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Storage of Emerging Fuels for the Army

by David R. Baker, Ana I. Alvarez, and Jonathan A. Boltersdorf

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DEVCOM Army Research Laboratory

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14. ABSTRACT The U.S. Army is increasingly focused on diversifying its energy sources to enhance operational flexibility and resiliency. Fuels, such as hydrogen, methanol, ethanol, and ammonia, offer promising solutions for distributed operations that cannot rely only on bulk logistic fuel resupply. However, storing these fuels poses significant technical challenges due to their unique properties and handling requirements. This report provides regulations, guidelines, and best practices for storing emerging fuels for distributed operations, enabling the Army to safely and efficiently store and transport these fuels in various operational environments. By addressing the storage challenges associated with emerging fuels, this project will help the Army accelerate the adoption of these fuels, which is critical for the Army's success in future operating environments.					
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Executive Summary

As the U.S. Army continues to explore emerging fuel sources to increase its capability in future distributed operations and enhance resilience against disrupted sustainment, the safe storage and handling of these fuels has become a critical concern. These emerging fuels, such as hydrogen, methanol, ethanol, and ammonia, can be produced at or near the point of need and offer numerous benefits, including strengthening operational resilience and improved energy security. However, the unique properties and characteristics of these fuels also pose distinct challenges and risks, particularly in terms of safety. In response to these challenges, this report provides a comprehensive overview of the regulations, guidelines, and best practices for the storage of emerging fuels, with a focus on ensuring the safe handling, storage, and use of these fuels in Army operations. Ultimately, this report reinforces the critical importance of careful planning and design in the storage and handling of emerging fuels, as the Army's ability to safely and effectively integrate these emerging fuels will be paramount to achieving its operational and energy security goals.

1. Introduction

The U.S. Army's ability to maintain overmatch and protect national interests relies heavily on its access to reliable and efficient energy sources. As the Army continues to modernize and transform to meet the challenges of a rapidly changing global security environment, the importance of energy has never been more critical.

The DoD's *Task Force on Energy Systems for Forward/Remote Operating Bases*¹ highlighted the need for the Army to reduce its dependence on fossil fuels and develop more resilient and secure energy systems because of projected disruptions to supply lines impacting the ability to perform bulk fuel resupply. This imperative was reinforced by subsequent Army strategy documents, including the *Army Modernization Strategy: Investing in the Future*.² Additionally, the *Army Multi-Domain Transformation: Ready to Win in Competition and Conflict*³ emphasized the need for the Army to leverage new technologies and energy sources to enhance its operational effectiveness and reduce its logistical footprint. The Army's projected future, as outlined in documents such as *Powering the U.S. Army of the Future*⁴ and the *USD(R&E) Technology Vision for an Era of Competition*,⁵ highlights the importance of developing and integrating new fuel options and energy technologies into its operations to reduce the number of risky fuel convoys. Most recently, the *Department of Defense Operational Energy Strategy*⁶ underscored the importance of energy as a critical component of military operations, and the need for the Army to develop more efficient and resilient energy systems to support its missions.

In this context, the point-of-need generation and storage of emerging fuels are critical components of the Army's energy strategy. If the Army adds new energy sources to its portfolio, such as hydrogen (H₂), methanol, ethanol, and ammonia, it must develop the infrastructure and protocols necessary to safely and efficiently store and handle these fuels. This study provides a comprehensive overview of the challenges and opportunities associated with the storage of emerging fuels and identifies relevant regulatory authorities, best practices, and recommendations for the Army to ensure the safe and efficient storage and handling of emerging energy sources.

2. Regulations

2.1 Overview

The Department of the Army publishes its own regulations for fuel and safety, in addition to following federal and industry standards. These regulations are designed

to provide specific guidance and requirements for the safe handling, storage, and use of fuel in Army operations. For example, Army Regulation (AR) 70-12 outlines the policies and procedures for the management of research, development, and acquisition of new technologies and systems.⁷ These Army publications provide guidance on potential spill and safety aspects of fuel handling and storage and are designed to help the Army ensure compliance with federal and state regulations.

Several important federal agencies and nonprofit organizations administer regulations that ensure the safety and protection of workers, communities, and the impacts of fuel spills in the United States regarding fuels and energy distribution. The Occupational Safety and Health Administration (OSHA) hazardous materials standard (29 CFR § 1910)⁸ covers a wide range of topics, including hazard communication, fall protection, electrical safety, and personal protective equipment (PPE) relevant to emerging fuels. This standard requires employers to ensure that methanol, ethanol, and ammonia are stored in accordance with the National Fire Protection Association (NFPA) standards.⁹ NFPA standards and codes are widely adopted by local and state governments and are often referenced by OSHA, Environmental Protection Agency (EPA), and Department of Transportation (DOT) regulations. The EPA requires facilities that store methanol, ethanol, and ammonia to obtain a permit and comply with regulations related to air emissions, wastewater discharge, and hazardous waste management.¹⁰ The DOT has hazardous materials regulations (HMR) that cover the safe transportation of hazardous materials with key provisions that include classification, packaging, and labeling requirements for tanks and cylinders, as well as placarding and documentation during transportation.¹¹

2.2 Summary of Key Agencies and Regulations

2.2.1 U.S. Army Regulations

- AR 70-12: Fuels and Lubricants—policies and responsibilities for fuels, lubricants, and associated products.⁷
- AR 700-143: Packaging of Hazardous Material—petroleum and water distribution operations. Guidance on the distribution, storage, and handling of petroleum products, including fuel.¹²
- AR 703-2: Petroleum Products Supply and Management—prescribes policy and assigns responsibilities for petroleum supply operations.¹³
- AR 750-1: Army Materiel Maintenance Policy—guidance on the maintenance of fuel-related equipment, such as fuel tanks and fuel-handling equipment.¹⁴

