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Risk Associated with the Use of Barriers in Hydrogen Refueling Stations

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1 Introduction

Separation distances are used in hydrogen refueling stations to protect people, structures, and equipment from the consequences of accidental hydrogen releases. Specifically, hydrogen jet flames resulting from ignition of unintended releases can be extensive in length and pose significant radiation and impingement hazards. Depending on the leak diameter and source pressure, the resulting separation distances can be unacceptably large. One possible mitigation strategy to reduce exposure to jet flames is to incorporate barriers around hydrogen storage, process piping, and delivery equipment. The effectiveness of barrier walls to reduce hazards at hydrogen facilities has been previously evaluated using experimental and modeling information developed at Sandia National Laboratories (Houf, et.al. 2008). The effect of barriers on the risk from different types of hazards including direct flame contact, radiation heat fluxes, and overpressures associated with delayed hydrogen ignition has subsequently been evaluated and used to identify potential reductions in separation distances in hydrogen facilities. Both the frequency and consequences used in this risk assessment and the risk results are described. The results of the barrier risk analysis can also be used to help establish risk-informed barrier design requirements for use in hydrogen codes and standards.

2 Barrier Effects on Consequences

Barrier walls will reduce the extent of unacceptable consequences due to hydrogen releases resulting from accidents involving high-pressure equipment. While reducing the extent of hydrogen jets, the walls may introduce other hazards if not properly configured. The configuration considerations include the height and width of the barrier as well as the structural strength of the wall. The potential consequences from hydrogen releases behind barriers are discussed in this section.

3 Direct Flame Effects

The presence of barriers will block a significant fraction of jet fires resulting from immediate ignition of hydrogen releases. Barriers that are higher than 2.4m will provide protection from direct flame contact for individuals on the protected side of the barrier (i.e., downstream of the barrier). Sufficiently high barriers are required to protect people at ground level from jet fires that may skim the top of barrier. In addition, the barriers must be wide enough to

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prevent exposure from jets resulting from leaks in all the hydrogen components. A three-wall barrier that encompasses the hydrogen components can be particularly effective in preventing exposure to jet fires. However, vertical barriers will deflect some jet fires down and back towards the hydrogen facility located upstream of the barrier resulting in a wider area of exposure for personnel who may be working on the facility and potentially resulting in additional component failures. Tilting the barrier at some angle will help reduce this effect.

As illustrated in Figure 1, an unignited hydrogen jet will be confined to a region essentially upstream of the barriers, greatly reducing the downstream (axial) extent of the unignited release as compared to the case with no barrier. A calculation of the horizontal extent of the concentration decay for a free jet by Houf and Schefer, 2007 indicates that the 8% mole fraction surface would extend 10.4 m from the jet exit while the 4% mole fraction surface would extend approximately 20.8m. With a vertical wall barrier, the extent of the 4% and 8% mole fraction surfaces are 3.2 m and 1.9 m, respectively from the jet nozzle. The surfaces in Figure 1 were calculated (Houf et al., 2008) using the FUEGO computer program developed by Sandia (Moen et al., 2002) for a 3.175 mm diameter leak at 10.3 MPa directed at the center of a 2.4m x 2.4m barrier and located 1.22 m away from the wall at a height of 1.22 m.

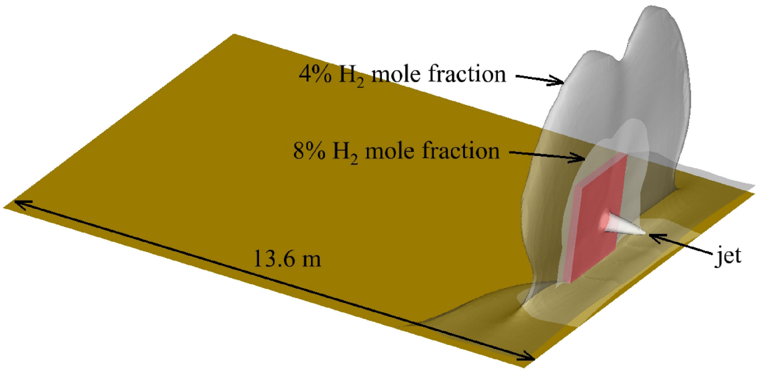

Figure 1: Illustration of the effect of barriers on unignited hydrogen envelopes.

