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Chemical Plant Accidents in a Nuclear Hydrogen Generation Scheme

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1. Introduction

A high temperature nuclear reactor (HTR) could be used to drive a steam reformation plant, a coal gasification facility, an electrolysis plant, or a thermochemical hydrogen production cycle. Most thermochemical cycles are purely thermodynamic, and thus achieve high thermodynamic efficiency.

HTRs produce large amounts of heat at high temperature (1100 K). Helium-cooled HTRs have many passive, or inherent, safety characteristics. This inherent safety is due to the high design basis limit of the maximum fuel temperature.

Due to the severity of a potential release, containment of fission products is the single most important safety issue in any nuclear reactor facility. A HTR coupled to a chemical plant presents a complex system, due primarily to the interactive nature of both plants. Since the chemical plant acts as the heat sink for the nuclear reactor, it important to understand the interaction and feedback between the two systems.

Process heat plants and HTRs are generally very different. Some of the major differences include: time constants of plants, safety standards, failure probability, and transient response. While both the chemical plant and the HTR are at advanced stages of testing individually, no serious effort has been made to understand the operation of the integrated system, especially during accident events that are initiated in the chemical plant. There is a significant lack of knowledge base regarding scaling and system integration for large-scale process heat plants coupled to HTRs. Consideration of feedback between the two plants during time-dependent scenarios is absent from literature. Additionally, no conceptual studies of the accidents that could occur in either plant and impact the entire coupled system are present in literature.

2. Proposed accident scenarios in an endothermic chemical plant coupled to a HTR

Transient or accident events initiated in the chemical plant are an important aspect of the safety of a coupled HTR chemical plant system. Several modes of chemical plant initiated accident scenarios are proposed. These scenarios include intra-reaction chamber piping system failures, reaction chamber failures, as well as process holding tank failures. Some of these scenarios were qualitatively presented at the 2009 OECD Nuclear Hydrogen Information Exchange [2]. In the interim, they have been further refined and the realism of the scenarios has been improved. These scenarios are part of the development of an overall modeling scheme for HTRs coupled to candidate process heat plants. This scheme is necessitated for safety evaluation of the coupled plant. Modeling details are described elsewhere [1, 3]. The chemical plant studied here is the Sulfur Iodine (SI) cycle. Each chemical reaction in the SI cycle takes place in a separate “section” of the chemical plant. These sections are dubbed section 1 – 3 and correspond to the numbered chemical reaction shown here. The main chemical reactions in the SI cycle are:

1. $I_2+SO_2+2H_2O \rightarrow 2HI + H_2SO_4$ (Bunsen reaction)
2. $H_2SO_4 \rightarrow H_2O + SO_2 + 1/2O_2$ (Sulfuric acid decomposition)
3. $2HI \rightarrow H_2 + I_2$ (Hydrogen Iodide decomposition)

3. Event test matrix

The following accident or operational events are studied in the transient test matrix [1]:

Case 1: A partial feed flow failure from section 1 (Bunsen reaction) to both section 2 (H_2SO_4 decomposition) and section 3 (HI decomposition) of the chemical plant.

Case 2: A partial recycle (product) flow failure from section 2 and section 3 to section 1.

Case 3: A leak out of the section 2 (H_2SO_4 decomposer).

Case 4: Time-to-SCRAM for helium inlet overcooling at different cold reactant injection rates.

Case 5: Helium inlet overcooling without SCRAM: power peaking analysis.

Case 6: Total loss of chemical plant.

Case 7: Parametric study of the steady state section 3 (HI decomposition) temperature.

Case 8: Control rod insertion.

The details of the coupled code system will be published in several forthcoming journal articles.

4. Selected results for case 1 – partial feed flow failure

In this example test case, the chemical species coupling within the chemical plant is perturbed. Complete results for the entire test matrix are given in Ref. [1]; some results for case 1 are reproduced here. This test case simulates a partial failure of section 1 of the chemical plant, the Bunsen reaction section. The test case begins with steady state operation at a nuclear reactor power of 268 MWt, assuming reactant recycling within each section of the chemical plant. At 5.0 seconds, a step change occurs in the flow rate from section 1 to section 2, the H_2SO_4 decomposer, and section 3, the HI decomposer. The magnitude of the step change in the base case is 50 %. In this case, the flow from section 1 to the other reaction sections is maintained at 50 %. The consequence of this is that the flow into the decomposer sections will continually decrease, but it also shows the cascade of the event throughout the chemical plant. As the event cascades back to section 1 of the chemical plant, the generation rate of the two acids will decrease, and the flow from section 1 to the other sections will continue to decrease. Because section 1 is saturated with I_2 and HI, the limiting species in the cascade is SO_2.