- AR 385-10: The Army Safety and Occupational Health Program—guidance on safety procedures for handling and storing fuel, as well as emergency response procedures in case of a fuel spill or other incident.¹⁵
- ATP 4-43: Petroleum Supply Operations—refueling and storage procedures during operations.¹⁶
- DA PAM 385-24: The Army Radiation Safety Program—awareness of potential RF frequency impacts on fueling operations (added to 385-10).¹⁷
- TM 5-650: Central Boiler Plants—fuel handling and storage: guidance on the safe handling and storage of fuel, including procedures for receiving, storing, and issuing fuel.¹⁸
- AR 420-1: Army Facilities Management—guidance on the management of fuel storage facilities, including the design, construction, and maintenance of fuel storage tanks and other facilities.¹⁹
- AR 200-1: Environmental Protection and Enhancement—policy includes management of storage tank systems used to store oil and hazardous substances in an environmentally safe manner.²⁰
- AR 700-141: Hazardous Materials Information Resource System.²¹
- AR 11-42: Army Corrosion Prevention and Control Program.²²

2.2.2 Occupational Safety and Health Administration

OSHA codes of federal regulations (CFRs) include the following:^{8, 23–25}

- 29 CFR § 1910.103: Hydrogen storage and handling
- 29 CFR § 1910.106: Flammable and combustible liquids
- 29 CFR § 1910.109: Explosives and blasting agents
- 29 CFR § 1910.111: Covers design, storage, and handling of anhydrous ammonia
- 29 CFR § 1910.119: Process safety management of highly hazardous chemicals
- 29 CFR § 1910.120: Hazardous waste operations
- 29 CFR § 1910.146: Confined space entry
- 29 CFR § 1910.301: Electrical safety

2.2.3 Environmental Protection Agency

40 CFR § 68 Subpart G: Risk Management Plan (Clean Air Act) requires risk management and emergency response planning for facilities with more than 10,000 lb of anhydrous ammonia, unless used for agriculture, or 20,000 lb of more than 20% ammonia.¹⁰

2.2.4 National Fire Protection Association

NFPA hazardous materials codes include the following:^{9,26}

- NFPA 1: Uniform Fire Code
- NFPA 2: Hydrogen Technologies Code
- NFPA 30: Flammable and Combustible Liquids Code
- NFPA 50A: Standard for Gaseous Hydrogen Systems at Consumer Sites
- NFPA 50B: Standard for Liquefied Hydrogen Systems at Consumer Sites
- NFPA 55: Compressed Gases and Cryogenic Fluids Code
- NFPA 70: National Electrical Code
- NFPA 400: Hazardous Materials Code—focuses on the safe storage and fire protection of ammonia.²⁶

2.2.5 Department of Transportation

Department of Transportation (DOT) standards include the following:¹¹

- 49 CFR § Parts 171–180: HMR covers the transportation of hazardous materials.
- 49 CFR § Part 190: Establishes Pipeline and Hazardous Materials Safety Administration (PHMSA), which oversees the safe transport of ammonia via pipelines under DOT regulations.¹¹

2.2.6 American Petroleum Institute

American Petroleum Institute (API) standards include the following:²⁷

- API Standard 620: Design and Construction of Large, Welded, Low-Pressure Storage Tanks
- API Standard 650: Welded Steel Tanks for Oil Storage
- API Standard 653: Tank Inspection, Repair, Alteration, and Reconstruction

2.2.7 Underwriters Laboratories

The Underwriters Laboratories (UL) standards include the following:²⁸

- UL142: Standard for aboveground tanks materials for flammable and combustible liquids
- UL2085: Standard for protected above-ground tanks for flammable and combustible liquids

2.2.8 American Society for Testing and Materials

American Society for Testing and Materials (ASTM) standards include the following:^{25,29,30}

- ASTM E681: Standard Test Method for Concentration Limits of Flammability of Chemicals²⁹
- ASTM D323: Standard Test Method for Vapor Pressure of Petroleum Products (Reid Method)²⁹
- ASTM D4806: Standard Specification for Denatured Fuel Ethanol for Blending with Gasolines for Use as Automotive Spark-Ignition Engine Fuel²⁹
- ASTM D5797: Standard Specification for Fuel Methanol (M70-M85) for Auto Spark Ignition Engines²⁹
- ASTM D5798: Standard Specification for Ethanol Fuel Blends for Flexible-Fuel Automotive Spark-Ignition Engines²⁵

2.2.9 American National Standards Institute

American National Standards Institute (ANSI) standards include the following:

- ANSI K61.1-1999: Comprehensive guidelines for the safe handling of anhydrous ammonia.³¹
- ANSI B31-2001: Power piping³²

2.2.10 Compressed Gas Association

Compressed Gas Association (CGA) requirements documents include the following:

- CGA G-2.1-2023: Requirements for the Storage and Handling of Anhydrous Ammonia³³
- ANSI/CGA G-5-2024: Hydrogen³⁴

3. Use Cases

Power and energy are critical to all Army operations, and their use varies considerably depending on the specific use case, scale and mission requirements. For example, a Soldier will employ fuels much differently than an autonomous platform or a vehicle. As the Army continues to modernize, the fighting doctrine for Soldiers, vehicles, and other platforms will continue to evolve. Modernization provides opportunities to develop new ways of employing energy to enhance Warfighting functions in the future operational environment. This section outlines how different users of power and energy can employ emerging fuels to enhance projected future mission capabilities.

3.1 Vehicles

The current paradigm for all vehicles uses the jet fuel JP-8 to combust in either an internal combustion piston engine or a turbine engine. JP-8 is a highly energy-dense liquid hydrocarbon derived from petroleum. The energy density of JP-8 enables vehicles high mobility across the battlefield, which is key for operational requirements, and its liquid state at standard conditions makes distribution simple without the need for pressurized fittings or compressor pumps. The nearly exclusive use of JP-8 for vehicle power for over three decades has resulted in efficient refueling procedures, tested in training and global operations.

The power demands of tactical vehicles, especially during maneuver, all but require a fuel as energy dense as JP-8. The fuel consumption rates of various vehicles in different terrains are shown in Table 1. Lower energy-density fuels will inherently increase refueling frequencies and subsequently lower the time the vehicles are available for operations. As identified in discussions with the Army Petroleum Center (APC), the only new fuels that currently make sense for vehicles are drop-in replacements of JP-8: diesel or synthetic aviation fuels (SAFs). Without a significant decrease in vehicle power demand, there is little application beyond energy-dense hydrocarbon fuels.