4 Thermal Radiation Effects

Although a barrier may prevent direct contact to the flames from a jet fire, there is still a potential to be harmed by the thermal radiation from the ignited jet. Fortunately, the use of a barrier also reduces the percentage of hydrogen jet flames that can result in thermal radiation exposures to individuals. For those flames that hit the barrier, the flame will be redirected and reshaped by the barrier. The portion of the flame that extends over and around the barrier will result in radiation to individuals on the other side of the barrier. For flames that are directed over the wall, the portions of the flame not blocked by the wall can result in radiation to individuals on the other side of the barrier.

Houf et al., 2008 have performed experimental and analytical work to evaluate the impact of barriers when the jets hit the barriers. The analytical results indicate that barriers will significantly reduce the axially extent of a specific radiation heat flux level by roughly a factor of 3. As indicated in Figure 2, a vertical barrier will substantially reduce the axial extent of a 4.7 kW/m^2 isosurface (i.e., in the direction of the jet). However, the extent of the isosurface in the lateral and vertical directions parallel to the barrier is greater than for a free jet with no barrier.

The residual risk from flames that are directed above the top of a barrier can be eliminated by proper selection of the barrier height and distance from the hydrogen components. This can be illustrated using the model developed by Houf and Schefer, 2007 and the geometry shown in Figure 3.

