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Next Generation Nuclear Plant Phenomena Identification and Ranking Tables (PIRTs)

Volume 6: Process Heat and Hydrogen Co-Generation PIRTs

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Next Generation Nuclear Plant Phenomena Identification and Ranking Tables (PIRTs)

Volume 6: Process Heat and Hydrogen Co-Generation PIRTs

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ABSTRACT

A Phenomena Identification and Ranking Table (PIRT) exercise was conducted to identify potential safety-0-related physical phenomena for the Next Generation Nuclear Plant (NGNP) when coupled to a hydrogen production or similar chemical plant. The NGNP is a very high-temperature reactor (VHTR) with the design goal to produce high-temperature heat and electricity for nearby chemical plants. Because high-temperature heat can only be transported limited distances, the two plants will be close to each other. One of the primary applications for the VHTR would be to supply heat and electricity for the production of hydrogen. There was no assessment of chemical plant safety challenges.

The primary application of this PIRT is to support the safety analysis of the NGNP coupled one or more small hydrogen production pilot plants. However, the chemical plant processes to be coupled to the NGNP have not yet been chosen; thus, a broad PIRT assessment was conducted to scope alternative potential applications and test facilities associated with the NGNP. The major conclusions are as follows:

- ***NGNP vs a commercial high-temperature reactor.*** The PIRT panel examined safety issues associated with the NGNP and a commercial plant. For the NGNP, only a small fraction of the heat is expected to be used to produce hydrogen or other chemicals, with most of the heat used to produce electricity. In contrast, for a commercial high-temperature reactor application, all of the heat might be used for production of hydrogen or other chemicals. Because the total chemical inventories determine the potential hazard to the nuclear plant from a chemical plant, the hazards of a small chemical plant associated with the NGNP may be significantly less. For the NGNP, there may be multiple generations of hydrogen production and other chemical technologies tested; thus, one must either envelope the safety implications of the different technologies or update the safety analysis with time.
- ***Chemical plant safety, regulatory strategy, and site layout.*** The safety philosophies for most chemical plants and nuclear power plants are fundamentally different. For hazards such as hydrogen leaks, the safety strategy is dilution with air to below the concentration of hydrogen that can burn in air. For example, a small amount of hydrogen in an enclosed room is an explosion hazard. However, a large release of hydrogen to the environment is a relatively small hazard when outdoors. Consequently, most chemical plants are built outdoors to allow rapid dilution of chemicals with air under accident conditions. The reverse strategy is used for nuclear plants, where the goal is to contain radionuclides because their hazard does not disappear if diluted with air. Primary chemical plant safety strategies include outdoor construction (no containment), controlled chemical inventory sizes, site layout features, and adequate separation distances between process and storage facilities. These differences must be recognized when considering safety challenges to coupled nuclear and chemical plants.
- ***Hydrogen.*** Accidental releases of hydrogen from a hydrogen production facility are unlikely to be a major hazard for the nuclear plant, assuming some minimum separation distances. This conclusion is based on several factors: (1) if hydrogen is released, it rapidly rises and diffuses, thus making it very difficult to create conditions for a large explosion and (2) a hydrogen burn does not produce high thermal fluxes that can damage nearby equipment. In addition to laboratory and theoretical analysis of hydrogen accidents, there is a massive knowledge base in the chemical industry with hydrogen accidents and, thus, a large experimental basis to quantify this hazard based on real-world experience.
- ***Heavy gases.*** Many chemical plants under accident conditions can produce heavy ground-hugging gases such as oxygen, corrosive gases, and toxic gases. Industrial experience shows that such accidents can have major off-site consequences because of the ease of transport from the chemical plant to off-site locations. If the chemical plant or the stored inventories of

chemicals are capable of releasing large quantities of heavy gases under accident conditions, this safety challenge requires careful attention. Oxygen presents a special concern. Most proposed nuclear hydrogen processes convert water into hydrogen and oxygen; thus, oxygen is the primary byproduct. Oxygen has some unique capabilities to generate fires. Equally important, these will be the first facilities that may release very large quantities of oxygen to the atmosphere as part of normal operations. There is a lack of experience. The phenomena associated with plume modeling and the effects of such plumes on the nuclear plant safety-related structures, systems, and components are of high importance.

- ***Heat exchanger failure.*** The second major class of safety challenges with high importance is associated with the failure of the intermediate heat transport loop that moves heat from the reactor to the chemical plant. Several different heat transport media are being considered including helium, helium-nitrogen mixtures, liquid salt mixtures, and high-temperature steam. High-temperature steam is required as a process chemical for some processes, such as the production of hydrogen using high-temperature electrolysis, thus steam could be the intermediate heat transport fluid. The choice of heat transport fluid will partly depend upon distance. Over longer distances, liquid salts and steam are expected to have lower heat-transport costs. For gas-phase intermediate heat transport systems, there are several specific phenomena of high safety importance.
    - ***Blowdown of intermediate heat transport loop.*** In certain pressure boundary failures, the blowdown could accelerate fluid flow through the primary heat exchangers. Depending upon the failure location, this may result in accelerated fluid flow of the cold heat-transport fluid through the intermediate heat exchanger and result in overcooling the reactor coolant because of enhanced heat transfer in the primary heat exchanger. After blowdown, there will be a loss of the heat sink.
    - ***Leak into reactor primary system.*** The total gas inventory in the intermediate loop may be significantly larger than the total inventory of gas in the reactor primary system. A large or small leak from the intermediate heat transport loop into the reactor in accident scenarios where the primary system depressurizes could add large inventories of gas to the reactor, providing a sweep gas to move fission products from the reactor core.
    - ***Chemical additions to reactor core.*** If steam or other reactive gases from the intermediate heat transport loop enter the reactor because of a heat exchanger failure, there is the potential for fuel damage—particularly given the much higher temperatures proposed for some applications of high-temperature reactors.
    - ***Hot fluids.*** If the heat transport loop fluid escapes into the reactor building, the high temperatures could cause significant damage.

The hazards associated with various chemicals and methods to minimize risks from those hazards are well understood within the chemical industry. Much but not all of the information required to assure safe conditions (separation distance, relative elevation, berms) is known for a reactor coupled to a chemical plant. There is also some experience with nuclear plants in several countries that have produced steam for industrial applications. The specific characteristics of the chemical plant, site layout, and the maximum stored inventories of chemicals can provide the starting point for the safety assessments.

While the panel identified events and phenomena of safety significance, there is one added caveat. Multiple high-temperature reactors provide safety-related experience and understanding of reactor safety. In contrast, there have been only limited safety studies of coupled chemical and nuclear plants. The work herein provides a starting point for those studies; but, the general level of understanding of safety in coupling nuclear and chemical plants is less than in other areas of high-temperature reactor safety.

FOREWORD

The Energy Policy Act of 2005 (EPAct), Public Law 109-58, mandates the U.S. Nuclear Regulatory Commission (NRC) and the U.S. Department of Energy (DOE) to develop jointly a licensing strategy for the Next Generation Nuclear plant (NGNP), a very high temperature gas-cooled reactor (VHTR) for generating electricity and co-generating hydrogen using the process heat from the reactor. The elements of the NGNP licensing strategy include a description of analytical tools that the NRC will need to develop to verify the NGNP design and its safety performance, and a description of other research and development (R&D) activities that the NRC will need to conduct to review an NGNP license application.

To address the analytical tools and data that will be needed, NRC conducted a Phenomena Identification and Ranking Table (PIRT) exercise in major topical areas of NGNP. The topical areas are: (1) accident analysis and thermal-fluids including neutronics, (2) fission product transport, (3) high temperature materials, (4) graphite, and (5) process heat and hydrogen production. Five panels of national and international experts were convened, one in each of the five areas, to identify and rank safety-relevant phenomena and assess the current knowledge base. The products of the panel deliberations are Phenomena Identification and Ranking Tables (PIRTs) in each of the five areas and the associated documentation (Volumes 2 through 6 of NUREG/CR-6944). The main report (Volume 1 of NUREG/CR-6944) summarizes the important findings in each of the five areas. Previously, a separate PIRT was conducted on TRISO-coated particle fuel for VHTR and high temperature gas-cooled reactor (HTGR) technology and documented in a NUREG report (NUREG/CR-6844, Vols. 1 to 3).

The most significant phenomena (those assigned an importance rank of "high" with the corresponding knowledge level of "low" or "medium") in the thermal-fluids area include primary system heat transport phenomena which impact fuel and component temperatures, reactor physics phenomena which impact peak fuel temperatures in many events, and postulated air ingress accidents that, however unlikely, could lead to major core and core support damage.

The most significant phenomena in the fission products transport area include source term during normal operation which provides initial and boundary conditions for accident source term calculations, transport phenomena during an unmitigated air or water ingress accident, and transport of fission products into the confinement building and the environment.

The most significant phenomena in the graphite area include irradiation effect on material properties, consistency of graphite quality and performance over the service life, and the graphite dust issue which has an impact on the source term.

The most significant phenomena in the high temperature materials area include those relating to high-temperature stability and a component's ability to withstand service conditions, long term thermal aging and environmental degradation, and issues associated with fabrication and heavy-section properties of the reactor pressure vessel.

The most significant phenomenon in the process heat area was identified as the external threat to the nuclear plant due to a release of ground-hugging gases from the hydrogen plant. Additional phenomena of significance are accidental hydrogen releases and impact on the primary system from a blowdown caused by heat exchanger failure.

The PIRT process for the NGNP completes a major step towards assessing NRC's research and development needs necessary to support its licensing activities, and the reports satisfy a major EPAct milestone. The results will be used by the agency to: (1) prioritize NRC's confirmatory research activities to address the safety-significant NGNP issues, (2) inform decisions regarding the development of independent and confirmatory analytical tools for safety analysis, (3) assist in defining test data needs for the validation and verification of analytical tools and codes, and (4) provide insights for the review of vendors' safety analysis and supporting data bases.

Farouk Eltawila, Director
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CONTENTS

LIST OF FIGURES

LIST OF TABLES

ACRONYMS

BLEVE	boiling liquid expanding vapor explosion
BOP	balance of plant
CTL	coal to liquids
DOE	Department of Energy
F-T	Fischer-Tropsch
FOM	figure of merit
H_2SO_4	sulfuric acid
HI	hydrogen iodine
HIPES	Hydrogen Intermediate and Peak Electrical System
HTE	high-temperature electrolysis
HTGR	high-temperature gas-cooled reactor
IHX	intermediate heat exchanger
INL	Idaho National Laboratory
NGNP	next generation nuclear plant
NIOSH	National Institute for Occupational Safety and Health
NRC	Nuclear Regulatory Commission
OSHA	Occupational Safety and Health Administration
PBR	pebble-bed reactor
PHHP	process heat and hydrogen production
PHX	process heat exchanger
PIRT	phenomena identification and ranking table
SMR	steam methane reformer
SNL	Sandia National Laboratory
SRNL	Savannah River National Laboratory
SO_2	sulfur dioxide
SO_3	sulfur trioxide
SSCs	systems, structures, and components
UVCE	unconfined vapor cloud explosion
VHTR	very high temperature gas-cooled reactor

1. INTRODUCTION

The next generation nuclear plant (NGNP) is being designed to demonstrate the role of next generation nuclear power systems in meeting the future U.S. energy needs, including providing alternate energy products for transportation or industrial uses. Nuclear plants currently provide base-load electricity but could also provide carbon-free high-temperature heat for process heat applications, including the production of hydrogen to meet transportation needs. Although current reactors can produce hydrogen through electrolysis, the Department of Energy (DOE) is examining potentially more efficient processes that use water, high-temperature heat, and electricity to produce hydrogen. The NGNP would produce that high-temperature heat.

The production of high-temperature heat for chemical processes involves new plant configurations and safety issues that must be considered in the safety evaluation for the NGNP. Unlike electricity, high-temperature heat can only be transported limited distances from the reactor to the chemical plant. This implies close proximity of the chemical plant and the nuclear plant. Equally important, the heat is transferred via an intermediate heat transport loop that directly couples the reactor to the chemical plant.

Although a range of applications is being considered with process heat being used for high-temperature chemical processing and other applications, the initial focus is on hydrogen production and the use of that hydrogen for many transportation and industrial applications. The hydrogen may be used for peak power production, coal liquefaction, and directly as a transport fuel. The advanced technologies currently being developed to produce hydrogen with nuclear energy are thermochemical cycles, hybrid cycles, and high-temperature electrolysis. These technologies require high-temperature heat and therefore would be located near the nuclear reactor. The nuclear chemical plant configurations being considered generally involve an intermediate loop to provide some degree of isolation from the process plant. Other isolation mechanisms being examined include separation distances and engineered berms. However, the coupling and proximity of the chemical plant introduces alternate heat and radiologic paths for interaction with the NGNP.

The phenomena of safety significance to the reactor that must be considered include (1) chemical releases, (2) thermal events on the chemical-plant process side, (3) failures in the intermediate heat-transport system, and (4) reactor events that impact chemical plant operations that, in turn, impact nuclear plant safety. This phenomena identification and ranking table (PIRT) for process heat and hydrogen was conducted to identify the events and phenomena that must be considered in evaluation the safety of the NGNP. The report is organized into four sections and two appendices.

- PIRT objectives and ground rules (Chap. 2).
- System description, including applications for the high-temperature heat that define the potential safety concerns for nuclear plant by its coupling to a chemical plant (Chap. 3).
- PIRT analysis (Chap. 4).
- Conclusions (Chap. 5).
- Applications for high-temperature heat (Appendix A).
- PIRT table (Appendix B).

2. PIRT OBJECTIVES AND GROUND RULES

The process heat and hydrogen production (PHHP) panel addressed the safety issues for the reactor that are a consequence of coupling the reactor to a chemical plant. This is in contrast to the other panels that examined phenomena within the nuclear plant. Some of the implications of that difference are described herein.

2.1 Objectives

The PIRT PHHP objectives are to (1) identify the safety-relevant phenomena that are introduced by coupling process heat or hydrogen production systems to the NGNP, (2) rank the importance of these phenomena in the assessment of the overall safety of the NGNP, and (3) assess the knowledge base.

Process heat applications and the generation of hydrogen introduce new issues not normally encountered when considering electrical generation. Not only are new phenomena involved depending on the process, but the approach to safety and response is often quite different. Containment of radionuclides vs dilution or dispersal of hazardous chemicals (hydrogen, oxygen, etc.) are examples of the differences in the approach and response to safety. The plant configurations that are driven by these philosophies are also dramatically different (outdoors vs confined). Key aspects that need to be accounted for are discussed below. These differences in approach were considered when setting the ground rules for the PHHP PIRT.

2.2 Ground Rules

There are several important ground rules associated with this activity.

The process heat and hydrogen applications are relatively early in development compared to the nuclear technology involved in NGNP. Candidate processes include high-temperature steam electrolysis and either the sulfur-iodine or the hybrid sulfur thermochemical cycle. All three of these technologies are still being developed, so the exact configuration of the coupled chemical plants is undetermined. Likely process stream temperatures, pressures, and compositions are generally known, but these could change with further developments. There are also other process options. Since the exact nature of the hazards is still somewhat ill-defined, the analysis considered generic applications, not detailed specific chemical flowsheets.

This is the first PIRT to address PHHP. As a consequence, emphasis was given on identifying safety challenges by categories that would help assure completeness. However, this strategy also limits the depth of analysis.

Mechanisms for failures were not considered. We assumed that events happened. This is not a probabilistic assessment. Importance was assigned based on importance in accident scenario—not based on probability of occurrence.

The figures of merit (FOM) or criteria for assessing the importance considered primarily effects on equipment or effects on people (workers, public) as primary consequences.

2.3 Nuclear Plant PIRT, Not Chemical Plant PIRT

The focus of this PIRT is on the nuclear plant and not on the hydrogen or chemical process plant. The PIRT is being conducted by the U.S. Nuclear Regulatory Commission (NRC). In the United States, different agencies have responsibility for nuclear plants and chemical plants. The U.S. NRC is responsible for nuclear plant safety. Chemical plant safety is the responsibility of the U.S. Environmental Protection Agency with a strong role played by the Occupational Safety and Health Administration and state regulatory agencies.

The process plant needs to be a distinctly separate entity from the nuclear plant because the appropriate safety philosophy for a conventional chemical process is different than that for a nuclear reactor. As will be further explained below (Sect. 2.5), the safety philosophy is radically different. It is not practical or even safe to attempt to handle chemical process upsets or accidents by containment—the basis of nuclear safety. Controlled release of confined material to the environment is the preferred alternative at chemical plants to a potentially catastrophic explosion. This fundamental difference in safety strategies implies that there is a natural split between the safety analysis for the nuclear plant and the chemical plant.

As a result of these differences, it is necessary to treat the chemical plant as an external entity. The PIRT is focused on the nuclear plant. The adjacent, coupled chemical plant may be capable of initiating events, such as hazardous chemical releases, that could impact the operation of the nuclear plant. Some of these events could occur independently of operations at the nuclear plant, while others could be initiated by upsets in the intermediate heat transfer loop. Therefore, the PIRT needs to consider the entire range of possible process plant incidents and accidents and prioritize those events in terms of their impact on nuclear plant safety. In that sense, then, it can be said that this is a nuclear plant PIRT, and not a chemical plant PIRT.

2.4 Unique Characteristics of Coupled Nuclear and Chemical Plants

The NGNP is being designed for the dual roles for the provision process heat and for the generation of electricity. In evaluating the phenomena that may occur and influence the safety of the NGNP, it is important to first consider the fundamental characteristics of those dual roles that differentiate the NGNP from earlier generations of reactors.

2.4.1 Close-coupled nuclear and chemical plants

The user of the process heat, be it a hydrogen production plant, a petroleum refinery, or other chemical plant, will be located close to the reactor. The proximity of the process-heat user to the reactor is dictated by the greater difficulty in transporting heat over any distance, as compared with the transmission of high-voltage electricity.

There is one other important difference between production of electricity and providing heat to chemical plants. The demand for electricity by millions of customers averages together into a smooth and fairly predictable demand curve for electricity when totaled over a region of the country. The variations in electrical demand can usually be met through gradual adjustment in the outputs of individual plants and through the operation of some plants as baseload and others as peaking units. In a system with one or two reactors providing heat to one or two chemical plants, heat production by the reactor must be matched with the chemical plant demand for heat. Chemical and nuclear plant startup, changes in power loads, and shutdowns will be strongly coupled. Thus the interaction between the process heat user and the reactor is far more important than the usually small influence of the individual electricity customer on the operation of reactors connected to the grid. Anticipated transients within the hydrogen production plant may require a scram of the reactor or the dissipation of the reactor's complete output to a heat sink. Conversely, a scram of the reactor will require the safe shutdown of the hydrogen plant within a few minutes or the engagement of a large auxiliary heat source to maintain hydrogen production.

As currently proposed, the NGNP will primarily produce electricity with ~10% of the heat sent to the hydrogen production plant. Because only a small fraction of the heat is going to the chemical plant, transients in the NGNP caused by changes in heat demand from the chemical plant will be less than in a commercial very high temperature reactor gas-cooled (VHTR).

