SAN BERNADINO COUNTY TRANSPORTATION AUTHORITY

ZEMU CONCEPT FEASIBILITY STUDY

COLLATERAL RISK OF UPSET ANALYSIS

REV	DATE	DESCRIPTION
0	08-28-2020	For Review & Comment
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1 - INTRODUCTION

The San Bernardino County Transportation Authority (SBCTA) is proposing the Arrow Maintenance Facility (AMF) Zero Emission Multiple Unit (ZEMU) Vehicle Upgrades Project (Project) to facilitate the integration of a hydrogen (H2) fuel zero emission multiple unit rail vehicle into the planned Arrow service. The goal of the ZEMU pilot Project is to demonstrate the feasibility of low-or-zero emission railway technology consistent with state guidelines. In conjunction with this overarching goal, SBCTA's objectives for implementing the Project include the following:

- Integrate zero- or low-emission technologies into the Arrow's service fleet to further improve localized air quality and reduce emissions of criteria air pollutants.
- Enhance the Arrow service's operational flexibility and reliability through the provision of a ZEMU rail vehicle to supplement SBCTA's diesel multiple units (DMU).
- Support State of California's cap-and-trade programs through the provision and implementation of low- or zero-emissions technology for transit corridors traversing disadvantaged communities.
- Integrate safety improvements for hydrogen fuel use at the AMF.

The associated technical effort seeks to qualify the collateral consequence of an accidental explosion that results from hydrogen storage and fueling operations at AMF. The narrative that follows frames credible explosive events, which exceed minimum code considerations for storage of combustible materials, as well as categories of collateral consequences that were investigated. Guidance in NFPA and other applicable references to capture industry best practices focused on limiting the likelihood of a failure event. This approach is considered to provide a level of risk management that is aligned with other similar existing storage/fueling operations. The overarching assessment findings are intended to provide the baseline for informed decision-making by SBCTA to pursue mitigation measures where risk exceeds acceptable thresholds.

2 - GLOSSARY OF ACRONYMS

Acronym	Definition
AMF	Arrow Maintenance Facility
BLDG	Building
BLEVE	Boiling Liquid Expanding Vapor Explosion
CEQA	California Environmental Quality Act
DMU	Diesel Multiple Unit
GH2	Gaseous Hydrogen
IEMF	Inland Empire Maintenance Facility
LH2	Liquefied Hydrogen
SBCTA	San Bernardino County Transportation Authority
SCRRA	Southern California Regional Rail Authority

Acronym	Definition
VCE	Vapor Cloud Explosion
ZEMU	Zero Emission Multiple Unit

3 - PROJECT DESCRIPTION

SBCTA is currently constructing the AMF, previously referred to as the Inland Empire Maintenance Facility (IEMF), which will service SBCTA's DMU rail vehicle fleet for the Arrow service and start operations in 2021. The Southern California Regional Rail Authority (SCRRA) will operate and dispatch the Arrow service in coordination with SCRRA's existing Metrolink service.

The AMF or Project site is located in San Bernardino, California, near the intersection of North J Street and 3rd Street. The Project site is located to the northeast of the San Bernardino Santa Fe Depot and Metrolink Station platforms. Figure 2 depicts the Project site and immediate Project vicinity. Figure 3 illustrates the Project site, portions of the Project site subject to ZEMU-related improvements, and the approximate location of the ZEMU H2 Refueling Area. The Refueling Area is expected to be constructed to include additional space for - one charging station for the ZEMU onboard batteries, a H2 storage tank and associated fueling infrastructure. The ZEMU is planned to start testing and operation in 2023.

To provide flexibility for final design, SBCTA is considering the use of H2 in either gas (GH2) or liquid (LH2) form. Based on data provided and ZEMU operating requirements the following scenarios were investigated:

1. minimum 265-kg of GH2 as needed to operate a single day of complete service; or
2. 4000-kg of compressed LH2 delivered to the site every 15-days.

Scenario #1 frames a lower bound failure event that is based on the volume of H2 required for a single train to operate for a single day. There is no quantity of onsite fuel that is expected to be less than this volume. This scenario was used to evolve an understanding of the lowest possible collateral consequence. It is expected that maximum daily onsite storage of GH2 will be a greater amount to accommodate fueling of an empty train and replenishment of fuel reserves.

For both scenarios, the storage tank would be a temporary fixture that would be replaced once empty (Figure 1); it will be hauled off site, and replaced with a full tank. The tank would connect to an on-site control system, compressors, evaporators, and fueling hoses. If required, a liquid to gas conversion container may also be installed in the Refueling Area.

Figure 1 – Representative Temporary Hydrogen Storage Tank

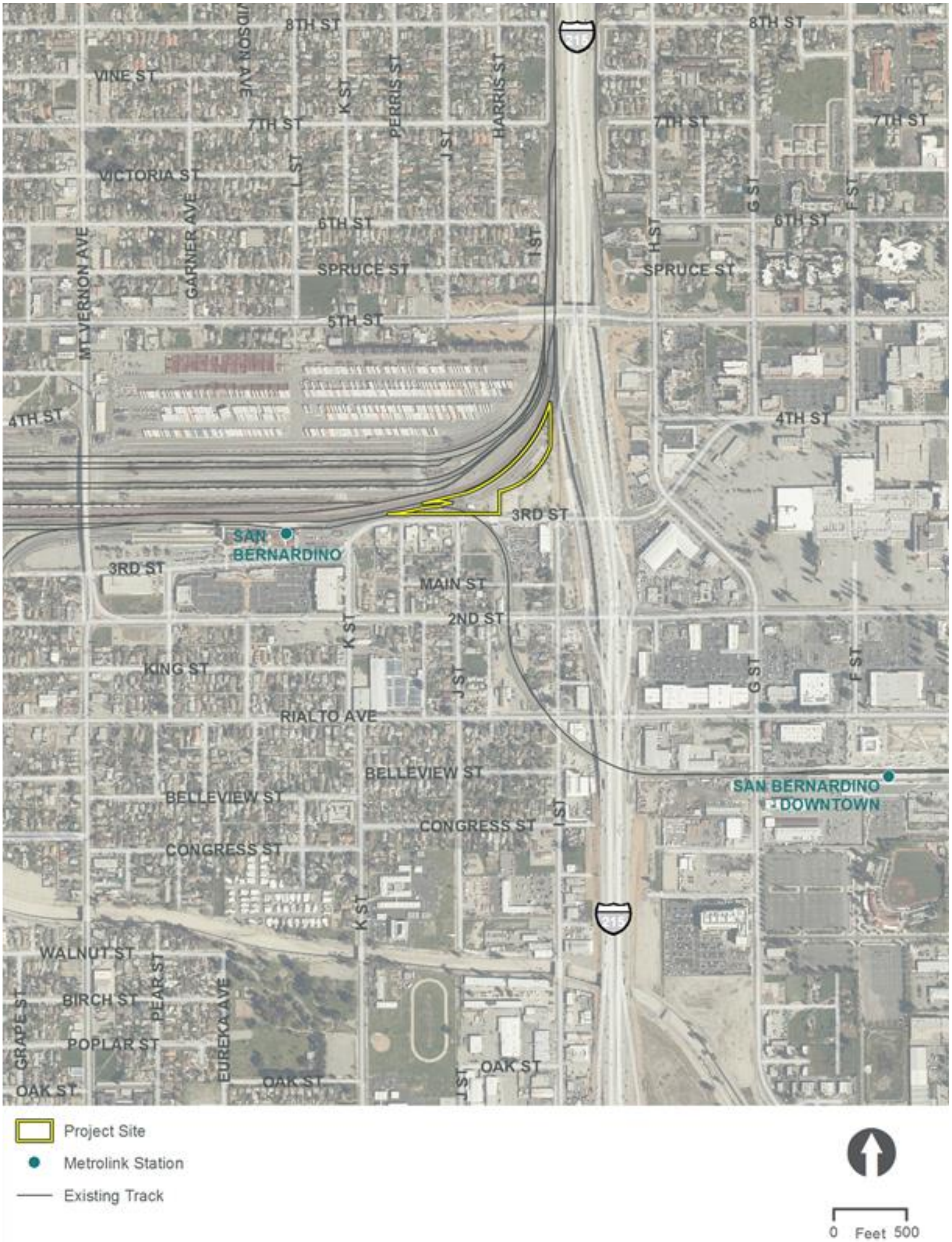


Figure 2 – Arrow Maintenance Facility (AMF) Project Site

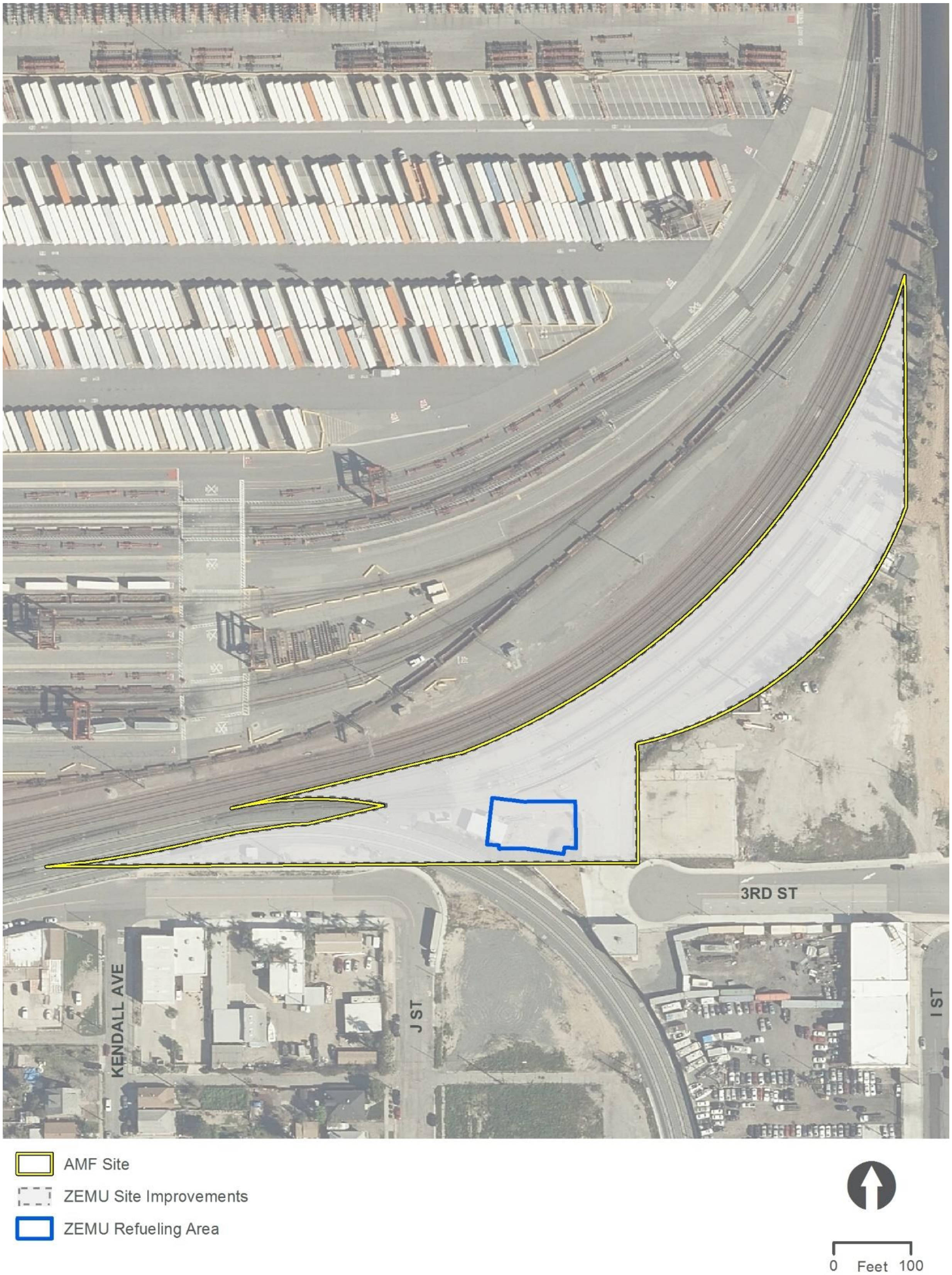


Figure 3 – Zero Emission Multiple Unit (ZEMU) H2 Refueling Area

4 - DESIGN BASIS ACCIDENTAL EXPLOSION

The subsections that follow discuss specific low-probability-high-consequence accidental explosion scenarios that were investigated. The nature of these accidents limits quantitative assessments to a binary event likelihood – 0% or 100%. The latter examines the instance where passive and active safety measures fail or prove to be ineffective. This approach is aligned with study objectives emphasizing consequence-based mitigation but is inherently conservative as it assumes that any and all conditions necessary to result in a full catastrophic failure exist. The, ultimate, discussion of collateral risk and recommendation of mitigating actions conservatively assumes that all industry standard passive and active safety measures that may be in place to minimize event occurrence fail or prove to be ineffective.

VAPOR CLOUD EXPLOSION (VCE)

A Vapor Cloud Explosion (VCE) results from the ignition of a cloud of flammable vapor, gas or mist in which flame speeds accelerate to sufficiently high velocities to produce significant overpressure. The following VCE scenarios were explored:

1. Ignition of a 265-kg mass of GH2; and
2. Ignition of a 4000-kg mass of LH2.

In both instances, the assessment assumed that the entire volume of stored gas instantaneously or gradually leaks into the atmosphere and collects in a semi-dense cloud that lingers in place. The volume of leaked gas is then exposed to an ignition source that results in a flame front traveling at supersonic speeds. This upper bound event was compared against a lower bound event that considered a more dispersed cloud and a flame front traveling at or less than the speed of sound. This burn scenario is commonly referred to as a deflagration event and is associated with a less violent pressure wave.

The lower and upper bound VCE events were, ultimately, considered in evaluating collateral consequences attributed to high-magnitude overpressures and thermal radiation. Appendix A further details specific assumptions underlying the VCE assessment.

BOILING LIQUID EXPANDING VAPOR EXPLOSION (BLEVE)

A Boiling-Liquid-Expanding-Vapor (BLEVE) event describes the instantaneous vaporization and rapid expansion of a stored superheated liquid. This scenario is specific to LH2 storage and fueling operations and is not applicable to alternatives that rely on GH2. BLEVE formation is, additionally, dependent on exposure of the stored liquids to an external energy source that cause tank contents to be heated above their normal atmospheric boiling points. Without an external energy source, a BLEVE event is not considered to be credible.

Figure 4 provides a visual representation of sequence of events leading to a BLEVE. Rupture of the storage tank, ultimately, leads to rapid depressurization and allows the entire volume of superheated liquid to instantaneously vaporize. The violent expansion of the vaporized tank contents exerts explosive overpressures on surrounding surfaces. An additional thermal hazard exists if the vapor is combustible and an ignition source is present. In such an event, a fireball will be generated simultaneously with the explosive overpressures generated by the accident.

The BLEVE event was considered in evaluating collateral consequences attributed to high-magnitude overpressures, thermal radiation, and high-velocity debris impact. The latter consideration accounted for the potential for fragments of the ruptured tank to be thrown from the explosion epicenter.

Appendix C further details specific assumptions underlying the BLEVE assessment.

