measurement time was 30 min. In the study, a professional hand-held electric angle-grinder with abrasive grinding-discs was used for the mechanical de-coating procedure.

Task 3 (T3): Cutting in de-coated steel performed over a length of 20m taking 35 min. Cutting in de-coated steel was carried out inside Ship A. The conditions were similar to those during the cutting of coated steel. Due to the small size of the de-coated area, this experiment provided a relatively short exposure time for data collection.

2.2. Facility B, ship B

Facility B is a small-scale outdoor ship recycling facility in which vessels are dismantled by the quayside and moved to a ramp when light enough to be dragged onto land. The facility was operating from Monday to Friday with an 8 h/day work schedule with a total of 8 workers. At the time of this study the work activities were the removal of the fishing vessel superstructure and general cutting of ship sections into smaller pieces. Three tasks were measured for exposure levels of heavy metals in Facility B.

Task 4 (T4): cutting coated steel in a confined space; a very confined space of approximately 8–10 m^3 on board the vessel with poor ventilation, for 10 min.

Task 5 (T5): cutting coated steel in a semi-confined space, approximately 8–10 m^3, with the roof removed for 7 min.

Task 6 (T6): cutting in a secondary dismantling zone, in an open-air location within the yard for 114 min for the torch cutter and 92 min for the fire watcher. The wind speed during the open air measurements was recorded as 1.5–3 m/s and the temperature as 12 ± 3 °C.

Table 1 shows the above described tasks with the number of the measurements and the workers monitored.

2.3. Sample collection

Personal breathing zone samples were collected for both inhalable and respirable fractions for the workers during the execution of the tasks (Table 1). Samples for the inhalable dust, respirable dust, and metals in dust were collected on 25 mm, 0.8 μm mixed cellulose membrane filters using Institute of Occupational Medicine (IOM) samplers with the following specifications: 100 μm at 2L/min inhalable fraction and 4 μm at 2.5L/min respirable (with MultiDust foam) for 50% cut point detection, which is the size of the dust that the device collects with 50% efficiency, operating with a flow rate of 2 L/min and detection capacity for particles up to 100 μm in aerodynamic diameter. MultiDust foam discs were utilised to allow for the separation of the respirable and inhalable

Table 1
Tasks and measurement specifications for ships A and B.

Task	Sampling measurements	Fraction Inhalable	Fraction Respirable	Sampling duration (min)	Conditions	Facility & ship
T1	1 cutter	X	X	55	Confined	A
	1 helper	X	X			
T2	2 cutters	X	X	30	Confined	A
T3	1 helper	X	X	35	Confined	A
T4	1 helper	X	X	10	Confined	B
	1 cutter	X	X			
T5	1 helper	X	X	7	Semi-confined	B
	1 cutter	X	X			
T6	3 cutters	X	X	114 and 92	Open air	B
	1 helper		X			

Note: X indicates when respirable and/or inhalable fractions are measured.

fractions of total airborne particles. The samplers were attached to GilAir® personal sampling pumps via flexible tubing and were calibrated using a portable flow meter with a flow rate of 2 L/min for the total inhalable dust fraction and 2.5 L/min for the respirable dust fraction samplers. In order to separate the respirable dust fraction from the inhalable dust fraction pre-separators of model SKC and flow rates of 1–5 L/min were used. The volume of air passing through the sampler is calculated by multiplying the mean volumetric flow rate in cubic metres per minute by the sampling time in minutes (Health and Safety Executive, 2020).

The inhalable particulate fraction is that fraction of a dust cloud that can pass through the nose or mouth. The respirable particulate fraction is that fraction of the inhaled airborne particles that can penetrate beyond the terminal bronchioles into the gas-exchange region of the lungs.

The respirable and inhalable fractions of total airborne particles were obtained from the samples through measuring the net weight gain (mg) of the sample substrate and dividing it by the volume of air sampled (m^3) to give the average dust concentration in milligrams per cubic metre of air (mg/m^3). All measurements were carried out in accordance with the guidance of the European Standard EN 482, 'Workplace exposure - General requirements for the performance of procedures for the measurement of chemical agents' (European Standard EN 482, 2012).

