LESSONS LEARNED FROM THE USE OF VIRTUAL REALITY FOR OCCUPATIONAL SAFETY AND HEALTH TRAINING IN THAMES TIDEWAY TUNNEL

Manuel Tender[1,2], Paul Fuller[4], Alex Vaughan[3], Peter Demian[4], Vivien Chow[4], Firmino Silva[1], João Couto[5], Ricardo Santos[2]

[1] ISLA-Polytechnic Institute of Management and Technology, School of Technology (PORTUGAL)
[2] ISEP-Instituto Superior de Engenharia do Porto (PORTUGAL)
[3] *Ferrovial / Laing O' Rourke Joint Venture* (UNITED KINGDOM)
[4]University of Loughborough (UNITED KINGDOM)
[5]University of Minho (PORTUGAL)

Abstract

New Key Technological Developments (KTD) are leading to a challenging paradigm shift in the way Occupational Safety and Health (OSH) is managed in the Architecture, Engineering, Construction, and Operations (AECO) sector. Previous research has shown that these developments have the potential to reduce the risks and costs associated with accidents and occupational diseases at work. This paper reports on a pilot case study covering the implementation of BIM and Virtual Reality for OSH training purposes related to the operation of a Tunnel Boring Machine (TBM). The actors involved included designers, BIM/OSH specialists, construction managers, and training staff. The aim of the research was to identify the benefits, barriers and challenges associated with the implementation of these KTD's in a Joint Venture (JV) organisation delivering part of a complex megaproject in Central London. A tablet-based approach was selected to overcome some of the challenges of implementation identified. The resulting areas of benefits included: better safety in design, improved hazard perception: enhanced risk awareness and increased familiarization prior to working in the hazardous environment of tunnel construction, emergency rescue training, and maintenance training. The main benefits from this are the resulting productivity gains - Tideway estimates that the project could potentially see a 20% reduction in training time, a 10% reduction in accidents and near-misses and significant increases in employee understanding of hazards and risks onsite, which can improve project outcomes significantly. The key lessons learned are the need to keep costs down, the necessity of system portability and ease of access. The results of the study will assist organisations that are interested in the adoption of these KTD's and provide valuable insights to the wider construction industry. This will enable companies to improve how OSH is managed and promote the uptake of KTD for OSH purposes.

Keywords: Virtual Reality, Tunnelling Boring Machine, Health and Safety Management, Lessons learned, Thames Tideway Tunnel

1 INTRODUCTION

1.1 AECO and Key Technological Developments

The Architecture, Engineering, Construction and Operation (AECO) sector has witnessed several key challenges in recent years: low productivity, shortage of qualified staff, insufficient innovation, a lack of consistent processes, standardization and automation, the need tfor a large amount of technical documentation, and an aversion to adopting new technologies [11].

Key Technological Developments (KTD) tools have become increasingly important in providing better integration for the development of Architectural, Structural and Mechanical, Electrical and Plumbing (MEP) Project designs, given their proven advantages to respond to a growing need for optimizing processes, procedures and decision-making throughout the entire construction lifecycle [11].

The AECO sector represents a fundamental driving force in world economy growth and remains a key indicator on a country's prosperity. BIM may be considered today as the methodology that fulfilled the promise of innovation through digitalization of an industry normally reluctant to adopt novel or disruptive solutions need to be found to solve old problems exacerbated by a plethora of new challenges.

Virtual Reality (VR), along with other types of reality substitution, superposition or enhancement, have already proved their worth on several industries but still need to find general acceptance in the AECO industry. In the context of Industry 4.0, it might also be worth mentioning that Augmented Reality (AR) and VR are important components of the emerging concept of the "metaverse". It can also be said that the correct management of OSH is a critical factor to the success of any construction project and has been widely recognized as one of the most influential aspects in companies' overall performance [2].

