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Safety risk modeling and major accidents analysis of hydrogen and natural gas releases: A comprehensive risk analysis framework

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ARTICLE INFO

Article history:
Received 12 May 2015
Received in revised form
5 July 2015
Accepted 26 July 2015
Available online 3 September 2015

Keywords:
Risk modeling
Risk assessment
QRA
Hydrogen safety
Consequence
HAZOP

ABSTRACT

The potential safety risk of hydrogen production is often the most important element to achieve authority approval and public acceptance. Safe application of hydrogen, especially in a large scale, will require adopting adequate risk control, which requires investment on reliable risk analysis methodology. In the present study, first of all, a reliable and comprehensive safety risk analysis methodology was developed for a hydrogen production plant in an oil refinery, that consists of two qualitative methods: Hazard and Operability (HAZOP) and Preliminary Risk Analysis (PRA), a hybrid method: Event Tree Analysis (ETA) and a quantitative method: Quantitative Risk Assessment (QRA) along with a risk and consequence simulator. A HAZOP study along with the PRA technique was used for determining main hazardous sources and carrying out a qualitative risk analysis. The incident outcomes of the identified high risk scenarios were modeled using the PHAST 6.7 simulator and the frequencies of the initial events and incident outcomes were calculated using risk assessment data directory of International Association Oil & Gas Producers (OGP) and ETA, respectively. Finally, the vulnerability areas of the incident outcomes were determined and the societal risk of hydrogen plant was shown using a 'Frequency vs. Number of fatality' graph, known as 'F–N' curves. The findings show that the maximum vulnerability distance is caused by the vapor cloud explosion (280 m, at 0.01 bar) and the jet fire (275 m, at 4 kW/m^2), respectively. The societal risk of the plant fell in the As Low As Reasonable Practical (ALARP) and intolerable regions according to the F–N curve of UK HSE (Health, Safety Executive) The reformer were the highest and the heat exchanger was the lowest contributor to the total risk. Therefore, the ALARP principle should be applied to indicate the appropriate ways to reduce risks and, for the intolerable risks, the system must be modified structurally, functionally, or organizationally.

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http://dx.doi.org/10.1016/j.ijhydene.2015.07.117

Nomenclature

ALARP	As low as reasonable practical
API	American petroleum institute
BLEVE	Boiling liquid expanding vapor explosions
BN	Bayesian network
CFD	Computational fluid dynamics
CCPS	Center for chemical process safety
CoMo	Cobalt and Molybdenum
CO	Carbon monoxide
DOE	Department of energy
DR	Desulfurizer reactor
FTA	Fault tree analysis
ETA	Event tree analysis
F–N	Frequency-Number of fatality
HAZOP	Hazard and operability
HE	Heat exchanger
HSE	Health and Safety Executive
HPA	Hydrogen purification absorber
LFL	Lower flammability limit
MVR	Maximum vulnerability range
OGP	International association oil & gas producers
PF	Probability of fatality
PHAST	Process hazard analysis software tool
RFT	Reformer furnace tube
PRAF	Proposed risk analysis framework
PSA	Pressure swing adsorption
PGV	Purge gas vessel
QRA	Quantitative risk assessment
QADS	Quantitative assessment of domino scenarios
RBM	Risk based maintenance
SR	Societal risk
TNO	Netherlands organization for applied scientific research
TNT	Trinitrotoluene
VCE	Vapor cloud explosion
WRA	Weighted risk analysis
P_r	Probit value
Q	Thermal radiation, W/m^2
t	Exposure time, s
P_o	Overpressure of blast wave, Pa
P_f	Probability of fatality
P_d	Population distribution
r	Radial distance
r_1	Radial distance at PF 1%
A	Area of the circle with a radius of r
A_1	Area of the circle with a radius of r_1
M_{choked}	Mass flow discharge, kg/s
T_1	Temperature, K
A	Hole area, m^2
R_g	Gas constant, 8314 Pa m^3/mole K
g_c	Gravitational constant, N s^2/kg m
M	Molecular weight, kg/mole
K	Ratio of specific heat capacity

Introduction

The global need for energy is rising and an ever-increasing need for an energy carries can be felt. Hydrogen is one of the most promising substance with many advantages that can be utilized in this sector [1]. Hydrogen is an environment-friendly fuel; the only matter that is produced when hydrogen is burned in an internal-combustion engine is harmless water vapor [2]. Hydrogen can be easily stored in different ways including high-pressure cylinder, in the form of a cryogenic liquid fuel, hydrides, or on carbon fibers. As a raw material, moreover, hydrogen has many industrial applications such as the production of fertilizers, dyes, drugs, plastics, and so on [2,3].

Despite all the above-mentioned advantages, producing, storing, transporting, and using hydrogen as a secondary fuel always bring various risks to the surrounding environment. The hazards of hydrogen arise from its wide range of flammability and the substantial amount of energy released if it burns or explodes. Furthermore, hydrogen-related accidents are not rare and history has witnessed several accidents associated with hydrogen [1]. A variety of global sources, consisting of the industrial, governmental and academic facilities, 208 accidents have been recorded in hydrogen production plants by U.S. Department of Energy (DOE) from 1995 to 2013 [4,5]. Table 1 provides a summary of major hydrogen accidents [6].

In order to prevent such accidents and their consequences, the risk of all hydrogen-related activities must be properly determined using new and more accurate risk analysis tools.

In the last few years, there were several studies addressing various aspects of hydrogen safety with different objectives and methodologies that including: risk assessment/analysis on fueling stations [7–11], on distribution System [10], private car [12], and production facility [4]; consequence assessment/analysis on fueling stations [13,14], and hydrogen applications [15]; QRA (Quantitative Risk Analysis) on fueling stations [16,17], and on generation unit [2]; risk/accident modeling on hydrogen station [18,19]. It can be clearly seen that the most studies are carried out on refueling stations, its transportation and other consumer facilities. This is surely a good step, but researchers pay less attention to other sectors, especially on the production plants. Therefore, the risk studies of hydrogen activities cycle cannot be considered matured [2,4,20].

In addition, in the previous studies, only one specific method or approach, especially, Computational Fluid Dynamics (CFD) or QRA is most often used. However, in the present study, a comprehensive approach that includes qualitative (HAZOP and PRA), semi quantitative (ETA) and quantitative (QRA) methods in order to safety risk modeling and major accidents analysis of hydrogen and natural gas release is used.

Furthermore, approximately 99% of hydrogen produced and consumed in industry is generated by natural gas reforming which increases the risks of fire and explosion [1,2].

In the process industry, safety issues are actually vital because inadequate control for loss prevention can result in a catastrophic accident which may be beyond the plant boundary limits [21]. Extensive and safe production,