Process Safety and Environmental Protection 96 (2015) 82–97

Contents lists available at ScienceDirect

Process Safety and Environmental Protection

journal homepage: www.elsevier.com/locate/psep

Hazard analysis and safety assurance for the integration of nuclear reactors and thermochemical hydrogen plants

Zhaolin Wang[a,*], *Edward Secnik*[b], *Greg F. Naterer*[c]

[a] *Clean Energy Research Laboratory, University of Ontario Institute of Technology, Oshawa, ON L1H 7K4, Canada*
[b] *Lassonde School of Engineering, York University, 4700 Keele St, Toronto, ON M3J 1P3, Canada*
[c] *Faculty of Engineering and Applied Science, Memorial University of Newfoundland, St. John's, Newfoundland A1B 3X5, Canada*

ARTICLE INFO

Article history:
Received 8 November 2013
Received in revised form 16 April 2015
Accepted 29 April 2015
Available online 8 May 2015

Keywords:
Nuclear hydrogen production
Nuclear safety
Heat hazard
Chemical hazard
Hydrogen safety
Process integration

ABSTRACT

The challenges and approaches of the safety and risk management for the hydrogen production with nuclear-based thermochemical water splitting have been far from sufficiently examined, as the thermochemical technology is still at a fledgling stage and the linkage of a nuclear reactor with a hydrogen production plant is unprecedented. This paper focuses on the safety issues arising from the interactions between the nuclear heat source and thermochemical hydrogen production cycle, and also between the proximate individual processes in the cycle. As steam is utilized in many thermochemical cycles for the water splitting reaction, and heat must be transferred from the nuclear source to hydrogen production plant, this paper particularly analyzes and quantifies the heat hazard for the dynamic scenarios of start-up and shutdown of the hydrogen production plant. Potential safety impacts on the nuclear reactor are discussed. It is concluded that one of the main challenges of safety and risk management is efficient rejection of heat in a shutdown accident. Several options for the measures to be taken are suggested. Chemical hazards that may propagate to the nuclear plant zone due to the integration to thermochemical hydrogen production cycles are also examined, and hazard prevention approaches are proposed from the aspects of control at the source, control along the path, and control at the nuclear workplace. It is concluded that linking to high temperature electrolysis (HTE) is safer than to other cycles for the minimization of chemical hazards, and most non-redox thermochemical cycles involve corrosive and very toxic gases that may enter the nuclear zone. It is preferable that the thermochemical processes are confined to a closed building and the vent for the building serves as a hazard absorber. Another option is to protect the infrastructure of the nuclear plant from ingress of hazardous gases. It is expected that the newly reported results of the heat and chemical hazard analysis in this paper could help predict potential hazards and take appropriate measures to prevent risks arising from the linkage of different nuclear reactors and thermochemical cycles.

---

* *Corresponding author at*: 2000 Simcoe St N, CERL, University of Ontario Institute of Technology, Oshawa, ON L1H 7K4, Canada. Tel.: +1 905 721 8668x3478.

E-mail addresses: zhaolin.wang@uoit.ca (Z. Wang), edward.secnik@lassonde.yorku.ca (E. Secnik), gnaterer@mun.ca (G.F. Naterer).

http://dx.doi.org/10.1016/j.psep.2015.04.009

1. Introduction

Nowadays, hydrogen is a necessity for the production of fertilizer and upgrading of heavy oils, with the demand increasing and growing rapidly. Hydrogen is a promising alternative fuel for our future vehicles and home heat supply. Especially, if hydrogen is produced from clean energy, the usage of hydrogen would reduce pollutant and greenhouse gas emissions that are detrimental to our atmosphere and climate (Forsberg, 2007). Currently, the hydrogen production is mainly produced from fossil fuels, e.g., steam methane reforming and coal gasification (US Energy Information Administration, 2008). To achieve a clean hydrogen production, researchers have been developing new methods in the past decades. Among the methods, high temperature electrolysis (HTE) and thermochemical hydrogen production cycles using clean energy to split water thermally through intermediate chemical compounds and reactions have attracted more and more interest (O'Brien et al., 2006; Sadhankar et al., 2005; Lewis and Taylor, 2006; Kubo et al., 2004; Wang et al., 2012, 2013). Nuclear energy is considered as a major thermal energy source to meet the heat requirement of high temperature electrolysis and thermochemical cycles.

