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Light Water Reactor Sustainability Program

Nuclear-integrated Hydrogen—Code and Licensing Separation Distance Considerations

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September 2024

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SUMMARY

This report supports the fiscal year 2024 Flexible Plant Operations and Generation research pathway for the Light Water Reactor Sustainability Program focus related to nuclear-integrated hydrogen-production via co-location of high-temperature electrolysis facilities (HTEFs) at existing nuclear power plant sites. Previous research in this area [1] specifically addressed licensee self-evaluation of new HTEF interfaces with nuclear power plant design and licensing bases under 10 Code of Federal Regulation (CFR) 50.59.

A key element of introducing a co-located HTEF at any existing (or new) NPP is to ensure that the placement of new pressurized-hydrogen facility piping, and components do not introduce new failure-modes and effects that challenge Systems Structures and Components important to nuclear safety as a result of hydrogen detonation and the consequential pressure-loading (detonation pressure-wave) and thermal heat-flux resulting from the combustion of the hydrogen gas.

Because evaluation of fire-protection changes is not applicable to the 10 CFR 50.59 licensee self-evaluation process, this report specifically identifies applicable code-based regulatory pathways for licensing and fire-protection that should be examined by nuclear power plant licensees when determining and self-evaluating minimum required separation-distance approaches for HTEF under both Appendix R and National Fire-Protection Association Standard 805 plant-licensing bases. Alternate approaches to separation-distance research, as described in previous Idaho National Laboratory research [1,2], are also discussed to aid in conservative plant-specific licensee evaluation of separation distances based on lessons learned from previously identified natural gas transmission line concerns near the Indian Point Nuclear Power Plant [3]. All approaches described herein are elements to be considered in developing a successful strategy for licensee regulatory self-evaluation.

The intended audience for these research results would most likely be utility licensees evaluating early site-specific conceptual designs for co-located HTEFs at nuclear power plants, including related impacts onsite fire-protection programs and plans.

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CONTENTS

FIGURES

TABLES

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ACRONYMS

CDF	core-damage frequency
CFR	Code of Federal Regulations
DOE	Department of Energy
FEED	front-end engineering and design
FMEA	failure-modes and effects analysis
FPEE	fire-protection engineering evaluation
FPP	Fire-Protection Plan/Program
FSAR	final safety analysis report
HP	high pressure
HTE	high-temperature electrolysis
HTEF	High-temperature electrolysis facility (hydrogen island)
HyRAM+	Hydrogen Plus Other Alternative Fuels Risk Assessment Models
INL	Idaho National Laboratory
LAR	license-amendment request
LERF	large early-release frequency
LP	low pressure
LWRS	Light Water Reactor Sustainability
MP	medium pressure
MW_{DC}	Megawatt direct current (electrical power)
MW_e	megawatt electrical rating (electrical power)
MW_{nom}	megawatt (nominal hydrogen plant electrical powering requirement)
MW_{th}	megawatt thermal rating (thermal power)
NFPA	National Fire-Protection Association
NRC	Nuclear Regulatory Commission
OCA	owner-controlled area
PA	protected area
PRA	probabilistic risk assessment
RG	Regulatory Guide
SNL	Sandia National Laboratories
SSC	system, structure, or component
TNT	trinitrotoluene

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Nuclear-integrated Hydrogen—Code and Licensing Separation Distance Considerations

1. INTRODUCTION

1.1 Background: The State of Nuclear-integrated Hydrogen-Facility Siting Research

Since the early 2020s, the Department of Energy (DOE) Light Water Reactor Sustainability Program Flexible Plant Operations and Generation Pathway at Idaho National Laboratory (INL) has provided critical laboratory-led research in support of nuclear-integrated hydrogen adoption as a potential alternate-energy stream for U.S. nuclear power lants (NPPs). This key research pathway has progressively and rigorously built the case for nuclear-integrated hydrogen by high-temperature electrolysis (HTE) as an alternate-energy stream to add to NPP resiliency and flexibility in the face of electric-grid pressures related to widespread growth of renewable-energy generation and the pressures of low-cost natural gas.

Over this time, one preeminent aspect of the research and development has been the establishment of successful paths to regulatory approval by the nuclear industry's primary licensing authority: the Nuclear Regulatory Commission (NRC). The specific regulatory-research approach was focused on three key areas, represented in Figure 1.

Figure 1. Regulatory-research areas related to nuclear-integrated hydrogen.

The detailed progression of the research in these areas has led to significant accomplishments in all three areas, as most recently described in [1,2,4]. A general visualization of the progressive research approach and corresponding deliverables is provided in Figure 2 and Figure 3 respectively.

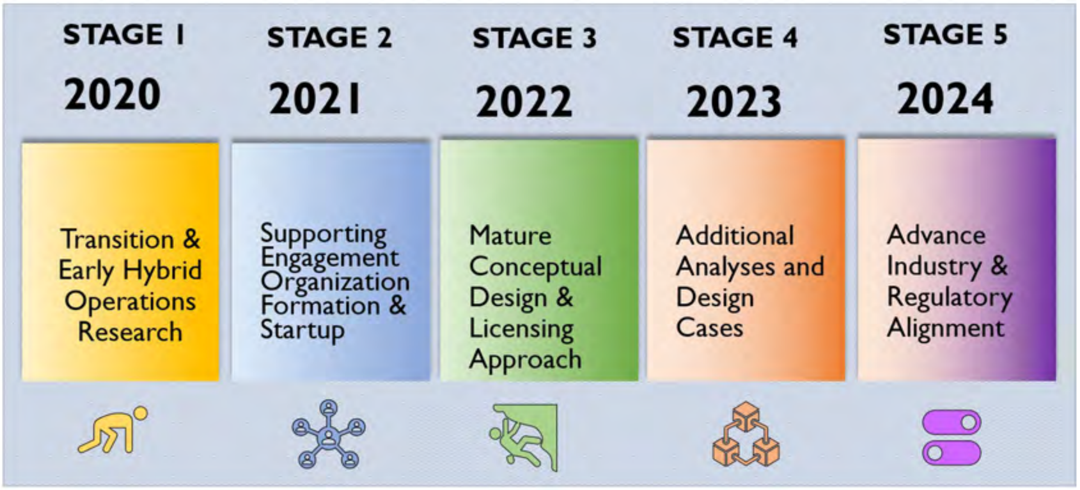

Figure 2. Progressive regulatory approach to nuclear-integrated hydrogen.

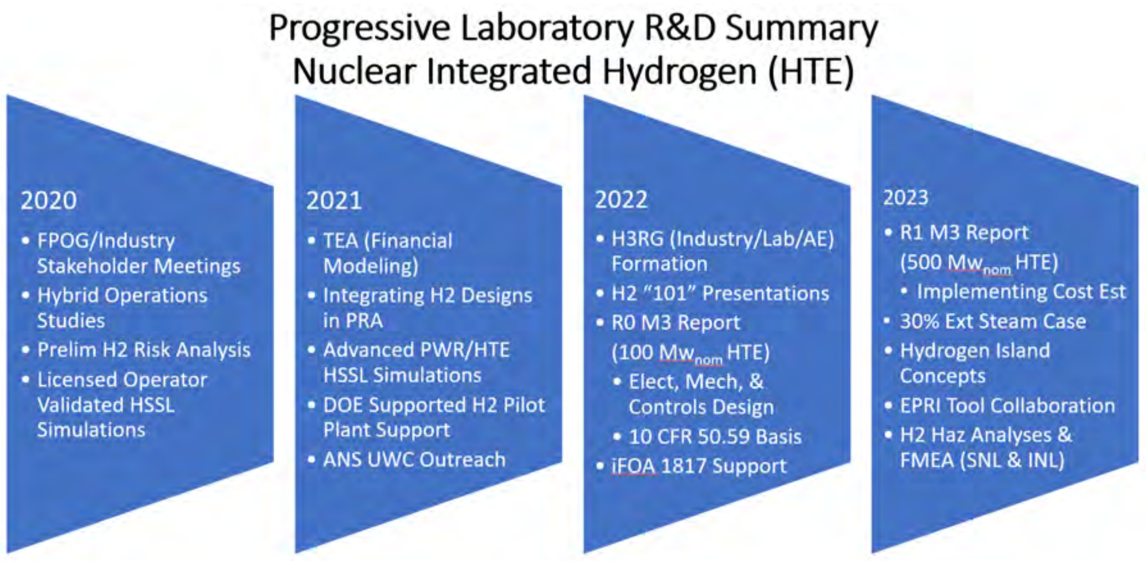

Figure 3. Summary of nuclear-integrated hydrogen research.

A key element of introducing a co-located high-temperature electrolysis facility (HTEF) at any existing (or new) NPP is to ensure that the establishment of new pressurized-hydrogen facility piping, and components do not introduce new failure-modes and effects that conflict with the system, structure, or component (SSC) pressure-loading and heat-flux assumptions explicitly described in or inferred from the NPP's original license. A preeminent design consideration associated with co-locating an HTEF in proximity to NPP SSCs is the capability to locationally site pressurized-hydrogen piping systems. The piping in owner-controlled areas (OCAs) must be sufficiently far from any NPP SSCs important to safety and must limit bulk pressurized storage on-site via routing of pressurized discharge lines directly to buried offsite hydrogen-network pipelines or industrial users. Onsite hydrogen-storage tanks associated with the HTEF will be kept small; thus, they are not addressed separately as leakage sources in this report. Industry research on hydrogen tank failures is available for further information [5].

1.2 Background and Common Evaluation Elements

The original licensing approach for fire-protection requirements varied widely across the industry in scope and content. This situation presented unacceptable variation and uncertainty relative to ensuring compliance with the regulations. Consequently, the NRC issued guidance in Generic Letter 86-10 [6], "Implementation of Fire-Protection Requirements," requiring licensees to incorporate their FPP into their final safety analysis report (FSAR) and amend their operating license to establish a standard fire-protection license condition.

The standard fire-protection license condition allows licensees to make changes to approved FPPs without prior NRC approval provided that the changes do not adversely affect the ability to achieve and maintain safe-shutdown in the event of a fire. Additionally, changes to specific features of the FPP may be made unless they involve a change to the license or technical specifications or require an exemption from existing regulations.

The revised standard license condition also resolved ambiguity relative to the relationship of proposed fire-protection changes with 10 CFR 50.59 [7–9]. 10 CFR 50.59(c)(4) provides that when applicable regulations establish *more specific* criteria for controlling changes, 10 CFR 50.59 does not apply. Therefore, applying 10 CFR 50.59 to FPP changes is not required. FPP changes conducted under the provisions of the license condition require a written evaluation establishing a conclusion that the changes do not adversely affect the ability to achieve and maintain safe-shutdown in the event of a fire. The evaluation should also include an assessment of the impact of the change on the existing fire-hazards analysis, as well as the effects on combustible loading and distribution. This assessment should also consider whether circuits or components, including associate circuits, for a train of equipment needed for safe-shutdown could be affected, or whether a new element could be introduced into the area.

All NPPs have a FPP that satisfies Criterion 3 of 10 CFR 50 Appendix A. This plan describes the overall FPP for the facility that falls into one of three classification groups:

1. Plants with operating licenses issued before January 1, 1979, and a deterministic FPP (also known as “pre-79” or “Appendix R” plants).
2. Plants with operating licenses issued after January 1, 1979, and a deterministic FPP (also known as Regulatory Guide (RG) 1.189, Revision 5 [9], (“post-79” or “BTP” plants).
3. Plants that have adopted a risk-informed, performance-based FPP through 10 CFR 50.48(c) 2120] (also known as “NFPA 805” plants).

This report specifically identifies applicable licensing and regulatory pathways based on fire-protection codes. These should be examined by NPP licensees when determining and self-evaluating minimum required HTEF separation-distance approaches for both Appendix R and National Fire-Protection Association (NFPA) 805 plant-licensing bases. Alternate separation distance research approaches as described in previous Light Water Reactor Sustainability (LWRS) Program research [1,2] are also discussed to aid in conservative plant-specific licensee evaluation of separation distances based on lessons learned from previously identified natural gas transmission line concerns near the Indian Point Nuclear Power Plant [3]. All approaches described herein are elements to be considered in developing a successful licensee regulatory self-evaluation strategy.

