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Risk Management Analysis

Blue Grass Chemical Agent-Destruction Pilot Plant (BGCAPP) GB Hydrolysate Transportation Risk Assessment

Site: BGCA/BGCAPP	Study Number: RM-20-008

An evaluation of the risk of transporting treated GB hydrolysate from BGCAPP to a treatment, storage, and disposal facility (TSDF) was conducted. The regulations for hazmat classification, handling, loading, and transport were reviewed for safe transport of the hydrolysate in tanker trucks. A transportation risk assessment was conducted for the BGCAPP GB hydrolysate using the Army approach by determining accident frequency and event consequences for (1) an accident/incident with a release/leak and (2) an accident with a release and a fuel fire. Overall, the results determined from modeling indicate that the transportation risk is *Low.*

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1 INTRODUCTION

1.1 Background

Neutralization of sarin (GB), a chemical warfare agent at the Blue Grass Chemical Agent-Destruction Pilot Plant (BGCAPP), generates a hydrolysate waste stream. The generated hydrolysate is pH-adjusted to between 13 and 14 by the addition of sodium hydroxide to prevent a reverse reaction. The term "hydrolysate" in this transportation risk assessment (TRA) refers to the caustic-adjusted hydrolysate, unless otherwise noted. The hydrolysate was originally intended to be treated onsite by the supercritical water oxidation (SCWO) process. In its review of the criteria for successful treatment of the hydrolysate, the National Academies of Sciences, Engineering, and Medicine (NASEM 2015) considered offsite treatment of the hydrolysate in the event that the SCWO underperformed or failed altogether. The offsite treatment would help reduce the risk to the community by enabling timely completion of treatment operations at BGCAPP.

The decision was made in August 2020 to not use the SCWO system due to multiple issues discovered during testing that raised reliability concerns. Offsite treatment of GB hydrolysate at a commercial treatment, storage, and disposal facility (TSDF) is being considered as an alternative to onsite disposal, as addressed above. Shipment of the waste to a TSDF is a viable option if the potential risk to the public in the event of a transportation accident is acceptable. A TRA identifies and assesses potential risks to the public due to accidents during transport of hazardous waste. The Army previously performed TRAs to support planned shipment of certain types of agent-contaminated secondary waste from specific Army facilities to permitted TSDFs. These shipments subsequently have been completed safely and without incident.

As described in the relevant sections, this TRA uses some of the methodology and/or certain information/data presented in the following previously published risk assessment studies:

- *Bounding Transportation Risk Assessment for >1 Vapor Screening Level (VSL) Waste* (CMA 2014) (hereinafter Bounding TRA)
- *Risk Assessment for Storage and Processing of GB Hydrolysate at the Blue Grass Chemical Agent-Destruction Pilot Plant* (SAIC 2011) (hereinafter BGCAPP Risk Assessment)
- *Newport Chemical Agent Disposal Facility, Transport Safety Plan and Risk Evaluation for Shipment of NECDF Caustic Hydrolysate* (CMA 2007) (hereinafter NECDF Transport Safety Plan)

This TRA does not consider risk from potential accidents during handling, loading, or unloading the wastes at BGCAPP or at the TSDF. Documents that address hazards during these activities, such as job hazard analyses or monitoring plans, will be developed

independently from this TRA. In addition, this TRA is just one element of the Army's program to ensure protection of the public, workers, and the environment during shipment operations. Other documents will be prepared to cover (1) monitoring and characterization of the waste, (2) packaging and segregation of the waste, (3) loading and unloading operations, (4) transportation planning and procedures, and (5) emergency response planning and procedures.

1.2 Objective

The objective of this TRA is to assess the risk related to offsite shipment—via a commercial hazardous waste carrier—of treated GB hydrolysate from the BGCAPP site in Richmond, Kentucky, to a TSDF.

2 DESCRIPTION OF WASTE TO BE SHIPPED

The hydrolysate is composed of a number of GB degradation products, sodium hydroxide, and water. Table 2-1 lists constituent characteristics and estimated concentrations (i.e., weight fractions)—as adapted from the BGCAPP Risk Assessment.

The concentration of GB in the hydrolysate is based on the hydrolysate clearing limit of 52 parts per billion. The specific gravity of the hydrolysate is approximately 1.09. The weight fractions are higher in the rocket campaign hydrolysate than in the projectile campaign hydrolysate. Therefore, the higher concentrations (more conservative) are used for analysis in this TRA. It is noted that while these concentrations may vary, it was assumed that these values represent the average mass fractions over time over the number of shipments.

GB hydrolysate is designated as a listed hazardous waste in Kentucky, with waste code N301 – Agent hydrolysate associated with GB munitions.

In addition, the following Resource Conservation and Recovery Act characteristic hazardous waste codes may apply (Hullman 2020):

- D002 (Corrosive)
- D004 (Arsenic)
- D005 (Barium)
- D006 (Cadmium)
- D007 (Chromium)
- D008 (Lead)
- D009 (Mercury)
- D010 (Selenium)
- D011 (Silver)

Table 2-1. Hydrolysate Constituent Characteristics and Estimated Concentrations [a]

Chemical Compound	Abbreviation	Molecular Weight (grams per mole)	Projectile Campaign (weight fraction)	Rocket Campaign (weight fraction)
O-isopropyl methylphosphonofluoridate	GB	140.1	5.2×10^{-8} [b]	5.2×10^{-8} [b]
Sodium O-isopropyl methylphosphonate	NaIMPA	160.1	2.71×10^{-2}	4.15×10^{-2}
Disodium methylphosphonate	Na_2MPA	140.0	1.90×10^{-3}	2.91×10^{-3}
O,O'-diisopropyl methylphosphonate	DIMP	180.2	1.07×10^{-3}	1.64×10^{-3}
Sodium methylphosphonofluoridate	NaFA	120.0	4.27×10^{-4}	6.55×10^{-4}
Sodium fluoride	NaF	42.0	1.64×10^{-2}	2.52×10^{-2}
Tributylamine	TBA	185.4	1.63×10^{-3}	2.51×10^{-3}
Isopropanol	IPA	60.1	2.27×10^{-4}	3.48×10^{-4}
N,N'-diisopropylurea	DIU	144.2	1.1×10^{-4}	1.69×10^{-4}
Sodium hydroxide	NaOH	40.0	6.99×10^{-3}	7.64×10^{-3}
Water	H_2O	18.0	9.44×10^{-1}	9.17×10^{-1}
Total			**1.00**	**1.00**

Notes:

a Mass fractions in this table are based on those reported in the BGCAPP Risk Assessment (SAIC 2011) with adjustments made for dilution (as shown in Hullman 2020) due to more water being used now than was anticipated to be used when making the original estimate.

b GB concentration based on the hydrolysate clearing limit of 52 parts per billion (Kiley 2020).

Sources:

- Hullman, David (Leidos), BGCAPP Field Office, email dated 1 July 2020, with Battelle Calculation Spreadsheet Attachment, Expected Hydrolysate Waste Profile.
- Kiley, Jeff (PEO ACWA), email dated 13 December 2020.
- SAIC (Science Application International Corporation), *Risk Assessment for Storage and Processing of GB Hydrolysate at the Blue Grass Chemical Agent-Destruction Pilot Plant,* September 2011.

GB hydrolysate is also a Department of Transportation (DOT) hazardous material (hazmat) belonging to Class 8 (corrosive material) category, due to its pH (between 13.0 and 14.0). Toxicity studies (ECBC 2009a, 2009b) concluded that GB hydrolysate does not warrant being classified as a DOT Class 5, Division 6.1 Poison.

3 PACKAGING AND TRANSPORTATION REQUIREMENTS

3.1 DOT Transport Regulations

49 Code of Federal Regulations (CFR) 172 prescribes the requirements for shipping papers, package marking, labeling, and transport vehicle placarding applicable to the shipment and transportation of each class of hazmat. In addition, it prescribes requirements for emergency response, training, and safety and security plans.

49 CFR 173 prescribes requirements for preparing the hazmats for shipment, including packaging requirements and quantity limitations. 49 CFR 173.50 prescribes requirements for packaging of Class 1 hazmats.

49 CFR 177 prescribes requirements for transportation via public highway by motor vehicle, including inspections, driver training, segregation and separation, and loading and unloading requirements for each class of hazmat.

49 CFR 178 prescribes testing requirements for packaging and containers used for transportation of hazmats.

3.2 Transport Vehicle

The transport vehicle has the following specifications:[1]

- DOT-412 tanker – 5,000 gallon
- Specially built to carry corrosives
- Typically made from stainless steel
- Maximum allowable working pressure (MAWP): 5–25 pounds per square inch gauge (psig)

[1] Source: www.Barrgo.com

- Equipped with pressure relief devices
- Pressure relief devices activate at 1.5 times the MAWP

3.3 Description of General Transport Requirements

Transport requirements for hazmats are governed by DOT regulations, as described in Section 3.1. General provisions applicable during the transportation phase (49 CFR 177.800, 177.801, 177.804, 177.810, 177.816, 177.817, and 177.823) include the following:

- Transport without unnecessary delay, from and including the time of commencement of the loading of the hazmat until its final unloading at destination
- Availability of records, equipment, packaging, and containers under the control of a motor carrier, insofar as they affect safety in transportation of hazmats
- Compliance with safe clearance requirements for highway-rail grade crossings in 49 CFR 392.12
- Prohibition of texting and use of handheld telephones while driving, in accordance with 49 CFR 392.80 and 392.82
- Compliance with requirements of hazmat transport restrictions in vehicular tunnels
- Driver training in accordance with 49 CFR 177.816 and 49 CFR 390 through 397, including:
  - Pre-trip safety inspection
  - Use of vehicle controls and equipment, including operation of emergency equipment
  - Operation of vehicle, including turning, backing, braking, parking, handling, and vehicle stability
  - Procedures for maneuvering tunnels, bridges, and railroad crossings
  - Requirements pertaining to attendance of vehicles, parking, smoking, routing, and incident reporting
  - Loading and unloading of materials, including compatibility, segregation, package handling, and load securement
  - Specialized training for cargo tanks and portable tanks including emergency control features of the tank, center of gravity, fluid-load surge on braking, properties and

hazards of material transported, and retest and inspection requirements for cargo tanks

- Availability of shipping papers to authorities in the event of accident or inspection
- Marking and placarding a transport vehicle containing a hazardous waste in accordance with 49 CFR 172
- Prohibition on moving a transport vehicle containing a hazardous waste during an emergency unless:
  - The vehicle is escorted by a representative of a state or local government
  - The carrier has permission from the DOT
  - Movement of the vehicle is necessary to protect life or property.