There are still many challenges hindering the fast industrialization of high temperature electrolysis and thermochemical cycles, although these methods are viewed as promising options for the future clean fuel supply, they are unprecedented and no sufficient industrial operation experience has been acquired, particularly from the perspective of operation safety when a hydrogen production plant is linked with a nuclear reactor. Traditional nuclear safety research has been focusing on the safety of nuclear reactor core and its thermal hydraulic system, and the chemical plant safety has examined the probability of fires, blasts, leaks, and spills (Baindur, 2008). However, the likelihood of obtaining a permit to construct such a nuclear and hydrogen combination without proposing measures to be taken for avoiding risks and accidents is questionable, because the linkage may result in complex mutual interactions between the hydrogen production and nuclear power plants. In other words, the safety assurance must consider the mutual interactions and not be only limited to the hydrogen production plant.

A number of investigators have speculated about some disastrous situations when a fire or blast of hydrogen takes place. The worst scenario could be a severe damage or detonation of nuclear reactor core caused by the blast of hydrogen plant (Smith et al., 2005; Baindur, 2008; Piera et al., 2006). The probability of detonation was quantified, and a minimum separation distance between nuclear reactor and hydrogen production units was suggested to avoid the detonation. To minimize the risk, some measures were proposed (Baindur, 2008; Piera et al., 2006), including putting a 100 kg on-site limit for hydrogen storage, quickly piping hydrogen out as produced, location of the nuclear plant control room outside of the dispersion zone for chemical release. Detrimental impacts of the chemicals in a hydrogen production plant on the nuclear reactor were examined qualitatively and some risk-mitigating design modifications were proposed to minimize the probability of nuclear core damage. The modifications include constructing an earthen barrier between the nuclear and chemical facilities, constructing the nuclear facility primarily underground, constructing blast panels near the chemical facility to dampen overpressure events, constructing the chemical facility primarily underground and moving the nuclear plant control room offsite.

The transient behavior and related dynamic safety issues arising from the linkage of nuclear and thermochemical hydrogen production plants have attracted more attention in recent years. Studies on small-scale dynamic fluctuations of the heat requirements of S–I thermochemical hydrogen production plants have been reported (Yan et al., 2012; Shin et al., 2013). Some investigators examined the hydrogen production plant as a heat sink, so the coupled nuclear and hydrogen production system would experience a loss-of-heat-sink (LOHS) if one of the hydrogen processes or equipment failed (Brown et al., 2012; Brown and Revankar, 2012). They also assessed possible influences of various transient events initiated in an S–I thermochemical hydrogen production cycle on the nuclear reactor. They modeled the event propagation from the hydrogen plant to the nuclear reactor based on the analysis of different failures of the constituent processes and equipment of the hydrogen production cycle. Although no measures were proposed to prevent the events, the model provided a good basis to improve future safety assurance.

Past research of safety issues has put significant forward-looking contributions to the development of nuclear-based hydrogen production. However, most have focused on a specific thermochemical cycle so the generalization of measures to be taken for minimizing thermal and chemical hazards is yet to be assessed. As heat must be transferred to thermochemical cycles and high temperature electrolysis, this paper will quantitatively examine the hazards caused by the interactive heat exchange between nuclear and various hydrogen production cycles from the perspectives of heating fluid failure and heat rejection, by adopting a top-down approach to identify the system boundary so that the results can be utilized for different hydrogen production cycles rather than only a specific cycle. Large scale surplus heat disposal in the start-up or emergency shutdown operation of different hydrogen production cycles will be examined. A significant difference between thermochemical water splitting and high temperature electrolysis (or steam electrolysis) for hydrogen production is that a thermochemical cycle usually consists of more thermal and chemical processes than high temperature electrolysis. When these processes are integrated together to form a closed loop, their interactions may complicate the safety issues. This paper will also examine the influences of these interactions on the safety of thermal and chemical hazard management.

2. Potential thermal hazards of nuclear/hydrogen plant exchange

2.1. *Material and energy flows between nuclear reactor and hydrogen plant*

Before looking into the details of nuclear reactor and hydrogen production plant, a top-down approach can be used to study the linkage of nuclear reactor and hydrogen production plant so that the material and energy flows across their boundary and the mutual impacts can be expressed in a simplified chart. Fig. 1 shows the material and energy flows.

Fig. 1 shows that there are one material and two energy flows across the boundary. In this paper, the study of the mutual interactions starts from examining the flows. The energy flows include heat and electricity. Since a hybrid thermochemical cycle consists of both electrolytic and thermal