1.2 AECO and OSH

Accidents persist, despite several improvements in construction processes. Factors influencing this, include the increasing complexity of site operations and increasing fragmentation in the supply chain and subcontractors. OSH presents several challenges namely in terms of communication and training:

1) Communications: there is still a lack of collaborative working approaches [3], and it is still done orally [4] and using personal experience [5], and based paper-based two-dimensional drawings, which are error-prone, subjective [6] and sometimes out of date; communication methods tend not to be systematic [7] which hinders the exchange of information between stakeholders;

2) Training: several countries have adopted human-led approaches, both in classroom and in the field [8], to ensure a minimum level of training through lectures, videos, or demonstrations. These traditional training methods often fail to achieve the desired goals due to their significant limitations. For example: indoor static classroom presentations with no hands-on training elements which often fail to engage with the workers leading to a lack of interest, which impedes the retention and retrieval of critical safety concepts [9]. Due to their passive nature traditional training methods such as classroom, on-site presentations, or video-based guides do not necessarily allow a practitioner to test their understanding (as a result they must wait until they physically try to perform what they have been taught before it is known if they have understood the material [10]); the complexities and spatial characteristics of the specific construction site are not properly represented. The transient and temporary nature of the workforce hinders the implementation of new technologies as not all employees are at the same skill levels; there may be a lack of knowledge transfer due to workers not being taught in their native language or have low literacy levels and do not properly understand the training message. In terms of tunnelling activities training, new approaches must be found in order to minimize associated specific risks. Tunnelling risks are as extensive as those involving works above the surface, or even more so. Tunnelling works are prone to several types of emergency situations, particularly collapse, electrification/electrocution, being hit by a vehicle, roadway accidents, intoxication and lack of oxygen.

1.3 OSH through KTD

However, when it comes to OSH, KTD are not yet used as often as is the case in other specialties [12]. The literature indicates that the construction industry, especially larger general contractors and in complex projects, is developing an increased understanding of the application of KTD in real cases of design, construction, and facilities management and are starting to adopt KTD for use in OSH management [14] in order to overcome the challenges identified. The application of KTD to OSH management has the potential to offer innovative and exciting developments in the workplace, and has positive impacts on the optimization of times and costs with an increased production efficiency, and a better connection between production and safety [11]. A number of advantages have been shown to arise from the adoption of KTD for OSH management: more effective sharing of HSW information in a virtual environment and reduced likelihood of losing information; better visualization and interpretation of design through immersive learning environments; a decrease in the amount of time needed to produce outputs; favorable impacts on schedules and costs; savings in HSW practitioners' time; more focus on greater precision; and more strategic ways to improve safety for everyone in the workplace [11]. Several researchers in the field have identified technical and scientific gaps in terms of research covering the integration of KTD in OSH management systems and have advocated the need for new studies covering:

- the benefits of using digital technologies to improve OSH outcomes [16];
- the theorical validity of the advantages that have been identified using suitable case studies [17];
- the lack of success in technology transition from construction safety research into practice [18].

VR has been widely used for safety training since 2000. In a previous phase of the research [11] the authors evaluated the level of applicability of KTD for each OSH area identified from an analysis of the Council Directive 92/57/EEC [15]. Usage of VR for hazard risk identification and training was evaluated, using a Low/Medium/High level of applicability scale as "High".

Previous research covering training using VR has indicated that VR training has several advantages over traditional training methods including:

- training is performed in a risk-free and realistic virtual construction site;
- workers' behavior in several unsafe work scenarios can be evaluated;
- a reduction in the time it takes for a learner to become competent and operational in their field of work, and they produce memorable and lasting experiences for trainees;
- a lower required level of language proficiency and literacy and increase the understanding of those in construction who lacks fluency in English removing any language barrier;
- optimization of risk identification (the ability to identify hazardous conditions before starting a task is a valuable tool to promote proactive HSW management);
- simulation of different scenarios;
- on-site construction situations and operations can be modeled;
- aids creation of accident scenarios;
- training can be replayed as often as the trainee chooses;
- conditions of accidents and near-misses can be simulated.

This paper addresses the need for more research with a real case example (pilot study) in Thames Tideway Tunnel (Tideway) project by Ferrovial Agroman UK and Laing O' Rourke Construction Joint Venture (FLO JV) - "Virtual Reality Tunnel Boring Machine" (VR TBM). The case example aimed to retrieve lessons learned from it, analysing the benefits, barriers and challenges, of using VR to transform the way Occupational Safety and Health (OSH) is managed and assessing the benefits, barriers and challenges associated with this approach. This pilot study will have a special focus in areas such as improving hazard perception, awareness, to improve risk assessment, and training during the construction phase and to develop familiarization prior to accessing or working in the hazardous environment of tunnel construction. Affordable and mobile technology to deliver the experience was one of the key aims of the project.