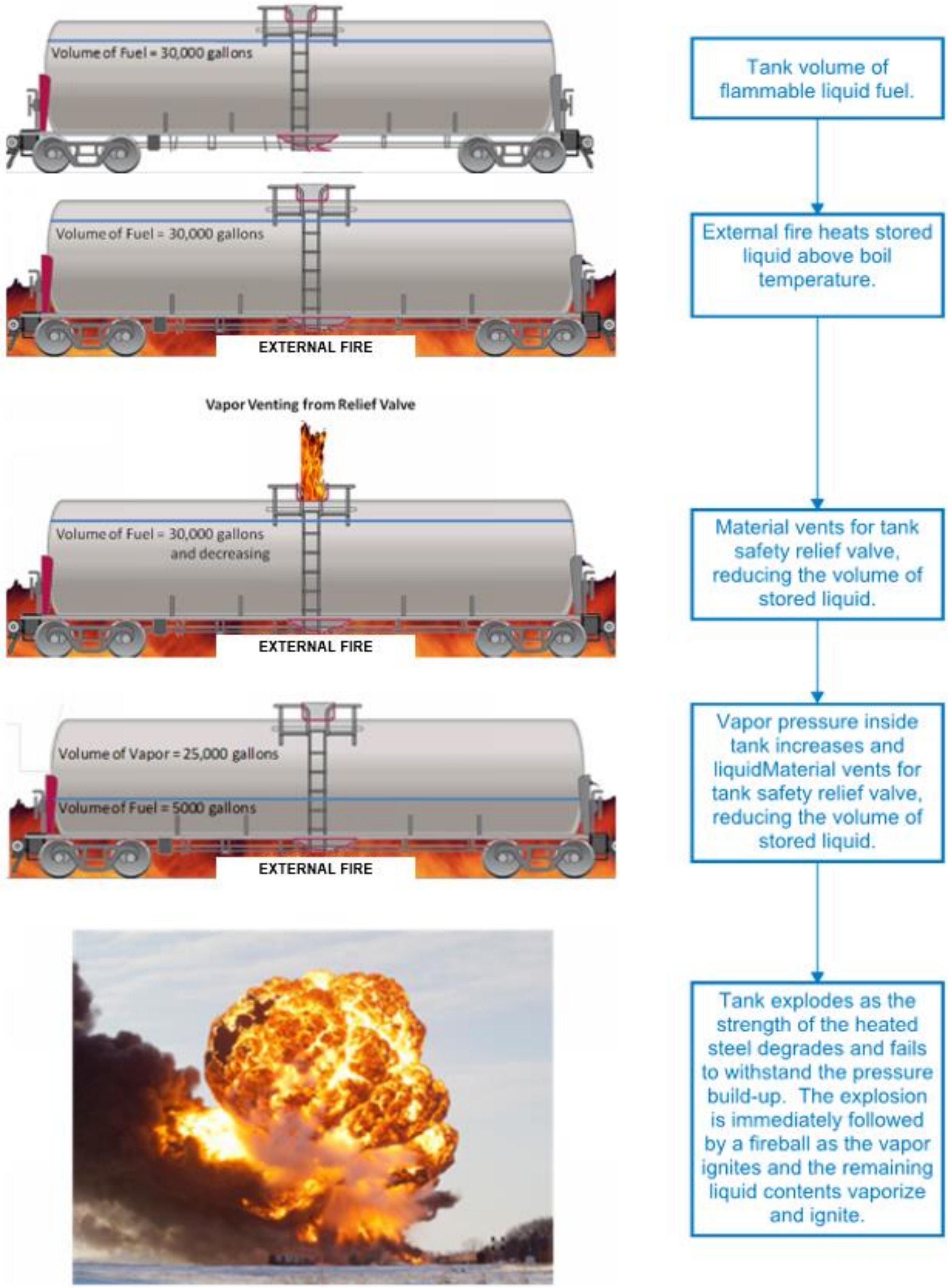


Figure 4 – Sequence of Events for BLEVE Formation

5 - CONSEQUENCE CATEGORIES

The scope of the completed assessment largely examined collateral consequences at adjacent properties. The table below correlates explosive event with consequence type, and the discussion that follows further discusses the details of each consequence category.

Table 1 – Summary of Consequence Categories

Event	Load/Hazard Type	Consequence Category
VCE (GH2)	Overpressure	Building (Bldg) Damage (structural); Bldg Damage (window); Injury
	Thermal Radiation	Injury
VCE (LH2)	Overpressure	Bldg Damage (structural); Bldg Damage (window); Injury
	Thermal Radiation	Injury
BLEVE (LH2)	Overpressure	Bldg Damage (structural); Bldg Damage (window); Injury
	Thermal Radiation	Injury
	Debris	Injury

COLLATERAL BUILDING DAMAGE

The foremost performance goal is that of global stability such that localized damage resulting from defined accidental explosions can be absorbed in a controlled manner without inciting disproportionate collapse of the structural system. Table 2 summarizes a generalized performance hierarchy to understand the increasing scale of consequence relative to macroscopic performance objectives. Consistent with the performance threshold underlying code-based design for natural hazards (earthquakes, wind, etc.) as well as the low likelihood of occurrence for an accidental gas, it is recommended to target "Life-Safety" and "Collapse Prevention" as thresholds of allowable building damage.

The completed assessment did not include an exhaustive study of building typologies in the area surrounding the Project site. As a simplification, the following generalized structural system types were considered based on visual observations using Google Maps:

- (Bldg Type #1) single-story pre-engineered metal, moment frame with corrugated (or insulated) metal wall and roof panels;
- (Bldg Type #2) two-story reinforced concrete building with exterior building walls and interior reinforced concrete frame structure;
- (Bldg Type #3) two-story steel moment frame structure with lightly reinforced CMU infill walls and a concrete or metal roof structure supported on steel joists; and
- (Bldg Type #4) two-story small light-framed timber bearing wall building/residence.

Figure 5 through Figure 10 provide a visual mapping of building locations around the Project site and show representative buildings. The resistance of these building types to explosive overpressure loads was determined consistent with information compiled by the U.S. Army Corps of Engineers in Engineering Technical Letting (ETL) No.

1110-3-495. This document was additionally referenced to estimate resistance of typical monolithic (single-pane) glass windows that are expected to characterize existing construction.

In addition, to these typical building types, the structural damage assessment considered nearby segments of elevated Highway 215 on/off ramps and roadway crossings that are in proximity to the storage/fueling area. Limited information was available to characterize the as-built condition of elevated roadways. Damage models associated structural robustness with assumed construction of piers, which are considered to be the critical element affecting stability and resistance to deck collapse. The points that follow identify conservative assumptions that were used to represent vulnerability of existing roadway piers.

1. Piers were assumed to be cantilever elements with supported deck segments providing negligible restraint against deflection in the transverse direction.
2. Piers were assumed to be constructed with minimum 4000-psi normal weight (150 lb/ft^3) concrete and be minimum 6-ft diameter circular cross-sections with a minimum 2% gross longitudinal reinforcement ratio.
3. Pier construction was assumed to be consistent with conventional seismic design requirements and incorporate transverse hoop or spiral reinforcement within plastic hinge zones, intended to establish confinement of the cross-section core as needed to enable ductile yielding under large deflections.
4. Pier construction was assumed to be consistent with conventional seismic design requirements and incorporate development of longitudinal reinforcement into the foundation as needed to preclude brittle failure at the base of pier under large deflections.

Appendices A, B and C provide details of the structural damage assessment for design basis VCE and BLEVE events, highlighting areas where severe damage is expected.

Table 2 – Structural Damage Summary

Design Objective	Damage Category	Total Bldg Damage	Damage Description	Repairable/ Reusable
Immediate Occupancy	Minimal	0-10	Window damage is extensive and light or local damage to nonstructural members. Persons will suffer minor lacerations from window glass fragments or other non-structural member debris.	Yes
Limited Disruption	Minor	10-20	Little or no damage to major structural members and some damage to nonstructural components. Persons will suffer mostly minor and some serious lacerations and blunt trauma from window glass fragments or nonstructural member debris.	Most Probably
Life-Safety	Moderate	20-40	Some deformation of structural members and extensive nonstructural damage. Majority of persons will suffer lacerations and blunt trauma from window glazing fragments or other nonstructural member debris. Zero to 10 percent of personnel suffer fatalities.	Possible
Collapse Prevention	Heavy	40-60	Large deformation of structural members and major nonstructural component damage. Majority of persons will suffer serious injuries with 10 to 40 percent suffering fatalities.	Very Unlikely
Collapse	Severe	60-100	Building collapse and massive destruction is expected. Little left standing. Majority of personnel will suffer fatalities.	No

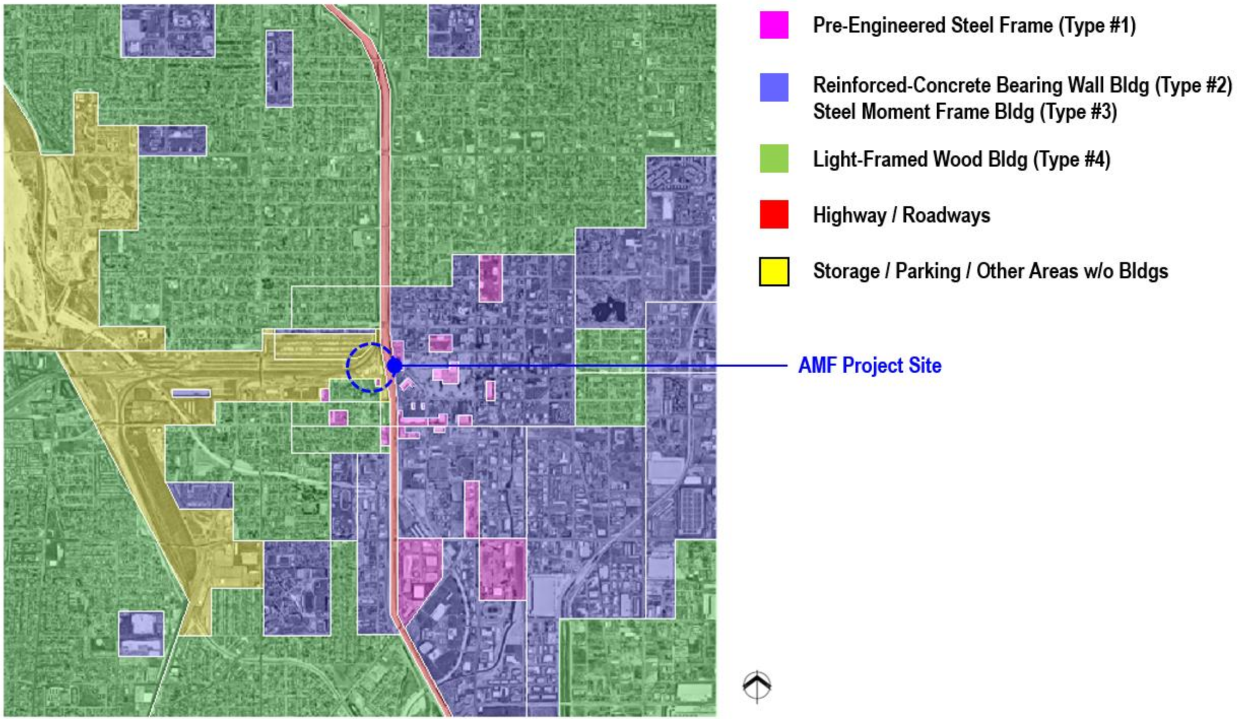


Figure 5 – Large-Scale Project Site Map w/ Adjacent Buildings Types

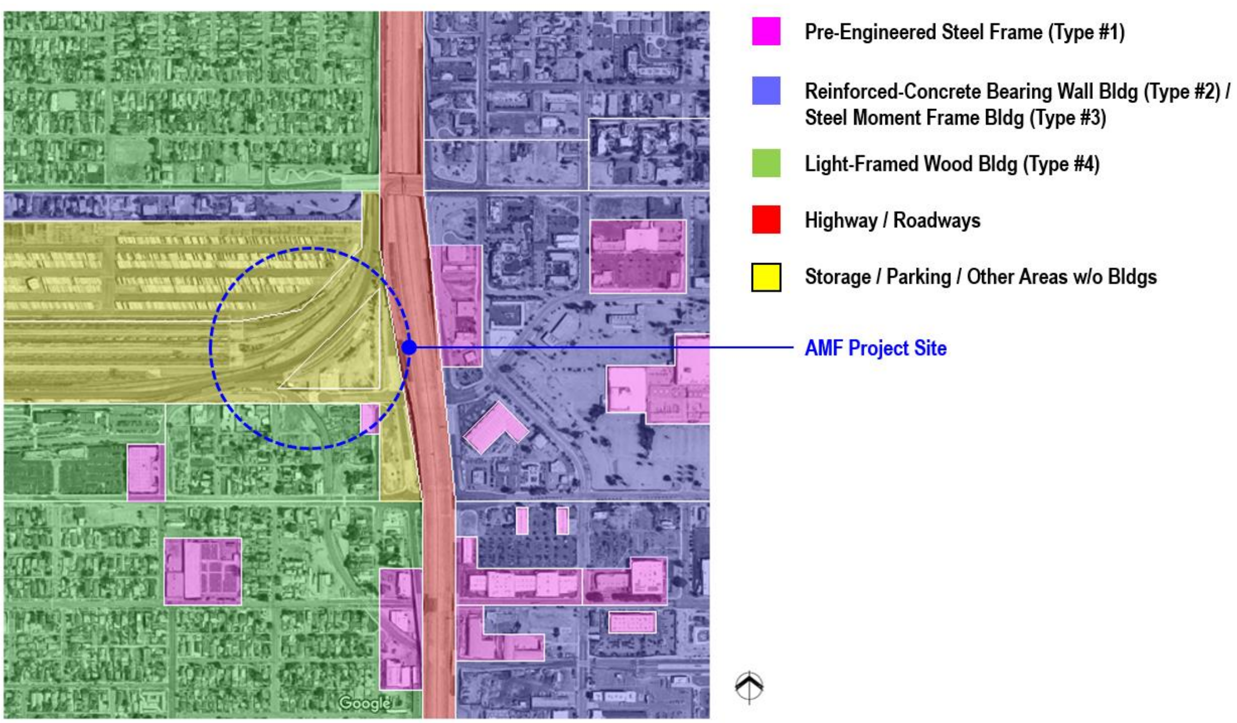


Figure 6 – Small-Scale Project Site Map w/ Adjacent Buildings Types

Figure 7 – Representative Pre-Engineered Steel Frame Building (Type #1)

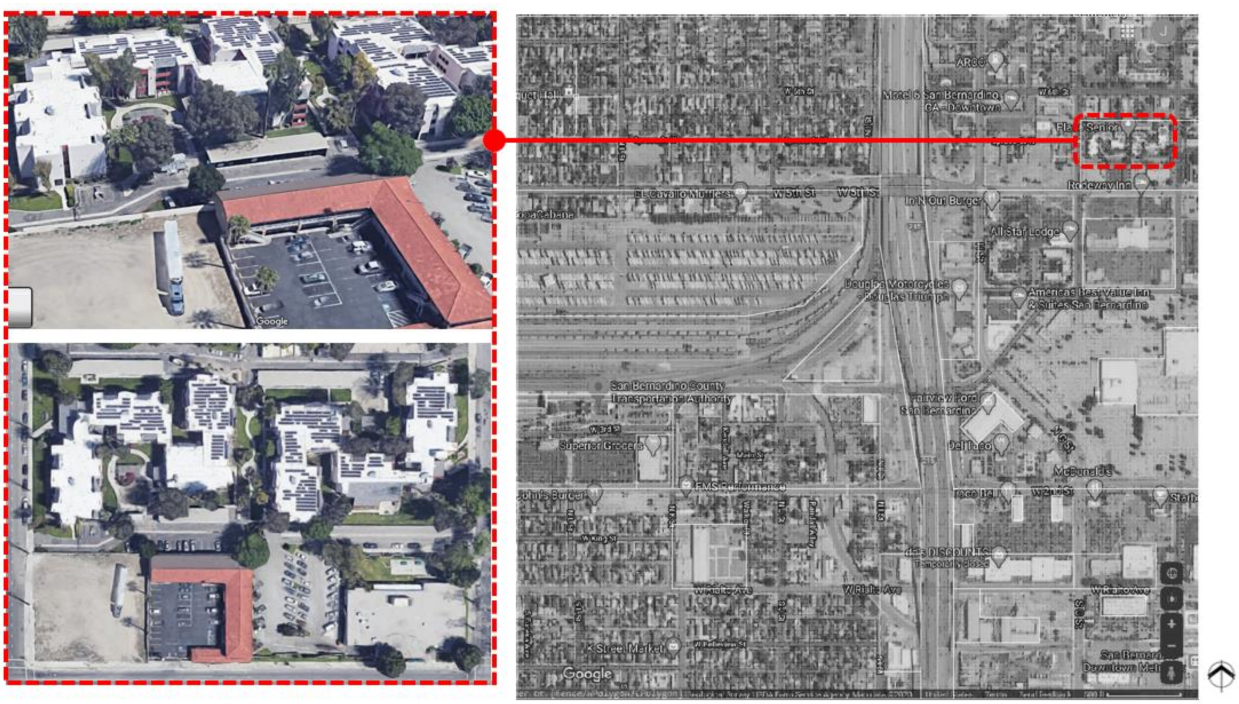


Figure 8 – Representative Reinforced Concrete Bearing Wall Building (Type #2)