3.4 Loading and Unloading

The hydrolysate will be transferred from the hydrolysate storage tanks into the tanker truck in accordance with the BGCAPP Standing Operating Procedure. This TRA assumes that prior to transfer, the truck will be inspected to ensure all safety features are present and functioning as intended. The TRA also assumes that, at the conclusion of the transfer operation, the truck will be inspected per the Standing Operating Procedure to ensure that valves are closed, caps secured, and pressure relief devices present to ensure that the tanker truck is ready to begin transporting the hydrolysate.

Although this TRA does not address the risk of accidents during loading and unloading, general regulatory requirements (49 CFR 177.834) applicable during hazmat loading and unloading operations include the following:

- No loading or unloading should occur unless the handbrake is securely set and all other reasonable precautions are taken to prevent motion of the motor vehicle.
- A qualified person must attend the cargo tank at all times during loading and unloading.
- A qualified person must be within 25 feet of the cargo tank.
- Cargo motor vehicles must not be driven unless all manholes are closed and secured, and all valves and other closure devices are closed and free of leaks.

3.5 Description of Additional Specific Transport Requirements

Additional operational measures will be implemented that will further increase the safety and security of the shipments. Some measures may overlap with the general procedures outlined in

Section 3.3. The requirements/operational measures outlined in this section were originally developed for the NECDF Transport Safety Plan in 2007, but are currently considered valid as representative requirements. However, as stated in Section 1.1, separate documents will be prepared to cover transportation and emergency response planning and procedures. As such, a project-specific Transportation Plan for shipping the BGCAPP GB hydrolysate—incorporating specific requirements, if any, from the state, Centers for Disease Control and Prevention, and/or community—will be prepared by the selected transporter and submitted to Program Executive Office, Assembled Chemical Weapons Alternatives (ACWA) prior to shipment.

- Trucks will remain in visual contact with each other.
- Trucks will endeavor to drive and/or park on paved surfaces at all times.
- Trucks will be attended at all times in accordance with DOT requirements and in compliance with all motor carrier safety regulations.
- Trucks will stop approximately every 2 hours to conduct a vehicle safety inspection and inspect the security of the load.
- Trucks will always be driven using team drivers. Trucks will be driven “straight through,” according to the prescribed route. Breaks will be limited to required safety/security inspections, lavatory breaks, and reasonable rest stops for meals.
- Each truck will carry a copy of emergency response notification numbers with the shipping papers.
- Each truck will be tracked using satellite GPS methods, be equipped with cellular phones, and maintain routine contact with company dispatch.
- Trucks will observe prescribed travel routes and observe posted speed limits at all times. Any variation of more than 1 mile from the prescribed route must be reported to dispatch.
- Trucks will be equipped with basic spill kits.
- Drivers will receive specific training regarding hydrolysate, leak recognition, spill defensive measures, immediate hazard assessment, and site control. At a minimum, drivers will be trained to the Occupational Safety and Health Administration (OSHA) Hazardous Waste Operations and Emergency Response (HAZWOPER) Emergency Responder Awareness Level. Drivers will be capable of evacuating the area and summoning additional resources.
- Safety, environmental/technical, and medical services support, as provided by the TSDF, will be on call during the hydrolysate transportation activities.

Qualifications of drivers for hydrolysate transport will include the following:

- Drivers will have current commercial driver's license (CDL), with the necessary endorsements to haul hazmats.
- Drivers will be DOT certified for hazmat transport.
- Drivers will be trained, at a minimum, to the OSHA HAZWOPER Emergency Responder Awareness Level and will complete the prescribed training regarding the Transportation Safety Plan and hydrolysate. Drivers will be current on all training required by DOT and Federal Motor Carrier Safety Administration regulations.
- Drivers will participate in random drug/alcohol testing in accordance with their company policy and DOT/Federal Motor Carrier Safety Administration regulations.
- Drivers will receive training in the Emergency Response Plan developed by the emergency response company contracted to support the hydrolysate transport.

4 METHODOLOGY

4.1 Overview of Methodology

The general methodology used in this TRA relies on the accepted Army risk management approach. The methodology is similar to that used in the Bounding TRA (for example, the same hazard severity and hazard probability definitions are used).

Historically, Department of the Army Pamphlet (DA PAM) 385-61 (DA 2002) has been the basis for the Army risk management program for chemical-agent-related hazards. Appendix F of DA PAM 385-61 (2002 version) provides an overview of the Army strategy for a risk management program. It states in part:

> Risk assessment, as a part of risk management, provides a useful tool for estimating the effectiveness of existing and proposed safeguards against chemical agent mishaps. The potential for and consequences of mishaps must be carefully analyzed. The risk assessment must consider not only the traditional MCEs [Maximum Credible Events] and resulting consequences, but also the probabilities and consequences of any realistic accident scenario that could present a risk to worker, the environment or the public.

The risk management requirements cited in the 2002 version of DA PAM 385-61 were rolled into DA PAM 385-30, *Mishap Risk Management* (DA 2007), which was subsequently revised and retitled as *Risk Management* (DA 2014).

As outlined in DA PAM 385-30, the risk assessment is used to establish priorities for corrective action and resolution of identified hazards. Consistent with these objectives, this TRA evaluates

the risk of the potential accident and release scenarios based on the combination of hazard probability and severity.

Figure 4-1 provides the Department of the Army model for risk acceptance according to DA PAM 385-30. Risk categories range from *Low* to *Extremely High*. Low risks are generally considered acceptable without mitigation, whereas higher risk categories generally require mitigation. The decision to mitigate or accept specific hazards is left to the discretion of Army authorities.

The probabilities and severities in Figure 4-1 may be categorized—as shown in Tables 4-1 and 4-2, respectively—using schemes provided in DA PAM 385-30. The 2014 version of DA PAM 385-30 no longer specifies the probability values for each category and states that it is often hard to determine objective or numerical probability values but efforts should be made to use the numerical probability values. This TRA uses the values provided in 2007 version, as shown in Table 4-1, as a guide in determining the risk level for the accident scenario.

Severity (expected consequence)	**Probability (expected frequency)**				
	Frequent A	**Likely B**	**Occasional C**	**Seldom D**	**Unlikely E**
Catastrophic I	Extremely High				
Critical II		High			
Moderate III			Medium		
Negligible IV				Low	

Figure 4-1. Qualitative Risk Evaluation Matrix (adapted from DA PAM 385-30)

Table 4-1. Probability Categories per DA PAM 385-30

Description	Level	Single Item or Activity
Frequent	A	Likely to occur often in the life of an item, with a probability of occurrence greater than 10^{-1} in that life.
Probable or Likely	B	Will occur several times in the life of an item, with a probability of occurrence less than 10^{-1} but greater than 10^{-2} [1 time/100 opportunities] in that life.
Occasional	C	Likely to occur some time in the life of an item, with a probability of occurrence less than 10^{-2} but greater than 10^{-3} [1 time/1,000 opportunities] in that life.
Seldom or Remote	D	Unlikely but possible to occur in the life of an item, with a probability of occurrence less than 10^{-3} but greater than 10^{-6} [1 time/1,000,000 opportunities] in that life.
Unlikely or Improbable	E	So unlikely, it can be assumed occurrence may not be experienced, with a probability of occurrence less than 10^{-6} in that life.

Source: Department of the Army (DA), DA Pamphlet (DA PAM) 385-30, *Mishap Risk Management*, Headquarters, Washington, D.C., 10 October 2007.

Table 4-2. Hazard Severity Descriptions in DA PAM 385-30

Hazard Severity	Level	Description
Catastrophic	I	*Definition:* Death, unacceptable loss or damage, mission failure, or unit readiness eliminated. *Quantitative Value:* One or more deaths or permanent total disabilities.
Critical	II	*Definition:* Severe injury, illness, loss, or damage; significantly degraded unit readiness or mission capability. *Quantitative Value:* One or more permanent partial disabilities or hospitalization of at least three personnel.
Moderate	III	*Definition:* Minor injury, illness, loss, or damage; degraded unit readiness or mission capability. *Quantitative Value:* One or more injuries or illnesses resulting in lost time.
Negligible	IV	*Definition:* Minimal injury, loss, or damage; little or no impact to unit readiness or mission capability. *Quantitative Value:* One or more injuries or illnesses requiring first aid or medical treatment.

Source: Department of the Army (DA), DA Pamphlet (DA PAM) 385-30, *Risk Management*, Headquarters, Washington, D.C., 2 December 2014.