This report thus summarizes:

1. Accepted experientially based fire-protection-code requirements (and associated licensing bases) that establish minimum separation distances between NPP SCCs important to safety and proposed new co-located HTEFs outside NPP PA’s.
2. Bounding of deterministically based fire-protection augmented-evaluation methodologies based on an assumed guillotine break, the worst-case failure of high-pressure HTEF piping.

Both cases provide numerically derived separation distances and are presented herein for utility licensees’ consideration in early development of conceptual designs such as front-end engineering and design (FEED) studies for co-located HTEFs at NPPs, including related impacts on-site FPPs and plans.

Generalized licensee self-evaluation approaches are also outlined for original plant-specific fire-protection licensing commitments either under10 CFR 50 Appendix R (deterministic) [10] or NFPA 805 (probabilistic) [11].

Several constructive interactions have occurred between INL and NRC under a longstanding research memorandum of understanding. These discussions have been foundational in sharing laboratory research results and in identifying areas of regulatory interest regarding co-location of HTEF’s within NPP OCAs. None of the conclusions of this report should, however, be interpreted as having NRC concurrence or approval.

2. HTEF SEPARATION RESEARCH

2.1 High-Level Considerations

2.1.1 Introduction

This report summarizes the FY 2024 research focus by the Flexible Plant Operations and Generation Pathway regarding regulatory evaluation of co-locating HTEFs within an existing NPP's OCAs, as represented in Figure 4, which shows simplified NPP-HTEF electrical and steam-extraction interconnections as well as the concepts of maintaining separation between pressurized-hydrogen equipment and sensitive SSCs. The laboratory researched the capacity of such an integrated HTEF, which would be approximately 350 tons/day, based on 500 MW_{DC} powering and 100 MW_{th} steam extraction [1].

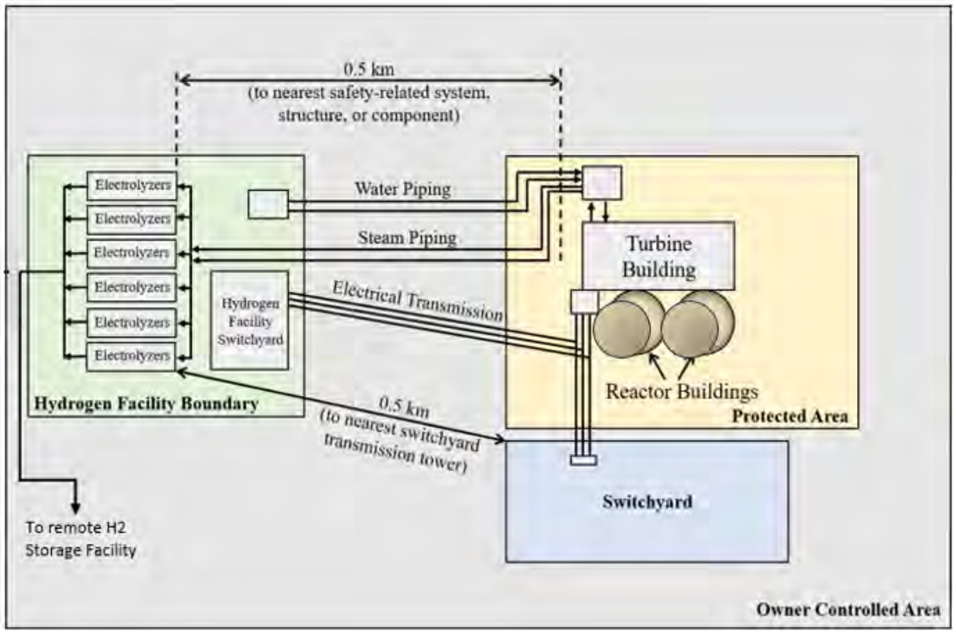

Figure 4. Generic nuclear-integrated HTEF layout.

The specific intent of this report is to lay out areas to be considered by NPP licensees in performance of self-evaluation of a licensing-approval pathway in support of co-locating an HTEF in the plant OCA. The focus here is on methods to determine appropriate separation distances between NPP SCCs important to safety and new HTEF pressurized-hydrogen-system components that may be subject to leakage or failure effects, which represent the potential for fire and/or detonation impacts on the NPP.

The importance of a proper evaluation of the area for hydrogen-system separation is not new from an NPP design or licensing perspective. All existing light-water reactors employ compressed hydrogen onsite for process functions, including electrical generator inerting, chemical and volume-control system coolant hydrogenation, and radioactive waste system functions. Original siting of all such compressed hydrogen storage equipment was designed to applicable fire-protection codes and considered within the original plant-licensing bases (including for determination of separation distance from NPP SSCs). New compressed hydrogen on-site, associated with co-location of an HTEF, will be similarly designed and considered for separation distance. Although a new HTEF was not considered as part of the original NPP licensing-basis, as will be demonstrated below, the applicable code and licensing guidance will be used, but under a self-evaluation process, as a change to the facility. This report outlines guidance to be considered in such a licensee self-evaluation of a change to the facility resulting from co-location of an HTEF within the OCA (including the basis for determining separation distance).

The introduction of a large-footprint HTEF, producing up to 350 tons of pressurized-hydrogen per day [1] may appear at first glance to introduce significantly increased fire and detonation hazards relative to the traditional compact for an existing onsite compressed hydrogen facility. However, this new co-located facility may in fact be similar to, or able to be enveloped by, the fire and detonation risks of the existing onsite facilities through careful application of design. Figure 5 diagrammatically shows the assumed layout of a new HTEF as described under [1].

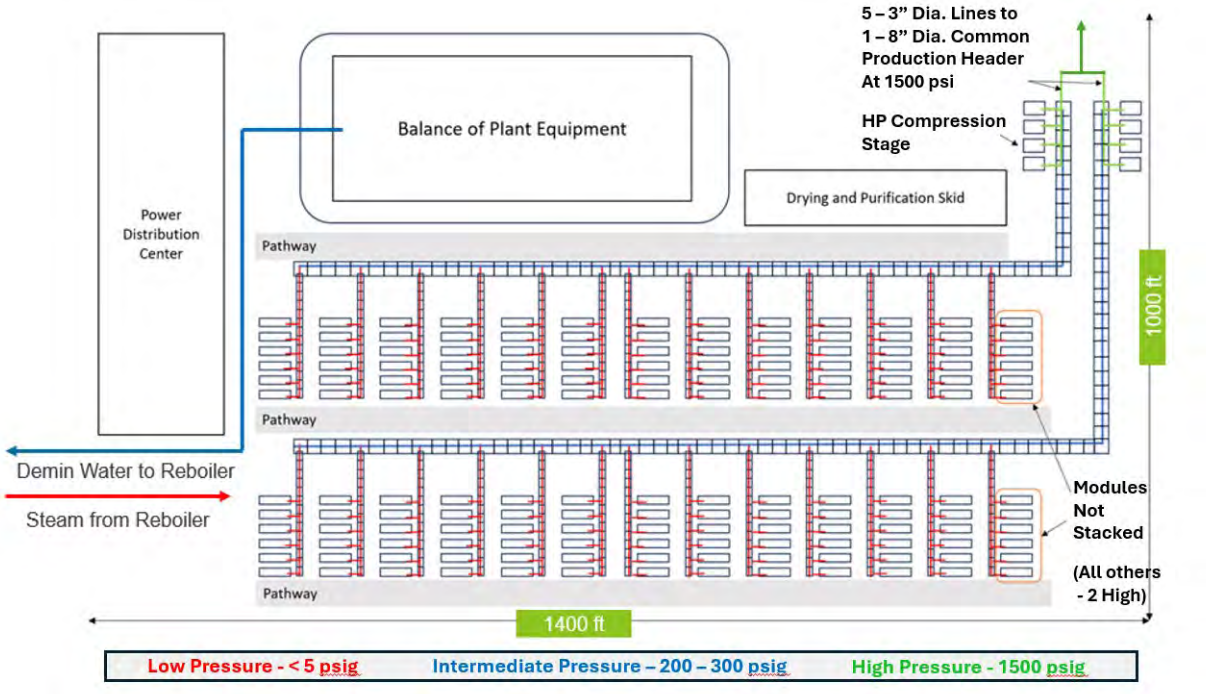

Figure 5 Layout of a generic 500-MWnom HTEF.

Characterizing the credible effects of leakage, or even gross failures, from HTEF pressurized-system components is key to understanding the analysis basis that would be applied when determining separation distances between discrete parts of the HTEF and the NPP SSCs important to safety. Some of these considerations are:

- As shown in Figure 5, the HTEF is made up of many near-atmospheric low-pressure electrolysis modules ganged into "stamps." The total electrical consumption of the stamps defines the nominal plant rating in MW_{DC}. A typical HTEF subcomponent is shown in Figure 6. This low-pressure (LP) first stage of the HTEF equipment and piping-system represents negligible risk of fire (heat-flux) or detonation pressure-wave impacts on NPP SSCs, assuming even incredible gross failure of all the modules simultaneously. Such LP introduction of hydrogen to an open atmosphere would quickly disassociate and be diluted below both the lower flammability limit and lower explosive limit. Other module-design approaches employing greater low-stage pressure (e.g., 15 psig) are likewise expected to be bounded from a separation-distance standpoint by assumed leaks and failures of similar HP process-piping sections.
- Figure 6 also shows the pressurized process-piping-system associated with an LP HTEF design, as described in Reference 1, segmented into three or more progressively compressed piping stages:
  - LP (<5 psig)—Red
  - Medium pressure (MP, 200–300 psig)—Blue
  - HP (1500 psig or more)—Green.

Figure 6. LP high-temperature electrolysis module.

The HP piping-system sections create the greatest potential for localized jets related to hydrogen leakage that, when assumed to be ignited, must be credibly evaluated for heat-flux and detonation-pressure-wave exposures as a function of distance. The calculational methods to determine separation distance required by fire-protection codes, as conservatively evaluated by the research [2,4,14] are described in detail under Sections 2.2 and 2.3 respectively. HP piping-section elements are also limited compared to the longer, low-risk LP and MP piping sections. This inherently limits this source of leak-risk potential and maintains only a very limited HP hydrogen-storage within the footprint of the HTEF, orienting the routing of HP lines to direct any assumed leakage directionally away from NPP SSCs and burying HP lines as they are directed away from the HTEF toward nearby industrial users or existing hydrogen-network transport systems. This offsite routing of hydrogen to end users is represented in Figure 7.

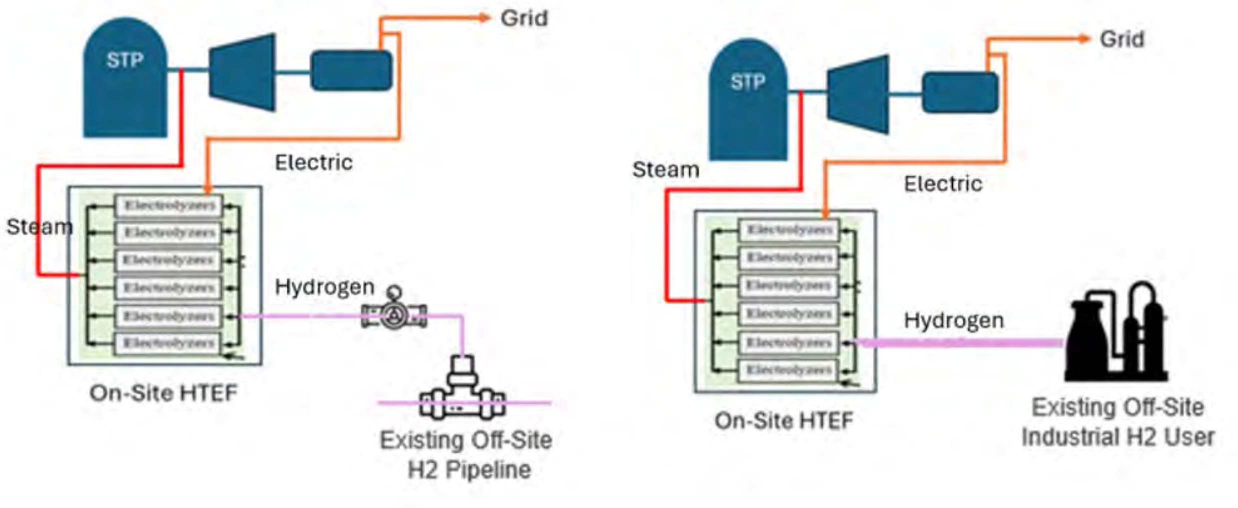

Figure 7. Common offsite hydrogen-transmission schemes.