Figure 9 – Representative Light-Framed Wood Building (Type #4)

Figure 10 – Elevated Roadway Segment

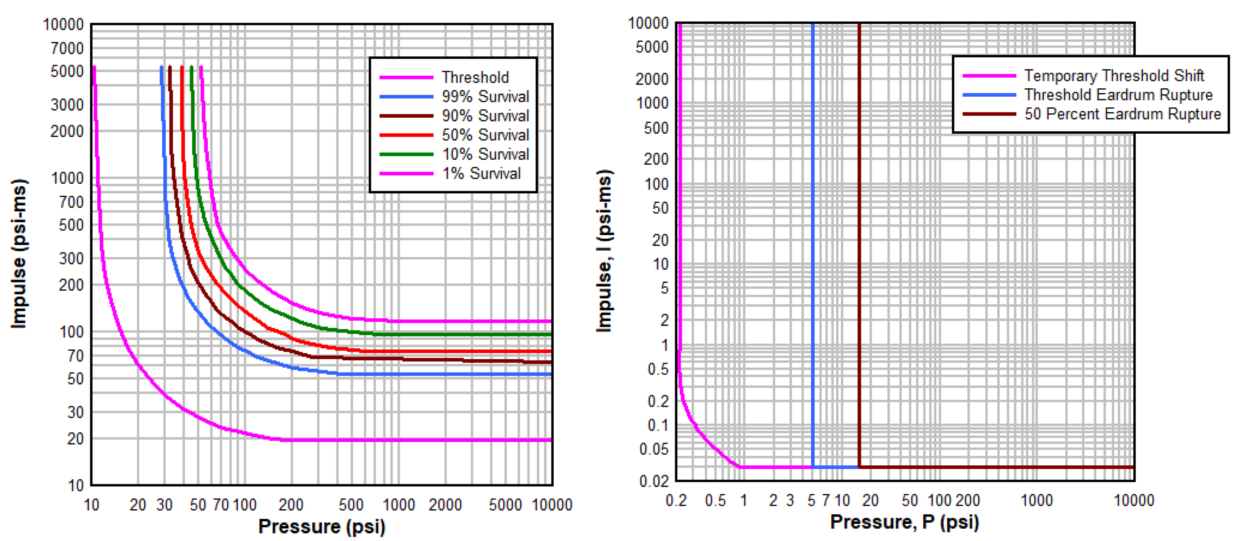
COLLATERAL INJURY HAZARDS – OVERPRESSURE & DEBRIS

Expected injury at increasing distances from the explosion epicenter was evaluated in accordance with UFC 3-340-02. This technical reference document provides guidance to estimate injury survivability based on weight of the individual and load intensity. The UFC document describes the following three classes of injuries:

- Primary Injury – lung damage (critical organ injury) and eardrum rupture (non-critical organ injury) resulting from blast pressure
- Secondary Injury – bodily harm and lacerations due to fragment projectiles
- Tertiary Injury – blast impulse induced movement/falls resulting in bone fractures and contusions

The considered VCE and BLEVE events were specifically evaluated with respect to primary and secondary injury classes. Tertiary injuries were considered to be evaluated by inspection of structural damage assessment, with a high-risk of injury correlated to vulnerability of significant structural damage.

Figure 11 depicts performance curves from UFC 3-340-02 that were used to assess primary injury potential. These diagrams plot performance curves on a two-dimensional load space, enabling identification of high-intensity overpressure ranges for which various levels of injury severity are expected. The data for lung damage is used as a representation of critical organ injury that is credibly lethal. The performance curves highlight expected levels of survivability. The data for ear drum rupture is representative of non-lethal injuries, potentially sustained from exposure to high-magnitude overpressures. Appendices A, B and C provide details of the primary injury damage assessment for design basis VCE and BLEVE events, highlighting areas where severe injuries are expected.



Lethal Injury (Lung Damage) Non-Lethal Injury (Ear Drum Rupture)

Figure 11 – Performance Limits for Primary Injuries

Human tolerance to fragment impact (secondary injury hazards) is very low. Fragments can generally be classified as follows:

- Primary Fragments are small, high-speed projectiles formed from the ruptured tank and/or equipment located immediately adjacent to the explosion.
- Secondary Fragments are larger and are typically generated from damaged components/building elements in close proximity to the focus of the explosion. Secondary fragments are heavier and can, consequently, cause serious injuries at lower velocities.

Table 3 summarizes the threshold of serious bodily injury resulting from impact by flying debris consistent with information provided in UFC 3-340-02. These thresholds were used to confirm injury potential at varying distances away from the accidental gas explosion.

For the purposes of this assessment, primary fragments were based on a large mass of rupture tank that is propelled away from the explosion. Secondary fragment hazards were considered to be addressed by inspection. Appendix C summarizes the assessment of fragment-induced injuries for design basis BLEVE events. This injury class is not associated with VCEs.

Table 3 - Threshold of Serious Injury to Personnel due to Fragment Impact (reproduced from UFC 3-340-02)

Critical Organ	Fragment Weight (lb)	Fragment Velocity (fps)	Energy (ft-lb)
Thorax	> 2.5	10	4
	0.1	80	10
	0.001	400	2.5
Abdomen & Limbs	>6.0	10	9
	0.1	75	9
	0.001	550	5
Head	>8.0	10	12
	0.1	100	16
	0.001	450	3

COLLATERAL INJURY HAZARDS – THERMAL RADIATION

A fireball may occur during a VCE or BLEVE event when a flammable hydrogen release ignites prior to extensive mixing with surrounding air. The completed assessment considered a point source fireball model, consistent with Center for Chemical Process Safety guidelines, to calculate intensity of thermal radiation received at a target 6 ft above the ground always having a direct line of sight to the fireball for simplicity. Dynamic evolution of the fireball was ignored conservatively, by assuming constant radiation from a point source located at 0.75 times the fireball diameter from grade consistent with guidance in technical references. The atmospheric transmissivity was, additionally, conservatively assumed to be constant (1.0) and correspond to zero relative humidity. The resulting heat flux received from the fireball at a target was, thereby, determined as a simple function of - available mass of hydrogen; radiative fraction of heat (that can vary between 0.13 to 0.4 depending on storage pressure); and the radial distance along the ground from the assumed location of the fireball.

This baseline for estimating the radiative potential of a fireball was, ultimately, correlated with various types of human injury and building damage criteria summarized in Table 4 below. Criteria for crack glass or damage to light-framed wood buildings was determined to be less severe than comparable requirements for overpressure resistance and was not explicitly evaluated. Figure 12 and Figure 13 depict that areas where building damage is expected for the design basis VCE and BLEVE events. Thermal radiation hazards were, ultimately, only explicitly evaluated with respect to collateral risk of injury.

Table 4 - Intensity of Heat Radiation and Corresponding Consequences

Injury or Building Damage Criteria	Intensity of Heat Radiation [Btu(th)/s.ft^2]
Insufficient to Cause Discomfort for Long Exposure	0.141
Threshold for Pain	0.194
Threshold for Cracking of Glass	0.352
Threshold for First Degree Burn	0.371
Threshold for Piloted Ignition of Wood	1.322

Figure 12 – Expected Extents of Cracked Glass (blue) and Structural Damage (red) for GH2 (265-kg) Scenarios

Figure 13 – Expected Extents of Cracked Glass (blue) and Structural Damage (red) for LH2 (4000-kg) Scenarios

6 - SUMMARY OF ASSESSMENT FINDINGS

The completed assessment examined collateral risk through the lens of event likelihood and severity. In all instances, the potential event severity assumed the sequence of initial conditions needed to precipitate a VCE or BLEVE would occur. Table 5 provides a qualitative assessment of accident "likelihood/credibility" to balance expected event severity as needed to prioritize risk reduction measures. There are significant levels of uncertainty associated with variables that define event likelihood, precluding a more probabilistic or other quantified expression of likelihood within the context of this simplified study. Table 5, instead, provides a qualified assessment of "likelihood" that considers the credibility that ideal conditions will exist for an accidental explosion to occur.

The points that follow itemize specific considerations that contribute to the determination of VCE event likelihood. These collectively result in a conservative assessment of collateral risk. A less conservative baseline cannot be leveraged within the context of this study without introducing potentially arbitrary assumptions that, in turn, give way to levels of uncertainty in the concluded results.

1. VCE formation assumes failure of all safety and monitoring systems that are intended to detect onset of storage tank destabilization or early stages of a gas leak.
2. VCE assessment assumes the entire volume of stored H2 gradually or instantaneously leaks from the tank and collects in a relatively dense cloud that lingers in place. This negates any consideration for ambient conditions that would result in dispersion of gas, rather than formation of a vapor cloud. This assumption also negates any assumption of a partial leak.
3. VCE assessment assumes that the formed vapor cloud is exposed to an ignition source.

4. Upper Bound VCE events assume that ideal conditions are present to enable a deflagration to detonation transition. These conditions are typically more characteristic of a vapor cloud that forms within a constrained volume rather than open air.

The points that follow itemize specific considerations that contribute to the determination of BLEVE event likelihood. These collectively result in a conservative assessment of collateral risk. A less conservative baseline cannot be leveraged within the context of this study without introducing potentially arbitrary assumptions that, in turn, give way to levels of uncertainty in the concluded results.

1. BLEVE assessment assumes that all safety and monitoring systems in place to detect change in internal pressure or temperature fail.
2. The BLEVE assessment assumes that undamaged storage vessel is exposed to an external energy source that creates an internal vapor pressure imbalance. Without sufficient exposure to an external energy source that creates a rise in internal tank pressure and temperature a BLEVE event is not expected to occur.
3. Evaluations of debris resulting from tank rupture neglect energy losses and assume that critical fragment shapes can form. The assessment discounts likelihood of formation for these large, high-energy fragments.

Based on event likelihood, it is recommended to limit consideration of risk reduction measures to lower bound (deflagration) VCE events. Higher levels of uncertainty underly the likelihood of occurrence for upper bound (detonation) VCE and BLEVE events, resulting in an unfavorable cost-benefit balance in pursuing risk reduction beyond integration of robust and redundant safety and monitoring systems or other lost “cost” strategies.

Table 6 further builds on the assessment of event likelihood and severity and identifies the specific performance thresholds that were used to bound “acceptable risk”.

Table 7 provides a detailed summary for individual damage categories that identifies minimum distance away from the storage area at which collateral risk drops to acceptable levels. Table 8 further details estimated building damage as a percentage of structural loss relative to the total area of each represented building type.

The points that follow further summarize key assessment findings.

1. The Arrow Maintenance Facility building is expected to be most similar to Building Type #1 (pre-engineered steel frame structure). For all considered accident scenarios, this building is expected to sustain significant damage and require replacement.
2. Infrastructure and equipment within a 20-50 ft radius from the H2 storage area is expected to be significantly damaged. This distance defines the potential crater expected to form at-grade and does not preclude damage to infrastructural or equipment beyond this radius.
3. The LH2 VCE deflagration event is expected to be more destructive than the equivalent GH2 scenario. This is purely a function of H2 gas quantity.
4. A significant collateral risk associated with the VCE deflagration event (both GH2 and LH2 storage options) is the potential glass breakage at adjacent properties within a 3100-ft radius. It is expected that building occupants within this radius will sustain injuries resulting from flying glass debris. The most severe damage and injuries are expected within a 1855-ft radius.

Table 5 – Summary of Design Basis Event Likelihood and Severity

Design Basis Event	Relative Likelihood/Credibility	Relative Severity
VCE – GH2 / Deflagration (Lower Bound)	Low	Low
VCE – GH2 / Detonation (Upper Bound)	Very Low	High
VCE – LH2 / Deflagration (Lower Bound)	Low	High
VCE – LH2 / Detonation (Upper Bound)	Very Low	Very High
BLEVE – LH2	Very Low	Moderate

Table 6 – Summary of Recommended Threshold for Acceptable Performance

Damage/Consequence Category	Recommended Threshold for Acceptable Performance
Building Damage	Moderate Damage
Elevated Roadway Damage	Moderate Damage
Window Damage	Low Fragment Hazard
Injury – Overpressure / Lethal	≥99% Survival Likelihood
Injury – Overpressure / Non-Lethal	Temporary Discomfort / Hearing Loss
Injury – Thermal Radiation	Discomfort for Long Duration Exposure
Injury – Debris	≥ Trajectory Range for 10-deg Launch Angle

Table 7 – Summary of Collateral Risk Assessment Results

Damage/Consequence Category	Distance to Achieve Acceptable Performance				
	VCE (GH2)		VCE (LH2)		BLEVE (LH2)
	Lower (Deflagration)	Upper (Detonation)	Lower (Deflagration)	Upper (Detonation)	
Bldg Damage – Type #1	0-ft	1000-ft	990-ft	3165-ft	0-ft
Bldg Damage – Type #2	0-ft	730-ft	1030-ft	3175-ft	0-ft
Bldg Damage – Type #3	0-ft	730-ft	1030-ft	3175-ft	0-ft
Bldg Damage – Type #4	310-ft	775-ft	760-ft	2555-ft	166-ft
Elevated Roadway Damage	810-ft	1338-ft	1815-ft	5210-ft	0-ft
Window Damage	3100-ft	6065-ft	3100-ft	18,470-ft	1130-ft
Injury – Overpressure (Lethal)	0-ft	145-ft	0-ft	376-ft	55-ft
Injury – Overpressure (Non-Lethal)	156-ft	595-ft	390-ft	1470-ft	157-ft
Injury – Thermal Radiation	735-ft	735-ft	2100-ft	2100-ft	2100-ft
Injury - Debris	n/a	n/a	n/a	n/a	3890-ft

Table 8 – Summary of Collateral Building Damage Assessment Results

Bldg Type	Bldg Description	Total Modeled Area	% Unacceptable Performance [1]				
			Deflagration		Detonation		BLEVE (LH2)
			VCE (GH2)	VCE (LH2)	VCE (GH2)	VCE (LH2)	
Type #1	Pre-Engineered Steel Frame	2,071,824	0%	2%	1%	99%	0%
Type #2	Reinforced Concrete Bearing Wall	8,702,294 SF	0%	1%	0%	79%	0%
Type #3 [2]	Steel Moment Frame	n/a	n/a	n/a	n/a	n/a	n/a
Type #4	Light-Framed Wood	7,954,823 SF	1%	8%	9%	90%	0%
Roadway [3]	Reinforced Concrete	1,251,926 SF	3%	72%	49%	100%	0%

1 - Refer to Table 2. For the purposes of this results summary, "unacceptable" performance was defined as building damage exceeding "moderate" thresholds.