4.2 Hazard Definition

The approach outlined in this section defines hazard severity based on two response zones: (1) the initial isolation zone and (2) the secondary control zone. The distance to the boundary of these zones depends on the chemical spilled, as specified in the Emergency Response Guidebook (ERG 2016). The guidebook defines distances for small spills and large spills—this TRA considers a large spill, which is defined in the guidebook as a spill that involves quantities greater than 208 liters (55 US gallons) for liquids and greater than 300 kilograms (660 pounds) for solids. Since the GB hydrolysate will be shipped as a DOT Class 8 corrosive liquid, Guide 154 (from ERG 2016) is applicable. This guide addresses toxic and/or corrosive (non-commercial) substances. The evacuation criteria for this category of chemicals are not listed in the Isolation Distances table (Table 1 in ERG 2016), but instead refer to the *Public Safety* requirements specified in Guide 154, which call for an immediate isolation distance of 50 meters for a spill, regardless of whether it is a small or large spill. The secondary control zone distance is not specified.

In the event of an accident, personnel involved in the convoy will initially isolate and evacuate the area within the Emergency Response Guidebook recommended distance of 50 meters of the site. This TRA assumes isolation and evacuation will be accomplished within 30 minutes of the accident. The TRA also assumes that it will take up to 2 hours for first responders to arrive at the accident scene, evacuate the secondary zone, and terminate the vapor release. Although the Emergency Response Guidebook (ERG 2016) does not specify a secondary control zone distance for this substance, this TRA assumes a distance of 200 meters, which is typically the shortest secondary zone distance value for other chemicals in Table 1 of the guidebook.

The hazard is characterized in terms of hazard distances, which are the distances necessary for the chemical concentration to fall below specific concentration levels, as it disperses. For GB, the concentration levels are based on established Acute Exposure Guideline Levels (AEGLs). For example, the 30-minute AEGL-1 hazard distance is the distance required for the GB concentration to fall below the 30-minute AEGL-1 concentration. Hazard distances are calculated using a plume dispersion model, specifically, the Army-sponsored D2PC software (Whitacre et al. 1987).

For the other chemical constituents, this TRA uses concentration levels based on established Protective Action Criteria (PAC) levels[2] for each chemical since AEGLs are not established for these chemicals. PAC for chemicals are essential components for planning and response to uncontrolled releases of hazardous chemicals.

[2] https://www.energy.gov/ehss/protective-action-criteria-pac-aegls-erpgs-teels

The benchmark values established for GB (AEGL-1, AEGL-2, and AEGL-3) and for each of the other chemicals (PAC-1, PAC-2, and PAC-3) represent the following health impacts:

- AEGL-1: Notable discomfort, irritation, or certain asymptomatic non-sensory effects. However, the effects are not disabling and are transient and reversible upon cessation of exposure
- AEGL-2: Irreversible or other serious, long-lasting adverse health effects or an impaired ability to escape
- AEGL-3: Life-threatening health effects or death
- PAC-1: Mild transient health effects
- PAC-2: Irreversible or other serious health effects that could impair the ability to take protective action
- PAC-3: Life-threatening health effects

The established AEGL values are based on 10-minute, 30-minute, 60-minute, 4-hour, and 8-hour exposure. Since 2-hour AEGL concentrations are not available, they were derived using the procedures described in Appendix A of *Acute Exposure Guideline Levels for Selected Chemicals* (NRC 2003).

The established PAC values are based on a 1-hour exposure. For this TRA, PAC concentrations were needed for two exposure durations: 30 minutes (establishing the initial isolation zone) and 2 hours (establishing the secondary control zone). Appendix C describes the derivation of these PAC values.

Table 4-3 presents a set of hazard severity definitions that provide the same acceptable exposure levels both inside and outside the initial isolation zone, the only difference being the duration of the exposure in these two areas. The hazard severity definitions reference AEGL-1, -2, -3, and PAC-1, -2, and -3 concentrations for 30-minute and 2-hour exposures. Exposures at greater than the AEGL-3/PAC-3 concentration could lead to life-threatening effects for susceptible receptors. Exposures at greater than the AEGL-2/PAC-2 concentration, but less than the AEGL-3/PAC-3 concentration, could result in irreversible or other serious health effects. Exposures at greater than the AEGL-1/PAC-1 concentration, but less than the AEGL-2/PAC-2 concentration, could result in mild transient health effects. Table 4-4 presents the 30-minute and 2-hour AEGL concentrations for GB and PAC concentrations for each chemical evaluated for this TRA (see Sections 6.1 and 6.2).

Table 4-3. Hazard Severity Definitions Used for TRA

Hazard Severity	Level	Proposed Definition and Rationale
Negligible	IV	*Proposed Definition:* a. 2-hour AEGL-1/PAC-1 hazard distance < distance to secondary control zone boundary (200 meters) b. 30-minute AEGL-1/PAC-1 hazard distance < distance to initial isolation zone boundary (50 meters) *Rationale:* a. Ensuring that the 2-hour AEGL-1/PAC-1 hazard distance does not reach the nearest member of the public ensures that there are negligible health effects. b. Ensuring that the 30-minute AEGL-1/PAC-1 hazard distance does not extend beyond the initial isolation zone would likely ensure negligible health effects for bystanders.
Moderate	III	*Proposed Definition:* a. 2-hour AEGL-2/PAC-2 hazard distance < distance to secondary control zone boundary (200 meters) b. 30-minute AEGL-2/PAC-2 hazard distance < distance to initial isolation zone boundary (50 meters) *Rationale:* a. Ensuring that the 2-hour AEGL-2/PAC-2 concentration does not reach the nearest member of the public ensures that injuries are minor. b. Ensuring that 30-minute AEGL-2/PAC-2 hazard distance does not extend beyond the initial isolation zone would likely ensure only minor injuries for bystanders.
Critical	II	*Proposed Definition:* a. 2-hour AEGL-3/PAC-3 hazard distance < distance to secondary control zone boundary (200 meters) b. 30-minute AEGL-3/PAC-3 hazard distance < distance to initial isolation zone boundary (50 meters) *Rationale:* a. Ensuring that the 2-hour AEGL-3/PAC-3 concentration does not reach the nearest member of the public ensures that injuries are not fatal, although they may be serious. b. Ensuring that the 30-minute AEGL-3/PAC-3 hazard distance does not extend beyond the initial isolation zone would likely ensure that injuries are not fatal, although they may be serious.

Notes:

AEGL Acute Exposure Guideline Level
PAC Protective Action Criteria

Table 4-4. AEGL and PAC Concentrations for Chemicals

Chemical/Hazard Level	30-minute Concentration [a] (mg/m^3)	2-hour Concentration [a] (mg/m^3)
O-isopropyl methylphosphonofluoridate (GB)		
AEGL-1	0.004 [b]	0.002 [c]
AEGL-2	0.050 [b]	0.025 [c]
AEGL-3	0.19 [b]	0.10 [c]
Tributylamine (TBA)		
PAC-1	0.466	0.185
PAC-2	5.17	2.05
PAC-3	30.2	12.0
O,O'-diisopropyl methylphosphonate (DIMP)		
PAC-1	3.40	1.35
PAC-2	37.80	15.0
PAC-3	226.8	90.0
N,N'-diisopropylurea (DIU)		
PAC-1	0.031	0.012
PAC-2	0.344	0.137
PAC-3	2.016	0.80

Notes:

a All PAC values are derived values. See discussion in Appendix C.
b Established values from NRC 2003, Appendix A
c Concentration derived as $(K/2)^{0.5}$ (formula and K values are from NRC 2003, Appendix A)

AEGL Acute Exposure Guideline Level
mg/m^3 milligrams per cubic meter
PAC Protective Action Criteria

Source: NRC (National Research Council). 2003. *Acute Exposure Guideline Levels for Selected Chemicals.* Volume 3. Washington, DC: The National Academies Press. https://doi.org/10.17226/10672.

4.3 Technical Approach

Section 4.1 presents a brief discussion of the methodology for this TRA. This technical approach describes the specific steps taken to complete this assessment and identifies key assumptions made in the analysis for a fire scenario. Sections 5 and 6 detail the analysis approach.

The following steps were completed to determine the transportation risks during shipment:

- Develop the transportation accident scenario to be assessed.
- Determine the hazard probability by estimating the probability of a truck accident that results in a spill and a fire, using available data for hazmat transportation accidents.
- Assess the hazard consequences from inhalation (using D2PC), dermal contact, and aquatic impacts.
- Determine the risk level based on the hazard probability and consequences in accordance with Section 5.2.

5 WASTE TRANSPORT TRUCK ACCIDENT PROBABILITY

5.1 Transportation Routing

Different transportation routes could be used to ship the GB hydrolysate from BGCAPP to the TSDF. The transporter will select a shipment route based on consideration of several factors, such as avoiding major population centers/sensitive land areas and ensuring adequate emergency response capabilities. The transporter will also ensure that the route is selected in accordance with the National Hazardous Materials Route Registry (80 Federal Register [FR] 23859). The selected route often will not be the shortest route available. A distance of 2,000 miles is assumed for this TRA. This distance will cover potential TSDFs in most states.

5.2 Truck Accident Probability Estimation

A baseline frequency for truck accidents was obtained from a Battelle study of hazmat truck shipments (Battelle 2001, Tables 24 and 25). Data are provided for accidents involving a vehicle crash and for all incidents related to hazmat transport. Incidents include vehicle crashes as well as non-accident leaks that occur during loading, unloading, and transport. Only releases resulting from vehicle accidents and leaks during transport are considered in this TRA.

The accident rate from the 2001 Battelle study for transportation of Class 8 materials is 1.32×10^{-7} accidents per mile. The accident/incident rate (incidents include leaks en route with no accident) from the 2001 Battelle study for transportation of Class 8 materials is 4.092×10^{-7} accidents or incidents per mile.

This TRA evaluates the following scenarios:

- Scenario 1 – Accident/incident occurs, causing a release
- Scenario 2 – Accident occurs, causing a release and a fuel fire.