- An HTEF co-located in an OCA would, in most cases, be sited hundreds of meters from any NPP SSC important to safety out of practical necessity. It would generally reside within the PA fence. Siting considerations such as security-plan standoff from the PA fence line would likely mandate such a standoff, independent of the numerical and code methods described in Section 2.2 of this report.
- Fire-protection codes widely accepted for determining design and safe standoff distances between commercial pressurized-hydrogen systems and critical sensitive infrastructure and facilities [12–14] are directly and indirectly based on the experience-based premise that credible pressurized-hydrogen-system leakage is manifested in small leaks, rather than gross failures. Significant safety margins are also included in these tabular separation-code methodologies [13]. Thus, without the credible expectation for gross failures (which have been evaluated for augmented separation distance in the research [2,4] as described in Section 2.3 of this report), minor leakage from HTEF components located in the OCA are expected to manifest worst-case in localized flame (heat-flux) without mass aggregation to support detonation; thus it would not represent a credible challenge to NPP SCCs located within the PA.

Given these considerations, this report focuses on evaluating separation of a co-located HTEF with credible leakage assumptions, as described in NPFA 55 [13] (and in Section 2.2 of this report), based on highly conservative failure-modes and effects analysis (FMEA) [15] assuming full guillotine break of the highest pressure (1500 psi) compression-stage piping in the least-favorable orientation (as described in Section 2.3 of this report). A licensee self-evaluation approach for addition and integration of a co-located HTEF is also outlined in Section 3.

2.2 Licensing Requirements

2.2.1 Original Plant Fire-Licensing Requirements

Currently licensed NPPs are either licensed under deterministic or probabilistic fire-protection regulations:

- Appendix R—Fire-Protection Program for Nuclear Power Facilities Operating Prior to Jan 1, 1979 [11]
- NFPA 805—Performance-Based Standard for Fire-Protection for Light Water Reactor Electric Generating Plants, 2001 edition [11].

Both regulatory frameworks for fire-protection at NPP sites support co-locating systems to store compressed gaseous hydrogen to support generator inerting, chemical- and volume-control and gaseous radwaste system functions within the PA of NPPs. Safe separation distances between these original plant storage facilities for hydrogen-production support were historically assessed based on NFPA 55 [13] or NFPA 50A [14] flammable gas regulation rules, depending on plant-license vintage. Eventually, both Appendix R and NFPA 805 NPPs were able to credit use of the more-modern NFPA 55 calculational methods to identify minimum separation distances between hydrogen systems and SSCs.[a] Some of the history behind this is captured in Appendix A.

Thus, existing fleet NPPs are either currently approved for, or have a self-evaluation pathway to the use of NFPA 55 for current-day evaluation of HTEF separation distance from NPP SSCs important to safety.

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[a] RG 1.205 methodologies in support of transitioning to from Appendix R to NFPA 805 (through the license-amendment request process from original 10 CFR 50.48[b] to 10 CFR 50.48[c] [20] respectively) were not considered germane to this report’s description of pathways to NFPA 55.

2.2.2 Current NFPA 2 Fire-Licensing Requirements

An HTEF located in an NPP OCA today would likely be designed to hydrogen-specific NFPA 2, Hydrogen Technologies Code [12]. As described within NFPA 2, the intent “shall be to provide fundamental safeguards for the generation, installation, storage, piping, use, and handling of hydrogen in compressed gas (GH_2) form or cryogenic liquid (LH_2) form.” Thus, the general associated piping and equipment and other code safety standards to be employed for the HTEF as a standalone GH_2 facility in the NPP OCA currently would be expected to meet NFPA 2. However, this code is not directly referenced within the licensing pedigree of either Appendix R or NFPA 805 plants. Employing this widely accepted code standard would, however, be wisely included as a design-evaluation basis provided under the Fire-Protection Engineering Evaluation (FPEE) allowed by both Appendix R and NFPA 805 plant self-evaluation processes for the change to the facility associated with co-location of an HTEF.

The separation distance determination between this co-located NFPA 2 facility and nearby NPP SSCs important to safety would be addressed by NFPA 55, or conservatively defined by other criteria (e.g., HyRAM+ or RG 1.91, “Evaluation of Explosions Postulated to Occur on Transportation Routes near Nuclear Power Plant Sites [16,17],” separation methodologies) as directly allowed by both Appendix R and by FPEE under NFPA 805 licensed NPPs. NFPA 2 ensures suitable industry standards for a proven safe configuration for an HTEF and is thus a supporting underlying premise for the separation-distance calculation done under NFPA 55[b].

2.3 Licensing Codes and Standards

2.3.1 NFPA 55 Derived Separation Distances

NFPA 55 establishes allowable table-based minimum separation distances between compressed hydrogen gas systems and credible leakage dimensions as a function of

- Overall pipe diameter: Table 10.4.2.2.1(a), “Minimum Distance (D) from Outdoor Bulk Hydrogen Compressed Gas Systems to Exposures—Typical Pipe Size”
- Low System Pressures: Table 10.4.2.2.1(b), “Minimum Distance (D) from Outdoor Bulk Hydrogen Compressed Gas Systems to Exposures by Maximum Pipe Size with Pressures >15 to $\leq$3,000 psig” [c]
- High System Pressures: Table 10.4.2.2.1(c), “Minimum Distance (D) from Outdoor Bulk Hydrogen Compressed Gas Systems to Exposures by Maximum Pipe Size with Pressures >3000 psi to $\leq$15,000 psig.”

Tables are arranged into fire-exposure groups for similar risks (including Group 3 exposures for “Building or structure constructed of noncombustible or limited-combustible materials” such as at NPPs). A through-wall leak area of 1% of the main-line national pipe size internal area forms the derivation basis for the NFPA 55 pre-calculated table-separation dimension in meters. The current code use of leak size as a percentage of main-line size is based on statistical methods enveloping credible leak data experience that most leaks are within 1% of main-line area. A 50% safety factor is also added to the table’s separation results for all minimum required separation distances per Appendix A of NFPA 55.

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[b] An NFPA 2 industry-expert working group is currently considering changes to NFPA 2 to better address hydrogen-specific applications. This includes review of the tabular separation-distance determination methodology. Appendix B addresses some of the proposed changes. Licensee adoption of future hydrogen-specific changes from this working group should be considered as they become available (especially in separation-distance methodology).

[c] The inherent fire safety conclusion drawn under Section 2.1.1 based on the LP first stage HTEF technology evaluated herein (approximately 5 psig) is enveloped by the lower applicability threshold as defined under NFPA 55 for LP Systems (>15 psig).

[d] Note: If choosing the latter HyRAM+ method, numerical tool calculation equivalency demonstration may be required via software verification and validation against the RG methodology as part of the licensee self-evaluation approach.

2.3.2 Elective Separation-Distance Methodologies

Where new evaluation methodology may be considered for site-specific licensing or for additional conservatism to improve public [3] understanding and acceptance of the risks related to a new MW-level co-located HTEF, licensees should also be able to use other generally accepted code or numerical bases to self-evaluate appropriate minimum required separation distances. This separation-case development could reasonably draw on previous methods (including those described under [1,2]) including:

- RG 1.91 [17] is a guide used to evaluate explosive sources located near an NPP, but outside of the OCA. The regulatory guide uses a trinitrotoluene (TNT)-mass-equivalence calculation in a detonation-analysis methodology based on a defined, calculated, credible mass release of hydrogen. This credible mass release was derived conservatively in [1,2] from a hydrogen-facility's pre-conceptual design of a 500 MW hydrogen-production facility and FMEA [14], which assumed guillotine breakage of hydrogen-transport lines throughout the facility. This included lower-pressure sections of the large-footprint facility up to the combined high-pressure (1500 psi) 8-in. output header of the facility. This type of evaluation can be performed directly using the RG methodology, which includes nomographs for peak positive pressure versus scaled ground distance and distance from explosion versus quantity of explosives (RG 1.91 Figure 2, Figure 3, and Figure 4 [17]) or via modern tools such as HyRAM+ [16] that can numerically determine equivalent results.[d] A sensitivity study between the factors used in RG 1.91 and HyRAM+ will be provided in the update to [2] to be published in September 2024.
- Use of HyRAM+ Bauwens or similar methodology based on full guillotine pipeline-break assumption and continuous mass-flow rate in a release from a calculated break in a given orifice size (derived from an architect engineer-led FMEA) [12].
- The application of a previously performed RG 1.91 offsite explosive risk separation distance evaluation may present a reasonable technical basis for applying that distance to a new onsite (OCA) hydrogen risk. Although this was clearly not the intent of RG 1.91, it may represent a credible alternate separation distance methodology if the mass of hydrogen determined by FMEA for an onsite HTEF line break were enveloped by the original RG 1.91 explosive content assumptions. In that case, a previous enveloping offsite RG 1.91 separation distance calculation basis could potentially be used for the new HTEF. This evaluation approach (which would not specifically address heat-flux effects) has not been developed by any of the research to date and thus it is not explored further within this report.

In the previous research work [1,2,4,15] both methods—the HyRAM+ Bauwens and TNT-mass-equivalence calculation—were applied to an assumed guillotine break of the largest main pressurized line. This provides separation distance over-conservatism compared to widely accepted NFPA 55 methodologies, as expected. However, these larger HyRAM+ separation distances are not expected to be problematic in practice with respect to HTEF siting based on a review of several actual NPP site configurations [2] and are in-line with expectations for safe siting distances to explosive sources located outside of the OCA [17]. Additionally, non-numerically derived separation distance factors would potentially be conservatively driven by other site-specific considerations, such as security-plan setback requirements for locating equipment near the PA fence line.[e]

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[e] Although not specifically prohibited, based on wide-spread adoption of NFPA 55 as an accepted well-vetted standard across multiple industries, it is not recommended that alternative methodologies be adopted with the intent of establishing closer separation distances than specified in NFPA 55. The research intent of developing alternate calculation methodologies for separation distances is to provide bounding calculational conservatism that deterministically confirm NPP SSC and surrounding public safety [28] of a large-scale HTEF footprint based on worst-case failure assumptions applied to the most vulnerable pressurized hydrogen system piping and components.

2.3.2.1 HyRAM+ Specific Methodology

The HyRAM+ pipeline-break methodology run in either TNT-equivalence or Bauwens mode defines the resultant two-dimensional profile of a hydrogen plume, with peak heat-flux (flame) and hydrogen-mass (detonation) zones to respective heat-flux (37.5 kW/m^2 and overpressure (1.0 psi) limits [16]. The aspects of these numerical tools and their application are described thoroughly in [1,2,4]. Specific summary aspects of their use related to separation distance determination from the perspective of elective conservative numerical-tool use options are provided below.

Heat-Flux

The heat-flux zone allows characterization of heat-flux in kW/m^2, which can subsequently be used to define the separation distance at which the applied heat-flux to NPP SSCs is below specified types of fragility damage to SSCs. Table 1 from [18] specifies such fragility limits for fire-related heat-flux on various types of damage (applicable to both nuclear and non-nuclear SSCs).

Table 1. Damage to structures and equipment from thermal radiation.