2 - Type #3 buildings could not be readily distinguished from Type #2 buildings. Building damage models grouped Type #2 and Type #3 buildings together and provided a damage evaluation based on lower bound estimates of structural resistance.

3 - Damage models conservatively grouped both elevated and at-grade highways/roadways together. The "total modeled area" and estimated area of "unacceptable performance" are not specific to vulnerable segments of elevated roadway.

7 - RECOMMENDATIONS

The completed assessment evaluated the potential for properties adjacent to the AMF to be damaged and individuals sustain critical injuries in the event of an accidental gas explosion within the defined storage area. The technical evaluation considered a range of gas explosion scenarios to bound the risk analysis but, ultimately, focused on deflagration events stemming from gas leak and subsequent formation of a vapor cloud as the more credible design basis event. This accident scenario risk propagation of high-magnitude overpressure and thermal radiation from the explosion epicenter. Scenarios that investigated a 4000-kg volume or stored LH2 indicate a much higher potential for damage and injuries.

The points that follow highlight baseline recommendations to be considered in pursuing mitigation as part of the project's final design engineering..

1. Maximize the separation of electrical equipment, fuel storage, or other components potentially serving as an ignition source from the storage and fueling areas in accordance with NFPA 2 requirements at minimum.

2. Divide the total volume of stored gas into multiple smaller capacity tanks that are separated consistent with NFPA 2 or NFPA 55 recommendations to avoid collocations of significant quantities of combustible materials and to minimize the likelihood of sympathetic combustion events.
3. Exterior envelope of enclosed or semi-enclosed buildings at the AMF site are recommended to be treated with fireproofing and equipped with a water spray or deluge system to cool surfaces exposed to intense thermal radiation.
4. Because there is a high level of uncertainty relating to the shape of a vapor cloud and location where it may form, strategies that investigate moving the storage area are not considered to provide a significant benefit relative to overpressure hazards. It is, however, recommended to maximize separation of storage tanks from on-site occupied areas as well as high-value assets as a passive fire safety strategy. Similar considerations are recommended in siting storage tanks relative to adjacent properties. NFPA 55 is recommended as a reference in determining safe separation distances for bulk hydrogen systems.
5. With the exception of those required for compliance with NFPA 2, introduction of shield walls or other barriers are not recommended. These elements risk creating a more confined vapor cloud with a higher explosive yield than estimated. Where above ground storage is provided, it is recommended to minimize the presence of obstructions that would prevent cloud dispersion.
6. Where permanent storage options or those not readily categorized as "Vehicular Gaseous Fuel Systems" are used, supplement NFPA 2 with NFPA 55 for determination of minimum recommendations for compressed gas or cryogenic fluid storage applications.

These recommendations are consistent with the characterization of evaluated accidental explosions as "low-probability-high-consequence" events. There are few opportunities to manage the scale of consequence within the context of the proposed project. The provided recommendations, however, leverage industry best practices to limit the likelihood of a failure event to the greatest extent possible. This approach provides a level of risk management that is aligned with other similar existing storage/fueling operations based on relatively low probability of occurrence.

As part of final engineering design, further exploration or refinement of these assessment results is determined to be necessary, efforts are recommended to include the considerations that follow.

1. It is recommended to reexamine assumed construction and representation of structural resistance of the columns supporting the elevated roadway to better estimate damage for the 4000-kg (LH2) VCE/deflagration event.. It is, additionally, recommended to update risk models to more clearly differentiate between elevated versus at-grade roadways to better estimate expected damage.
2. Further investigation of hazards stemming from a LH2 spill and resulting localized pool fire as well as a jet fire resulting from a tank leak is recommended. Estimation of radiative fluxes from such events require advanced analyses requiring explicit assumptions regarding the flow characteristics and pooling of liquid hydrogen, beyond the scope of this preliminary study.

8 - REFERENCES

[1] "American Society of Civil Engineers - Blast Protection of Buildings" Standard (ASCE 59-11).

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APPENDIX A – GASEOUS HYDROGEN (GH2) VCE ASSESSMENT

General Assumptions

1. The VCE assessment assumes that the entire volume of stored GH2 (265-kg) is able to leak out of the storage tank without detection and accumulate in a vapor cloud.
2. The VCE assessment assumes that the vapor cloud, once formed, is exposed to an ignition source.
3. The lower bound VCE event assumes a nominal level of vapor dispersion, slowing the flame propagation through the cloud. This event is characterized by a lower Mach number (0.36) and is more characteristic of a deflagration rather than detonation event.
4. The upper bound VCE event assumes a densely packed vapor cloud, in which a flame front can rapidly propagate. This event is characterized by a high Mach number (5.2) that is typical of a detonation event.

Initial Condition Assumptions

1. All safety and monitoring systems fail.
2. The vapor cloud forms immediately above the storage tank and does not rise to higher elevations.

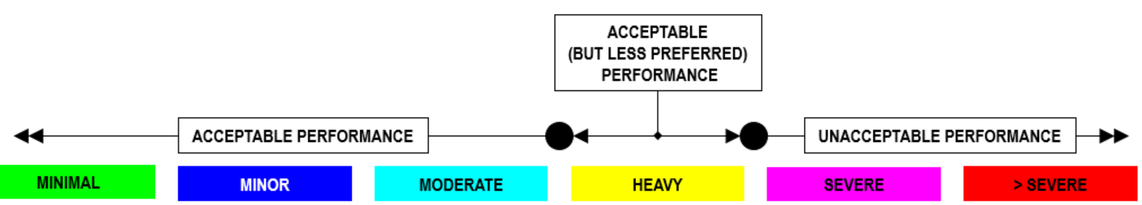
Damage Assumptions & Results

1. The Arrow Maintenance Facility is assumed to be most similar to Building Type #1 (pre-engineered frame structure). This building is expected to sustain Severe damage in the event of an VCE (lower or upper bound).
2. There is expected to be a significant cratering within a 20-ft radius of the GH2 storage tank. All at-grade infrastructure and equipment within this radius is assumed to be significantly damaged.
3. Assessments of window glass fragmentation are also assumed to inform understanding of potential injury to building occupants. Areas characterized by or exceeding a "High Fragment Hazard" are expected to be associated with a high risk of injury to building occupants resulting from flying glass debris.

TITLE:	GENERAL NOTES & ASSUMPTIONS
DIAGRAM/SKETCH (SK) NO.:	SK-101
DATE:	08/27/2020

Lower Bound Damage at Pre-Engineered Bldgs (Deflagration)

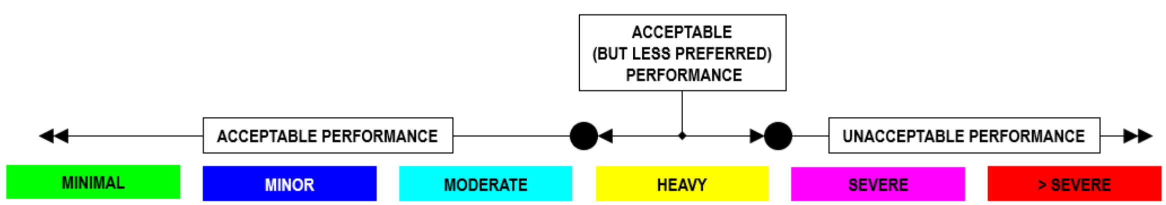
Upper Bound Damage at Pre-Engineered Bldgs (Explosion)



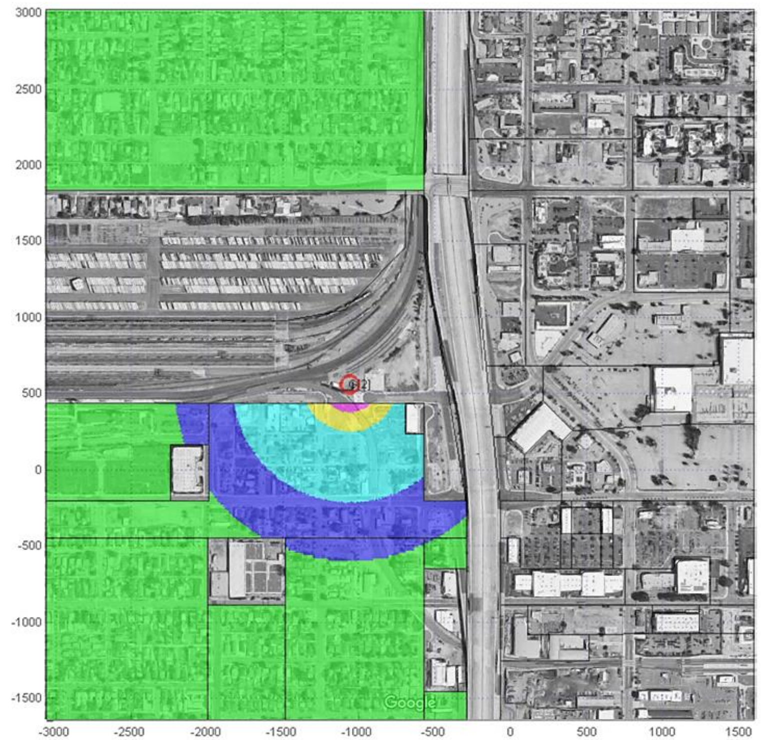
	TITLE:	DAMAGE ASSESSMENT – BLDG TYPE #1
	DIAGRAM/SKETCH (SK) NO.:	SK-102A
	DATE:	08/27/2020

Lower Bound Damage at Reinforced Concrete Bldgs (Deflagration)

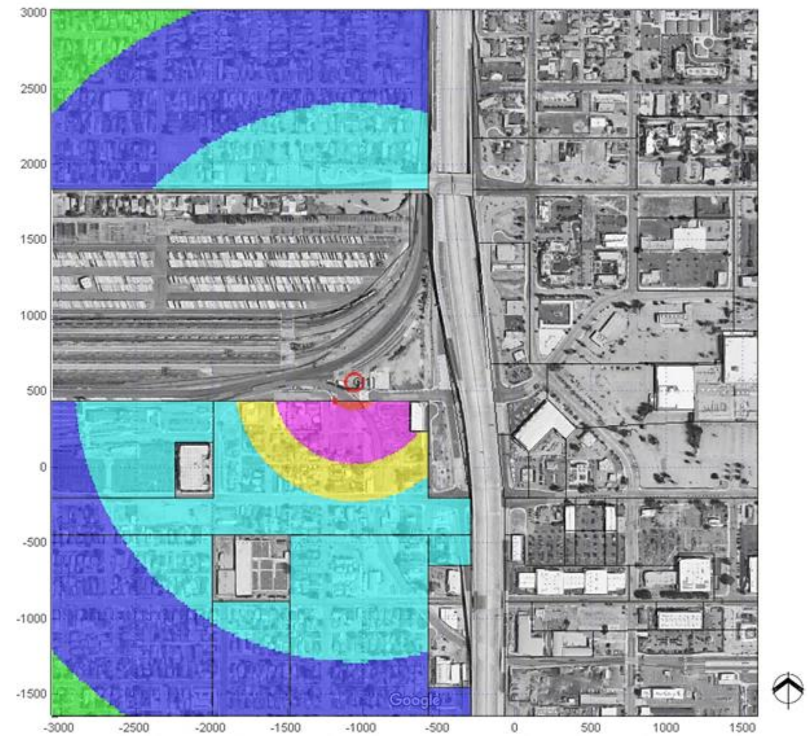
Upper Bound Damage at Reinforced Concrete Bldgs (Explosion)



	TITLE:	DAMAGE ASSESSMENT – BLDG TYPE #2 & TYPE #3
	DIAGRAM/SKETCH (SK) NO.:	SK-102B
	DATE:	08/27/2020



Lower Bound Damage at Light-Framed Wood Bldgs (Deflagration)



Upper Bound Damage at Light-Framed Wood Bldgs (Explosion)

ACCEPTABLE (BUT LESS PREFERRED) PERFORMANCE

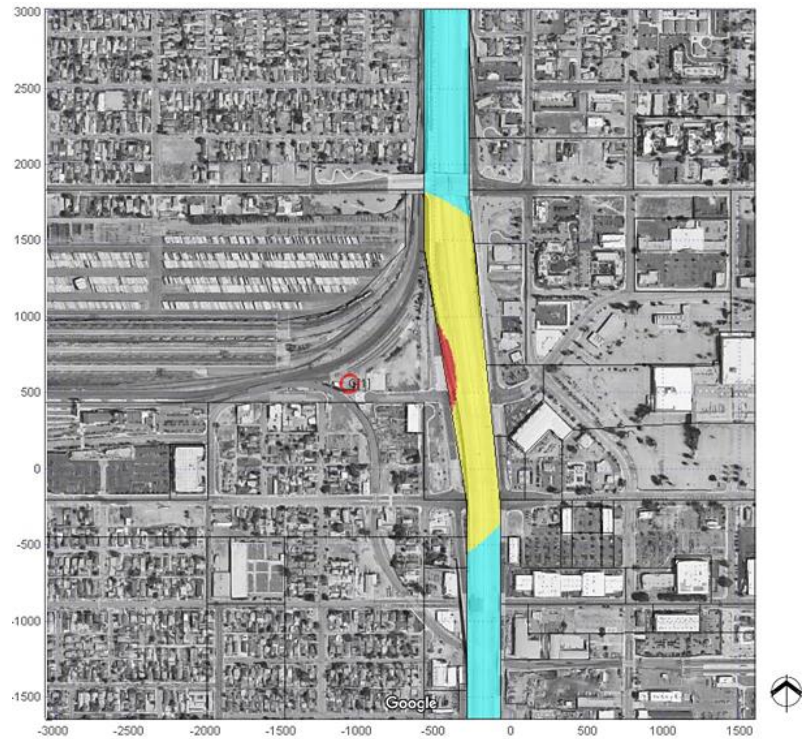
ACCEPTABLE PERFORMANCE

UNACCEPTABLE PERFORMANCE

MINIMAL | MINOR | MODERATE | HEAVY | SEVERE | > SEVERE

	TITLE:	DAMAGE ASSESSMENT – BLDG TYPE #4
	DIAGRAM/SKETCH (SK) NO.:	SK-102C
	DATE:	08/27/2020

Lower Bound Damage at Elevated Roadways (Deflagration)



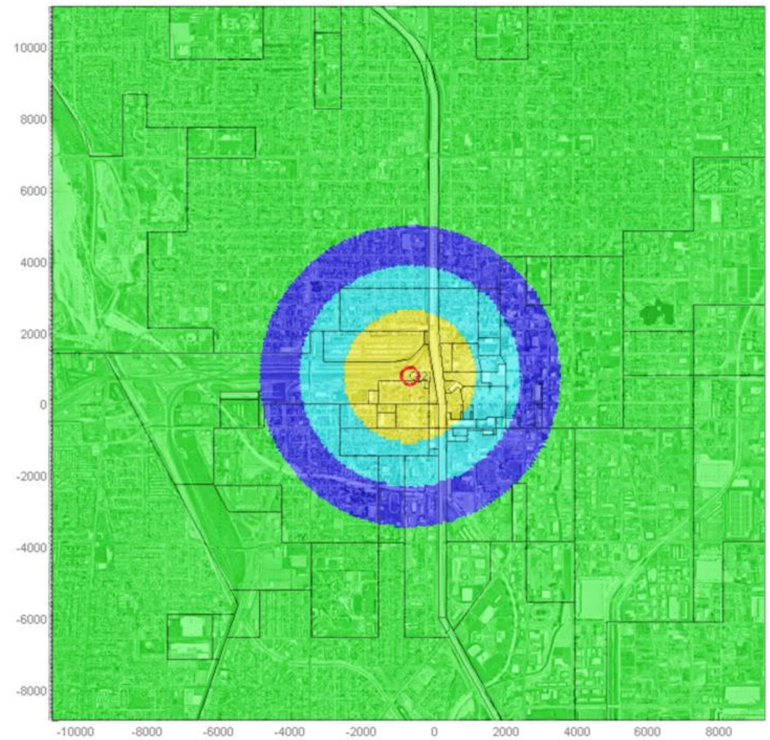
Upper Bound Damage at Elevated Roadways (Explosion)