2.4.2 Product characteristics

The process heat role of the NGNP is different from the generation of electricity because the chemical or hydrogen plant will be producing a physical product that will be distributed to the public. Thus the possible spread of radioactive contamination can extend wherever those physical products, (e.g., hydrogen, refined petroleum products, fresh water, steel) are distributed. The movement of any contamination will have to be strenuously controlled. This requirement is particularly true in controlling tritium diffusion through high-temperature materials to the intermediate heat transport loop and then to the chemical plant, because that tritium would be chemically indistinguishable from the hydrogen product.

2.5 Differences Between Nuclear and Chemical Plant Safety Philosophy

There is a fundamental difference in the safety design philosophy between chemical plants and nuclear plants, dictated by the nature of the hazardous materials that each plant handles. Nuclear reactors are designed to contain all fuel materials and to release coolants only under very controlled conditions. The reactor itself is enclosed in a massive concrete structure, and the response to any transient is to close all pathways for the release of radioactive materials, while transferring decay heat across intact boundaries.

In contrast, most chemical plants, particularly those plants and refineries processing combustibles, are built in the open. This open air construction prevents the accumulation of flammable or explosive concentrations. Small leaks from valves and flanges are allowed to escape, subject to regulatory limitations. In the event of a plant upset, the inventory of large vessels is often intentionally flared, releasing the combustion products to the atmosphere. Of course, this difference in design philosophy is motivated by the distinctions between chemical and radioactive hazards. Combustible materials are often voluminous, but their hazards are largely eliminated when burned. The quantities of radioactive materials are small, but no chemical process can eliminate that radioactivity.

The difference in safety philosophy between the nuclear plant and the coupled hydrogen or chemical process plant makes it necessary to separate their operations. Because inadvertent releases of hazardous chemicals are a possible consequence of serious upsets or accidents at a chemical plant, the coupled process needs to be situated far enough from the nuclear heat source such that safe operation of the nuclear reactor is not impacted by any conceivable calamity at the process plant. Should that prove to be impractical (e.g. due to excessive heat loss in the intermediate heat transfer loop), an earthen berm separating the two plants may be a suitable alternative. Hardening of the vital structures at the nuclear plant and remote location of specific chemical process operations that entail the highest risk of hazardous chemical release are other potential palliative measures.

Physical separation is only one aspect. It is likely that the hydrogen or chemical plant will be owned and operated by a different entity than the owner and operator of the nuclear plant. Furthermore, while the operation of the nuclear plant will be overseen by the NRC, the chemical plant will fall under the purview of the U.S. Environmental Protection Agency and the Occupational Safety and Health Administration (OSHA). This implies that different rules and procedures will be in effect at the two plants.

Consequently, the coupled hydrogen or chemical process plant should not be treated as an extension of the nuclear plant, but as an external facility that can impact reactor operation. The PIRT should consider chemical releases at the process plant as external events. Furthermore, it needs to take into account all possible interactions between the chemical process and the intermediate heat transfer loop, which provides the only direct connection between the two plants.

2.6 PIRT Process Description

The PIRT process is an expert elicitation methodology to identify what is important to safety. The methodology has been extensively used for nuclear systems. In the context of high-temperature reactors, they have been built, and there have been extensive safety studies (including PIRT analysis) of the reactor in the context of accidents initiated within the reactor. In contrast, there have been only limited safety studies[1] on the close coupling of high-temperature reactors with chemical plants where there is a strong coupling between the nuclear system and another industrial system. The PIRT evaluation is a multistep process.

The PIRT process was outlined in our introductory meeting by the NRC coordinator, Sudhamay Basu. It consists of nine steps that are discussed below.

Step 1—Define Issue Driving a Need for a PIRT

It is proposed to use the VHTR to provide process heat to industry and for the production of hydrogen. This implies close coupling of the reactor with the associated chemical plants. As a consequence, there are new safety issues associated with the interactions between the two plants and accidents within the chemical plant that can impact nuclear plant safety.

Step 2—PIRT Objectives

The major objectives are to identify the safety-relevant phenomena and knowledge base and rank them in an approximately quantitative way. Because the specific chemical plants to be coupled to the NGNP have not yet been defined, a broad-based strategy was adopted to be inclusive of expected long-term applications for high-temperature heat.

Step 3—Hardware and Scenarios

Hardware—There are three major systems: the NGNP, the intermediate heat transport system that moves heat from the reactor to the chemical plant, and the chemical plant. The general reactor

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[1] Y. Inagaki et al., "Research and Development on System Integration Technology for Connection of Hydrogen Production System to an HTGR," *Nuclear Technology*, **157**, 111–119 (February 2007).

characteristics are well defined. There are a limited number of intermediate loop options. There are many possible chemical plants.

Accident scenarios—Four classes of accident scenarios were defined. These were then broken into more detailed scenarios. The four categories are

- ***Chemical plant releases.*** This class of accidents includes both steady-state and accidental releases of chemicals from the chemical plants. Six classes of releases were defined: hydrogen, oxygen, flammables, corrosives, toxic gases, and asphyxiates.
- ***Process thermal events.*** This includes a wide variety of transients in the heat demand from the chemical plant.
- ***Heat transport system failures.*** This includes all accidents that result from failures of the intermediate loop. The accident scenarios go through the intermediate loop, whereas the chemical releases above refer to releases from the chemical plant that reach the nuclear plant via a plume.
- ***VHTR upsets.*** This class of accidents includes those initiated in the reactor that progress to the chemical plant with subsequent feedback events to the reactor creating the potential for a radiological release.

Step 4—Evaluation Criteria: Figure of Merit

The safety evaluation criteria at the top level are dose to the pubic. For the scenarios defined above, that routes to fuel damage are (1) direct damage to safety systems, structures, and components (SSCs) and (2) incapacitation of the operating crew. In many cases, the specific route to core damage is not well defined because the accident scenarios can damage many systems.

Step 5—Knowledge Base

The knowledge base for process heat and hydrogen systems is found primarily in the chemical industry that has different safety and regulatory strategies. In this context, much of the regulatory knowledge base is within the Environmental Protection Agency and other organizations.

Step 6—Identify All Plausible Phenomena

The major phenomena were identified and defined.

Step 7—Assign Importance Relative to Figures of Merit

Step 8—Assess Current Level of Knowledge

In most cases there is a large knowledge base, including a large experience base. However, in many cases this knowledge base has not been assembled for such applications.

Step 9—Documentation

The results are documented.

2.7 PIRT Panel Members

The members of the process heat and hydrogen production PIRT panel included Dr. Charles Forsberg of Oak Ridge National Laboratory, Dr. Maximilian Gorensek of the Savannah River National Laboratory, Dr. Stephen Herring of Idaho National Laboratory, and Dr. Paul Pickard of Sandia National Laboratories. This PIRT panel is one of several PIRT panels addressing NGNP safety phenomena. Other experts participated in some of the discussions, but voting was limited to the above members.

3. SYSTEM DESCRIPTION: HIGH-TEMPERATURE REACTORS, PROCESS HEAT APPLICATIONS, AND HYDROGEN PRODUCTION

The traditional application for nuclear energy has been the generation of steam, primarily for the production of electricity. Some reactors also sell steam for industrial users and district heat. VHTRs produce high-temperature heat that can be used as process heat for industrial applications and for the production of hydrogen. Unlike the production of steam for electricity production, many of these applications are for industrial facilities where accidents in the industrial facilities could impact the safety of the nuclear reactor. The other potential application of high-temperature heat is the production of hydrogen with its associated safety challenges. This creates a different set of safety challenges that must be examined to assure reactor safety under all credible events. This chapter briefly describes the reactor system, the potential applications, and the intermediate loop that couples the reactor with the chemical plant.

3.1 Reactor

The purpose of the NGNP is to provide process heat for a variety of needs, such as hydrogen production, chemical processing and petroleum refining, as well as for the production of electricity. The designs have evolved from the development of the high-temperature gas-cooled reactor (HTGR) in the United States and Japan and the pebble bed reactor (PBR) in Germany. The most recent ancestor of the HTGR is Fort St. Vrain in Colorado and the HTTR at Oarai, Japan. The most recent ancestors of the PBR are the THTR (1983–89) in Julich, Germany and a new small test reactor in China.

The NGNP is currently the subject of three separate design studies, so there is no definitive set of design parameters. Nevertheless, Table 3.1 lists the common parameters and the accepted ranges for others. It is proposed to be a helium-cooled, graphite-moderated reactor with an annular reactor core located below grade in a silo. The nuclear fuel particles will consist of uranium oxide or uranium oxycarbide kernels, about 0.5 mm in diameter, enclosed in layers of pyrolytic graphite and silicon carbide, followed by a second layer of pyrolytic graphite and a buffer layer of graphite. The overall particle diameter will be about 1.0 mm.

Table 3.1. Preconceptual design parameters for the NGNP

NGNP parameters	
Reactor type	Pebble bed or prismatic block
Reactor power	500–600 MW(t)
Primary coolant	Helium
Inlet temperature	350–490°C
Outlet temperature	850–950°C
Coolant pressure	7–9 MPa
Active core height	10–11 m
Inner core/reflector diameter	2 m
Outer core diameter	4 m
Side reflector outer diameter	6 m
RPV outer diameter	7 m
RPV length	30 m

The fuel would be contained within either hexagonal blocks or 60-mm-diameter spheres ("pebbles"). Two conceptual designs are being developed using the block (or "prismatic") arrangement, with teams led by AREVA and General Atomics. The pebble bed conceptual design team is led by Westinghouse.

3.2 Nuclear Process Heat and Hydrogen Production Applications

The NGNP strategy is the development of a private-government partnership to build the NGNP demonstration plant. As a consequence, the final NGNP design objectives will be jointly determined by the government and private partners. Potential applications will determine the types and kinds of chemical plants that are coupled to the NGNP as part of the demonstration program. This implies that many different types of chemical plants may be coupled to the NGNP over its lifetime to meet different needs. This section describes the currently identified potential applications for nuclear process heat and hydrogen production that, in turn, define the safety challenges.

There are multiple methods to produce hydrogen using heat, heat and electricity, and electricity using nuclear energy. Table 3.2 lists some of the mainline hydrogen production options that are currently being investigated.

Table 3.2. Partial list of nuclear hydrogen production options

Process	Primary nuclear plant inputs	Chemical plant inputs	Outputs	Chemistry (chemicals in inventory)
Steam reforming of natural gas[a]	Heat	Natural gas Water	H_2 CO_2	$CH_4 + H_2O \rightarrow CO + 3H_2$ $CO + H_2O \rightarrow H_2 + CO_2$
Electrolysis	Electricity	Water	H_2, O_2	$2H_2O$ (water) $\rightarrow 2H_2 + O_2$
High-temperature electrolysis	Heat, steam, electricity	Steam	H_2, O_2	$2H_2O$ (steam) $\rightarrow 2H_2 + O_2$
Hybrid-sulfur	Heat, electricity	Water	H_2, O_2	$2H_2SO_4 \rightarrow 2SO_2 + 2H_2O + O_2$ (Heat in at 850°C) $2H_2O + SO_2 \rightarrow H_2 + H_2SO_4$ (Electricity)
Sulfur-iodine	Heat	Water	H_2, O_2	$2H_2SO_4 \rightarrow 2SO_2 + 2H_2O + O_2$ (Heat in at 850°C) $2HI \rightarrow I_2 + H_2$ (Heat in at 450°C) $I_2 + SO_2 + 2H_2O \rightarrow 2HI + H_2SO_4$ (Heat reject at 120°C)

[a] Steam reforming of natural gas is the primary process used in the United States for hydrogen production. It is an endothermic process that requires heat. Traditionally this heat is provided by burning natural gas. With a nuclear hydrogen system, natural gas is still used for the hydrogen production, but the nuclear system provides the external heat source.

The potential hazards from the hydrogen plant are identified by the chemical plant inputs, chemical plant outputs, and the process chemistry. All options involve handling of hydrogen. Most options (except steam reforming of methane with nuclear heat) involve production of oxygen as a byproduct. Steam reforming of methane with nuclear heat involves handling large inventories of methane—a flammable gas. For some processes, hazardous chemicals are used internally within the process and recycled within the process. Under accident conditions these chemicals may be released to the environment. Corrosive chemicals include sulfuric acid (H_2SO_4), sulfur dioxide (SO_2), sulfur trioxide (SO_3), and hydrogen iodine (HI). Chemicals such as iodine (I_2) and HI are also toxic. Depending upon the temperature and pressure, each of these chemicals can be a liquid, a mist, or a gas.

There are multiple markets for high-temperature nuclear process heat and hydrogen. The markets can have a strong influence on the safety challenges associated with co-siting a nuclear plant and hydrogen plant. For many of these applications, if nuclear hydrogen is available, there will be incentives to also purchase the oxygen byproduct and high-temperature heat.

The use and purchase of oxygen will likely require high-pressure oxygen pipelines to the nearby facilities and may imply oxygen storage. This creates a separate but coupled set of safety challenges for the nuclear-hydrogen plant. The choice of which hydrogen production technology to use may be partly determined by the demand for oxygen. Equally important, if there is a demand for oxygen, the hydrogen plant design is likely to be different than when oxygen is a waste that is released to the atmosphere. If oxygen is to be used, the hydrogen plant will be designed to produce and maintain the oxygen at high pressures to avoid expensive compression of oxygen. This impacts the inventories and conditions (pressure and temperature) of the oxygen within the hydrogen plant and may also impact inventories and conditions of other process chemicals within the hydrogen plant. This, in turn, impacts the potential safety issues associated with a hydrogen plant next to a nuclear plant.

If heat is also required by the industrial customer, this implies relatively close siting of the chemical plants to the nuclear plants and other associated safety challenges. Table 3.3 summarizes some of these markets.

Table 3.3. Markets for high-temperature process heat, hydrogen, and oxygen production

Use	H_2	O_2	Heat
Pipeline	X		
Chemical-steel	X		
Oil refinery	X	?	X
Liquid fuels from coal	X	X	X
Shale oil			X
Peak electricity production	X	X	X

There is an important economic factor that will favor nuclear-hydrogen applications that require hydrogen, oxygen, and heat.[2]

The production of hydrogen using nuclear energy is in competition with hydrogen produced from fossil fuels and other energy sources. If the customer only needs hydrogen, the choice of hydrogen production technology will be based on the cost of hydrogen ($/kg hydrogen). However, if the customer

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[2] C. W. Forsberg, *Competitive-Advantage Markets for Hydrogen from Nuclear Energy: Peak Electric Power, Liquid Fuels from Coal and Biomass, and Refineries*, Oak Ridge National Laboratory (in press).

needs hydrogen, oxygen, and heat, the costs of all three will be considered. Consider a case where the choices are using nuclear energy or natural gas to meet all three needs.

- ***Natural gas.*** If the customer chooses a plant to convert natural gas to hydrogen, the customer must also buy a plant to separate oxygen from air and furnace to produce heat form natural gas.
- ***Nuclear.*** If the customer chooses a nuclear hydrogen plant, the plant produces hydrogen and byproduct oxygen. The nuclear plant can also produce heat where the cost of heat from a nuclear plant is generally about half or less than heat from natural gas.

In the above examples, nuclear hydrogen will become competitive first in those markets where there is a need for hydrogen, oxygen, and heat. Consequently, there is a high likelihood that the first commercial markets for nuclear hydrogen will be markets where (1) oxygen, (2) heat, and/or (3) oxygen and heat are also needed. This economic factor has also potential implications on what types of plants are coupled to the VHTR and to the NGNP—the test bed for using nuclear energy to supply high-temperature heat for chemical plant operations. Appendix A further describes some of these markets and thus other chemical plants that may be ultimately associated with using process heat from a VHTR. The characteristics of these other chemical plants have implications for VHTR safety, and thus this will need to be considered as future plants are built.

3.3 Intermediate Loop and Heat Exchanger Description

Hydrogen production using a high-temperature reactor requires the efficient transfer of the high-temperature heat from the primary reactor coolant to the thermochemical or electrolytic process. It is anticipated that the heat source and the hydrogen process plant will be coupled through an intermediate heat transfer loop that provides the desired degree of isolation between nuclear and hydrogen production plants. The NGNP demonstration plant is a dual-purpose demonstration plant that initially may send 10% of its heat to a hydrogen production plant and the remainder of the heat to a power cycle for electricity production. It is recognized that future commercial plants may be single- or dual-purpose configurations depending on market requirements. At this stage of nuclear hydrogen development, the evaluation should consider both options.

The high-temperature intermediate loop poses unique challenges in materials, heat exchanger design, safety, and supporting system designs. There are system interface technical challenges and safety implications for both thermochemical and high-temperature electrolysis approaches, but thermochemical safety issues are viewed as enveloping most of the key concerns. Hydrogen or process heat plants involve high temperatures (600–950°C) and often involve corrosive or toxic chemical species. The highly corrosive species involved in some processes require innovative design approaches and possibly development of new materials. The use of ceramic or clad components to take advantage of higher corrosion resistance is likely for many high temperature processes. The safety implications of the new materials, and design approaches, and collocation of the combined nuclear and process plants also pose new considerations. Evaluation of the safety and regulatory implications for candidate processes will be an important consideration in process selection.

3.3.1 Working fluid options

The options for working fluids to transport heat up to 950°C over significant distances are currently considered to be liquid salts (fluorides or chlorides) and inert gases. The working fluid and the design of the loop and heat exchangers will significantly impact heat transfer efficiency, pressure drops, and pumping requirements. Intermediate loop designs will attempt to minimize pumping power losses and maximize thermal efficiency and be constructed of cost-effective materials. The use of liquid salts as an intermediate loop working fluid could significantly reduce pumping power requirements and the size and cost of the intermediate loop in comparison with helium, but materials issues pose significant challenges at these temperature. These engineering factors indicate that liquid-salt heat transport systems have lower relative capital costs and energy consumption as the transport distances increase; thus, the choice of heat transport fluid will be partly determined by the distances heat must be transported. The baseline option is helium; but, no definitive decisions have been made.

3.3.2 Intermediate loop configurations

The primary configuration being considered involves an intermediate loop with parallel or concentric pipes (hot leg internal to cold) to transfer heat. The intermediate heat exchanger (IHX) between the reactor side and the intermediate loop is a significant challenge at these temperatures. Materials strength and creep at 900°C for helium loops, and materials corrosion (and strength) for the liquid salts are key issues. The primary heat exchanger operates very near the outlet temperature of the reactor and must be designed to nuclear standards, and function in very high temperatures and significant pressure differentials. Optimum designs would minimize requirements for new materials development. Process side heat exchangers (PHX) are needed that survive 900°C and highly corrosive acid working fluids. Innovative designs using ceramic or clad components are needed that are not only highly effective but are reliable and durable in the chemical environment.

