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Example Implementation for Cascading Leaks in Large-Scale Hydrogen Storage Risk Assessments

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ABSTRACT

Leaks in a hydrogen system can have destructive effects on other components within the system, leading to cascading leaks. The risk of cascading leaks is not currently quantified in many existing risk frameworks, but the prevalence of cascading failures in historical hydrogen facility accidents necessitates further study. A method for quantifying the probability, frequency, and risk of cascaded leaks is proposed. The method provides example scenarios of metrics that would set off cascading failures from each physical effect, including a jet fire melting the O-ring of another component, and an overpressure event from an initial explosion shearing off another component from the system. Cascading leak frequencies and individual risk are calculated for an example hypothetical system. While cascading leaks are quantitatively demonstrated to add to the overall risk, their contributions are small and may not add value to a risk assessment when analyzed in this rigorous quantitative framework.

ACKNOWLEDGEMENTS

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EXECUTIVE SUMMARY

Cascading failures, which are adverse events that cause a chain reaction of adverse events, are common in many industries. In hydrogen storage systems, cascading failures can present themselves as accidental releases that may ignite and cause further damage and leaks elsewhere in the system. Historical examples of cascading leaks exacerbating hydrogen storage facility damage include the 1985 Norway ammonia plant accident and the 2019 Santa Clara hydrogen refueling facility accident. As the development of the hydrogen industry and construction and operation of hydrogen facilities continues to grow, further study of cascading leaks can help prevent future accidents. While existing frameworks were found for cascading failures within applications such as power systems, the found literature lacks quantitative methods that can be applied directly to hydrogen systems. Therefore, a cascading failure framework and example calculations have been proposed.

An event sequence diagram was developed to include the possibility of a cascaded leak caused by an initial leak. The generic event sequence diagram from the HyRAM+ software was modified to include the possibilities that either a jet fire or an explosion from an initial leak can cause a cascaded leak in another component. A jet fire is a continuous, ignited flame caused by immediate ignition of the flammable gas leak. An explosion is an overpressure resulting from delayed ignition of a flammable mass.

Example metrics or criteria for the occurrence of cascading leaks were identified. An initiating leak resulting in a jet fire was assumed to cause a cascaded leak in another component if the flame temperature impinging on the other component at any point in time exceeded the melting temperature of the O-ring. An initiating leak resulting in an explosion was assumed to cause different levels of damage to other components based on qualitative overpressure metrics found in literature. Leak sizes for cascaded leaks from each of these metrics were selected based on judgment of the authors. The components were assumed to leak in one of two directions, parallel and antiparallel to the piping, although the possibility of different leak angles and orientations and a proposed method of accounting for them were also explored.

Example leak scenarios with graphical visualizations of metrics of interest (jet fire temperature and explosion overpressure) were provided and the frequency and individual risk for one of the scenarios was presented. Both the annual frequency of the second (or cascaded) leak, and the risk to an individual in the vicinity of the initiating and secondary leaks, were shown to be orders of magnitude below the annual frequency and individual risk of the initiating leak. The negligible contribution of the cascaded leak to overall risk was attributed to unique features of this particular example, including assumptions of leak size and orientation.

The contribution of the cascaded leak to overall risk also depended on the cascade occurring at all. The occurrence of a cascade leak was found to greatly depend on the size and orientation of the initial leak and its ignition probability, which, although uncertain, contributed greatly to overall risk. Also, the risk contribution from multiple cascaded leaks became increasingly smaller, especially compared to the initiating leak. Therefore, while the method proposed in this report can be applied to multiple cascaded leaks, the required effort to do so may result in diminished risk insights for owner-operators. Aspects of this framework are qualitatively helpful to hydrogen owner-operators concerned about cascading leaks.

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ACRONYMS AND TERMS

Acronym/Term	Definition
HyRAM+	Hydrogen Plus Other Alternative Fuels Risk Assessment Models
IEEE	Institute of Electrical and Electronics Engineers
P&ID	piping and instrumentation diagram
PRD	pressure relief device

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1. BACKGROUND

Cascading failures are events in which the consequences of failure can lead to further failures in the system; the subsequent failures can likewise cause failures in a cascading fashion. "Failure" can be defined differently for each system; in hydrogen storage and refueling systems, one major failure that can occur is a leak. A cascading failure can occur when the consequences of an initial leak, such as a fire or explosion, cause a leak elsewhere in the system. Cascading failures can be especially important to consider for large-scale storage systems, due to the larger flowrates and greater storage quantities that can lead to larger and longer-duration leaks that may be more likely to cause subsequent damage and induce additional failures.

There is a historical motivation for modeling these types of failures. In 1985, a combination of operational and design weaknesses in an ammonia plant in Norway led to a ruptured gasket and hydrogen leak [1]. The plume detonated in multiple locations throughout the facility, and, among other damages that occurred, the main explosion sheared off a second hydrogen pipe. This second leak led to jet fires and more explosions. In 2019, a human error-induced leak at a gaseous hydrogen refueling facility in Santa Clara, California led to an explosion and jet fire [2]. The thermal effects of the jet fire reached other components, namely pressure relief device seals and O-rings that melted and subsequently began to leak and ignite into new jet fires. Cascading failures can lead to more harm to people and more damage to infrastructure than single leaks and therefore are important to consider for risk assessments.

Several existing studies have developed cascading failure risk assessment methodologies for energy systems. Liang et al. proposed a Bayesian method of calculating the risk of cascading failures in integrated electricity-gas energy systems, where the initial failure can occur in the form of a pipeline leak or a power system short-circuit and the probability of subsequent failures occurring is based on the operation state of the multi-energy coupling devices in the system [3]. That risk assessment involved understanding the load shedding and calculating the coverage of the loads of failed nodes by nodes that are still online. The IEEE Computing & Analytical Methods Subcommittee presented different risk assessment methodologies including historical data, deterministic simulation, probabilistic simulation, and high-level statistical models to calculate the risk of consecutive tripping events in power systems [4]. Lam et al. compiled risk factors and potential mechanisms of cascading failures in hydrogen energy system networks but did not present a method for quantifying these risks [5]. Risk assessment frameworks and the data required are dependent on the system that is being analyzed, as well as the definition and mechanisms of cascading failure used. However, existing literature can be used to guide the development of a risk assessment method even if the exact methodology cannot be directly applied.

In this study, both initial and cascaded failures are defined as unintended hydrogen releases from components in the storage system. The initial leak is assumed to be caused by general wear and degradation of components over time. The initial leak has some probability of resulting in a consequence such as a jet fire or an explosion, which can result in physical effects like high heat fluxes and overpressures that may cause trauma-induced leakage on other components in the system. This report describes a risk assessment framework for cascading failures that was built on the current probabilistic model for single failures in hydrogen storage and dispensing systems in the Hydrogen Plus Other Fuels Risk Assessment Models (HyRAM+) [6]. Several generic examples are provided as case studies for evaluating cascading leak frequencies in specific systems.

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2. GENERIC CASCADING LEAK FRAMEWORK

The increase in human risk from cascading leaks in a hydrogen storage system is two-fold. Risk is defined in the HyRAM+ documentation as a metric comprised of a frequency and consequence of an event. The possibility of cascades introduces additional leak pathways for each component compared to single leaks, leading to higher leak frequencies. Additionally, there could be overlaps in physical outcomes from cascaded leaks – for example, if jet fires from two components both emit a harmful heat flux, a person within the overlapping region could experience even higher thermal doses. In this case, the consequence in terms of a metric like probability of fatality could increase for that person. Furthermore, a cascaded leak may increase the area affected by thermal radiation and overpressure, potentially causing harm to more people. Besides this potential compounding of consequences from cascaded leaks in the system, there is also the possibility that a time delay between cascaded events could increase the duration of harmful physical effects in the overall facility. For example, in some cases it may be preferable to wait for a single jet fire to burn out completely instead of extinguishing the fire, since the hydrogen could still leak and accumulate; ignition of the flammable cloud after accumulation would result in an even higher consequence explosive event. However, if the initial jet fire causes a leak and jet fire in another component, the duration of the second jet fire may exceed the duration of the first. Additionally, cascading leaks can escalate consequences in the system – a jet fire may cause another component to leak and result in the even worse consequence of an explosion.

The event tree used in HyRAM+ [6], shown below in Figure 2-1, was used as a basis for the cascading leak framework.

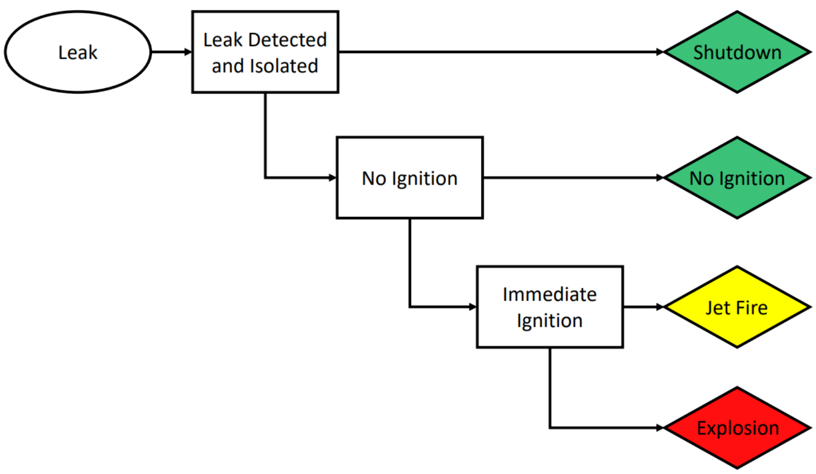

Figure 2-1. Default event sequence diagram used for a single leak in HyRAM+ [6].

This event sequence diagram shows that when a leak occurs, it may be detected and isolated, resulting in no adverse consequences. If it is not detected and isolated but simply disperses with no ignition, this is also a no-consequence outcome. However, there is also the possibility that the leaking fuel will ignite either immediately, resulting in a jet fire, or after a delay and accumulation of fuel, resulting in an explosion. In Figure 2-1, the jet fire and explosion are highlighted as consequential outcomes of a leak that can cause potential harm to people within the vicinity of the leaking component. These outcomes can also cause harm to other components in the system, which is the basis of the cascading leak event sequence diagram in Figure 2-2. In this case, the jet fire or the explosion may lead to a cascaded leak in another component, or the system may be shut down before other components are affected. Note that Component 1 and Component 2 are not necessarily adjacent (although they can be) and denote different components within the cascading leak sequence.

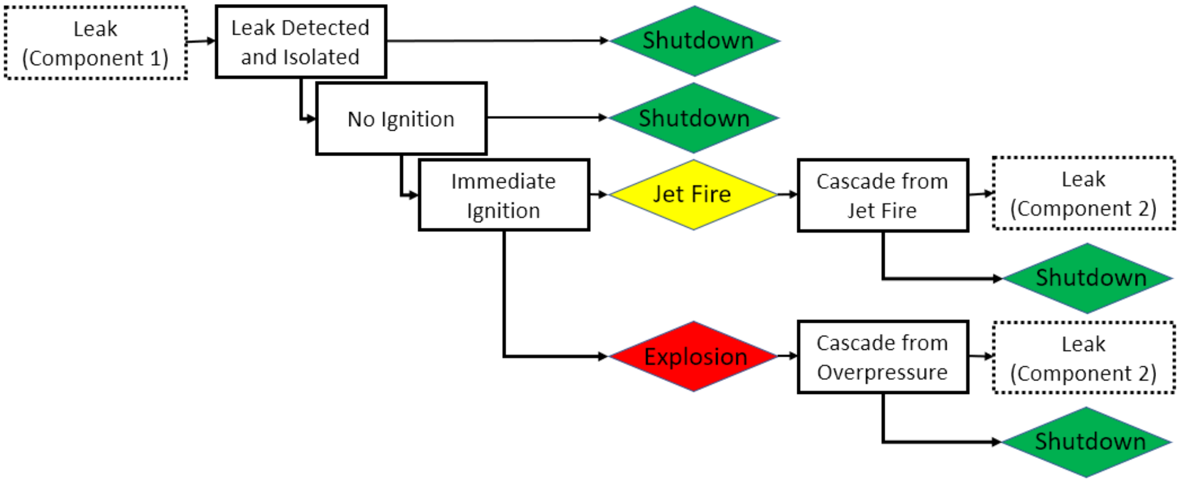

Figure 2-2. Proposed event sequence diagram for cascading leaks.

This modified framework does not differentiate between physical mechanisms for cascading leaks. There are multiple ways that either a jet fire or an explosion can lead to a leak in another component. For example, a jet fire may impinge on another component and melt the O-ring, causing a small to moderately sized leak. The heat flux from a long-lasting jet fire impinging on another component may cause damage to the metal component body itself, which could cause a larger leak. Similarly, there are multiple mechanisms or scenarios through which an explosion from an initial leak can damage other components. For example, overpressure could cause tensile, compressive, shear, or other types of failures in another component depending on factors like the type of component, the material from which it is made, and the angle between the blast wave and the component. These examples are not exhaustive, and future efforts may explore these different failure mechanisms more explicitly. All these as well as any other cascading leak modes are encapsulated in the "Cascade from Jet Fire" and "Cascade from Overpressure" boxes in Figure 2-2.

Knowledge or assumptions about the spatial layout and orientation of components are needed to evaluate a system when incorporating cascading leaks in a quantitative risk assessment. Specific information about the system design can help generate a comprehensive list of potential cascading leak pathways. The risk from the initial leaking component can be computed by identifying all possibilities or scenarios in which that component causes a cascade failure in any other components in the system. The risk from all those leaks can then be summed to the risk from the initial leak to determine overall risk from all physical effects from the initial leaking component to a person in the vicinity. Another way to frame the overall risk is to determine how each component in the system could leak, considering both normal operations and the potential damage from jet fires and explosions from leaks in other components. The sum of all these risks would result in the overall risk to a person from that specific initial leaking component. A graphical summary of these two approaches is shown in Figure 2-3.

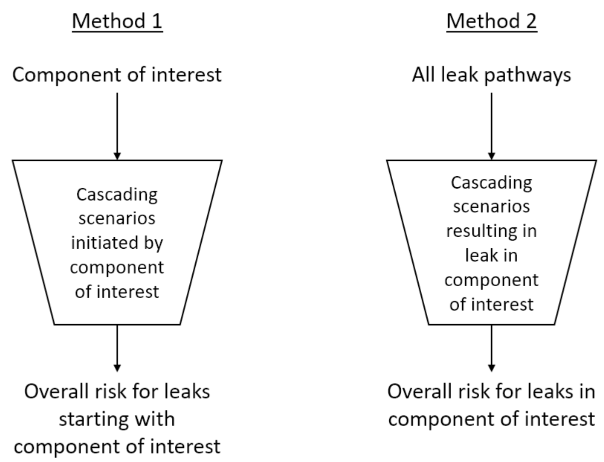

Figure 2-3. Graphic of two proposed approaches for calculating risk of cascading leaks.