Sampling periods varied for different tasks and the two locations, 30–55 min (averaging 40 min for the means of T1-T3 measurements) in the UK yard and 7–50 min (averaging 21 min for the means of T4-T6) in the Spanish yard. In order to compare different task durations fairly and to assess these against country-specific working day occupational limits an 8-h time weighted average (8h-TWA) of exposure was calculated in all cases. This approach follows UK legislation and guidance whereby the occupational exposures in any 24-h period are treated as equivalent to a single uniform exposure for 8 h (Health and Safety Executive, 2020). Thus the 8h TWA may be represented mathematically by Equation (1):

$$\frac{\sum ci\ ti}{\sum ti} = \frac{c1t1 + c2t2 + \ldots .cntn}{8} \tag{1}$$

Where.

c1 is the occupational exposure concentration
t1 is the associated exposure time in hours
$\sum ti$ is the shift length in hours (i.e. 8 h)

In the present study single extended sampling periods were used, so the continuous air sampling reflects time integrated concentrations over this period, rather than a statistical average from point measurements. EH40/2005 (Health and Safety Executive, 2020) states that the 8-h TWA approach is specifically used to include the effects of prolonged exposure, whereas 15 min TWAs maybe used to assess short term exposure where this is more relevant to the agent concerned. Where 15 min TWAs are not provided these may be estimated as 3 times the 8-h TWA. In the absence of further information on the variability of dust levels and the working assumption that the work task periods measured were chosen as being representative of the working shift as a whole, extrapolation and calculation of 8-h TWAs and comparison to the (lower) 8-h TWA thresholds represents a precautionary approach to estimating workplace exposure and environmental impacts. This follows the Precautionary Principle, introduced after the 1972 Stockholm Conference and a core principle of European environmental policy and law (Treaty, 1992).

2.3.1. *Preliminary analysis*

To characterise the types of metal used in the steel coatings, we collected paint chip samples from various steel parts of Ship A and Ship B. The chips were sent to an accredited laboratory where they were analysed for elements of concern using an inductively coupled plasma optical emission spectroscopy (ICP-OES) analysis method. Fig. 1 shows examples from the sample collection on Ship A.

A summary of the analysis is shown in Table 2. According to further analysis of these preliminary samples the paint coatings in ship A did not contain asbestos.

Paint sample 2 (Table 2) is the sample from the coating subjected directly to the oxy-fuel torch cutting.

A preliminary paint analysis was also conducted for the 10-year-old ship at Facility B. Three different paint chip samples were collected from the working area and sent to an accredited laboratory for analysis.

Summary of the analysis is shown in Table 3.

The metal contents and chemical composition of paints in Ship A and Ship B are very variable as can be seen in Tables 2 and 3 respectively, presumably due to their different age, vessel type, colour and purpose of paint.

Ship A has high levels of lead compared to ship B, reflecting the widespread use of lead pigments in UK paints in the 1960s. Cadmium concentrations in ship A are near to the detection level, but in ship B they are up to 4.8 mg/kg. Chromium content varies widely for both sets of paint samples, with examples of high levels in both cases. This was only a preliminary exploratory analysis as the main scope of this study was to estimate the potential occupational exposure to the main elements revealed by the preliminary paint analysis. The occupational exposure limits for dust and these metals are tightly regulated (Health and Safety Executive, 2020; https://www.hse.gov.uk/paper/dust.htm, 2022; https://www.hse.gov.uk/lead/health-effects.htm, 2022; Límites de exposición profesional para, 2021) by both the British and Spanish governments. The limits for the metals relevant to the current study can be seen on Table 4, which in each case are averages over an 8 h day.