This test case represents a partial Bunsen reactor failure and a partial reactant flow pipe failure. The case is useful as a demonstration of the type of loss-of-heat sink accident that would occur following a pipe break in the chemical plant. Generally, the response of section 2, the majority of the heat sink, is very rapid, and the nuclear reactor power will decrease quickly according to the fraction of mass lost. The case also shows the cascade throughout the chemical plant, because the output of section 1 slowly decreases based on the decreased recycle input from section 2 and the residence time. The total time for this cascade process is on the order of an hour. The reaction rates within the chemical plant in the event of the 50% feed flow failure are shown in Fig. 1.

Several parametric studies were performed, for 0.1, 0.2, 0.3, 0.4, and 0.5 fractional losses of reactant input to section 2. The resultant reactor power for each of these events is shown in Fig. 2. The HTR power decreases according to the fraction of input to section 2 lost. The continuing heat sink loss due to the cascade effect is also evident after the initial power decrease. Thus this test case successfully demonstrates the following phenomena: (1) partial loss-of-heat sink due to accident, (2) response of the various sections of the chemical plant, and (3) the resultant cascade throughout the chemical plant and the entire coupled plant. The impact of including xenon-feedback in the calculation is shown for the chemical plant in Fig. 3.

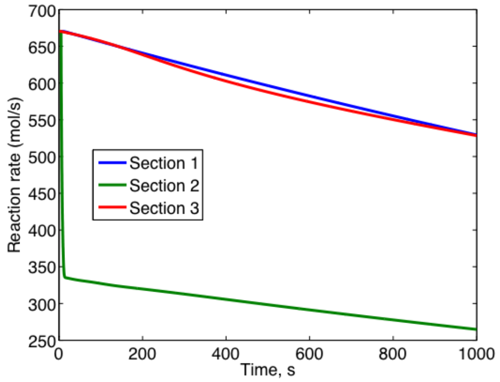

Fig. 1. Reaction rates within the chemical plant for Case 1 – 50% partial feed flow failure.

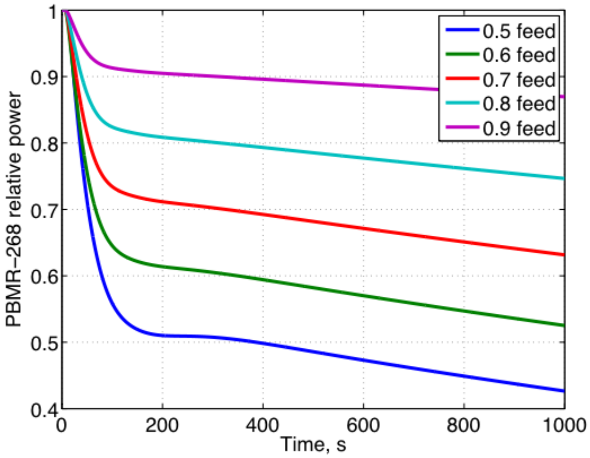

Fig. 2. HTR neutronic power for various feed flow failures within the chemical plant.

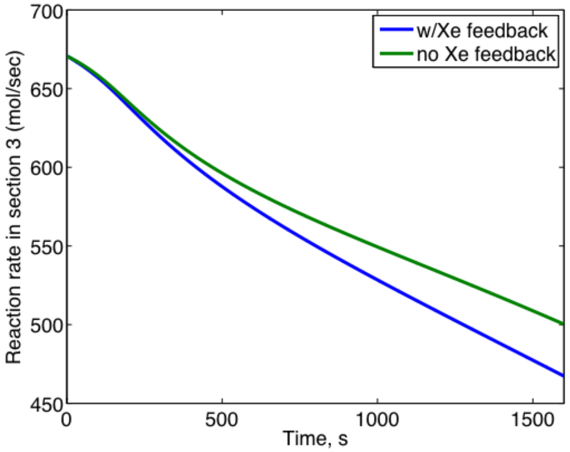

Fig. 3. Impact of xenon-feedback within the HTR on HI decomposition reaction rates within the chemical plant.

Full results for the transient test matrix [1] will be published in several forthcoming journal articles.

ACKNOWLEDGMENT

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