In this report, examples of Method 1 are provided; a component of interest is selected as an initiating leak point, and cascading leak scenarios from an initial leak in that component are considered. As the conclusions of the report suggest, this method already involves significant accounting for components and leaks, which is why the examples are not comprehensive and do not include all possible scenarios. Method 2 would require physical effect simulations for every possible scenario in order to collect all scenarios resulting in a leak in the component of interest, which is more time-consuming than Method 1.

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3. CASCADING LEAK EXAMPLES

3.1. System Specification and Metrics of Interest

An example study on potential cascading leak scenarios was conducted on a generic gaseous hydrogen system, shown in Figure 3-1 below. This system contains a compressed gaseous hydrogen cylinder with a built-in pressure relief device (PRD), a compressor, and two valves. A 10-mm inner diameter pipe size was used for all components in the examples shown in the following section.

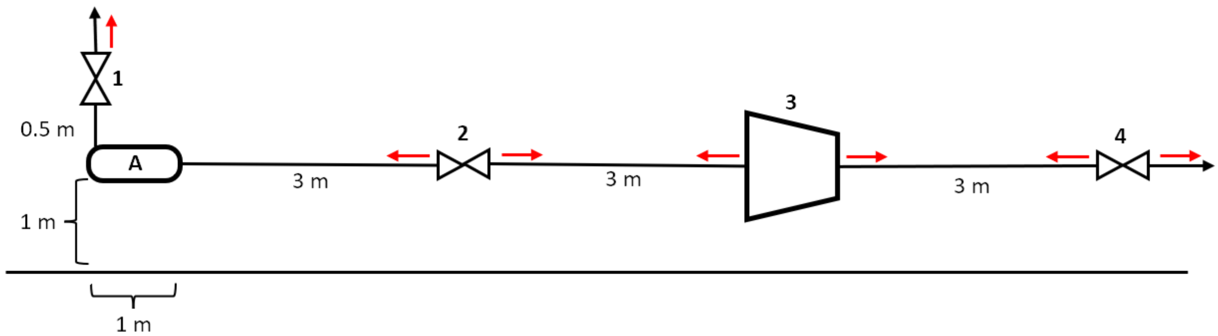

Figure 3-1. Simplified piping and instrumentation diagram (P&ID) for gaseous hydrogen storage tank. Red arrows indicate leak points and directions.

Table 3-1. Gaseous Hydrogen P&ID Component Legend

P&ID Label	Component
1	PRD
2	Valve
3	Compressor
4	Valve
A	Storage cylinder

In this example system, the four numbered components were considered the potential initial points for a hydrogen release. The studied leaks were all assumed to occur at the connections between components. The PRD is designed to vent hydrogen to the environment to relieve pressure in the storage cylinder, so hydrogen releases from it are not always unintended. However, the PRD was still included as a potential component whose release of hydrogen can lead to damage of other components. The upward venting of the PRD and horizontal leaks for the other components were the release directions considered in the study. Although leaks can occur at an angle, the lack of data on leak angles and knowledge on leak mechanisms prevented in-depth investigation into this possibility in this report. Therefore, each leak was assumed to occur parallel or antiparallel to the leaking component. These leak directions are also conservative assumptions since they led to each leak pointing directly at adjacent components. A summary of all tested scenarios is provided in Appendix A.

A graphic of the leak points in the study is shown in Figure 3-2. The graphic shows that only the connections between piping and other components like valves were considered as leak points, rather than including pipes as potential leak points. Excluding the piping also simplifies the plume characterization, since piping could obstruct a plume and introduce turbulence or variation of its flow path in ways that are challenging to define without more detailed computational fluid dynamics analysis. Similarly, the components themselves were defined as points in space that can act as leak points but that do not have volume. Only the storage cylinder is shown with some volume because its potential burst failure mechanism depends on, for example, a jet fire impinging on any part of its walls.

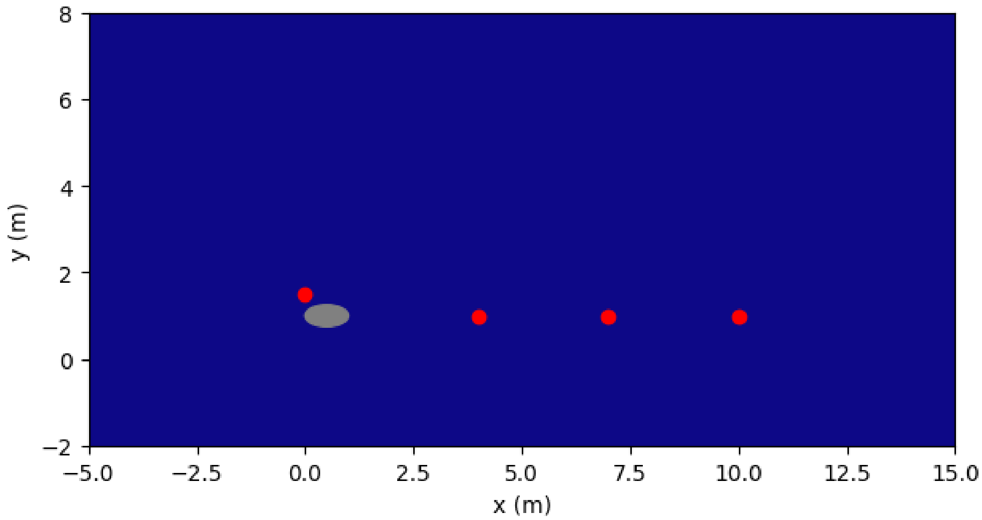

Figure 3-2. Layout of storage cylinder (gray ellipse) and other components (red points) used for HyRAM+ visualizations.

Figure 2-2 showed that two potential consequential outcomes of a leak are a jet fire and an explosion. Both scenarios were considered in this study as events from an initial leak that can cause damage and a subsequent release elsewhere in the system. As discussed in Section 2, there are several mechanisms by which either a jet fire or an explosion from an initial leak can cause further damage in the system. The example for a cascaded leak from a jet fire in this report is a scenario in which a jet flame from an initial leak impinges on another component and causes O-ring thermal failure and subsequent leakage. This type of failure would likely result in a release smaller than a full-bore leak; while there is also limited data to use as a basis for sizes of cascaded leaks, this mechanism is assumed to cause a 1% leak in the affected component in this report. A nitrile (Buna-N) O-ring was assumed with a failure temperature of 250°F (394 K) [7]. This is just one example of a damage mechanism for the purposes of illustrating this framework; other systems and component types may have different damage mechanisms to consider.

Rather than determining a physical mechanism for overpressure damage (for example, shear versus tensile failures in a component), overpressure metrics from existing sources were used to estimate the potential damage within the system caused by an explosion. Several different sources provided the damage characterizations described in Table 3-2.

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Table 3-2. Aggregated Overpressure Damage Metrics

Overpressure Range (kPa)	Damage Extent	Source
20-30	"Slight deformations of a pipe-bridge"	[8]
35-40	"Displacement of a pipe-bridge, breakage of piping"	[8] and [9]
40-55	"Collapse of a pipe bridge"	[8]
20.4-27.7	"Rupture of storage tanks"	[10]
50-100	"Failure of connecting pipes"	[8]

While piping was not considered in this study, these metrics were used as proxies for the connections between piping and the components of interest since other component-specific information was unavailable. The overpressure ranges and damage characteristics in Table 3-2 were then used to generate the proposed cascading leak assumptions in Table 3-3.

Table 3-3. Assumed Characterization of Damage from Cascaded Leaks due to Overpressure

Overpressure Range (kPa)	Assumed Characterization of Damage in Affected Component (Percentages Show Leak Area Based on Pipe Cross-Sectional Area)
20-35	1% leak and cylinder rupture
35-50	10% leak
50	100% leak

These metrics were selected using Table 3-2 as a guide. The 20-35 kPa range was assumed for a leak with a size of 1% of the cross-sectional area of the piping and other components. This selected range was based on the 20-30 kPa overpressure range at which "slight deformations of a pipe-bridge" occur; the range is extended to 35 kPa, which is the lower bound for "displacement of a pipe-bridge" and "breakage of piping," which is the next higher extent of damage. This range also encapsulates the 20.4-27.7 kPa range at which "rupture of storage tanks" occurs, which is why cylinder rupture was also assumed to occur in this range. The 35-50 kPa overpressure range was assumed to cause a 10% leak. This selection was made as an intermediate leak size and an intermediate extent of damage between the lower overpressure bound of 35 kPa causing "displacement of a pipe-bridge" and "breakage of piping," and the lower overpressure bound of 50 kPa causing "failure of connecting pipes." The 50 kPa overpressure was then used as the lower bound for full-bore, or 100%, leaks.

A steady-state leak was assumed for both the jet fire and explosion cases, and temporal effects were not modeled. For example, a flame must impinge on a component for a certain amount of time before it damages the component enough to cause a leak. All flames were assumed to be sustained long enough to damage whichever components they could reach. The Baker-Strehlow-Tang (BST) overpressure method [6] and a flame speed of Mach 5.2 was used for the overpressure calculations.

3.2. Results

3.2.1. Jet Fire Temperature Cascading Releases

A contour of the jet flame temperature was plotted for each scenario, with lines marking the flame region that exceeds 400 K, or the upper temperature limit for the selected O-ring material. Figure 3-3 shows the largest possible release from the PRD. Contours for releases of all sizes from the PRD are provided in Figure B-1 in Appendix B.

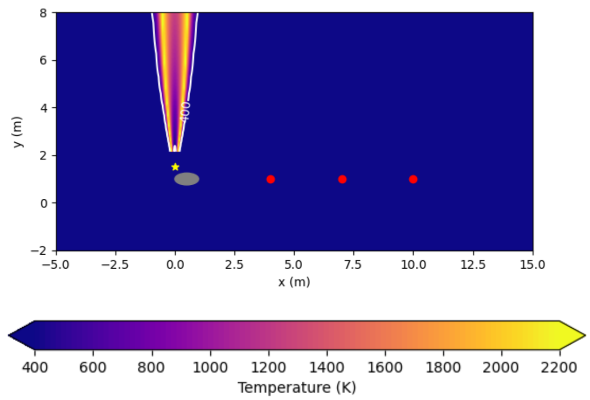

Figure 3-3. Jet fire temperature contours for upward release from Component 1 (PRD) that is 100% of pipe cross-sectional area (10 mm diameter piping). The white contour shows the boundary within which the temperature is at least 400 K (260°F).

Different PRD designs exist, so PRD releases can represent either normal operation or malfunctions. For example, some PRDs are designed to have full-bore releases each time they are activated, in which case the full-bore plume from the PRD would occur during normal operation while smaller releases might only be expected when the PRD has been worn or damaged in some way. Conversely, PRDs that are designed to open incrementally might have smaller releases. Regardless, since the PRD is designed to open only under high pressure or temperature conditions, it is usually installed in a location and orientation in which a full-open release of hydrogen would not impinge on people or other equipment.

Temperature contours for a jet fire from a non-full-bore release (10% of pipe cross-sectional area) from Component 2 (valve) are shown in Figure 3-4.

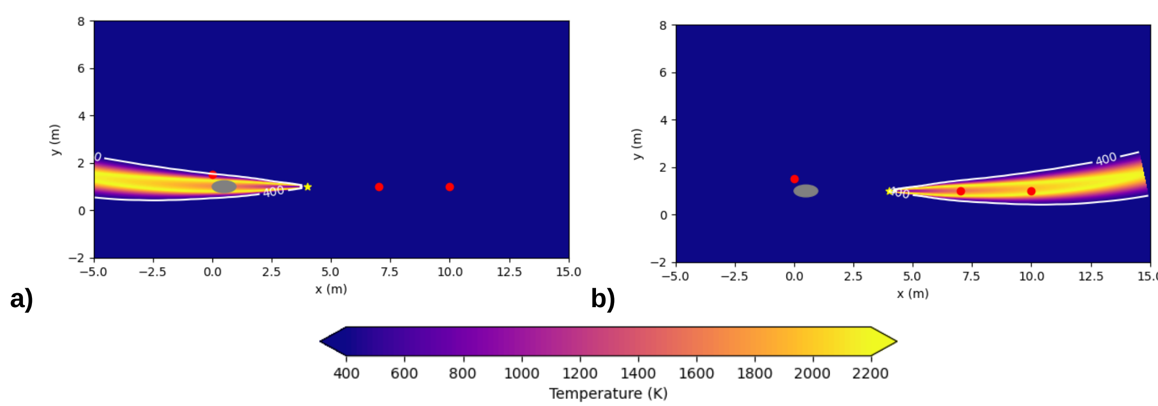

Figure 3-4. Jet fire temperature contours for a) leftward and b) rightward release from Component 2 (valve) that is 10% of pipe cross-sectional area (10 mm diameter piping).

The flame from the leftward plume appears to impinge on both Component 1 (PRD) and the storage cylinder itself. The heat from the fire could damage the PRD, for example through the melting of its O-ring. However, this is likely of lower concern than the potential burst that could occur from the impingement of the jet fire on the pressure vessel. If the jet fire causes temperature to rise sufficiently within the vessel and the PRD does not vent fast enough, the vessel could burst due to internal overpressure. The flame on the rightward plume impinges on both Component 3 (compressor) and Component 4 (valve), which could cause thermal damage to their O-rings as well as the parts of the compressor. These contours show that even a less than full-bore leak can damage multiple other components in the system.

As previously mentioned, the temperature contours for jet fires from the rest of the leak sizes are shown in Appendix B. The 10% leaks were discussed in this section, but it is evident from contours in the appendix that even smaller leaks can cause damage to neighboring components.

3.2.2. Explosion Overpressure Cascading Releases

The overpressure contours for a 1%, 10%, and 100% leak in Component 1 (PRD) are shown in Figure 3-5.