ACCEPTABLE (BUT LESS PREFERRED) PERFORMANCE

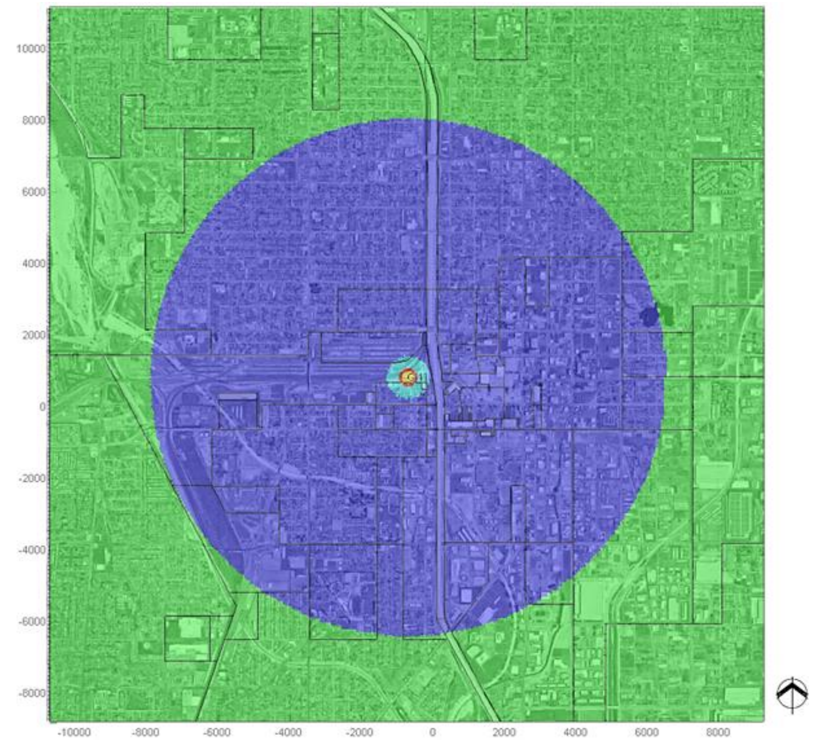
ACCEPTABLE PERFORMANCE | UNACCEPTABLE PERFORMANCE

MINIMAL | MINOR | MODERATE | HEAVY | SEVERE | > SEVERE

	TITLE:	DAMAGE ASSESSMENT – ELEVATED REINF. CONC. ROADWAYS
	DIAGRAM/SKETCH (SK) NO.:	SK-102D
	DATE:	08/27/2020



Lower Bound Damage to Windows (Deflagration)



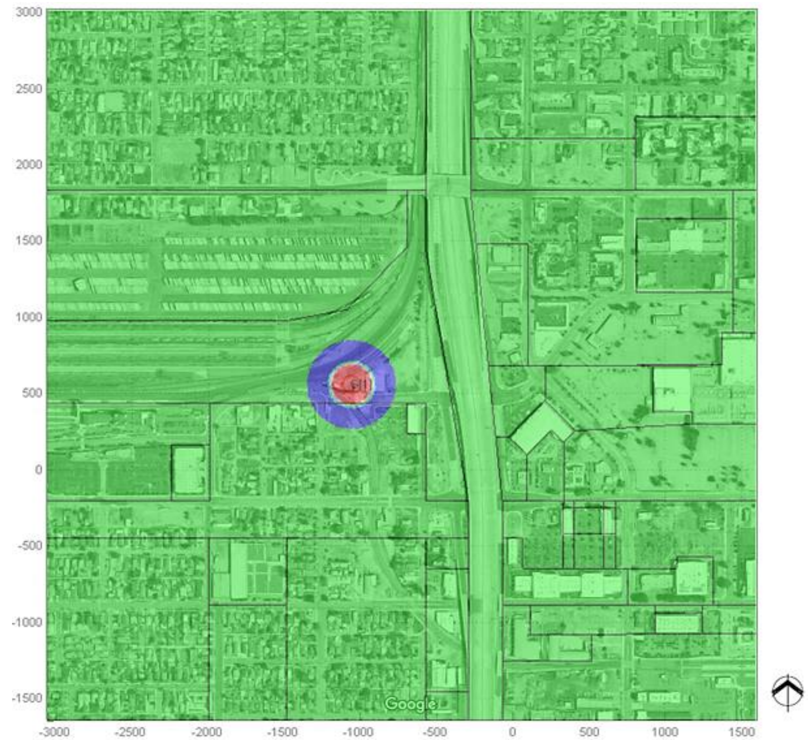
Upper Bound Damage to Windows (Explosion)

ACCEPTABLE PERFORMANCE ◄◄ ● ►► UNACCEPTABLE PERFORMANCE

BREAKAGE | LOW FRAGMENT HAZARD | HIGH FRAGEMENT HAZARD | > HIGH FRAGMENT HAZARD

	TITLE:	DAMAGE ASSESSMENT – WINDOWS
	DIAGRAM/SKETCH (SK) NO.:	SK-103
	DATE:	08/27/2020

Lower Bound Risk of Injury to Critical Organs (Deflagration)

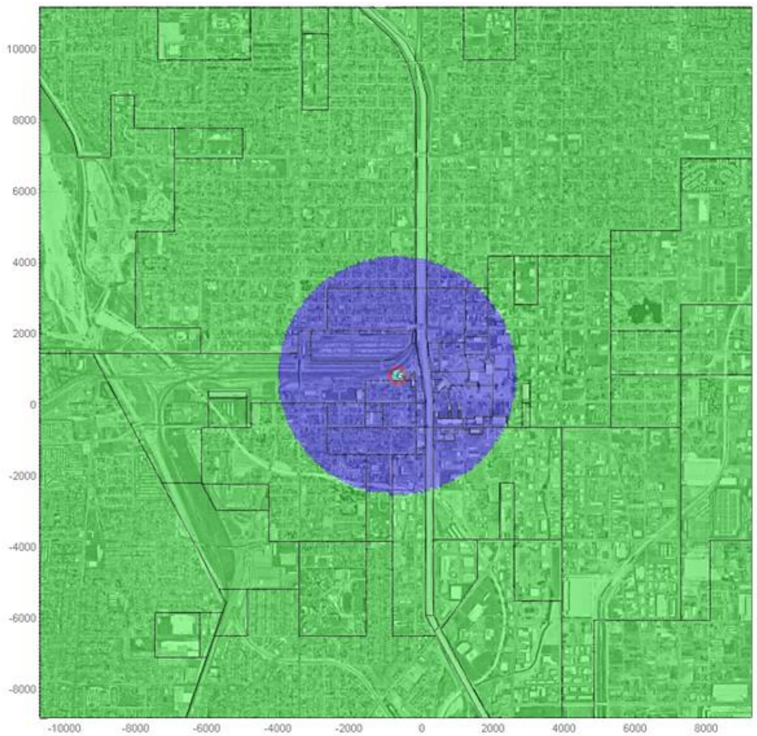


Lower Bound Risk of Injury to Critical Organs (Explosion)

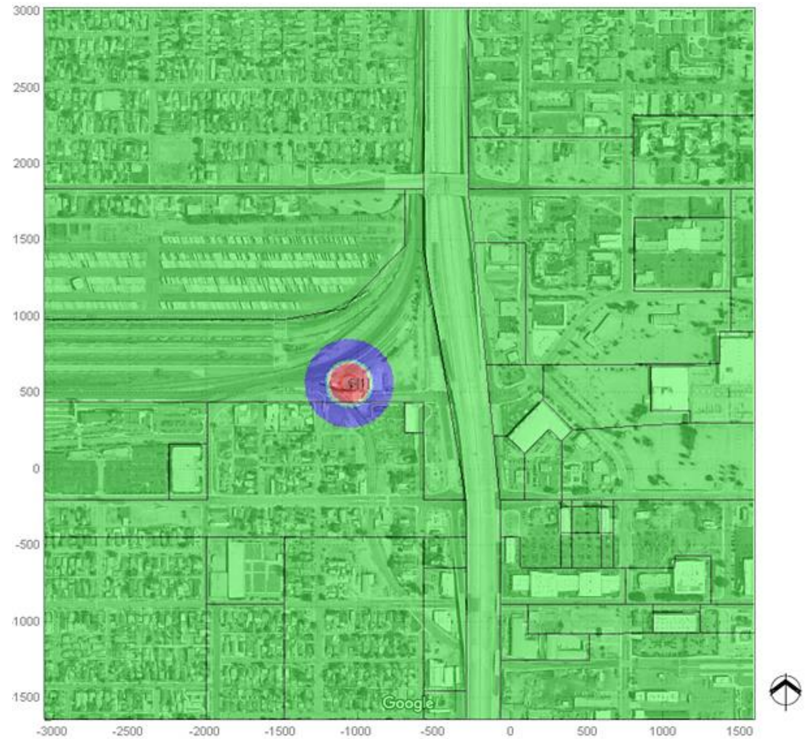
ACCEPTABLE PERFORMANCE — UNACCEPTABLE PERFORMANCE

NO INJURY | >99% SURVIVAL | 99% SURVIVAL | 90% SURVIVAL | 50% SURVIVAL | ≤10% SURVIVAL

TITLE:	DAMAGE ASSESSMENT – INJURY/OVERPRESSURE (LUNG DAMAGE)
DIAGRAM/SKETCH (SK) NO.:	SK-104A
DATE:	08/27/2020



Lower Bound Risk of Injury to Non-Critical Organs (Deflagration)



Lower Bound Risk of Injury to Non-Critical Organs (Explosion)

◀◀ ACCEPTABLE PERFORMANCE ● UNACCEPTABLE PERFORMANCE ▶▶

NO EXPECTED INJURY	TEMPORARY HEARING LOSS/DISCOMFORT	0-50% LIKELIHOOD OF EARDRUM RUPTURE	>50% LIKELIHOOD OF EARDRUM RUPTURE

	TITLE:	DAMAGE ASSMT – INJURY/OVERPRESSURE (EAR DRUM RUPTURE)
	DIAGRAM/SKETCH (SK) NO.:	SK-104B
	DATE:	08/27/2020

ACCEPTABLE PERFORMANCE

UNACCEPTABLE PERFORMANCE

NO EXPECTED INJURY

DISCOMFORT FOR LONG EXPOSURE

FIRST DEGREE BURN

SECOND DEGREE BURN

	TITLE:	DAMAGE ASSMT – INJURY/THERMAL RADIATION
	DIAGRAM/SKETCH (SK) NO.:	SK-104C
	DATE:	08/27/2020

APPENDIX B – LIQUID HYDROGEN (LH2) VCE ASSESSMENT

General Assumptions

1. The VCE assessment assumes that the entire volume of stored LH2 (4000-kg) is able to leak out of the storage tank without detection and accumulate in a vapor cloud.
2. The VCE assessment assumes that the vapor cloud, once formed, is exposed to an ignition source.
3. The lower bound VCE event assumes a nominal level of vapor dispersion, slowing the flame propagation through the cloud. This event is characterized by a lower Mach number (0.36) and is more characteristic of a deflagration rather than detonation event.
4. The upper bound VCE event assumes a densely packed vapor cloud, in which a flame front can rapidly propagate. This event is characterized by a high Mach number (5.2) that is typical of a detonation event.

Initial Condition Assumptions

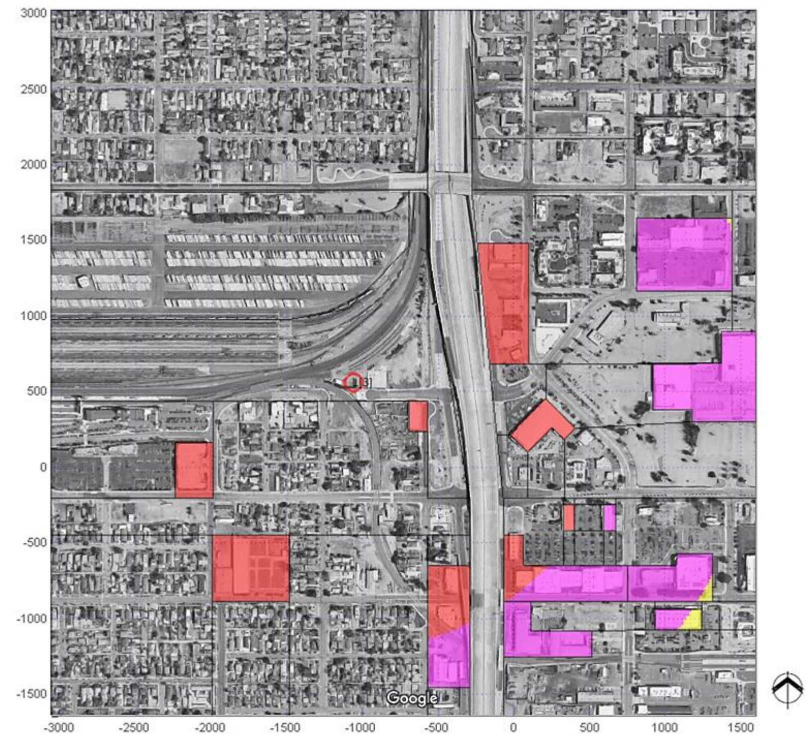
1. All safety and monitoring systems fail.
2. The vapor cloud forms immediately above the storage tank and does not rise to higher elevations.

Damage Assumptions & Results

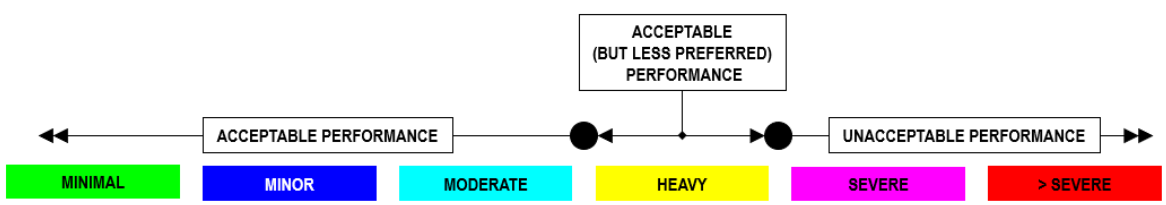
1. The Arrow Maintenance Facility is assumed to be most similar to Building Type #1 (pre-engineered frame structure). This building is expected to sustain Severe damage in the event of an VCE (lower or upper bound).
2. There is expected to be a significant cratering within a 50-ft radius of the LH2 storage tank. All at-grade infrastructure and equipment within this radius is assumed to be significantly damaged.
3. Assessments of window glass fragmentation are also assumed to inform understanding of potential injury to building occupants. Areas characterized by or exceeding a "High Fragment Hazard" are expected to be associated with a high risk of injury to building occupants resulting from flying glass debris.