3. Results

The potential exposure to levels of iron, manganese, cobalt, nickel, copper, zinc, arsenic, antimony, lead, cadmium, total dust and respirable dust were measured for all cases, with the mean value of exposure (TWA) in mg/m^3 calculated using the Equation (1) for the duration of

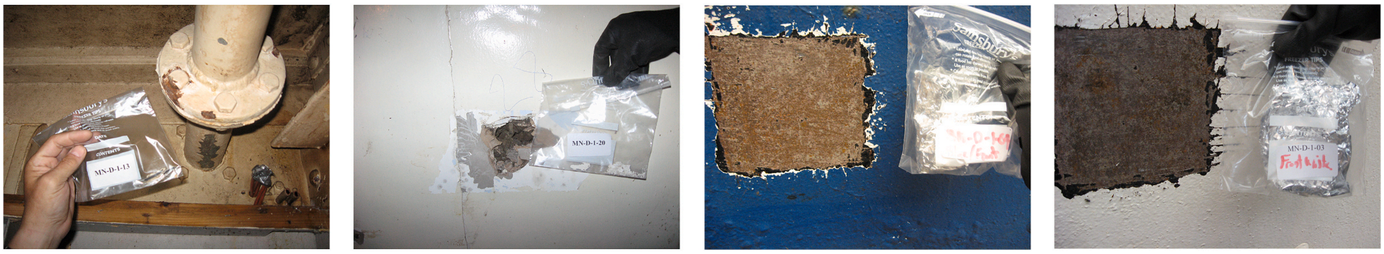

Fig. 1. Sample collection
Note: from left to right, sample 1,2,3,4.

Table 2
Preliminary paint sample analysis from the ship to be dismantled in Facility A (mg/kg).

Element	Limit of detection	Sample 1	Sample 2	Sample 3	Sample 4
Lead	0.3	43,200	89,400	212,000	163,000
Cadmium	0.1	0.4	0.4	0.4	7.4
Chromium	0.15	653	701	63.0	78.1
Mercury	0.05	0.63	0.14	2.31	2.52
Tin	0.035	7.4	7.50	5.0	44.1

Table 3
Preliminary cpaint sample analysis from the ship to be dismantled in Facility B (mg/kg).

Element	Limit of Detection	Paint sample/colour		
		White	Cream	Red
Arsenic	0.2	3.0	1.7	14
Cadmium	0.1	1.1	0.9	4.8
Chromium	0.15	270	1100	47
Copper	0.2	90	26	510,000
Lead	0.3	27	480	230
Mercury	0.05	<0.05	<0.05	0.05
Nickel	1	27	10	57
Zinc	1	9300	2200	51,000

Table 4
UK and Spanish occupational limits for 8 hour time-weighted average exposure (8h-TWA).

	UK		Spain	
	Inhalable	Respirable	Inhalable	Respirable
Dust*	10	4	10	3
Iron	5		5	
Manganese	0.2		0.2	0.05
Cobalt	0.1		0.1	
Nickel	0.5		0.1	
Copper	0.2			0.01
Zinc	10	4		2
Arsenic	0.1		0.01	
Antimony	0.5		0.5	
Lead*	0.15		0.15	
Cadmium	0.025		0.01	0.002

Note: UK limits from EH40/2005 (Health and Safety Executive, 2020).
Lead is regulated separately, so lead and dust limits are from (https://www.hse.gov.uk/paper/dust.htm, 2022) & (https://www.hse.gov.uk/lead/health-effects.htm, 2022).
Spanish limits are from (Límites de exposición profesional para, 2021).

each task. The results of the measurements can be seen in Table 5, compared to the TWA 8h limits. This is a worst case comparison based on the assumption that the workers might perform the same cutting tasks continuously for 8 h.

A total of 25 different measurements are reported for tasks involving cutting steel on ship A and ship B (Table 5). 16 of these measurements were obtained by monitoring cutters and 9 measurements by monitoring helpers. 9 of these measurements were conducted on Ship A (T1-T3), and 16 on Ship B (T4-6). 4 of the measurements were conducted in semi-confined spaces, 14 in confined spaces, and 7 in the open air. The measurements include, where possible, two fractions, respirable and inhalable. The analysis of the measurements of dust and metals divided by working task can be seen on Table 5. Unfortunately, for the T1 cutter task, a problem with the filter prevented further use of the analysis.