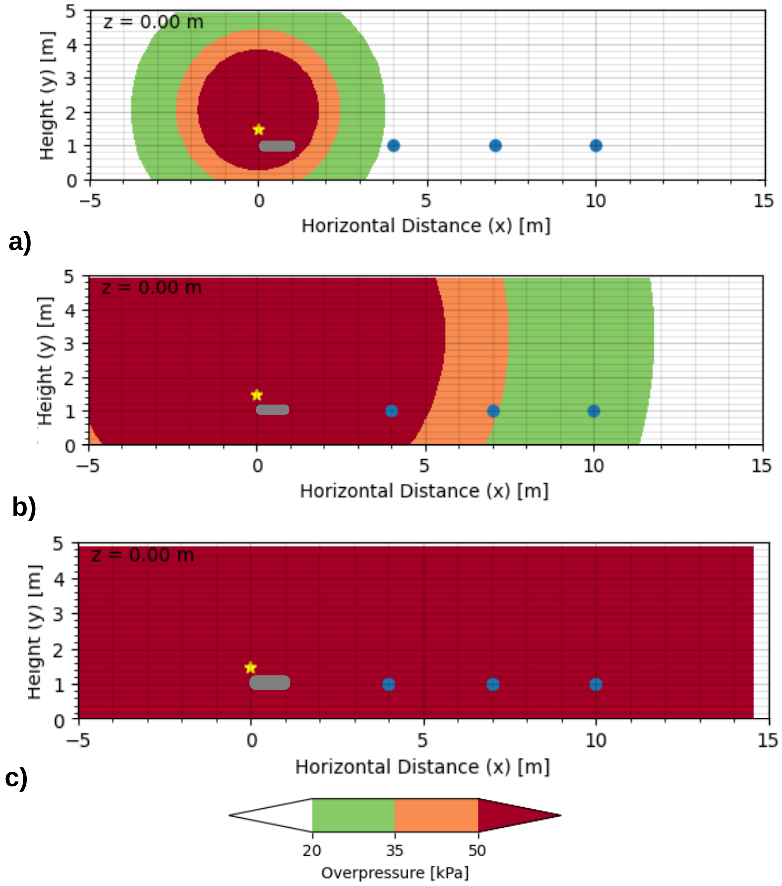

Figure 3-5. Explosion overpressure contour for upward release from Component 1 (PRD) that is a) 1%, b) 10%, and c) 100% of pipe cross-sectional area (10 mm diameter piping). The yellow star represents the leaking component (in this case, the PRD), the gray cylinder represents the hydrogen storage tank, and the blue dots represent Component 2, 3, and 4.

The graphs in Figure 3-5 show that the overpressure from an explosion can further damage the component that was initially releasing hydrogen – Figure 3-5(a) and Figure 3-5(b) respectively show 1% and 10% releases from the PRD that, in the event of an explosion, could cause overpressure damaging enough to cause a 100% release from the PRD (see Table 3-3). These three release sizes also show how larger releases lead to the availability of more flammable mass and overpressure outcomes that reach farther. The explosion from the 1% release affects Component 1 (PRD), potentially causing damage that would lead to a subsequent 100% release; it also has a high enough overpressure to rupture the storage cylinder. The explosion from the 10% release affects the same components as the 1% release, as well as other components; according to the overpressure cascade characterization in Table 3-3, it could lead to a 100% leak in Component 2 (valve), a 10% leak in Component 3 (compressor), and a 1% leak in Component 4 (valve). The explosion from the 100% PRD release causes maximum damage in all components included in the P&ID.

Overpressure contours for a 1% leak from both directions in Component 2 (valve) are shown in Figure 3-6.

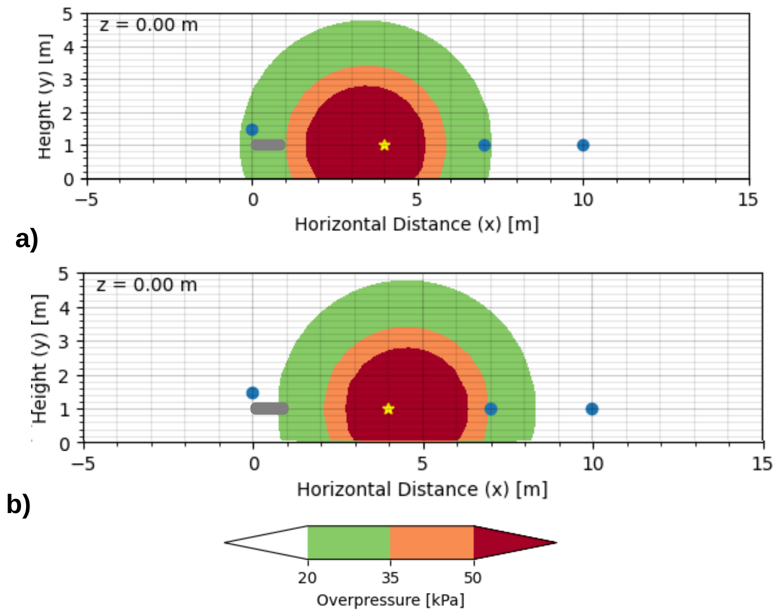

Figure 3-6. Explosion overpressure contour for a) leftward and b) rightward release from Component 2 (valve) that is 1% of pipe cross-sectional area (10 mm diameter piping).

While the overpressure contours are much less directional than the jet flames, the direction of a leak can still cause subsequent damage. The contours in Figure 3-6 illustrate how the direction of the leak can result in different consequences. For example, the leftward leak from Component 2 may cause damage to Component 1 (PRD), the storage vessel, and Component 2 (valve). Meanwhile, a rightward leak from Component 2 may cause damage to Component 2 (valve) and possibly the storage vessel.

3.2.3. Example Cascading Failure Sequences

An example of a potential pathway of events leading to a cascading leak is shown in Figure 3-7. In this example, a 1% leftward leak from Component 2 (valve) ignites into a jet fire that impinges on both the pressure vessel and Component 1 (PRD). The flame melts the O-ring on Component 1 (PRD), causing a release of hydrogen directly upwards. As discussed earlier, the PRD is likely to be oriented so that any released plume or jet flame does not impinge on anything else in the system; thus, this second release would not cause any further cascades. The impingement of the original Component 2 flame on the pressure vessel may be of more concern, since a failure to prevent rapid temperature and pressure rise within the vessel could lead to a vessel burst. In the current cascading leak model, there is no way to determine the effects of temperature, time, and PRD activity on the probability of a pressure vessel burst, however, a venting or leaking PRD would reduce the probability of a pressure vessel burst. Therefore, in this report, the pressure vessel is conservatively assumed to always burst if a flame is impinging on it.

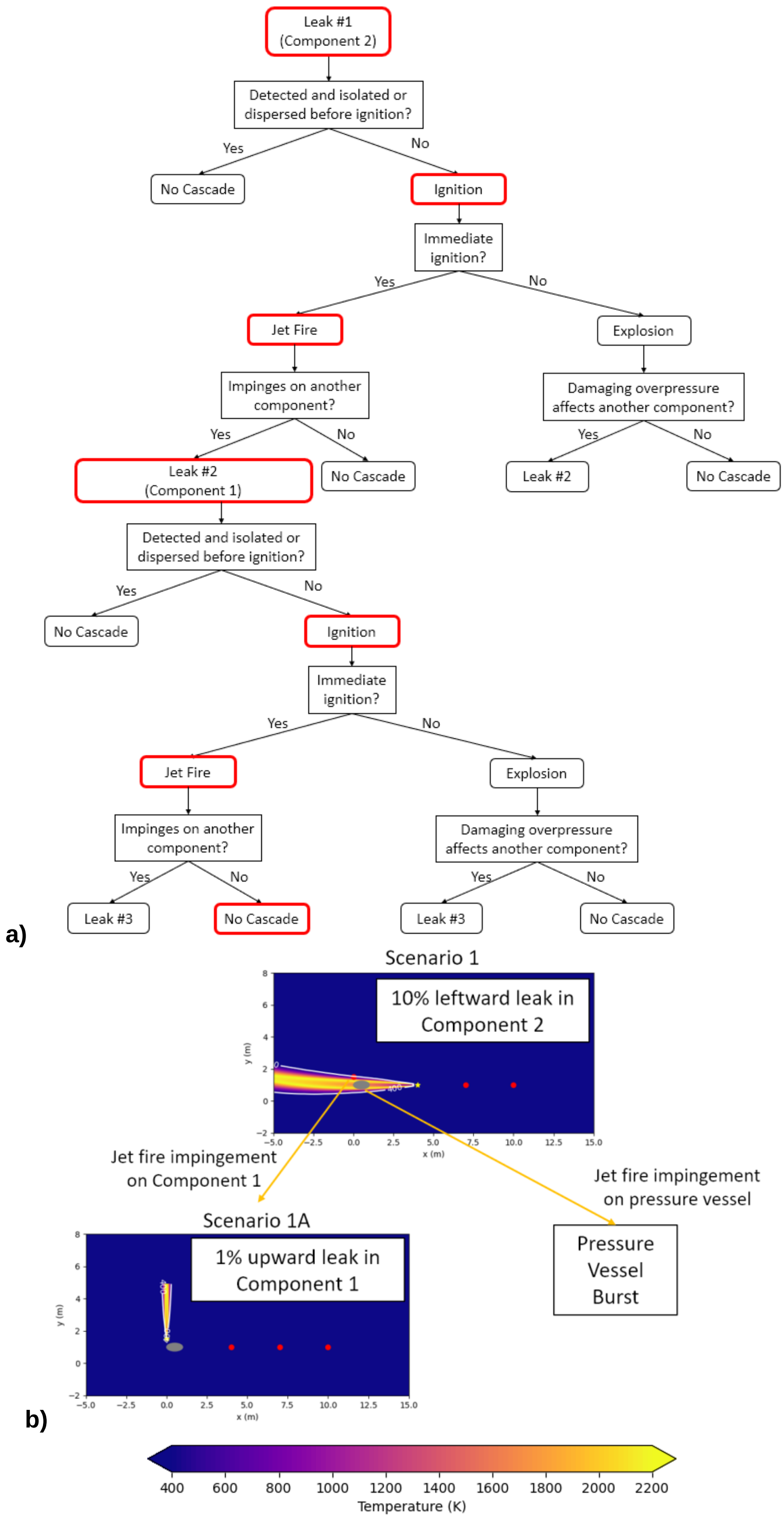

Figure 3-7. a) Example cascading leak sequence of events initiated from a jet fire from a 10% leftward leak in Component 2 and b) associated graphics.

Another example of a potential cascading leak sequence is shown in Figure 3-8. Here, a 1% rightward leak in Component 4 ignites after a delay, resulting in an explosion. This initial event causes two cascading pathways to occur in parallel for Components 3 and 4. Component 3 experiences a 20-35 kPa overpressure, leading to a 1% leak and jet fire. Since there is no way to determine the direction of the cascaded leak for an overpressure event, two directions of directly leftward and directly rightward were considered as possibilities. If the 1% jet fire from Component 3 points to the left, it would impinge on Component 2; only a 1% rightward leak was considered as an outcome here under the assumption that the part of the component facing the jet fire is the one that experiences the cascaded leak. The cascade accounting stops there because a jet fire impinging on Component 3 from Component 2 would lead to a 1% leftward leak in Component 3, which already occurred in the previous step of the sequence. Likewise, if the leak in Component 3 were pointing rightward, the cascading possibilities would be symmetrical to the rightward leak, except with the involvement of Component 4 instead of Component 2.

Meanwhile, the original explosion from Component 4 also affects component 4 itself with an overpressure of over 50 kPa, causing a full-bore leak. Again, the directionality of a leak that cascades from an explosion is unknown, so both rightward and leftward 100% leaks were considered. The rightward leak does not impinge on anything in the figure, although this P&ID is truncated and in reality, it would likely affect another downstream component not shown here. The leftward leak impinges on all the components shown. Impingement on the PRD would lead to a 1% upward leak, which could ignite into a flame, and impingement on the pressure vessel would lead to a burst. The flame would also cause 1% rightward leaks in both Components 2 and 3. If these leaks ignited into jet fires, the Component 2 leak would impinge on and lead to a 1% leftward leak and potential jet fire in Component 3.

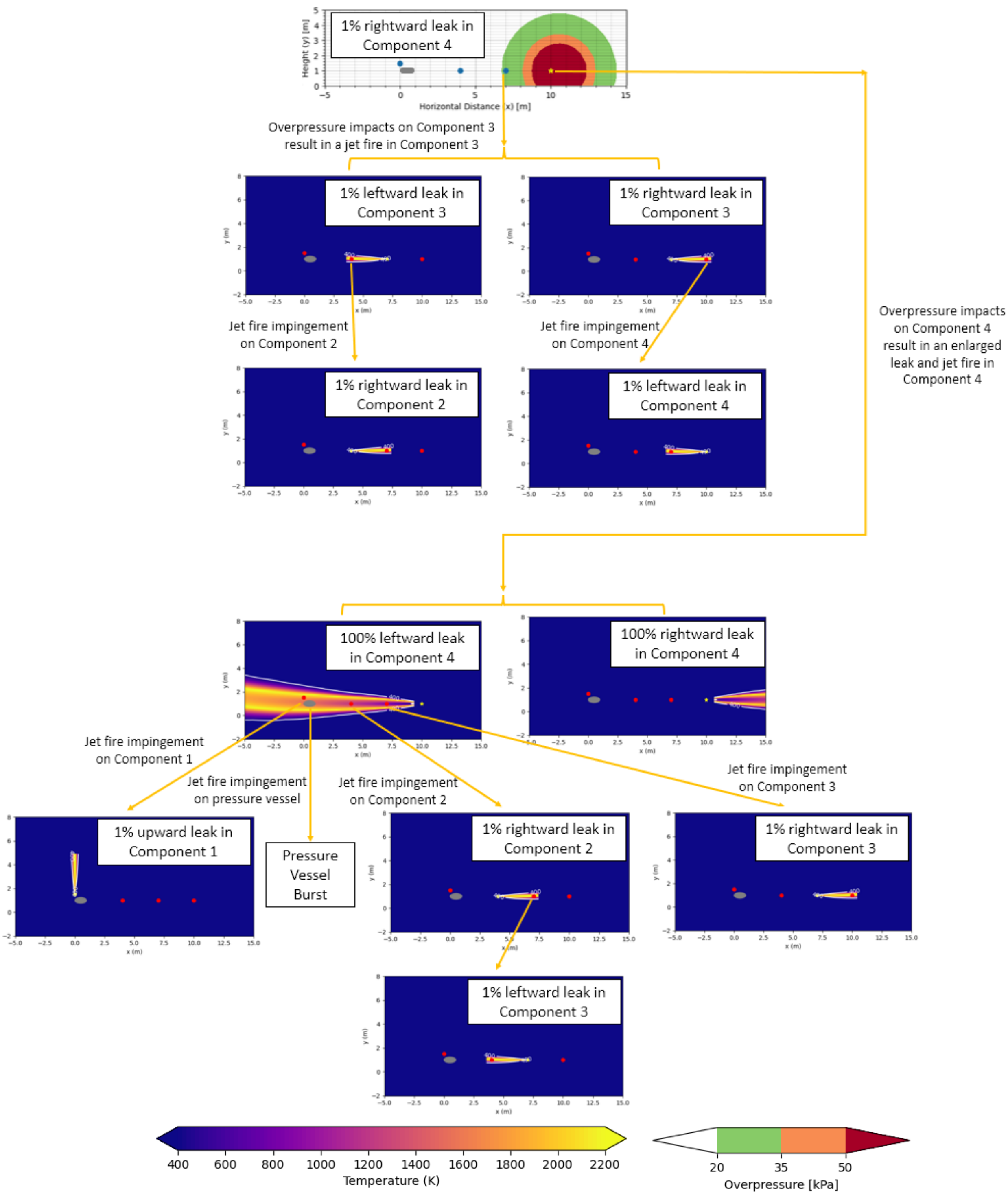

Figure 3-8. Example cascading leak sequence of events initiated from an explosion from a 1% rightward leak in Component 4.