Thermal Radiation Intensity (kW/m^2)	Type of Damage
4	Glass breakage (30 min exposure)
12.5–15	Piloted ignition of wood, melting of plastics (>30 min exposure)
18–20	Cable insulation degrades (>30 min exposure)
10 or 20	Ignition of fuel oil (120 or 40 s, respectively)
25–32	Unpiloted ignition of wood, steel deformation (>30 min exposure)
35–37.5	Process equipment and structural damage (including storage tanks) (>30 min exposure)
100	Steel structure collapse (>30 min exposure)

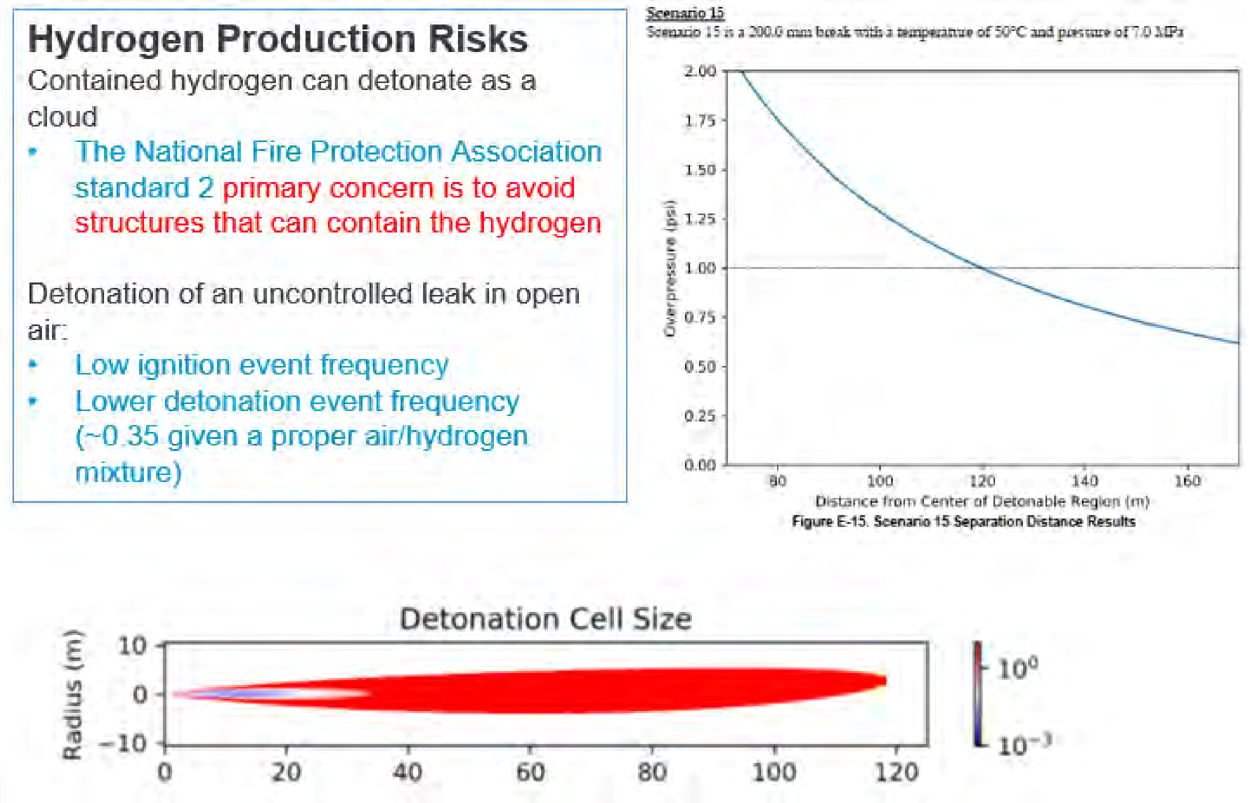
Elective use of HyRAM+ to determine heat-flux-based conservative separation distances beyond NFPA 55 minimum requirements would identify an appropriate fragility limit from Table 2 (e.g., 35 kW/M^2 for equipment and structure type SSCs) and select a separation distance that conservatively limits heat-flux below the applicable type of damage to be avoided. It is noted that Table 2 has a time-dependency element compared to HyRAM+ calculational results that assumes a constant-dimensioned hydrogen heat-flux independent of time. It is assumed that by implementing NFPA 2 [12] design features that include reverse and excess-flow check valves, the duration of any hydrogen fire due to a pressurized piping-system leak would be short and would progressively diminish as isolated piping sections depressurize to atmospheric levels. This should be built into the design of the HTEF based on a detailed FMEA.

A similar hybrid separation distance approach could be employed using historical NUREG/CR-3330 [26, 27, 28, 29], with HyRAM+ calculated separation distance conservatively selected to remain below the NUREG-based temperature limit of 350°F at the first structural-rebar location versus more-modern heat-flux methodology.

Detonation Effects

The hydrogen-mass zone (as shown on Figure 8, blue) defines the detonable mass of hydrogen contained within the overall jet to be applied for calculation of pressure-wave effects as a function of distance. It is noted that the hydrogen leakage risk research [2,4] confirmed:

- The code bases around cloud-initiated fire concerns associated with hydrogen release to open atmosphere are conservative, based on the highly dispersive qualities of hydrogen in air.
- The validity of the jet-shaped hydrogen plume made up of majority combustible (red/white) and minority (blue) detonable dimensions, per Figure 8. [4].



Hydrogen Production Risks

Contained hydrogen can detonate as a cloud

- The National Fire Protection Association standard 2 primary concern is to avoid structures that can contain the hydrogen

Detonation of an uncontrolled leak in open air:

- Low ignition event frequency
- Lower detonation event frequency (~0.35 given a proper air/hydrogen mixture)

Scenario 15

Scenario 15 is a 200.0 mm break with a temperature of 50°C and pressure of 7.0 MPa

Figure E-15. Scenario 15 Separation Distance Results

Figure 8. Hydrogen fuel-production risks.

An alternate calculational feature of the HyRAM+ tool is the ability to run a TNT-equivalent methodology calculation for pressure-wave separation distance consistent with RG 1.91. This RG specifically describes an effective methodology for determining minimum safe distances from NPP SSCs to generic off-site explosive sources such that “any explosion that might occur... is not likely to have an adverse effect on plant operation or prevent a safe-shutdown.” Additionally, under the RG methodology, a detailed NRC review of the off-site explosive source would not be required. Although the RG was not specifically intended to be used as an evaluation tool for pressure effects from leak-related detonations of hydrogen facilities located within the OCA, the fundamental methodologies described within the RG have been used widely to evaluate the effects of assumed off-site detonations on NPPs since the 1970s and are considered technically sound and transportable to evaluation of new detonation sources within the OCA of NPPs.

If HyRAM+ or other similar calculational tool is used to perform a RG 1.91-type separation calculation for a co-located HTEF within a NPP OCA, independent verification and validation of the software results against the tabular regulatory guide results is recommended to ensure stated equivalency or as a minimum, verifies that the resultant separation distance meets or exceeds applicable NFPA standards within the site fire-protection plan.

A general assumption made under research inputs to this report [1,2] is that HTEF oxygen byproduct will be vented such that no adverse interaction on hydrogen flammability is possible. The details of such a process venting design should be further developed under future FEED studies.

2.3.3 Detailed Separation-Methodology Comparisons

This section compares the results of different code and numerical calculation methodologies for determining HTEF separation distances due to assumed hydrogen pipe leakage and breaks. The reference HTEF design attributes below from [1] are used for all separation methodologies:

- 500-MWnom HTEF rating
- 500-MW_e and 100-MW_{th} extraction
- HTEF daily production of 350 tons/day
- High-pressure hydrogen of 1500 psig
- Largest high-pressure pipe size of 3-in. ID.

Reference 3 defined several leakage cases from which calculated separation distances were determined to maintain acceptable overpressure and radiant heat-flux impacts on NPP SSCs. Not all cases were included in this report, but the following conservative leakage scenario cases are included:

- The simplified 500 MW_{nom}-base HTEF design [4] assumed that a 100-MW_{nom} HTEF with a single 3-in. second-stage discharge line is effectively replicated five times and ganged into a common 8-in. discharge header that is routed underground within an engineered barrier.
- Based on realistic conservative assumed failure scenarios of a single 3-in. second-stage discharge line, only a single failure of a 3-in. high-pressure compressed gas line is assumed (Case 6 [3]). Concurrent 3-in header failures were not deemed credible.
- Several lower-pressure leakage scenarios (Cases 1–5) were also evaluated [4]. These were not limiting for overpressure or heat-flux separation-distance determination base on low driving-head pressures and, as such, are not discussed in detail herein.
- An assumed guillotine break on the 8-in. common production header (Case 7), and the resultant overpressure results were calculated [4] and are presented herein. It is, however, assumed that risks associated with a large-diameter high-pressure common production header would likely be mitigated by routing within a simple engineered barrier (at least for unburied pipe lengths within the HTEF).
- An assumed leakage Case 8 from a 1000 kg hydrogen tank at 5000 psig was also considered [4]. Because minimal hydrogen-storage was assumed for the NPP site OCA (as previously stated in this report), this case was not evaluated herein. Tank-leakage scenarios will continue to be evaluated under future research projects.
- LP (magenta) separation distances circumscribed in Figure 9 are represented as localized, discrete separation distances. This was based on the previous assumption [2] that, although cascading detonations were possible between individual LP modules, the sequential effects would not aggregate into detonations greater than that associated with any individual module. This could be evaluated in more detail in future FEED studies.

Based on the above design inputs and leakage scenarios researched, Table 2 and Table 3 show the comparative minimum overpressure and radiant heat-flux separation distances derived between HyRAM+, RG 1.91 numerical tools, and how HyRAM+ separation results track comparatively with NFPA 55 when calculating distance via the NFPA 55 code orifice sizes tables.

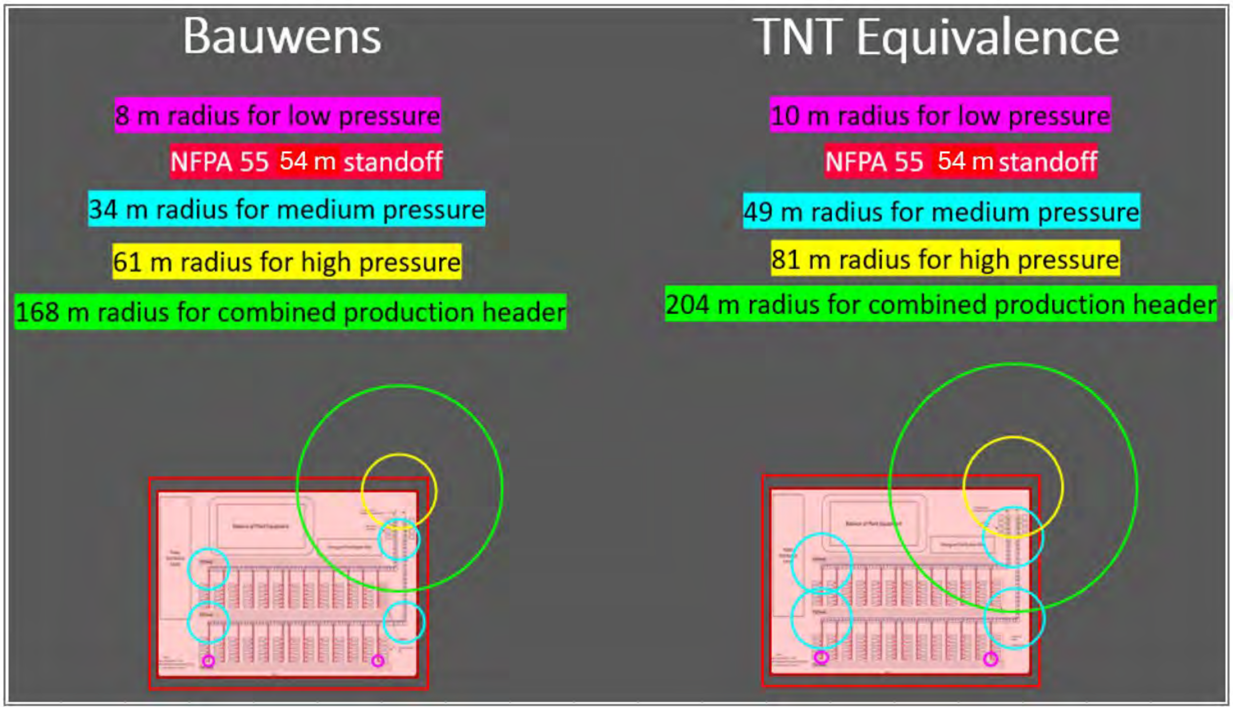


Figure 9. Bauwens versus TNT-equivalence-detonation safe-separation distances.