For T1, workers cut the coated steel with the oxy-fuel-torch cutting method. For Task 2, two workers cleared the coating from the steel using mechanical grinding and at a later stage (Task 3) cut the de-coated steel with the oxy-fuel-torch cutting method. Mechanical grinding exposure levels and decoated steel cutting exposure levels were recorded separately. For measurements taken on Ship B, all measurements were recorded normally, and the missing values indicate they were below the detection limit, or the calculated exposure was insignificant.

For both respirable and inhalable dust, the observed average exposures for workers on ship A and ship B were in most cases well above the occupational exposure limits when extrapolated to an 8 h period. Exceptions were for the open air tasks (T6) and the helper in a confined space with no paint cutting (T3) case (Figs. 2 and 3). For the worst location and task (T2, mechanical de-coating), measured inhalable dust was 28 times higher than the suggested occupational limit, while respirable dust was over 10 times higher than the UK limit. The results for the helper (T1) are also worrying, with both inhalable and respirable environmental dust above the limit by more than 4 or 10 times. For the Spanish yard and respective limits of 3 mg/m^3 respirable dust the mechanical cleaning and confined space cutters are exposed to more than 29 times the limit.

3.1. Iron

Iron is higher than the permitted inhalable limits (5 mg/m^3) in the cases of confined spaces for both ships, with the maximum values represented by the T4 helper and cutter, of 115 and 70 mg/m^3 respectively.

3.2. Manganese

As might be expected manganese was also above the inhalable limits (0.2 mg/m^3) for the confined space tasks with high exposure levels of Fe.

3.3. Arsenic

Arsenic is generally above the Spanish inhalable limit (0.01 mg/m^3) except for the open air and semi confined spaces, with the worse cases the confined space for tasks T1, T3, T4 for both helpers and cutters. Inhalable arsenic dust exposure for the cutter is also well above the British limits (0.1 mg/m^3).

3.4. Antimony

Antimony did not exceed the inhalable limit for any of the

Table 5
Results of the airborne particulate measurements in UK (T1-T3) and Spain (T4-T6) recalulated as time-weighted averages (mg/m^3).

Task	Fraction	Job Title	Sampling Time	Volume	Dust	Iron	Manganese	Cobalt	Nickel	Copper	Zinc	Arsenic	Antimony	Lead	Cadmium
			(min)	(m^3)	TWA	TWA	TWA	TWA	TWA	TWA	TWA	TWA	TWA	TWA	TWA
T1[a]	Respirable	Cutter	55		**41.6**										
T1	Inhalable	Cutter	55	0.111	**61.4**	**7.86**	0.061	0.0117	0.036	0.03	3.61	**0.208**	0.09	**28.00**	0.0025
T1	Inhalable	Helper	55	0.113	**48.8**	3.10	0.03	0.004	–	0.018	2.48	0.098	0.068	**20.40**	0.0018
T1	Respirable	Helper	55	0.135	**43.7**	1.56	0.023	0.0031	–	–	2.82	***0.104***	0.073	***22.26***	0.0022
T2	Rspirable	Cutter	30	0.074	**43.5**	***16.3***	0.127	0.0063	–	–	0.435	0.016	0.006	***4.35***	–
T2	Inhalable	Cutter	30	0.06	**281.5**	**66.2**	**0.464**	0.0497	0.063	0.152	4.80	0.06	0.073	**29.8**	
T3	Inhalable	Helper	35	0.041	**13.3**	4.35	0.036	0.0027	–	–	0.386	0.063	0.003	**0.772**	
T 3	Respirable	Cutter	35	0.052	**11.6**	3.48	0.029	0.0025	–	–	0.348	0.087	0.004	***1.53***	
T3	Inhalable	Cutter	35	0.043	**30.5**	**15.7**	0.089	0.0103	–	0.063	0.422	**0.155**	0.005	**1.9**	
T3	Respirable	Helper	35	0.052	**4.4**	–	0.014	–	–	–	–	0.052	–	***0.516***	
T4	Inhalable	Helper	10	0.02	**230**	**115**	**1.3**	0.011	**0.155**	1.3	8	**0.115**	0.07	**7.05**	–
T4	Respirable	Helper	10	0.025	**72**	***22***	**0.264**	0.0044	0.092	**1.52**	**8.8**	***0.088***	0.108	***5.36***	–
T4	Inhalable	Cutter	10	0.02	**175**	**70**	**0.75**	0.014	**0.255**	2.55	15	**0.15**	0.17	**10.1**	0.006
T4	Respirable	Cutter	10	0.025	**88**	***38.8***	**0.52**	0.005	0.092	**1**	**6**	***0.096***	0.044	***5.36***	–
T5	Inhalable	Helper	7	0.014	7.143	–	0.017	–	–	–	0.243	–	–	0.093	
T5	Respirable	Helper	7	0.018	**7.429**	–	0.01	–	–	–	0.223	–	–	0.086	
T5	Inhalable	Cutter	7	0.014	**11.43**		0.028	–	–	–	0.393	0.01	–	0.121	
T5	Respirable	Cutter	7	0.018	**7.43**	–	0.03	–	–	–	0.349	0.01	–	0.097	
T6	Inhalable	Cutter	50	0.1	**20**	**6.3**	0.042	0.002	**0.25**	0.23	0.32	0.007	0.002	0.018	**0.012**
T6	Inhalable	Cutter	42	0.084	**10.6**	–	0.055	–	–	0.405	0.25	0.003	–	0.009	–
T6	Respirable	Cutter	50	0.125	**6.8**	1.04	0.011	–	**0.128**	0.065	0.12	0.005	0.001	0.014	**0.011**
T6	Respirable	Cutter	42	0.105	**5.43**	–	0.027	–	–	**0.362**	0.267	0.003	–	0.011	–
T6	Respirable	Helper	92	0.23	0.65	–	0.002	–	–	0.01	0.01	–	–	–	–
T6	Inhalable	Cutter	22	0.044	**14.09**	–	0.05	–	–	1	0.636	0.005	–	0.025	–
T6	Respirable	Cutter	22	0.055	**8**	–	0.022	–	–	**0.709**	0.527	0.004	–	0.022	–