Because the hydrolysate is not flammable, the fire is assumed to be the result of a fuel release. The event tree in Figure 5-1 depicts the modeled scenarios. Table 5-1 summarizes the basis for the event frequencies and probabilities. Sections 5.2.1 and 5.2.2 describe the calculation methodology used to determine the event frequencies for the scenarios shown in Figure 5-1.

Initiating Event	Release	Fire	Outcome
Accident Occurs	No Release		Accident – No Release
	Release	No Fire	Accident with Release (Scenario 1)
		Fire	Accident with Release and Fire (Scenario 2)
Incident Occurs	No Leak		Incident – No Release
	Leak		Incident – Release (Scenario 1)

Figure 5-1. Event Tree for Class 8 Materials

Table 5-1. Basis for Event Frequencies and Probabilities

Parameter	Reference	Value
Accident frequency per mile for Class 8 materials	Battelle 2001, Table 24	1.32×10^{-7} accidents per mile
Accident/incident frequency per mile for Class 8 materials (includes leaks en route)	Battelle 2001, Table 25	4.092×10^{-7} accidents/incidents per mile
Event tree conditional probability of a release, given an accident, for Class 8 materials	Battelle 2001, Table 6	0.284
Event tree conditional probability of no fire, given a release, for Class 8 materials	Battelle 2001, Table 6	0.973
Event tree conditional probability of fire, given a release (fuel), for Class 8 materials	Battelle 2001, Table 6	0.027
Number of accidents for Class 8 materials	Battelle 2001, Table 9	257
Number of en route incident leaks for Class 8 materials	Battelle 2001, Table 9	539
Total number of incidents plus accidents for Class 8 materials	Battelle 2001, Table 9	4,926
Miles per shipment	Assumption	2,000 miles

Reference: Battelle, *Comparative Risks of Hazardous Materials and Non-hazardous Materials Truck Shipment Accidents/Incidents*, Columbus, Ohio, March 2001.

5.2.1 Scenario 1 Calculation Methodology

For Scenario 1, a release can occur as a result of an accident or other incident that results in a leak en route. Therefore, the total probability of a release for Scenario 1 is determined by adding the probability of a release due to an accident and the probability of a release due to an incident other than an accident that results in a release.

The frequency of a release due to an accident is determined by multiplying the accident rate (1.32×10^{-7} per mile) by the conditional probability of a release given an accident (0.284), multiplied by the conditional probability of no fire given a release (0.973) (see Figure 5-1), which equals 3.65×10^{-8} per mile ($1.32 \times 10^{-7} \times 0.284 \times 0.973$).

Next, the conditional probability of a leak from an en route incident is determined by dividing the number of en route leaks (539) by the total number of accidents and incidents (4,926) minus the number of accidents (257), which equals 0.115 (539 ÷ (4,926 – 257)). Then, the accident frequency (1.32×10^{-7}) was subtracted from the accident/incident frequency (4.092×10^{-7}) to give the incident-only frequency of 2.77×10^{-7} ($4.092 \times 10^{-7} - 1.32 \times 10^{-7}$). The

frequency of an en route leak was then determined by multiplying the incident-only frequency (2.77×10^{-7}) by the conditional probability of an en route leak (0.115) to give a probability of 3.19×10^{-8} per mile ($2.77 \times 10^{-7} \times 0.115$).

Finally, to obtain the total probability for Scenario 1, the two frequencies (3.65×10^{-8} and 3.19×10^{-8}) are summed to give 6.84×10^{-8}, which is the per mile frequency of a release/leak given an accident/incident. This value was then multiplied by the shipping distance (2,000 miles) to give the frequency of an accident/incident with a release/leak per shipment to the TSDF ($6.84 \times 10^{-8} \times 2{,}000 = 1.37 \times 10^{-4}$).

5.2.2 Scenario 2 Calculation Methodology

For Scenario 2, since a fire results primarily from an accident causing a leak or rupture of the fuel tank, only the accident rate of 1.32×10^{-7} is used. (The incident leak rate is not relevant.) The conditional probability of a release given an accident is 0.284, as in Scenario 1. The accident release rate of 0.284 applies to both the hydrolysate being transported and the fuel in the fuel tank. The data offer no easy way to distinguish between the probability of a hydrolysate release versus a fuel release versus both a hydrolysate and a fuel release. Therefore, to be conservative, the accident release rate (0.284) is applied to hydrolysate in Scenario 1 and to hydrolysate and fuel in Scenario 2. Thus, the accident rate is multiplied by the conditional rate of release given an accident (0.284), and by the conditional rate of a fire given a release (0.027) and then by the distance (2,000 miles) for shipment to the TSDF to give the frequency of 2.02×10^{-6} for an accident with a fuel release and a fire per shipment ($1.32 \times 10^{-7} \times 0.284 \times 0.027 \times 2{,}000$).

5.2.3 Calculated Event Frequencies

Table 5-2 summarizes the results of the accident/incident event frequencies per shipment from BGCAPP to the TSDF for the two scenarios.

Table 5-2. Calculated Event Frequencies per Shipment from BGCAPP to TSDF

Event	Scenario 1 Frequency	Scenario 2 Frequency
Accident/incident per shipment	1.37×10^{-4}	2.02×10^{-6}

6 HAZARD AND CONSEQUENCE ASSESSMENT

This TRA evaluates the following types of hazards associated with a tanker truck accident/incident:

- Injuries/fatalities due to exposure (vapor inhalation) to a release/leak of hydrolysate
- Injuries/fatalities due to exposure (vapor inhalation) to a fuel-spill fire
- Injuries/fatalities due to dermal contact with the hydrolysate
- Aquatic impacts due to release of hydrolysate into water bodies

Injuries or fatalities from exposure to a hydrolysate release are based on either the corrosive or the toxicity characteristics of the hydrolysate, as determined from the composition and the toxicity of the individual constituents and of the mixture as a whole. A liquid mixture spill releases the more volatile constituents through evaporation. Exposure to individuals occurs through inhalation of the vapors or through dermal contact with the liquid.

6.1 Exposure via Vapor Inhalation from Spill

Based on the chemical composition of the hydrolysate, as shown in Table 2-1, the following constituents represent organic compounds that could potentially evaporate:

- O-isopropyl methylphosphonofluoridate (GB)
- Tributylamine (TBA)
- O,O'-diisopropyl methylphosphonate (DIMP)
- N,N'-diisopropylurea (DIU)
- Isopropanol (IPA)

IPA is a commercially available household product and is relatively non-toxic from an acute inhalation toxicity perspective. For example, based on the 1-hour published PAC levels,[3] the PAC-1 concentration for IPA is 400 parts per million (ppm) compared to TBA (0.049 ppm) or DIMP (0.37 ppm), or three orders of magnitude higher (less toxic). DIU is even more toxic. Therefore, IPA is not considered in the analysis.

The model used in this TRA was also used for the baseline chemical agent disposal facility quantitative risk assessments (QRAs), as described in BGCAPP Risk Assessment.

[3] https://www.energy.gov/ehss/protective-action-criteria-pac-aegls-erpgs-teels

The QRA evaporation model uses Equation 1 for calculating the evaporation rate of each chemical for outdoor spills:

$$E_m = \frac{3.53 \times 10^3 \, u^{0.78} \, MW \, P_v}{Sc^{0.67} \, d^{0.11} \, P_a \, T} \tag{1}$$

where:

E_m	=	evaporation rate (grams per second-square meter [g/s m^2])
Sc	=	Schmidt number = μ/(Dρ) (dimensionless)
D	=	diffusivity of the vapor in air (square centimeter per second [cm^2/s])
μ	=	dynamic viscosity of air (grams per centimeter second [g/cm-s])
ρ	=	density of air (grams per cubic centimeter [g/cm^3])
u	=	wind speed (meters per second [m/s])
d	=	length of spill surface in the downwind direction (meters)
P_v	=	vapor pressure at temperature T (standard atmosphere [atm])
T	=	temperature at the surface of liquid (kelvin [K])
P_a	=	total ambient pressure at the liquid surface (atm)
MW	=	molecular weight

Equation 1 requires that the diffusivity of the evaporating chemical be calculated. The manual for the ALOHA® model (USEPA 2007) provides the following simple equation (Equation 2) for calculating the diffusivity:

$$D_E = D_{H2O} \sqrt{\frac{MW_{H2O}}{MW_E}} \tag{2}$$

where D_{H2O} and MW_{H2O} are the diffusivity and molecular weight of water (2.4×10^{-5} square meters per second and 18 grams per mole, respectively), and D_E and MW_E are the diffusivity and molecular weight of the evaporating chemical.

The vapor pressure used in Equation 1 is the partial pressure of the chemicals of interest. The vapor pressures of GB at the temperatures of interest are estimated using the Antoine equation (adapted from Penski 1994, as cited in Abercrombie 2003) (Equation 3):

$$P_v = 10^{[A + B/(T - 273.15 + C)]} \tag{3}$$

Where P_v is the vapor pressure (millimeters of mercury [mm Hg]); A, B, and C are GB-specific constants (A = 8.5916, B = -2424.5, C = 273); and T = temperature (K).

The vapor pressures for TBA, DIMP, and DIU are estimated from a combination of Trouton's rule and the Clausius-Clapeyron equation (Castellan 1971) (Equation 4):

$$\ln(P_v) = 19\left(1 - \frac{T_{bp}}{T_0}\right) + 8.5 \ln\left(\frac{T_{bp}}{T_0}\right) \tag{4}$$

where P_v is the vapor pressure of the compound in pure form (atm), T_{bp} is the boiling point (K), and T_0 is the reference temperature (298 K).

To calculate the partial pressure of each chemical of interest, the mole fraction of each chemical is calculated using Raoult's law (Equation 5). To use Raoult's law, the mole fraction of each constituent X_i is first determined based on its concentration (weight fraction) in the mixture and its molecular weight:

$$X_i = \frac{\frac{W_i}{MW_i}}{\sum_{i=0}^{n} \frac{W_i}{MW_i}} \tag{5}$$

where W_i and MW_i are the weight fraction and molecular weight for each constituent in the mixture.