No decisions have been made about the operating pressure of the intermediate loop. It may be the same pressure as the reactor primary loop or at a significantly different pressure. A helium loop must be operated at moderate or high pressure to minimize pumping losses. A salt-cooled loop can operate at any desired pressure by installation of a pressurizer with an inert gas. The salts are essentially incompressible; thus, the gas pressure in the pressurizer determines system pressure. The details of the chemical plant will in many cases determine pressures. In some cases the strength of corrosion-resistant materials will require lower pressures in intermediate heat-transport loops. In other cases higher pressures will be desired to maximize heat transfer. In some chemical reactors the rate of chemical reactions and the size of the chemical reactor are determined by the rate of heat transfer through the process heat exchanger. High-pressure helium is less efficient in heat transfer than low-pressure liquid salts; consequently, in some chemical systems the use of helium heat-transfer systems increases the size of process equipment in the chemical plant.[3] Consequently, the choice of intermediate loop fluid may be determined partly by chemical plant requirements.

The IHX and PHX are both critical components that provide pathways for communication of thermal and materials between plants—thereby introducing additional considerations into the safety evaluation of the NGNP. All sources of potential interaction between the plants must be considered to define separation and isolation criteria and assess regulatory requirements. Codes and guidelines relevant to the combined plant need to be assessed and issues identified.

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[3] D. F. McLaughlin et al., "Hydrogen Costs for the PBMR Thermal Reactor and the Westinghouse Process," 2005 American Institute of Chemical Engineer's Annual Meeting, Cincinnati, Ohio, 2005.

4. SCENARIOS, EVALUATION CRITERIA, PHENOMENA, AND EVALUATIONS

The Process Heat and Hydrogen Production Panel developed the PIRT evaluation using the following strategy.

- The types of accident events that were possible were identified, and the qualitative result or direct consequence of that event was estimated (i.e., H_2 release from a process plant failure, primary helium blowdown from an IHX failure). The question being addressed was what kind of challenge to the NGNP could this event cause?
- The next step was to examine the phenomena that controlled the severity of the potential insult or impact on NGNP. The characteristics of released materials, conditions associated with the release, magnitude of the thermal event, and potential timing all were considered in defining the magnitude of the potential threat to NGNP.
- The final step was to evaluate the potential impact on the NGNP resulting from that event. The impacts on the NGNP were generally categorized as effects on safety related plant equipment or systems, or the impact on people, workers, workers with safety related functions, or the public.

The importance of any phenomenon was rated high (H), medium (M), or low (L) based on the following considerations.

- If the material release or thermal event could potentially effect the likelihood or severity of core damage, then it was considered high importance
- If the event would impact operations or contribute to other safety-related events—but not strongly impact the severity of an accident, then it was medium importance
- If the event was considered to primarily impact operations, but have limited effects on the reactor, or workers, then it was low importance

The knowledge base estimate was a combination of expert opinions on the status of the tools and data available for quantifying these accident sequences and consequences at the current stage of development.

- If the tools and data base were considered available now—the knowledge base was considered adequate to perform the safety analysis—and it was rated high. If either the tools or the database was considered incomplete in some area, it was rated medium. If one or both were missing and the analysis required significant R&D to establish the basis, it was rated low.

Table 4.1 summarizes the results of the PIRT analysis. The accident scenarios were broken into four major classes: (1) accidents at the chemical plant that could impact the neighboring nuclear plant via the atmosphere (explosions, fire, gas releases), (2) process thermal events in the chemical plant that could impact the reactor by changes in heat demand, (3) failures of the intermediate heat-transport system between the reactor and the chemical plant that could impact nuclear plant safety, and (4) accidents in the nuclear plant that could impact chemical plant conditions resulting in a chemical plant accident or other event that further impacted the nuclear plant. This chapter and the PIRT assessment are organized by these four categories.

Table 4.1. Summary process heat and hydrogen PIRT chart

	Event	Evaluation criterion	Issue (phenomena, process, etc.)	Importance[1]	Knowledge base[1]
Chemical releases	H_2 release	Damage of SSCs	Blasé effects Heat flux	M L	H M
		Operator impairment	Burn and heat flux to people (VHTR operators)	L	M
	O_2 release	Damage of SSCs	Plume behavior Allowable concentrations Spontaneous combustion	H H H	H M M
		Operator impairment	Burn to VHTR operators	M	M
	Flammable release	Damage of SSCs	Plume behavior Heat flux Blast effects	M M M	H H H
		Operator impairment	Burns to people	M	H
	Corrosive release	Damage of SSCs	Plume behavior Allowable concentrations	M M	H M
		Operator impairment	Burns to people	M	M
	Toxic gas release	Operator impairment	Plume behavior Toxic concentrations and effects	M M	M M
	Suffocation gas release	Damage of SSCs	Plume behavior Backup power/O_2 concentrations	M M	H H
		Operator impairment	Concentration for people	M	H
Process thermal events	Loss of heat load	Damage of SSCs	Loss of heat sink to reactor	M	M
	Temperature transient	Damage of SSCs	Cyclic loading Harmonics	M L	M M
Heat transport system failures	IHX failure (intermediate heat exchanger)	Damage of SSCs	Blowdown effects, large mass transfer, pressurization of either secondary or primary side	H	M
	PHX failure (process heat exchanger)	Damage of SSCs	Fuel and primary system corrosion	H	M
	Mass addition to reactor (He)	Damage of SSCs	Turbomachinery response; potential for N_2 He mixture	M	M
	Mass addition to reactor (hydrogeneous material, e.g., steam)	Damage of SSCs	Reactivity spike due to neutron thermalization. Chemical attack of TRISO layers and graphite	H H	M M

Table 4.1 (continued)

	Event	Evaluation criterion	Issue (phenomena, process, etc.)	Importance[1]	Knowledge base[1]
	Loss of intermediate fluid	Damage of SSCs	Loss of heat sink; cooling, then no heat sink; IHX hydrodynamic loading	H	M
VHTR events that impact chemical plant	Anticipated operations: tritium transport (long-term safety)	Dose to VHTR plant workers.	Diffusion of ^{3}H	L	H
		Dose to process gas users: industrial and consumers.	Diffusion of ^{3}H	L	H
	Radiologic release pathways through HX loops and plant	Dose to public	Accident radionuclide release	M	M
	Generic power or thermal transients initiated in VHTR	SSC, stress on IHX or other component in contact with BOP	Stress causes stress on other SSC component	L	M

[1] H, M or L (high, medium, or low).

4.1 Chemical Releases

Plants that use process heat from a nuclear reactor for production of hydrogen or other purposes can have normal or accidental releases of gases that can impact reactor safety by multiple mechanisms. The potential impact on reactor safety depends upon the particular gas or vapor, the quantity, and the plume properties. Analysis of chemical releases is chemical plant specific. The hazards described herein apply to some but not all possible chemical plants. A summary of the PIRT analysis for this class of events is shown in Table 4.2.

For accident analysis, both normal and accidental chemical plant releases must be considered. Chemical plant experience shows that the most dangerous accidents beyond the plant chemical boundary are usually associated with the release of a heavy ground-hugging plume that can flow off-site. For such accidents, the plume behavior, inventory, and factors such as relative elevations of the chemical plant and nuclear plant are critical factors in any safety analysis. Six classes of releases were addressed by the PIRT panel and are described within this section.

Chemical releases can impact nuclear plant safety by three mechanisms. The first is an explosion at the chemical plant that creates shock waves that can damage reactor systems. The second is fire at the chemical plant that creates high heat fluxes onto the reactor plant. The third is migration of a gas or aerosol from the chemical plant to the nuclear plant. Historically, most catastrophic chemical plant accidents with off-site consequences have involved the third mechanism and thus the mechanism of most concern in terms of nuclear plant safety. It is a common concern in almost all chemical releases.

The potential for a chemical to be transported off the chemical plant site under accident conditions depends upon four factors: (1) the chemical, (2) the inventory, (3) the pressure before the accident, and (4) the temperature before the accident. For example, cold sulfuric acid does not usually present a significant risk beyond the chemical plant site; however, it can become a major potential accident source term if at high pressure and temperature where its release would form a plume or fine aerosol. In a number of hydrogen production processes, sulfuric acid is a gas at high temperature and pressure.

Table 4.2. Summary of chemical release events and PIRT assessment

Event	Evaluation criterion (figure of merit)	Issue (phenomena, process, etc.)	Importance[1]	Knowledge base[1]
H_2 release	Damage of SSCs	Blast effects	M	H
		Heat flux	L	M
	Operator impairment	Burn and heat flux to people (VHTR operators)	L	M
O_2 release	Damage of SSCs	Plume behavior	H	H
		Allowable concentrations	H	M
		Spontaneous combustion	H	M
	Operator impairment	Burn to VHTR operators	M	H
Flammable research	Damage of SSCs	Plume behavior	M	H
		Heat flux	M	H
		Blast effects	M	H
	Operator impairment	Burns to people	M	H
Corrosive release	Damage of SSCs	Plume behavior	M	H
		Allowable concentrations	M	M
	Operator impairment	Burns to people	M	H
Toxic gas release	Operator impairment	Plume behavior	M	M
		Toxic concentrations and effects	M	M
Suffocation gas release	Damage of SSCs	Plume behavior	M	H
		Backup power/O_x concentrations	M	H
	Operator impairment	Concentration for people	M	H

[1] H, M, or L (high, medium, or low).

In this context, the potential for a serious off-site release of a chemical in an accident is often determined by the Joule-Thompson effect. Because of the importance of this phenomenon in determining whether a chemical release can create an off-site plume that could impact nuclear plant safety, it is described herein. When gas pressure is suddenly reduced, the temperature of the gas changes. Whether the gas temperature increases or decreases depends upon the inversion temperature of the particular gas. The degree of cooling or heating depends upon specific gas, the initial pressure, and the initial temperature.

Under most conditions, the gas will cool. Oxygen has an inversion temperature of 477°C. Below this temperature oxygen gas cools as it is depressurized. If the oxygen cools sufficiently, its density will be greater than that of air. For many gases, if the pressure drop is sufficiently large, some of the gas will condense as a liquid. Standard techniques can determine the buoyancy of the gas that is released. This mechanism can create a concentrated ground plume that in still air flows downhill to lower elevations. Two gases have very low inversion temperatures: helium (24 K) and hydrogen (193 K). As a consequence, if these gases are released, above their inversion temperatures they heat up, become more buoyant, and disperse.

There are several general observations about all potential chemical plant releases.

- ***Plant layout.*** One of the most important design parameters for chemical plant safety is the plant layout. Chemical plants have separation distances between process units, so an accident in one unit does not result in an accident in the next unit. Storage facilities with large chemical inventories are separated from process units. Plants have berms around storage tanks and some process units to limit accident consequences. In terms of nuclear plant safety, the plant layout of the chemical plant with respect to the nuclear plant (distance, relative elevations, etc.) is the most important single safety system to assure chemical plant releases do not impact nuclear plant safety.

- ***Inventory.*** Since the Bhopal disaster with the release of a toxic heavy gas, there has been a general recognition that total hazards are tightly coupled to the total chemical inventories. In the context of nuclear plant safety, it implies that the risks from the chemical plants for the proposed NGNP will be much less than for a commercial plant. The current proposals for the NGNP are to connect it to small test-bed hydrogen production facilities with only small fraction of the energy that is produced by the reactor being sent to the chemical plant.
- ***Inherent safety.*** The chemical industry was worked to use inherent safety where possible. This is a strategy to design away accidents or reduce consequences by choosing operating conditions that minimize the consequences of accidents.

4.1.1 Hydrogen releases

The product of a nuclear hydrogen plant is gaseous hydrogen. In most cases, the hydrogen will be transported to storage sites or the customer by pipeline. In such cases, the site inventory will be limited. In some cases, hydrogen may be stored on site. Under such conditions there may be larger storage inventories. Table 4.3 shows the ratings and comments of the PIRT panel for hydrogen releases from the hydrogen production facility in terms of safety implications for the nuclear plant.

There are two figure of merit (FOM) or evaluation criteria. The first FOM is damage, wear, or impairment of the safety-related reactor plant SSCs because of (1) a hydrogen leak resulting in an explosion with blast effects on the nuclear plant or (2) a hydrogen leak resulting in a fire and the heat flux that could damage the nuclear plant. The second FOM is operator injury or impairment from burns.

The PIRT panel concluded that there was an intermediate importance associated with blast effects from hydrogen. Two panel members rated the importance as medium. One panel member rated the importance high—partly because of the historical perception that hydrogen is highly dangerous (the Hindenburg effect where a spectacular fire occurred while the Hindenburg Zeppelin was landing in New Jersey in the late 1930s). One panel member rated the importance low. The medium importance rating is a consequence of two factors: (1) the extreme buoyancy and diffusion of hydrogen that makes it difficult to create a large local hydrogen inventory in open air that could cause a major blast and (2) the wide combustion limits of hydrogen imply that hydrogen would likely ignite before a major inventory could form above a chemical plant and explode under accident conditions.

There is one implicit understanding among the panel members. Hydrogen in confined spaces is highly dangerous, but hydrogen outdoors presents far fewer hazards because it rapidly diffuses upward. Chemical plants manufacturing and using hydrogen are never enclosed in buildings or other structures for this explicit safety reason. This is a fundamental difference in the design of nuclear plants vs chemical plants.

The knowledge base was ranked high by all members of the panel because of (1) the widespread use of hydrogen in the chemical industry for almost a century and (2) the large experience base with hydrogen accidents. Hydrogen is used (1) to make ammonia, which is the primary fertilizer used in the United States and (2) in refineries to remove sulfur and convert heavy crude oil to gasoline, diesel, and jet fuel. As a consequence, there are numerous standards and technical conferences on hydrogen plant safety that reflect the importance of hydrogen plant safety for the chemical industry. There is also a massive experience base from real accidents.

Table 4.3. PIRT chart for hydrogen releases

FOM	Issue (phenomena, process, etc.)	Comments	Importance[1]					Rationale	Knowledge level[1]					Rationale
			C	M	P	S	A		C	M	P	S	A	
SSCs	Blast effects		M	L	H	M	M	C/S–high buoyancy and rapid diffusion of gas before it can explode P–political rationale, hydrogen explosions are politically sensitive—partly because a lack of a general understanding of hydrogen in confined spaces (inside buildings) vs outdoors in a chemical plant environment	H	H	H	M	H	C–large experience base (codes and experiments); ammonia plant experience (every 2 years a conference with an emphasis on "How to avoid hydrogen fires that burn down plant" S–methane and LNG studies M–extensive experience base; handling is very well understood; hydrogen accidents very well understood (explosion, flux, and burns)
	Heat flux		L	L	M	L	L	C–low infrared signature when hydrogen burns S–buoyancy and rapid diffusion	M	H	H	M	M	C–"Such a non-problem that has not been studied in great detail." S–codes and experiments mentioned above
Operator	Burn and heat flux to people (VHTR operators)		L	L	L	L	L	C–low infrared signature S–buoyancy and rapid diffusion	M	H	H	M	M	C–"Such a non-problem that has not been studied." S–primarily a hazard if confined by overhead or curtain wall structures

[1] H, M, or L (high, medium, or low).

The PIRT panel concluded that the importance of the heat flux from a hydrogen fire was low, with one panel member ranking it as having medium importance. Unlike hydrocarbon fuels, pure hydrogen flames emit low levels of visible and infrared radiation. The knowledge base was ranked as medium. Two panel members gave a medium rating, and two panel members gave a high knowledge rating. The knowledge level is at least medium because of (1) the widespread use of hydrogen in the chemical industry and (2) the large experience base with accidents. The difference in panel member assessments of the knowledge level partly reflects questions about whether the phenomena have been of sufficient importance to result in extensive studies of the phenomena. In this context, radiating heat from a hydrogen fire primarily depends upon heating some impurity in the air or impingement of the flame on a surface to create a high thermal flux.

All of the PIRT panel members concluded that the importance of hydrogen burns to operators at the nuclear reactor was low based on the factors above that apply to SSCs, the added factor that operators can move when they determine a hazard exists, and that the hazard to operators is primarily limited to operators outside the plant in the area between the reactor and chemical plant. The experience base is medium.

There is one caveat. If hydrogen is stored as a cryogenic liquid and accidentally released, it can form ground hugging plumes and create high hazards. Except for aerospace applications, hydrogen is generally used as a gas, and thus the above ratings apply.

4.1.2 Oxygen releases

A nuclear hydrogen plant (except for nuclear heat for steam reforming of natural gas) converts water into hydrogen and oxygen. Oxygen is the byproduct. The oxygen may be sold if there is a local market or it may be vented to the atmosphere. Oxygen that is sold may be transported to storage sites or to the customer by pipeline. In such cases, the site inventory will be limited to the inventories within the hydrogen process. Some processes, such as the hybrid sulfur cycles, have process inventories of oxygen at medium pressures and relatively low temperatures. For example, the hybrid sulfur process produces a mixture of oxygen and sulfur dioxide at moderate pressures and then uses a scrubber at medium pressure to remove the sulfur dioxide. The medium-pressure oxygen is then lowered to atmospheric pressure and released. There may be significant inventories of oxygen in the process, and thus the safety assessments must include this oxygen.

Oxygen is the one unique characteristic of a nuclear hydrogen plant from the perspective of chemical plants. Today we produce hydrogen by steam methane reforming (SMR)—a process that does not generate oxygen. The largest new SMR plant under construction today will have a hydrogen output roughly equal to the three-unit Browns Ferry Nuclear Power Station if all the electricity was used for electrolysis. That plant will produce hydrogen by steam reforming of natural gas and thus not produce oxygen. In terms of hydrogen production rates, a nuclear hydrogen plant will not be that different from existing hydrogen production plants. There is nothing unique or special about the quantities of hydrogen that will be handled. In contrast, there are no major facilities that potentially produce large quantities of oxygen as a byproduct. There are no major facilities today that release large quantities of oxygen to the atmosphere.

Table 4.4 is the PIRT chart for oxygen releases. Unlike other chemicals, oxygen may be continuously released to the atmosphere. Thus accident releases and normal releases must be considered.

Table 4.4. PIRT chart for oxygen releases

FOM	Issue (phenomena, process, etc.)	Comments	Importance[1]					Rationale	Knowledge level[1]					Rationale
			C	M	P	S	A		C	M	P	S	A	
SSCs	Plume behavior	Ground hugging gas movement? Oxygen may be released during normal operation so there is also a significant concern about routine nonaccident behavior.	H	M	H	H	H	C–Do long-term oxygen releases change local environment conditions with higher materials degradation or making the materials more flamable by chem. absorption of oxygen? P–importance of plume issue; want to know where the O_2 goes; worst case is low temperature release. M–small inventory, but possibility of plume is important.	H	H	H	M	H	S–need better modeling of effects of structures on flow and mixing. C–models are approximate plume behavior. P–the tools and knowledge are available; models do not have any new physics or considerations M–such extensive experience with working with O_2 in industry; understand effects on equipment well.
	Allowable concentrations	What oxygen levels cause damage?	H	M	M	H	H	C–high, partially over concerns over both accident and long-term elevated levels; is there a chance of locally high concentrations in NGNP that are higher than designed for? Are we changing chemical properties of equipment, I&C, and people if locally high O_2 concentrations? P–importance of plume issue; want to	L	H	H	M	M	S–question is really one of what flammable material is present and what are ignition sources. P–the tools and knowledge are available; models do not have any new physics or considerations. M–such extensive experience with working with O_2 in industry; understand effects on some equipment as well.