Table 2. HyRAM+ (Bauwens) versus TNT equivalence (RG 1.91) detonation-safe overpressure-separation analysis.

	HyRAM+ (Bauwens) (@ 1 psi)	HyRAM+ (TNT Mass Equivalence Method) (@ 1 psi)	Cases [4]
Leak Size Assumed	76-mm-diameter orifice	76-mm-diameter orifice	Case 6 (3-in. pipe)
Calculated Separation	61 m	81 m	Case 6 (3-in. pipe)
Leak Size Assumed	203 mm diameter	203 mm diameter	Case 7 (8-in. pipe)
Calculated Separation	168 m	204 m	Case 7 (8-in. pipe)
Bounding Calculated Separation	168 m	204 m	—

These comparative-analysis findings may be visualized via Figure 9 for the detonation safe-separation distances for LP, MP, HP, and combined-production HP piping sections overlaid on the generic 500-MW_{nom} HTEF layout, represented in Figure 5.

Table 3. HyRAM+ versus NFPA 55 heat-flux safe separation analysis.

	HyRAM+ (@ 37.5 kw/m^2)	NFPA 55 (Group 3 Exposure)[f]	Cases [4]
Leak Size Assumed	76-mm-diameter orifice	7.6 mm diameter orifice (1% of pipe diameter)	Case 6 (3-in. pipe)[g]
Calculated Separation	88 m	21 m	Case 6 (3-in. pipe)
Leak Size Assumed	203 mm diameter orifice	20.3-mm-diameter orifice	Case 7 (8-in. pipe)
Calculated Separation	168 m	55 m[h]	Case 7 (8-in. pipe)
Bounding Calculated Separation	208 m	54 m	—

These comparative tabular analysis findings may be visualized via Figure 10 for the heat-flux safe-separation distances for LP, MP, HP, and combined-production HP piping sections overlaid on the generic 500-MW$_{nom}$ HTEF layout, represented in Figure 5.

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[f] NFPA Table 10.4.2.2.1(b) establishes minimum separation based on maximum pressure of 3000 psi and included 50% margin on separation values. HyRAM+ was calculated for actual design pressure (1500 psig) with no margins added.

[g] NFPA Table 10.4.2.2.1(b) allows interpolation of minimum separation distance up to 3-in. pipe size per Appendix A of NFPA 55. In the absence of larger pipe size data, Table 3 above interpolates the separation effects of an 8-in. pipeline with a 1% cross-sectional area leak. Because this was outside the stated interpolation limits of NFPA 55, the results were compared to a similar heat flux evaluation performed under HyRAM+ [4] for a 1% area leak. The conservative NFPA 55 separation distances were about twice that of the HyRAM+ results. This was probably at least in part due to the 50% safety factor built into the NFPA 55 separation tables compared to HyRAM+ without safety factors applied and the 3000-psi upper limit associated with NFPA 55 tables versus HyRAM+ calculation basis of 1500 psi from the assumed system design.

[h] The NFPA 55 separation distance boundary determined under Table 3 is conservatively applied in Figure 10 and Figure 11 from the HTEF footprint “perimeter” versus the most conservative high-pressure “leak location” for simplicity versus locally applying it at each pressurized piping section throughout the HTEF.

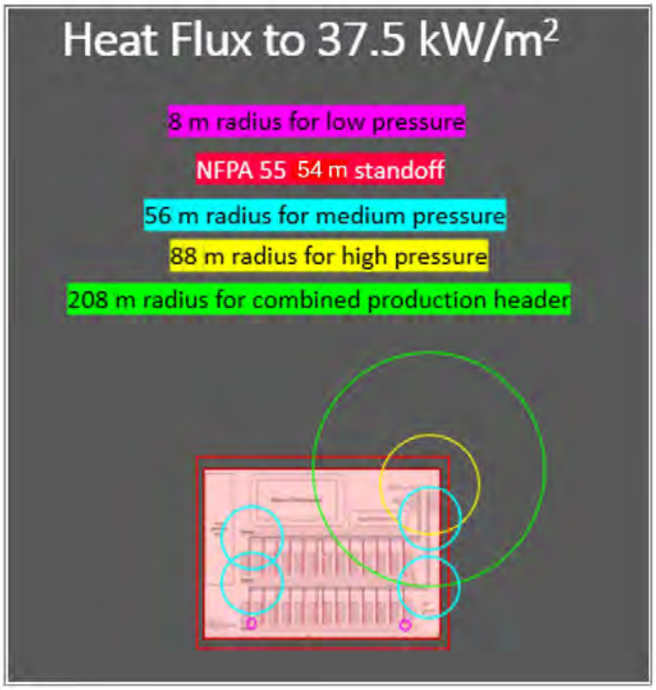


Figure 9. Bauwens versus NFPA 55 safe heat-flux distances.

Figure 11 represents a rollup compilation of the bounding detonation or heat-flux separation values extracted from Table 2 and Table 3:

- HyRAM+ analyzed guillotine break leakage (Bauwens and TNT equivalent methodology) by HTEF piping size and pressure class
- Corresponding NFPA 55 code is based on an assumed leakage area 1% of maximum pipe cross-sectional area and worst-case pressure applied for NPP (Group 3) type exposures.

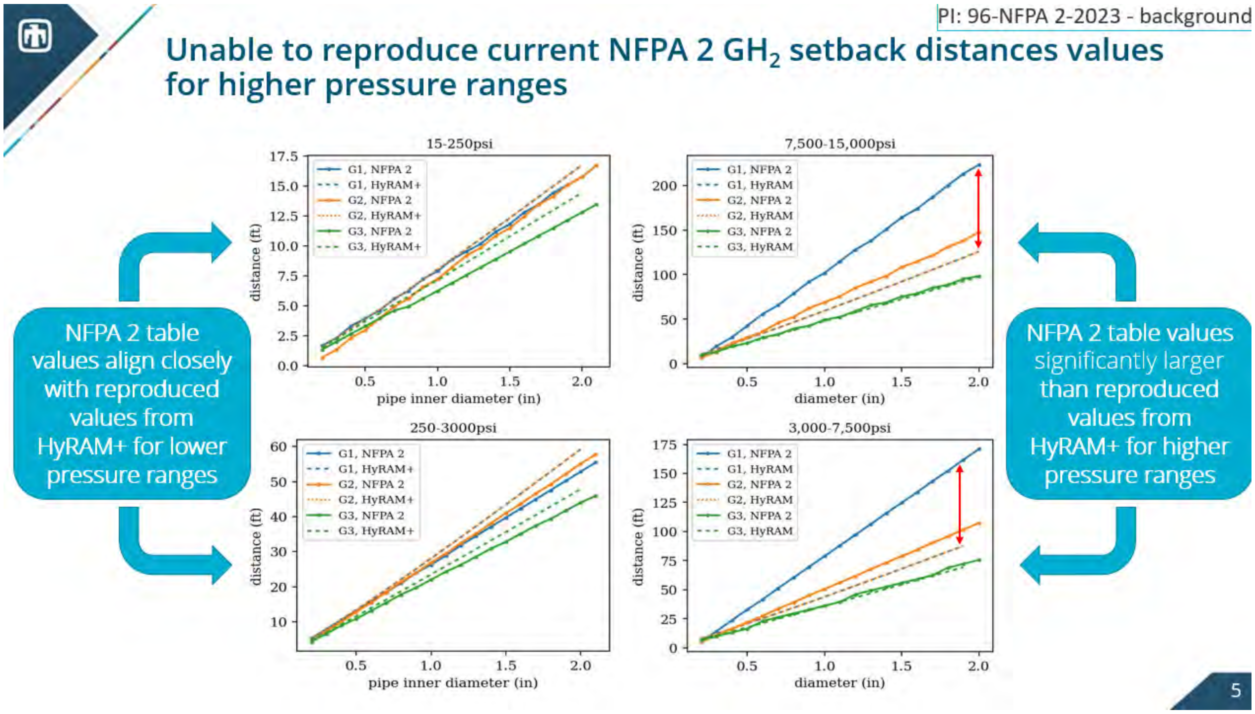
This visual representation of bounding-detonation or heat-flux-separation distances is provided simply to show the effects of selecting different methodology-derived separation values applied for maximum assurance of acceptable NPP SSC interaction impact with a co-located HTEF. Other variations on the use of such individual numerical separation-determination methodologies or the simple use of NFPA 55 code tabular separation distances should also be technically justifiable as a basis for licensee self-evaluation.

Figure 10. Generic 500-MW$_{\text{nom}}$ HTEF-NPP site layout with bounding safe detonation and heat-flux distances.

Although not specifically used in any of this report's separation distance determination approaches, NPP licensee FPEE self-evaluations of the future may find value in understanding how HyRAM+ computational leakage results track against the tabular separation results from NFPA 2 (and 55) for 1% of cross-sectional area-leakage assumptions. Sandia National Laboratories (SNL) made a presentation at the April 2024 NFPA 2 working-group meeting comparing setback distance results on this topic. Figure 12 summarizes these comparative results which show that HyRAM+ leak orifice size calculations tracked well with NFPA 55 1% leakage results through 3000 psig line pressures. Above 3000 psig, NFPA 2 table values became significantly larger than those calculated by HyRAM+. Based on discussions with SNL code-committee participants, there is no indication that these differences were intentional by the technical committee of NFPA 55 at the time, and so these differences may simply have been an oversight or data-transposition error. Pending possible clarifications in future NFPA 2 code versions, these differences will need to be kept in mind while using table values or linear equations from NFPA 2 or 55 for setback distances for pressures above 3000 psig to compare resultant values from the table and those calculated using HyRAM+.

Because of the common underlying fundamentals between the generic combustible-gas analysis methods described under NFPA 55 and for hydrogen-specific gas analysis under NFPA 2, these results do provide confidence in the conservatism of the underlying leak-calculation method that formed the basis for the NFPA 55 tabular approach. HyRAM+ leak analysis for hydrogen pressures above 3000 psig would need to address these divergent (non-conservative) findings compared to tabular use of the NFPA 55 for separation distance as part of any analysis involving HyRAM+ in lieu of the NFPA 55 tables. This may be applicable in particular if the current NFPA conservative separation bias above 3000 psi were not supported due to spatial design limitations of the real estate available to locate the HTEF after applying the separation-distance requirement.

As noted in Appendix B, NFPA 55 is expected to transition to NFPA 2 in the next code revision, and these code inconsistencies may be addressed at that time.



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Unable to reproduce current NFPA 2 GH_2 setback distances values for higher pressure ranges

NFPA 2 table values align closely with reproduced values from HyRAM+ for lower pressure ranges

NFPA 2 table values significantly larger than reproduced values from HyRAM+ for higher pressure ranges

Figure 11. April 2024 NFPA 2 working-group meeting setback-distance comparison (NFPA 2 versus HyRAM+).

3. LICENSEE SELF-EVALUATION

Section 1.2 describes historical classification of schemes used to satisfy regulatory requirements for separation of elements within NPPs. Specifically, it delineates the use of traditional, deterministic risk analyses for licenses established before and after January 1979 (Appendix R and BTP plants, respectively, and labeled Group 1 and 2 in this section) and the employment of a risk-informed, performance-based FPP, in what is called NFPA 805 (or Group 3) plants. This section of the report discusses the self-evaluation approach of each of these plant FPPs in more detail.

Independent of the FPP classification, the first step in self-evaluating a co-located HTEF is to clearly define the change and conduct an impact review. If the change is determined to be minor, documenting the change and basis is sufficient. Next, a preliminary risk screen is performed to evaluate whether the impact is potentially more than minimal for NFPA 805-licensed plants. The results of this screen determine whether a qualitative risk evaluation is sufficient; otherwise, a more-detailed quantitative evaluation would be necessary. Once the risk evaluation is complete, the results are compared against the change in core-damage-frequency (CDF) and large early-release-frequency (LERF) acceptance criteria. Assuming the risk-acceptance criteria are met, separation distance determination by NFPA 55—as described in Section 2.3.1 and/or alternate methodologies as described in Section 2.3.2—would be adequate. Should these criteria be exceeded, it would be prudent to explore alternate plant-change strategies, but these are outside the scope of this research report.

