CHEMICAL ENGINEERING TRANSACTIONS
VOL. 32, 2013
A publication of AIDIC
The Italian Association of Chemical Engineering
Online at: www.aidic.it/cet
Chief Editors: Sauro Pierucci, Jiří J. Klemeš
Copyright © 2013, AIDIC Servizi S.r.l.,
ISBN 978-88-95608-23-5; **ISSN** 1974-9791
DOI: 10.3303/CET1332075

Vulnerability Assessment for Human Targets due to Ash Fallout From Mt. Etna

Micaela Demichela*[a], Giuseppe Maschio[b], Maria Francesca Milazzo[c], Ernesto Salzano[d]

[a]Dipartimento di Scienza Applicata e Tecnologia, Politecnico di Torino, corso Duca degli Abruzzi 24, 10129 Torino, Italy
[b]Dipartimento di Ingegneria Industriale, University of Padova, Via F.Marzolo 9, 35131 Padova, Italy
[c]Dipartimento di Ingegneria Elettronica, Chimica e Ingegneria Industriale, University of Messina, Viale F.Stagno D'Alcontres 31, 98166, Messina
[d]Istituto di Ricerche sulla Combustione, CNR, via Diocleziano 328, 80124 Napoli
micaela.demichela@polito.it

The volcanic ash fallouts are able to affect the human health and the integrity of industrial facilities. The study of the effects associated with ash emissions was the objective of the PRIN project carried on by the authors of this paper. The activities of the project allowed to define a simplified procedure for the vulnerability assessment of human and industrial targets, that has been applied to the area surrounding Mt. Etna. Recent several ash fallouts from this volcano have caused significant problems to the resident population, traffic and industrial activities. The application of the study to this territory provided a vulnerability mapping to support the decision making both in terms of the definition of protection measures and of the emergency planning and management.

1. Introduction

Literature shows that volcanic ash fallouts are able to affect the human health and the integrity of industrial facilities. The study of the damage on the infrastructure and industrial installations are due to many authors: Spence et al. (2004) studied the effects of eruptive phenomena on civil and industrial infrastructure; among the possible effects of ash fallout, Baxter et al. (1982) and Scandone (1993) analyzed the reduction of water treatment (either industrial or civil installation) and accidents related to the transport of hazardous materials due to slippery road conditions; finally other researchers are focusing on the estimation of the vulnerability of some industrial facilities to ash fallout, such as storage tanks (Milazzo et al., 2012a) and filters (Milazzo et al., 2012b).
In recent literature and legislation, the effects of particulates, produced naturally and by human activity, on pollution and human health have been considered. The particulates may be classified as “coarse" or “fine” depending on the size of the particles. In contrast with gaseous pollutants, fine particulates have a highly heterogeneous composition, physical-chemical characteristics, modes of generation, diffusion, absorption by organisms and pathology. The toxicity of the particles also depends on their chemical composition, in particular on the substances adsorbed on their surface.
With regard to volcanic ash, the particle surface has irregular accumulations of sublimates (Cimino and Toscano, 1998) produced by the condensation of gases in the eruption cloud (mainly SO_2, SO_2 converted into H_2SO_4, H_2O, HF, HCl) and adsorption of harmful substances in the atmosphere. In this way these substances can be introduced into the human body by inhalation.
Recently the WHO (World Health Organization) supported researches to update the state of knowledge on the relationship between atmospheric pollution and human health. The literature on the health risks associated with volcanic ash indicates that there is the possibility that people repeatedly exposed to particulates inhalation lead to symptoms of silicosis and other effects. A survey about these symptoms was made at Montserrat (Searl et al., 2002) where the exposure of the population to the volcanic ash was measured (particles less of 10 μm), the particles contained about 20% of crystals of cristobalite (SiO_2), a