[a] Note: Due to problems with the filter, T1 respirable dust data for cutter is missing. Figures in bold exceeded the national limits (see Table 4). Figures are shown in bold italic where these are respirable levels without specific limits but which still exceed limits for inhalable dust.

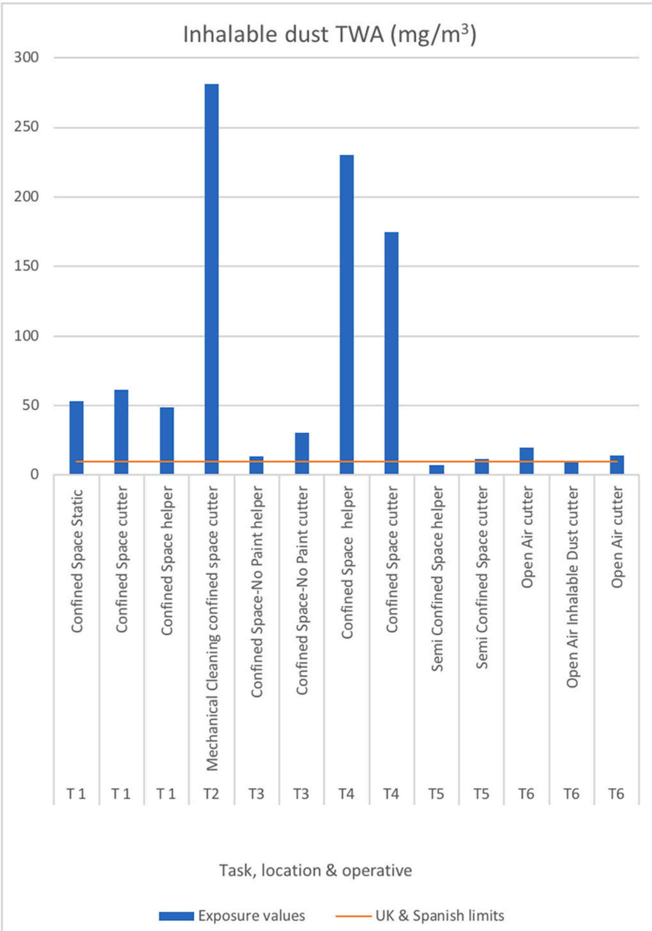

Fig. 2. Potential inhalable dust exposure compared to the British and Spanish limits (see Table 5 for values close to the threshold).