The presented sequences in Figure 3-7 and Figure 3-8 show examples but not an exhaustive list of all events that could occur in the event of each initiating leak. Cascaded leaks are shown resulting in jet fires rather than explosions just because immediate ignition is more likely than delayed ignition, but either event is a possibility. Additionally, there is high uncertainty regarding the directionality of cascaded leaks since there are multiple leak points on some components. When a jet fire impinges on another component, it is likely that it would affect the side of the component facing the jet fire. However, the detailed mechanisms for component leaks from overpressure and the factors which impact leak directionality caused by initiating explosions are not explored in this study.

3.2.4. Example Cascading Leak Risk Assessment

Understanding the overall leak frequency of a component from cascading events in addition to the leak frequency from normal operations is necessary for characterization of risk from cascading leaks. HyRAM+ has default annual frequencies for leaks occurring during normal operation, with examples for the components included in the generic P&ID provided in Table 3-4. It is important to note that these values have significant uncertainty given the nascence of hydrogen fueling infrastructure.

Table 3-4. Default Assumed Median Leak Frequencies for Valves and Compressors for Hydrogen (High Uncertainty) [6]

Component	Annual Leak Frequency (by Leak Size)				
	0.01%	0.1%	1%	10%	100%
Valve	2.87E-3	5.86E-4	5.44E-5	2.47E-5	4.82E-6
Compressor	9.97E-2	1.70E-2	4.57E-3	1.52E-4	1.46E-5

There is limited information about the breakdown of these leaks by leak point on each component. In this discussion, the leak frequency from each leak direction is assumed to be the overall component leak frequency divided by the number of leak directions for a particular component (all of the components in the example P&ID have two leak directions, except for the PRD, which has one leak direction). For example, the HyRAM+ default leak frequency for a full-bore release from a valve from any direction is 4.82×10^{-6} leaks per year; therefore, a leftward and rightward leak are assumed to have the same leak frequency of 2.41×10^{-6} leaks per year. This assumes that a leftward and rightward leak are equally likely, which may not be a valid assumption for all components.

In addition, risk calculations require not only information on leak frequencies but also an understanding of how likely it is for consequential physical outcomes to occur. In the examples provided in Section 3.2.1, the cascading failures show conservative scenarios where a consequential physical effect like a jet fire always occurs from cascaded leaks. However, there is only some probability that a jet fire or explosion will occur from a leak. The probability of overall ignition is based on the probability that the leak is not detected or isolated before ignition happens. A default probability of detection and isolation of 0.9 is used in HyRAM+ [6]. The probability of immediate and delayed ignition is then based on default HyRAM+ values, shown in Table 3-5.

Table 3-5. Default HyRAM+ Ignition Probabilities for Hydrogen [6]

Release Rate (kg/s)	Ignition Probability	
	Immediate	Delayed
<0.125	0.008	0.004
0.125-6.25	0.053	0.027
>6.25	0.230	0.120

As an example, the proposed sequence of events in Figure 3-7 can be traced for event frequencies. For ease of following the sequence, the initiating leak is labeled and referred to as "Scenario 1" while the cascaded leak is labeled and referred to as "Scenario 1A." The pressure vessel burst is not included in the example. The frequency of Scenario 1 (a 10% leak in Component 2) is calculated using Equation 3-1.

$$f_{Scenario\ 1} = \frac{f_{10\%\ leak}}{N_{leak\ points}} \times (1 - P_{Detection\&Isolation}) \times P_{Jet\ Fire,Scenario\ 1} \qquad \text{Equation 3-1}$$

where $f_{10\%\ leak}$ is the frequency of a 10% leak based on the default HyRAM+ values for normal operations, $N_{leak\ points}$ is the number of leak points on the component in question, $P_{detection\&isolation}$ is the probability of detection and isolation, and $P_{Jet\ Fire,Scenario\ 1}$ is the probability of a jet fire based on the mass flow rate out of the 10% leak in this scenario. Using a 10% valve leak frequency of 2.47×10^{-5}/year during normal operations, 2 potential valve leak points, a 0.9 probability of detection and isolation, and a 0.053 probability of immediate ignition (based on a 0.4 kg/s leak flow rate for a 10% leak in a component with a 10-mm diameter), the frequency of Scenario 1 is 6.5×10^{-8}/year.

The frequency of the cascaded jet fire in Component 1 (shown in Scenario 1A of Figure 3-7) is given by Equation 3-2.

$$f_{Scenario\ 1A} = f_{Scenario\ 1} \times (1 - P_{Detection\&Isolation}) \times P_{Jet\ Fire,\ Scenario\ 1A} \qquad \text{Equation 3-2}$$

Using the Scenario 1 frequency of 6.5×10^{-8}/year, the 0.9 probability of detection and isolation, and a 0.008 probability of immediate ignition (based on a 0.04 kg/s leak flow rate, assuming 10% of Scenario 1's leak flow rate), the frequency of Scenario 1A is 5.2×10^{-11} /year. There is additional uncertainty in these probabilities for a cascading leak beyond the limited nature of available data. Regardless, it is evident that the probability of a jet fire occurring in a second component would be several orders of magnitude lower than the probability of a jet fire occurring in the first component.

Ideally, this type of frequency analysis would be conducted for each possible cascading failure scenario for each component and leak size. However, the comprehensiveness of this approach may not justify the time and effort required. In the example provided above, the frequency of the first cascade is already three orders of magnitude lower than the initial leak; a second cascade would likely also drop several orders of magnitude in frequency. Frequencies below some threshold should be considered negligible for the purposes of calculating useful values of risk. Further study on these cascading failure frequencies may help determine the extent to which calculations on subsequent leaks contribute to risk in a meaningful way. The consequence component of risk should also be considered, since, as mentioned in Section 0, the consequences experienced by an individual in the vicinity of multiple leaks may be additive.

The risk to a person from all the events in a cascading leak scenario can also be computed additively. The risk from each individual leak can be calculated using the product of the frequency and consequence of the scenario (Equation 3-3); these risks can then be added up for each cascade, or scenario from an initiating leak, to calculate total risk (Equation 3-4).

$$Risk_{Scenario} = f_{Scenario} \times c_{Scenario} \qquad \text{Equation 3-3}$$

$$Total\ Risk = \sum_{All\ Scenarios} Risk_{Scenario} \qquad \text{Equation 3-4}$$

For an example risk calculation, a person is assumed to be standing perpendicular to the piping, one meter away from the PRD in the +z direction (shown below in Figure 3-9). Since HyRAM+ evaluates risk at individual points, the point chosen as the person's location is (0, 1.5, 0) (in the format of (x, y, z)). The person is assumed to be exposed to the jet fire from that location for 30 seconds, which is based on the HyRAM+ default thermal exposure time [6].

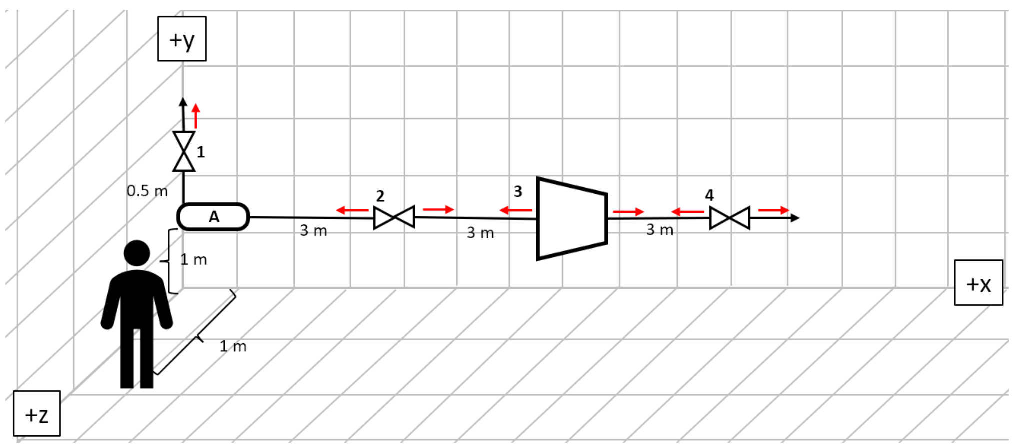

Figure 3-9. Configuration for example risk calculation.

For Scenario 1, the 10% leftward leak from Component 2 (valve) leads to a 56.2% probability of fatality from the heat flux effects of the jet fire. The individual risk for the Scenario 1 leak is evaluated to be 3.7×10^{-8} fatalities per year. The subsequent leak in Scenario 1A, the 1% upward leak from Component 1 (PRD), has a jet fire with a probability of a fatality of around 4×10^{-19}. The individual risk for the Scenario 1A leak is evaluated to be 2.0×10^{-29} fatalities per year, which is negligible. In this case, the total risk to the person would be dominated by the first leak, which already has a low order of magnitude, since full-bore leaks are infrequent. The cascaded leak of Scenario 1A has a much lower risk than the initiating leak of Scenario 1, for three reasons. First, there is a lower frequency of a cascade occurring. Second, the subsequent leak is assumed to be smaller than the original leak. Third, the orientation of the PRD leak means the heat flux dose received by the person is quite low. The compounding effects of lower probability of cascaded leaks, the likelihood of smaller cascaded leaks (at least for this jet fire impingement scenario), and orientation of the leak, which may not be directed towards the individual at risk, result in a negligible increase in risk from a secondary leak. This decrease in risk would likely continue for tertiary and subsequent leaks. This result indicates that accounting for cascading leaks in this highly detailed framework may not be useful, since there are many calculations required and little value added in quantifying additional, yet increasingly negligible, risk. There are more conservative assumptions that could be made – for example, the cascaded leak could be larger, or oriented more directly towards the person at risk. Either way, the first leak must be oriented in a specific way for the second leak to occur, and that second leak still must ignite, and the probabilities of these two factors are responsible for a secondary leak leading to a risk that is orders of magnitude lower than a primary leak in many situations.

Since risk is the sum of the product of the frequency and consequence of each scenario, both aspects should be considered when studying cascading leaks. As shown with the example in this report, if the cascaded leak has a comparable consequence to the initial leak, its risk will be lower because of its lower frequency of occurrence. However, there may be cases in which the cascaded leak has a much higher consequence than the initiating leak – for example, if a jet fire from an initial leak impinges on a pressure vessel and causes a rupture. In this case, the risk of the cascaded leak may be comparable to (or greater than) the risk of the initiating leak because of its high-consequence outcome, even if the frequency is lower. Nevertheless, if the frequency of a cascaded leak is several orders of magnitude lower than the frequency of the initiating leak, as in the example provided above, the consequence of the cascaded leak would need to be several orders of magnitude higher than the consequence of the initiating leak in order for their risks to be comparable. A current lack of existing models for estimating the probability of a pressure vessel rupture from an impinging jet flame prevented a quantitative comparison of these scenarios in this study.

A possibility for time delays between subsequent leaks in the cascade was mentioned previously. The example risk calculation presented above assumes that both jet fires happen simultaneously and that the person is exposed to their heat fluxes at the same time. However, there would likely be a time delay – the O-ring would not instantaneously melt or thermally degrade when impinged upon by the jet fire – which would mean that the person might not even be exposed to the second jet fire for the full 30 seconds, making the risk from that secondary leak even lower.

3.2.5. Leak Direction Considerations

As discussed previously, the leak directions pointing parallel or antiparallel to the hydrogen flow direction are conservative, since they represent the worst-case angle scenario for cascading failures. In reality, leaks can occur at angles to the direction of the piping. Leak frequency data is often not granular enough to specify frequency of each leak angle, but the actual leak frequency of each angle can be estimated by binning different angles. An example of using 12 different angle bins on the x-y plane is shown for jet fires in Figure 3-10 below. Angles can also be in the x-z or y-z planes, but since the components in this example P&ID are all aligned in the x-y plane, only these angles are shown.

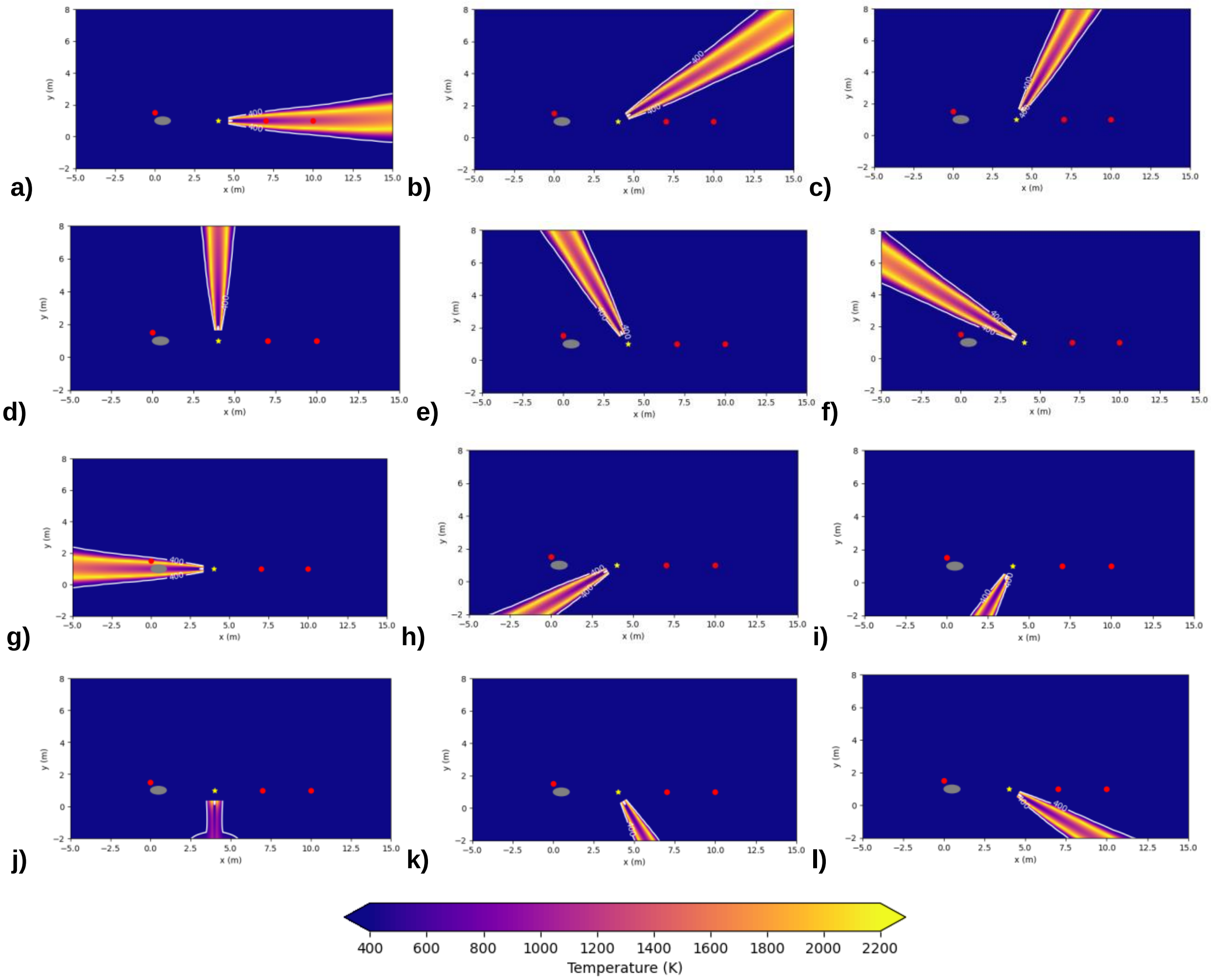

Figure 3-10. Jet fires from full-bore (100%) leaks at 12 binned angles along horizontal angles from the original 0 rad (0°), b) π/6 rad (30°), c) π/3 rad (60°), d) π/2 rad (90°), e) 2π/3 rad (120°), f) 5π/6 rad (150°), g) π rad (180°), h) 7π/6 rad (210°), i) 4π/3 rad (240°), j) 3π/2 rad (270°), k) 5π/3 rad (300°), and l) 11π/6 rad (330°).