Please cite this article as: Demichela M., Maschio G., Milazzo M.F., Salzano E., 2013, Vulnerability assessment for human targets due ash fallout from mt. etna, Chemical Engineering Transactions, 32, 445-450 DOI: 10.3303/CET1332075

mineral considered to be toxic to the lungs. It has been estimated that exposure to about 0.5 mg/m^3 for 24 hours (the maximum exposure in the northern part of the island) could lead to serious cases of silicosis in two or three years. Exposure to lower concentrations (0.1 mg/m^3, as in the central area of the island) would lead to the same result with an exposure of 8-10 years. The effects of inhalation are comparable to those of exposed workers in mine. Finally the 24 hours exposure exceeded the standards of American occupational medicine.
This paper focuses on the assessment of the vulnerability for people due to the exposure to the breathable fraction of ash and its mapping. The article is articulated as follows:

- definition of Probit functions for specific effects on human health through the analysis of literature data concerning medical studies on this topic;
- vulnerability mapping for the territory surrounding Etna through the use of iso-concentration map for dispersions of ash in the atmosphere and a Geographical Information System (GIS) software.

2. Methodology

Given the occurrence of a volcanic eruption with emission of ash, the calculation and mapping of the vulnerability for people can be executed by means of the procedure of Figure 1. In the following sections each step of the procedure is described.

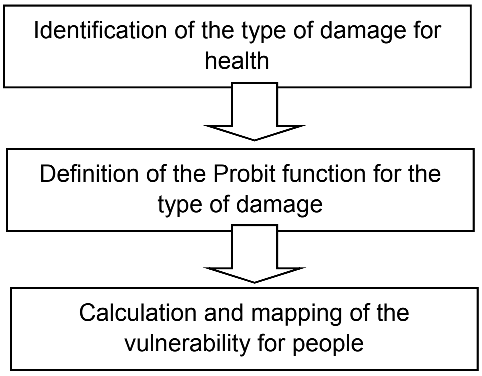

Figure 1: Procedure for the calculation and estimation of the vulnerability

2.1 Identification of the type of damage for health

In this section a review of potential undesired effects for health is given with the aim to choose a specific damage for which the vulnerability maps could be derived (as indicated in Figure 1).
As detailed in Horwell and Baxter (2005), studies of the respiratory effects of different types of volcanic ash have been undertaken only in the last 40 years, mostly, since the eruption of Mt. St.Helens in 1980. The acute and chronic health effects of volcanic ash depend upon the particles’ size (particularly the proportion of respirable-sized material), the mineralogical composition (including the crystalline silica content) and the physicochemical properties of their surface. These parameters influence the biological reactivity of particles and, hence, their respiratory health effects. All properties vary among different volcanoes and even among eruptions of the same volcano, but adequate information on these key characteristics is not reported for most eruptions.
The incidence of acute respiratory symptoms (e.g. asthma, bronchitis) varies greatly after ash fallout. Individuals with pre-existing lung diseases, including asthma, can be at increased risk of their symptoms being exacerbated after inhalation of fine ash. A comprehensive risk assessment, including toxicological studies, to determine the long-term risk of silicosis from chronic exposure has been undertaken only in the eruptions of Mt. St. Helens (USA) in 1980 and of Soufrière Hills, Montserrat, onwards 1995. A long-term silicosis hazard has been identified during the Soufrière Hills eruptions, subsequently sufficient exposure data and toxicological information made possible a probabilistic risk assessment for outdoor workers and the population of getting silicosis.
Freshly erupted ash differs from other natural dusts. The un-weathered particle surfaces are not oxidised or leached, they can carry condensed volatiles such as acids, polycyclic hydrocarbons and trace metals. Fine ash particles tend to fall in roughly spherical clusters (<100 µm), which readily break up on impact in dry conditions or when resuspended by vehicles and other human activity. Sulphuric and other acids

adsorbed from the gases in the plume may be present on the surface of the ash particles, potentially causing the irritancy of the airways.

The acid salts can also combine with rain in forming crusts on top of deposits which make the ash less easily re-suspended by wind. At very low ash concentrations, sulphur dioxide (SO_2) or acid aerosols can trigger asthma attacks to asthmatic patients, thus, before the respiratory symptoms are associated to the ashes, the exposure to the gas plumes needs to be excluded.