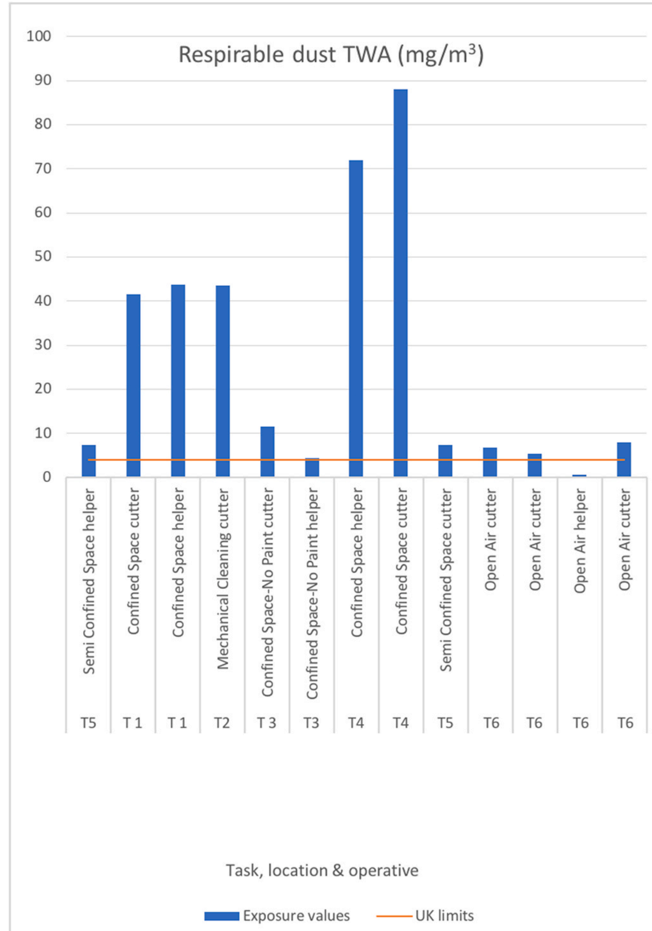

Fig. 3. Potential respirable dust exposure and the British limits (see Table 5 for values close to the threshold).

measurements.

3.5. Lead

Lead measurements are of particular concern. They revealed that the open-air cutting tasks were within the recommended limits. However, all of the measurements for both inhalable and respirable levels for each of the confined space tasks (1–4) exceed the inhalable limits (0.15 mg/m^3), with the task 1 and 2 the highest at up to nearly 30 mg/m^3.

3.6. Cadmium

Cadmium slightly exceeded the limits of both respirable and inhalable fraction for one cutter during the open air task 6. This result is not easy to interpret.

3.7. Cobalt

Cobalt was within the limits for all the measurements.

3.8. Nickel

Nickel was within the UK limits for the inhalable fraction, however for the cases of the cutter and helper of task 4 inhalable fraction it was over the Spanish limit.

3.9. Copper

Copper was not detectable for many measurements including respirable and inhalable fractions, however when present it was commonly over the Spanish limit for the respirable fraction. The maximum concentration was found for task 4 in a confined space, for which the respirable fraction exceeded the respective limit (0.01 mg/m^3) by a factor of 152.

3.10. Zinc

Although Zn was typically present in cutting dusts, only confined space task 4 on ship B exceeded the stricter Spanish respirable limits.

4. Discussion

This study measured ship recycling workers' environmental and potential occupational exposure by inhalation and respiration of metals and As in fumes generated by cutting steel during two real cases. Here the workers were provided with PPE but in less well-regulated developing world facilities this might not be the case, since these are not controlled or regulated (Sunaryo et al., 2021).

