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Risk Analysis for Ethylene Oxide used for Sterilization - A Case Study

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Ethylene oxide (ETO) constitutes a hazardous chemical entity, characterized as a colorless gas with properties of toxicity, carcinogenicity, and ecotoxicity. This chemical also presents a significant risk of forming explosive mixtures when combined with air or other oxidizing agents. The article delineates a selection of incidents and accidents occurring in companies where+ ETO is operationally implemented. A case study is conducted to investigate the risks associated with an enterprise employing ETO as a sterilization technology, where storage and transportation of ETO also occur. The identification of primary accident risk sources is performed utilizing the Purple Book CPR 18E selection method. Human health impacts are evaluated using the dispersion model ALOHA 5.4.7. The objective of this contribution is to assess the risk of ETO within the company and to propose recommendations aimed at mitigating the risks associated with severe accidents.

* 1. Introduction

The issues of risk analysis of hazardous substances and industrial accidents are closely related. Chemicals have been identified and employed throughout history, and the chemical industry is indispensable to human existence. Numerous chemical substances are defined by hazardous properties, including explosivity, flammability, toxicity, and ecotoxicity. Throughout the entire life cycle of chemicals, which encompasses production, packaging, transport, storage, use, and disposal, the hazardous properties of these substances are linked to accidents and disasters. The severity of these consequences is exacerbated by both the intensity of the hazardous properties and the quantity of chemicals involved (Sikorova et al., 2019).

Ethylene oxide is a compound with marked reactivity that is extensively employed within the chemical industry, particularly serving as an intermediate in the synthesis of chemicals, such as polyester and polyethylene terephthalate (PET) or chemicals, which might be directly produced from it, such as acrylonitrile, ethylene glycol, etc. (Dever et al., 2024). ETO is also used in the sterilization of materials such as food, spices, and medical equipment (Kirman et al., 2020). It is predominantly introduced into the environment via industrial activities. ETO demonstrates significant toxicity towards plant life, insects, and mammals (Marsh et al., 2019).   
The fact that ETO is a carcinogen for animals has been known for decades (Lynch et al., 1984), its carcinogenicity for humans was confirmed in later studies and then in 2006 USEPA reassessed the cancer potency of ETO on its IRIS database, resulting in the derivation of a unit risk value that is approximately 50-fold higher than its preceding value. This large change in cancer potency estimated for ETO has initiated changes in its regulation, such as the amount that can be released from facilities that produce or use ethylene oxide and the level of exposure considered acceptable (Kirman et al., 2020).

Human exposure to ethylene oxide transpires primarily through inhalation; however, more ways exist (Dever et al., 2024). First, ETO is produced in the body from endogenous ethylene via multiple pathways, such as bacterial production in the gastrointestinal tract or systemic formation in the liver (Kirman et al., 2020). Second, ETO is metabolically generated in the body after exposures to exogenous ethylene from a variety of sources including incomplete combustion of cigarette smoke and vehicle fossil fuels, and natural processes including forest fires, ripening of fruits and vegetables, and volcanoes (Kirman et al., 2020). Third, ETO and ethylene are components of tobacco smoke and therefore smokers and non-smokers have different exposure profiles to ethylene oxide (Kirman et al., 2020). Fourth, some workers are exposed to elevated concentrations of ethylene oxide in the workplace air (Kirman et al., 2020). Fifth, some populations near industrial or sterilisation facilities are also exposed to elevated levels of ETO in the air as a result of emissions (Olaguer et al., 2019). Finally, additional pathways such as dietary exposures to ethylene (a plant hormone) present in fruits, vegetables, or grains are also possible (Yin et al., 2017). All of these pathways contribute to total exposure to ETO, but their relative importance to human populations and individuals is variable and uncertain. This has also led to increased public attention and concern about the potential adverse health effects associated with exposures to or near facilities that use ETO (Hogue 2019; Olaguer et al. 2019).