Table 1. Fuel consumption rates for selected Army tactical vehicles.³⁵

Vehicle	Idle (gal/h)	Cross-country (gal/h)	Road (gal/h)
M1 Abrams	17.3	56.6	44.6
M2/3 Bradley	1.4	18.0	8.6
M113 APC	1.0	10.5	8.9
M88 Hercules	2.0	42	31
M9 ACE	1.4	12.6	9.3
M109A6 Paladin	2.2	16.0	11.8
MLRS	1.3	15.0	8.6

Emerging fuels and new power solutions can be employed on vehicles with hybrid system designs, whereby internal combustion engines are used for peak power but electrical power through batteries or fuel cells during idle, which allows energy savings for range extension and a side benefit of greatly reduced acoustic signatures. By limiting the sound signature, units can limit their exposure while stationary, providing an opportunity termed “silent watch.”³⁶ Some electrically

powered mobility during critical mission times, while silent, can also occur with hybrid power trains and provide a surprise element for vehicle operations.³⁷

3.2 Soldiers

The electrical energy source for dismounted Soldiers, or any Soldier-borne energy storage, is batteries. Soon, most batteries will be rechargeable to minimize logistics of transporting many pallets of single-use batteries to forward locations. The rechargeable battery concept is based on assured electrical power but is agnostic as to where that electrical power comes from.³⁸

The current paradigm for battery recharging uses gensets fueled with JP-8 as part of the “one-fuel” policy⁶ to electrically power battery charging devices at the platoon level outside the continental U.S.³⁸ Emerging fuels can be used either as drop-in replacement hydrocarbons to power the same gensets or fuel cells. These fuel cells could be carried by individual Soldiers or as squad/platoon chargers, pushing energy resupply far forward in the sustainment chain. DC power from local energy sources, such as photovoltaics (PVs) or wind, can charge batteries but is susceptible to intermittency in the available resources. Storing that energy in a fuel produced near the point of need provides energy assurance throughout a mission while still sourcing energy locally, thereby disentangling energy supply chains. Battery charging onboard vehicles is also a viable option in which the vehicle fuel is the energy resource and the options for emerging fuels will be the same as for the vehicle use case.

Outside of batteries, new options for Soldier power are emerging. Reformed methanol-powered fuel cells have been experimented for individual Soldier use at 20 and 50 W. Methanol is liquid, like JP-8, at ambient conditions and can be distributed in individual cannisters, supplying fuel cells within rucksacks. These fuel cells can provide direct power to equipment if wired through a distribution manager but can also charge batteries for individual Soldiers while in the field, away from more standard recharging options.

3.3 Autonomy

3.3.1 Air Autonomy

Unmanned aerial systems (UASs) are split into four classes depending on weight and their power demands are roughly a linear relation to the maximum take-off weight (Table 2).

Table 2. UAS categories and power demands.

Type	Max take-off weight (lb)	Power demand (W)	Example platform
Group I	0–20	~10	RQ-11B Raven
Group II	21–55	~1,000	ScanEagle (Navy)
Group III	56–1,320	~30,000	RQ-7B Shadow
Group IV	>1321	~125,000	MQ-1C Gray Eagle

Group I UASs are powered with electrical motors where onboard rechargeable batteries provide energy storage. Though there are some demonstrations of PV deployed on fixed-wing Group I UASs to supplement the initial battery charge, battery recharging typically occurs when the system returns to the operator. In this case they are electrically agnostic, similar to the Soldier use case, and can take advantage of any fuel and power generation system. Because of their electrically agnostic nature, Group I UASs can easily be coupled with power generated from emerging fuels, including nonhydrocarbon fuels synthesized near the point of need.

Group II UASs are larger and can handle longer-duration flights due to their larger battery capacity. When fully powered through battery storage, they have the same advantages with emerging fuels as Group I. Additionally, their larger size allows them to include onboard fuel cells for electrical power, as has been employed with the Marine Corps Stalker system that uses propane, and the Navy’s Hybrid Tiger program demonstrated with H₂.^{39,40} Fuel cells allow onboard fuel storage and the benefits associated with the much-higher energy density in chemicals compared to batteries. These systems have shown more than 600% range extension⁴¹ due to the increased fuel energy density and power conversion efficiency. Any emerging fuel suitable for use in a fuel cell will be suitable for Group II UASs.

The power demands and weight restrictions of Group III and IV UASs also require high-energy-density fuels coupled with efficient combustion for power generation just like vehicles. Drop-in hydrocarbon alternatives to JP-8, like SAFs, would be the primary options in these cases. Higher-power fuel cells may be employed for Group III, but the weight of the fuel cell with fuel storage may become limiting yet can provide auxiliary electrical power.⁴²

3.3.2 Ground Autonomy

Unmanned ground vehicles (UGVs) are not as developed as UASs and have a much smaller commercial presence. As such, the DoD and Army are leading much of what is required from these systems. There are no defined tiers for UGV systems like for UAS ones, but they can be generally classified as small, medium, and large based on their size and their conceptual application. Small UGVs are Soldier portable for reconnaissance and surveillance to work directly with a specific Soldier for short-duration tasks. Medium UGVs are envisioned to operate as supply carriers and are often referred to as “mules” and can weigh roughly 1 ton. Large UGVs are full tactical vehicles with options for fires, weighing nominally around 6 tons.⁴³

Power demand estimates for these platforms are extremely varied as the terrain and the uncertain weight of mission-specific hardware have outsized impacts on maneuverability compared to the simple air medium for UASs. As a rough estimate, small systems operating for periods of less than one day can use around 1 kWh of energy supplied by batteries at 500 W peak draw. The batteries will use a large part of the available space in these systems and small UGVs are the most impacted by the low energy density of batteries. To recharge batteries, the system would need to return to a charging location and be able to take advantage of emerging fuels generating electrical power.⁴³

Medium and large systems will need to pull 30–150 kW peak power during maneuver, just from a drivetrain. These rates would require too much battery load to fit into the platform, so hybrid combustion/fuel cell power has been identified as a promising solution. Fuel cells have the additional benefit of being silent, which overcomes the acoustic signature issues of most tactical vehicles. The fuel cell can be powered with reformed emerging fuels and replenished in the field through synthesized fuels.

