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Nuclear Plant/Hydrogen Plant Safety: Issues and Approaches

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NUCLEAR PLANT/HYDROGEN PLANT SAFETY: ISSUES AND APPROACHES

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Abstract – The U.S. Department of Energy, through its agents the Next Generation Nuclear Plant Project and the Nuclear Hydrogen Initiative, is working on developing the technologies to enable the large scale production of hydrogen using nuclear power. A very important consideration in the design of a co-located and connected nuclear plant/hydrogen plant facility is safety. *This study provides an overview of the safety issues associated with a combined plant and discusses approaches for categorizing, quantifying, and addressing the safety risks.*

I. INTRODUCTION

The U.S. Department of Energy (DOE) is actively pursuing the development of advanced nuclear reactors that will provide greater efficiencies, stronger proliferation resistance, lower capital costs, and greater sustainability than today's generation of operating commercial reactors. These advanced reactor concepts are known as "Generation IV" [1]. One of the Generation IV concepts is the Very High Temperature Reactor (VHTR), a gas-cooled thermal fission reactor that will be capable of providing large quantities of high-temperature thermal energy (greater than 1173 K) for use in the production of hydrogen or other industrial applications. In 2005, the U.S. Energy Policy Act [2] authorized the creation of the Next Generation Nuclear Plant (NGNP) Project and named the Idaho National Laboratory (INL) to lead the multi-laboratory effort to develop a Generation IV nuclear reactor facility that would be capable of generating electricity, hydrogen, or both, on a large scale. The NGNP Project is focused on the development of the VHTR and is working closely with another DOE program, the Nuclear Hydrogen Initiative (NHI), to develop advanced hydrogen production methods (e.g., S-I Process [3], High-Temperature Electrolysis [4], etc.) that can utilize the high-temperature thermal energy produced by the VHTR to produce efficiently hydrogen from the splitting of water.

The NGNP is envisioned as a co-located nuclear plant/hydrogen plant facility (Fig 1).

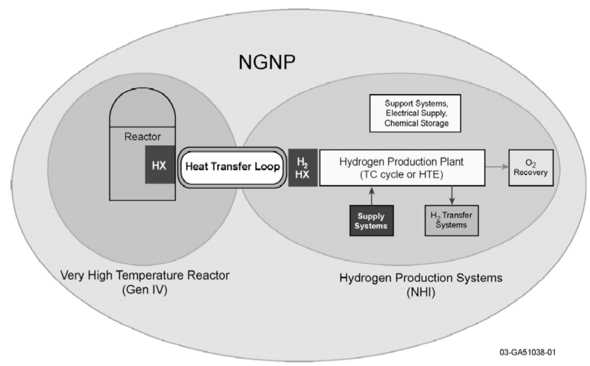

Fig. 1. Schematic of NGNP Facility

In the NGNP, the high temperature thermal energy produced by the nuclear reactor is transmitted to the hydrogen production plant through an intermediate heat exchanger (IHX), a heat transfer loop, and at least one process heat exchanger (PHX) [5].

Technically, the challenges of creating such a system are many, and much research thus far has been on the development of enabling technologies including materials identification and property measurements, component design, measurement of physical data to fill knowledge gaps, and the development and testing of integrated system models.

The results of this research have been encouraging, and the development discussions are evolving from examining questions of the type 'Can it be done?' to the type 'Can it be done safely, efficiently, and at acceptable cost?'. Safety is of utmost importance in the co-location of a nuclear plant and a hydrogen plant, and a strong safety case will be needed to support eventual U.S. Nuclear Regulatory Commission (NRC) licensing of the NGNP facility, as required in the U.S. Energy Policy Act. Though commercial nuclear plants have been constructed in the general region of chemical plants, no large-scale chemical plant is co-located and directly connected to a nuclear reactor. A premise of the NGNP Project and the NHI is that co-location and connection of a nuclear plant with a chemical plant, specifically a VHTR and a hydrogen production facility, can be done safely and in a manner acceptable to the NRC.

This article describes safety concerns related to the co-location and combined operation of a nuclear plant and a hydrogen production plant, strategies for quantifying the risks, and possible approaches for mitigating the risks through engineering and operational controls (defense-in-depth). It is the incremental risk associated with the hydrogen plant that is of interest here rather than the risks associated with the nuclear reactor itself, as it is assumed that the general nuclear engineering community already understands such risks. As with any complex engineering system, the application of safety controls to the NGNP must be balanced by their impacts on plant functionality and economics. After achieving the required level of safety, the application of additional controls must be balanced and not so onerous as to make the whole project uneconomical. Recommendations are provided for future work.