For this system setup, only the angles parallel (0 rad) and antiparallel (π rad) show impingement of the initial jet fire onto any other component. In the initial framework presented above, there were two leak directions considered, and each leak direction was assumed to leak for half of the overall component leak frequency. Adding in the possibility for more leak directions would reduce the frequency for each direction even more: instead of the frequency of a jet fire from Component 2 (valve) impinging on Component 1 (PRD) and the storage cylinder being half of Component 2 leak frequency, it would be one-twelfth of the Component 2 leak frequency (or a different fraction, depending on how many discrete leak directions are considered).

It is also possible that cascaded leaks occur at different angles, which could potentially change the risk to an individual as well. For simplicity, the possibility of angled cascaded leaks was not considered in this analysis as a conservative assumption.

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4. CONCLUSIONS

Cascading leaks in hydrogen storage systems can increase risk to personnel and infrastructure through the higher frequencies of leaks per component due to leak mechanisms besides wear from normal operations, and through the potentially higher consequences experienced during multiple simultaneous leaks. Understanding this type of failure can facilitate more accurate assessments of risk in hydrogen systems and promote risk-preventative system design.

An event sequence diagram was modified from the default HyRAM+ diagram for a single leak; the diagram shows that a jet fire or explosion from an initial leak has some probability of causing a leak in another component. The cascaded leak may be caused by a multitude of mechanisms, including thermal degradation of a component O-ring from a jet fire and shearing of a storage cylinder from explosive overpressure. This leak can then be treated similarly to the initial leak in that it can also be shut down, disperse, or ignite into a jet fire or explosion. While the provided event sequence diagram is general, some understanding of a specific system layout is required in order to conduct the type of cascading leak assessments included in this report.

Two examples of cascading failure sequences from initial leaks in a generic P&ID were provided using cascading consequences based on the example jet fire failure mechanism – impingement and melting of the component O-ring – and damage information informed by overpressure probits. Notably, based on the assumption that all leaks were directly parallel or antiparallel to their components, many of the adjacent or proximate components were affected by jet fires, even from smaller leaks like those that were 1% of the component cross-sectional area. Additionally, the overpressure contours showed that an explosion from a leak could damage the original leaking component even further.

Examples of using the event sequence diagram to calculate leak frequencies for different scenarios were also provided. These examples showed that, using the assumptions described in this report, the frequency of a cascaded leak can be several orders of magnitude lower than the frequency of the initial leak. Further study on the implications of the decreasing leak frequencies on risk from cascading leak sequences is recommended to understand the degree of detail that is useful in cascading failure analyses. In particular, identifying a risk threshold below which the risk is considered negligible may help make this framework useful for owner-operators.

Understanding a specific system layout and the potential for cascading leaks can be helpful in designing or operating hydrogen storage systems safely. Design choices such as component spacing and orientation, the presence of fire or blast walls between certain areas within the system, and elimination of possible ignition sources in areas most likely to experience leaks can be informed by a cascading leak analysis.

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APPENDIX A. SUMMARY OF SCENARIOS

Initial Leaking Component	Leak Direction	Leak Size As Percentage of Pipe Cross-Sectional Area	Physical Outcome of Initial Leak
Component 1 (PRD)	Upward	0.01%	Jet Fire
		0.1%	
		1%	
		10%	
		100%	
		0.01%	Explosion
		0.1%	
		1%	
		10%	
		100%	
Component 2 (Valve)	Leftward	0.01%	Jet Fire
		0.1%	
		1%	
		10%	
		100%	
	Rightward	0.01%	
		0.1%	
		1%	
		10%	
		100%	
	Leftward	0.01%	Explosion
		0.1%	
		1%	
		10%	
		100%	
	Rightward	0.01%	
		0.1%	
		1%	
		10%	

Initial Leaking Component	Leak Direction	Leak Size As Percentage of Pipe Cross-Sectional Area	Physical Outcome of Initial Leak
		100%	
Component 3 (Compressor)	Leftward	0.01%	Jet Fire
		0.1%	
		1%	
		10%	
		100%	
	Rightward	0.01%	
		0.1%	
		1%	
		10%	
		100%	
	Leftward	0.01%	Explosion
		0.1%	
		1%	
		10%	
		100%	
	Rightward	0.01%	
		0.1%	
		1%	
		10%	
		100%	
Component 4 (Valve)	Leftward	0.01%	Jet Fire
		0.1%	
		1%	
		10%	
		100%	
	Rightward	0.01%	
		0.1%	
		1%	
		10%	
		100%	

Initial Leaking Component	Leak Direction	Leak Size As Percentage of Pipe Cross-Sectional Area	Physical Outcome of Initial Leak
	Leftward	0.01%	Explosion
		0.1%	
		1%	
		10%	
		100%	
	Rightward	0.01%	
		0.1%	
		1%	
		10%	
		100%	

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APPENDIX B. JET FIRE TEMPERATURE CONTOURS

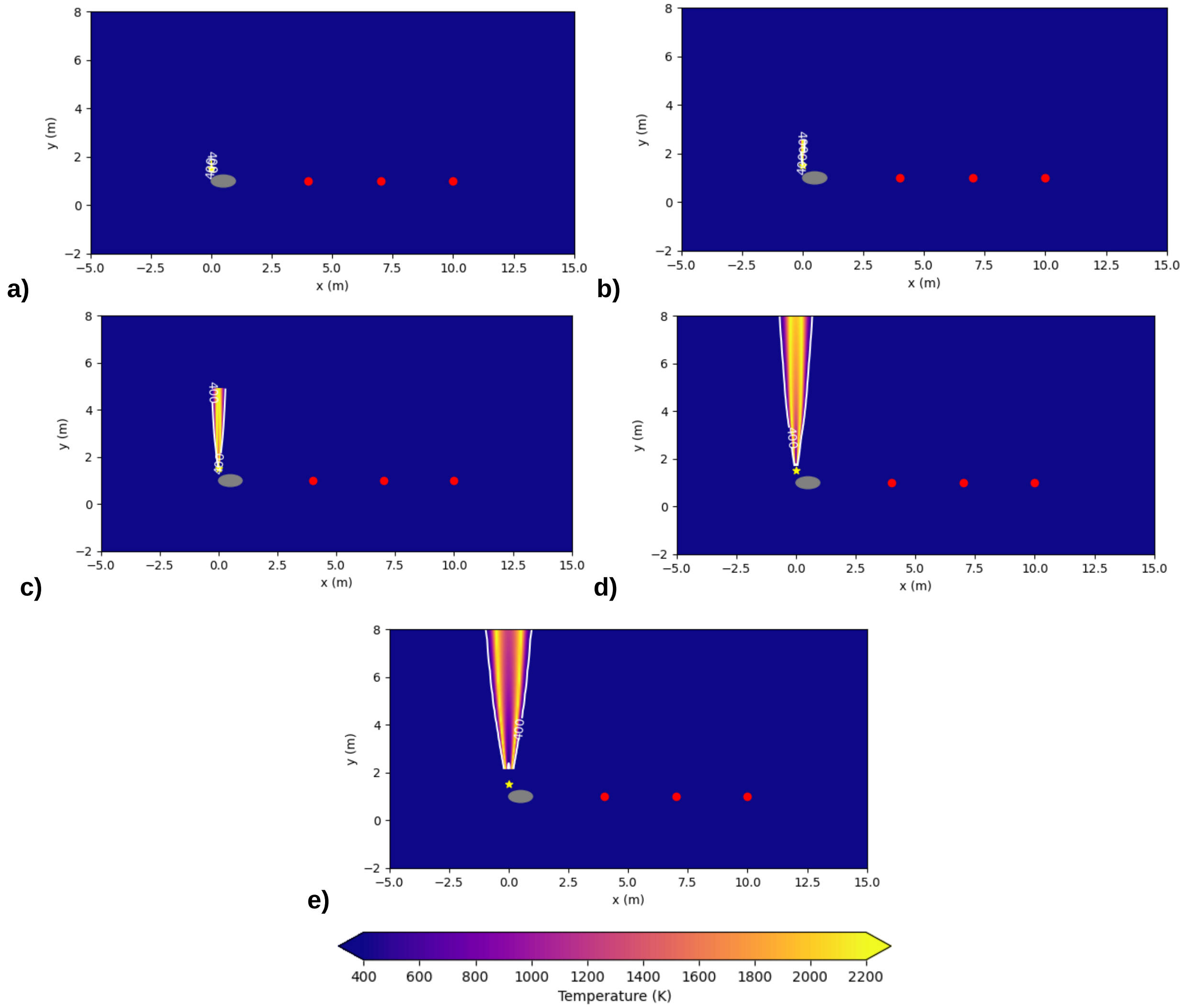

Figure B-1. Jet fire temperature contour from component 1 (PRD) for an upward release that is a) 0.01%, b), 0.1%, c) 1%, d) 10%, and e) 100% of pipe cross-sectional area (10 mm diameter piping). The temperature boundary of 400 K (260°F) is marked in white.

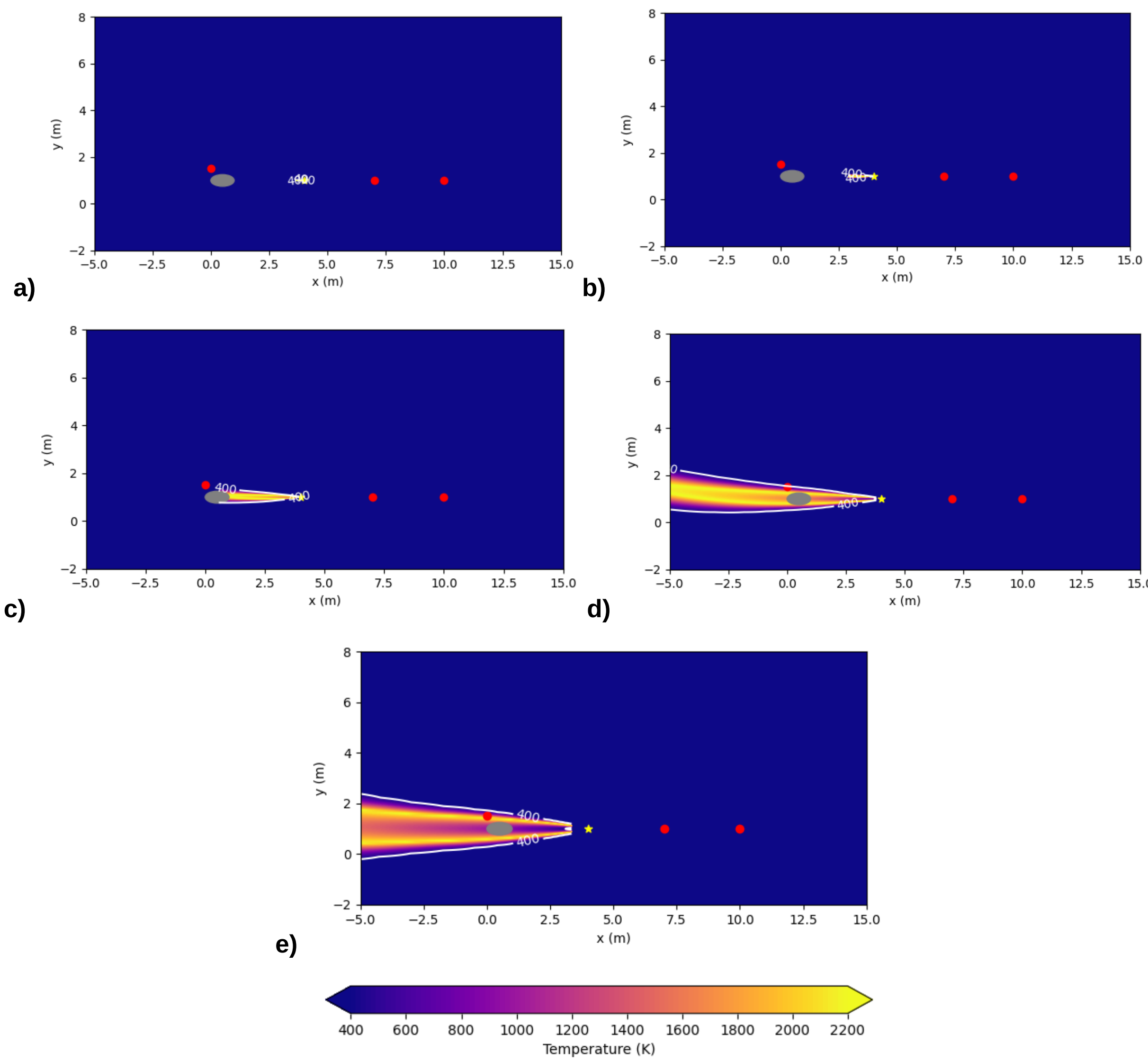

Figure B-2. Jet fire temperature contour from component 2 (valve) for a leftward release that is a) 0.01%, b) 0.1%, c) 1%, d) 10%, and e) 100% of pipe cross-sectional area (10 mm diameter piping). The temperature boundary of 400 K (260°F) is marked in white.