The grain size of ash particles is of critical importance and is conventionally defined in terms of the aerodynamic diameter. Particulate matter less than 10 μm diameter (PM10) is classed as thoracic, it is breathable if the size is less than 4 μm. The finer respirable particles can be breathed into the alveolar region of the lung and have the greatest toxic potential.

Recent research has shown that fine particles (<1 μm), and ultrafines, (<0.01 μm), are likely to be the most toxic, but whether this applies to volcanic ash is not yet clear. Until recently, volcanologists did not routinely analyse PM10 or PM4, thereby compounding the lack of information available for evaluating the health effects of eruptions.

The reactivity of particles within the lung is related to the surface area and number of particles more than the mass of particles. It is, therefore, useful to quantify mineral assemblages in terms of number or surface area percent as well as weight percent.

The morphology of the ash particles may have health significance. Insoluble particles in the form of fibres may cause respiratory hazards similar to asbestos, depending upon the fibre length and width. Hazardous fibres are those whose length–diameter ratio is greater than 3, with a diameter less than 3 μm and a length greater than 5 μm.

Assessment of the mineralogical composition of volcanic ash is a crucial step in health hazard assessment. Silicic volcanic ash often contains crystalline silica, as quartz, cristobalite or tridymite polymorphs. Exposure to crystalline silica is well known in industry to cause silicosis, a fibrotic lung disease; it may also be a cause of lung cancer for workers who have developed silicosis. If present, it is the most potentially toxic mineral in volcanic ash. Cristobalite is perhaps the most toxic silica polymorph and this is particularly pertinent in volcanic settings, where it may be manufactured in a volcanic dome by devitrification of volcanic glass or in the volcanic edifice by vapour phase crystallisation from a hydrothermal system.

Several studies have shown that Fe^{2+} in volcanic ash could give toxic effects in lungs as seen by crystalline silica.

2.1.1. Respiratory health hazards of volcanic ash

Many of the studies which aim to observe the possible long-term effects of volcanic ash on respiratory health are of limited value because these have scarce information on the quantity and content of the respirable fraction. Only the eruptions of Mt. St.Helens and the Soufrière Hills volcano have had robust and full characterisation studies mainly related to effects of the ash emissions on human health.

This characterization studies is a basic requirement before evaluating the acute and chronic health hazard in the population. In general terms, the respiratory health effects of most concern are summarized below:

1. Acute (short term) respiratory effects: The acute manifestations observed after heavy ash fallouts include attacks of asthma and bronchitis, with an increased reporting of cough, breathlessness, chest tightness, and wheezing due to irritation of the lining of the airways by fine particles. Sometimes, especially in older people, asthma attacks can be fatal. Inhalation of fine ash can also exacerbate previously present disease, e.g. chronic bronchitis or advanced heart problems. The acute respiratory effects are variable after the fallout, while mortality, as an end point, is rarely examined in any of the studies.
2. Chronic (long term) respiratory effects: The chronic health condition of most concern is silicosis, a diffuse nodular fibrosis (scarring) of the lungs. For silicosis to occur, three main conditions have to be fulfilled:
   (1) a high proportion of fine particles in the ash;
   (2) a high concentration of crystalline silica (quartz, cristobalite or tridymite);
   (3) exposure to significant amounts of ash, typically over a period of years to decades.

   Early lung changes cause no symptoms and most sufferers remain in this mild category, but the condition can progress even after exposure has ceased and may lead to premature death.

   No human cases of silicosis or other chronic lung disorders due to volcanic ash have been reported in any of the literature papers examined, but very few of the studies included the long-term health consequences of exposure.

To achieve our aims, in this paper, we focused on one effect such as the increase in the surface area of lymph nodes associated with the inhalation of cristobalite.

2.2 Definition of Probit functions for damage to human health

In probability theory and statistics, the Probit function is the quantile function, i.e., the inverse cumulative distribution function (CDF), associated with the standard normal distribution. It has applications in exploratory statistical graphics and specialized regression modelling of binary response variables. The method, in particular, was applied by Finney (1971) on toxicological applications.