Table 4.4 (continued)

FOM	Issue (phenomena, process, etc.)	Comments	Importance[1]					Rationale	Knowledge level[1]					Rationale
			C	M	P	S	A		C	M	P	S	A	
								know where the O_2 goes; worst case is low temperature, release. M–small inventory, but possibility of plume is important.						
	Spontaneous combustion	What levels cause spontaneous combustion?	H	M	M	H	H	S–May not easily dispersed if released in large quantities. P–Importance if plume issue; want to know where the O_2 goes; worst case low-temperature release M–small inventory but possibility if plume important.	M	H	H	M	M	S–Question is really one of what flammable material is present and what are ignition sources. P–The tools and knowledge is available; models do not have any new physics or considerations.
Operator	Burn to people		M	M	L		M		H	H	H		H	C–hospitals have large accident knowledge of oxygen use.

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[1] H, M, or L (high, medium, or low).

There are two FOM or evaluation criteria. The first FOM is damage, wear, or impairment of the safety-related reactor plant SSCs because of (1) oxygen causing a fire or (2) oxygen degrading equipment over time. The second FOM is operator injury or impairment from burns.

The PIRT evaluation concluded that there was a high importance associated with oxygen releases from the hydrogen plant; three of the four members of the PIRT panel concluded that there was a high importance associated with oxygen releases from the hydrogen plant and the associated plume behavior. The fourth panel member rated the importance as medium.

The high importance rating is a consequence of several factors: (1) nuclear hydrogen plants will produce massive quantities of pure oxygen, (2) if oxygen escapes from the chemical plant it will cool as it is depressurized and thus potentially (depending upon temperature and pressure within the process plant) create a heavy gas cloud that can flow at ground level to the reactor, (3) spontaneous combustion for many materials becomes likely with pure oxygen, and (4) materials such as steel that are normally considered as noncombustible can burn in an oxygen atmosphere if ignited.

There is also a secondary concern. If the process plant is continuously releasing oxygen, there is the potential for locally higher oxygen concentrations that may have secondary impacts. The potential quantities of oxygen are greater than have been previously handled, and for some applications the oxygen may be stored in very large quantities. In terms of nuclear plant safety, the critical questions are the inventories, temperatures, and pressures of the oxygen. These determine plume characteristics.

The knowledge base for plume behavior was rated as high with three of the four panel members rating the knowledge base as high and the fourth panel member rating the knowledge base as medium. There is some concern about modeling plume behavior in complex systems—particularly nuclear systems where some types of passive safety systems have natural circulation of air to cool the reactor and are driven by heat from the reactor.

The importance of the allowable concentrations of oxygen in terms of nuclear plant structures, systems, and components was rated high with two of the panel members rating the allowable oxygen concentration of high importance and two of the panel members rating the allowable oxygen concentration of medium importance. It was assessed that there was a medium level of knowledge about the allowable concentrations of oxygen in terms of safety impacts on structures, systems, and components with three members of the panel assessing the knowledge level as high and one panel member assessing the knowledge level as low.

There is a massive knowledge base from the oxygen industry and from the use of oxygen in hospitals. However, there is a consensus concern by the panel about the possible impacts of long-term locally elevated levels of oxygen from the continuous release of oxygen from the hydrogen production facility. Oxygen, like other gases in the atmosphere, can be considered as a pollutant if the concentrations are significantly different from normal atmospheric levels. Oxygen permeates many materials, and increases in the oxygen content of materials could significantly change their characteristics in a fire and some of their other properties. Furthermore, oxygen accelerates degradation of most materials. The wide spread in panel member assessments of the knowledge base for safe levels of oxygen is based on this specific concern of the impacts of long-term exposures to oxygen—not ultrahigh oxygen levels as may be seen under accident conditions. There is no regulatory standard for release of oxygen because there never has been a need for such a standard.

If there are high concentrations of oxygen, there is a much higher probability that many materials will "spontaneously combust" from very small static discharges. The importance of this phenomenon was rated high with two of the panel members rating the phenomenon as having a high importance and two panel members rating the phenomena as of medium importance. It was assessed that there was a medium level of knowledge about the allowable concentrations of oxygen with two members of the panel assessing the knowledge level as high and two panel members assessing the knowledge level as medium. While the potential for spontaneous combustion in oxygen environments is known for many materials, there are a large number of materials where this characteristic is poorly characterized.

The PIRT panel evaluation concluded that the importance of oxygen release for the operators was medium, based partly on the fact that operators can move when they determine a hazard exists. The knowledge base was rated high because of the experience of the oxygen industry, the much larger scale experience with oxygen in hospitals, and the large research knowledge base developed for deep sea divers and astronauts.

4.1.3 Flammable releases

Water-splitting hydrogen production plants are not the only processes to produce hydrogen. Today most hydrogen is produced by steam reforming of natural gas. This is an endothermic process for hydrogen production where about 30% of the natural gas is used to produce high-temperature heat to drive the chemical reactions. There has been significant work on using high-temperature heat from nuclear reactors to assist this method of hydrogen production. Because the process involves large quantities of natural gas, some nuclear hydrogen processes have the potential for large-scale release of flammable gases. In addition, high-temperature heat from nuclear reactors is being considered as a heat source for oil refineries, shale oil and tar sands production facilities, and coal gasification and liquefaction processes. All of these involve the production of flammable gases and/or liquids in large quantities. Flammable fluids will be present in process streams at elevated pressures and at high (or low) temperatures. There will also inevitably be on-site storage of intermediates and products, possibly in large tanks.

Two FOM or evaluation criteria are identified as associated with flammable fluid releases. The first FOM is damage, wear, or impairment of the safety-related reactor plant SSCs because of (1) a leak of flammable fluid resulting in an explosion with blast effects on the nuclear plant or (2) a flammable fluid leak resulting in a fire with significant heat flux that could damage the nuclear plant. The second FOM is operator injury or impairment from burns.

Table 4.5 shows the ratings and comments of the PIRT panel for flammable releases from the coupled chemical process facility in terms of safety implications for the nuclear plant.

Table 4.5. PIRT chart for flammable releases

FOM	Issue (phenomena, process, etc.)	Comments	Importance[1]					Rationale	Knowledge level[1]					Rationale
			C	M	P	S	A		C	M	P	S	A	
Damage, wear, or impairment of SSCs	Plume behavior	How far away from leak explosion occurs (dispersion?)	M	M	M		M		H	H	H		H	Consensus: large experience base on accidents in industry
	Heat flux	Design of equipment should eliminate this mode. Carbon-based fire is serious. Carbon atoms (soot) radiate large heat fluxes.	H	M	M		M	C–heat flux tends to start cascading fires in neighboring components.	H	H	H		H	Consensus: large experience base on accidents in industry
	Blast effects	Fuel/air mixture dependent upon stoichiometric mixture, vaporization, conditions, etc.	M	M	M		M		H	H	M		H	Consensus: large experience base on accidents in industry
Operator injury or impairment	Burns to people	VHTR plant operators	M	M	M		M		H	H	H		H	

[1] H, M, or L (high, medium, or low).

The PIRT evaluation concluded that there was overall a moderate importance associated with flammable releases from the process plant for the safety-related reactor plant SSCs. The intermediate importance rating is a consequence of several factors: (1) flammable hazards can be situated far from the nuclear plant by design, (2) the magnitude of the potential fire or blast can be diminished by keeping local inventory at a minimum, (3) infrared radiation from hydrocarbon fires is more intense than from a hydrogen flame, and (4) the flammability envelope is smaller for hydrocarbons than it is for hydrogen. The PIRT panel also concluded that the knowledge base for flammable releases is high.

Three separate issues were considered with regard to damage, wear, or impairment of SSCs: plume behavior, heat flux, and blast effects.

Plume behavior determines how far from the source of the leak an explosion or flame can occur. When the gas or vapor density is greater than that of air, flammable concentrations can accumulate at low levels and travel away from the source. Plumes are capable of transporting flammable vapors a considerable distance, but the use of berms or other impediments to flow can reduce that risk. Remotely siting storage tanks and minimizing process vessel inventory are also effective ways to diminish the risk of plumes that could affect the nuclear plant. All three panelists who evaluated this hazard assigned it a moderate importance rating. The petroleum refining and chemical process industries have extensive experience with flammable releases, and there is a significant body of literature on the subject. Consequently, the panelists all rated the knowledge base as high.

Heat flux is arguably the most serious hazard posed by a flammable release. While hydrogen flames give off little thermal radiation, hydrocarbon flames have an intense infrared signature. As one panelist pointed out, the presence of carbon allows the formation of soot, which, when heated by flame, emits infrared radiation. The heat can be so intense that a burning fuel storage tank in a refinery can have a cascade effect, setting off fires in adjacent tanks unless a sufficient separation distance is maintained between neighboring tanks. The importance may be high within the boundaries of the chemical plant, but physical separation should be sufficient to lower the importance with respect to nuclear plant SSCs to a moderate level. Two of the three panelists who evaluated this hazard assigned it a moderate importance rating, with the third rated it as high importance. Because the petroleum refining and chemical process industries have extensive experience with flammable releases, there is a significant body of literature on the subject, so the panelists all rated the knowledge base as high.

The accidental release of a flammable gas or vapor could result in an unconfined vapor cloud explosion (UVCE). If the accidental release involves a liquid above its atmospheric boiling point, the result could be a boiling liquid expanding vapor explosion (BLEVE). Blast effects from an UVCE or BLEVE in the coupled chemical process plant could conceivably impact the nuclear plant through debris missiles or overpressure. As in the case of heat flux, this hazard is certainly of high importance within the process plant, but physical separation and appropriate use of earth berms should reduce its importance for nuclear plant SSCs. Consequently, all three panelists who evaluated it assigned it a moderate importance rating. The panelists also rated the knowledge base as high, based on extensive experience with flammable releases within the petroleum refining and chemical process industries and on the significant body of literature on the subject.

The PIRT evaluation concluded unanimously that the importance of flammable releases for the operators was also moderate based partly on the factors above that apply to SSCs and partly on the fact that operators can move whenever they determine that a hazard exists. The knowledge base was unanimously rated high because of the extensive experience of the oil and gas and the chemical process industries with personnel protection from flammable hazards.

4.1.4 Corrosive releases

The thermochemical processes being developed by the Nuclear Hydrogen Initiative for splitting water into hydrogen and oxygen all involve highly corrosive chemicals. For example, the two sulfur cycles that are the leading candidates for NGNP (sulfur-iodine and hybrid sulfur) share high-temperature vaporization and decomposition of concentrated sulfuric acid as a common process step. The sulfur-iodine cycle also uses iodine as a reagent in the Bunsen reaction, forming hydrogen iodide by reaction between iodine and sulfur dioxide. The hydriodic acid that results from the dissolution of hydrogen iodide in water is one of the strongest of the halide acids. Other cycles being considered, such as the calcium-bromine, also involve highly corrosive substances like bromine and hydrogen bromide. This implies that the accidental release of corrosive liquids and vapors in the coupled chemical process needs to be considered for the PIRT.

Table 4.6 shows the ratings and comments of the PIRT panel for corrosive releases from the coupled chemical process facility in terms of safety implications for the nuclear plant.

There are two FOM or evaluation criteria. The first FOM is damage, wear, or impairment of the safety-related reactor plant SSCs because of material corrosion. The second FOM is operator injury or impairment from chemical burns.

As noted in the discussion that follows, the panelists had a wide range of opinions on the importance and knowledge base for corrosive releases. This is at least partly due to the fact that the actual thermochemical cycle that will be used to produce hydrogen has yet to be decided. While hydrogen and oxygen will be present in the water-splitting process, the other details are still being worked out.

The PIRT evaluation concluded that there was overall a moderate importance associated with corrosive releases from the hydrogen plant for the safety-related reactor plant SSCs. The intermediate importance rating is a consequence of several factors: (1) corrosive hazards can be situated far from thenuclear plant by design, (2) the magnitude of the potential corrosion hazard can be diminished by keeping local inventory at a minimum, and (3) corrosion acts over longer time scales so appropriate action can usually be taken before the damage has serious consequences. The PIRT panel also concluded that the knowledge base for corrosive releases is high with respect to plume behavior, but moderate with respect to allowable concentrations.

Two separate issues were considered with regard to damage, wear, or impairment of SSCs: plume behavior and allowable concentrations.

Plume behavior determines how far from the source of the leak corrosive gases or vapors can move. When the gas or vapor density is greater than that of air, a corrosive cloud can accumulate at low levels and travel away from the source. Plumes are capable of transporting corrosive vapors a considerable distance, but the use of berms or other impediments to flow can reduce that risk. Remotely siting storage tanks and minimizing process vessel inventory are also effective ways to diminish the risk of corrosive plumes that could affect the nuclear plant. Panelists had diverging opinions as to the importance of plume behavior. Two assigned it low importance, while a third rated it as medium and the fourth as high. The *significantly higher (than air) density of sulfuric acid and hydrogen iodide were cited as justification for* the high importance rating. Plume behavior should be process-specific, leading to the moderate importance rating. Low ratings were justified on the basis of small inventories (especially for NGNP) with minimal opportunity for large leaks, and on the relatively long time scale for corrosion, giving ample time for corrective action. The consensus rating was conservatively set at medium.

Table 4.6. PIRT chart for corrosive releases

FOM	Issue (phenomena, process, etc.)	Comments	Importance[1]					Rationale	Knowledge level[1]					Rationale
			C	M	P	S	A		C	M	P	S	A	
Damage, wear, or impairment of SSCs	Plume behavior	Ground hugging gas movement?	M	L	L	H	M	S–acid and HI are much heavier than air. C–process specific. M–Small inventories minimize. Opportunity for large leaks. P–longer term effect; these things will not happen quickly.	H	H	M	H / L	H	S–is chemical dependent. M–extensive industrial data base
	Allowable concentrations	What chemical levels cause damage?	M	L	L	M	M		M	H	M	L	M	S–low for HI and high for sulfuric acid
Operator injury or impairment	Burns to people	VHTR plant operators	L	L	M	H	M	C–people sense corrosives. Example: hydrogen sulfide and cyanide are equally toxic, but more people die from cyanide since it is not “sensed” in time.	H	H	M		H	C–standard industrial chemicals

[1] H, M, or L (high, medium, or low).

Similarly varying ratings were also given for the knowledge base. Two panelists rated the knowledge base as high, primarily due to the extensive industrial database. A third panelist assigned the knowledge base a medium rating, while the fourth gave it a split, High/Low rating—high for sulfuric acid and low for hydrogen iodide. Taking these factors into account, the panel's consensus rating for the knowledge base was high.

The allowable concentration of a corrosive gas or vapor in air is the other consideration for damage, wear, or impairment of SSCs. Panelists had a split decision, with two assigning this issue medium importance, and the other two giving it low importance. Physical separation, inventory limits, and the long time scale over which corrosion takes place can be cited as supporting factors for the consensus medium importance rating. The knowledge base assessment also had a wide range: one high, one low, and two medium ratings. A medium rating for the knowledge base was set by consensus.

The PIRT evaluation consensus for the importance of corrosive releases for the operators was set at moderate based partly on the fact that people can take action and move when they sense the presence of a corrosive gas or vapor. Eye irritation, scratchy or dry throat, cough, choking sensation or tightness of breath, bad taste in the back of the mouth, and chemical odors can all be indicators of a corrosive agent. Individual panelists' assessments varied considerably, with two low, one medium, and one high rating. Only three panelists rated the knowledge base for operator injury or impairment due to corrosive releases. Two panelists gave a high rating, since the likely compounds are standard industrial chemicals with well-established and understood effects on humans, while the other assigned a medium rating. The consensus rating for the knowledge base was set at high.

4.1.5 Toxic gas releases

Some hybrid and thermochemical processes for the production of nuclear hydrogen have large inventories of toxic chemicals that are part of a cyclic process. The inventory of these materials is fixed by the plant design. For example, the sulfur iodine process has hydrogen iodine (HI) and iodine (I_2), both toxic chemicals. Under some accident conditions a toxic gas release can be generated. Other nuclear hydrogen processes, such as high-temperature electrolysis, do not have any significant toxic chemicals associated with the hydrogen production process. Many corrosive chemicals are toxic; however, in most cases their corrosive characteristics dominate the hazard. Corrosive chemicals are a hazard to both equipment and operators whereas toxic chemicals are primarily a hazard to the operator. Table 4.7 shows the PIRT chart for this hazard.

Some perspective can be provided by comparing the toxicity of some of the compounds that may be used in some processes relative to hydrogen fluoride. The National Institute for Occupational Safety and Health (NIOSH) exposure limits are iodine (I_2): 0.1 ppm (1 mg/m^3), hydrogen fluoride (HF): 3 ppm (2.5 mg/m^3); hydrogen bromide (HBr): 3 ppm (10 mg/ m^3); and bromine (Br_2): 0.1 ppm (0.7 mg/m^3). The immediate dangers to life and health concentrations are iodine (I_2): 2 ppm; hydrogen fluoride (HF): 30 ppm; hydrogen bromide (HBr): 30 ppm; and bromine (Br_2): 3 ppm based on the NIOSH Pocket Guide to Chemical Hazards.

There is one FOM or evaluation criterion: operator impairment caused by poisoning of the operator by inhalation or sorption through the skin of the toxic chemical.

The PIRT panel evaluation concluded that toxic gas release was of intermediate importance because there will be instrumentation to detect such releases and the operator can take corrective action. There are two important phenomena.

Table 4.7. PIRT chart for toxic gas releases

FOM	Issue (phenomena, process, etc.)	Comments	Importance[1]					Rationale	Knowledge level[1]					Rationale
			C	M	P	S	A		C	M	P	S	A	
Operator	Plume behavior	Ground hugging gas movement?	M	L	H	H	M	S–heavier-than-air condenses on surface and maintains toxic levels. M–small inventories in use in NGNP. P–concentrations not high in NGNP, but toxic materials are present. Public question over toxic releases. Spread in answers sense differing judgments on toxicity levels of certain toxins present in accident.	H	H	M	L	M	S–three phase dispersion phenomena (harder to model). M–well understood phenomena (example, at former work, was necessary to employ dispersion models to understand toxic phenomena in the lab). P–knowledge is there, but details are not a common set of chemicals worked with. MSDS sheets may be well known, but the transport vectors are not well understood. Potential quantities are in ppm. We know about immediate toxicity, but not about low ppm toxicity for VHTR workers. C–the EPA, OSHA, and insurance company will force knowledge base before a build is licensed.
	Toxic concentrations and effects	VHTR plant operators	M	L	H		M		H	H	M	L	M	

[1] H, M, or L (high, medium, or low).

The first phenomenon is plume behavior. The primary hazard is the creation of a heavy gas plume that flows toward the nuclear plant. In terms of individual phenomena, the importance of plume modeling was rated medium with a split within the panel on the importance of the plume as a phenomenon. Two panel members rated plume behavior high, one panel rated plume behavior of intermediate importance, and one panel member rated it of low importance. There was a similar split among panel members about the knowledge base. Although the knowledge base associated with plume modeling is well understood, most of the potential toxic chemicals associated with hydrogen production will tend to sorb on surfaces and thus reduce the toxic gas concentrations. On the other hand, for some toxic chemicals relatively small concentrations can be extremely hazardous. The sorption of toxic gases on surfaces is highly dependent upon the specific chemical.