The partial pressure of each constituent in the mixture is then calculated using Equation 6:

$$P_{vm,i} = P_{vp,i}\, X_i \tag{6}$$

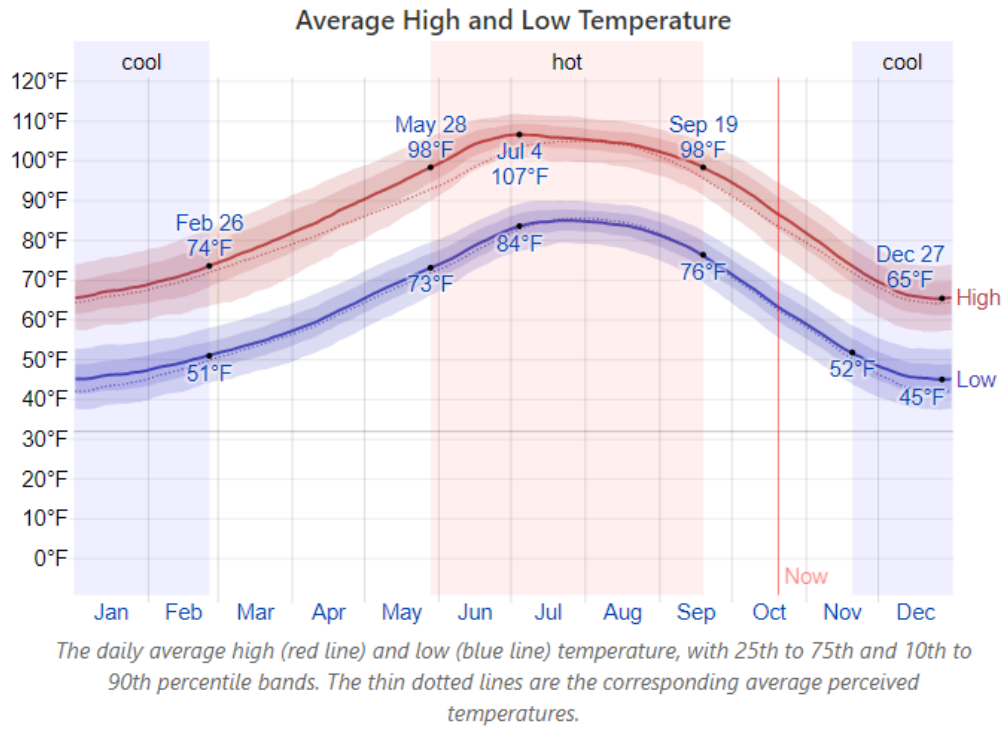
where $P_{vm,i}$ is partial pressure of constituent *i* in the mixture, and $P_{vp,i}$ is the vapor pressure of constituent *i* in pure form. The calculated partial pressures are substituted for P_v in Equations 1 and 2.

Equations 1 through 6 are used to calculate the evaporation rates for each constituent of the hydrolysate under consideration. While the exact proportions of the various constituents in the vapor release vary with temperature, calculations show that, overall, TBA is the dominant contributor to the evaporative release in terms of mass, followed by DIMP.

Since the evaporation rate estimate using Equation 1 requires the temperature of the surface of the liquid and the wind speed, these parameters were determined using meteorological data from a worst-case (relative to temperature) location in the United States (Phoenix, Arizona). Figures 6-1 and 6-2 show the average temperature and wind speed in the Phoenix area. The highest average daytime temperature is 107°F (41.7°C). The corresponding average nighttime temperature is 84°F (29°C) during the same period. The wind speed corresponding to the time of the highest average temperature is approximately 7.0 miles per hour (from Figure 6-2) (or 3.1 m/s).[4]

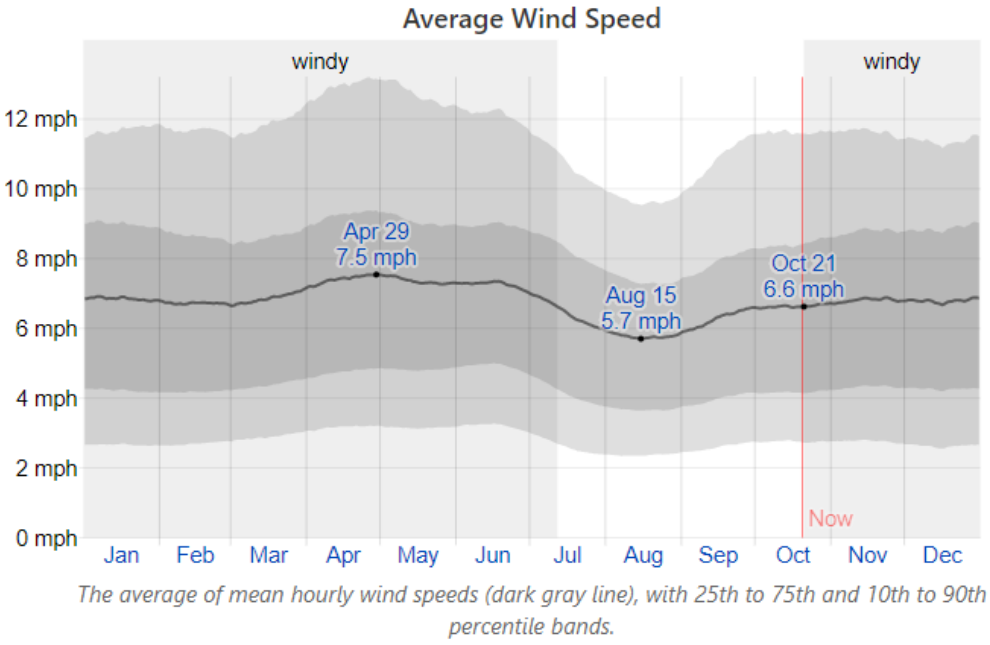
Table 6-1 summarizes the results showing the evaporated masses of each constituent.

[4] Calculations show that 3.1 m/s is conservative. Using a lower wind speed produces a lower downwind hazard because of reduced evaporation.



Source: www.weatherspark.com

Figure 6-1. Average Temperatures in Phoenix, Arizona



Source: www.weatherspark.com

Figure 6-2. Average Wind Speeds in Phoenix, Arizona

Table 6-1. Calculated Mass of Chemical Released Due to Evaporation from 5,000-gallon Hydrolysate Spill

Liquid Temp. (°C)	Wind Speed (m/s)	GB (g)	TBA (g)	DIMP (g)	DIU (g)
41.7	3.1	2.40×10^{-2}	1.25×10^{2}	8.41×10^{1}	1.0×10^{0}
29	3.1	1.19×10^{-2}	5.32×10^{1}	3.61×10^{1}	3.79×10^{-1}

Notes:

DIMP O,O'-diisopropyl methylphosphonate
DIU N,N'-diisopropylurea
g grams
GB O-isopropyl methylphosphonofluoridate
m/s meters per second
TBA tributylamine

The calculated mass of the chemicals from Table 6-1 is then input into D2PC, an atmospheric dispersion model. D2PC is a Gaussian plume model that calculates the distance to specified exposures or concentrations. To determine the potential health effects from exposure to a vapor release, the model calculates the downwind ground distance to reach the 30-minute and 2-hour AEGL-1/PAC-1 concentrations, which are compared to Table 4-3 to determine the hazard consequence. (It was not necessary to calculate the corresponding AEGL-2/PAC-2 and AEGL-3/PAC-3 distances based on the results of the AEGL-1/PAC-1 distances).

As with any computer model, there are a number of variables that must be input in order to model a specific accident scenario. In D2PC, these inputs are referred to as *dispersion control characteristics*. Table 6-2 lists the control characteristics that represent worst-case conditions for the evaporation scenario.

The D2PC model was run at the same temperatures and wind speed (as shown in Table 6-1), using D stability factor for daytime and F stability factor for nighttime release in order to generate the AEGL-1/PAC-1 distances. Table 6-3 summarizes the results. The results indicate that the criteria shown in Table 4-3 for a *Negligible* hazard severity (2-hour AEGL-1/PAC-1 less than 200 meters and 30-minute AEGL-1/PAC-1 less than 50 meters) are met for both daytime and nighttime transport.