Probit analysis is used to analyze dose-response or binomial response experiments in a variety of fields. It is commonly used in toxicology to determine the relative toxicity of chemicals to living organisms. This is done by testing the response of an organism under various concentrations of each of the chemicals in question and then comparing the concentrations at which one encounters a response. As discussed above, the response is always binomial (e.g. death/no death) and the relationship between the response and the various concentrations is always sigmoid. Probit analysis acts as a transformation from sigmoid to linear and then runs a regression on the relationship (Figure 2).

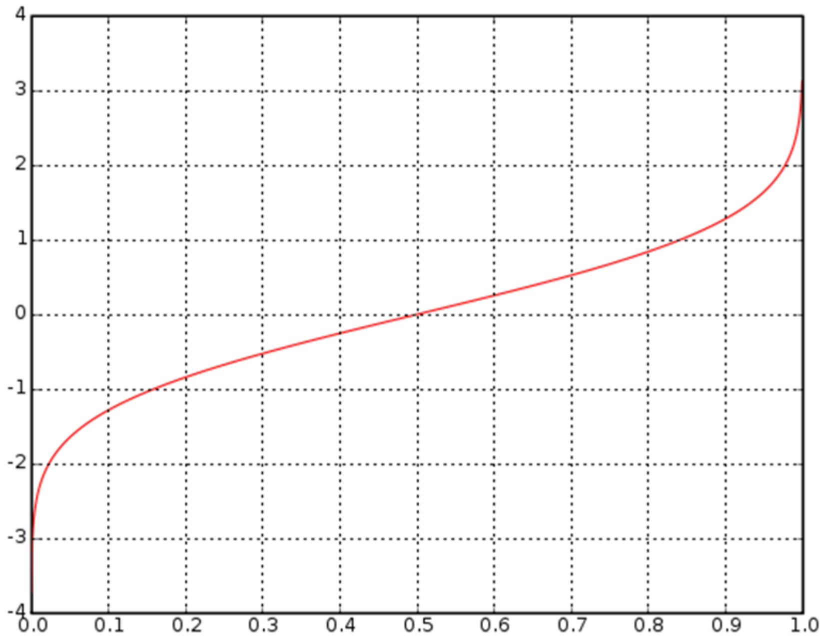

Figure 2. Probit function plot

The linear expression for the Probit function is:

$$Pr = K1 + K2 \log V \tag{1}$$

Pr is the Probit variable, K1 and K2 are parameters characteristic of the substance taken into account and V is the intensity of the factor that causes the damage (e.g. toxic concentration).

It is well known that the use of Probit functions for the analysis of the effects due to the inhalation of toxic substances is widespread. In this work we propose a novel use of the Probit functions, such as integrated within a vulnerability mapping procedure related to a certain effect on human health.

Given the considerations of the above section and the data from the literature with reference to the “in vivo” tests, a Probit function has been developed.

Using the data given in Lee and Richards (2004), it is possible to identify a relation between some instilled doses (1 mg, 2.5 mg, 5 mg) of ashes, in terms of their more critical components (anortite, for the 90% of the breathable fraction and cristobalite, for the 99% of the breathable fraction), and their effects on the mice’s lungs after 13, 25 and 49 weeks from the exposure. The consequences taken into account are related to the increase in the surface area of lymph nodes. The maximum value of Pr has been associated with the maximum surface increase associated to the cristobalite dust for each week, obtaining the following function:

Pr = 29 + 31,47 log V (2)

where V is the instilled cristobalite dose in mg.
In Hously et al. (2002) a relation within the instilled dose and a breathable concentration is given: a dose of 1 mg is comparable to 39 mg/m^3 per 8 days. This ratio has been used to re-evaluate the Probit function with reference not to the dose, but to a concentration, obtaining the following:

Pr = -58,82 + 52,75 log V (3)

where V is the breathable cristobalite concentration in mg/m^3.

2.3 Vulnerability mapping
To achieve a vulnerability mapping using the Probit function defined in the previous section, iso-concentration maps and georeferenced cartography of the site are necessary. Maps from Google Earth have been used and by means of a GIS software, such as ArcGIS, information have been visualized.