Specific self-evaluation process elements, as described in Sections 3.1 (for Groups 1 and 2) and 3.2 (for Group 3) may lead to FPP changes for any of the three program categories. Common FPP-change initiators may result from alteration of plant hardware or plant program documents and procedures that affect the FPP. In addition to changes directly related to fire-protection, this type of change may include plant changes that are not directly associated with the fire-protection system or procedures, but that could, for example, affect the results of the post-fire, safe-shutdown circuit analysis. Another example of an FPP change is an *in situ* condition (physical or programmatic) that is an FPP regulatory noncompliance or a fire-protection licensing-basis noncompliance and which the licensee does not intend to correct through a plant or programmatic modification.

3.1 Appendix R Plants

3.1.1 Group (1) and (2) Plants—Appendix R or RG 1.189 Plant Change Processes, Respectively

The March 22, 1975, fire at the Browns Ferry Nuclear Power Plant (near Decatur, Alabama) fundamentally changed how the NRC dealt with fire-protection at U.S. nuclear power plants. Event guidance before the Browns Ferry fire was very broad, so a deterministic method was created in guidance documents like BTP APCSB 9.5-1. The NRC developed this approach when the best fire-risk tools available to staff and the industry looked at an entire system. The NRC lists deterministic requirements in 10 CFR 50.48(b) and Appendix R of 10 CFR Part 50. Current guidance is provided in RG 1.189, which provides plants with an acceptable approach to meeting these requirements.

Both Appendix R and RG 1.189 licensing-basis plants would start the self-evaluation process by screening out proposed change using 10 CFR 50.59 plant-specific procedures. Although early Appendix R plants have unique plant-specific licensing under BTP APCSB 9.5-1 [21], which was issued before Appendix R was issued, the NRC later issued RG 1.189 to address all NPPs that are licensed under the Appendix R licensing-basis, covering both Group 1 and 2 plants, so that any plant changes made currently would fall under RG 1.189 guidance.

RG 1.189, Section 1.8.1, “Change Evaluations” states, “If an existing plant has adopted the standard license condition for fire-protection and incorporated the FPP in the... FSAR,” the licensee may make changes to the approved FPP without the Commission’s prior approval (per RG 1.189, Revision 5, page 31) only if those changes would not adversely affect the ability to achieve and maintain safe-shutdown in the event of a fire. The FSAR should include or reference the evaluation that documents the change. In addition to planned changes, nonconforming conditions (see Section 1.7.7 for examples) may also require an evaluation. Note that the standard license condition mentioned above was implemented via Generic Letters 86-10 [6] and 88-12 [22] for most currently operating NPPs. The standard license condition phrase “not adversely affect the ability to achieve and maintain safe-shutdown in the event of a fire” means to maintain sufficient safety margins.

Additional details are described in Section 1.8.1 that in summary points to NRC staff noting that industry guidance document NEI 02-03 [24], “Guidance for Performing a Regulatory Review of Proposed Changes to the Approved Fire-Protection Program,” Revision 0, issued June 2003, can provide useful guidance for performing change evaluations in accordance with the plant’s fire-protection licensing condition and approved FPP. Although the NRC has not specifically endorsed NEI 02-03, if rigorously followed, it represents a licensee self-evaluation methodology that is expected to withstand routine regulatory triennial inspection scrutiny related to co-located hydrogen-facility design, code use, and standoff determination.”

The proposed HTEF located in the OCA (outside the PA) would need to consider the RG 1.189 design criteria in Sections 2.1.4, “External and Exposure Fire-Hazards,” 4.1.8, “Explosion Prevention,” and 7.5, “Flammable Gas Storage and Distribution,” all of which refer to NFPA 55, “Compressed Gases and Cryogenics Fluids Code.” NFPA 55, Chapter 10, “Gas Hydrogen Systems,” includes tables with criteria that allow plants to determine the minimum distance from a bulk hydrogen compressed-gas system located outdoors to specified exposures at the NPP facility. Use of these criteria will document that appropriate separation from the NPP is ensured for any safety considerations.

Using the plant-specific process for documenting the impact of the HTEF located in the OCA will provide the basis for allowing this change without prior NRC approval.

3.2 NFPA 805 Plants

3.2.1 Group (3) Plants—NFPA 805 and NEI 04-02 Process

The FPPs for early plants were prescriptive in nature, without the benefit of later-developed risk-informed, performance-based numerical techniques. To address this shortcoming, NFPA 805, “Performance-Based Standard for Fire-Protection for Light Water Reactor Electric Generating Plants,” 2001 Edition, was established as a voluntary alternative for demonstrating compliance with 10 CFR 50.48(b) and (f). In 2004, the NRC amended 10 CFR 50.48 to endorse this NFPA standard, among other things.

3.2.1.1 Relative NFPA 805 Requirements and Guidance

The plant-change evaluation is a required step in the methodology for all changes to previously approved FPP elements. NFPA 805, Section 2.2.9, states that:

> *In the event of a change to a previously approved fire-protection program element, a risk-informed plant change evaluation shall be performed and the results used as described in 2.4.4 to ensure that the public risk associated with fire-induced nuclear fuel damage accidents is low and the adequate defense-in-depth and safety margins are maintained. [NFPA 805, Section 2.2.9]*

Section 2.4.4 of NFPA 805 provides the criteria against which the change evaluations are evaluated. It states that:

> *A plant change evaluation shall be performed to ensure that a change to a previously approved fire-protection program element is acceptable. The evaluation process shall consist of an integrated assessment of acceptability of risk, defense-in-depth, and safety margins. [NFPA 805, Section 2.4.4]*

Details regarding the acceptance criteria are provided in Sections 2.4.4.1, 2.4.4.2, and 2.4.4.3 of NFPA 805.

- Section 2.4.4.1 requires the change in public-health risk from any plant change be acceptable to the NRC, as demonstrated by the change in CDF and LERF. The NRC has already established acceptable quantitative changes to the CDF and LERF in RG 1.174 [25]. The NRC modified the quantitative acceptance criteria for making changes to the licensee’s FPP without prior NRC review and approval. These acceptance criteria will be included in the licensee’s post-transition fire-protection license condition. Specifically, these criteria should be applied to show that the public-health risk associated with fire-induced nuclear fuel damage related to the change is acceptably low.
- Sections 2.4.4.2 and 2.4.4.3 for defense-in-depth and safety margin simply repeat the criterion in Section 2.2.9 that requires the adequate maintenance of these factors. Criteria for complying with these requirements also are provided in RG 1.174 and this guidance. Note that Sections 2.4.4.2 and 2.4.4.3 also indicate that the deterministic approach for meeting the performance criteria “shall be deemed to satisfy” requirements for defense-in-depth and safety margin.

Under the risk-informed, performance-based regulatory framework, FPP changes may be made without prior NRC approval, except where:

- 10 CFR 50.48(c) changes that do not meet the acceptance criteria or other conditions of the approved license condition.
- Under 10 CFR 50.48 (c)(2)(vii), changes to the program that use NFPA 805 performance-based methods in determining the licensee's compliance with the FPP elements and minimum design requirements in Chapter 3 of NFPA 805.
- 10 CFR 50.48 (c)(4) changes to the program that use risk-informed or performance-based alternatives to compliance with NFPA 805 (i.e., methods that differ from those prescribed by NFPA 805).
- Combined changes where any individual change would not meet the risk-acceptance criteria of the license condition.

For those changes that do require NRC approval, the licensee will submit the request for approval of any changes to the NRC pursuant to 10 CFR 50.48(c) and 10 CFR 50.90 [26]. For changes that involve acceptance of an existing nonconforming condition, appropriate compensatory measures should be established and should remain in place until the license-amendment is approved by the NRC.

3.2.2 Methodology/Process Changes

Plant-specific implementation of the methodology and requirements of NFPA 805, Chapter 2, are addressed in the NFPA 805 safety evaluation for the plant. Therefore, changes to the methodology for implementing NFPA 805 should be reviewed as part of the plant-change process. Changes related to NFPA 805, Chapter 2, may not be the types of changes that can be measured in terms of change in risk or maintaining defense-in-depth and safety margins. Changes to methodologies, however, should be reviewed to determine acceptability and need to obtain approval from the NRC.

Methodology changes may be made to the plant FPP within the bounds of the license condition. Changes to the FPP related to NFPA 805, Chapter 2, can be made under the following circumstances:

- The change meets the literal requirements of NFPA 805 Chapter 2.
- The change is editorial or trivial in nature and clearly has no adverse impact on the FPP.
- The change is consistent with the plant-specific licensing-basis, as defined in the NFPA 805 safety evaluation or accepted by the NRC in a formal process such as the NFPA 805 Frequently Asked Questions process, and the results meet the appropriate acceptance guidelines.

Additional guidance on fire probabilistic risk assessment (PRA) methods and determination of fire PRA technical adequacy are provided in Appendix J.

3.3 Self-Evaluation of Plant-Interfacing HTEF Modifications

Although the focus of this research report is on aspects of fire-protection-specific evaluations associated with ensuring no adverse HTEF-detonation or heat-flux effects are imposed on NPP SSCs important to safety, plant-interfacing modifications involving electrical-feed and steam-extraction modifications between the NPP and the HTEF are also licensee evaluation requirements, as discussed in [1,2]. Electrical and mechanical interfacing modifications associated with a co-located HTEF are graphically shown in Figure 13. Unlike the specific fire-protection evaluation aspects described herein, the 10 CFR 50.59 process is applicable for evaluation of the risk-effects of implementing such interfacing modifications and their potential effects on NPP risk. As concluded in Reference 1, it is expected that licensee self-evaluation of these plant-interfacing modifications can successfully be evaluated under 10 CRF 50.59.

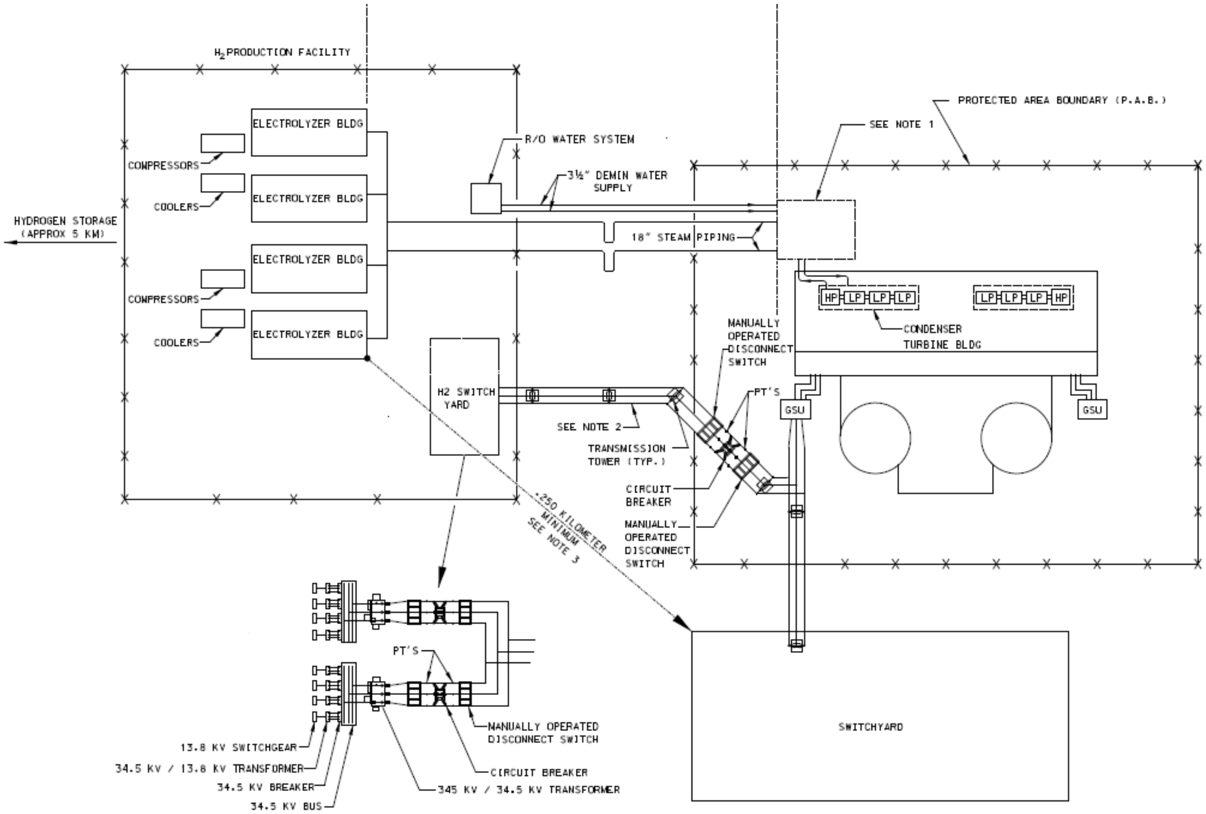

Figure 12. Electrical and mechanical interfacing modification representation.