Table 6-2. D2PC Dispersion Control Characteristics for Evaporative Release

Control Characteristic	Input Values Used	Rationale
Location	NDF	Not defined because location is not fixed
Height of Mixing Layer	400 meters	Daytime mixing layer height based on average conditions for summer
	250 meters	Nighttime mixing layer height is lower than daytime. A lower mixing height results in a greater ground level concentration.
Munition Type	NON	Non-munition for hydrolysate
Agent Type	GB	Agent GB
	NA	Non-agent chemical
Release Type	EVP	Evaporation from an unconfined spill
Stability Type	D	D stability for worst-case daytime release
	F	F stability for worst-case nighttime release
Wind Speed	3.1 m/s	From Figure 6-2, corresponding to time of highest average temperature (7.0 miles per hour = 3.1 m/s)
Spill or Airborne Source	mg	Iteratively determined such that the D2PC calculated airborne mass equals the evaporated mass in Table 6-1.
Surface Temperature	41.7°C	Based on highest average daytime temperature (107°F = 41.7°C) from Figure 6-1
	29°C	Based on nighttime average low temperature corresponding to the highest daytime temperature period, from Figure 6-1 (29°C = 84°F)
Atmospheric Pressure	760 mm Hg	Default sea level
Surface Code	CON	Concrete is worst case as compared to gravel or other surface
Release Duration	120 minutes	Corresponds to time for cleaning up the spill

Table 6-2. D2PC Dispersion Control Characteristics for Evaporative Release

Control Characteristic	Input Values Used	Rationale
FMW, FMV, VAP, BPT	TBA: 185.355, 238.25, 2.35×10^{-4} (9.61×10^{-5}), 488	• FMW = molecular weight • FMV = molecular volume (FMW/density in g/cm^3) [a] • VAP = vapor pressure (mm Hg) at 41.7°C. (Value in parenthesis is for 29°C) • BPT = boiling point (K) [b]
	DIMP: 180.184, 182.93, 1.61×10^{-4} (6.64×10^{-5}), 487.5	
	DIU: 144.218, 177.17, 2.23×10^{-6} (8.09×10^{-7}), 538.4	
IMA	1	Method of assessment control
NCI	2	Number of concentrations of interest
CI	GB: 0.002 0.004	30-minute and 2-hour AEGL-1 (for GB)/PAC-1 concentrations in ascending order
	TBA: 0.185 0.466	
	DIMP: 1.35 3.40	
	DIU: 0.012 0.031	

Notes:

a Density data were obtained from Safety Data Sheets for TBA, DIMP, and DIC (DIC was used due to lack of information on DIU, as discussed in Appendix C):
- ThermoFisher Scientific. 2018. *Tributylamine.* Safety Data Sheet. Revision 4. January.
- ThermoFisher Scientific. 2018. *Diisopropyl methylphosphonate*. Safety Data Sheet. Revision 3. January.
- Kemilab. 2018. *N,N'-Diisopropylcarbodiimide*. Safety Data Sheet. Version 9. May.

b Boiling point data obtained from www.lookchem.com

AEGL Acute Exposure Guideline Level
DIC diisopropylcarbodiimide
DIMP O,O'-diisopropyl methylphosphonate
DIU N,N'-diisopropylurea
g/cm^3 grams per cubic centimeter
GB O-isopropyl methylphosphonofluoridate
K kelvin
m/s meters per second
mg milligrams
mm Hg millimeters of mercury
PAC Protective Action Criteria
TBA tributylamine

Table 6-3. D2PC Modeling Results for 5,000-gallon Hydrolysate Spill

Chemical	Surface Temp. (°C)	Wind Speed (m/s)	Atmospheric Stability Factor	Mass Released (g)	2-hour PAC-1 Distance (m)	30-minute PAC-1 Distance (m)
GB	41.7	3.1	D (daytime)	2.40×10^{-2}	23	15
	29	3.1	F (nighttime)	1.19×10^{-2}	17	10
TBA	41.7	3.1	D (daytime)	1.25×10^{2}	0	0
	29	3.1	F (nighttime)	5.32×10^{1}	0	0
DIMP	41.7	3.1	D (daytime)	8.41×10^{1}	0	0
	29	3.1	F (nighttime)	3.61×10^{1}	0	0
DIU	41.7	3.1	D (daytime)	1.0×10^{0}	0	0
	29	3.1	F (nighttime)	3.79×10^{-1}	0	0

Notes:

DIMP O,O'-diisopropyl methylphosphonate
DIU N,N'-diisopropylurea
g grams
GB O-isopropyl methylphosphonofluoridate
m meters
m/s meters per second
PAC Protective Action Criteria
TBA tributylamine

6.2 Exposure via Vapor Inhalation from Fire

Fires occur in a small percentage of accidents involving hazmat releases. In the case of hydrolysate transport, the fire is unlikely to be sustained because the fuel source (truck fuel) would quickly deplete and the fire would be extinguished. Even if the hydrolysate were subjected to a fire, the liquid would heat very slowly and would reach a maximum at the boiling point of water.

This TRA evaluates the following two cases as worst-case scenarios:

- Case 1: The hydrolysate remains in the tanker and the burning fuel heats up the hydrolysate to its boiling point.
- Case 2: The hydrolysate is spilled from the tanker and the burning fuel is intermixed with the spilled hydrolysate

6.2.1 Case 1

The pressure increase in the tanker is approximated using the following process. Since water is the predominant component (91.7%) in the hydrolysate compared to the organic compounds (4.7%), it is assumed that the air space in the tanker is mostly water vapor. Although water vapor does not behave like an ideal gas,[5] the ideal gas equations can still be used to approximately estimate pressure inside the tanker using Equation 7.

$$P_1/T_1 = P_2/T_2 \tag{7}$$

where:

- P_1 = Initial pressure = 14.7 pounds per square inch absolute (psia) (atmospheric)
- P_2 = Final pressure
- T_1 = Initial temperature = 274 K (1°C, worst-case temperature of the tank contents)
- T_2 = Final temperature = 382 K (109°C is the boiling point of water at an estimated higher pressure of 20 psia[6])

Solving for P_2 gives 20.5 psia. The pressure increase equals 5.8 psig (20.5 – 14.7).

The MAWP of a DOT-412 tanker is between 5 to 25 psig (see Section 3.2). The pressure relief valve activates at 1.5 times the MAWP. Based on the lower MAWP of 5 psig, the pressure relief valve would activate at 1.5 times 5 psig, or 7.5 psig. A worst-case pressure increase of 5.8 psig will not cause the pressure relief device to release any vapor.

6.2.2 Case 2

The standard fuel tank capacity for large trucks is between 120 and 150 gallons.[7] Long-haul trucks may carry a fuel tank on each side. It is not likely that this amount of fuel could be intermixed fully with the 5,000 gallons of spilled hydrolysate. Therefore, as a worst case, it is assumed that only half of the hydrolysate is exposed to the burning fuel. The other half will be subject only to evaporation. In addition, because of the small quantity, it is assumed that a fire will be 30 minutes in duration. Most of the organic vapors released in the fire will be consumed by the fire. Based on the criteria used in the WebPuff dispersion model (WebPuff Version 5.4) for GB, it is estimated that 90% of the mass released will be consumed, and only 10% will be released.

The burning fuel will float on top of the spilled hydrolysate due to its lower specific gravity. The temperature of the spilled hydrolysate will rise to 100°C. Therefore, the evaporative release is

[5] https://chemistry.stackexchange.com/questions/103724/can-ideal-gas-law-be-applied-to-water-vapour
[6] https://www.engineeringtoolbox.com/boiling-point-water-d_926.html
[7] https://www.truckloadindexes.com/data-commentary/how-many-gallons-does-it-take-to-fill-up-a-big-rig

modeled at 100°C for the portion of the hydrolysate exposed to the fire. The other portion is modeled at the temperatures determined in Table 6-1 (41.7°C and 29°C). Table 6-4 provides the results showing the evaporated masses of each constituent (IPA was not considered in the analysis, as explained in Section 6.1). Table 6-5 lists the D2PC input parameters used for the fire scenario. Table 6-6 provides the results of the fire and evaporation dispersion modeling.

Table 6-4. Calculated Mass of Chemical Released Based on 2,500-gallon Hydrolysate Spill

Liquid Temp. (°C)	Wind Speed (m/s)	GB (g)	TBA (g)	DIMP (g)	DIU (g)
100	3.1	1.63×10^{-1}	1.24×10^{3}	8.33×10^{2}	1.61×10^{1}
41.7	3.1	1.20×10^{-2}	6.24×10^{1}	4.21×10^{1}	5.02×10^{-1}
29	3.1	5.95×10^{-3}	2.66×10^{1}	1.80×10^{1}	1.89×10^{-1}

Notes:

DIMP O,O'-diisopropyl methylphosphonate
DIU N,N'-diisopropylurea
g grams
GB O-isopropyl methylphosphonofluoridate
m/s meters per second
TBA tributylamine

Table 6-5. D2PC Dispersion Control Characteristics for Fire Case 2 Scenario

Control Characteristic	Input Values Used	Rationale
Location	NDF	Not defined because location is not fixed
Height of Mixing Layer	400 meters	Daytime mixing layer based on average conditions for summer
	250 meters	Nighttime mixing layer height is lower than daytime. A lower mixing height results in a greater ground level concentration
Munition Type	NON	Non-munition for hydrolysate
Agent Type	GB	Agent GB
	NA	Non-agent chemical
Release Type	FIR	Fire
	EVP	Evaporation from an unconfined spill

Table 6-5. D2PC Dispersion Control Characteristics for Fire Case 2 Scenario

Control Characteristic	Input Values Used	Rationale
Stability Type	D	D stability for worst-case daytime release
	F	F stability for worst-case nighttime release
Wind Speed	3.1 m/s	From Figure 6-2, corresponding to time of highest average temperature (7.0 miles per hour = 3.1 m/s)
Surface Temperature	41.7°C	Based on highest average daytime temperature (107°F = 41.7°C) from Figure 6-1
	29°C	Based on nighttime average temperature corresponding to the highest daytime temperature period, from Figure 6-1 (29°C = 84°F)
NQI, Q (mg), TQ (min)	Fire: 1, Q, 30	Number of source intervals = 1. Q = 10% of mass release based on Table 6-4. Duration of release = 30 minutes due to limited quantity of fuel.
	Evaporation: 1, Q, 120	Number of source intervals = 1. Q = iteratively determined such that the D2PC calculated airborne mass equals the evaporated mass in Table 6-4. Duration of release = 120 minutes.
Atmospheric Pressure	760 mm Hg	Default sea level
Surface Code	CON	Concrete is worst case as compared to gravel or other surface.
FMW, FMV, VAP, BPT	TBA: 185.355, 238.25, 2.35×10^{-4} (9.61×10^{-5}), 488	• FMW = molecular weight • FMV = molecular volume (FMW/density in g/cm^3) [a] • VAP = vapor pressure (mm Hg) at 41.7°C. (Value in parenthesis is for 29°C.) • BPT = boiling point (K) [b]
	DIMP: 180.184, 182.93, 1.61×10^{-4} (6.64×10^{-5}), 487.5	
	DIU: 144.218, 177.17, 2.23×10^{-6} (8.09×10^{-7}), 538.4	
Output Control Code	1	Lists diffusion parameters in the output
Heat Released	238,846 cal/s (1 MW) [c]	A low heat release value results in lower plumes and, therefore, higher ground level concentrations.
Cloud Radius	Not applicable	Default
IMA	1	1 = Concentration (mg/m^3) for evaporation case 0 = Dosage (mg-min/m^3) for fire case
	0	
NCI	2	Number of concentrations of interest
NDI	2	Number of dosages of interest