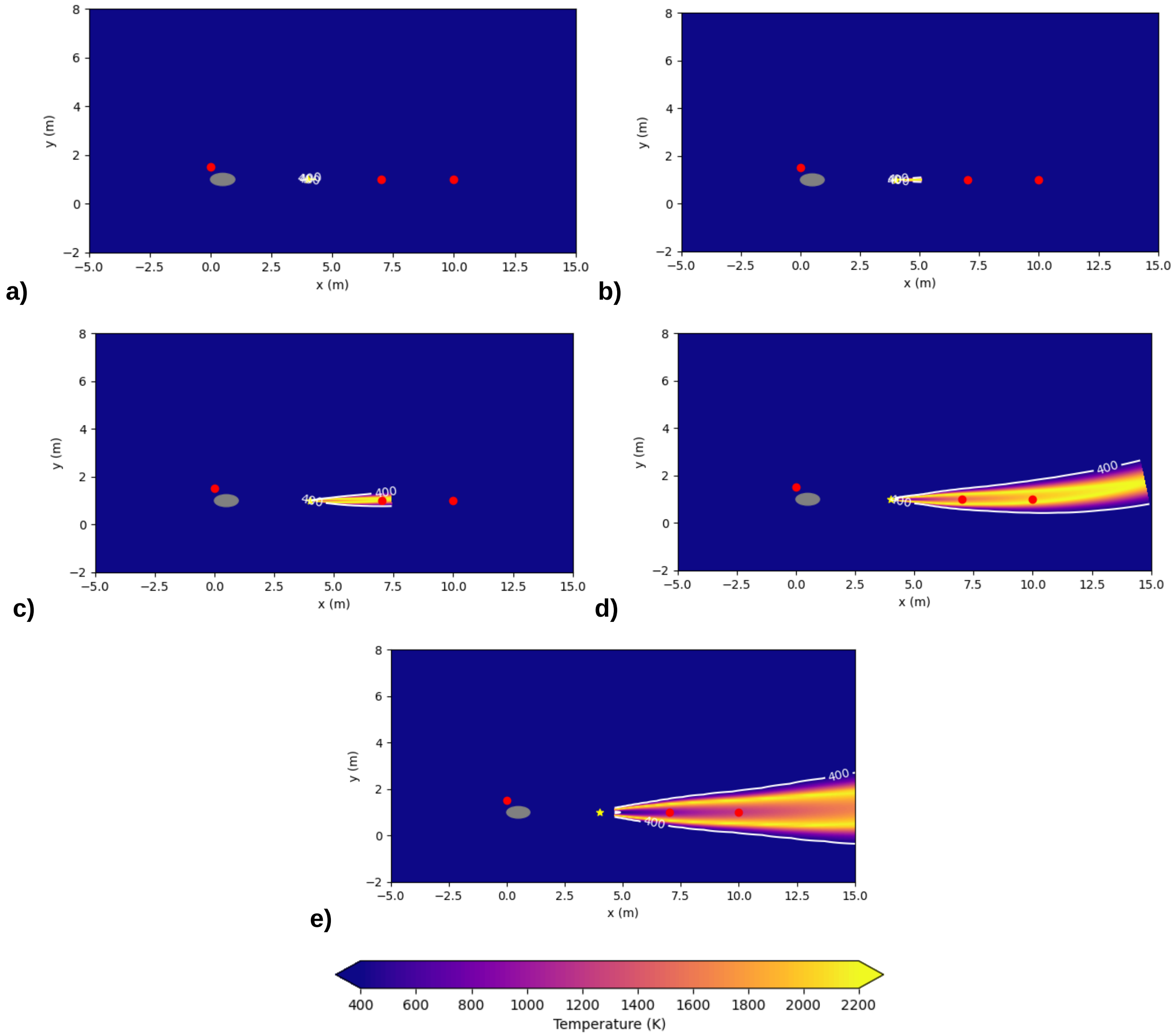

Figure B-3. Jet fire temperature contour from component 2 (valve) for a rightward release that is a) 0.01%, b) 0.1%, c) 1%, d) 10%, and e) 100% of pipe cross-sectional area (10 mm diameter piping). The temperature boundary of 400 K (260°F) is marked in white.

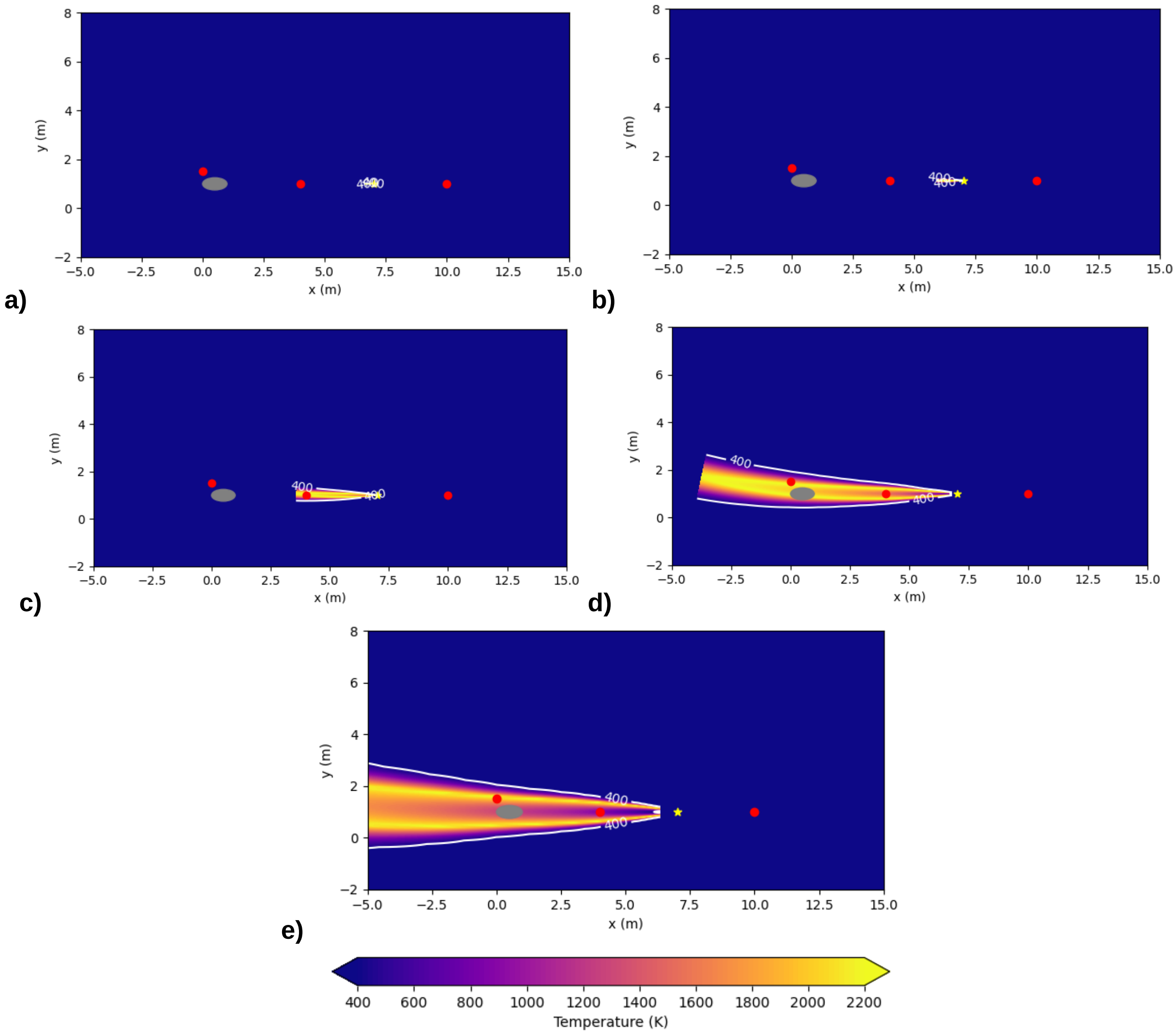

Figure B-4. Jet fire temperature contour from component 3 (compressor) for a leftward release that is a) 0.01%, b) 0.1%, c) 1%, d) 10%, and e) 100% of pipe cross-sectional area (10 mm diameter piping). The temperature boundary of 400 K (260°F) is marked in white.

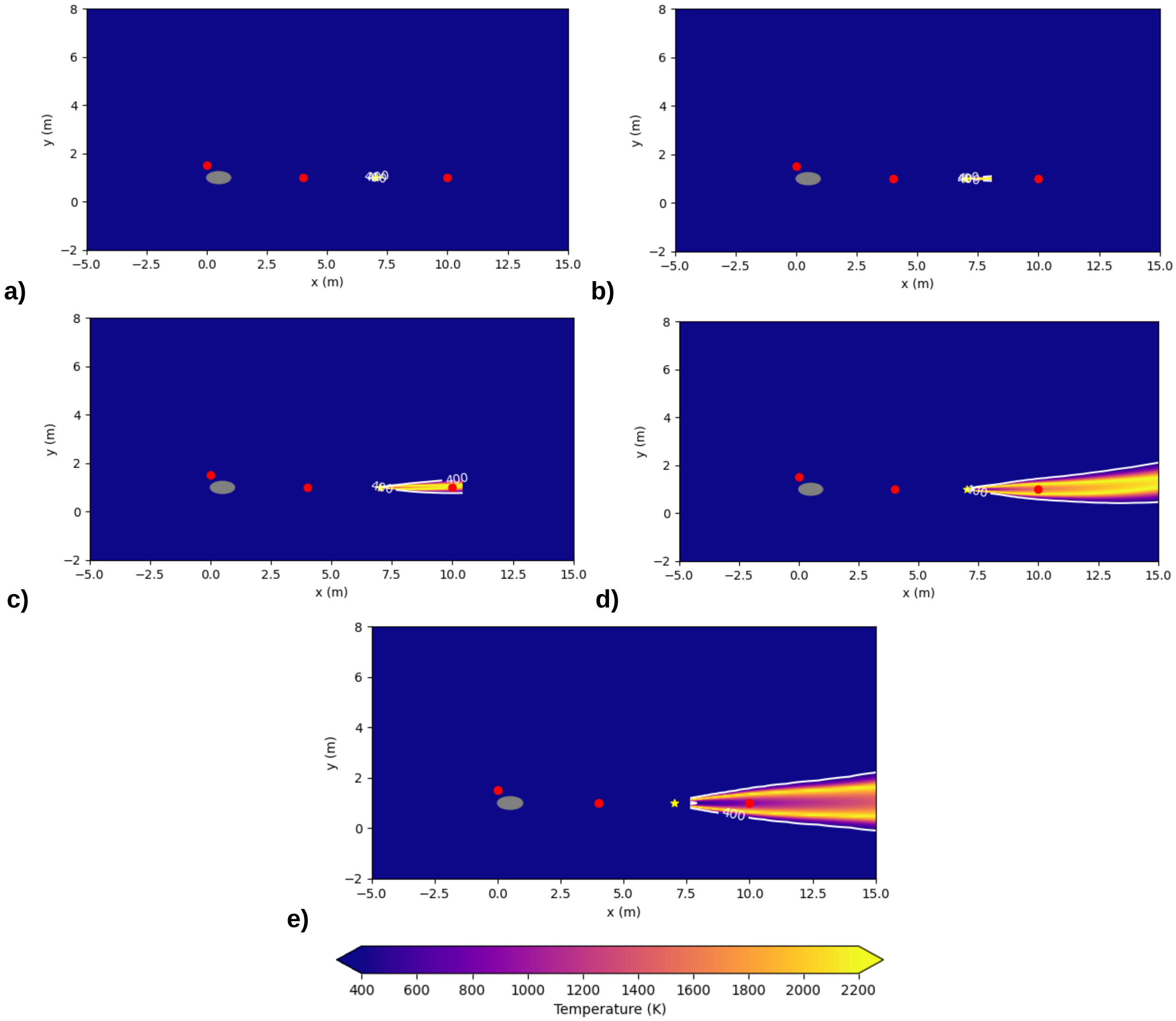

Figure B-5. Jet fire temperature contour from component 3 (compressor) for a rightward release that is a) 0.01%, b) 0.1%, c) 1%, d) 10%, and e) 100% of pipe cross-sectional area (10 mm diameter piping). The temperature boundary of 400 K (260°F) is marked in white.

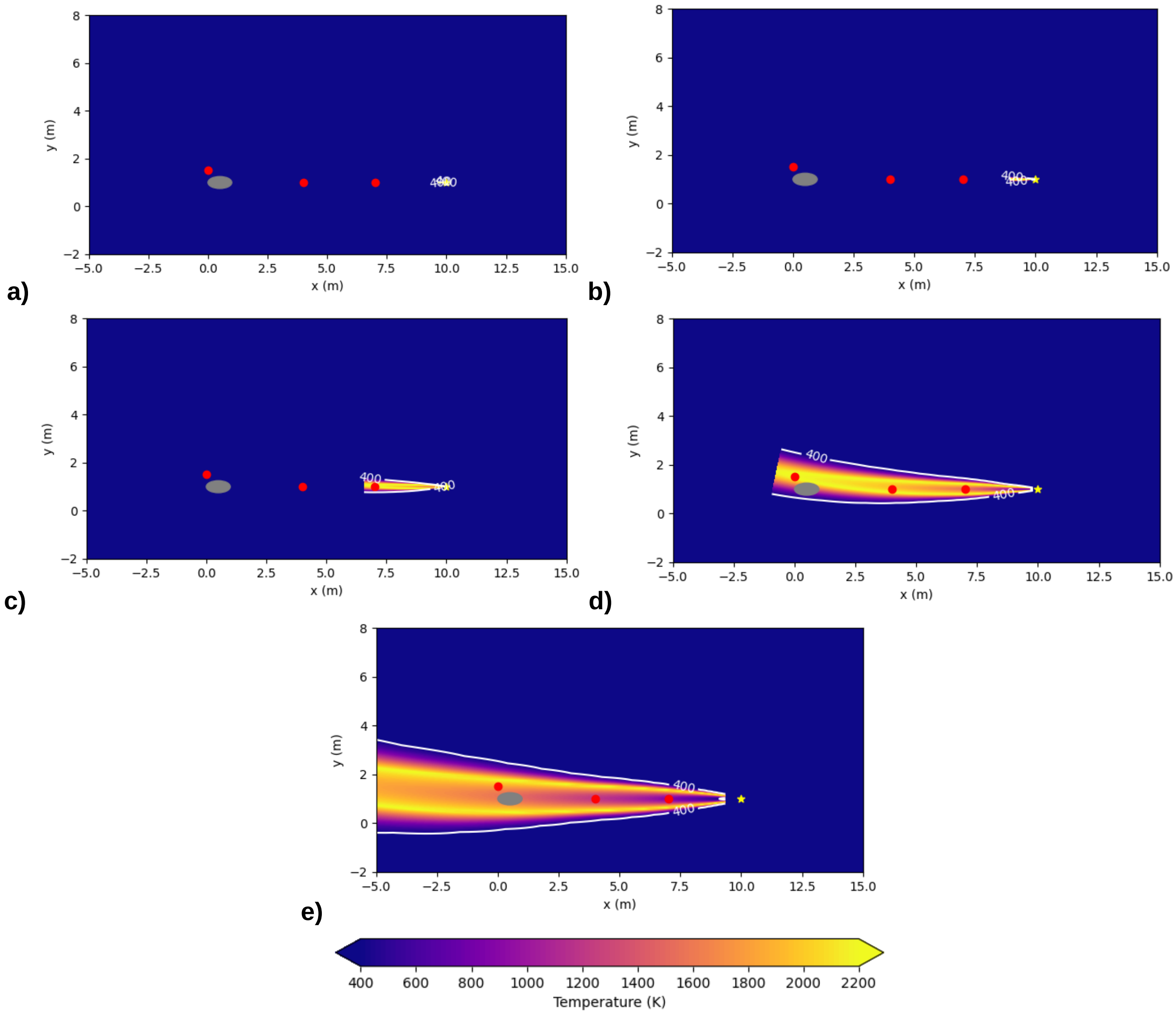

Figure B-6. Jet fire temperature contour from component 4 (valve) for a leftward release that is a) 0.01%, b) 0.1%, c) 1%, d) 10%, and e) 100% of pipe cross-sectional area (10 mm diameter piping). The temperature boundary of 400 K (260°F) is marked in white.