II. SAFETY CONCERNS

In categorizing safety concerns for a co-located nuclear plant/hydrogen plant facility such as the NGNP, there is a spectrum of adverse events that can occur externally to the nuclear plant. For convenience, three tiers of events are postulated: primary, secondary, and tertiary. Primary events are here defined as accidents or equipment failures at the hydrogen plant or the intermediate heat transfer loop that lead to nuclear reactor core damage and the significant release of radioactive materials from the nuclear reactor into the environment. Such an event would be an extraordinary failure of controls and would have far- reaching effects on near-by communities and to the nuclear power industry in general. Secondary events concern failures that result in crippling damage to equipment, leaks of regulated chemicals into the environment, and that may lead to injury to human operators. The third tier of events involves impacts to normal operation caused by unscheduled plant occurrences (e.g., unplanned shutdowns, minor equipment failures, etc.) and events that have adverse economic impacts on combined plant operations but do not cause physical damage to the plant or harm to personnel. While less of a safety issue than an operational issue, deviation from normal operating conditions can create conditions that may lead to human error or may shorten the usable lifetime of equipment, and this in turn may create conditions for a higher tier event.

Of these three tiers, the NRC is most concerned with first tier events. The NRC's primary mission [6] is to "...protect public health and safety and the environment from the effects of radiation from nuclear reactors, materials, and waste facilities...." Installation of a co-located and connected hydrogen production plant is a perturbation on the established nuclear power generation model, and so the incremental risk imposed by the hydrogen production plant must be carefully determined to support an NRC license application. In the end, the NRC must be convinced that the co-location and connection of a hydrogen production facility to a VHTR poses no statistically significant increased hazard to the nuclear plant. Therefore, characterization of the causes and impacts of phenomena leading to nuclear reactor damage by phenomena external to the nuclear reactor must take precedence in all safety analyses of the combined facility.

Prevention of a first tier event is a necessary but not sufficient condition in establishing the safety and design features of the NGNP. The success of the NGNP will depend on preventing and mitigating second and third tier events too. Since the NGNP concept involves a non-nuclear hydrogen production plant, other regulatory bodies such as the U.S. Environmental Protection Agency (EPA) and the U.S. Occupational Safety and Health Administration (OSHA) will impose rules and standards to ensure safe operation of the hydrogen plant and, more broadly, to prevent second tier events. The meaning and impact of such rules and standards must be understood and incorporated into plant designs and operations. Lastly, the NGNP designers and operators will be responsible for their own benefit for building and operating a combined facility that is reliable, inspectable, easily repaired, and predictable, so that the frequency of third tier events is minimized.

The broad classes of safety events may be caused by predecessor events. Some predecessor events are:

- Seismic activity
- H_2 explosions
- Chemical fires (H_2, O_2, and other reactive materials)
- Chemical releases (gas and liquid)
- Equipment degradation and malfunction
- Human error

A greater understanding of the frequencies, effects, and mitigating or preventive measures for such predecessor events may be gained by employing a variety of tools and approaches.

III. APPROACHES

The most useful tools and approaches for understanding and affecting the incremental risk related to the hydrogen plant are quantitative risk analysis, plant modeling and simulation, data collection and analysis, hydrogen plant architectural analysis, and efforts related to continuous improvement. These are explained below.

III.A. Quantitative Risk Analysis

Quantitative risk analysis (also called probabilistic risk assessment or probabilistic safety analysis) is a process of developing and understanding numerical estimates of risk [7]. Historical experience, analytical methods, and acquired knowledge and intuition form the foundation of quantitative risk analyses (QRAs), and QRA tools are used to help answer the questions "How likely is it?", "What can go wrong?", and "What are the impacts?" when examining possible safety-related occurrences. In QRA, possible hazards are first identified, and then are analyzed for frequency and impact. The relationships between individual occurrences (e.g., failure of a pump, operator error) and overall impacts of those occurrences (e.g., hydrogen leak) can be complex, and the probabilities and consequences of individual occurrences and must be assessed collectively to arrive at an overall understanding of risk.

Though the chemical process industry has traditionally relied on shared experience and deterministic models to assess risk in chemical plants, the incremental risk of combining a hydrogen production plant with a nuclear plant is less understood, and there is no historical precedent. QRA will be needed to assess the risks, and the NRC will expect to see a QRA of the combined facility when it is reviewing the license application of the NGNP [8].