The power and energy demand of UGVs make emerging fuel use in fuel cells especially attractive versus batteries as the mission time is extended beyond 1–2 days. The battery energy density is too low to make it feasible for extended duration without human intervention, which is the primary goal for autonomous systems.

3.4 Installations

Emerging fuels offer an opportunity to harden bases against homeland cyber threats on the energy grid.⁴⁴ The static nature of installations allows for a wider design set and leniency away from containerization requirements since parts do not need to fit on a truck for constant transport. Bases are also the best use case to take advantage

of low-density ubiquitous energy sources to convert into emerging fuels because they have the space available.

For power generation, emerging fuels can power backup generation,⁴⁵ primary generation, and fuels for nontactical vehicles, which have lower power demands than tactical vehicles.⁴⁶ In addition to directly powering platforms and buildings on the installation, emerging fuels can conduct education, training, and experimentation to identify any unforeseen impacts of their use.

3.5 Aircraft

Manned aircraft (rotor or fixed wing) have the highest energy-density requirements to maintain operations for a reasonable amount of time and because the power demand is directly impacted by how much fuel the airframe needs to lift. A UH-60, for example, can consume 120 gal/h⁴⁷; additionally, the impacts of fuel on safety are larger since if an engine becomes inoperable due to faulty fuel, the likelihood of a casualty is the highest of all use cases.

Drop-in emerging fuels, such as SAF, which can match JP-8 energy density and pass the same performance characterization tests required of JP-8, are suitable for use in manned aircraft as the safety concerns are built into the testing procedures.⁴⁸

Any emerging non-drop-in fuel, like H₂, will struggle to meet the energy-density requirements for aircraft. Their emergent nature also implies that their reliability has not been tested in the field for decades like JP-8 has been. As part of this study, discussions with APC and other sustaining elements indicated there would be hesitancy by end-users. For non-drop-in fuels to be employed, there will need to be significant demonstrated benefit in experimentation, either through silent operations using fuel cell power, or outsized logistical benefits.

4. Fuels

4.1 Hydrogen

The non-drop-in emerging fuel option with the highest technical readiness is H₂. It is the most studied emerging fuel for its synthesis through electrolysis of water and the reformation techniques of steam reformation and catalytic partial oxidation. Using water as a feedstock is attractive since it is a readily available resource in most distributed operating environments for point of need synthesis. H₂ has the highest specific energy of any nonnuclear material at 142 MJ/kg (higher heating value [HHV], 119 MJ/kg lower heating value [LHV]) and can be combusted for power or used for electrochemical power in fuel cells, which show high efficiencies

around 50%. This is a 2.8-fold increase over JP-8 (43 MJ/kg), but the volumetric energy density depends on the storage medium. There are many commercial demonstrations of H₂ for power, ranging from personal vehicles to buses to stationary building power, and the Department of Energy (DoE) has made great efforts to create an economical H₂-based infrastructure.⁴⁹

The storage of H₂ is the most problematic factor in its use, because though it has a high specific-energy density, the volumetric density of H₂ is low. When stored in any container, the weight of the container itself outweighs the contents severalfold. This implies that large volumes are needed to move energy in the form of H₂. In use cases where volume is constrained, such as UASs, UGVs, or Soldier-borne systems, the energy density creates a size burden on the platform that can impact the engineered system capability.

4.1.1 State (Liquid/Gas/Chemical)

H₂ is most commonly stored and transported as a compressed gas. Because of the specific-density issues, large efforts have been made to increase the storage density either through very high pressures (up to 10,000 psi), through liquification (<−240 °C), or using chemical adsorbates that bind the H₂ into solid chemical nanostructures. The state at which H₂ is stored and transported depends largely on the use case, and in the commercial world, the most economical cases determine how H₂ will be stored or transported.

4.1.1.1 Compressed gas

Compressing H₂ gas for storage is the simplest method to increase the energy density from 0.012 MJ/L at 1 atm up to reasonable storage densities like 5.9 MJ/L at 1000 bar (14,500 psi). There are several compression methods available, all of which are standard gas compression techniques, but the small size of the H₂ molecule imparts a challenge on the equipment so tolerances must be tight to limit leaks.⁵⁰ Additionally, compression itself takes energy to reach the desired storage pressure and can take greater than 10% of the available chemical energy.⁵¹

Figure 1 shows the rise in energy density as pressure increases at common room temperatures. The target DoE goal has been 1000 bar for compressed storage and distribution in vehicles because of the energy density and feasibility of materials to reach these pressures. See Section 4.1.2 for further discussion on tank design.

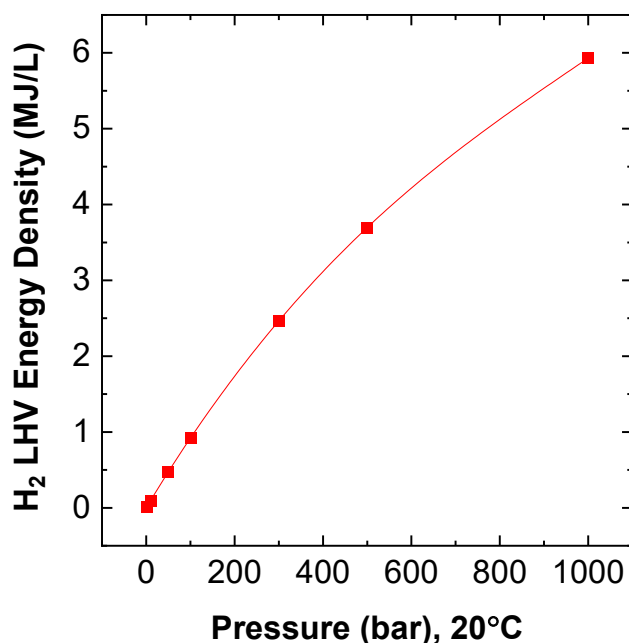


Figure 1. H₂ LHV energy density vs. pressure at 20 °C.⁵²

Long-distance distribution of H₂ can pass through pipeline infrastructure similarly to compressed natural gas. This is an option for stable regions and domestic uses, but mobile architectures will need to rely on compressed gas tanks, which have standard regulations for their transport and storage. One option for overland transport is truck containers, sometimes referred to as “Tube Trailers.”⁵³ Due to the wall-area pressures, these containers are limited to 250 bar, but the whole trailer can carry up to 900 kg (127.8 GJ or 35.5 MWh) per trailer.