The second important phenomena are the allowable concentrations of toxic gases in terms of operator impairment. There is a caveat. There is a good understanding of toxicities for gases generally used in industry; however, the knowledge base is low for some of the chemicals proposed in some thermochemical cycles. However, if it is decided to commercialize a process with a specific toxic chemical where toxicity data are limited, the Toxic Substances Control Act and other regulatory requirements will require developing an understanding of the potentially toxic chemicals. In this context, the knowledge base should be obtained by regulatory agencies for the construction of a chemical plant.

4.1.6 Asphyxiate gas releases

Chemical processes often involve the use of gases (or vapors) that can be considered benign with respect to the hazards considered thus far, but that could adversely affect equipment operability and/or human health by displacing atmospheric oxygen. The pressurized helium fluid in the intermediate heat transfer loop is an example. A helium leak in a confined space could create an environment incapable of sustaining life and in which personnel would be incapacitated within seconds and would ultimately suffocate. Other potential asphyxiates that could be found in a chemical process include nitrogen and carbon dioxide. Displacing air with an inert gas could also incapacitate equipment. For instance, if diesel generators are needed for backup power in the event of a grid failure, they would be rendered inoperable by an inert gas plume at the air intake.

Table 4.8 shows the ratings and comments of the PIRT panel for asphyxiate gas releases from the coupled chemical process facility in terms of safety implications for the nuclear plant. There are two FOM or evaluation criteria. The first FOM is damage, wear, or impairment of the safety-related reactor plant SSCs because of oxygen displacement. The second FOM is operator injury or impairment from asphyxia.

The PIRT evaluation concluded that there was a moderate importance associated with asphyxiate releases from the coupled chemical plant for the safety-related reactor plant SSCs. The intermediate importance rating is a consequence of several factors: (1) suffocation hazards can be situated far from the nuclear plant by design, (2) the magnitude of the potential suffocation hazard can be diminished by keeping local inventory at a minimum, and (3) affected SSCs are limited to those that require an oxygen-containing atmosphere for proper operation. The knowledge base for the effect of asphyxiate releases on safety-related reactor plant SSCs was rated as high.

Two separate issues were considered with regard to damage, wear, or impairment of SSCs: plume behavior and oxygen concentrations needed for backup power systems.

Plume behavior determines how far from the source of the leak asphyxiates can move. When the gas or vapor density is greater than that of air, an invisible suffocating blanket can accumulate at low levels and travel away from the source. Remotely siting inert-gas storage and minimizing process vessel inventory are effective ways to diminish the risk of asphyxiate plumes that could affect the nuclear plant. Panelists had diverging opinions as to the importance of plume behavior. Two assigned it low importance, while the third rated it as medium. The possibility of plume formation and the resulting potential for incapacitation of auxiliary diesel power led to the moderate importance rating. Low ratings were justified on the basis of small inventories (especially for NGNP) with minimal opportunity for large leaks. The consensus rating was conservatively set at medium. All three panelists rated the knowledge base as high.

The importance of oxygen concentrations needed to operate backup power systems was also rated as medium.. The panelists gave a split decision, with two rating the importance as low and two as medium. A moderate importance rating presumes the use of auxiliary diesel power with the potential for incapacitation due to reduced oxygen concentrations by displacement with asphyxiate. (A separate issue is an oxygen release that would result in high oxygen levels that could have other impacts on diesel engine performance; see Sect. 4.1.2.) Low ratings were justified on the basis of small inventories (especially for NGNP) with minimal opportunity for large leaks. The consensus rating was conservatively set at medium. Again all voting panelists rated the knowledge base as high.

The PIRT evaluation concluded that the importance of asphyxiate releases for the operators was moderate, based on the fact that while the potential hazard can be easily mitigated by design and operating strategy, when asphyxia does occur, it can strike with no warning. Two panelists rated the importance as medium and one as low, making an intermediate rating the conservative choice. The knowledge base was unanimously rated as high because all potential suffocants are standard industrial chemicals with well-established safe handling procedures and well-understood effects on humans.

4.2 Process Thermal Events

Transients and failures in the chemical systems using the process heat are further separated from the reactor than those in the heat transport system and thus have a lower potential for core involvement. Therefore, they are considered of medium importance. Assuming that the heat transport system remains intact during a process system upset or failure, the reactor thermal transient will be mitigated by the thermal mass of both the intermediate coolant and the piping and heat exchangers. To identify the dominant phenomena that might be reflected back on to heat removal from the reactor core, two broad classes of process thermal events were evaluated: loss of heat load and temperature transients.

Table 4.8. PIRT chart for asphyxiate gas releases

FOM	Issue (phenomena, process, etc.)	Comments	Importance[1]					Rationale	Knowledge level[1]					Rationale
			C	M	P	S	A		C	M	P	S	A	
Damage, wear, or impairment of SSCs	Plume behavior	Ground hugging gas movement?	M	L	L		M	C–if safety-related air-based power systems (example: diesel start); location of diesel vs suffocation gas.	H	H	H		H	C–performance of combustion systems under low O_2 concentrations.
	Backup power/O_2 concentrations	Assume diesel generator part of safety system	M	L	L	M	M	C–if safety-related air-based power systems (example: diesel start); location of diesel vs suffocation gas.	H	H	M		H	C–performance of combustion systems under low O_2 concentrations.
Operator injury or impairment	Concentration for people	VHTR plant operators	M	L	M		M		H	H	H		H	

[1] H, M, or L (high, medium, or low).

- ***Loss of heat load.*** This class of events includes those failures and transients where the chemical plant reduces heat consumption with diminished heat removal from the intermediate loop. Heat is being used in endothermic chemical reactions. If, for any reason, the chemical feeds to these chemical reactors decrease the chemical reactors will use less heat and return the intermediate heat transfer fluid at higher temperatures.
- ***Temperature transients.*** Because of the complexity and interconnecting loops in a thermochemical hydrogen production cycle, there is the potential for heat to be added to the intermediate loop on a transient basis during some process heat systems upsets. These transients could also be intensified through maladjustment of the process control software in the process heat system.

The types and magnitude of the transients from the chemical plant that reach the reactor are strongly dependent upon the design of the intermediate loop and the choice of heat transfer fluid. With gas-cooled intermediate heat transport loops, thermal transients in the chemical plant will rapidly appear at the reactor because of the high velocities associated with gases in such systems. With liquid-cooled intermediate heat transport loops, thermal transients in the chemical plant will take longer to arrive at the nuclear plant because of the lower velocities associated with liquid flows in industrial systems.

For some types of liquid heat transport systems, transients will be highly damped before arrival at the reactor. The high volumetric heat capacity of liquids and their low pressure allows the use of heat storage tanks in the intermediate loop to dampen any thermal transient from the chemical plant to the nuclear reactor or from the nuclear reactor to the chemical plant. The extreme industrial example of this is the design of solar power towers that use a liquid salt heat transfer fluid from the solar collector to the steam generators that produce steam for the turbines. In these systems there are salt storage tanks that store several hours of flow by the salt to enable power production when the sun is not shining. The storage tanks decouple the solar power tower from electricity production. No decisions have yet been made on the choice of intermediate loop that will determine whether chemical plant upsets will be seen by the reactor.

Table 4.9 summarizes the two classes of events considered, the phenomena anticipated, the safety-related criteria, the importance to reactor safety, and knowledge levels in the current practice.

Table 4.9. Summary of process thermal events and PIRT assessment

Event	Evaluation criterion (figure of merit)	Issue (phenomena, process, etc.)	Importance[1]	Knowledge base[1]
Loss of heat	Damage SSCs	Loss of heat sink to reactor	M	M
Temperature transient	Damage of SSCs	Cyclic loading	M	M
		Harmonics	L	M

[1] H, M, or L (high, medium, or low).

4.2.1 Loss of heat load

The chemical process heat system will contain a complex range of piping, reaction vessels and control valves, very little of which will be designed, tested, or maintained to the standards of the nuclear reactor. The process heat system may also contain mixtures of chemicals whose interactions are not fully understood from past experience. Thus energy releases from the process heat system may result in damage, wear, or impairment of SSCs. The PIRT evaluation of these phenomena on reactor safety is shown in Table 4.10.

Phenomena/Criteria: The most severe transient in this class is a guillotine break in one of the chemical process loops to the chemical reactors that are supplied heat from the reactor. Once the chemical feeds are stopped, no heat is used by the process. It is assumed that the process fluid is lost and the highly endothermic chemical reactions absorbing the heat stop. The intermediate coolant would then return to the IHX with no heat removed, and the transient would be seen at a reduced scale in the primary coolant. If either the process fluid or the intermediate coolant is a compressed gas, the transient time would be short because of the high velocities associated with gas flows in industrial equipment. The transient times would be longer if liquids are used in both systems.

Importance: Because the loss of heat load in the process heat system is at a greater distance from the nuclear reactor, both physically and thermally, the importance of this class of event was judged to be medium. Furthermore, such loss of heat load transients would undoubtedly be one of the reactor design criteria. Finally, the thermal mass of the intermediate coolant and the associated heat exchangers would slow and mitigate the transient as seen by the reactor.

Knowledge: The level of knowledge of this transient was rated at high or medium by members of the panel. Those rating it high said that designers have good analytical capabilities of modeling a loss of heat load. Those rating the level of knowledge as medium said that there is very little operating experience with the chemicals and reactors involved in the process heat system.

4.2.2 Temperature transient

The chemical process heat system will contain reagents interacting through a complex series of endothermic and exothermic reactions. Some of the proposed hydrogen production flowsheets have batch operations where the heat demand by a single chemical reactor will change with time. In most cases, there will be multiple chemical reactors to provide a relatively constant demand for heat. However, the process characteristics and the complexity of the processes involved have the potential for starting and amplifying thermal transients. The PIRT evaluation of these phenomena on temperature transient is shown in Table 4.11.

Phenomena/Criteria: The criteria applied to these phenomena are the potential for damage, wear, or impairment of the reactor SSCs. Because this phenomenon is apt to be of smaller magnitude than the guillotine pipe breaks discussed above, the damage to SSCs may be of a long term and not immediately noted. The entire phenomenon may also be dismissed as an artifact of instrumentation or numerical oscillations in the control software until substantial damage has been done.

Importance: Because only a portion (~10%) of the heat output of the NGNP will be used by the demonstration scale process heat system, a transient in the process heat system is already well-diluted in its impact on the reactor. The panel all rated the importance of this phenomenon as medium or low.

The possibility of harmonics in the process heat system due to control-induced oscillations was discussed. Given that the heat load is well-separated from the reactor and that the damage to SSCs is more likely to be accelerated wear on BOP instrumentation, the importance of this phenomenon is low.

Table 4.10. PIRT chart for loss of heat load

FOM	Issue (phenomena, process, etc.)	Comments	Importance[1]					Rationale	Knowledge level[1]					Rationale
			C	M	P	S	A		C	M	P	S	A	
SSCs	Loss of heat sink to reactor	Guillotine break in loops, and coolant leaks out	M	M	M	M	M	C–potential for cooling then loss of heat sink if break in secondary loop coolant M–responses to this event are part of reactor design requirements P–thermal mass slows time response	H	M	M	H	M	M–some statistical experience in industry on these events happening S–Good dynamic modeling capabilities

[1] H, M, or L (high, medium, or low).

Table 4.11. PIRT chart for temperature transients

FOM	Issue (phenomena, process, etc.)	Comments	Importance[1]					Rationale	Knowledge level[1]					Rationale
			C	M	P	S	A		C	M	P	S	A	
SSCs	Cyclic loading	Concern about batch processes with cyclic heat demand: issue for materials panel. Note: These rankings could possibly be different if larger process heat loads are involved. Brinkman: There is a big difference between 10% and 100% thermal load from the cogeneration plant. Experience with HTR in Germany in 1980s. Thermal and pressure transients could complicate the design of the IHX. P–this is the most highly stressed component in the system. Potential propagation path for IHX failure. For PWR S/G component, which is experience with higher pressure on primary vs secondary side?	M	M	M	L	M	M–in NGNP only fraction of BOP will go into process heat (10%). P–cyclic stress on heat exchangers, but there is a damping effect. There are large thermal masses involved.	M	M	M		M	M–these situations are amenable to modeling. C–experience base on high-temperature exchangers is limited.

Table 4.11 (continued)

FOM	Issue (phenomena, process, etc.)	Comments	Importance[1]					Rationale	Knowledge level[1]					Rationale
			C	M	P	S	A		C	M	P	S	A	
	Harmonics	Coupling of chemical plant control system with NGNP. Paul and Max: Is this an issue? Is there a scenario where this could realistically occur? Since process heat only 10% of BOP goes to hydrogen plant, most goes toward the PCS. Thermal transients in VHTR or coupling system that could be amplified by the presence of the hydrogen plant and feedback into the reactor core, resulting in FPT.	L	L	L		L	C–slow harmonics more of a reliability/ economics issue than safety issue. P–difficult to think of this scenario with large heat sink reactors.	M	M	M		M	

[1] H, M, or L (high, medium, or low).

Knowledge: Many of the individual phenomena in a process are not well-understood. However, the theoretical understanding of oscillations and harmonics is fairly well-developed. Therefore, the panel classified the level of knowledge for this phenomenon as medium.

4.3 Heat Transport System Failures

Failures or upsets in the heat transport system can potentially have significant implications for core involvement and were therefore considered to have the potential to be of high importance. Events in the intermediate heat transport system, the IHX between the reactor helium and the intermediate heat transport fluid, or the PHX between the intermediate heat transport system fluid and the chemical plant process chemicals all have implications for thermal upsets or materials losses/additions to the primary reactor coolant system.

Many of the implications of the various heat transport system failures can be interrelated (heat exchanger failures could lead to loss of intermediate fluids, etc.). To comprehensively identify the controlling phenomena, failures in components were postulated, and the phenomenological implications of each failure were evaluated. Although this results in the identification of phenomena that may have already been discussed, it does assure completeness and consideration of subtle differences in the different paths. The range of heat transport events that could impact reactor safety was considered in several categories:

1. ***IHX failure:*** Depending on the specific configuration involved, the failure of an IHX includes events as severe as a direct compromise of the primary reactor coolant boundary. Failure of the IHX was considered to include events that could lead to primary or secondary blowdown, leakage paths from the secondary to the primary system resulting in mass additions or losses to or from the primary, and a range of thermal upset conditions.
2. ***PHX failure:*** Failure of the process heat exchanger involves the loss of a boundary between the process side in the chemical plant and the intermediate loop. This could lead to loss of heat load, material blowdown or additions to the secondary system, with the associated implications for the primary.
3. ***Mass addition to reactor (helium):*** Although the mass addition to the reactor would necessarily involve some compromise of the IHX, the effects of the helium addition, pressure and heat transfer capabilities should be considered independently of the failure mode that caused it.
4. ***Mass addition to reactor (hydrogenous material, e.g., steam):*** If mass additions to the primary system could potentially involve hydrogenous materials (water), the effects are potentially more severe. Reactivity and chemical interactions must be considered.
5. ***Loss of intermediate fluid:*** The loss of the intermediate working fluid potentially involves both pressure and thermal transient events for the primary system. Although the thermal and pressure transient will depend on the specific design, and the effects could be similar to other heat transport system failures, the event was considered separately since timing and pressure histories could be unique.

Table 4.12 summarizes the range of events that were considered, the key phenomena involved, the safety-related criteria, and the importance for reactor safety and the level of knowledge.

Table 4.12. Summary PIRT table for intermediate heat transport system failures

Event	Evaluation criteria	Issue (phenomena, process, etc.)	Importance[1]	Knowledge base[1]
IHX failure	Damage, wear, or impairment of SSCs	Blowdown effects, large mass transfer, pressurization of either secondary or primary side	H	M
PHX failure	Damage or impairment of SSCs	Fuel and primary system corrosion	H	M
Mass addition to reactor (helium)	Damage, wear, or impairment of SSCs	Turbomachinery response; potential for N_2/He mixture	H	H
Mass addition to reactor (hydrogenous material, e.g., steam)	Damage, wear, or impairment of SSCs (TRISO layers fission product confinement)	Reactivity spike due to neutron thermalization.	H	M
		Chemical attack of TRISO layers and graphite	H	M
Loss of intermediate fluid	Damage, wear, or impairment of SSCs	Loss of main heat sink; cooling, then no heat sink; IHX hydrodynamic loading	H	M

[1] H, M, or L (high, medium, or low).

4.3.1 IHX failures

The IHX is a critical component in the development of the NGNP thermal heat transport system. The high outlet temperatures challenge the limits of current, materials capabilities for strength and creep behavior. Any compromise of the IHX has direct implications for the integrity of the primary system. The IHX is a highly stressed component, and pressure and thermal transients may therefore have implications for safety not only in the near term but also in reducing margins in the longer term. The failure mode depends on construction and operational conditions but a range of severity of failures and the rates of mass transport or thermal transients were discussed. Table 4.13 summarizes the PIRT panel conclusions.

Phenomena/Criteria: Under the most severe conditions, failure of the IHX could potentially lead to rapid blowdown of the primary system, or potentially pressurization of the secondary side or containment. Other scenarios include blowdown of the secondary system and slower thermal or pressure events. Depending on the IHX design and the type of failure, the intermediate loop system and the intermediate working fluid could also be involved in rapid blowdown or pressurization events. The type of failure and the rate at which mass transport occurs and the timing of associated thermal and pressure transients must be considered in a comprehensive analysis to understand the effect on reactor primary or secondary system boundaries.

Importance: The importance of these IHX events was considered high because of potential to directly affect core cooling, primary system integrity, and radionuclide transport under accident conditions. If helium or another gas is the heat transport fluid in the intermediate heat transport system, the inventory in this system may be larger than the inventory in the primary reactor system. This has several potential implications.

- ***Rapid blowdown.*** Rapid blowdown events in the reactor with a major leak in the IHX imply that the blowdown events may be much longer because of the large intermediate loop gas inventory to be dumped to the primary system and then out of the reactor.
- ***Blowdown directions.*** Under many design options, the intermediate loop may be at lower pressure than the primary loop. An IHX failure dumps primary system helium into the intermediate loop that is outside containment. If there is a failure within that loop, it bypasses the containment systems. If the intermediate loop does not fail but there is an IHX failure and another primary system failure, primary helium may first flow into the intermediate loop and then flow out of the intermediate loop as the primary system depressurizes. Depending upon the leak size, this can significantly lengthen the blowdown time and increase radionuclide transport.

Table 4.13. PIRT chart for IHX failures

FOM	Issue (phenomena, process, etc.)	Comments	Importance[1]					Rationale	Knowledge level[1]					Rationale
			C	M	P	S	A		C	M	P	S	A	
Damage or wear of SSCs	Blowdown effects, large mass transfer; pressurization of either secondary or primary side.	Fluid hammer. Kevin Weaver: thermal and concentration gradients can work against the D/P such that chemicals can diffuse toward the IHX.	H	M	H		H	P–failure modes are equally important in both IHX and PHX. C–IHX is important because it is a boundary between the core and the secondary loop; small helium purge of a hot core. Small leaks more worrisome. Consensus: If salt intermediate loop, then no massive pressurization.	M	M	H		M	P–have models available that can handle these problems.