Ethylene oxide is subject to regulation under the Registration, Evaluation, Authorisation, and Restriction of Chemicals (REACH) framework within the European Union and is prohibited as a plant protection product (Dever et al., 2024). The utilization of ETO in domestic environments has been discontinued; however, the compound is extensively employed in industrial settings, primarily for the production of ethylene glycols (accounting for 75% of its total production), which are subsequently utilized in the manufacture of antifreeze, polyester, PET, and other products. ETO is also involved in the manufacturing of adhesives, lubricants, plasticizers, and thinners. In its pure form, ETO is utilized as a disinfectant for the sterilization of temperature-sensitive materials, serving as an alternative to steam and fungicides. As a volatile organic compound (VOC), it does not adhere to the surface of the sterilized object post-application, leaving no residue. In atmospheric conditions, it decomposes within days due to humidity and sunlight, and similarly, it degrades in water and soil within a brief period. (Dever et al., 2024) Under standard conditions, ethylene oxide presents as a colorless gas characterized by a distinctive sweet odor, and it is highly flammable. At 0 °C, it assumes a liquid state. Ethylene oxide exhibits solubility in both water and various organic solvents. Its notable reactivity renders it suitable for numerous industrial applications (Dever et al., 2024).

* + 1. Examples of significant crashed and accidents with ethylene oxide

Over the years, numerous industrial incidents involving ETO have been reported, underscoring the critical need for stringent safety measures, robust process control, and thorough risk assessment. This section highlights a series of notable ETO related accidents from different industries and geographic regions, illustrating the diverse challenges associated with its handling, storage, and use. The described incidents provide insights into common failure mechanisms, consequences, and the importance of preventive strategies in minimizing risks.

* SLOVNAFT Raffinery (Bratislava, SK): An explosion occurred in the reactor used for the synthesis of ETO through the oxidation of ethylene. This explosion was associated with the regeneration of the catalyst, which involved air oxidation. The oxygen content analyzer within the reactor's circulation system could be configured to operate within two different ranges. During the initiation of the process, the operator adjusted these ranges, inadvertently creating an explosive mixture within the circulation circuit. Although the accident did not impact the surrounding environment, the reactor sustained complete destruction (Skřehot et al., 2009).
* Industrias Químicas del Óxido de Etileno (IQOXE) (Tarragona, Spain): An explosion at an ETO facility in Tarragona, Spain, resulted in the fatalities of three individuals and injuries to seven others. The incident originated in the reactor, subsequently causing ignition of an adjacent storage tank. Authorities reported that no toxic substances were released; however, a temporary shelter was established for residents (Doyle, 2020).
* Private company (Veverská Bítýška, SK): ETO escaped from a compromised pipe originating from a faulty flange connected to the incinerator. However, due to the prompt and professional intervention by the Fire Rescue Service during the mitigation of the incident, there was no harm to human health or environmental contamination (Kolischova, 2014).
* ETO plant (Brandenburg, Kentucky USA): The contamination of ETO with an ammonia solution resulted in a rapid chemical reaction, leading to an explosion. This incident resulted in one fatality, three individuals sustaining serious injuries, and eighteen individuals reporting minor injuries (ACC, 2007).
* Detonation within a sterilization chamber during ETO sterilization (Sterigenics International, Ontario, California USA): The explosion resulted in injuries to four workers and caused substantial damage to facilities encompassing an area of 66,000 square feet. The primary factors contributing to the explosion were the inadequacy of the technical equipment installed at the site in preventing the formation of an explosive (ETO atmosphere upon interaction with the oxidizing agent, along with the employees' insufficient comprehension of the risks associated with the process (ACC, 2007).

This article seeks to undertake a risk assessment pertaining to a case study of a product sterilization system employing ETO, a substance classified as hazardous under CLP regulations. The primary objective of this risk analysis is to safeguard the populace in the region potentially impacted by such a system, with a focus on averting significant accidents.