Some initial work in this area was an evaluation of the minimum separation distance between the nuclear plant and the hydrogen plant [9]. From an engineering standpoint, the separation distance must be minimized to reduce thermal losses and to reduce the costs of the intermediate heat transfer loop, but the distance cannot be so small as to jeopardize the nuclear plant in the event of an accident at the hydrogen production plant. The events analyzed in this study were hydrogen explosions and the release of chemical clouds from a co-located Sulfur-Iodine hydrogen production plant. The goal of the study was to determine the minimum distance needed between the nuclear plant and hydrogen plant such that the incremental probability of causing nuclear core damage due to hydrogen explosion or a chemical release was no greater than 1.0E-6 events/year. The separation distance between the two plants is shown graphically in Figure 2. Event and fault trees were developed and analyzed using SAPHIRE [10]. The effects of hydrogen explosions were analyzed using an INL hydrogen explosion code [11], and chemical dispersions were modeled using ALOHA [12].

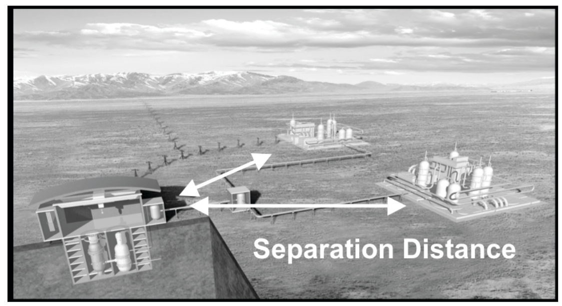

Fig. 2. A representation of the NGNP showing separation distance

The conclusions from this study were that a minimum separation distance of 110 m was needed between the nuclear plant and the hydrogen plant in the default configuration (shown in Figure 2) for hydrogen explosions involving up to 100 kg H_2. Determination of the minimum separation distance was chiefly a function of the blast effects of hydrogen explosions and was not significantly affected by chemical dispersion events. It was found that the separation distance could be reduced to as low as 60 m if blast deflection barriers or an earthen wall are placed between the two plants, or if the nuclear plant is placed below grade.

Developing the QRA for the NGNP should be an organizing principle around which safety-related information is collected and organized, and specific system designs are evaluated. As the QRA information is established, gaps in the supporting data will be identified and research needs will be refined. Assumptions will be defined explicitly and checked against the data collected. Plant models and designs will be constructed and analyzed in detail, and the information collected from preliminary QRAs will help developers understand which design changes may bear the most fruit in regards to risk reduction. In addition to the addressing the primary concern of how the hydrogen plant might affect the nuclear plant, QRA can be used to assess the risks of individual sub-systems within the hydrogen plant, or even to assess the risks associated with particular operational schedules and set points.

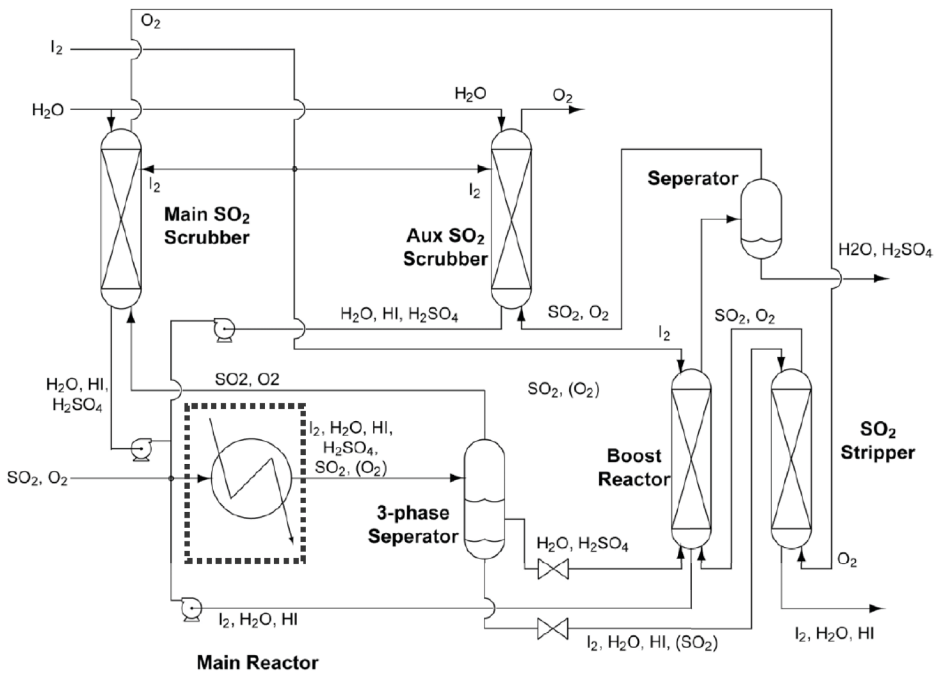

Figure 3. A flow sheet representation of H2SO4 section.