Table 6-5. D2PC Dispersion Control Characteristics for Fire Case 2 Scenario

Control Characteristic	Input Values Used	Rationale
CI	GB: 0.002 0.004	Concentrations for evaporation case: 30-minute and 2-hour AEGL-1 (for GB)/PAC-1 concentrations in ascending order
	TBA: 0.185 0.466	
	DIMP: 1.35 3.40	
	DIU: 0.012 0.031	
DI	GB: 0.06 0.12	Dosages for fire case; Dosage = concentration × time
	TBA: 5.55 13.98	
	DIMP: 40.5 102	
	DIU: 0.36 0.93	

Notes:

a Density data were obtained from Safety Data Sheets for TBA, DIMP, and DIC (DIC was used due to lack of information on DIU, as discussed in Appendix C):
- ThermoFisher Scientific. 2018a. *Tributylamine.* Safety Data Sheet. Revision 4. January.
- ThermoFisher Scientific. 2018b. *Diisopropyl methylphosphonate*. Safety Data Sheet. Revision 3. January.
- Kemilab. 2018. *N,N'-Diisopropylcarbodiimide*. Safety Data Sheet. Version 9. May.

b Boiling point data obtained from www.lookchem.com

c A heat release rate of 1 megawatt (MW) was selected to represent a typical truck fire. Studies have shown that heat release rates could be over 100 MW depending on the type and amount of material being transported. (Reference: Lönnermark, A. and Ingason, H., 2004. "Recent Achievements Regarding Heat Release and Temperatures during Fires in Tunnels." *First International Symposium and Safe and Reliable Tunnels, Innovative European Achievements.* Prague, Czech Republic.) Choosing a lower heat release rate is conservative because it reduces the rise height of the buoyant plume.

AEGL	Acute Exposure Guideline Level
cal/s	calories per second
DIC	diisopropylcarbodiimide
DIMP	O,O'-diisopropyl methylphosphonate
DIU	N,N'-diisopropylurea
g/cm^3	grams per cubic centimeter
GB	O-isopropyl methylphosphonofluoridate
K	kelvin
m/s	meters per second
mg	milligrams
mg/m^3	milligrams per cubic meter
$mg\text{-}min/m^3$	milligram-minutes per cubic meter
mm Hg	millimeters of mercury
PAC	Protective Action Criteria
TBA	tributylamine

Table 6-6. D2PC Modeling Results for Fire Case 2 Scenario

Chemical	Release	Surface Temp. (°C)	Wind Speed (m/s)	Atmospheric Stability Factor	Mass Released (g)	2-hour PAC-1 Distance (m)	30-minute PAC-1 Distance (m)
GB	Fire	41.7	3.1	D (daytime)	1.63×10^{-2}	0	0
	Fire	29	3.1	F (nighttime)	1.63×10^{-2}	0	0
	Evaporation	41.7	3.1	D (daytime)	1.20×10^{-2}	17	11
	Evaporation	29	3.1	F (nighttime)	5.95×10^{-3}	12	7
TBA	Fire	41.7	3.1	D (daytime)	1.24×10^{2}	0	0
	Fire	29	3.1	F (nighttime)	1.24×10^{2}	0	0
	Evaporation	41.7	3.1	D (daytime)	6.24×10^{1}	0	0
	Evaporation	29	3.1	F (nighttime)	2.66×10^{1}	0	0
DIMP	Fire	41.7	3.1	D (daytime)	8.33×10^{1}	0	0
	Fire	29	3.1	F (nighttime)	8.33×10^{1}	0	0
	Evaporation	41.7	3.1	D (daytime)	4.21×10^{1}	0	0
	Evaporation	29	3.1	F (nighttime)	1.80×10^{1}	0	0
DIU	Fire	41.7	3.1	D (daytime)	1.61×10^{0}	0	0
	Fire	29	3.1	F (nighttime)	1.61×10^{0}	0	0
	Evaporation	41.7	3.1	D (daytime)	5.02×10^{-1}	0	0
	Evaporation	29	3.1	F (nighttime)	1.89×10^{-1}	0	0

Notes:

DIMP O,O'-diisopropyl methylphosphonate
DIU N,N'-diisopropylurea
g grams
GB O-isopropyl methylphosphonofluoridate
m meters
m/s meters per second
PAC Protective Action Criteria
TBA tributylamine

The results indicate that, for the fire scenario, the chemical concentration does not reach the AEGL-1/PAC-1 at any distance due to the plume rise and atmospheric dispersion of the release. For the evaporation case, the hazard severity is *Negligible* (2-hour AEGL-1/PAC-1 is less than 200 meters and 30-minute AEGL-1/PAC-1 is less than 50 meters).

Based on the calculated results, the criteria shown in Table 4-3 for a *Negligible* hazard severity (2-hour AEGL-1/PAC-1 less than 200 meters and 30-minute AEGL-1/PAC-1 less than 50 meters) are met for both daytime and nighttime transport.

6.3 Exposure via Dermal Contact

Impacts of hydrolysate exposure from dermal contact are based on pH. The amount of sodium hydroxide present in the hydrolysate, as shown in Table 2-1, is 0.76 weight percent [$100 \times (7.64 \times 10^{-3})/1 = 0.76$]. Therefore, the hydrolysate is considered to be akin to a less than 1 weight percent solution of sodium hydroxide. According to National Institute for Occupational Safety and Health (NIOSH) Skin Notation Profiles (2011), a 1 percent aqueous solution of sodium hydroxide has a pH of about 13. Concentrations equal to or greater than this are considered corrosive to the skin. Less concentrated solutions of sodium hydroxide, although not corrosive, can be irritating to the skin.

In rabbits, a 4-hour exposure to a 2 percent solution of sodium hydroxide caused skin corrosion, whereas a 1 percent solution caused no damage (Vernot et al 1977). A 2 percent sodium hydroxide solution produced mild to moderate irritation for 75 percent of the 42 male volunteers (Willis et al 1988). More dilute solutions (for example, 0.5 percent or less) may be irritating to the skin but the transition point between corrosivity and irritation is a function of duration of skin contact.

Drivers will be required to keep the following in their individual gear bags:

- NIOSH-approved respirator with organic vapor cartridges
- Safety goggles or glasses
- Steel-toed shoes
- Hard hats

In addition, the truck spill kits and driver safety equipment will include, among other equipment, the following items:

- Chemical-resistant gloves
- Chemical-resistant coveralls
- Chemical-resistant show covers or “booties”

In the event of a spill, the driver training and spill/safety equipment will reduce the probability or severity of any dermal exposure from a hydrolysate spill.

Based on the Vernot and Willis studies, the hydrolysate concentration of the sodium hydroxide of 0.76 wt. percent, and the driver training and spill/safety equipment, it is concluded that the hydrolysate will not present a hazard that would lead to "one or more injuries or illnesses resulting in lost time." The likely hazard would meet the criteria of "one or more injuries or illnesses requiring first aid or medical treatment," which falls under a *Negligible* hazard severity per Table 4-2.

6.4 Aquatic Impacts

If the release were to occur in an area leading to a water body, the toxic chemicals in the hydrolysate could potentially impact freshwater organisms. The Edgewood Chemical Biological Center conducted an aquatic toxicity screening of two hydrolysates (ACWA GB hydrolysate[8] and Blue Grass GB hydrolysate) (ECBC 2009c). Both hydrolysates were neutralized to a pH of approximately 8.0 to negate the effects of the sodium hydroxide corrosivity. The ACWA GB hydrolysate was screened using freshwater organism *Ceriodaphnia dubia* in a 7-day survival and reproduction assay and bioluminescent bacterium *Vibro fisheri* in the microtox (MTX) assay. The Blue Grass GB hydrolysate was screened using the MTX assay only. Based on the study, the ACWA GB hydrolysate received a toxicity ranking of *Relatively Harmless (*based on *Ceriodaphnia* and MTX data). The Blue Grass hydrolysate received a toxicity ranking of *Practically Non-Toxic* (based on MTX data). Based on the aquatic toxicity, the toxic organic chemicals in the hydrolysate are not a significant threat to aquatic organisms.

6.5 Risk Evaluation

The event frequencies given in Table 5-2 are on a per-shipment basis. In order to determine the total frequency and consequence of an accident or incident during hydrolysate transport from BGCAPP over the life of the transport operation, it is necessary to multiply each by the total number of planned shipments.

The number of shipments is determined by dividing the estimated GB hydrolysate to be shipped offsite (1,020,000 gallons) (Hullman 2020) by the tanker truck capacity. Tanker truck capacities for chemical transport are usually about 5,000 gallons. This capacity translates into 204 shipments.

Table 6-7 summarizes the results of the total frequencies and consequences. Table 6-8 summarizes the information from Table 6-7 in qualitative terms, in accordance with Tables 4-1,

[8] ACWA GB-hydrolysate (GB/NaOH GB-8072) was produced using 7.5% GB (Sarin, Chemical Agent Standard Analytical Reference Material [CASARM] grade CAS#107-44-8; stabilized with TBA) in 6% sodium hydroxide.