* 1. Methodology

During the initial phase of the risk assessment, major accident risk sources were identified using the CPR 18E Purple Book selection model. This method for the identification and selection of risk sources was developed by the Netherlands Industrial Safety Institute (TNO) and is documented in the Guidelines for Quantitative Risk Assessment (Purple Book, 2005). The ensuing methodology applied in a case study pertaining to the assessment of human health impacts was the dispersion model ALOHA 5.4.7. ALOHA (Areal Location of Hazardous Atmospheres) represents a structured framework devised by the EPA Chemical Preparedness and Prevention Office (CEPPO) in collaboration with the National Oceanic and Atmospheric Administration (NOAA) Response and Recovery Office. This approach assists in determining the range of impact caused by the release of a toxic substance (ALOHA, 2016).

* 1. Case study

The facility will manage a hazardous substance, specifically ETO, within the sterilization chamber system and the ETO storage warehouse. The primary risk sources include individual pressure vessels, specifically barrels containing ETO, which will be transported to the site by truck, stored in a warehouse, and later processed at the evaporation plant to extract the gas. The facility’s location and its immediate surroundings are illustrated in the following Figure 1.

Obsah obrázku text, mapa, snímek obrazovky, software

Popis byl vytvořen automaticky

Figure 1: *The site of the factory structure alongside its adjacent locality*

* + 1. Risk site identification

The identification of the hazardous substance, ETO, in various segments of production necessitates risk assessment, as delineated in Table 1. Considering the aggregate intended quantity of approximately 4.8 tons of ETO, it is evident that the facility does not fall under the purview of the legislation regarding the prevention of major accidents, given that the threshold for inclusion in Group A is set at 5 tons. However, verification of the actual quantity of ETO is required, as the precise number of barrels stored, used in the sterilization process, and transported via truck cannot be conclusively ascertained from the existing project documentation. Additionally, the declaration that two sterilization chambers will initially be operational, with a third being constructed subsequently, suggests a potential increase in the quantity of ETO, thereby possibly necessitating the facility's inclusion under the Act on Prevention of Serious Accidents. Moreover, it is imperative to delineate the other technical gases present within the SO 06 Storage facility for technical gases, as the law mandates the aggregation of all hazardous substances with analogous properties in terms of flammability, toxicity, and environmental risk.

Table 1: List of hazardous substances placed in selected company

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| Storage No. | Facility No. | Facility | Hazardous properties | Quantity [tonnes] | State |
| Z1 | SO 04 | ETO warehouse | H331, H220 | 1.5 | liquefied gas |
| Z2 | SO 03 | Sterilization process | H331, H220 | 3 | liquefied gas |
| Z3 |  | ETO transport truck | H331, H220 | 2.5 | liquefied gas |

* + 1. Identification and selection of risk sources for detailed risk analysis

In the initial phase of the risk assessment, a selection of sources of major accident risks was conducted using the selection method outlined in the CPR 18E Purple Book. To assess risks within the framework of major accident prevention, a total of three facilities located within the operation of the planned ETO sterilization technology were evaluated (see Table 2). Indicative numbers were determined, and due to the short distance to the boundary of the facility, the selective numbers at a distance of 100 meters were evaluated as identical to the indicative numbers. An overview of all units assessed using the selection method, including the calculated indicative numbers, is provided below.

Table 2: Determination of indicator numbers by selective method

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Storage No | Facility | Hazardous properties | Amount Q  [kg] | Factors  O1 | Factors  O2 | Factors  O3 | Limit  Value G  [kg] | Indicator  No A |
| Z1 | Warehouse | Tox. | 1,500 | 0.1 | 0.1 | 10 | 300 | 0.50 |
| Z1 | Warehouse | Flam. | 1,500 | 0.1 | 0.1 | 10 | 10,000 | 0.02 |
| Z2 | Sterilization process | Tox. | 3,000 | 0.1 | 0.1 | 10 | 300 | 10 |
| Z2 | Sterilization process | Flam. | 3,000 | 1 | 0.1 | 10 | 10,000 | 0.30 |
| Z3 | Transport truck | Tox. | 2,500 | 1 | 1 | 10 | 300 | 83.33 |
| Z3 | Transport truck | Flam. | 2,500 | 1 | 1 | 10 | 10,000 | 2.50 |