4. CONCLUSIONS AND FUTURE ACTIONS

4.1 Conclusions

This report concludes that several viable paths allow NPP licensees to self-evaluate separation distances between future co-located HTEFs and NPP SSCs important to safety, both from a fire-protection code and nuclear-licensing-requirement standpoint.

Separation-distance determination by NFPA 55 has longstanding precedence and acceptance in both nuclear and non-nuclear hydrogen-facility siting. This report traces the applicability of NFPA 55 use for such siting for both NPPs licensed to Appendix R and NFPA 805 FPPs. Based on these reviews, use of NFPA 55 can confidently be used as an acceptable standard for calculating separation distances to NPP SSCs important to safety for currently licensed NPPs that are considering co-located HTEFs.

Additionally, this report explored possible alternate (or additional) separation-evaluation methodologies that build on either of these methods:

- Previous licensing-basis evaluation strategies involving TNT equivalence applied for evaluations of explosions postulated to occur at nearby facilities and on transportation routes ear NPPs [17].
- Modern numerical analysis tools that translate detailed FMEAs into rigorously calculated detonable mass and heat-flux (flame) dimensioned leak jets [2].

These elective separation methodologies also appear to be credible approaches when justified by detailed FPEE under current licensing regulation. Their use is most likely considered of value as additional HTEF separation-distance screening tools in conjunction with NFPA 55 as good practice to establish rigorous and conservative deterministic separation-distance margin. Although not required, it is expected that use of such tools for final separation-distance siting of a large HTEF co-located at an existing NPP would provide additional stakeholder understanding and acceptance for safety of both the NPP and any nearby community.

4.2 Future Actions

An independent-expert fire-protection engineering review of this research is planned in FY 2025. The intent of the review is threefold:

- Confirm the technical and licensing accuracy and conclusions of this report
- Add additional expert clarification, correction, and insights as needed
- Create a FPEE template to aid licensees in self-evaluation of separation distance determination between planned co-located HTEFs and NPPs via NFPA 55 separation-methodology for NPP SSC safety, as well as elective tools like those described for additional deterministic separation margin for safety assurance to both NPP and the nearby community.

The results of this expert review will be included in a revision to this report in FY 2025.

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Appendix A

Historical Regulatory Background

Regulatory background that supported the path to Appendix R and NFPA 805 NPPs being able to credit use of the more-modern NFPA 55 calculational methods to identify minimum separation distances between hydrogen systems and SSCs:

- Plants originally licensed to 10 CFR 50.48(b), Appendix R Part 50 may reference NFPA 55 through Regulatory Guide 1.189 (Fire-Protection for Nuclear Power Plants) Sections 2, 4, and 7 for installation of an HTEF which includes the excerpt below:

  > *The construction, installation, operation, and maintenance of bulk gas (including liquefied gas) storage and the related loading and dispensing systems should comply with good industry practice and the relevant NFPA standards, as applicable (e.g., NFPA 54, "National Fuel Gas Code" (Ref. 104), and NFPA 55)."*

- Plants that subsequently elected to transition from 10 CFR 50.48(b), Appendix R to 10 CFR 50.48(c), NFPA 805 under License-Amendment Request (LAR)[1] contain direct reference to NFPA 50A through NFPA 805 Section 3. Because NFPA 50A was withdrawn in 2004, a Frequently Asked Question section [27] and an update to NEI 04-02 [23] were supported by NRC to provide a method for the use of self-approved fire-protection engineering analyses post-transition to address NFPA 805, Chapter 3, requirements. Specifically, the method allowed fire-protection engineering analyses to address NFPA 805, Chapter 3, requirements for deviations from the codes, standards, and listings referenced in NFPA 805. This effectively positioned NFPA 805 transitioned plants to self-evaluate and adopt NFPA 55 under FPEE for use with subsequent NRC triennial fire-inspection review.

Appendix B

Near-Term Proposed Code-Committee Changes

Currently, many hydrogen-specific requirements reside in NFPA 55 (e.g., Chapter 10) and then are extracted so that the same requirements also appear in NFPA 2 (e.g., Chapter 7), while other hydrogen-specific requirements reside solely in NFPA 2. According to the scope and applicability statements for these codes, overlapping application to hydrogen systems exist, making it important for potential systems designers to consider both documents. NFPA leadership, as well as the chairs of both technical committees, recently decided that in the future, hydrogen-specific requirements should reside only in NFPA 2; thus, this content should be removed from NFPA 55. A joint working group, made of up members from both technical committees for NFPA 55 and NFPA 2, is currently reviewing both documents and submitting proposed changes to facilitate this change. This work is ongoing but is planned for implementation in the next editions of NFPA 55 and NFPA 2. These are currently planned for a 2026 release. Requirements or policies that reference NFPA 55 for hydrogen-specific requirements will need to be changed to reference NFPA 2 in the future.

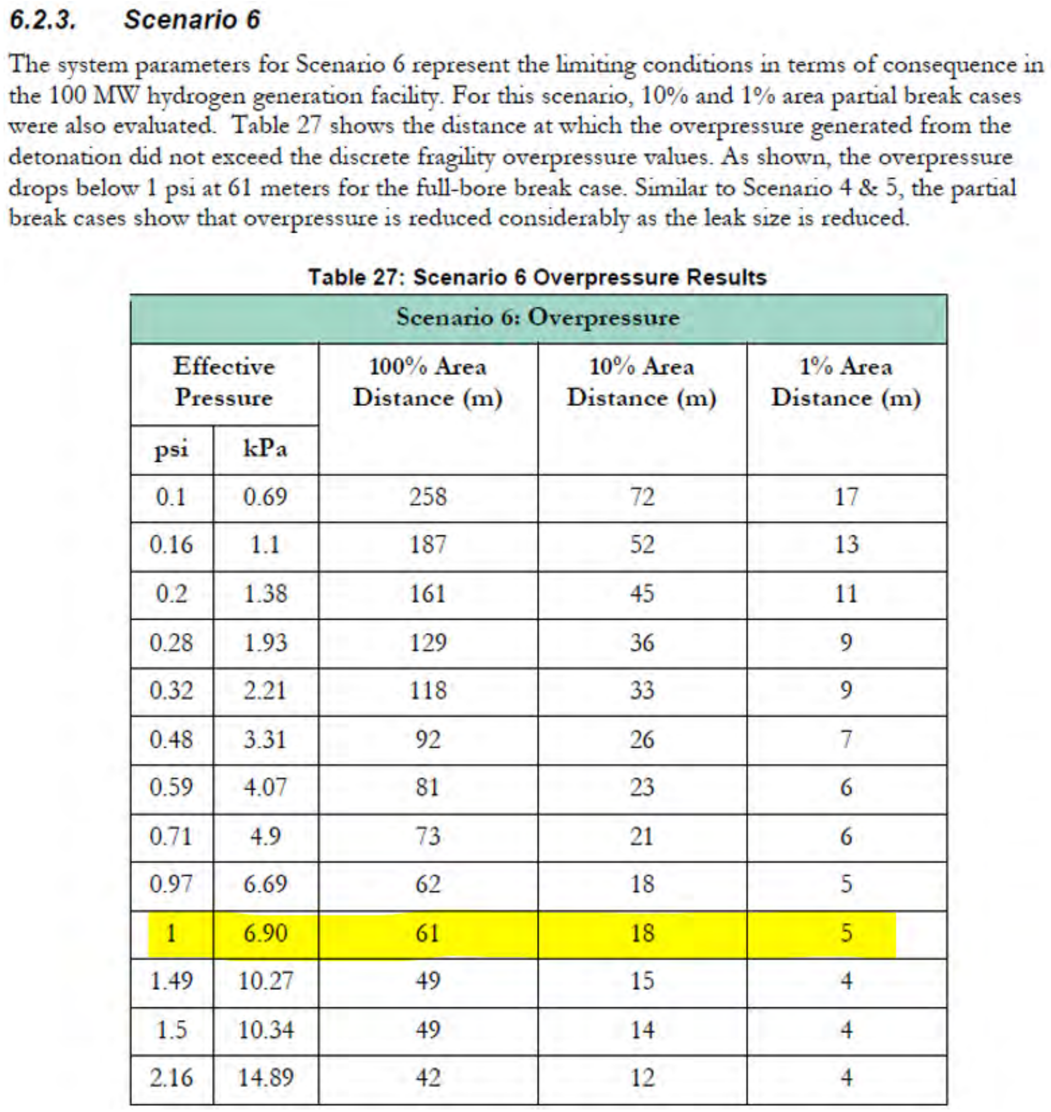
As discussed under Section 2.3.3, Footnote k, tabular separation distance determination under NFPA 55 is currently limited to pipe size interpolation up to 3-in. nominal pipe size. Given the likelihood of near-term HTEFs and low-temperature electrolysis facilities being developed in the MWe-scale rating range, larger common discharge-pipe sizes will need to be addressed by system designers when establishing code-required separation distances. This discrepancy was discussed with SNL expert participants on the NFPA 2 working-group committees as a requested addition to be considered in the next edition of NFPA 2.

Appendix C

HyRAM+ Calculation Excerpts from SAND2023-07884, Risk Analysis of a Hydrogen Generation Facility near a Nuclear Power Plant [4]

This appendix is provided for ease of reference between values discussed in this report and the supporting Sandia report [4] for bounding-detonation and heat-flux Scenarios 6 and 7 results for assumed 3- and 8-in.-pipe guillotine breaks, respectively.

Bounding Overpressure (at 1 psi):



6.2.3. Scenario 6

The system parameters for Scenario 6 represent the limiting conditions in terms of consequence in the 100 MW hydrogen generation facility. For this scenario, 10% and 1% area partial break cases were also evaluated. Table 27 shows the distance at which the overpressure generated from the detonation did not exceed the discrete fragility overpressure values. As shown, the overpressure drops below 1 psi at 61 meters for the full-bore break case. Similar to Scenario 4 & 5, the partial break cases show that overpressure is reduced considerably as the leak size is reduced.

Table 27: Scenario 6 Overpressure Results

Scenario 6: Overpressure				
Effective Pressure		100% Area Distance (m)	10% Area Distance (m)	1% Area Distance (m)
psi	kPa			
0.1	0.69	258	72	17
0.16	1.1	187	52	13
0.2	1.38	161	45	11
0.28	1.93	129	36	9
0.32	2.21	118	33	9
0.48	3.31	92	26	7
0.59	4.07	81	23	6
0.71	4.9	73	21	6
0.97	6.69	62	18	5
1	6.90	61	18	5
1.49	10.27	49	15	4
1.5	10.34	49	14	4
2.16	14.89	42	12	4

Figure 4 shows the overpressure as a function of distance from the leak location. As shown, the overpressure drops below 1 psi less than 20 meters for both of the partial breaks analyzed. The full-bore scenario drops below 1 psi at 61 meters from the leak location.