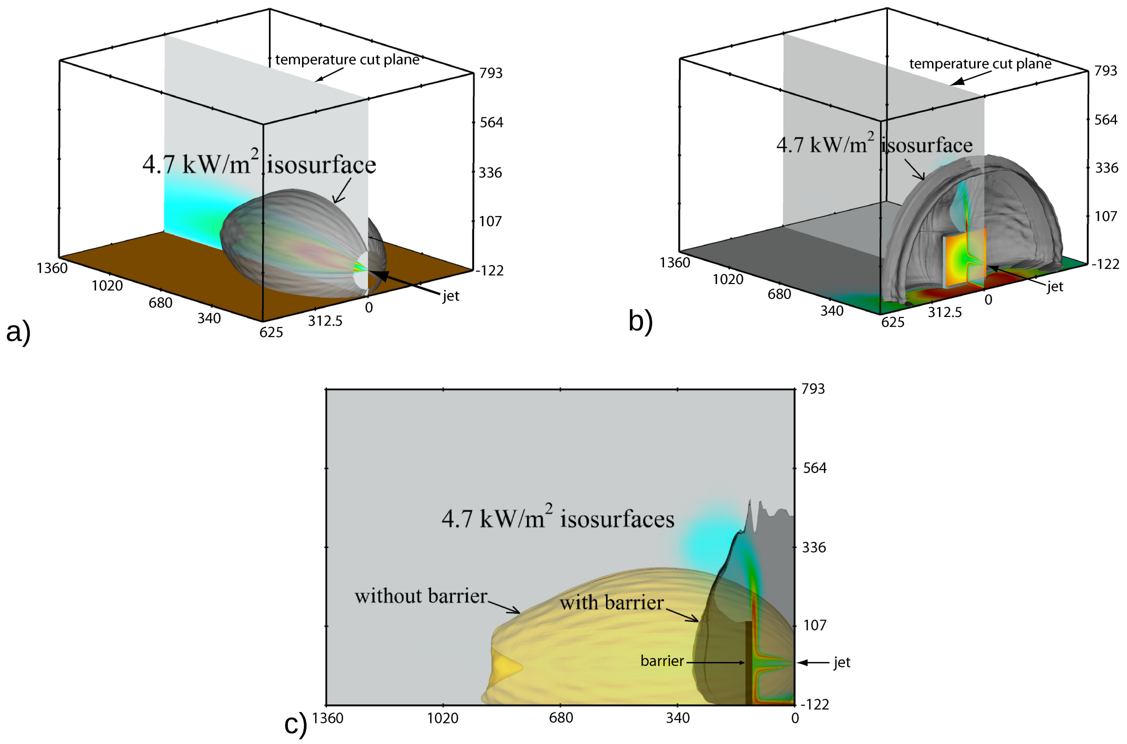

Figure 2: **Calculated isosurfaces for a thermal radiation heat flux of 4.7 kW/m^2 from hydrogen jet flames; (a) free jet flame with ground plane; (b) jet flame directed toward center of 1-wall vertical barrier; (c) side view of isosurfaces shown in (a) and (b), comparing horizontal and vertical extent of radiation field without and with a barrier; jet flow is from right to left with distances in centimeters.**

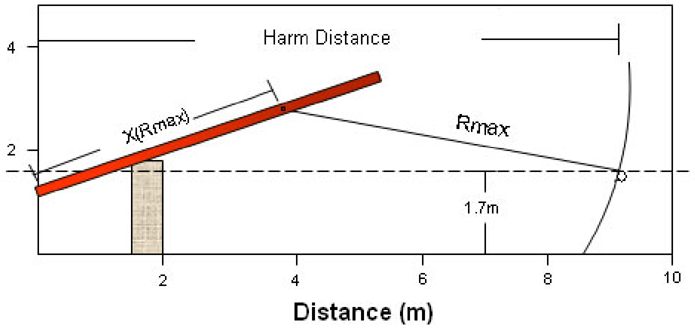

Figure 3: **Illustration of flame-barrier orientation resulting in thermal radiation exposure.**

To determine an approximate harm distance based on a thermal radiation heat flux when the flame passes over the top of the barrier, an arc of radius R_{max}, the maximum radius for a given heat flux level, originating from the axial location on the flame where the maximum heat flux occurs (designated as $X(R_{max})$ was drawn. R_{max} was calculated as the separation distance minus the $X(R_{max})$, roughly 0.7 times the flame length. A correlation for separation distance was available from prior work by Houf and Schefer, 2007. The intersection of this arc with y=1.7m, the height of an individual's head, was taken as the harm distance associated with a heat flux from a flame that passes over the top of the barrier.

A review of the geometry in Figure 3 indicates that increasing the angle between the flame and the barrier will increase the physical distance between an individual and the flame, thus reducing the distance R_{max} associated with a selected heat flux level. This angle can be increased by locating the wall closer to the equipment, increasing the wall height, or both. Figure 4 depicts an approximation for the decrease in harm distances for three heat flux levels as the angle of the flame is increased. There are several important points pertaining to this figure. First, flames with shallow angles will not substantially reduce the harm distance. Harm distance only begins to substantially decrease when the flames have angles greater than approximately 30 degrees. Second, there is an angle at which a given heat flux level will not occur at a target on the other side of the wall. For the 4.7 kW/m^2 heat flux level shown in Figure 4, that angle is 46 degrees. This implies that the orientation of the barrier and hydrogen source can be selected to ensure that a target will not be exposed to a selected heat flux level. An example of such an orientation involves selecting a very high wall height.