comment:G for ETO - LC50(4h) (rat)= 1,450 ppm, 500 < LC < 2,000, for gas G = 300

As shown in Table 2, the selection of assessed facilities using the selection method outlined in the CPR 18E Purple Book identified two units within the facility for quantitative risk analysis (QRA). The indicative numbers for the two selected units, Z2 – ETO in process and Z3 – ETO on a truck, as well as the selective numbers at a distance of 100 meters, exceed the value of 1. Therefore, it is necessary to proceed with a detailed risk analysis. The detailed evaluation of the following parts of the ETO technology system was conducted due to the proximity of the population. The specific risk sources to be assessed in detail are: Z2 (the process of extracting ETO from barrels); Z3 (the transport of barrels on a truck). These two units were selected as representative parts of the sterilization technology where an ETO release could potentially occur. Since the simultaneous release of ETO from multiple barrels is highly unlikely, the representative scenarios to be evaluated include: 1. Immediate release of ETO from a single barrel; 2. Continuous release of ETO from a single barrel through a small crack.These scenarios will be analyzed with respect to the toxic dispersion of the hazardous substance and the potential explosion of flammable vapors.

* + 1. Scenarios

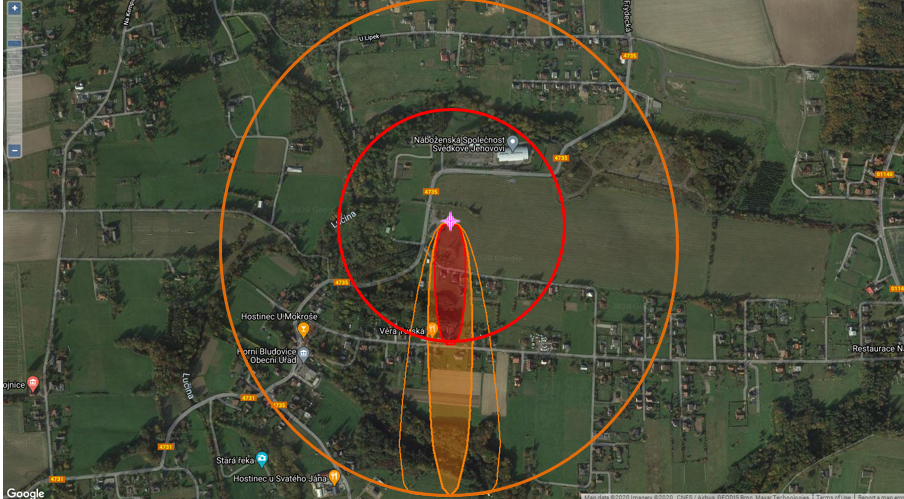
Emergency scenarios were determined for selected facilities representing the potentially most significant source of risk for the surrounding area. Z2 – Process of Extracting ETO from Barrels – Continuous Release from One Barrel (500 kg ETO). Ethylene oxide release – A release of ETO could occur due to a loss of integrity in the connected piping to the barrel or a leak in the vessel itself. The primary causes may include a ruptured hose, pipe corrosion, or a leaking valve on the pressure vessel. For this assessment, a serious scenario was selected, involving a 1 cm diameter hole representing pipeline damage, leading to a continuous release. This corresponds to scenario G2 according to the methodology outlined in the Purple Book. Z3 – Transport of Barrels on a Truck – Instantaneous Release from One Barrel (500 kg ETO). Ethylene oxide release – A release of ETO could occur due to the rupture of a pressure vessel (barrel) during unloading with a forklift, caused by a drop due to improper handling, or in the event of a severe truck accident. For modeling purposes, a catastrophic scenario was selected, involving a 10 cm length and 2 cm width hole, representing vessel damage and leading to an instantaneous release. This corresponds to scenario G1 according to the Purple Book methodology.