4.1.1.2 Liquid

Liquid phase H₂ allows for atmospheric pressure storage and has the added benefits of liquid distribution.⁵⁴ The density of liquid H₂ at 1 bar is 66 g/L, whereas even the highest pressure (700 bar) gas tanks today are only around 40 g/L. This increase in density directly relates to an increase in energy density compared with compressed H₂ from 4.75 MJ/L to 7.84 MJ/L.

There are two primary concerns with liquified H₂ as a storage mechanism: 1) cryogenic temperatures, and 2) heat of ortho-para conversion. The critical temperature of H₂ is –240 °C and the boiling temperature at 1 bar is –253 °C, thereby requiring cryogenic temperatures to liquify and significant insulation to store. These temperatures induce safety requirements when handling to prevent cold burns and energy costs to attain liquification temperatures.

H₂ has a unique challenge in that the spin state of each atom in the H₂ molecule has an impact on the energy to liquify. In the gaseous state, 75% of H₂ molecules have

nuclei with opposite spin (ortho-configuration) but thermodynamically 100% of the molecules are stable in the para-configuration. To flip from ortho- to para- requires 527 kJ/kg of energy, but the heat of vaporization is 446 kJ/kg. Therefore, if an ortho- molecule is not flipped before liquifying, it will vaporize before flipping, which results in a steady boil-off if spins are not flipped before liquification. This boil-off can be as much as 50% loss within 100 h. This ortho–para conversion induces a significant energy requirement for liquification beyond just standard heat of vaporization for most materials, but if the timing of H₂ liquification can be planned with the storage and end-use, the boil-off can be minimized.

4.1.1.3 Chemical

Covalent bonds and metal hydrides are other means to store H₂ densely, but not in its natural molecular state. Emerging fuels, like alcohols and ammonia, can be synthesized to convert H₂ into C–H or N–H chemical bonds but remain in liquid states with much higher density at ambient conditions. Reformation processes are needed to extract the H₂ from these compounds, which must be included in the balance of plant, but distribution and storage are much simpler for these more complex molecules. Several later sections in this study relate to this method.

Metal hydrides are an emerging commercial capability for H₂ storage, although research has been investigating these materials for decades. Hydrogen gas reacts with a metal and the resulting chemisorbed H₂ can diffuse into the metal lattice. To desorb the H₂ from the system, energy must be applied, typically as heat, though some can operate at room temperature with lower capacity. These operation temperatures can range from 20 °C up to 900 °C, though most operate between 100 and 400 °C.

Though metal hydrides operate at more reasonable pressures and temperatures than liquid or gas phase storage, they have similar weight density with the DoE target of 5.5 wt% to match compressed gas⁵⁵ and top literature storage densities reporting only 3.3–3.6 wt%.⁵⁶ These materials continue to be researched for higher storage capacity and lower parasitic kinetics, but the overall H₂ storage metrics must compete with the industry standards of liquid and gas storage. The full system, to include balance of plant, may show that metal hydrides are able to outperform cryogenic or compressed gas at the individual vehicle level but are not expected to be suitable for large storage vessels.

4.1.2 Materials

4.1.2.1 Compressed Gas

There are four types of compressed gas tanks used for H₂ storage developed to decrease the weight of storage of common stainless-steel cylinders. Type 1 cylinders are made of continuous metal walls—steel or aluminum. They are the heaviest of all the cylinders but are the most cost-effective option. The storage weight ratio H₂/empty weight is 0.075 to 0.11 and can maintain pressures up to 350 bar (~5000 psi).

Type 2 cylinders use a metal liner to prevent the leakage of H₂ and have a wrapping to provide wall strength. The metal liner still bears much of the strength against the H₂ pressure, and the outer wrapping is made of composite materials, usually carbon fiber. This lightweight wrapping reduces the weight for higher pressure containment by not using thicker metal walls. The storage weight ratio H₂/empty weight is 0.13 to 0.17 and can maintain pressures up to 700 bar (~10,000 psi).

Type 3 cylinders do not use metal to support the walls against internal pressure. Instead, the walls are fully constructed from composite materials like carbon fiber and use epoxy resins to create a solid wall, thereby reducing the weight of the tank even more than Type 2. Some use metal liners to prevent H₂ leakage but are thin and do not provide any wall strength. The storage weight ratio H₂/empty weight is 0.12 to 0.16 and can maintain pressures up to 700 bar (~10,000 psi).

Type 4 cylinders are fully composite like Type 3 and lightweight but add a polymeric liner to prevent H₂ leakage. This is the most advanced type of cylinder for H₂ storage. The storage weight ratio H₂/empty weight is 0.1 to 0.18 and can maintain pressures up to 700 bar (~10,000 psi).

A visual comparison of each type of H₂ storage cylinder is shown in Figure 2.