Taking in account the technical and scientific gaps identified in the literature review the following Research Question (RQ) was established: "*What practical lessons and good practices are there to be shared, based on the learning from the Tideway interventions, with wider industry and those involved in fields of OSH development and improvement?"*

Providing construction stakeholders with a list of KTD applicable to improving OSH management along with identifying their key benefits and barriers will facilitate better knowledge and understanding of OSH management. This in turn will encourage increased adoption of KTD solutions, especially amongst smaller contractors who are typically more likely to be resistant to change.

The following section identifies the overall context of the study whilst Section 3 presents the approach to the research methods and methodologies and Section 4 exposes the lessons learned. Section 5 covers the conclusions, explores limitations, and it explains what future studies should focus on.

2 TIDEWAY CASE STUDY

UK was preferred as a suitable location to conduct the research for the following reasons [19]:

- The UK has a large history of mega and complex projects and has several ongoing placing the country in a unique position of global influence [11]. There has been an effort and growing interest in innovation management in megaprojects in UK [20], and there is much to be explored in this area of research [19]. However, innovation on megaprojects remains "surprisingly underexplored in the megaproject management literature" [19]. UK has also played an active role in driving forward KD adoption perhaps leading to interest from professionals in other countries to follow the UK's progress [11];

- The UK adopts the important concept of applying lessons learned from projects both positive and negative. [11]. The lack of learning from projects results in similar errors to occurring and missed opportunities to improve performance;
- The process-based open innovation approach used on the Tideway project provided an opportunity to explore how innovation and learning legacy can be used as a way of transforming the infrastructure industry over time [19].

The Thames Tideway Tunnel Project was selected as it is a from the statistical population of construction project using a convenience sampling strategy. The authors have been carrying out previous research covering the use of OSH on this project which provides a rich understanding of the topic. The project is

the biggest infrastructure project (£4.2 billion pounds GBP) ever undertaken by UK water industry and one of largest in Europe. The project has a key objective of pursuing innovative technology as a way of improving cost-effectiveness, productivity and the quality of work delivered. There are some excellent examples how the issues identified are managed and Tideway management have put an emphasis on lessons learned from previous projects.

The Tideway project is being undertaken to renew the Victorian sewerage systems designed by Sir Joseph Bazalgette. Even though the sewer structure is still in good condition, despite its age, it has a shortcoming – due to the increase in population, millions of tonnes of sewage are discharged into the tidal section of the river Thames every year adding to pollution of the river. The Tideway project will provide a new super sewer infrastructure for London that will reduce the current high number of discharges of effluent into the river. This will dramatically improve the water quality of the river and give the city a wastewater system that it can rely on for the next 100 years. The scheme is designed to intercept existing Combined Sewer Outfalls (CSO's) located along or adjacent to the river with the construction of new interception chambers and shaft structures built into the foreshore sites of the existing river wall CSO's. The main transfer tunnel is 25km long and 7.2m internal diameter located predominantly beneath the central section of the Thames and will connect to 34 of the most polluting CSOs. It is being built under London's existing underground infrastructure, deep beneath the London Underground tube lines and utilities, and will pass through a variety of ground conditions. Construction commenced in 2017 with completion scheduled for 2023. The Tideway project has been let as three distinct contracts for three Main Work Contractors comprising Central, East and West. Ferrovial Agroman UK and Laing O' Rourke Construction Joint Venture (FLO) will be undertaking the Central section of the Tideway scheme as Principal Contractor and Designer. This section measures 12.7 kilometers in length, it is the largest of the tunnel's three sections and it is worth 746 million pounds, equivalent to 1,050 million euros. The Central Section of the Thames Tideway Tunnel project has 24 construction sites and is illustrated in Fig. 1.