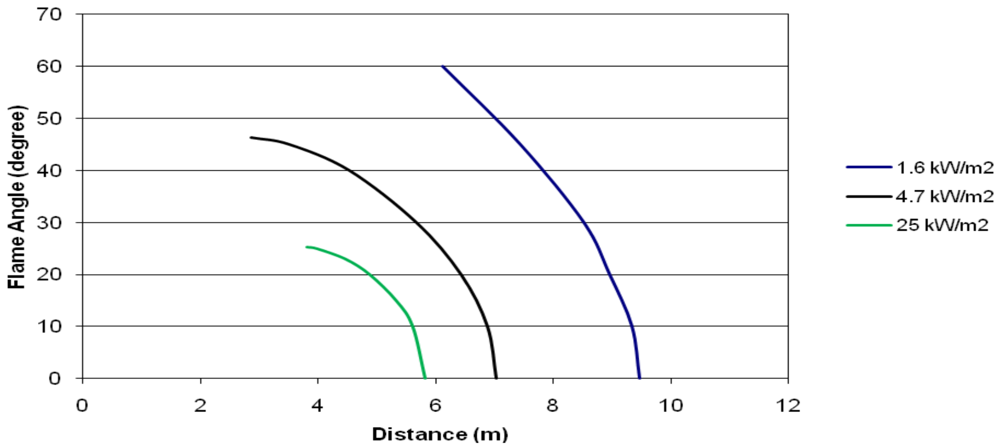

Figure 4: **Separation distances for radiation heat fluxes from hydrogen jets orientated at various angles.**

5 Pressure Effects

A potentially negative consequence related to the use of barriers is the increase in pressure resulting from a delayed ignition of hydrogen confined behind the barrier. The resulting overpressure may harm individuals on either side of the wall or cause failure of the barrier. These possibilities were analytically evaluated by Houf et al., 2008 for various release pressures, leak diameters, and ignition times using the FLACS (2009) Navier-Stokes code. Although the peak overpressures that were reported in Houf et al., 2008 could be relatively high (e.g., 65 kPa for a 9.09 mm leak at 1.83 MPa with ignition occurring at 2 seconds after initiation of the leak), these overpressures are very localized. Figure 5 provides an illustration of the overpressure and pressure impulse profiles on the entire barrier wall evaluated for a 3.28 mm leak in a 20.8 MPa system ignited at 2 seconds. The pressure increase on the wall is between 5 and 10 kPa and the pressure impulse is approximately 100 and 200 Pa-s. Similar results were obtained for a delayed ignition of a leak in a 103.5 MPa system. These types of overpressures and pressure impulses would only cause minor damage to reinforced structures or barrier walls (AICE, 1994).