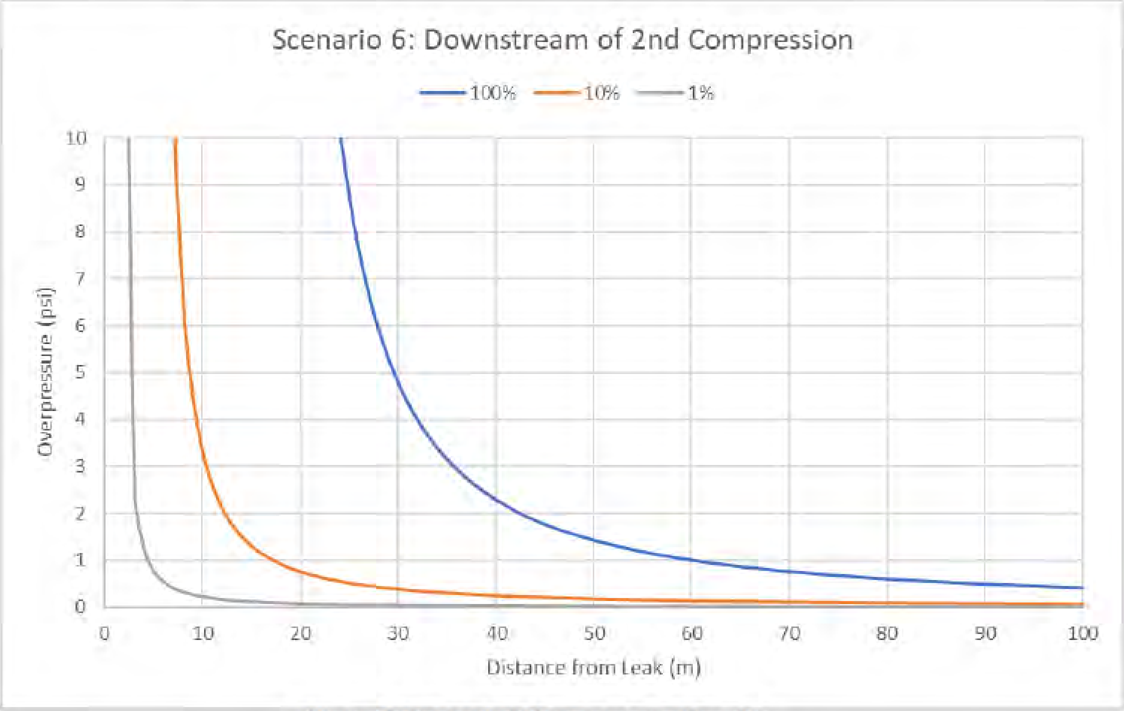


Figure 5: Scenario 6 Overpressure Results

6.2.4. *Scenario 7*

The system parameters for Scenario 7 are evaluated to inform the necessity for appropriate mitigation strategies for the 500 MW plant if a common header is used to transport the hydrogen to a storage facility. For this scenario, 10% and 1% area partial break cases were also evaluated. Table 28 shows the distance at which the overpressure generated from the detonation did not exceed the discrete fragility overpressure values. As shown, the overpressure drops below 1 psi at 168 meters for the full-bore break case. Similar to the other scenarios, the partial break cases show that overpressure is reduced considerably as the leak size is reduced.

Table 28: Scenario 7 Overpressure Results

Scenario 7: Overpressure				
Effective Pressure		100% Area Distance (m)	10% Area Distance (m)	1% Area Distance (m)
psi	kPa			
0.1	0.69	734	210	57
0.16	1.1	530	153	42
0.2	1.38	456	131	36
0.28	1.93	365	105	29
0.32	2.21	334	97	27
0.48	3.31	259	75	21
0.59	4.07	228	67	19
0.71	4.9	204	60	17
0.97	6.69	171	50	14
1	6.90	168	50	14
1.49	10.27	136	40	12
1.5	10.34	136	40	12
2.16	14.89	114	34	10

Figure 6 shows the overpressure as a function of distance from the leak location. As shown, the overpressure drops below 1 psi less than 50 meters for both of the partial breaks analyzed. The full-bore scenario drops below 1 psi at 168 meters from the leak location.

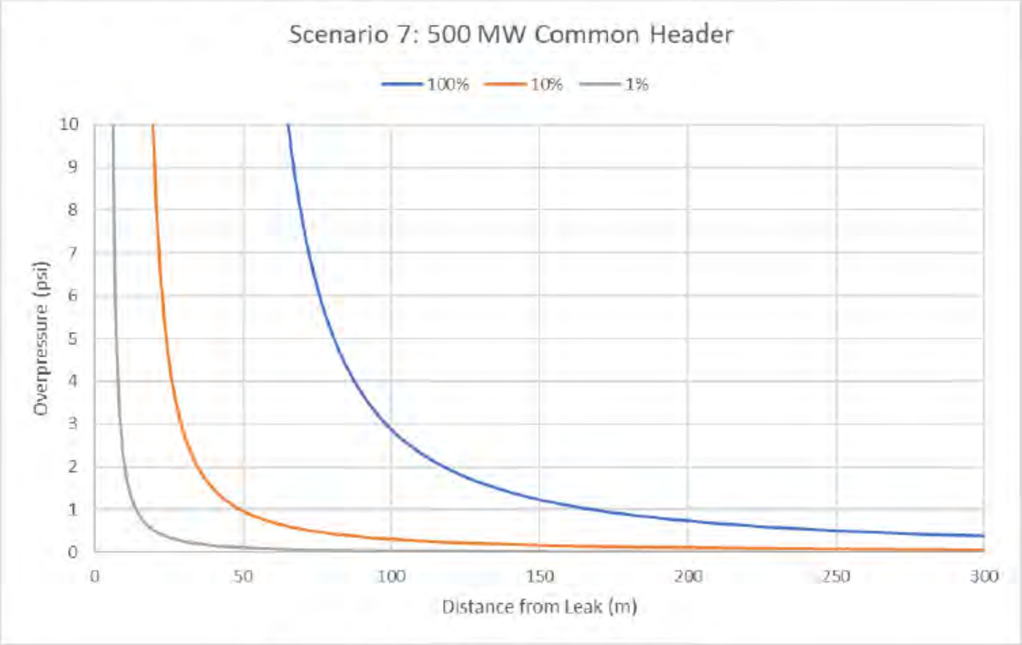


Figure 6: Scenario 7 Overpressure Results

Bounding Radiant Heat-Flux (at 37.5 kw/m^2)

6.3.3. Scenario 6

The system parameters for Scenario 6 represent the limiting conditions in terms of consequence in the 100 MW hydrogen generation facility for heat flux as well. For this scenario, 10% and 1% area partial break cases were also evaluated. Table 45 shows the results for the different radiation levels outlined in Section 4. As shown, the minimum heat flux sufficient to cause damage to process equipment (37.5 kw/m^2) occurs at 88 meters for the full-bore leak. As with overpressure, the heat flux is significantly reduced as the break size decreases.

Table 45: Scenario 6 Heat Flux Results

Scenario 6: Heat Flux			
Radiation Level (kw/m^2)	100% Area Distance (m)	10% Area Distance (m)	1% Area Distance (m)
1.6	192	60	17
5	135	44	13
9.5	115	38	12
12.5	108	36	11
25	94	33	11
37.5	88	31	10

Figure 17 shows the heat flux as a function of distance from the leak for Scenario 6. Similar to the overpressure, the full-bore leak results in much further distances to discrete heat flux values than the partial leak cases.

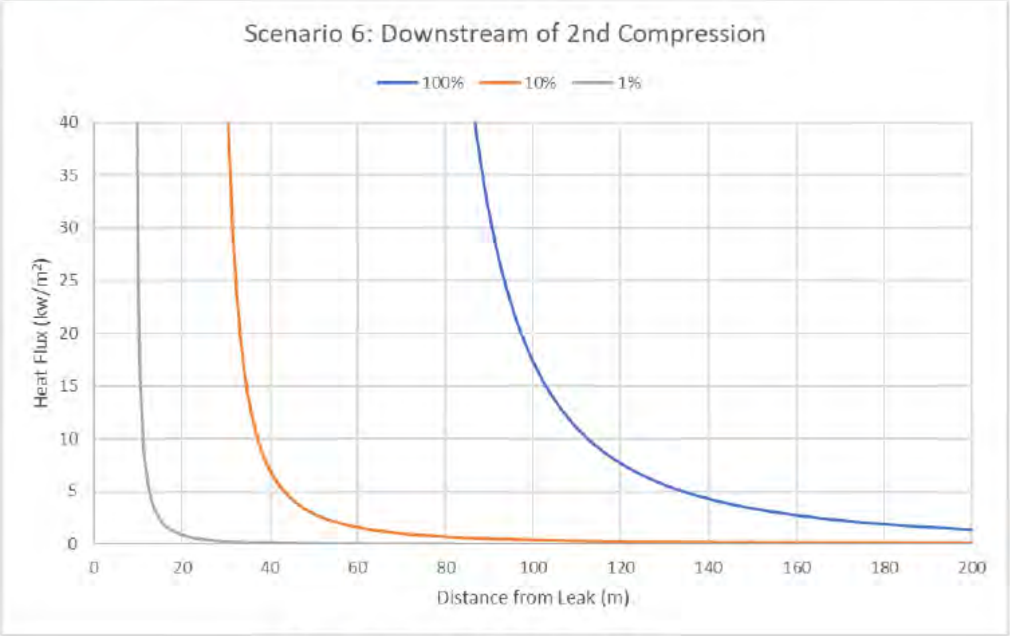


Figure 17: Scenario 6 Heat Flux Results

6.3.4. Scenario 7

The system parameters for Scenario 7 represent the limiting conditions in terms of consequence in the 500 MW hydrogen generation facility. For this scenario, 10% and 1% area partial break cases were also evaluated. Table 46 shows the results for the different radiation levels outlined in Section 4. As shown, the minimum heat flux sufficient to cause damage to process equipment (37.5 kw/m^2) occurs at 208 meters for the full-bore leak. As with overpressure, the heat flux is significantly reduced as the break size decreases.

Table 46: Scenario 7 Heat Flux Results

Scenario 7: Heat Flux			
Radiation Level (kw/m^2)	100% Area Distance (m)	10% Area Distance (m)	1% Area Distance (m)
1.6	503	157	48
5	344	111	36
9.5	286	94	31
12.5	266	89	30
25	226	78	27
37.5	208	74	26

Figure 18 shows the heat flux as a function of distance from the leak for Scenario 7. Similar to the overpressure, the full-bore leak results in much further distances to discrete heat flux values than the partial leak cases.

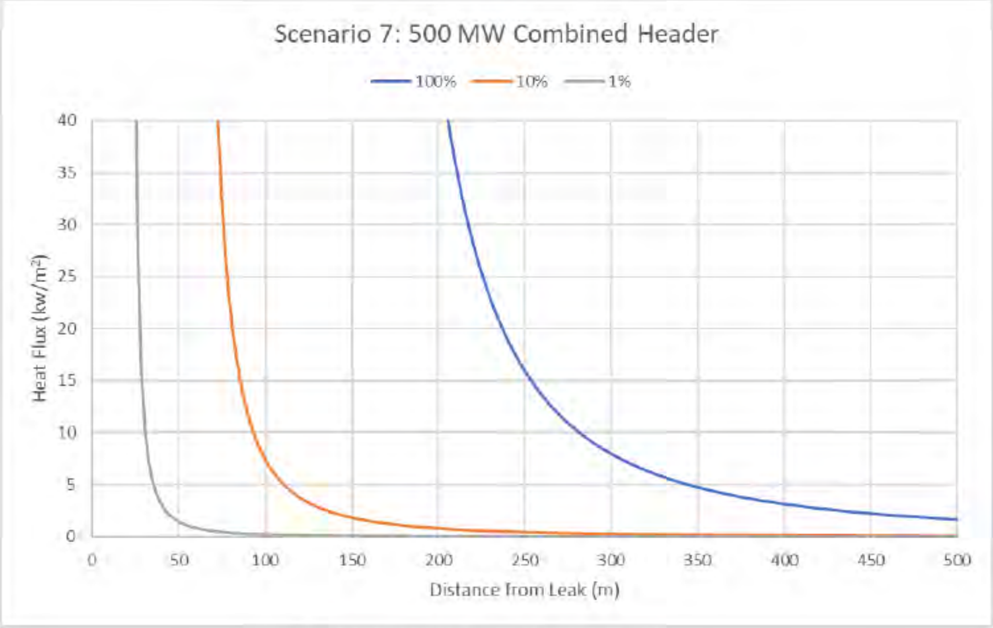


Figure 18: Scenario 7 Heat Flux Results