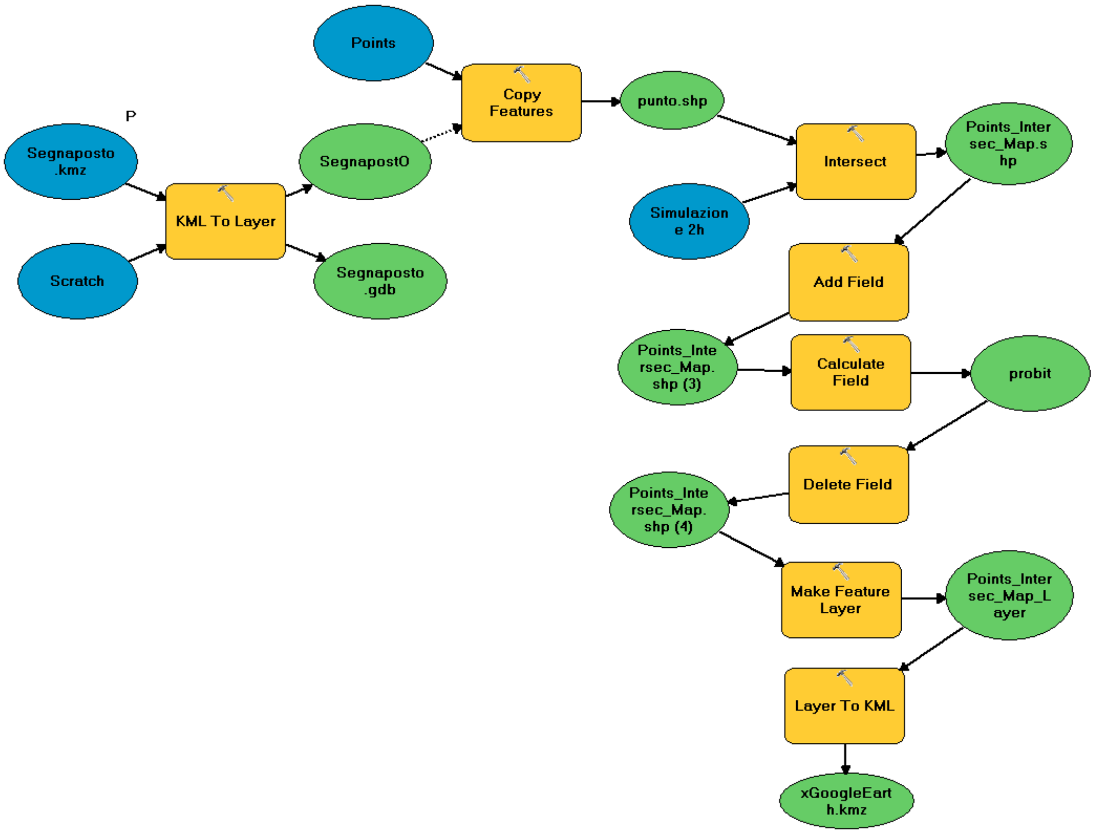

Figure 3: Diagram for vulnerability calculation using a Probit function

Once data and tools are available, it is possible to proceed as described below:

1. given the value of concentration, at the time t, in a given site with coordinates (x, y), a placeholder for the location must directly be inserted on Google Earth, then the concentration is added in the popup window. This information must be saved using the extension ".kml";
2. a model for the calculation of probability of damage of human health must be created using ArcGIS. It is based on the equations (2-3) and, after its launching, gives the vulnerability for the site. An example is shown in Figure 3. The output (vulnerability) is displayed in Google Earth and is saved in a new file ".kml".
3. given a set of points where the vulnerability is calculated, to achieve our objective (vulnerability mapping), the vulnerabilities also for the points where these are not known have to be estimated, this can be made through a spatial interpolation (as suggested by Milazzo et al., 2012c).