It must be understood that QRA is an evaluation tool and is not a design tool; that is, QRA can be used to evaluate given designs, but QRA will not provide the "right" design. The evaluated risks must be compared to the acceptable levels of risk, which is defined external to the QRA, and it will be the interplay between calculated risks, design configurations, costs, and acceptable risk that will provide the optimal design.

III.B. Plant Modeling and Simulation

As a foundation for developing a QRA for the NGNP, detailed plant models must be constructed for the combined facility so that the expected behaviors of individual systems and the integrated plant are understood. This modeling will involve analysis of steady-state and unsteady-state operations.

Studies of steady-state plant operations, at least of the hydrogen production plant, must start with the process flow sheet. An example of a process flow sheet for a section of the S-I Hydrogen Production Process [13] is shown in Figure 3. The flow sheet defines the mass and energy flows, temperatures, pressures, chemical compositions, and chemical/physical changes that occur in individual flow streams and process components at steady-state or time-invariant conditions. The flow sheet usually consists of a graphical representation, as shown above, and sets of tables, which provide detailed information on each process stream and component. Flow sheets can be generated manually, but are usually developed using commercial software packages such as Aspen Plus™.

Once the energy and mass flows are understood using detailed flow sheets, unsteady-state models must be developed also to understand the phenomena that may occur during start-up, shutdown, and off-normal events. Unsteady-state models are also important for developing and assessing the effectiveness of plant process control strategies. Supporting data for the development of unsteady-state models includes the calculation or measurement of individual time constants, heat and mass transfer information, chemical kinetics data and other time-variant data.

III.C. Data Collection and Analysis

The steady state and unsteady-state models will provide information on the expected performance of the plant, but this information must be compared to actual experience and measured data to at least verify the veracity of the models. During process development, it is very likely that there will be insufficient data to construct accurate models, and laboratory data will be needed to define or narrow the uncertainty bounds on certain process parameters, such as the performance of select catalysts or chemical separation processes

The flow sheets and unsteady-state models are abstractions of real processes, and data must be obtained on the real materials of construction and the performance of actual components. Such data is not only used to build real processes that resemble the models, but also to understand when models may deviate from actual performance, and, in the extreme, to understand how real components, systems, and processes can fail. Since the NGNP will be operating at high temperatures, pressures, and under difficult chemical conditions, it is especially important to choose the right materials of construction and to understand the effects of creep, cracking, erosion, and corrosion on the reliability of materials and components. Such information can be collected from materials studies, single component tests, integrated lab-scale tests, and pilot-scale plants. In such tests it is as important to define where the materials and components cannot survive as it is to determine how well the materials and components perform within the defined operating envelopes. Such information would be directly applicable to constructing the QRA.

Instead of relying solely on self-generated data, industrial information sources should be utilized to gather as much information as possible on component reliability, accident scenarios, and industry best practices in regard to plant design and the use of safety and control systems. Though efforts have been made to develop all-inclusive chemical plant accident databases [14], it is perhaps best to consult experts and to recover data that is specific to the chemical industries that are most relevant to hydrogen production, namely those currently involved in hydrogen and oxygen production, and those who produce the corrosive chemicals involved in some of the proposed hydrogen production processes (e.g., H_2SO_4, HI, I_2).

III.D. Hydrogen Plant Architecture

Another design factor that will receive more attention in NGNP design than is usually considered during chemical plant development is plant architecture. In isolation, the hydrogen plant components would likely be arranged to optimize energy conservation and to minimize the length of flow paths. The directional orientation of the plant may be determined by the size of the plant boundaries, the geography of the plant site, and the proximity to roads, rail lines, and pipelines for raw material and product delivery. The placement of certain process units within the plant boundary may be influenced somewhat by accident scenarios (e.g., avoiding the mixing of incompatible chemicals in the event of a spill), but the overall placement of units will usually have many degrees of freedom.