	TITLE:	GENERAL NOTES & ASSUMPTIONS
	DIAGRAM/SKETCH (SK) NO.:	SK-201
	DATE:	08/27/2020

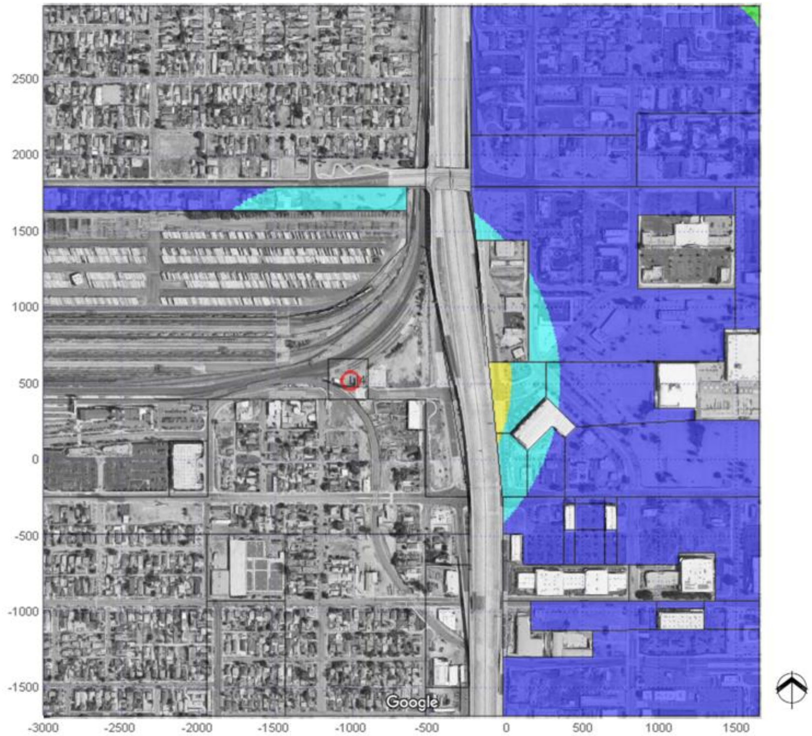
Lower Bound Damage at Pre-Engineered Bldgs (Deflagration)



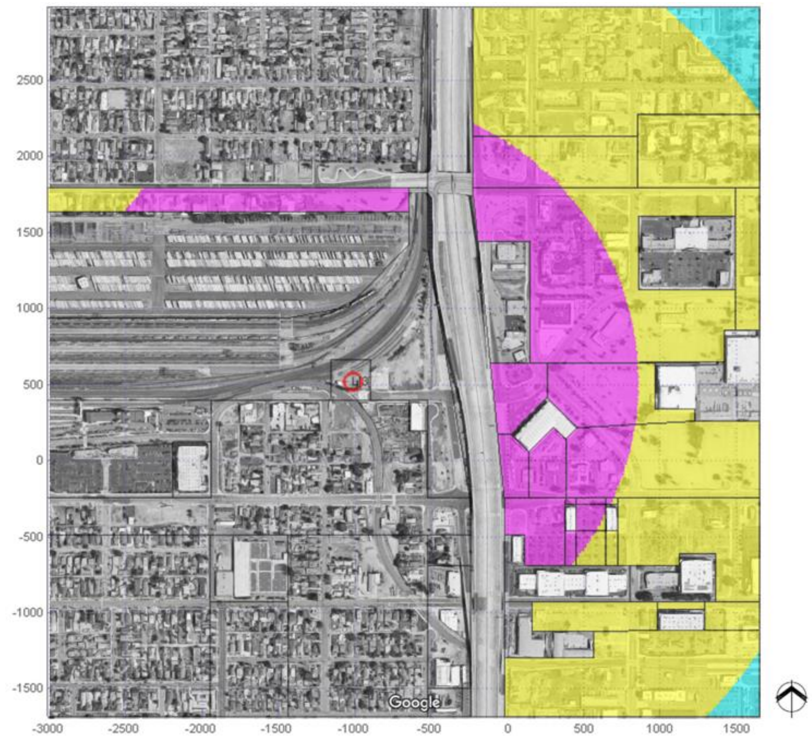
Upper Bound Damage at Pre-Engineered Bldgs (Explosion)



	TITLE:	DAMAGE ASSESSMENT – BLDG TYPE #1
	DIAGRAM/SKETCH (SK) NO.:	SK-202A
	DATE:	08/27/2020



Lower Bound Damage at Reinforced Concrete Bldgs (Deflagration)



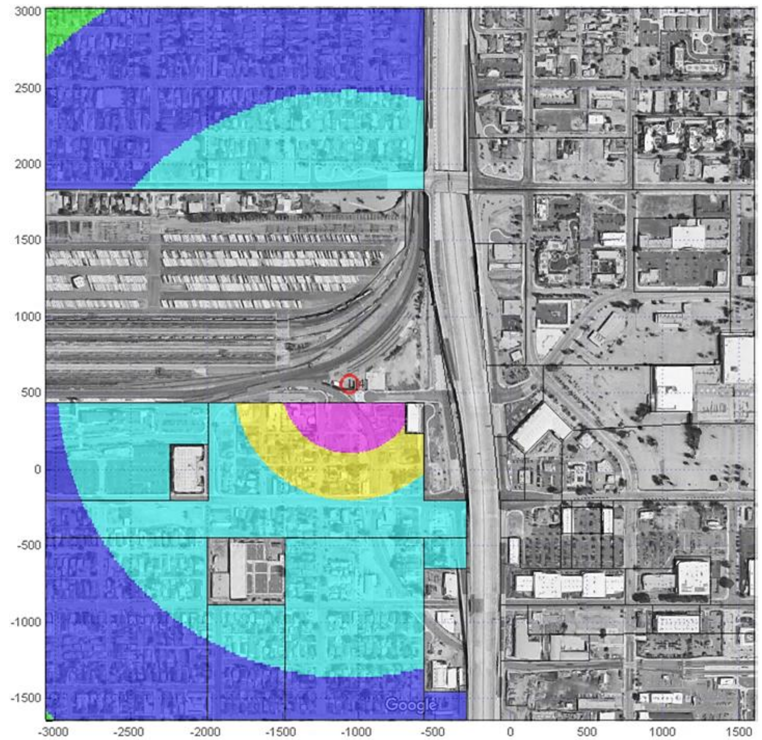
Upper Bound Damage at Reinforced Concrete Bldgs (Explosion)

ACCEPTABLE (BUT LESS PREFERRED) PERFORMANCE

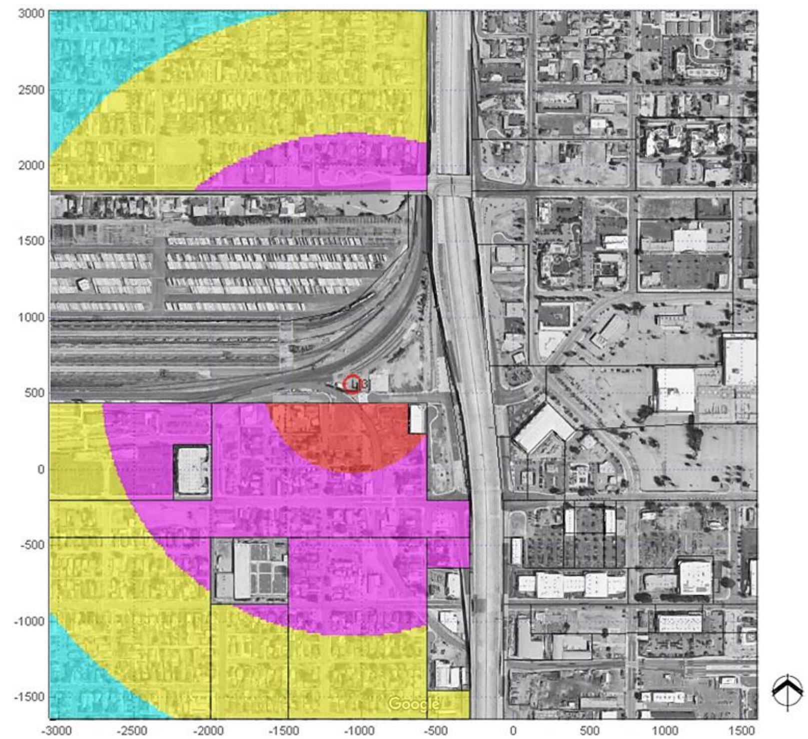
ACCEPTABLE PERFORMANCE — UNACCEPTABLE PERFORMANCE

MINIMAL	MINOR	MODERATE	HEAVY	SEVERE	> SEVERE

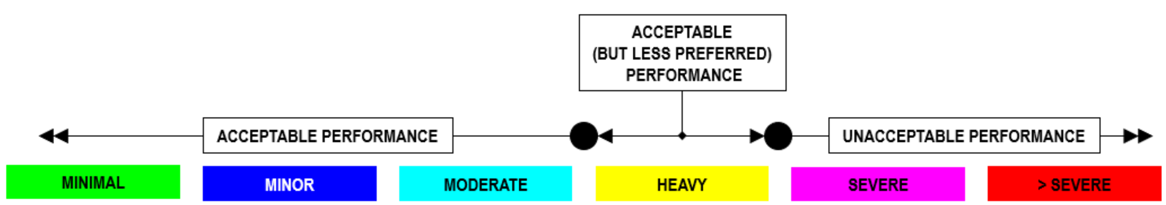
	TITLE:	DAMAGE ASSESSMENT – BLDG TYPE #2 & TYPE #3
	DIAGRAM/SKETCH (SK) NO.:	SK-202B
	DATE:	08/27/2020



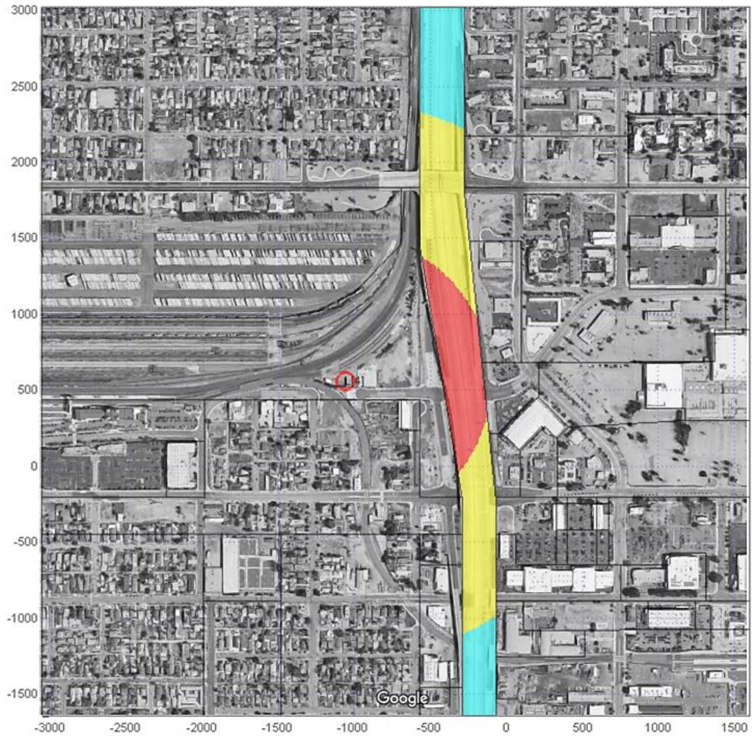
Lower Bound Damage at Light-Framed Wood Bldgs (Deflagration)



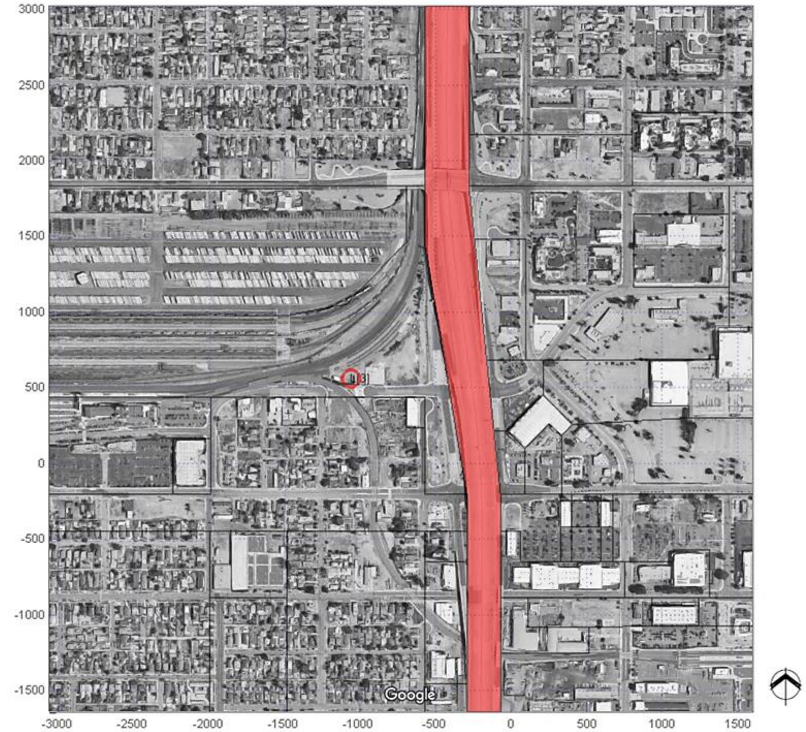
Upper Bound Damage at Light-Framed Wood Bldgs (Explosion)



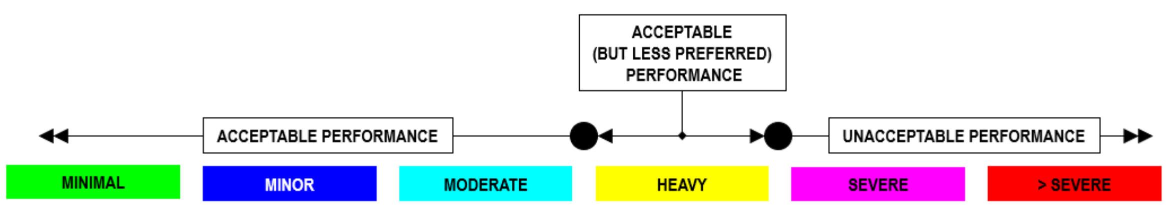
	TITLE:	DAMAGE ASSESSMENT – BLDG TYPE #4
	DIAGRAM/SKETCH (SK) NO.:	SK-202C
	DATE:	08/27/2020



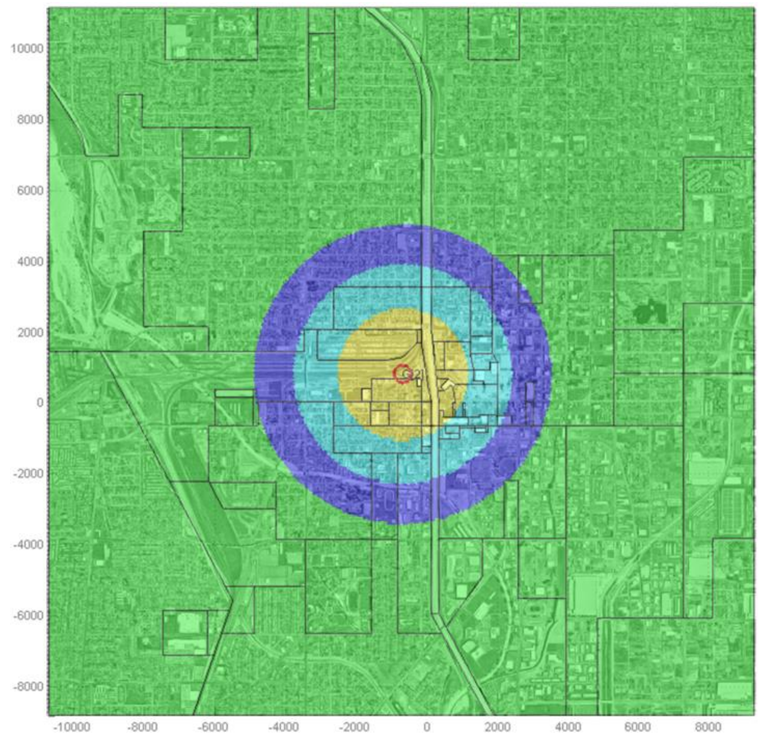
Lower Bound Damage at Elevated Roadways (Deflagration)



Upper Bound Damage at Elevated Roadways (Explosion)