Two cutting methods were compared, one based on prior mechanical de-coating followed by cutting, and the second, and most common method in practice, direct torch cutting of coated steel. Given the absence of an Inventory of Hazardous Materials (IHM), exploratory analyses were prepared for both ships and measurements began after making sure that the working task subject did not contain asbestos. This is a common problem in the ship recycling industry where neither composition nor quantity of potentially hazardous material used are well known and thus recycling management is more demanding (Jain et al., 2016). In this study, inhalable and respirable fractions for ship recycling workers during normal working operations were monitored and measured. Samples from these measurements were then analysed for their elemental contents.

The potential exposure to the dust and the metal agents shown in this study are worrying, especially for particulates, Fe and Pb. Adverse health effects due to the particulates can be separated into pneumoconiosis hazards and pulmonary irritants or toxic inhalants (Stern, 1981). It is well known that being exposed to iron, manganese, copper, chromium and zinc at these high levels can cause serious health risks such as pneumoconiosis, neurological disorders, irritation of the upper respiratory tract, gastric disturbances, metal fever, ulceration of the skin (Antonini et al., 2006; Flynn and Susi, 2009; Steel, 1968). Lead exposure has severe toxic effects on multiple organs and systems; anaemia, kidney failure, reduced heart rate variability, loss of appetite and stomach cramps, etc. (NIWL, 2005). The exposure to dust of steel workers has a cumulative effect (Hamzah et al., 2016) making the working population even more vulnerable through time.

Moreover, the emissions produced usually include other chemicals such as carbon monoxide, nitrogen, plastics, particulates, PCBs and general derivatives which depend on the combustion of the fuel used, pressure of the cutting gas, the thickness of the steel, cutting speed, environmental factors (temperature, humidity, atmospheric pressure) and the chemical composition of coatings and primers used on the steel (VMBG, 2007). The problem is not only limited to occupational exposure. Many other hazardous substances are commonly found near ship recycling yards, for example organic compounds (Nøst et al., 2015) or excessive emissions of CO_2 in areas surrounding ship recycling (Mitra et al., 2020). The metals detected in this study are also commonly detectable in sediments near ship recycling yards where they are probably due to cutting operations (Yılmaz et al., 2016). The adverse environmental and health effects can be additive due to the multiple emissions, which can constitute toxic chemical mixtures with even more complicated modes of actions which lead to enhanced toxicity. As a consequence, blood samples of workers should be tested for the heavy metals, in order check functioning of PPE and so avoid systemic poisoning.

Production of an IHM is a regulatory requirement and, prior to recycling, details of additional hazards in stores and wastes are added. The document can then be used to help an authorised recycling facility formulate a safer and more environmentally sound plan for decommissioning the ship. An IHM can help towards a safer ship recycling process, but new techniques and practices should be considered for minimising dust and toxic chemical agents (Gunbeyaz et al., 2020). In particular, removal of asbestos, PCBs, glass fibre, solid foam and waste oils according to the current practices does not always guarantee safe environmental and health practice *per se* (Du et al., 2018). Other waste management activities, such as those treating glass, clothes, electronic devices and plastics can involve toxic or harmful chemicals like those identified in this study, for which the analytical methods must be more sophisticated for reliably detecting and determining the type and the quantity of the harmful chemicals (Viczek et al., 2020). Interesting new technological methods such as the recovery of zinc from zinc-rich paint (which is usually used as coating for protecting the steel parts) (Xing et al., 2018), alongside the mechanical de-coating before the cutting activities could be beneficial for further reducing the exposure hazards.

Mitigation actions such as proper personal protective equipment and ventilation should help but these cannot be directly related to health condition improvements since there is inadequate knowledge of ill-health prevalence in waste recycling workers (Poole and Basu, 2017).

If further measures to protect health, safety and the environment are not taken, countries with a long tradition of ship recycling may soon opt out (Steuer et al., 2021) with unknown or less predictable consequences for the global shipping market.

5. Conclusions

Based on the results from both facilities, ship recycling workers are at high risk of exposure to airborne particulates and potentially toxic elements, unless protected by effective dust masks and other PPE. The exposure by inhalation to heavy metal was at excessively high levels for almost all cases studied, especially in Facility A for lead, which recycled a 50-year-old ship with old coating containing very high lead concentrations compared to Facility B.'s vessel. Occupational Exposure Limits for workers were potentially exceeded in confined spaces and for coated steel cutting for iron, lead, arsenic, manganese, total and respirable dust for several tasks.