Co-location and connection of a hydrogen production with a nuclear facility imposes very strong directional considerations, and the relative risk of the various possible hydrogen plant configurations is highly anisotropic. In regard to thermal energy transfer, the highest temperature sections of the hydrogen production plants must be placed as close to the nuclear reactor as possible. The hydrogen production components and hydrogen storage vessels must be placed as far away from the nuclear plant as possible. In the S-I Process, for instance, the highest temperature section (H_2SO_4 decomposition) is separated from the hydrogen production section (the HI decomposition), and such a separation is possible. In the case of High Temperature Electrolysis, the highest temperature component of the process is the hydrogen production unit, and so the inventory of hydrogen in the hydrogen production cells must be minimized by the removal of hydrogen as quickly it is produced, imposing additional constraints on the plant architecture.

To determine plant architectures, component sizes and connections must be determined using the flow sheet data, and then examined. Computer-aided design tools such as Autocad® would be useful at this stage of development. Then, the effects of proximity, plant geometry, chemical inventories, and so forth can be evaluated using other modeling tools to support development and revision of the QRA.

III.E. Continuous Improvement

Once the combined facility is operational, a number of practices can be employed to continue to reduce the incremental risk of operating the facility. Some practices are described below.

The QRA, once established, can be updated and revised as changes occur in materials, equipment design, component configurations, and plant operating conditions. By doing so, the potential safety or operational risk impacts of suggested process or plant improvements could be assessed on an equal basis with the current state of the plant. Such an analysis is especially helpful in determining whether a process or equipment change might not have unintended effects on locations removed from the point of interest.

Statistical process control techniques may be used to track the performance of individual processes over time and to spot long-term trends in performance that may not always be visible over short time scales.

A protocol of equipment inspections and surveillance can be established to monitor the effects of corrosion, fatigue, and other materials failure mechanisms on the integrity of process vessels. Such inspections are especially critical for process units that are exposed to highly corrosive and/or high-temperature environments. A combination of field data and laboratory materials data might be used to assess the useful remaining lifetime of process equipment, and select equipment can be replaced at regular intervals if necessary to protect against more costly failures in the future.

Lastly, an integrated plant safety philosophy such as the INL's Integrated Safety Management System [15] might be adopted to reinforce safe plant operations and to seek continuous improvement. At the INL, the guiding principles of the Integrated Safety Management System are:

- Line management responsibility for safety
- Clear roles and responsibilities
- Competence commensurate with responsibilities
- Balanced priorities
- Identification of safety standards and requirements
- Hazard controls tailored to work being performed
- Operations authorization
- Employee involvement

Its objective is to "incorporate safety into management and work practices at all levels, addressing all types of work and all types of hazards to ensure the safety of the workers, the public and the environment." An integrated safety approach is needed because analyses, models, and inspections alone are insufficient to ensure safe plant operation. The risk of human error in plant operation cannot be eliminated, but its effects might be reduced through careful management of work procedures and operations, and the collection, assessment and sharing of accident and "near-miss" incident data. While the INL's Integrated Safety Management System has been developed for specific application to the INL, its general goal of achieving continuous improvement in plant safety is applicable to any plant environment.

IV. NGNP PATH FORWARD

The NGNP is at a preliminary stage of development. Research and development work is taking place on individual components and enabling technologies, but the shape and configuration of the larger integrated system is still mostly undefined. In parallel with the system-specific development activities, work must begin on developing the detailed QRA, and this in turn will help define the needs for specific data from the laboratory and from steady-state and unsteady-state plant models. The goal at this stage is not to produce a fully detailed QRA but to determine what information is needed to support the QRA, so that budgets, schedules, and work scope can be more fully defined.

Research scope needs to be expanded to study second-tier events. The initial QRA study of plant separation distance [9] considered a first-tier event – damage to the nuclear core due to hydrogen explosion or chemical leak. Most other research and development work is being done to enable the plant to operate according to expectations, or, in other words, to prevent the plant from suffering third tier events. Studies have not yet been done to examine how things might fail, and this will need to be done to provide information for the integrated NGNP QRA.

V. SUMMARY

The NGNP is a Generation IV concept involving the co-location and connection of a VHTR with a hydrogen production plant. There is no commercial precedent for such a system, and extensive safety analyses will be needed to achieve the desired level of safety and risk. Recommendations of approaches to characterize and achieve safety and operational goals were provided including QRA, plant modeling and simulation, data collection and analysis, analyses of hydrogen plant architecture, and continuous improvement. The NGNP is at the start of the development process, and it is suggested that QRA be the organizing tool around which future safety-related research is performed.

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