The construction of vulnerability maps is a semi-automatic process, executed using a specific tool of ArcGIS software, named ModelBuilder. This tool permits to create and manage sequences of processing of geographical data, so-called geoprocessing. The ModelBuilder feeds the outputs of an operation into another one, thus these outputs become the inputs to the following operation, a recent use of geoprocessing concerns the emergency management of terrorist actions (see Milazzo et al., 2009).

3. Conclusions

Introducing the health effects within the parameters used to assess the vulnerability of the possible targets in a volcanic territory completes the set of tools developed within the project. The tool described in this work also allows a graphical representation of the vulnerability maps with the aim of supporting a multicriteria decision making for local authorities and emergency planners for this specific Na-Tech risk. Despite the system has been specifically developed for the Mt. Etna territory, it is of general application, given a local limit value for deposits and concentrations.

Acknowledgements

This research has been supported by the MIUR funded project PRIN 2008 entitled “Analysis of potentially critical scenarios on industrial installations and the infrastructure of Eastern Sicily and of health risks associated with explosive eruptions of Etna”.

References

Baxter P.J., Bernstein R.S., Falk H., French J., Ing R., 1982, Medical aspects of volcanic disasters: an outline of the hazards and emergency response measures, Disasters, 6, 268 -276.

Cimino G., Toscano G., 1998, Dissolution of trace metals from lava ash: influence on the composition of rainwater in the Mount Etna volcanic area. Environmental Pollution 99, 389-393.

Finney, D.J., 1971, Probit Analysis (3rd edition), Cambridge University Press, Cambridge, UK.

Horwell C.J, Baxter P.J., 2006, The respiratory health hazards of volcanic ash: a review for volcanic risk mitigation, Bull Volcanol, 69, 1–24

Housley D.G., Bérubé K.A., Jones T.P., Anderson S., Pooley F.D., Richards R.J., 2002, Pulmonary epithelial response in the rat lung to instilled Montserrat respirable dusts and their major mineral Components, Occup Environ Med, 59, 466–472

Lee S.H., Richards R.J., 2004, Montserrat volcanic ash induces lymph node granuloma and delayed lung inflammation, Toxicology 195, 155–165

Milazzo M.F., Ancione G., Lisi R., Vianello C., Maschio G.(2009). Risk management of terrorist attacks in the transport of hazardous materials using dynamic geoevents. Journal of Loss Prevention in the Process Industries, 22(5), 625-633.

Milazzo M.F., Ancione G., Lister D.G., Salzano E., Basco A., Maschio G., 2012a, Analysis of the effects due to fallout of ash from Mt. Etna on industrial installations. Chemical Engineering Transactions, 26, 123-128, doi: 10.3303/CET1226021.

Milazzo M.F., Ancione G, Lister D.G., Salzano E, Maschio G., 2012b, Potential damage to filtration systems due to volcanic ash fallout, Proc. of the 11th International Probabilistic Safety Assessment and Management Conference and the Annual European Safety and Reliability Conference 2012, PSAM11 ESREL 2012, 7, 5379-5387, Helsinki, 24-29 June 2012.

Milazzo M.F., Lisi R., Ancione G., Lister D.G., Maschio G., 2012c, Vulnerability maps for industrial facilities in areas with the potential volcanic ash fallout, Proc. of the 11th International Probabilistic Safety Assessment and Management Conference and the Annual European Safety and Reliability Conference 2012, PSAM11 ESREL 2012, 7, 5388-5397, Helsinki, 24-29 June 2012.

Scandone R., Arganese G., Galdi F., 1993, The evaluation of volcanic risk in the Vesuvian area. Journal of Volcanology and Geothermal Research, 58, 263- 271.

Searl A., Nicholl A., Baxter P.J., 2002, Assessment of the exposure of islanders to ash from the Soufriere Hills volcano, Montserrat, British West Indies, Occupational Environmental Medicine, 59(8), 523-531.

Spence R.J.S., Baxter P.J., Zuccaro G., 2004, Building vulnerability and human casualty estimation for a pyroclastic flow: a model and its application to Vesuvius, Journal of Volcanology and Geothermal Research, 133, 321-343.