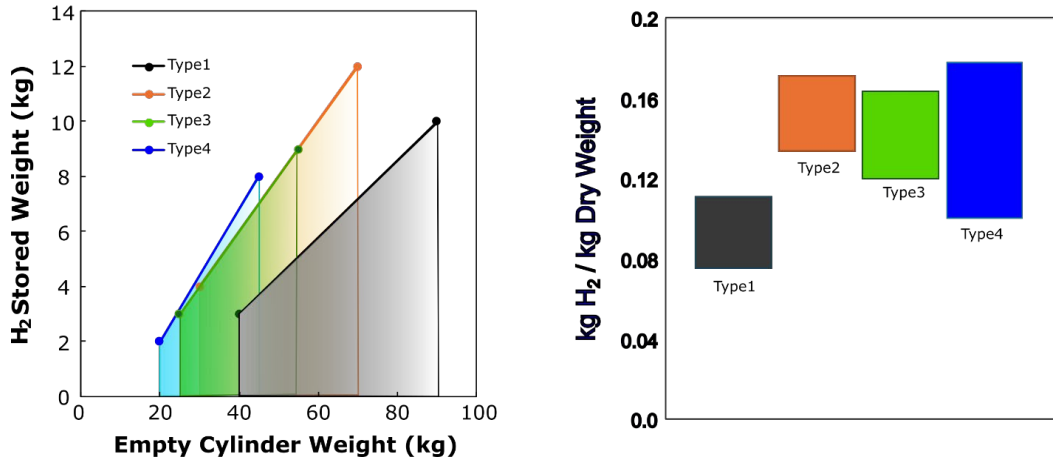


Figure 2. Ranges of H₂ storage capacity vs. the weight of the storage container for compressed H₂ separated by the type of compressed gas cylinder.

4.1.2.2 Liquid

Cryogenic temperatures required for liquid H₂ storage are the primary concern when constructing a liquid H₂ storage vessel. Energy transfer out of the vessel needs to be minimized to reduce boil-off rates; therefore, industrial storage uses spherical containers for on-site storage. A double-walled design is also common to limit wall heat transfer. The storage weight ratio of small dewars (H₂/empty weight) is 0.05 to 0.1,⁵⁷ and larger spheres are up to 0.11,⁵⁸ but this value ignores the weight of siting requirements such as cement pads.

The inner lining can be made of many types of materials depending on the requirement but the most common is austenite stainless steel to prevent H₂ embrittlement. Aluminum alloys, titanium alloys, and composite materials can be used as well, but are mostly used in the space industry for lightweight applications. A multilayered insulation containing reflectors, foam insulation, aerogels, perlite, and other materials commonly surround the inner lining, which is further surrounded by a vacuum before finally being finally encased by the outer wall. To this common storage design, active measures such as vapor-cooled shielding, which uses the evaporation of H₂ to keep the inner contents cool, and cooling the storage medium with liquid nitrogen (LN₂) can greatly increase the storage life of H₂ by 50% or more. These active methods will come at a cost of lost H₂ or energy to form LN₂.⁵⁴

4.1.2.3 Metal Hydride

Tanks that store H₂ in a metal hydride must balance heat transfer, H₂ flow rates, and some wall flexibility.⁵⁹ Heat management is the most critical factor to efficiently charge and discharge the potential H₂ capacity, but the proper temperature to maintain is highly dependent on the metal hydride material. The heat management is also dictated by exothermic charging reaction and the rate at which it stores H₂. Finally, uptaking H₂ causes the metal hydride particles to expand, which can cause some stress on the storage tank material.

To help with heat transfer from the metal hydride powder to the tank wall, powders are dispersed onto heat-transfer materials like aluminum foam or expanded natural graphite. These materials can wick heat energy away, but their addition reduces storage capacity so they must be optimized for the desired H₂ rates.

Tank structural materials, which include heat conducting internal fins, are not exotic, typically 316 steel, or brass.⁶⁰ Commercially available metal hydride storage vessels, which can fit 150–10,000 NL, have a storage weight ratio (H₂/empty weight) of around 0.01.^{61,62} This is an order of magnitude less than compressed gas or liquid storage, despite literature values being only slightly less. Again, the thermal conductivity is critical, and the geometry of the outside wall has more impact on storage operations than the material itself. Embrittlement of tank materials is possible, but heat transfer is such a significant design parameter that it overwhelms lifetime considerations.

4.1.3 Temperatures

The following is from OSHA's regulation 29 CFR § 1910.103:⁸

Gaseous hydrogen piping and tubing (above –20 °F) shall conform to the applicable sections of Pressure Piping section 2—Industrial Gas and Air Piping, ANSI B31.1-1967 with addenda B31.1-1969. Design of liquefied hydrogen or cold (–20 °F or below) gas piping shall use Petroleum Refinery Piping ANSI B31.3-1966 or Refrigeration Piping ANSI B31.5-1966 with addenda B31.5a-1968 as a guide.

Compressed gas cylinders should not be exposed to temperatures greater than 52 °C (125 °F) because of increased pressure.⁶³ Pressure relief valves are required to address the safety concerns, but venting can occur above these temperatures. Additionally, hoses and other valves for compressed gases are required by OSHA 29 CFR §1910 to be designed for use at a maximum of 130 °F. Distribution should therefore also be performed below these temperatures.

Cryogenic H₂ is inherently less than –240 °C. Any thermal management will need to keep storage and distribution temperatures below this.

4.1.4 Form Factors

4.1.4.1 Size

Compressed gas cylinders range from small lecture bottles holding 52 NI (4.64 g) up to tractor-trailer sizes, which can carry up to 900 kg H₂ per trailer,⁵³ while still being portable. Stationary storage can be much larger but would likely be cryogenic.

Cryogenic H₂ can be stored in any location, indoors or outdoors, up to 50 gal with some restrictions on what can be around it, such as ignition sources. When greater than 50 gal, there are more OSHA 1910 limitations on where tanks can be stored indoors.⁸ Anything above 600 gal must have storage outdoors with specific limitations on what can be near the storage vessel.

Size characteristics for metal hydride containers focus on heat transfer. A 3-mm wall-thickness storage vessel was simulated to have 6× faster charging rate than a wall of 7 mm, though maximum pressure considerations start to balance the thermal conductivity characteristics.⁶⁰ Typically, the cannisters will be cylindrical but their ability to operate at lower pressure means that they can take on prismatic forms as well, though these will be limited by maximum desired pressure.