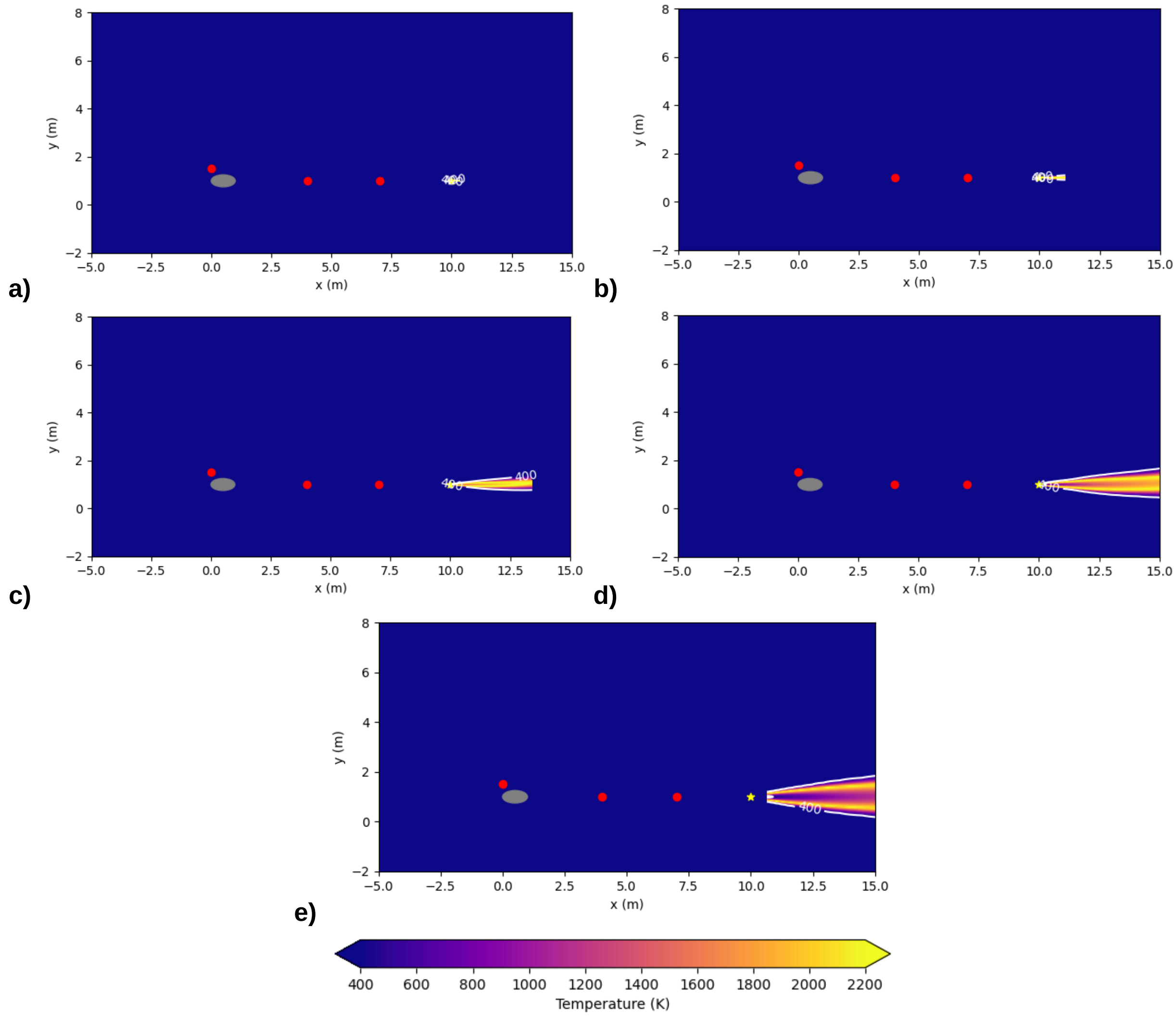

Figure B-7. Jet fire temperature contour from component 4 (valve) for a rightward release that is a) 0.01%, b) 0.1%, c) 1%, d) 10%, and e) 100% of pipe cross-sectional area (10 mm diameter piping). The temperature boundary of 400 K (260°F) is marked in white.

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APPENDIX C. EXPLOSION OVERPRESSURE CONTOURS

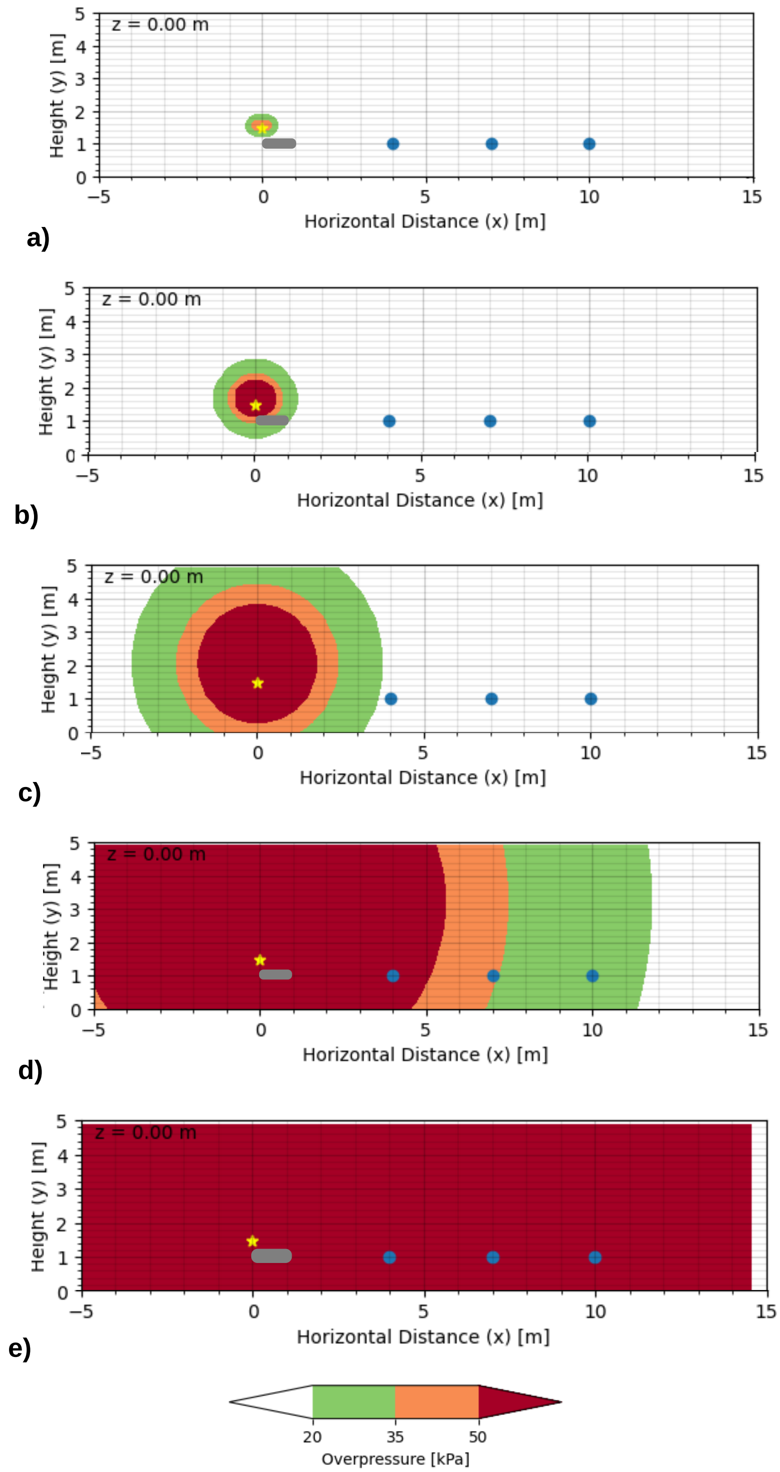

Figure C-1. Explosion overpressure contour from component 1 (PRD) for an upward release that is a) 0.01%, b) 0.1%, c) 1%, d) 10%, and e) 100% of pipe cross-sectional area (10 mm diameter piping).

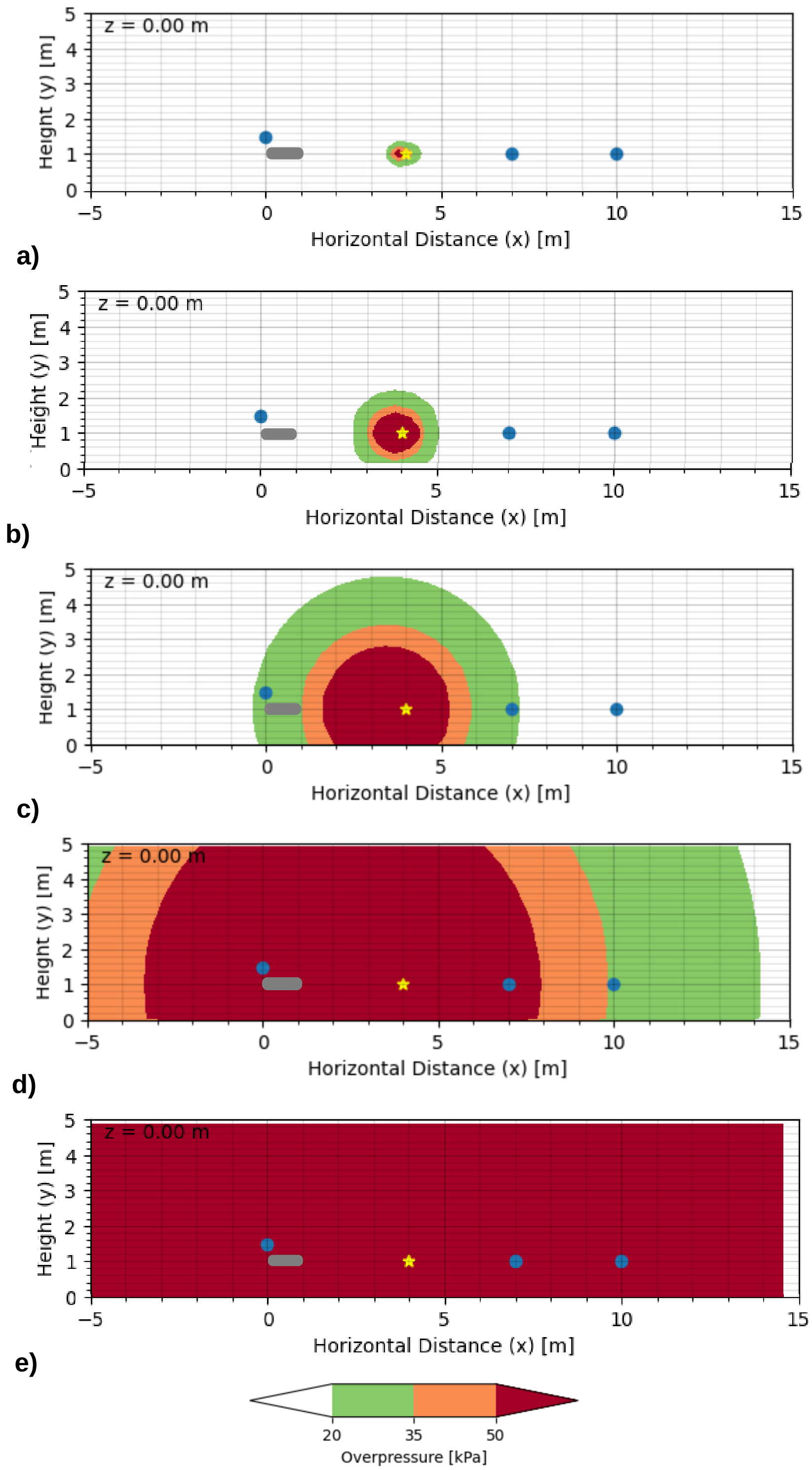

Figure C-2. Explosion overpressure contour from component 2 (valve) for a leftward release that is a) 0.01%, b) 0.1%, c) 1%, d) 10%, and e) 100% of pipe cross-sectional area (10 mm diameter piping).