[1] H, M, or L (high, medium, or low).

- ***Small leaks.*** If there is a primary system failure with blowdown and a small leak in the IHX, the intermediate loop can provide a sweep gas through the reactor core to transport radionuclides from the reactor core for hours or many days after the start of the accident sequence.

Knowledge: The knowledge base status was considered medium. Most tools are available to perform the analysis and in some cases high-speed computing capabilities are available to address these issues at a level of resolution and sophistication not available in earlier safety analyses. However, these configurations and components are unique, and the specific conditions and configurations can be important in determining consequences and mitigation options. It was considered important to further characterize the conditions and apply state of the art tools to this analysis—therefore, the current status was designated.

4.3.2 PHX failures

The PHX is the interface between the intermediate loop (or reactor heat source if it is a direct cycle design) and the chemical process. For the thermochemical processes being considered by the Nuclear Hydrogen Initiative, the process heat exchanger may be an innovative design using ceramic or other materials to mitigate the corrosive nature of the process fluids. For the high-temperature electrolytic (HTE) processes, the interface heat exchanger is essentially a high-temperature steam generator connected through the intermediate loop. Although it is not considered likely for NGNP, it is conceivable that the HTE process could be configured without an intermediate loop, and, therefore, some consideration of hydrogenous materials was considered. Table 4.14 summarizes the PIRT panel conclusions.

Phenomena/Criteria: The types of failures discussed for the PHX included process side failures that could lead to loss of process fluids and therefore thermal loads, failures that could lead to a materials communication path between the process and intermediate loop, and failures on the intermediate loop side that could result in loss of intermediate loop working fluids. The phenomena that need to be considered include the pressure and thermal events similar to those resulting from other heat transport system failures, but also the unique issues of corrosion of the heat transport system and potentially the primary system if a failure propagates to the IHX. The mass transport, pressure and thermal issues are similar to the IHX failure in the types of tools needed. The differences include the possibility of additional chemistry issues, and corrosion issues that may lead to impacts on the integrity of the IHX, but with a longer time scale than direct IHX failures.

Importance: The importance of PHX failures was considered high because of potential to impact the primary system integrity. PHX failures could lead to rapid thermal and pressure transients, with potential impacts on the IHX, but also lead to slower, possibly corrosive environments that in the longer term could compromise both primary and secondary boundaries. In addition, PHX failures could result in a range of chemical releases that are covered in Sect. 4.1. Because there is potentially an impact on the primary system, even with slower time scales, the failures were considered to have high importance.

Knowledge: The designs and integrity of PHX designs and materials are considered to be at an early stage, and therefore the knowledge base status was considered M. The PHX designs that are currently being considered include innovative ceramic designs that must be evaluated for failure modes and impacts. Most tools are there to perform the analysis, and in some cases high-speed computing capabilities are available to address these issues at a level of resolution and sophistication not available in earlier safety analyses. However, these configurations and components are unique, and the specific conditions and configurations can be important in determining consequences and mitigation options. It was considered important to further characterize the PHX components and conditions and apply state-of-the-art tools to this analysis—therefore, the current status was designated M.

4.3.3 Mass addition to reactor

The base case that was considered for the intermediate loop heat transport system was a high-pressure helium loop with pressures similar to that of the NGNP. The use of N_2 or He/N_2 gas mixtures is also being considered. Depending upon pressures of the two systems, the intermediate heat transport fluid may leak into the primary system with any heat exchanger failure. While Sect. 4.3.1 discussed heat exchanger failures under accident conditions, there is a second set of failures within the reactor due to mass addition or the chemical species of the heat transport fluid as shown in Table 4.15.

Phenomena/Criteria: For a helium working fluid, the phenomena considered were pressurization (primary, containment) transient thermal or pressure effects on other heat transport components, and the response of turbo machinery associated with circulators or electrical generation. If He/N2 mixtures, or other mixtures were involved, the same issues arise but with the addition of the corrosion and heat transfer coefficient issues involved in the alternative gas mixture. The reactivity effect of the He additions (or loss) from the primary system was considered to be small and would not drive additional considerations.

Importance: The importance of helium mass additions was considered medium because of small reactivity potential and the limited threat to the primary system from that aspect alone. Mass additions could lead to rapid thermal and pressure transients, with potential impacts on the IHX, but based on likely inventories and pressure differences, these heat transport mass additions were not considered to be able to compromise primary, secondary, or containment boundaries.

Knowledge: The thermal and fluid dynamic tools to analyze helium mass additions are available and capable of addressing these phenomena. The knowledge base was designated medium because the configurations, flow paths, and pressure characteristics are not well defined at this point in time. The configurations and components are unique, and the specific conditions and configurations will be important in determining consequences and mitigation options. It was considered important to further characterize the mass addition scenarios and effects on heat transport components and apply state-of-the-art tools to this analysis—therefore, the current status was designated medium.

Table 4.14. PIRT chart for PHX failures

FOM	Issue (phenomena, process, etc.)	Comments	Importance[1]					Rationale	Knowledge level[1]					Rationale
			C	M	P	S	A		C	M	P	S	A	
Damage or impairment of SSCs	Fuel and primary system corrosion.		M	H	H		H	P/M–PHX failure would precipitate problems in IHX; more critical. It is a unique threat to IHX; ultimate impact would be on IHX.	M	L	M		M	P–novel PHX designs at this point do not yet exist; no experience base.

[1] H, M, or L (high, medium, or low).

Table 4.15. PIRT chart for mass addition to reactor

FOM	Issue (phenomena, process, etc.)	Comments	Importance[1]					Rationale	Knowledge level[1]					Rationale
			C	M	P	S	A		C	M	P	S	A	
Damage, wear, or impairment of SSCs	Turbomachinery response; potential for N_2/He mixture. Brinkman: potential for nitride effects on material properties.	Rapid change in the load for the turbo-machinery and the dynamic response.	M	M	M		M	C–what will N_2do to heat transfer and combinations? How will it affect thermal transients in the core? P–in PCS and cog. There may be complications not considering.	M	M	M		M	P–because of complexity of IHX/helium flows. C–complexities if N_2 in secondary loop.

[1] H, M, or L (high, medium, or low).

4.3.4 Mass addition hydrogenous

Mass additions of hydrogenous materials were considered potentially important safety issues, depending on the configuration and rates (Table 4.16). The possibility of steam additions to the primary reactor system exists if the IHX is a high-temperature steam generator and the IHX fails. The high-temperature electrolysis process for hydrogen production requires steam. Many chemical plants have large energy demands for compressors. High-temperature steam is often used to provide the power for these systems. Less direct and less severe events could occur with steam generator failures on the process side, depending on configurations and pressure gradients, although the rates would be expected to be reduced. In general it is considered unlikely that the NGNP will consider a steam system without an intermediate loop, but the possibility has been proposed and should be included in the PIRT tables.

Phenomena: The possibility of hydrogenous materials entering the primary system under accident conditions introduces the possibility of (1) reactivity events and (2) chemical attack on graphite and fuel materials. This category accounts for the hydrogenous mass addition effects, but it is recognized that component failures such as those described above are likely to be the initiating event for mass additions. Quantities of steam sufficient to cause a significant reactivity effect are available, but the transport path and driving forces must be analyzed to define whether significant effects are likely. The corrosive effects were considered longer term in small amounts, but potentially significant in large additions at elevated temperatures.

Importance: The importance of hydrogenous mass additions was considered high because of the reactivity potential with possible power increases leading to a more severe thermal scenario. Hydrogenous mass additions could lead to thermal and pressure transients and corrosion issues if the introduction were severe.

Knowledge: The importance of hydrogenous additions is strongly configuration and failure mode dependant. Failures that could rapidly introduce material into the primary system are of first-order concern and are only possible for directly coupled steam generator configurations. The intermediate loop system buffer of these effects needs to be evaluated and failure modes defined for the general classes of configurations. The neutronic and thermal effects of hydrogenous material additions can be readily analyzed with available tools. The knowledge base was designated M because the configurations, flow paths, and pressure characteristics are not well defined at this point in time. The configurations and components are unique, and the specific conditions and configurations will be important in determining consequences and mitigation options. It was considered important to further characterize the mass addition scenarios and effects on heat transport components and apply state-of-the-art tools to this analysis.

Table 4.16. PIRT chart for mass addition to reactor: hydrogenous materials

FOM	Issue (phenomena, process, etc.)	Comments	Importance[1]					Rationale	Knowledge level[1]					Rationale
			C	M	P	S	A		C	M	P	S	A	
Damage, wear, or impairment of SSCs (TRISO layers; fission product confinement)	Reactivity spike due to neutron thermalization.	Power spike in fuel grains, could lead to TRISO-failure with prolonged high temperature.	H	H	H		H		M	M	M		M	
	Chemical attack of TRISO layers and graphite.	Steam and graphite react; TRISO Brinkman: AREVA more concerned with gases produced in core by the steam, rather than the chemical attack on fuel. Pressure relief valve would open in primary loop releasing hydrogen into containment.	M	H	H		H	C–(AVR/Fort St. Vrain experience)–accidentally dumped water into core in AVR; had to boil water off, no chemical attack. C–graphite attack and reformer gas production. **Fission product panel should be aware of this.	M	L	M		M	

[1] H, M, or L (high, medium, or low).

4.3.5 Loss of intermediate fluids

The loss of the intermediate fluid addresses failures in the intermediate loop piping and structure as opposed IHX or PHX failures (Table 4.17). The base case considered for the intermediate loop heat transport working fluid is high-pressure helium, but liquid salts (which potentially could be considered at lower working pressures) are also being considered as are mixtures of nitrogen and helium. The nitrogen helium mixtures have significantly lower costs than pure helium systems. The intermediate loop as the connector between the reactor and chemical plant may be hundreds to thousands of meters in length. In the chemical plant, it is likely that each loop connects to smaller loops that go to individual PHXs. As a consequence, it is one of the most exposed components in the entire nuclear-chemical plant system. It is a component where failure is a credible possibility over the life of the facility.

A failure in the heat transport system piping or structure, could lead to mass additions to blowdowns or pressurization of the containment/confinement depending on the failure location and path. The loss of the intermediate working fluid could lead to loss of heat sink or thermal transients depending on the failure mode and magnitude. The loss of working fluid also leads to the potential for severe pressure and thermal transients in the IHX, potentially leading to threats to the primary system.

Phenomena/Criteria: For loss of the helium working fluid, the phenomena considered were pressurization (confinement, containment) transient thermal or pressure effects on other heat transport components (IHX, PHX) and potential impact on the power generation system depending on the configuration. If He/N_2 mixtures, or liquid salts are involved, the same issues arise but with the addition of the corrosion and differing heat transfer considerations. Evaluation of failure modes and rates will require additional definition of intermediate loop designs.

Importance: The importance of a loss of intermediate fluid was considered high due to the potential for severe thermal and pressure transients that could affect the IHX and primary system.

- ***Thermal transients.*** Thermal transients can include both initial overcooling of the reactor followed by a loss of heat sink. If the break in the intermediate loop occurs after the intermediate fluid has been heated, the depressurization will increase flow of the cooler heat transfer fluid through the IHX. The much better heat transfer will overcool the primary system until the intermediate loop is depressurized. Because of the size of the intermediate loop, this can be a significant cooling effect.
- ***Pressurization transients.*** The IHX is the most stressed component in the system because it operates at the maximum temperatures.

Table 4.17. PIRT chart for loss of intermediate fluids

FOM	Issue (phenomena, process, etc.)	Comments	Importance[1]					Rationale	Knowledge level[1]					Rationale
			C	M	P	S	A		C	M	P	S	A	
Damage, wear, or impairment of SSCs	Loss of main heat sink (hydrodynamic loading on IHX; cutting margins down by increasing D/P over IHX; decrease operating life of IHX).	Rapid pulse cooling of reactor during depressurization of intermediate loop and IHX. Brinkman: Very rapid event. Self-closing valves act faster than I&C system.	H	H	H		H	P–loss of heat sink with all the blowdown effects. C–potential for high probability in plant lifetime. Perhaps could occur in reactor lifetime?	M	M	M		M	P–uncertainty about IHX design. M/P–good tools to work with currently, but design uncertainty exists.

[1] H, M, or L (high, medium, or low).

Knowledge: The thermal and fluid dynamic tools to analyze loss of working fluid events are available and capable of addressing these phenomena. The knowledge base was designated M because the configurations, flow paths, and pressure characteristics are not well defined at this point in time. The configurations and components are unique and the specific conditions and configurations will be important in determining consequences and mitigation options. It was considered important to further characterize the loss or working fluid scenarios and effects on heat transport components and apply state-of-the-art tools to this analysis—therefore, the current status was designated M.

4.4 VHTR Events That Impact the Chemical Plant

The VHTR can initiate events that impact the chemical plant. Table 4.18 summarizes these events. None of these sequences were rated of high importance, and only one event was rated as medium importance. That event was a reactor accident with failure of the IHX and release or spread of radionuclides to the environment via the chemical plant.

Table 4.18. Summary of VHTR events and PIRT assessment

Event	Evaluation criteria	Issue (phenomena, process, etc.)	Importance[1]	Knowledge base[1]
Anticipated operations: tritium transport (long-term safety).	Dose to VHTR plant workers.	Diffusion of ^{3}H.	L	H
	Dose to process gas users: industrial and consumers.	Diffusion of ^{3}H.	L	H
Reactor accidents: radiologic release pathways through HX loops and plant.	Dose to public.	Accident radionuclide release.	M	M
Generic power or thermal transients initiated in VHTR.	SSC; stress on IHX or other component in contact with BOP.	Stress causes stress on other SSC component.	L	M

[1] H, M, or L (high, medium, or low).

4.4.1 Tritium

The product of a nuclear-hydrogen plant or a nuclear plant coupled to any other chemical plant is a physical product, not electricity. As a consequence, it is important to assure that radioactivity from the nuclear plant not enter the product. The primary isotope of concern in this context is tritium. The radioactive isotope of hydrogen, ^{3}H or "tritium," is barely distinguishable chemically from the stable isotopes ^{1}H ("protium") and ^{2}H ("deuterium"). Therefore, it is crucial that the transport of tritium from the reactor to the process heat user or hydrogen production plant be controlled within regulatory limits for the public release via hydrogen-containing products. The PIRT assessment of this challenge is shown in Table 4. 19.

Table 4.19. PIRT chart for tritium releases

FOM	Issue (phenomena, process, etc.)	Comments	Importance[1]					Rationale	Knowledge level[1]					Rationale
			C	M	P	S	A		C	M	P	S	A	
Dose to VHTR plant worker.	Diffusion of ^{3}H.	Classic tritium diffusion. Brinkman: tritium is permeation, not diffusion! In THTR experience, tritium gas was so high, that had to declare the building as a controlled area. In Germany in 1980s, when HTR was considered to drive chemical processes, discussions with the regulator regarding the amount of allowable tritium in product plastics. P–a need for regulation to set activity standards in the product gas. P–ranked low since longer term.	L	L	L	H	L	C/P–is there a cheap and practical way to measure this?	H	H	H	H	H	

Table 4.19 (Continued)

FOM	Issue (phenomena, process, etc.)	Comments	Importance[1]					Rationale	Knowledge level[1]					Rationale
			C	M	P	S	A		C	M	P	S	A	
Dose to users.	Diffusion of ^{3}H.	Classic tritium diffusion. Brinkman: permeation, not diffusion.	M	L	L	H	L	S–more of a public acceptance/ political issue than an engineering one. C–tritium escape path into product is process dependent.	H	H	H	H	H	

[1] H, M, or L (high, medium, or low).

There are three primary sources of tritium within the high-temperature reactor.

- ***Ternary fission.*** Ternary fission, in which three fission fragments are produced, is a rare event among fissions with low energy neutrons, with a ternary to binary fission ratio of 0.2%. Of the ternary fissions, about 6% result in a triton (one proton and two neutrons). Thus tritium is produced in about 120 ppm of all fissions. For a 600-MW(t) reactor, such as the NGNP, ternary fission produces a tritium inventory of about 9.7 Ci (360 GBq) per day of operation. In the absence of failures in the TRISO particles, the tritium remains sealed in the fuel.
- ***Activation.*** Tritium can also be produced by trace amounts of beryllium and lithium (esp. ^{6}Li) in the fuel outer layers or graphite moderator in the reactor core. The amounts of such impurities can be kept low through the careful specification of raw materials.
- ***Helium.*** Natural helium contains about 137 ppm ^{3}He, which has a cross section for the ^{3}He(n,p)T reaction of 5330 barns. If we assume that the total primary He inventory is 3500 normal m^3 (600 kg), then the complete conversion of the ^{3}He content would produce about 820 Ci (30.4 TBq) of tritium. The time-constant for that activation is about 1 year. Actual production of tritium in the reactor would depend on the rate of helium leakage and its replacement with additional natural helium.

Tritium from fuel is transported from its source to the product through failure of the SiC layer on the TRISO fuel [currently a less than 1E-5 occurrence at end of life (EOL)] and then via concentration-driven diffusion through hot metal boundaries, such as heat exchangers and piping.

There are no established regulations for the tritium content of nuclear-produced hydrogen, but the Japanese have adopted a target value of 11.8 Bq/g H_2, resulting in a hydrogen user dose of 0.1 mSv/year.[4] This is approximately the same as the dose rate due to cooking with a natural gas stove due to the naturally occurring radioactivity in natural gas. This limit can be met if the permeation rate from the reactor to the hydrogen product is $<0.06\%$, which is well within present fuel and heat exchanger technology. This assumes that the average helium lifetime in the reactor is 2 years and no tritium contribution from activation of other core components that generate tritium. If it should be necessary to further reduce the migration of either tritium, strategies would include a further reduction in the SiC layer failure rate, use of another sealing material, such as ZrC, operation with lower maximum fuel temperatures at hot spots to reduce diffusion, use of double tubes in certain heat exchangers and instrumentation of monitor tritium concentrations throughout the reactor and intermediate plant. Inagaki et al., have also shown the importance of counter permeation as a method for reducing tritium transport.

The panel rated the importance of tritium to both the nuclear plant worker and the public as low and the knowledge level as high. However, the panel viewed the issue as high importance in terms of public acceptance—that is, it's not a safety issue but it is a highly sensitive political issue that requires careful attention of the NRC.[4]

4.4.2 Fission products

Fission products can migrate from the fuel to the reactor coolant either via leakage from failed microspheres or via diffusion through the microsphere coating on the part of a few elements, particularly

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[4] Y. Inagaki et al., "Research and Development on System Integration for Connection of Hydrogen Production System to an HTTR," *Nuclear Technology*, **157**(2), 111–119 (February 2007).

silver. Transported by the coolant, the fission products tend to plate out on cooler parts of the primary coolant system. The noble gases remain mixed with the primary coolant.

Fission products (excluding tritium) are unlikely to migrate into the hydrogen or other chemical products because (1) the diffusion of fission products through metal heat exchangers is essentially zero and (2) the chemistry of fission products are quite different chemically from the products of the hydrogen plant. The primary concerns (figure of merit) are the doses to maintenance workers and doses to the public due to the release of the primary coolant in transients that fail both the IHX and the intermediate heat transport system.