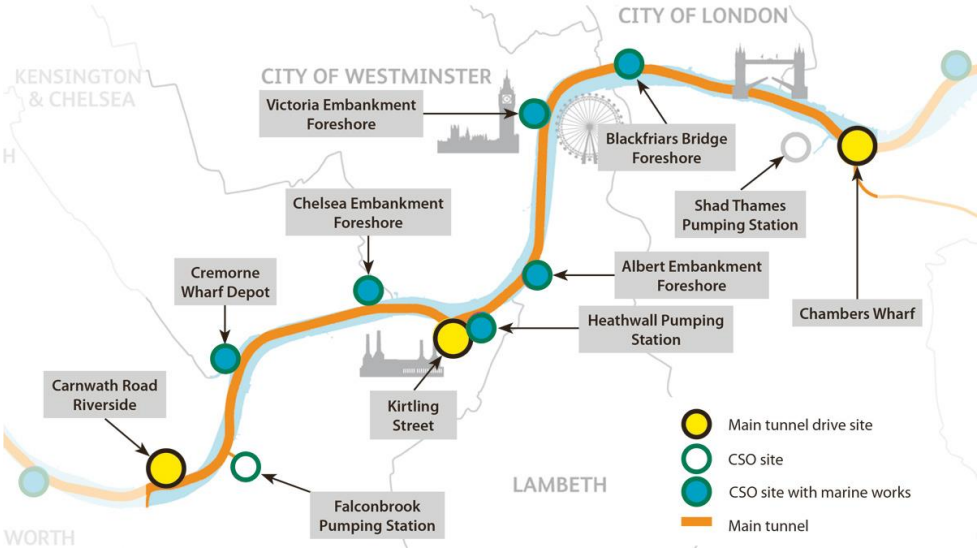


Fig. 1 – Tideway Central Section Map

Occupational risks related to these works include [11]:
- Structural hazards (ground settlements from temporary or definitive structures fragilities or collapse); lifting operations; confined spaces; working at height; flooding; migration of toxic/ explosive ground gases into the tunnel; dealing with services: water, electricity, gas; contact with unexploded ordinance; derailment, roll over and crushing by vehicles; fall of blocks and sprayed concrete fragments; trench collapse; risks related to lifting or moving operations (e.g. Tunnel Boring Machine (TBM) parts, segments, cofferdams); rupture of pipes or temporary structures; fall of person on the same level/to a lower level; fire and explosion onshore or offshore; electrocution; overturning of vessels; hypothermia, drowning; rock mass and sprayed concrete dust inhalation; fumes, diesel gas or fire smoke inhalation; biological risks: leptospirosis and water borne diseases, biological pathogens, live sewers, contaminated land; asbestos; chemical risks: shotcrete, concrete, sprays, petrol, cement, gases from live sewers, gases from soils; terrorist attacks due to site location near and adjacent to government buildings; noise; vibration; hyperbaric interventions; extreme temperatures; radiations; musculoskeletal problems; psychosocial risks e.g. stress and fatigue.

Tideway, as the Project Owner, has the objective of delivering a transformational approach to OSH better than any else currently experienced in construction [21]. This is intended to be achieved through better: leadership; organizational processes and procedures; communications; collaboration; and engagement. These factors have been the key to the successful OSH delivery of the activities carried out. FLO, as a contractor, is taking steps (namely through using new technologies) so that workers finish the project with a good understanding of OSH management and how transformational approaches can be adopted.

3 RESEARCH METHODOLOGY

The Central Section construction sequence provided an opportunity to investigate the advantages and disadvantages of using a VR based approach to OSH. The adopted methodology involves the researcher investigating an activity or process in depth over a period of time using a range of data collection processes (Cresswell 2009). The data collection consisted of interviews, direct observation and archival analysis.

The project was developed by FLO JV in partnership with Hobbs Studios, Thames Tideway Project and knowledgeable Health and Safety professionals within the industry (namely Innovate UK, University of Sheffield – Advanced Manufacturing Research Centre, and Advanced Forming Research Centre – University of Strathclyde). The first stage has been completed and has been used as a trial which took the form of a Virtual Reality (VR) model that could be used by FLO as part of their suite of training tools. A key objective was to improve the technical and logistical understanding of the works normally covered during inductions. The team have retained the industry's naming conventions, where new equipment is named after a saint. This tool has been named after St Barbara, the patron saint of mining, and a virtual St Barbara has been created to sit in the technology.

A proof of concept Induction Training module was developed using funding awarded from the Thames Tideway Innovation fund in June 2017. During the initial demonstration in May 2017, an improvement to the approach was identified which would save £80,000. Additional funding has been awarded by Innovate UK. This will be used to develop the Hyperbaric Interventions / Compressed Air Working and the Refuge Chamber modules. The next step will be to establish modules covering the Refuge Chamber the Build Area and Hyperbaric Interventions / Compressed Air Working.