Following the hierarchy of hazard control the follow general conclusion can be drawn regarding practical steps to help protect workers and the environment. Firstly, given the inherent requirements of ship dismantling, steel cutting cannot be eliminated. However, substitution of alternative methods to direct torch cutting might be possible in some situations and countries with greater or lesser success. For example, use of water-jet cutting might be likely to reduce fugitive dust emissions to the atmosphere or worker exposure by respiration but would still produce water-borne contaminated particulates requiring isolation, settlement and filtration to prevent water or sediment contamination. As an example of an engineering control, in this study a preparatory mechanical grinding procedure was compared to see if cutting de-coated steel will cause similar occupational health problems. Cutting de-coated steel is better than cutting coated steel directly, but still caused some heavy metal exposure, which exceeded the occupational health limits. Furthermore, the mechanical grinding required to de-coat the steel caused high exposure levels to the heavy metals and dust. Better de-coating solutions should be researched if de-coating is to decrease the overall exposure. In this study in semi confined spaces the exposure values of total and respirable dust, as well as several heavy metals are exceeded if 8-h exposures are assumed. However, for open air cases, total dust, respirable dust, copper, chromium and cadmium exposure levels also exceeded the exposure limit values. This suggests that even if it were practical to avoid confirmed space working altogether in ship recycling it might still not be sufficient to reduce exposure to acceptable levels. Thus, other suitable engineering controls are required relating to dust suppression, such as water sprays, ventilation and extraction in either case. Again, these would need suitable containment, settlement and or filtration systems in place to prevent environmental dispersion.

Finally, and as a last resort in the control hierarchy, employers must provide adequate personal protective equipment. Results from this paper demonstrate that workers are at high risk of occupational exposure to welding fumes and chemical agents involved in the processes of cutting steel in the absence of adequate PPE or other control measures. The majority of the measurements demonstrate that defined exposure limits are exceeded which requires immediate attention. The authors believe that the findings of this research study will attract attention towards further investigation of exposure to total dust and chemical agents during ship recycling processes and will become a starting point for more effective protective policies and prevention of occupational hazards through design.

Limitations

The calculations presented in this section are based on the filter analysis by the accredited laboratory. Due to circumstances at the facilities, measurements could only be carried out for short periods of time. In order to get more accurate 8 h TWA exposure values, measurements should be conducted during a whole working day rather than extrapolated by calculation. Future studies should combine direct measurements of the intake of heavy metals by the shipyard workers involved in dismantling activities.

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Institutional Review Board Statement: Ethical review was not requested, and approval was not required for this study, as the humans involved in the sampling were not the primary subjects: The research used environmental monitoring data obtained from air sampling equipment mounted, with prior consent, on workers who were fully protected by wearing appropriate personal protective equipment. The health of these workers is not directly the subject of the investigation, who were not tested in any way, rather the external environmental conditions created by the tasks they undertook. These measurements are then used indirectly to consider the possible effects on health of workers in ship dismantling facilities in general, including where PPE is possibly not provided or used. The publication of this data is considered to be justified by its relevance to the future protection of workers in developing countries.

Informed consent statement

Informed consent was obtained from all subjects involved in the study.

CRediT authorship contribution statement

Sefer Anil Gunbeyaz: Data curation, Writing – review & editing. **Evanthia Giagloglou:** Formal analysis, Writing – review & editing. **Rafet Emek Kurt:** Conceptualization, Methodology, Writing – original draft, Project administration. **Karin Garmer Rogge:** Conceptualization, Methodology, Investigation, Writing – original draft, Funding acquisition. **Selim Alkaner:** Investigation, Conceptualization, Project administration, Supervision. **Stuart A. McKenna:** Conceptualization, Methodology, Investigation, Writing – original draft. **Osman Turan:** Supervision, Project administration, Funding acquisition. **Richard Lord:** Validation, Formal analysis, Writing - review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The authors are unable or have chosen not to specify which data has been used.

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