4.1.4.2 Weight

The specific energy density of H₂ is its most desirable trait as a fuel, but the container weight is one of the largest setbacks at the system level for overall energy density. Compressed gas cylinders can hold 18% of their weight at a maximum as H₂, and this is for the most advanced containers. Liquified H₂ storage tanks are designed to minimize volume, not weight, and hold approximately 9% of their weight in H₂.⁶⁴ Metal hydrides can only hold at maximum 5%, but their pressures are much lower and can save empty weight for their size.

4.1.5 Storage Time

For long-term storage, H₂ can use compressed gas or metal hydrides. Cryogenic storage has known “boil-off” rates depending on the ambient conditions and will inherently lose capacity over time, on the order of days. As such, cryogenic liquified H₂ storage should be used for maximizing volumetric energy density in transport and liquified in conjunction with transport schedules. Hydrogen

embrittlement will impact some storage materials if improperly chosen to be the exposed wall material and must be engineered to combat short vessel lifetimes.

4.2 Alcohols

4.2.1 Methanol

Methanol is an emerging fuel option that can be produced by hydrogenation of carbon dioxide, steam reformation, and gasification of biomass. Most methanol is produced via steam-reforming of natural gas to create a synthesis gas that is fed into a reactor with a catalyst that yields methanol and water vapor. Various feedstocks can produce methanol, but natural gas is currently the most economical. Methanol has a specific energy of 22.7 MJ/kg (HHV, 19.9 MJ/kg LHV) (53% of JP-8's energy density) and can be combusted for power or used for electrochemical power in fuel cells and internal combustion engines, with an operating efficiency expected to approach 40%.^{30,65–68}

4.2.1.1 State (Liquid/Gas)

Methanol is a liquid at room temperature and atmospheric pressure, which simplifies its storage and handling compared to gaseous fuels.⁶⁹ Methanol has a moderate vapor pressure even at ambient temperatures, with vapors that are both flammable and toxic.^{30,66,70,71} Methanol vapors are invisible but can ignite when mixed with air. NFPA Code 30 and the OSHA 29 CFR § 1910.106 classifies methanol as a Class 1B flammable liquid.^{8,9}

Methanol is toxic if ingested, inhaled, or absorbed through the skin. Adequate ventilation, PPE, and handling procedures are critical to minimize exposure. In the event of a spill, methanol can be diluted with water to reduce its flammability and toxicity. Spill containment measures should be in place to manage any leaks or spills. Methanol is biodegradable and less environmentally persistent than some other fuels. However, spills can still cause localized environmental damage, especially to aquatic life.^{8,24,30,72} Methanol must be handled in accordance with AR 385-10 that includes requirements for PPE, safety procedures, and emergency response planning.¹⁵

4.2.1.2 Pressures

Methanol can be stored at atmospheric pressure in vented tanks. It does not require pressurization for storage due to its liquid state at normal temperatures. Methanol has a relatively low vapor pressure of 13 kPa (97.5-mm Hg) at 20 °C (68 °F) and it generates vapor that must be managed, particularly in warmer environments.^{30,65,66} Pumps, pipes, and other handling equipment should be rated to handle pressures

slightly above atmospheric to accommodate the vapor pressure of methanol. For safety considerations, ensure that all equipment is designed to withstand the pressures involved and use pressure-relief devices to manage any unexpected pressure buildup due to thermal expansion. Storage tanks should be equipped with proper venting systems to prevent pressure buildup and release methanol vapors safely. Ensure that handling areas are well ventilated to avoid accumulation of methanol vapors, which can be hazardous. Install pressure gauges on tanks to monitor and manage vapor pressure. Proper venting systems are designed to safely release vapor at a controlled rate, which ensures that the vapors are dispersed to minimize safety risks, especially in warmer weather conditions. By maintaining these pressure conditions, methanol can be safely stored and handled, ensuring its stability and preventing hazardous situations.^{24,30,65,67,69}

4.2.1.3 Materials

Proper grounding and bonding are required to prevent static discharge and potential fires due to methanol's low flash point, making it highly flammable.^{8,9,26,30,66} Storage tanks must include pressure relief valves and vent systems to handle vapor pressures, especially in warm environments.^{8,9} Corrosion management of containers for storage can include internal surface coatings (e.g., epoxy) and inert gas blanketing (e.g., nitrogen) that can further prevent corrosion by reducing atmospheric water absorption.^{8,9,24,30,67}

4.2.1.4 Temperatures

Methanol can be stored at ambient temperatures. Its liquid state at standard temperatures (20–25 °C [68–77 °F]) makes it convenient for storage without special cooling. The low freezing point of –97.6 to –97.8 °C (–143.7 to –144 °F) allows methanol to remain liquid in cold regions and can be stored at low to ambient temperatures. Methanol is flammable with a flash point of 11–12 °C (52–54 °F), which requires proper precautions like storage in cool areas and away from ignition sources. Methanol boils at 64.6 °C (148 °F). Storage temperatures should be well below this temperature threshold to prevent vaporization and pressure buildup. Equipment used to handle methanol, such as pumps and pipes, should be rated for the expected temperature range, typically from –20 to 40 °C (–4 to 104 °F).^{30,66,70} Store methanol away from direct sunlight and heat sources to prevent unnecessary temperature increases. Equip storage areas with appropriate fire-suppression systems, such as foam or dry chemical extinguishers. Use temperature sensors to monitor storage conditions, ensuring they remain within safe limits. By maintaining these temperature conditions, methanol can be safely stored and handled, ensuring its stability and preventing hazardous situations.^{24,30,66,70}

4.2.1.5 Form Factors

Methanol storage and handling are regulated by various industrial standards in the U.S., such as those from the NFPA Code 30 and the OSHA 29 CFR § 1910.106.^{8,9} Typically, methanol storage tanks are fabricated per recognized standards like UL142, UL2085, or the API 650 standard.^{27,28} Proper labeling and safety data sheets are required to inform users of the risks and safe handling practices associated with methanol. Methanol can be stored in standard liquid fuel containers if they use appropriate materials to prevent corrosion, degradation, contamination, and ensure safety. Methanol is a polar solvent, so it is more likely to experience galvanic corrosion than other fuels.^{24,30,66,67} Suitable storage containers and piping include metals, plastics, composites, aluminum, and coating/lined tanks.^{8,9,24,30,66,67} Established U.S. Army guidelines for methanol storage should be in accordance with AR 700-143 regarding tank design, construction, and installation, as well as safety features like ventilation and fire suppression systems.¹²