The panel (Table 4.20) rated the importance of fission product release with respect to the chemical systems as medium and the knowledge base as medium. There are multiple barriers that must fail before fission products can migrate into the intermediate loop and to the chemical plant.

4.4.3 Reactor Temperature Transients

Reactor transients would include any unplanned control-rod movements or changes in the primary coolant flow rate. The hazards associated with these transients are due to the thermal stresses on heat transfer surfaces and the challenges to control of the chemical plant. The heat transfer surfaces are barriers against tritium and fission product transport into the chemical plant product and repeated thermal stresses will lead to fatigue cracking. In the chemical plant, heat is used to drive endothermic chemical reactions that slow down as the rate of heat delivery decreases. In this context, there are self-regulation mechanisms in the chemical plant. Table 4.21 summaries these events

If the reactor is supplying steam to a high-temperature electrolysis plant, variations in the reactor output can lead to transients in the cell temperatures, shortening the life of the cells. The effects of transients on either the reactor or chemical plant side of the IHX can be mitigated through the use of an intermediate thermal mass to increase the time constants for transients. The effects of transients can also be mitigated through well-designed control algorithms in both the reactor and chemical plant. Finally, the hazards implicit in the transients can be reduced through reduction of the recirculating flows of reagents in the chemical plants, thus reducing the releasable inventory.

While such transients present challenges, the panel rated the importance of these transients to safety as low and the knowledge level as medium.

Table 4.20. PIRT chart for fission product release

FOM	Issue (phenomena, process, etc.)	Comments	Importance[1]					Rationale	Knowledge level[1]					Rationale
			C	M	P	S	A		C	M	P	S	A	
Dose to public	Accident radionuclide release.	Bypass of filter and containment.	M	L	M	H	M	C–most of the surface area in heat transfer mechanism resides in the heat exchanger. It is tough to build high-temperature leak-proof valves. M–loop would serve as natural confinement. (Cons: If salt intermediate loop, then low fission product transport).	M	M	M	H	M	P–since unique chemistry in cogeneration plant, in terms of fission product that need to consider.

[1] H, M, or L (high, medium, or low).

Table 4.21. PIRT chart for reactor temperature transients

Evaluation criterion	Issue (phenomena, process, etc.)	Comments	Importance[1]					Rationale	Knowledge level[1]					Rationale
			C	M	P	S	A		C	M	P	S	A	
SSC; stress on IHX or other components in contact with BOP.	Stress causes stress on other SSC component.	P & M: Not sure if this is an issue; may be addressed by other panels, but should probably be focused on effects of cogeneration impact on VHTR.	L	L	L		L	C–chemical plant has endothermic chemical reactions. Dampening of reactions without heat source. S–can transport fission products through chemical plant	M	L	M		M	M–difficult to envision these types of scenarios.

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[1] H, M, or L (high, medium, or low).

5. CONCLUSIONS

A PIRT evaluation was conducted to address the specific safety challenges from hydrogen plants and other process facilities to a high-temperature reactor that produces high-temperature heat for process applications, including the option of producing hydrogen. The major conclusions are as follows:

- ***NGNP vs. a commercial high-temperature reactor.*** The PIRT examined safety issues associated with the NGNP and a commercial plant. For the NGNP, only a small fraction of the heat is expected to be used to produce hydrogen or other chemicals with most of the heat used to produce electricity. In contrast, for a commercial high-temperature reactor application, all of the heat may be used for production of hydrogen or chemicals. Because the total chemical inventories determine the potential hazard to the nuclear plant from a chemical plant, the hazards of a small chemical plant associated with the NGNP may be significantly smaller than a commercial high-temperature reactor.
- ***Chemical plant safety, regulatory strategy, and site layout.*** The safety philosophy for most chemical plants is fundamentally different than the safety philosophy associated with nuclear power plants. For many hazards, such as a hydrogen leak, the safety strategy is dilution with air to below the concentration of hydrogen that can burn in air. For example, a small amount of hydrogen in an enclosed room is an explosion hazard. However, a large release of hydrogen to the environment is a relatively small hazard when outdoors. As a consequence, most chemical plants are built outdoors to allow rapid dilution of chemicals with air under accident conditions. The reverse strategy is use for nuclear plants where the goal is to contain radionuclides because their hazard does not disappear if diluted with air. The chemical plant safety strategy implies that controlling the size of the chemical inventories, the site layout, and the separation distances between various process facilities and storage facilities are the primary safety "devices" used to prevent small events becoming major accidents. This different safety strategy must be recognized and understood when considering safety challenges from nearby chemical plants.
- ***Hydrogen.*** Accidental releases of hydrogen from a hydrogen production facility are unlikely to be a major hazard assuming some minimum separation distances. This conclusion is based on several factors: (1) if hydrogen is released, it rapidly rises and diffuses making it very difficult to create conditions for a large explosion and (2) a hydrogen burn does not produce high thermal fluxes that can damage nearby equipment. In addition to laboratory and theoretical analysis of hydrogen accidents, there is a massive knowledge base in the chemical industry with hydrogen accidents and thus a large experimental basis to quantify this hazard based on real-world experience.
- ***Heavy gases.*** Many chemical plants under accident conditions can produce heavy ground-hugging gases such as oxygen, corrosive gases, and toxic gases. Industrial experience shows that such accidents can have major off-site consequences because of the ease of transport from the chemical plant to a nuclear plant or other facility. If the chemical plant or the stored inventories of chemicals are capable of releasing large quantities of heavy gases under accident conditions, this safety challenge requires careful attention. Oxygen presents a special concern because of its unique potential to create fires and because it is a unique hazard associated with these plants that are not normally seen in existing chemical plants in the context that it may be considered a waste and released to the atmosphere. The phenomena associated with plume modeling and the effects of such plumes on the nuclear plant safety-related structures, systems, and components are of high importance.

- ***Heat exchanger failure.*** The second major class of safety challenges with high importance is associated with the failure of the intermediate heat transport loop that moves heat from the reactor to the chemical plant. Several different heat transport media are being considered including helium, helium-nitrogen mixtures, liquid salt mixtures, and high-pressure steam. High-temperature steam is required as a process chemical for some processes, such as the production of hydrogen using high-temperature electrolysis; thus, steam (water) could be the intermediate heat transport fluid. For gas-phase intermediate heat transport systems, there are several specifics of phenomena of high importance. The total gas inventory in the intermediate loop may be significantly larger than the total inventory of gas in the reactor primary system. A heat transport system failure may first result in overcooling the reactor coolant because of enhanced heat transfer in the primary heat exchanger followed by the loss of the heat sink. Alternatively, a large or small leak from the heat transport loop into the reactor during many accident scenarios could add large inventories of gas to the reactor providing a sweep gas to move fission products from the reactor core. If steam or other reactive gases from the intermediate heat transport loop enter the reactor because of a heat exchanger failure, there is the potential for fuel damage—particularly given the much higher temperatures proposed for some applications of high-temperature reactors. These safety challenges define a second group of phenomena with high safety importance.

There is a large knowledge base within the chemical industry and the regulators of the chemical industry of the hazards associated with various chemicals and how to minimize risks from those hazards. This provides much but not all of the information that will be required to define conditions (separation distance, relative elevation, berms, other) to assure reactor safety when the reactor is coupled to a chemical plant. There is also some experience in the nuclear industry associated with various nuclear plants in several countries that have produced steam for industrial application. In all cases, the specific characteristics of the chemical plant, the proposed site layout, and the maximum associated stored inventories of chemicals provide the starting point for the safety assessments.

APPENDIX A

NUCLEAR PROCESS HEAT AND HYDROGEN APPLICATIONS

APPENDIX A

NUCLEAR PROCESS HEAT AND HYDROGEN APPLICATIONS

The NGNP strategy is the development of a private-government partnership to build the NGNP demonstration plant with an associated hydrogen production plant. However, if the technology is commercially deployed, the initial markets are likely to be (1) those that also require oxygen or high-temperature heat or (2) other markets that require high-temperature heat.

There is an important economic factor that will favor nuclear-hydrogen applications that require hydrogen, oxygen, and heat. The production of hydrogen using nuclear energy is in competition with hydrogen produced from fossil fuels and other energy sources. If the customer only needs hydrogen, the choice of hydrogen production technology will be based on the cost of hydrogen ($/kg hydrogen). However, if the customer needs hydrogen, oxygen, and heat, the costs of all three will be considered. Consider a case where the choices are using nuclear energy or natural gas to meet all three needs.

- ***Natural gas.*** If the customer chooses a plant to convert natural gas to hydrogen, the customer must also purchase a plant to separate oxygen from air and furnace to produce heat from natural gas.
- ***Nuclear.*** If the customer chooses a nuclear hydrogen plant. The plant produces hydrogen and byproduct oxygen that is either used or vented to the atmosphere. The nuclear plant can also produce heat where the cost of heat from a nuclear plant is generally about half or less than heat from natural gas.

In the above examples, nuclear hydrogen will become competitive first in those markets where there is a need for hydrogen, oxygen, and heat. Consequently, there is a high likelihood that the first markets for nuclear hydrogen will be markets where (1) oxygen, (2) heat, and/or (3) oxygen and heat are needed.

This implies that commercialized VHTR after the NGNP will potentially have other associated chemical plants associated with it and that safety assessments will have to consider the impacts of these chemical plants on nuclear plant safety. Because the NGNP goals are to develop a reactor for heat and hydrogen production, the program must consider these longer term aspects. This appendix describes these markets with Table A.1 providing a summary of such applications.

Table A-1. Markets for high-temperature process heat and hydrogen production

Use	H_2	O_2	Heat
Pipeline	X		
Chemical-steel	X		
Oil refinery	X	?	X
Liquid fuels from coal	X	X	X
Shale oil			X
Peak electricity production	X	X	X

A.1 Hydrogen Pipelines

There are several hydrogen pipelines in the United States, such as those in California, Texas, and Louisiana with a total length of ~460 miles. The pipelines couple hydrogen production plants (primarily today steam reforming of natural gas), refineries, and other chemical plants. If hydrogen is used directly as a fuel for transportation, it will in most cases be delivered from the nuclear hydrogen plant to the market by pipeline. If the market for nuclear hydrogen is a pipeline, then the safety issues are only those associated with the hydrogen production plant. This is the most competitive market for hydrogen because the only economic parameter of importance is cost per kilogram of hydrogen delivered.

A.2 Ammonia and Other Chemical Plants

There are a limited number of chemical plants that use massive quantities of hydrogen. For these chemical plants, the hydrogen requirements are sufficiently large as to justify the full use of a nuclear hydrogen production plant, if the economics are favorable. The primary chemical in this category is ammonia, the primary fertilizer used in the United States.

Ammonia plants require massive amounts of motive power to operate compressors. If a nuclear-hydrogen ammonia plant was built, there would also be strong incentives to use steam from the nuclear plant to provide motive power for the ammonia plant compressors—a major operating cost for these plants. For such coupled nuclear hydrogen applications, the safety assessments would include hydrogen production, the production of steam for the associated chemical plants that consume the hydrogen, and potential releases from the chemical plants.

A.3 Oil Refining

Modern refineries consume 15 to 20% of the energy content of each barrel of oil that is processed with much of that energy used in the form of high-temperature heat. About 7.5% of U.S. energy is consumed by refineries to produce the liquid fuels that meet about 39% of the U.S. energy demand. Another perspective can be gained from Fig. A.1 that shows the total greenhouse gas released from extraction of crude oil from the earth to its use in the form of diesel fuel for a sport utility vehicle (SUV). The greenhouse gas releases are normalized to a mile of travel. The primary greenhouse gas is carbon dioxide; thus, the same figure shows where the energy is consumed from extraction of crude oil to moving the SUV a mile down the road.

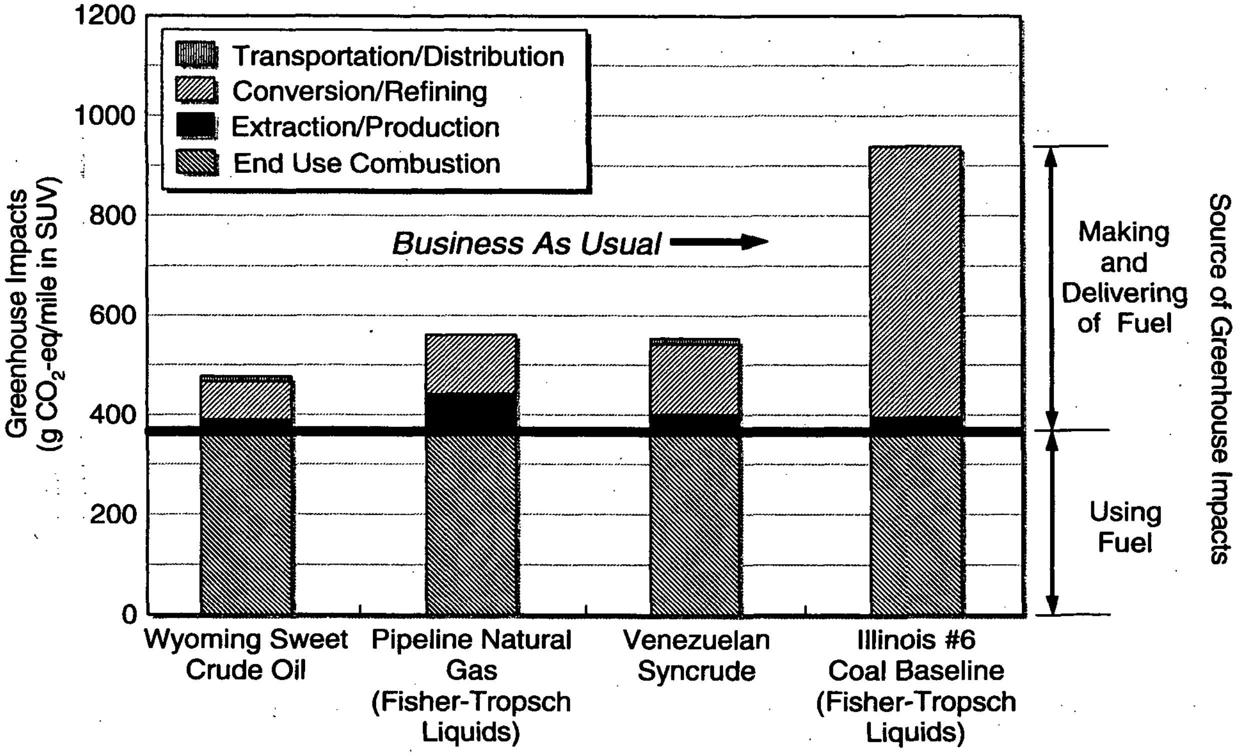

Fig. A.1. Equivalent carbon dioxide releases per SUV mile for diesel fuel produced from different feedstocks.

For high quality crude oil such as Wyoming sweet (low-sulfur) crude oil, most of this energy input is at the refinery in the form of heat for (1) distillation columns to separate the various components of crude oil and (2) conversion of low-value hydrocarbons into high-value gasoline, diesel, and jet fuel by processes such as thermal cracking. For high-sulfur crude oil, much of the energy that is required is used to make hydrogen to remove sulfur from the fuel. For heavy oil and coal feed stocks, much of the additional energy is used to make hydrogen to increase the hydrogen-to-carbon ratio in the fuel; that is, make gasoline, jet fuel, and diesel.

Refineries are the largest users of hydrogen in the United States. They are the logical near-term market for hydrogen. If the refinery is the customer, there are incentives to buy hydrogen and high-temperature process heat. In terms of reactor safety, there are the chemical hazards associated with the hydrogen plant plus the refinery hazards that are primarily associated with large fires.

A.4 Liquid Fuels from Coal

The process for converting coal to liquids (CTL) was developed in Germany in the 1920s and by World War II became the source of 90% of that nation's liquid fuel requirements. The South African company—Sasol is planning two CTL plants in China,* and in the United States some nine states are

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*Sasol Plans,"Two Coal-to-Liquid Fuel Projects," published in *China Daily* on January 30, 2007; downloaded at http://www.china.org.cn/english/BAT/198162.htm.

actively considering CTL plants. Global liquid coal production is expected to rise from 150,000 bpd today to 600,000 in 2020 and 1.8 million bpd in 2030.[**]

The most advanced process for producing liquid fuels from coal is gasification followed by the Fischer-Tropsch (F-T) process.[†] The process first gasifies the coal with steam and oxygen to form syngas (a mixture of hydrogen and carbon monoxide). The F-T process then converts the syngas to liquid fuel after the syngas H-to-C ratio has been adjusted to ~2. Because the H-to-C ratio in coal is 0.8, coal liquefaction is fundamentally a process to add hydrogen to carbon to raise the H-to-C ratio to ~2—that of high-quality liquid fuels. On a per plant basis, coal liquefaction plants are the largest users of hydrogen in the world. If nuclear hydrogen was available, all of the carbon in the coal could be converted into liquid fuels instead of much of the coal being used to make hydrogen.

The safety considerations are similar to refineries except coal liquefaction processes require oxygen and use any oxygen generated by the nuclear hydrogen plant. This implies oxygen at high pressure and possibly the storage of oxygen.

A.5 Shale Oil and Tertiary Oil Recovery

The United States has sufficient oil shale to meet domestic oil demands at current consumption rates for a century. New methods for shale oil recovery are being developed that involve drilling wells into oil shale, using electrical heaters to raise the bulk temperature of the oil shale to initiate chemical reactions that produce light crude oil, and then pumping the oil to the surface. High-temperature reactors using an intermediate heat transfer loop can provide the high-temperature heat and thus avoid the losses of converting heat to electricity and then back to heat. About 60 GW(t) of heat would be required at about 700°C to produce 5 million barrels of oil per day—a quarter of our national oil demand.

Although this is a very large potential use of high-temperature process heat, the heat is transferred underground away from the reactor. Consequently, it is one of a limited number of high-temperature process heat applications where the process facility (the oil shale) would not be expected to have a significant potential safety impact on the reactor.

A.6 Peak Electricity Production

The Hydrogen Intermediate and Peak Electrical System (HIPES) is an advanced system for the production of peak electricity. Hydrogen and oxygen are produced by a nuclear hydrogen facility; the hydrogen and oxygen are stored in underground caverns using the same technology used for storage of natural gas; and the hydrogen and oxygen are used to produce peak electric power using special fuel cells or a special steam turbine. The steam turbine variant combines hydrogen, oxygen, and water in a special combustor to produce very high-temperature steam that is directly fed to a steam turbine. There is no steam boiler. Elimination of the boiler increases efficiency and reduces capital costs.

[**] *Newsweek*, "Special Energy Edition," December 2006–February 2007.

[†] David Gray, NRCB on Energy and Environmental Systems Workshop, October 2005.

This potential application stores both hydrogen and oxygen; thus, the reactor safety analysis must consider the hydrogen production plant, hydrogen storage facilities, and oxygen storage facilities.