* + 1. Assessment of impacts on human health

Table 3: List of hazardous substances located in the facility

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Scenario | Amount | Max.of release amount  [kg/min] | Leakage time  [min] | Accident range  [m] |  |  |
| Z2 a  Z2 b | 500  500 | 9  7.5 | 57  60 | 39  43 |  |  |
| Z3 a  Z3 b | 500  500 | 500  449 | 1  2 | 313  235 |  |  |

For the purposes of evaluating the potential ranges of the toxic ETO vapor cloud and the spread of flammable gas, neutral climatic conditions occurring most frequently throughout the year (wind speed 5 ms-1) and an inverse situation representing the worst meteorological conditions for dispersion (wind speed 1.7 ms-1) were taken into account, see wind rose. The most critical outcomes pertain to the immediate emission of ETO from a compromised barrel (scenario Z3), in which the lethal concentration is projected to extend approximately 313 meters under neutral atmospheric conditions or 235 meters during an inversion layer event. In scenario Z2, whereby ETO is emitted within a building, the diffusion into the external environment is significantly curtailed, culminating in the formation of a noxious cloud that could endanger the operator. Considering the building's proximity to the civilian area, it is plausible that the dissemination of the toxic cloud might affect the adjacent population, located approximately 50 meters to the south. Individuals positioned in open areas within the impacted zone are exposed to a severe risk of fatality. Occupants within surrounding edifices receive partial protection; nonetheless, 10% of the total number of inhabitants in these buildings are still at a severe risk of fatality. Graphical representations of the worst-case consequences of toxic dispersion under neutral conditions are shown in Figure 2.



*Figure* 2*:* The extent of the most severe accident for the case of neutral air stability and the worst wind direction (red color - fatal zone, orange color - injury zone)

* 1. Results and Discussion
     1. Assessment of the acceptability of the risk of major accidents

Within the delineated area affected by a lethal concentration of ETO, with a radius extending approximately 313 meters or 235 meters under inversion conditions, the population at risk is estimated to be 70 individuals, residing in 20 houses located to the south. According to the methodology detailed in the Purple Book, 93 % of these residents are sheltered within buildings, resulting in a mortality rate of only 10 % for this group, whereas the remaining 7 % are externally exposed and consequently face a 100% mortality risk from the toxic cloud. As a result, it is projected that approximately 11 individuals may face mortal danger, approximately 6 residing indoors and 5 outdoors. In scenario Z2, the risk assessment indicates that two employees are also at risk of fatality. The social risk evaluation was conducted in alignment with Decree No. 227/2015 Coll., which stipulates the acceptability of risk based on the permissible frequency of events that could endanger multiple lives due to a major accident. The acceptable frequency, denoted as Fp, for newly constructed buildings is determined by the following relationship:

(1)

Where:

Fp acceptable accident frequency [year-1],

N number of fatal injuries due to accidents.

The results of the risk assessment are presented in the following table, which takes into account the most serious scenarios (ETO leaks).

Table 4: Risk assessment of the analyzed scenarios

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| Scenario | Fh  (Year -1) | Human endangerment  (No of deaths) | | Fp  (Year -1) | Risk |
| ETO leak (Z2) | 5 x 10-5 | 2 | 2,5 x 10-5 | | unacceptable |
| ETO leak (Z3) | 2.5 x 10-6 | 11 | 8,2 x 10-7 | | unacceptable |

* 1. Conclusions

The potential risks associated with the proposed construction of the company's production, storage, and administrative facilities must be evaluated as socially unacceptable. The selected site, located in close proximity to residential areas, is deemed inappropriate. As a result, it is recommended that the investor explores alternative sites that maintain a sufficient separation from residential areas. Regarding the proposed construction of a production plant in Prostřední Bludovice, it is essential to maintain a buffer zone with a radius of 200 meters from existing residential sectors. Should adherence to this buffer zone prove to be unfeasible, an alternative site that offers greater suitability for such construction must be considered.

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