The VR model was created using a visual support tool using Unreal Engine software (developed by Epic Games) supplied by Hobs 3D. This software allows the user to navigate in a virtual environment to train, explore and modify design of a TBM prior to assembly and delivery to site thus improving hazard perception, awareness and develops familiarization prior to accessing or working in the hazardous environment of tunnel under construction. Hardware medium was a tablet Microsoft Surface Pro 4; a VR Stereographic Projection Optoma 3D Projecto; VR headset Optoma ZD302 3D glasses and a gaming compatible laptop. Usually the virtual TBM is housed in a large cardboard pod – measuring around 6m by 4m, which can be easily transported to exhibitions and workshops. Not only can it be dismantled easily, but the pod can be recycled at the end of its useful life. This is significantly more cost effective than traditional VR pods which can cost between £80-£100k. The cardboard pod cost £4k.

The process was initiated with a working group from the Hobs 3D teams, digital team and the OSH team to create an accurate 3D BIM model. The 3D BIM model was then reviewed by the FLO OSH Lead and Tunnelling OSH Manager to ensure all high-risk areas were captured within the model and the key areas highlighted that need to be reached within the final virtual model. The 3D model was then created using the virtual model using the Unreal Engine software.

Subsequently there was a discussion of the content of the training and key areas and routes of the TBM that they would like to follow in the eventual 360-degree image tour. Digital team then takes the 360-degree camera and follow the agreed upon route and takes the 360-degree photographs at the before specified locations. This tool has various customizable options. Users can adjust the height, add logos and include multisensory features such as 4D sound, changing temperatures, smells and multiple screens, adding an extra level of immersion; ideal for environment simulation.

The VR TBM has been designed with three core principles in mind; Accessibility, Portability and Affordability which differentiates it from anything similar. The instructor can guide viewers, immersed using VR glasses, through the virtual TBM space (Figs. 2 and 3) allowing them to interact with the TBM and environment enabling remote site orientation as well as health and safety training before entering hazardous environments including hyperbaric conditions. This provides the ability to rotate and move around the TBM using the 360-degree imaging from the comfort of a non-TBM environment, allows the

inductor to highlight high risk areas, dangerous components, pedestrian walkways, fire points, first aid points, emergency exits, areas of work and more, exactly how they would see it on TBM, without having to go on site.



Fig 2 – Still shot of VR TBM

The TBM construction sequence was complex in terms of the many activities that were occurring and also highlighting to the users the risk of these concurrent works happening at different places. These activities included: the build area of TBM; refuge chamber; hyperbaric interventions; segment magazine area; locomotive training; emergency escape.

Data information about benefits and barriers were collected through participant direct observation (namely site visits), 8 workshops (6 end users each- miners, civil engineers, mechanical engineers, TBM operators, Health and Safety team, fitters, electricians,etc) with verbal feedback and presenting, to take advice and guidance, to industry stakeholders and leaders (4 events with 20 people in each forum) such as Transport for London, London Underground, Thames Water and High Speed 2. Traditionally, similar VR systems would be costly, and the equipment would be difficult or cumbersome to transport. This would also make the equipment inaccessible to many. FLO presented in a Dragon's Den style competition called Tideway's Great Think where they successfully pitched for £20,000 from 4 industry dragons to further develop the concept.



Fig 3 – Still Shot of VR TBM Build Area

4 LESSONS LEARNED

4.1 SUCCESSFUL FACTORS

The pilot study, through feedback from participants' experience with the system, noted that the use of VR for TBM training had the following advantages:

- It provided the opportunity for users to become familiar with the working area/functions and practice interactive scenarios in a safe and controlled environment;
- Users could be assessed on their understanding and knowledge prior to being placed in the environment before workers are required underground and in most cases before the TBM has even been manufactured. Note that some working areas of the TBM are only accessible during high-risk activities such as compressed air working;
- Enhances the user's knowledge of key components and working areas of the actual TBM far in advance of the TBM even being assembled thus reducing the time it takes for real life familiarization training by 30%:
- Within a few minutes the user can become familiar with a TBM configuration by travelling in a VR environment starting at the rear of the TBM and working their way to the front;
- Making the experience interactive encourages questions and all persons present to participate;
- The system is portable (can be transported in a small case on public transport or in a vehicle) and does not require an expert to assemble;
- Designers are able to experience how the TBM will look before it is constructed and how TBM will interact with its environment as well as identifying improvements and the designing out of hazards and risks which is a priority. They will also have the opportunity to identify not only design issues/concerns but also improve the ergonomics related to personnel working on the TBM;
- Allows significant increases in how workers identify safety risks when dealing with problems that are difficult to detect during onsite safety training with real-life hazards;
- Enables better learning (70% of learning is visual), greater reliability and accuracy, understanding and information retention of TBM;
- The cognitive load placed on workers is reduced and retention of information is improved;
- Increases workers' enthusiasm to learn;
- Reduces the time spent analyzing drawings to confirm particularities of TBM;
- Provides the operatives a collective insight of the TBM and a chance for workers to familiarize themselves with their future surroundings and allow them an opportunity to plan how to circulate and work within a TBM;
- Improves the health and safety planning of the works in TBM creating a reduction in risks;
- Better emergency planning e.g. London Fire Brigade can use the tool for training which enables time to be used effectively and prevents them the need to access a working TBM in what is already a tight and congested environment;
- Generates time and cost savings in the form of reduced abortive work and/or wasted time and an increase in production;

t can be used to other functions than training by reducing the need for visits to a busy active site which could have increased risk levels.

There was noticed that this system has also the potential to encourage school children and students into the industry. It demonstrates not only the workplace but also the technology used in the industry. The Tunneling and Underground Construction Academy had expressed interest for using the VR TBM to train apprentices and use it for familiarization training within their courses.

4.2 CHALLENGES

It also was discovered that this tool presents the following challenges:

- It was felt in some quarters, particularly in the tunnelling department that 3D Virtual Reality Training could not replicate real life scenarios however, some working areas of the TBM are only accessible during high-risk activities such as compressed air working. Other areas such as the Refuge Chamber which is a place of sanctuary on the TBM in the event of fire in the tunnel/on the TBM require a sequence for it to operate correctly. It was not intended to replace real life training with a VR solution, it was to enhance real life training.
- There was at the outset a resistance to the traditional methods of communicating information that involve 2D drawings, PowerPoint and historical information. This is usually a one-way method of communication in which the audience is dictated too and can be reluctant to ask questions; This is a traditional challenge that is not unique to VR implementation;

5 CONCLUSIONS

The use of VR in construction has increased over the past few years. The uses of VR for OSH-based TBM training include the following: TBM familiarization, emergency rescue training, maintenance training, STEMET activities, safety in design and creating digital twins. This approach can lead to a

paradigm shift in the prevention of work accidents or near-misses through its impact on risk identification, implementation of preventive measures, better communication and use for training.

Applying VR to OSH management has positive impacts by optimizing the time and costs involved in TBM operation. This will increase production efficiency and provide a better connection between production and OSH which will improve financial performance. Lessons learned from this tool may be applied to most civil projects from building bridges to power stations and provide a future legacy for the sector and make the sector act in a more targeted way to improve risk management. It will also help increase the use of VR for OSH training. Each project shall be studied particularly as there is no 'one size fits all' approach. It will also influence decision makers globally e.g. regulatory bodies, standards institutions, etc.

As the TBM starts operating the VR TBM can be twinned digitally so that it will receive real time data and live camera feeds that will enhance the user's experience. Audio can be added to mimic the sounds expected as the user travels along the VR TBM. Although there are variations in the way TBM's are manufactured, the modules and scenarios are similar in most respects. This reduces the costs of further development of the tool. Blue chip clients such as Tideway, High Speed 2 and TfL have expressed interest in the VR TBM concept and are considering the inclusion of the requirement to use immersive technologies in the works information. This builds on the BIM requirements already in place on major projects.

Future studies should focus on:
- developing of further modules in the areas of TBM Familiarization, operation and use of Refuge Chamber, the Build area, Hyperbaric Interventions / Compressed Air Working etc. These modules will cover user interaction as part of hazard/risk perception and learning where users can observe activities and choose the correct options thus learning and becoming more familiar with the operations. As other VR modules are completed, they will be available for the wider industry to use;
- continue exploring lessons learned from major projects and others kind of projects.

A long-term aspiration will be to actually operate a TBM using VR which will reduce or potentially remove workers from the hazardous environment.

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