APPENDIX B

GENERAL PIRT CHART: PROCESS HEAT AND HYDROGEN

Table B-1. General PIRT chart: process heat and hydrogen (Work table generated during meetings and used to record panel results)

Accident Class	Event (added column based on hazard identification last meeting)	Evaluation criterion	Issue (phenomena, process, etc.)	Comments	Importance[1] (H/M/L)					Rationale	Knowledge level[1] (H/M/L)					Rationale
					C	M	P	S	A		C	M	P	S	A	
Chemical releases	H_2 release	Damage, wear, or impairment of safety-related reactor plant systems, structures, and components (SSCs).	Blast effects		M	L	H	M	M	C/S–High buoyancy and rapid diffusion of gas before it can explode. P–Political rationale. M–Low since.	H	H	H	M	H	C–Large experience base (codes and experiments); ammonia plant experience (every 2 years) Conference Themes: "How to avoid hydrogen fires that burn down plant." S–Methane and LNG studies. M–extensive experience base; handling is very well understood; hydrogen accidents very well understood (explosion, flux, and burns).
			Heat flux		L	L	M	L	L	C–low infrared signature. S–buoyancy and rapid diffusion.	M	H	H	M	M	C–"Such a non-problem that hasn't been studied." S–codes and experiments mentioned above.

Table B-1 (continued)

Accident Class	Event (added column based on hazard identification last meeting)	Evaluation criterion	Issue (phenomena, process, etc.)	Comments	Importance[1] (H/M/L)					Rationale	Knowledge level[1] (H/M/L)					Rationale
					C	M	P	S	A		C	M	P	S	A	
		Operator injury or impairment	Burn and heat flux to people		L	L	L	L	L	C–low infrared signature. S–buoyancy and rapid diffusion.	M	H	H	M	M	C–Such a non-problem that hasn't been studied." S–Primary hazard if confined by overhead or curtain wall structures.
	O_2 release	Damage, wear, or impairment of SSCs	Plume behavior	Ground hugging gas movement? This is routine behavior; no acc	H	M	H	H	H	C–are changing local environment conditions with oxygen plume? P–importance of plume issue; want to know where the O_2 goes; worst case is low temp. release; M–small inventory, but possibility of plume is important.	H	H	H	M	H	S–need better modeling of effects of structures on flow and mixing. C–models are approximate plume behavior. P–the tools and knowledge is available; models don't have any new physics or considerations. M–Such extensive experience with working with O_2 in industry; understand effects on equipment well
			Allowable concentrations	What oxygen levels cause	H	M	M	H	H	C–high partially over concerns	L	H	H	H	M	Consensus perspective: high

Table B-1 (continued)

Accident Class	Event (added column based on hazard identification last meeting)	Evaluation criterion	Issue (phenomena, process, etc.)	Comments	Importance[1] (H/M/L)					Rationale	Knowledge level[1] (H/M/L)					Rationale
					C	M	P	S	A		C	M	P	S	A	
				damage?						over both accident and long-term elevated levels; Is there a chance of locally high concentrations in NGNP that are designed for? Are we changing chemical properties of equipment, I&C, and people. P–importance of plume issue; want to know where the O_2 goes; worst case is low temp. release. M–small inventory, but possibility of plume is important.						knowledge of accident behavior, but concern about continuous release for nth gen. designs. S–standards in chemical process industry and hospitals. C–long-term exposure issues. P–the tools and knowledge is available; models don't have any new physics or considerations. M–such extensive experience with working with O_2 in industry; understand effects on equipment well
			Spontaneous combustion	What levels cause spontaneous combustion?	H	M	M	H	H	S–may not easily dispersed if released in large quantities P–importance of plume issue; want to know where the O_2 goes; worst case is low temp.	M	H	H	M	M	S–question is really one of what flammable material is present and what are ignition sources P–the tools and knowledge is available; models

Table B-1 (continued)

Accident Class	Event (added column based on hazard identification last meeting)	Evaluation criterion	Issue (phenomena, process, etc.)	Comments	Importance[1] (H/M/L)					Rationale	Knowledge level[1] (H/M/L)					Rationale
					C	M	P	S	A		C	M	P	S	A	
										release; M–small inventory, but possibility of plume is important						don't have any new physics or considerations M–such extensive experience with working with O_2 in industry; understand effects on equipment well
		Operator injury or impairment	Burn to people (VHTR operators)		M	M	L		M		H	H	H		H	C–hospitals have large accident knowledge of oxygen use.
	Flammable release Note: not currently in baseline studies for NGNP, but could become so in the future.	Damage, wear, or impairment of SSCs	Plume behavior	How far away from leak explosion occurs (dispersion?)	M	M	M		M		H	H	H		H	Consensus: large experience base on accidents in industry
			Heat flux	Design of equipment should eliminate this mode. Carbon based fire is serious. Carbon atoms (soot) radiate large heat fluxes	H	M	M		M	C–heat flux tends to start cascading fires in neighboring components.	H	H	H		H	Consensus: Large experience base on accidents in industry
			Blast effects	Fuel/air mixture dependent upon stoichiometric mixture, vectorization,	M	M	M		M		H	H	H		H	Consensus: large experience base on accidents in industry

Table B-1 (continued)

Accident Class	Event (added column based on hazard identification last meeting)	Evaluation criterion	Issue (phenomena, process, etc.)	Comments	Importance[1] (H/M/L)					Rationale	Knowledge level[1] (H/M/L)					Rationale
					C	M	P	S	A		C	M	P	S	A	
				conditions, etc.												
		Operator injury or impairment	Burns to people	VHTR plant operators	M	M	M		M		H	H	H		H	
	Corrosive release	Damage, wear, or impairment of SSCs	Plume behavior	Ground hugging gas movement?	M	L	L	H	M	S–acid and HI are much heavier than air. C–process specific M–small inventories; min. opportunity for large leaks. P–longer term effect; these things will not happen quickly.	H	H	M	H/ L	H	S–is chemical dependent; M–extensive industrial database
			Allowable concentrations	What chemical levels cause damage	M	L	L	M	M		M	H	M	L	M	S–low for HI and high for sulfuric acid.
		Operator injury or impairment	Burns to people	VHTR plant operators	L	L	M	H	M	C–people sense corrosives; example; hydrogen sulfide and cyanide are equally toxic, but more people die from cyanide sense it isn't "sensed" in time.	H	H	M		H	C–standard industrial chemicals
	Toxic gas release	Operator injury or impairment	Plume behavior	Ground hugging gas movement?	M	L	H	H	M	S–heavier-than-air condenses on surface and maintains toxic	H	H	M	L	M	S–three phase dispersion phenomena. (harder to model)

Table B-1 (continued)

Accident Class	Event (added column based on hazard identification last meeting)	Evaluation criterion	Issue (phenomena, process, etc.)	Comments	Importance[1] (H/M/L)					Rationale	Knowledge level[1] (H/M/L)					Rationale
					C	M	P	S	A		C	M	P	S	A	
										levels. M–small inventories in use in NGNP P–concentrations not high in NGNP, but toxic materials are present. Public question over toxic releases. Spread in answers sense differing judgments on toxicity levels of certain toxins present in accident.						M–well understood phenomena (example, at former work, was necessary to employ dispersion models to understand toxic phenomena in the lab.) P–knowledge is there, but details are not a common set of chemicals worked with. MSDS sheets may be well known, but the transport vectors are not well understood. Potential quantities are in ppm. We know about immediate toxicity, but not about low ppm toxicity for VHTR workers. C–the EPA, OSHA, and insurance company will

Table B-1 (continued)

Accident Class	Event (added column based on hazard identification last meeting)	Evaluation criterion	Issue (phenomena, process, etc.)	Comments	Importance[1] (H/M/L)					Rationale	Knowledge level[1] (H/M/L)					Rationale
					C	M	P	S	A		C	M	P	S	A	
																force knowledge base before a build is licensed.
			Toxic concentrations and effects	VHTR plant operators	M	L	H		M		H	H	M	L	M	
	Suffocation gas release	Damage, wear, or impairment of SSCs	Plume behavior	Ground hugging gas movement?	M	L	L		M	C–if safety related air-based power systems (example: diesel start); location of diesel vs. suffocation gas.	H	H	H		H	C–performance of combustion systems under low O_2 concentrations
			Backup power/O_2 concentrations	Assume diesel generator part of safety system	M	L	L	M	M	C–if safety related air-based power systems (example: diesel start); location of diesel vs. suffocation gas.	H	H	H		H	C–performance of combustion systems under low O_2 concentrations
		Operator injury or impairment	Concentration for people	VHTR plant operators	M	L	M		M		H	H	H		H	
Process thermal events	Loss of heat load	Damage, wear, or impairment of SSCs	Loss of heat sink to reactor	Guillotine break in loops, and coolant leaks out	M	M	M	M	M	C–potential for cooling then loss of heat sink if break in secondary loop-helium. M–response to this event is part	H	M	M	H	M	M–some statistical experience in industry on these events happening. S–good dynamic modeling capabilities.

Table B-1 (continued)

Accident Class	*Event* (added column based on hazard identification last meeting)	Evaluation criterion	Issue (phenomena, process, etc.)	Comments	Importance[1] (H/M/L)					Rationale	Knowledge level[1] (H/M/L)					Rationale
					C	M	P	S	A		C	M	P	S	A	
										of reactor design requirements. P–thermal mass slows time response.						
	Temperature transient	Damage, wear, or impairment of SSCs	Cyclic loading	Concern about batch processes with cyclic heat demand (Alert materials panel!!) Note: These rankings could possibly be different if larger process heat loads are involved. Brinkman: There is a big difference between 10% and 100% thermal load from the co-generation plant. Experience with HTR in Germany in 80s. Thermal and pressure transients could complicate the design of the IHX. Calculations need to be performed	M	M	M	L	M	M–in NGNP only fraction of BOP will go into process heat (10%). P–cyclic stress on heat exchangers, but there is a damping effect. There are large thermal masses involved.	M	M	M		M	M–these situations are amenable to modeling C–experience base on high temperature exchangers is limited.

Table B-1 (continued)

Accident Class	Event (added column based on hazard identification last meeting)	Evaluation criterion	Issue (phenomena, process, etc.)	Comments	Importance[1] (H/M/L)					Rationale	Knowledge level[1] (H/M/L)					Rationale
					C	M	P	S	A		C	M	P	S	A	
				with the full range of operating conditions in both the VHTR and the co-generation. Plate vs tube IHX components Design D/P for plate 10–20 bar. Design D/P for tube 80 bars. Need to account for D/P in transients on secondary system. Potential for massive failure in plate IHX P–this is the most highly stressed component in the system. Potential propagation path for IHX failure. For PWR S/G component, what is experience with higher pressure on primary vs secondary side?												
			Harmonics	Coupling of chemical plant control system with NGNP.	L	L	L		L	C–slow harmonics more of a reliability/ economics issue	M	M	M		M	

Table B-1 (continued)

Accident Class	Event (added column based on hazard identification last meeting)	Evaluation criterion	Issue (phenomena, process, etc.)	Comments	Importance[1] (H/M/L)					Rationale	Knowledge level[1] (H/M/L)					Rationale
					C	M	P	S	A		C	M	P	S	A	
				Paul & Max: Is this an issue? Is there a scenario where this could realistically occur? Since process heat, only 10% of BOP goes to hydrogen plant, most goes towards the PCS. Thermal transients in VHTR or coupling system that could be amplified by the presence of the hydrogen plant and feedback into the reactor core, resulting in FPT.						than safety issue. P–difficult to think of this scenario with large heat sink reactors.						
Heat transport system failures	IHX failure (intermediate heat exchanger)	Damage, wear, or impairment of SSCs	Blowdown effects, large mass transfer; pressurization of either secondary or primary side.	Fluid hammer Thermal and concentration gradients can work against the D/P such that chemicals can diffuse towards the IHX	H	M	H		H	P–failure modes are equally important in both IHX and PHX. C–IHX is important because it is a boundary between core and secondary loop; small helium purge of a hot	M	M	H		M	P–have models available that can handle these problems.

Table B-1 (continued)

Accident Class	Event (added column based on hazard identification last meeting)	Evaluation criterion	Issue (phenomena, process, etc.)	Comments	Importance[1] (H/M/L)					Rationale	Knowledge level[1] (H/M/L)					Rationale
					C	M	P	S	A		C	M	P	S	A	
										core. Small leaks more worrisome to Charles. Consensus: If salt intermediate loop, then no massive pressurization						
	PHX failure (process heat exchanger)	Damage or impairment of SSCs	Fuel and primary system corrosion		M	H	H		H	P/M–PHX failure would precipitate problems in IHX; more critical. It is a unique threat to IHX; ultimate impact would be on IHX	M	L	M		M	P–novel PHX designs at this point do not yet exist; no experience base.
	Mass addition to reactor (helium)	Damage, wear, or impairment of SSCs	Turbomachinery response; potential for N_2/He mixture Brinkman: potential for nitride effects on material properties.	Rapid change in the load for the turbomachinery and the dynamic response	M	M	M		M	C–what will N_2 do to heat transfer and combinations. How will it affect thermal transients in the core? P–in PCS and cog. There may be complications not considering.	M	M	M		M	P–because of complexity of IHX/ helium flows. C–complexities if N_2 in secondary loop.
	Mass addition to reactor (hydrogenous material, e.g., steam)	Damage, wear, or impairment of SSCs (TRISO layers; fp confinement)	Reactivity spike due to neutron thermalization	Power spike in fuel grains, could lead to TRISO failure with prolonged high temperature	H	H	H		H		M	M	M		M	

Table B-1 (continued)

Accident Class	Event (added column based on hazard identification last meeting)	Evaluation criterion	Issue (phenomena, process, etc.)	Comments	Importance[1] (H/M/L)					Rationale	Knowledge level[1] (H/M/L)					Rationale
					C	M	P	S	A		C	M	P	S	A	
		Damage, wear, or impairment of SSCs (TRISO layers fp confinement)	Chemical attack of TRISO layers and graphite	Steam and graphite react; TRISO Brinkman: AREVA more concerned with gases produced in core by the steam, rather than the chemical attack on fuel. Pressure relief valve would open in primary loop, releasing hydrogen into containment.	M	H	H		H	C–(AVR/Fort St. Vrain experience)-accidentally dumped water into core in AVR; had to boil water off, no chemical attack. C–graphite attack and reformer gas production. Fission product panel should be aware of this.	M	L	M		M	
	Loss of intermediate fluid	Damage, wear, or impairment of SSCs	Loss of main heat sink (hydrodynamic loading on IHX; cutting margins down by increasing D/P over IHX; decrease operating life of IHX)	Rapid pulse cooling of reactor during depressurization of intermediate loop and IHX Brinkman: Very rapid event. Self-closing valves act faster than I&C system	H	H	H		H	P–loss of heat sink with all the blowdown effects. C–potential for high probability in plant lifetime. Perhaps could occur in reactor lifetime?	M	M	M		M	P–uncertainty about IHX design. M/P–good tools to work with currently, but design uncertainty exists.

Table B-1 (continued)

Accident Class	Event (added column based on hazard identification last meeting)	Evaluation criterion	Issue (phenomena, process, etc.)	Comments	Importance[1] (H/M/L)					Rationale	Knowledge level[1] (H/M/L)					Rationale
					C	M	P	S	A		C	M	P	S	A	
VHTR events that impact cogeneration plant	Anticipated operations: Tritium transport (long-term safety)	Dose to VHTR plant workers	Diffusion of ^3H	Classic tritium diffusion Brinkman: Tritium is a permeation, not a diffusion! In THTR experience, tritium gas was so high, that had to declare the building as a controlled area. In Germany in 80s, when HTR was considered to drive chemical processes, discussions with the regulator regarding the amount of allowable tritium in product plastics. P–a need for regulation to set activity standards in the product gas. Paul: Ranked low since longer term.	L	L	L	H	L	C/P–is there a cheap and practical way to measure this?	H	H	H	H	H	

Table B-1 (continued)

Accident Class	Event (added column based on hazard identification last meeting)	Evaluation criterion	Issue (phenomena, process, etc.)	Comments	Importance[1] (H/M/L)					Rationale	Knowledge level[1] (H/M/L)					Rationale
					C	M	P	S	A		C	M	P	S	A	
		Dose to process gas users: industrial and consumers	Diffusion of ^{3}H	Classic tritium diffusion Brinkman: Permeation, not diffusion	M	L	L	H	L	S–more of a public acceptance/political issue than an engineering one. C–tritium escape path into product is process dependent.	H	H	H	H	H	
	Reactor accidents: radiologic release pathways through HX loops and plant	Dose to public	Accident radionuclide release	Bypass of filter and containment	M	L	M	H	M	C–most of the surface area in heat transfer mechanism resides in the heat exchanger. It is tough to build high temperature leak-proof valves. M–loop would serve as natural confinement (Cons: If salt intermediate loop, then low FP transport)	M	M	M	H	M	P–since unique chemistry in cogeneration plant, in terms of fp that need to consider.

Table B-1 (continued)

Accident Class	Event (added column based on hazard identification last meeting)	Evaluation criterion	Issue (phenomena, process, etc.)	Comments	Importance[1] (H/M/L)					Rationale	Knowledge level[1] (H/M/L)					Rationale
					C	M	P	S	A		C	M	P	S	A	
	Generic power or thermal transients initiated in VHTR (for example, turbine trip)	SSC; stress on IHX or other component in contact with BOP	Stress causes stress on other SSC component	Paul & Max: Not sure if this is an issue; may be addressed by other panels, but should probably be focused on effects of co-generation impact on VHTR.	L	L	L		L	C–chem. plant has endothermic chemical reactions. Dampening of reactions without heat source. S–can transport fission products through chemical plant.	M	L	M		M	M–difficult to envision these types of scenarios.

[1] H, M, or L (high, medium, or low).

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10. SUPPLEMENTARY NOTES

S. Basu, NRC Project Manager

11. ABSTRACT *(200 words or less)*

A Phenomena Identification and Ranking Table (PIRT) exercise was conducted to identify potential safety related physical phenomena for the Next-Generation Nuclear Plant (NGNP). The NGNP is a very high-temperature reactor (VHTR), one of the primary applications of which would be to supply heat and electricity for the production of hydrogen. The primary application of this PIRT is to provide information to support the safety analysis of the NGNP, a prototype VHTR. It is planned to couple one or more small hydrogen production pilot plants to the NGNP. However, the chemical plant processes to be coupled to the NGNP have not yet been chosen; thus, a broad PIRT assessment was conducted to scope alternative potential applications and test facilities associated with the NGNP.

The hazards associated with various chemicals and methods to minimize risks from those hazards are well understood within the chemical industry and the chemical plant regulators. This provides much but not all of the information that will be required to define conditions (separation distance, relative elevation, berms, other) to assure reactor safety when the reactor is coupled to a chemical plant. There is also some experience in the nuclear industry associated with various nuclear plants in several countries that have produced steam for industrial applications. In all cases, the specific characteristics of the chemical plant, the proposed site layout, and the maximum associated stored inventories of chemicals provide the starting point for the safety assessments. The experience, safety studies, and safety-related experiments have provided a reasonably good understanding of high-temperature reactor safety. The work herein provides a starting point for those studies; but, the general level of understanding of safety in coupling nuclear and chemical plants is less than in other areas of high-temperature reactor safety.

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PIRT, Next Generation Nuclear Plant, process heat, hydrogen co-generation

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