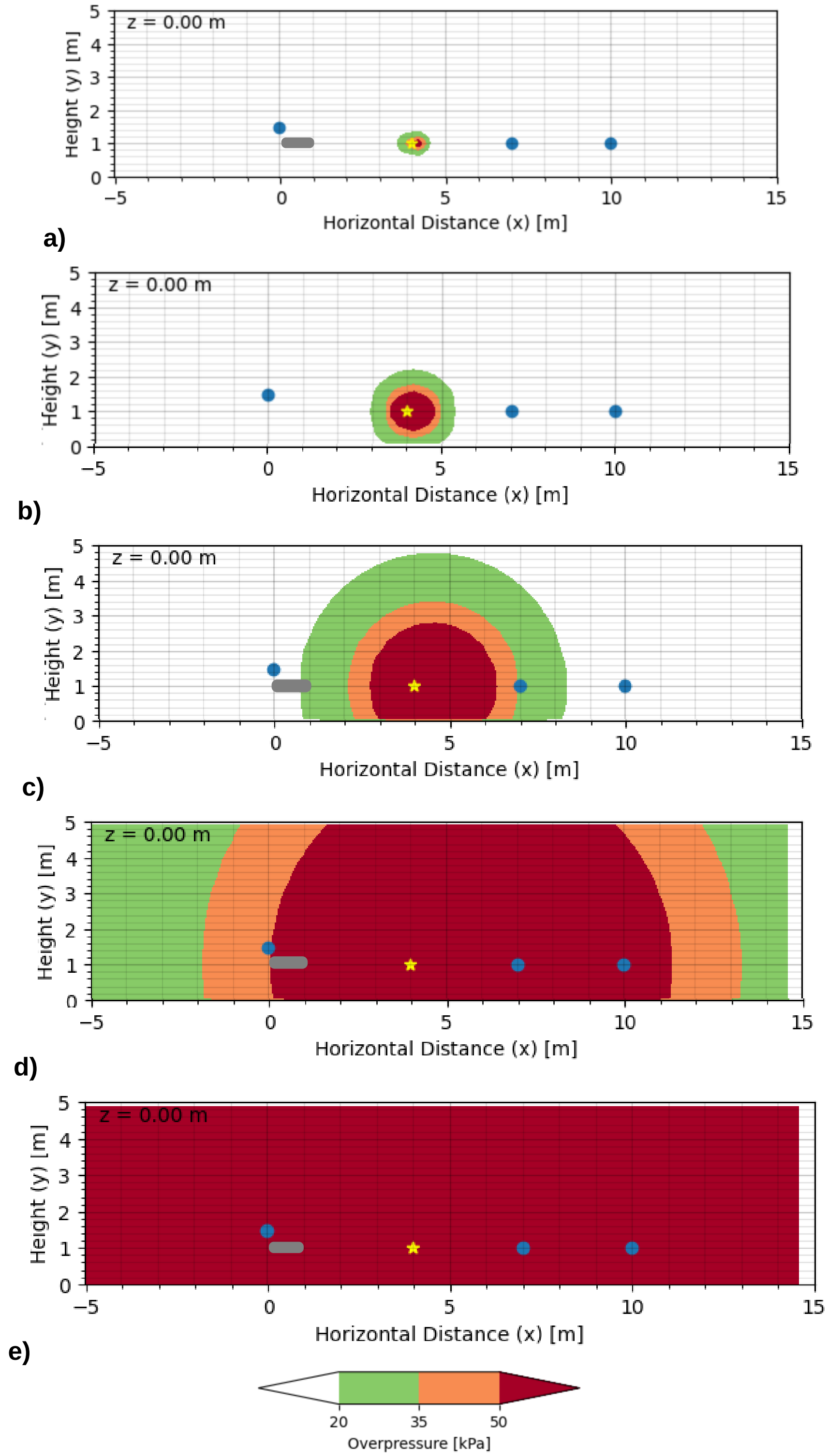

Figure C-3. Explosion overpressure contour from component 2 (valve) for a rightward release that is a) 0.01%, b) 0.1%, c) 1%, d) 10%, and e) 100% of pipe cross-sectional area (10 mm diameter piping).

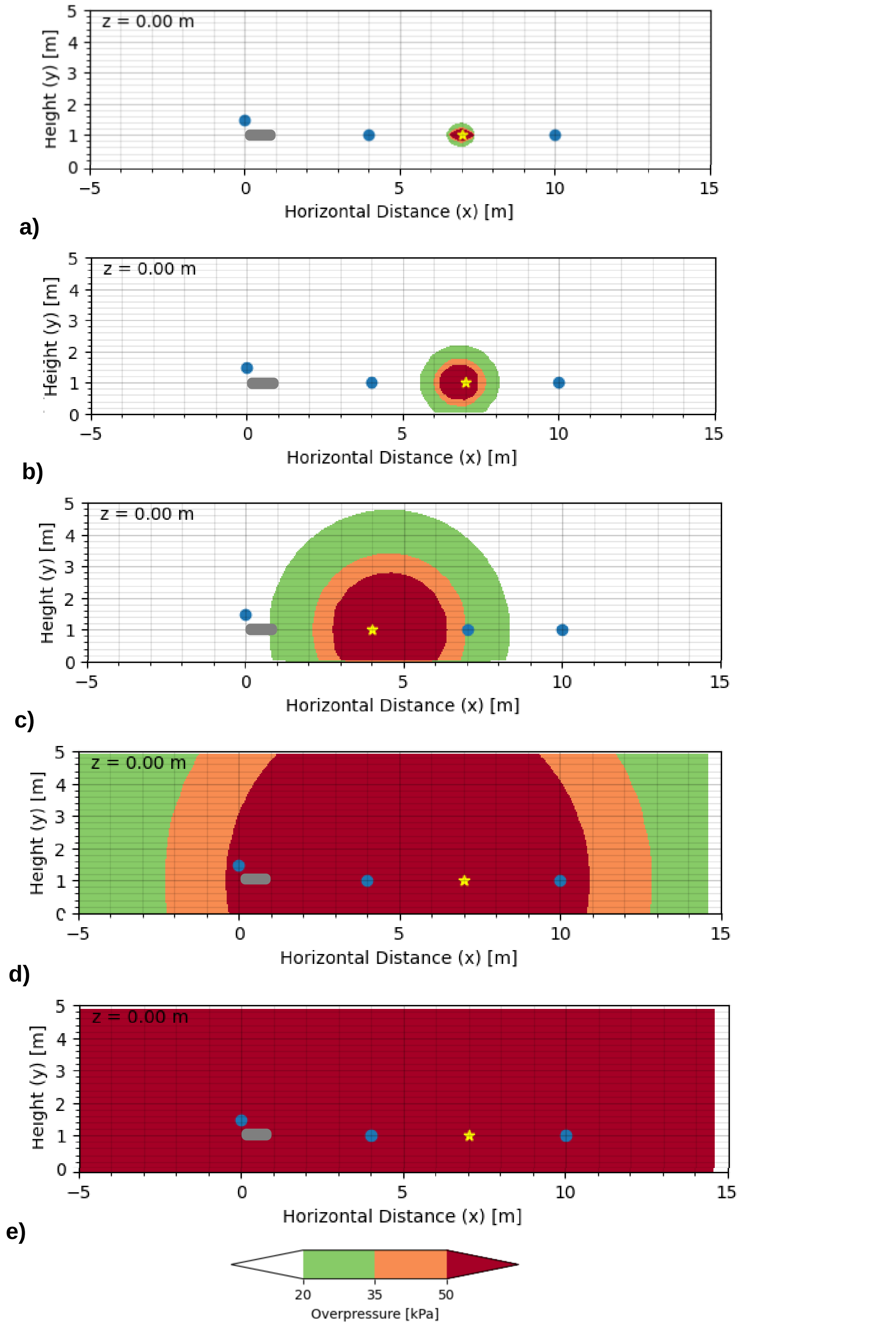

Figure C-4. Explosion overpressure contour from component 3 (compressor) for a leftward release that is a) 0.01%, b) 0.1%, c) 1%, d) 10%, and e) 100% of pipe cross-sectional area (10 mm diameter piping).

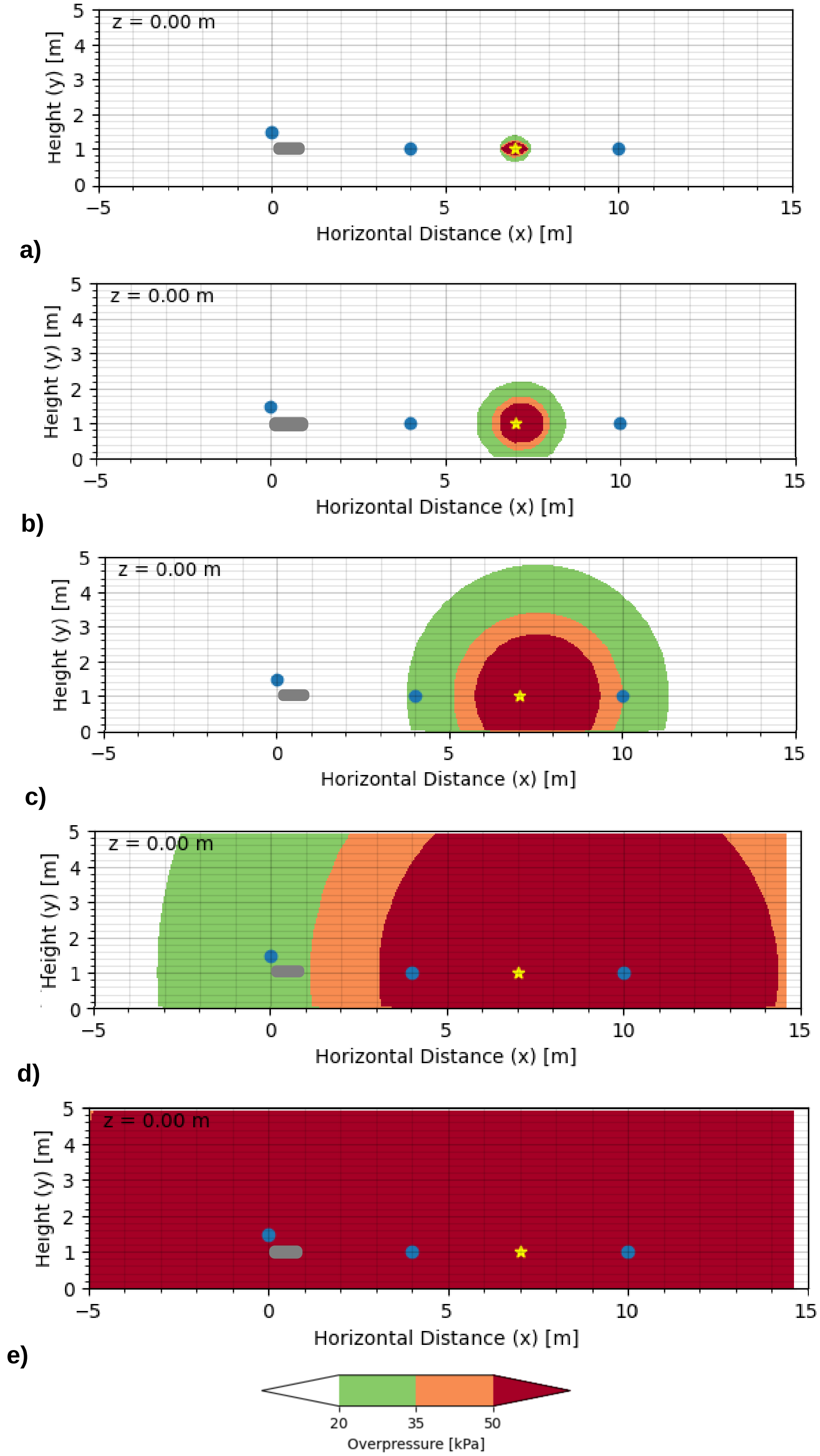

Figure C-5. Explosion overpressure contour from component 2 (compressor) for a rightward release that is a) 0.01%, b) 0.1%, c) 1%, d) 10%, and e) 100% of pipe cross-sectional area (10 mm diameter piping).

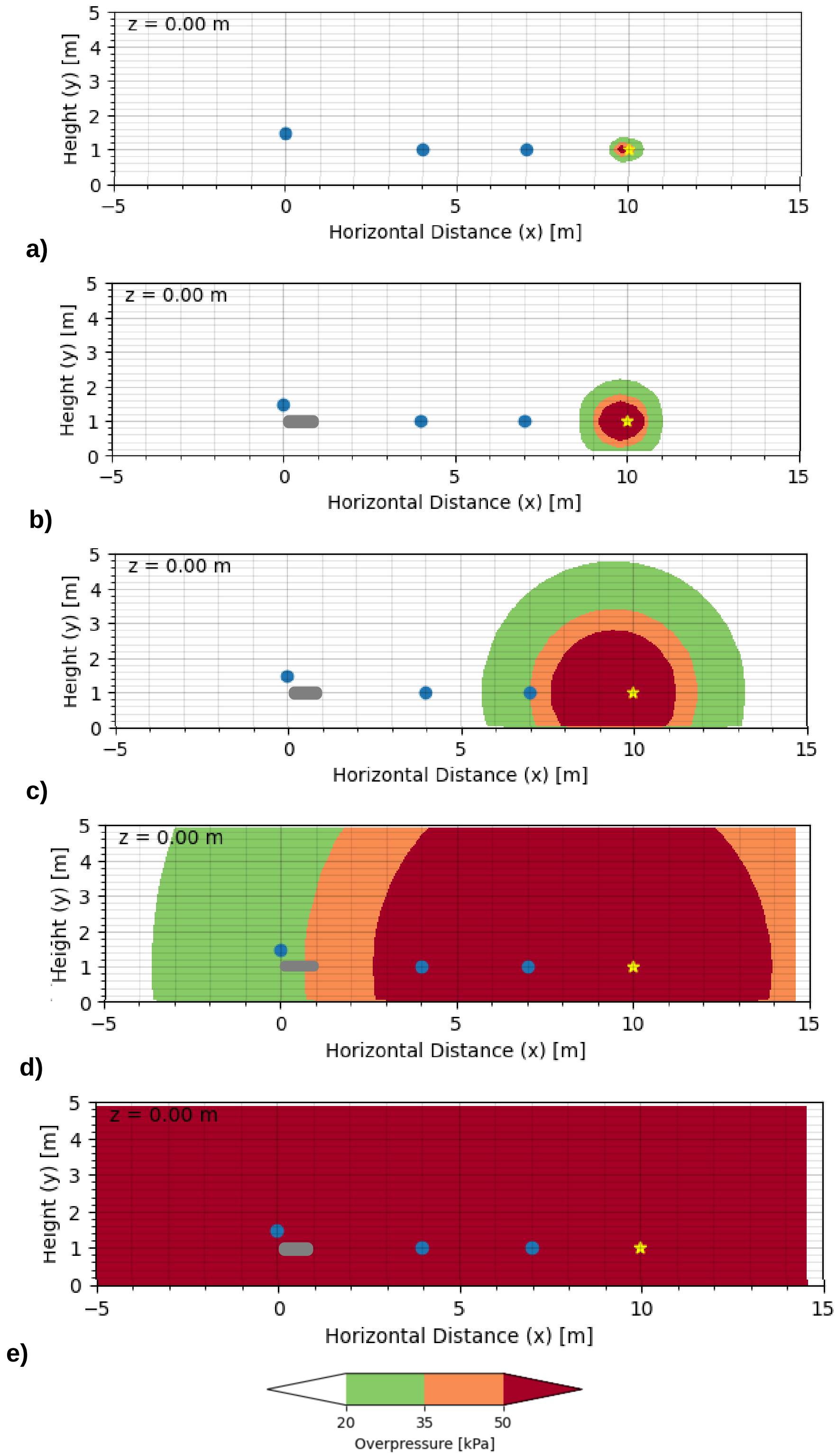

Figure C-6. Explosion overpressure contour from component 4 (valve) for a leftward release that is a) 0.01%, b) 0.1%, c) 1%, d) 10%, and e) 100% of pipe cross-sectional area (10 mm diameter piping).

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