	TITLE:	DAMAGE ASSESSMENT – ELEVATED REINF. CONC. ROADWAYS
	DIAGRAM/SKETCH (SK) NO.:	SK-202D
	DATE:	08/27/2020



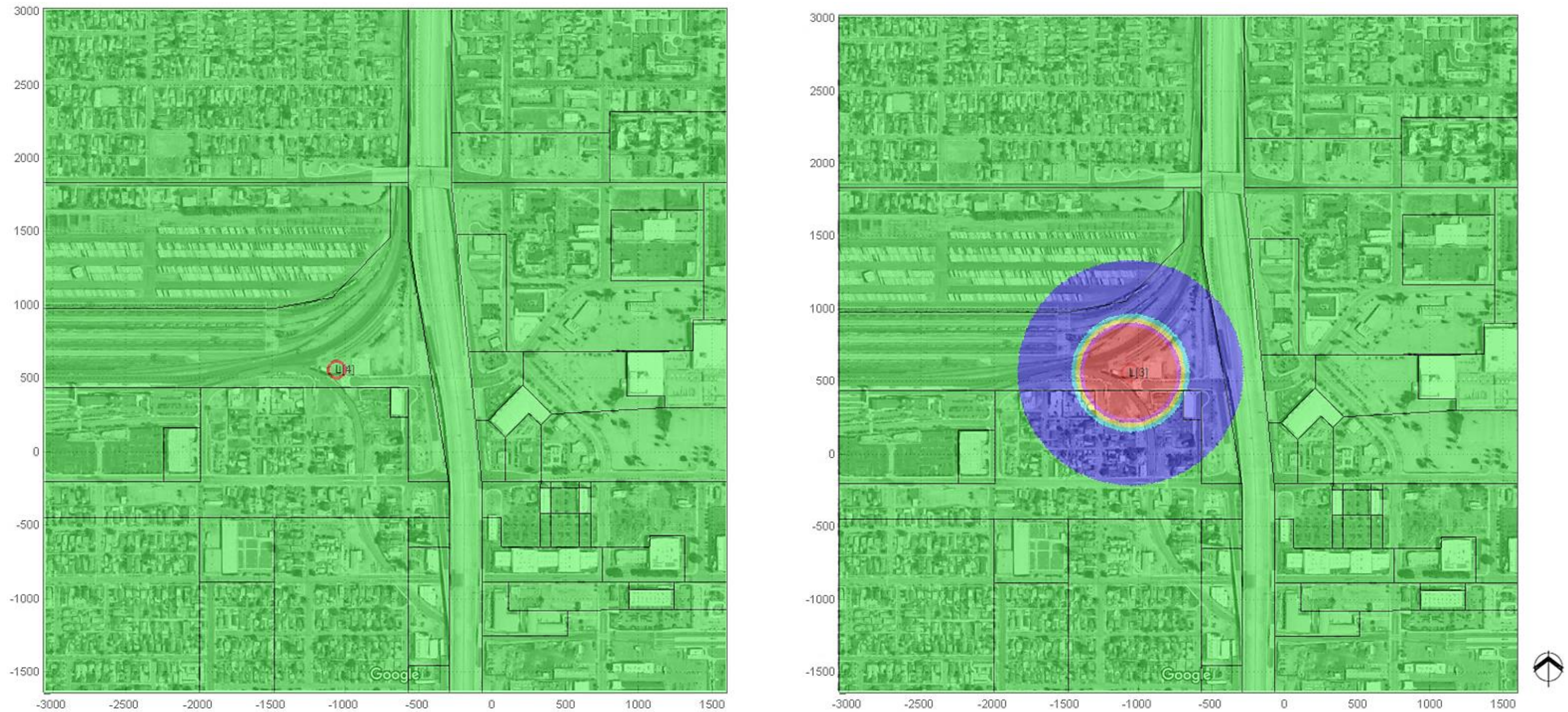
Lower Bound Damage to Windows (Deflagration)

Upper Bound Damage to Windows (Explosion)

ACCEPTABLE PERFORMANCE — UNACCEPTABLE PERFORMANCE

BREAKAGE | LOW FRAGMENT HAZARD | HIGH FRAGEMENT HAZARD | > HIGH FRAGMENT HAZARD

TITLE:	DAMAGE ASSESSMENT – WINDOWS
DIAGRAM/SKETCH (SK) NO.:	SK-203
DATE:	08/27/2020



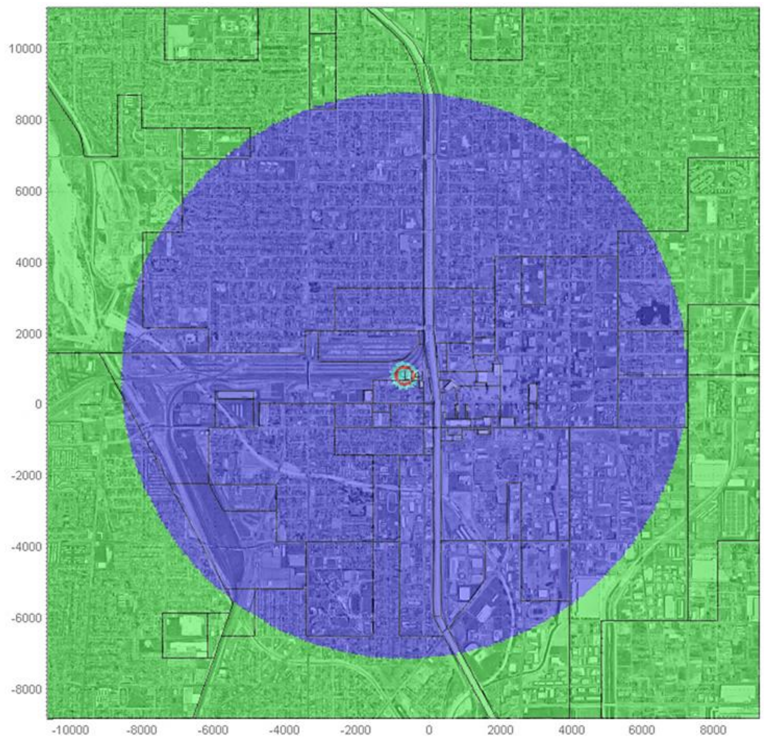
Lower Bound Risk of Injury to Critical Organs (Deflagration)

Upper Bound Risk of Injury to Critical Organs (Explosion)

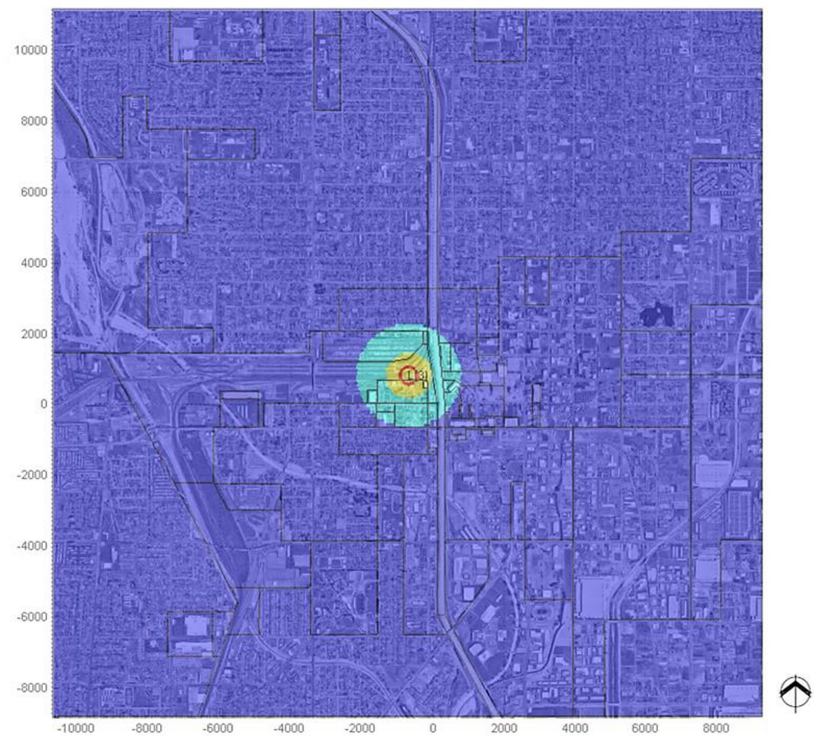
ACCEPTABLE PERFORMANCE | UNACCEPTABLE PERFORMANCE

NO INJURY | >99% SURVIVAL | 99% SURVIVAL | 90% SURVIVAL | 50% SURVIVAL | ≤10% SURVIVAL

	TITLE:	DAMAGE ASSESSMENT – INJURY/OVERPRESSURE (LUNG DAMAGE)
	DIAGRAM/SKETCH (SK) NO.:	SK-204A
	DATE:	08/27/2020



Lower Bound Risk of Injury to Non-Critical Organs (Deflagration)

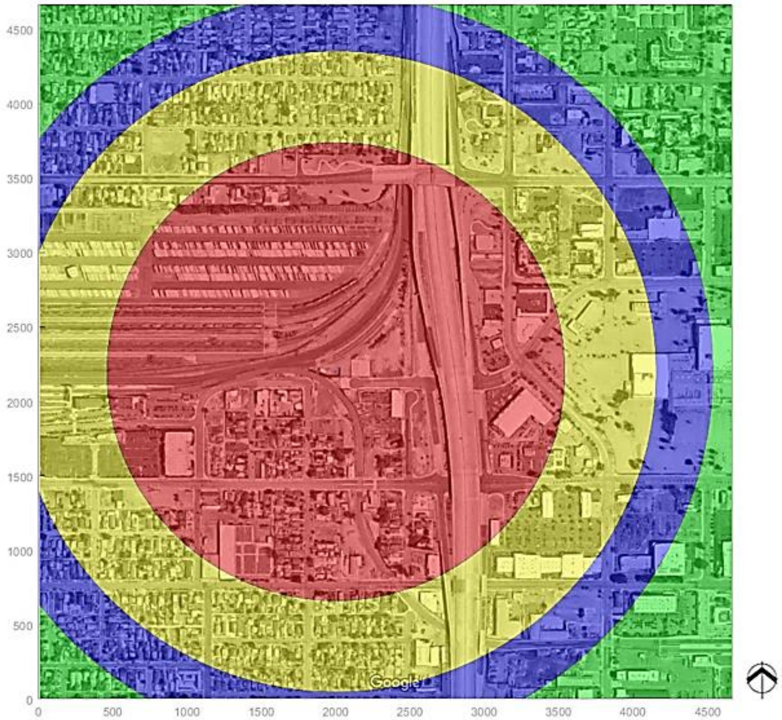


Upper Bound Risk of Injury to Non-Critical Organs (Explosion)

ACCEPTABLE PERFORMANCE | UNACCEPTABLE PERFORMANCE

NO EXPECTED INJURY | TEMPORARY HEARING LOSS/DISCOMFORT | 0-50% LIKELIHOOD OF EARDRUM RUPTURE | >50% LIKELIHOOD OF EARDRUM RUPTURE

	TITLE:	DAMAGE ASSMT – INJURY/OVERPRESSURE (EAR DRUM RUPTURE)
	DIAGRAM/SKETCH (SK) NO.:	SK-204B
	DATE:	08/27/2020



ACCEPTABLE PERFORMANCE

UNACCEPTABLE PERFORMANCE

NO EXPECTED INJURY

DISCOMFORT FOR LONG EXPOSURE

FIRST DEGREE BURN

SECOND DEGREE BURN

	TITLE:	DAMAGE ASSMT – INJURY/THERMAL RADIATION
	DIAGRAM/SKETCH (SK) NO.:	SK-204C
	DATE:	08/27/2020

APPENDIX C – LIQUID HYDROGEN (LH2) BLEVE ASSESSMENT

General Assumptions

1. The BLEVE assessment assumes that the LH2 (4000-kg) is stored in a steel (or material with equivalent density) tank.
2. The BLEVE assessment assumes that the supercooled LH2 occupies 80% of the available tank storage volume vapor cloud, once formed, is exposed to an ignition source.
3. The BLEVE assessment determines a pressure at failure rooted in the potential stored energy within the tank as vapor pressure and internal temperature builds. This determination is correlated to an equivalent TNT explosion and used as the baseline to assess building damage and injury.

Initial Condition Assumptions

1. All safety and monitoring systems fail.
2. An initiating event (fire) that results in a rise in internal tank temperature is assumed to occur.

Damage Assumptions & Results

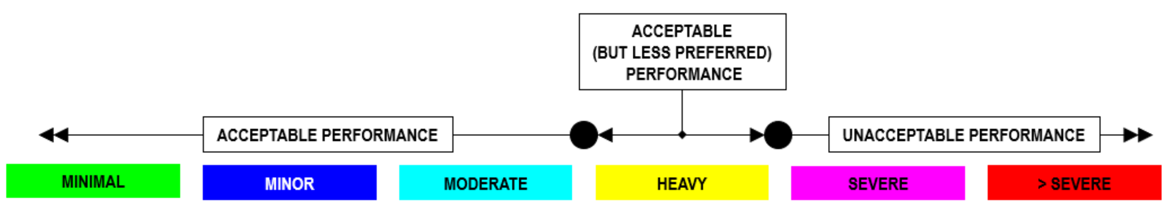
1. The Arrow Maintenance Facility is assumed to be most similar to Building Type #1 (pre-engineered frame structure). This building is expected to sustain Severe damage in the event of a BLEVE.
2. There is expected to be a significant cratering within a 30-ft radius of the LH2 storage tank. All at-grade infrastructure and equipment within this radius is assumed to be significantly damaged.
3. Assessments of window glass fragmentation are also assumed to inform understanding of potential injury to building occupants. Areas characterized by or exceeding a "High Fragment Hazard" are expected to be associated with a high risk of injury to building occupants resulting from flying glass debris.