4-2, and 4-3. For all scenarios, the consequence is considered to be *Negligible.* In accordance with the Qualitative Risk Evaluation Matrix (Figure 4-1), the results indicate that the risk level is *Low.*

Table 6-7. Total Frequencies and Consequence Results

Scenario	Total Frequency [1a]	Consequence [2b]
1 – Accident/Incident Release/Leak	2.79×10^{-2}	*Inhalation:* • 2-hour AEGL-1/PAC-1 hazard distance < secondary control zone distance of 200 meters • 30-minute AEGL-1/PAC-1 hazard distance < initial isolation zone distance of 50 meters *Dermal:* One or more injuries or illnesses requiring first aid or medical treatment
2 – Accident with Fuel Release and Fire	4.13×10^{-4}	*Inhalation:* • 2-hour AEGL-1/PAC-1 hazard distance < secondary control zone distance of 200 meters • 30-minute AEGL-1/PAC-1 hazard distance < initial isolation zone distance of 50 meters

Notes:

a Results are based on 204 shipments multiplied by the frequencies in Table 5-2.
b The concentration of GB and relevant chemicals does not reach the 30-minute/2-hour AEGL-1/PAC-1 concentrations at 50/200 meters, respectively.

AEGL Acute Exposure Guideline Level
PAC Protective Action Criteria

Table 6-8. Risk Level Determination

Scenario	Frequency	Consequence	Risk
1 – Accident/Incident Release/Leak	B – Probable or Likely	IV – Negligible	Low
2 – Accident with Fuel Release and Fire	D – Seldom or Remote	IV – Negligible	Low

7 RISK MITIGATION

The authority for acceptance of the risk lies with the BGCAPP Site Project Manager, and any risk mitigation efforts or required actions will be determined by the BGCAPP Site Project Manager.

8 SUMMARY AND CONCLUSIONS

An evaluation of the risk of transporting treated GB hydrolysate from BGCAPP to a TSDF was conducted. The regulations for hazmat classification, handling, loading, and transport were reviewed for safe transport of the hydrolysate in tanker trucks. A TRA was conducted for the BGCAPP GB hydrolysate using the Army approach by determining accident frequency and event consequences for (1) an accident/incident with a release/leak and (2) an accident with a release and a fuel fire. Overall, the results indicate that the transportation risk is *Low.*

APPENDIX A. ABBREVIATIONS

ACWA	Assembled Chemical Weapons Alternatives
AEGL	Acute Exposure Guideline Level
atm	standard atmosphere
BGCAPP	Blue Grass Chemical Agent-Destruction Pilot Plant
CASARM	Chemical Agent Standard Analytical Reference Material
CDL	commercial driver's license
CFR	Code of Federal Regulations
cm^2/s	square centimeters per second
DA PAM	Department of the Army Pamphlet
DIC	diisopropylcarbodiimide
DIMP	O,O'-diisopropyl methylphosphonate
DIU	N,N'-diisopropylurea
DOT	Department of Transportation
FR	Federal Register
g/cm^3	grams per cubic centimeter
g/cm-s	grams per centimeter second
$g/s\ m^2$	grams per second-square meter
GB	sarin; O-isopropyl methylphosphonofluoridate
hazmat	hazardous material
HAZWOPER	Hazardous Waste Operations and Emergency Response
K	kelvin
LD_{50}	median lethal dose
m/s	meters per second
MAWP	maximum allowable working pressure
mg/m^3	milligrams per cubic meter
mm Hg	millimeters of mercury
MTX	microtox
NIOSH	National Institute for Occupational Safety and Health
OSHA	Occupational Safety and Health Administration
ppm	parts per million
psia	pounds per square inch absolute
psig	pounds per square inch gauge
QRA	quantitative risk assessment
SCWO	supercritical water oxidation
TBA	tributylamine
TEEL	Temporary Emergency Exposure Limits
TRA	transportation risk assessment
TSDF	treatment, storage, and disposal facility

APPENDIX B. REFERENCES AND SOURCE MATERIALS

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APPENDIX C. DERIVATION OF 2-HOUR AND 30-MINUTE PROTECTIVE ACTION CRITERIA (PAC) CONCENTRATIONS

PAC concentrations for chemicals are established for a duration of 1 hour (https://www.energy.gov/ehss/protective-action-criteria-pac-aegls-erpgs-teels). For this transportation risk assessment (TRA), PAC concentrations were needed for two exposure durations: 30 minutes and 2 hours.

Data for chemical toxicity of hazardous compounds often can be plotted using an equation (NRC 2003) of the following form:

$$C^n t = k \tag{C-1}$$

where:

C = concentration for an observed toxic endpoint
t = exposure duration (minutes)
n = exponent determined based on the toxicity data
k = constant

The approach outlined in this appendix is consistent with the default approach used in Acute Exposure Guideline Level (AEGL) and Temporary Emergency Exposure Limits (TEEL) development.

Assumption: $C^n t$ = constant, where n=1 for times greater than 1 hour and n=3 for times less than 1 hour (conservative).

The *n* values for many vapors and gases are derived from experimentally determined miosis and lethality data, and range from 0.8 to 3.5 (NRC 2003). For example, for chemical agents, the *n* value derived is 2 for extrapolation to a time less than 1 hour. Using a higher *n* value is conservative as it results in a lower derived concentration. Therefore, this TRA uses an *n* value of 3 for the derivation of the 30-minute concentration.

Table C-1 shows the calculated values of $C^n t$ for both cases for tributylamine (TBA). As an example, $k = (0.37)^3 \times 60 = 3.039$.

Table C-1. Calculation of the Constant k for TBA

Calculation Expression	PAC-1 (mg/m^3)	PAC-2 (mg/m^3)	PAC-3 (mg/m^3)
Established 1-hour PAC value [a]	0.37	4.1	24
$k = C^n t$ (n=3)	3.039	4,135.3	829,440
$k = C^n t$ (n=1)	22.2	246	1,440

Notes:

a Established values from https://www.energy.gov/ehss/protective-action-criteria-pac-aegls-erpgs-teels, converted from parts per million to mg/m^3.

mg/m^3 milligrams per cubic meter
PAC Protective Action Criteria
TBA tributylamine

Using the calculated value of k, the PAC concentration for 30-minute exposure is:

$C = (k/t)^{(1/n)}$

As an example, $C = (3.039/30)^{(1/3)} = 0.466$.

Table C-2 shows the calculated 30-minute and 2-hour PAC values for TBA.

Table C-2. Calculated 30-minute and 2-hour PAC Values for TBA

Calculation Expression	30-minute Exposure Value (mg/m^3)			2-hour Exposure Value (mg/m^3)		
	PAC-1	PAC-2	PAC-3	PAC-1	PAC-2	PAC-3
$C= (k/t)^{(1/n)}$	0.466	5.17	30.2	0.185	2.05	12.0

Notes:

mg/m^3 milligrams per cubic meter
PAC Protective Action Criteria

Check if results match the k value:

$k = C^n t = 0.466^3 \times 30 = 3.039$, which matches the value in Table C-1.

Similarly, Table C-3 summarizes the 30-minute and 2-hour PAC values for O,O'-diisopropyl methylphosphonate (DIMP).

Table C-3. Calculated 30-minute and 2-hour PAC Values for DIMP

Established 1-hour Exposure Value [a] (mg/m^3)			Calculated 30-minute Exposure Value (mg/m^3)			Calculated 2-hour Exposure Value (mg/m^3)		
PAC-1	PAC-2	PAC-3	PAC-1	PAC-2	PAC-3	PAC-1	PAC-2	PAC-3
2.7	30	180	3.40	37.80	226.8	1.35	15	90

Notes:

a Established values from https://www.energy.gov/ehss/protective-action-criteria-pac-aegls-erpgs-teels.

mg/m^3 milligrams per cubic meter
PAC Protective Action Criteria

For N,N'-diisopropylurea (DIU), established 1-hour PAC values were not available; therefore, PAC values were estimated. DIU is formed from the hydrolysis of diisopropylcarbodiimide (DIC) (Munro et al. 1999). Therefore, DIU can be assumed to have similar chemical characteristics to DIC. However, DIC is more toxic than DIU (Munro et al. 1999). The median lethal dose (LD_{50}) value for DIU is not available, so the more conservative LD_{50} value for DIC [36 milligrams (intravenous, mouse)] (Kemilab 2018) was used. The PAC value for DIU was estimated based on the ratio of the LD_{50} value of DIU to the LD_{50} value of TBA (560 milligrams per kilogram, per Munro et al. 1999) multiplied by the PAC value of TBA.

DIU PAC-1 = (DIU LD_{50})/(TBA LD_{50}) × (TBA PAC-1) = 36/540 × 0.37 = 0.025 milligrams per cubic meter (mg/m^3)

DIU PAC-2 = (DIU LD_{50})/(TBA LD_{50}) × (TBA PAC-2) = 36/540 × 4.1 = 0.273 mg/m^3

DIU PAC-3 = (DIU LD_{50})/(TBA LD_{50}) × (TBA PAC-3) = 36/540 × 24 = 1.6 mg/m^3

Using these estimated DIU PAC values in lieu of established 1-hour PAC values, the same procedure used for TBA and DIMP was performed to estimate the 30-minute and 2-hour PAC values for DIU. Table C-4 summarizes the calculated values.

Table C-4. Calculated 30-minute and 2-hour PAC Values for DIU

Derived 1-hour Exposure Value (mg/m^3)			Calculated 30-minute Exposure Value (mg/m^3)			Calculated 2-hour Exposure Value (mg/m^3)		
PAC-1	PAC-2	PAC-3	PAC-1	PAC-2	PAC-3	PAC-1	PAC-2	PAC-3
0.025	0.273	1.6	0.031	0.344	2.016	0.012	0.137	0.80

Notes:

mg/m^3 milligrams per cubic meter
PAC Protective Action Criteria