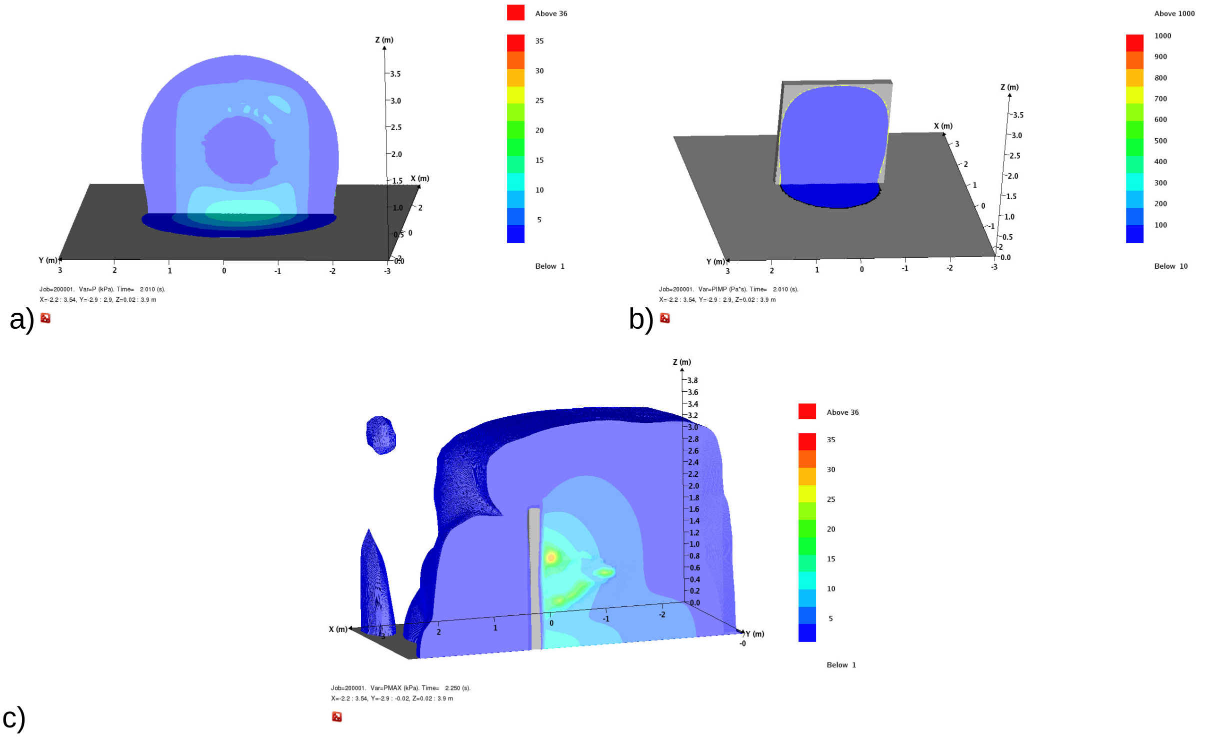

Figure 5: **FLACS results for a 3.28 mm leak in a 20.8 MPa system ignited at 2 seconds, (a) pressure on wall, (b) pressure impulse on wall, and (c) maximum pressure contour on both sides of the wall.**

Figure 5 also illustrates the maximum pressure predicted to occur on both sides of the barrier. Upstream of the barrier, the maximum overpressures are between 10 and 15 kPa and downstream of the barrier the pressures are only between 1 to 2 kPa. These types of pressures would not cause any direct harm to a person (Jeffries et al., 1997).

6 Risk Evaluation

As indicated in the previous discussion, the use of properly designed barriers will remove the potential for direct contact with jet flames, reduce the distance of unignited jets, reduce the isosurfaces for various thermal radiation heat fluxes, and not result in any substantial increase in pressure that would harm people or structures. Thus, barriers provide a means to reduce the risk to the public from unintended releases of hydrogen. This reduction in risk also allows for the opportunity to reduce the separation distances at a hydrogen facility. Estimates of the risk reduction potential were generated by Sandia using the risk model generated for evaluation of the separation distances selected for incorporation into the NFPA-2 and NFPA-55 hydrogen standards (LaChance et al., 2009) and the consequence results reported in Houf et al., 2008. The system configurations and associated leakage frequencies utilized in LaChance et al., 2009 were utilized in the barrier risk assessment, thus allowing for direct comparison of the risk with and without a barrier. The barrier wall was assumed to be 2.4 m high and separated from the hydrogen equipment by 1.22 m Table 1 provides a comparison of the risk to an individual located at the facility lot line.

Table 1: Estimated risk reduction from the use of barriers.

System Pressure (MPa)	Leak Diameter[1] (mm)	Separation Distance to Facility Lot Line[2] w/o Barrier (m)	Individual Risk at Facility Lot Line (fatalities /yr)	
			w/o Barrier	Barrier
1.83	9.09	14.0	2.0E-5	5.4E-6
20.78	3.28	14.0	2.1E-5	5.5E-6
51.81	1.37	8.8	3.6E-5	1.1E-5
103.52	1.24	10.4	3.5E-5	1.0E-5

[1] Leak diameter corresponds to 3% of the largest flow area in the system

[2] Separation distance specified in NFPA-55, based on selected leak diameter.

As indicated in Table 1, the presence of a barrier can be used to reduce the risk to a person standing at the facility lot line. The use of a barrier can also be used to reduce the separation distances. For a risk level equivalent to the risk without a barrier, the separation distance to the facility lot line can be shortened to approximately 3.5 m (measured from edge of the facility and not the barrier). The separation distance from the barrier for the example facilities would be approximately 2 m.

Acknowledgements

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