Damage Assumptions & Results (Cont'd)

4. Assessments of debris-induced injuries assume the following fragment geometries – 1/2 tank volume resulting from a radial rupture (50% mass fragment); end cap resulting from a radial rupture (6.5% mass fragment); large strip resulting from a longitudinal seam weld rupture (8.8% mass fragment); and a small strip resulting from a longitudinal seam weld rupture (1% mass fragment).
5. Assessments of debris-induced injuries assume 5-deg, 10-deg and 45-deg launch angles. The latter is commonly discounted as conservative in industry standards.
6. Assessments of debris-induced injuries assume a brittle tank failure and no energy losses. Ductile tank failures are typically found to have a 0-20% energy dissipation, reducing the initial kinetic energy of flying fragments.
7. Assessments of debris-induced injuries conservatively neglected the influence of drag in estimating fragment range

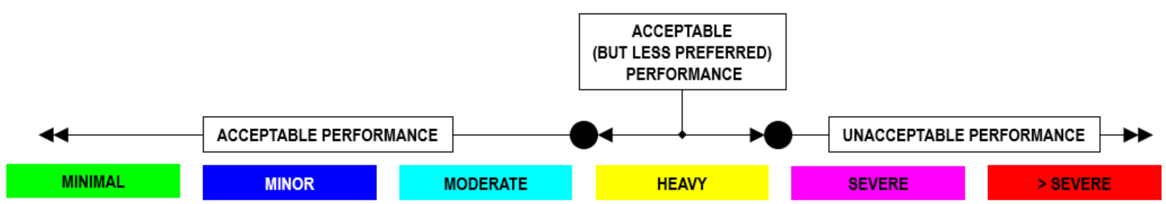
TITLE:	GENERAL NOTES & ASSUMPTIONS
DIAGRAM/SKETCH (SK) NO.:	SK-301
DATE:	08/27/2020

Damage at Pre-Engineered Bldgs



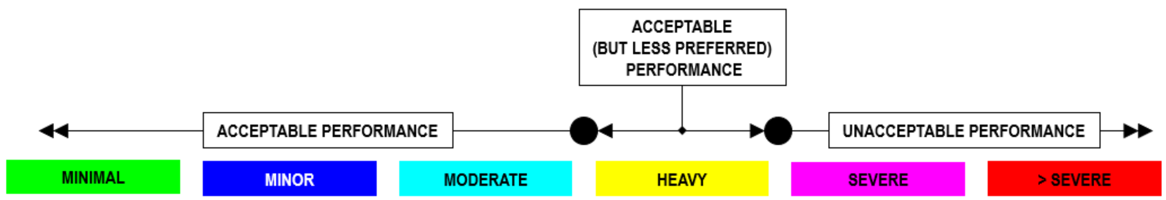
	TITLE:	DAMAGE ASSESSMENT – BLDG TYPE #1
	DIAGRAM/SKETCH (SK) NO.:	SK-302A
	DATE:	08/27/2020

Damage at Reinforced Concrete Bldgs

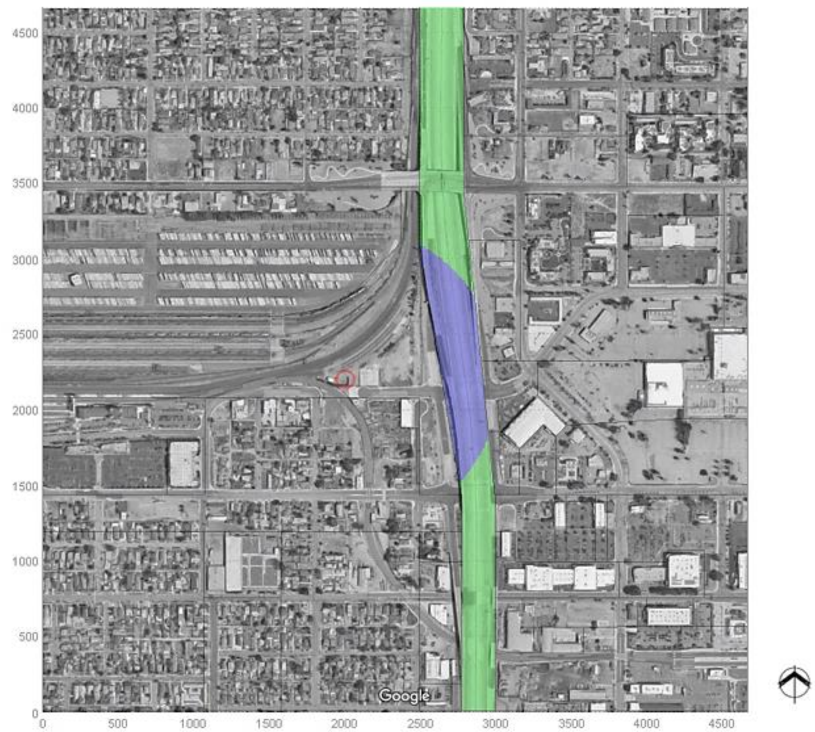


	TITLE:	DAMAGE ASSESSMENT – BLDG TYPE #2 & TYPE #3
	DIAGRAM/SKETCH (SK) NO.:	SK-302B
	DATE:	08/27/2020

Damage at Light-Framed Wood Bldgs



	TITLE:	DAMAGE ASSESSMENT – BLDG TYPE #4
	DIAGRAM/SKETCH (SK) NO.:	SK-302C
	DATE:	08/27/2020



Damage at Elevated Roadways

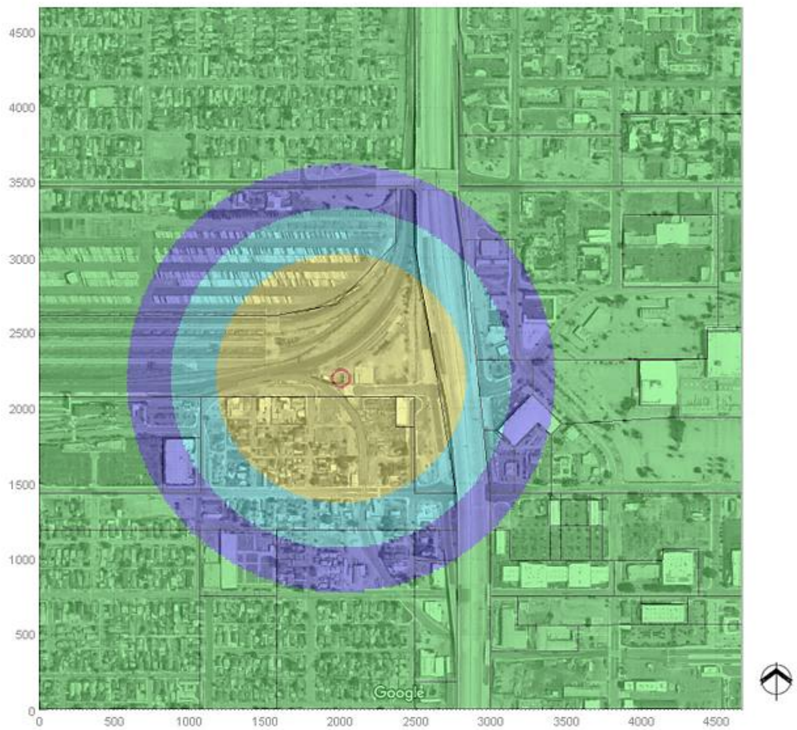
ACCEPTABLE (BUT LESS PREFERRED) PERFORMANCE

ACCEPTABLE PERFORMANCE

UNACCEPTABLE PERFORMANCE

MINIMAL | MINOR | MODERATE | HEAVY | SEVERE | > SEVERE

TITLE:	DAMAGE ASSESSMENT – ELEVATED REINF. CONC. ROADWAYS
DIAGRAM/SKETCH (SK) NO.:	SK-302D
DATE:	08/27/2020



Damage to Windows \

ACCEPTABLE PERFORMANCE — UNACCEPTABLE PERFORMANCE

BREAKAGE	LOW FRAGMENT HAZARD	HIGH FRAGEMENT HAZARD	> HIGH FRAGMENT HAZARD

	TITLE:	DAMAGE ASSESSMENT – WINDOWS
	DIAGRAM/SKETCH (SK) NO.:	SK-303
	DATE:	08/27/2020

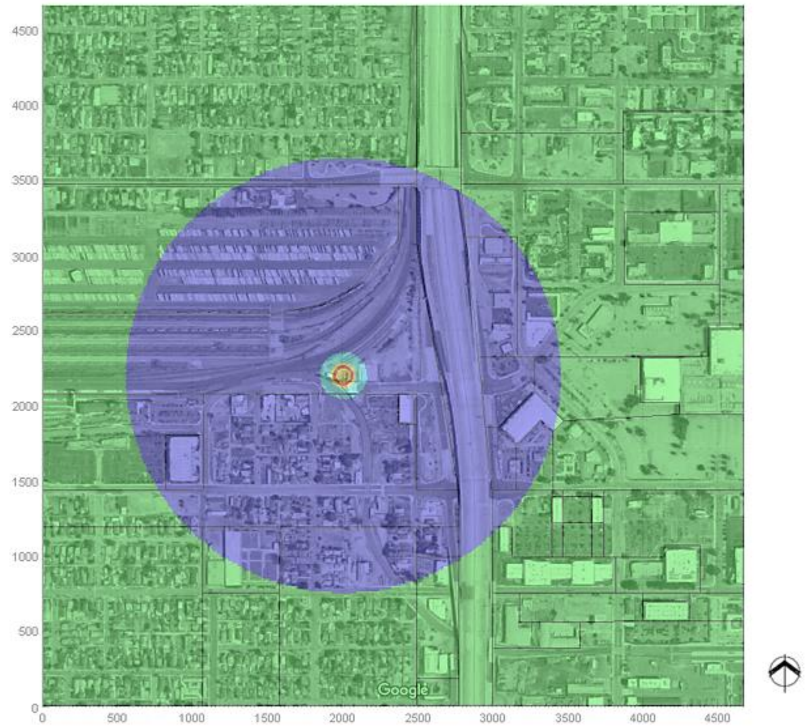
Risk of Injury to Critical Organs

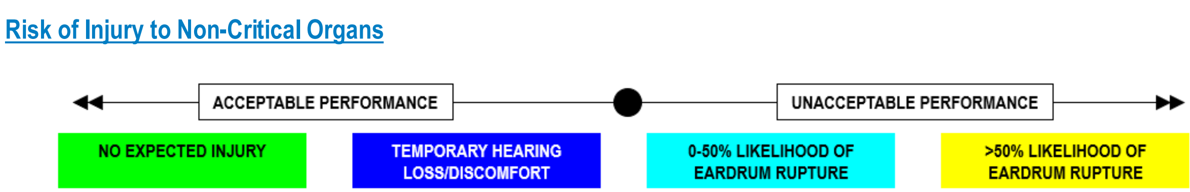
ACCEPTABLE PERFORMANCE

UNACCEPTABLE PERFORMANCE

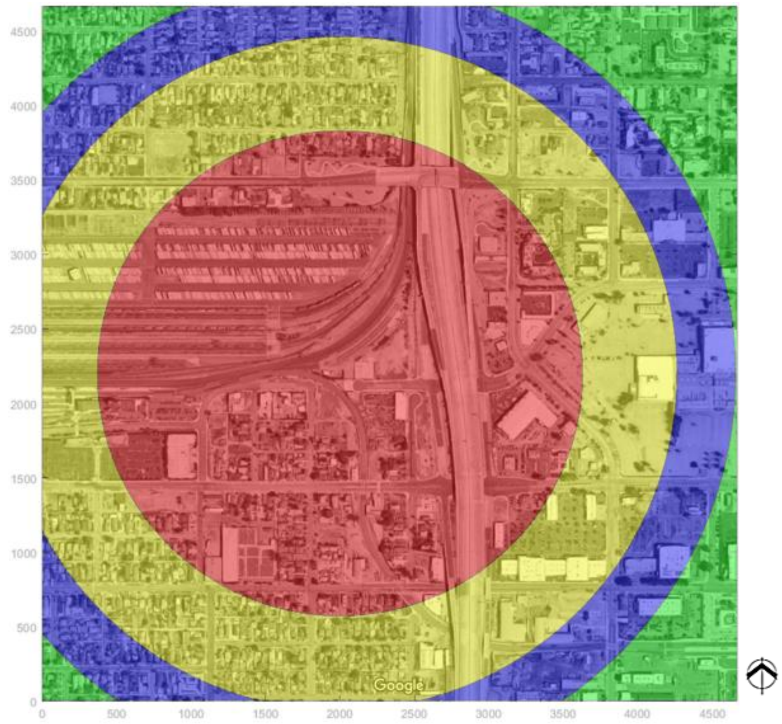
NO INJURY | >99% SURVIVAL | 99% SURVIVAL | 90% SURVIVAL | 50% SURVIVAL | ≤10% SURVIVAL

	TITLE:	DAMAGE ASSESSMENT – INJURY/OVERPRESSURE (LUNG DAMAGE)
	DIAGRAM/SKETCH (SK) NO.:	SK-304A
	DATE:	08/27/2020





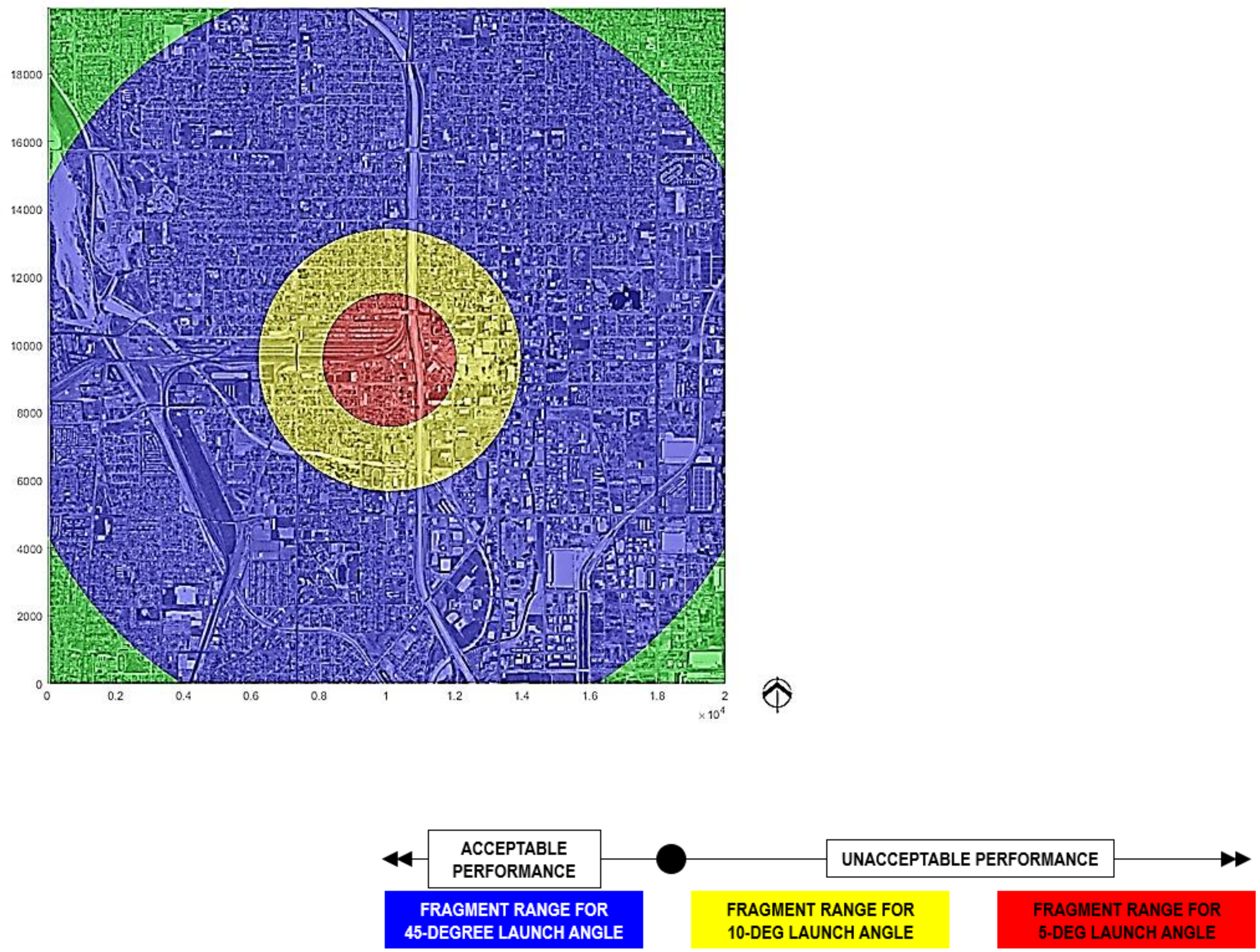
	TITLE:	DAMAGE ASSMT – INJURY/OVERPRESSURE (EAR DRUM RUPTURE)
	DIAGRAM/SKETCH (SK) NO.:	SK-304B
	DATE:	08/27/2020



ACCEPTABLE PERFORMANCE | UNACCEPTABLE PERFORMANCE

NO EXPECTED INJURY	DISCOMFORT FOR LONG EXPOSURE	FIRST DEGREE BURN	SECOND DEGREE BURN

	TITLE:	DAMAGE ASSMT – INJURY/THERMAL RADIATION
	DIAGRAM/SKETCH (SK) NO.:	SK-304C
	DATE:	08/27/2020



	TITLE:	DAMAGE ASSMT – INJURY/DEBRIS
	DIAGRAM/SKETCH (SK) NO.:	SK-304D
	DATE:	08/27/2020