Stainless steel (316 and 304 grades) is preferred for long-term storage due to its resistance to corrosion and degradation. Carbon steel storage tanks are suitable for cost-effective short-term storage but can corrode over time, especially in the presence of water. As a long-term storage solution, this requires regular inspection and maintenance to prevent corrosion, which can increase the cost over the lifetime. Aluminum is generally suitable for short-term methanol storage, but less common and less ideal for long-term storage due to its potential for corrosion. High-density polyethylene (HDPE) tanks are widely used for both short- and long-term storage as they are resistant to methanol-induced breakdown and less prone to corrosion. Polypropylene is also suitable for methanol storage, with good chemical resistance properties. Fiberglass-reinforced plastics (FRPs) are suitable for both short- and long-term storage and they are often used for large storage tanks due to it combining the strength of fiberglass and the chemical resistance of plastics. Epoxy coatings are often used to line steel tanks to prevent corrosion and chemical interactions over time. Glass-lined is ideal for long-term storage due to its inert nature, preventing any chemical reaction with methanol.^{24,30,65-67} In summary, short-term storage options include carbon steel, aluminum, HDPE, and polypropylene, while long-term storage options include stainless steel, glass-lined tanks, HDPE, polypropylene, and FRPs.

Choosing the right container and material depends on the specific storage duration, environmental conditions, and regulatory requirements. Regular inspection and maintenance are essential to ensure the safe and effective storage of methanol. Storage form factors need to consider the container's corrosion resistance, chemical compatibility, durability, and regulatory compliance. The material must resist methanol-induced corrosion to ensure integrity over time. The storage material

must not react chemically with methanol, which could compromise safety and fuel quality. For long-term storage, materials should withstand environmental factors such as temperature fluctuations and UV exposure (for outdoor tanks). Storage containers must comply with relevant industry standards and regulations, such as those from NFPA, OSHA, state and other local agencies.^{8-10,24,28,30,66}

4.2.1.5.1 Size

Both OSHA and NFPA provide guidelines for methanol fuel container sizes, addressing both storage and transportation to ensure safety in handling flammable substances like methanol. OSHA guidelines (29 CFR § 1910.106) classify methanol as a Class 1B flammable liquid, which has specific requirements for approved container sizes for storage and handling.^{8-12,24,28,30,73}

- Portable containers:
 - 1 gal for glass containers (if purity requires glass, otherwise not preferred)
 - 5 gal for metal containers or approved plastic containers (such as HDPE)
- Safety cans: Up to 5 gal in size
- Drums: For larger volumes, methanol can be stored in 55-gal drums

NFPA sets specific container size limits based on the classification of the liquid and its flash point. For Class 1B flammable liquids like methanol, the NFPA limits container sizes to the following:

- 1 qt for glass containers in general use (unless purity requires larger sizes)
- 5 gal for approved plastic or metal containers
- 60 gal for steel drums
- 660 gal for portable tanks (with certain provisions such as venting and secondary containment)^{8,9,12,24,28,30}

The quantity of methanol stored in a building is limited based on the building's fire safety classification and hazard levels. Typically, small quantities (under 120 gal) can be stored in flammable-liquid storage cabinets, but larger quantities require compliance with NFPA 30, including considerations for ventilation, fire suppression, and spacing.⁷³ Methanol stored indoors in amounts over 10 gal must be housed in a flammable-liquid storage cabinet or dedicated flammable-storage room, equipped with automatic sprinklers, fire-resistant walls, and ventilation to manage vapors and meet fire codes.^{8-10,28,30}

Methanol transportation follows the U.S. DOT guidelines; however, both OSHA and NFPA play a role in defining safe handling during transit. DOT sets limits on the amount of methanol that can be transported without special placards or permits:

5-gal safety cans for smaller quantities and 55 gal drums for larger commercial shipments. For bulk shipments, methanol is typically transported in International Organization for Standardization (ISO) tanks or tanker trucks that must comply with venting, pressure relief, and flammable-material placarding requirements.^{8-12,24,28,30}

4.2.1.5.2 Weight

The weight of methanol stored in a tank is typically limited to 80% of the tank's capacity to allow for expansion and to prevent overfilling. Table 3 outlines the weight and capacity of a standard 55-gal open-top drum commonly used to store methanol for two typical drum materials. According to OSHA 29 CFR § 1910.120 and NFPA 30, the maximum weight of methanol that can be stored in a single container is 13,000 lb (5900 kg). The density of methanol is about 0.792 kg/L, so safety calculations must be made to ensure structural integrity of the storage containers and facilities.^{8,9,24,28,30,66,70}

Table 3. Common commercially available 55-gal drum of methanol with weight and capacity for two common drum materials with “open top” configurations.

Drum material	Drum capacity (L)	Drum weight (kg)	Methanol volume (L)^a	Methanol weight (kg)	Total weight (kg)	Fuel-to-storage weight ratio
Lined Steel	208.2	20.4	166.6	131.9	152.3	6.5
HDPE – plastic	208.2	11.8	166.6	131.9	143.7	11.2

^a Assuming liquid methanol density (0.792 g/mL) and maximum capacity of 80%, the remaining head space allows for vapor expansion.

4.2.1.6 Storage Time

Storage time for methanol as a fuel largely depends on the type of container, environmental conditions, and container sealing quality to prevent contamination or evaporation. Methanol is hygroscopic—it absorbs moisture from the air. Longer storage times increase the chance of methanol absorbing water from the air—even small amounts of water can lower the fuel quality, making it less efficient. Significant temperature variations can shorten storage time due to expansion and contraction of the liquid and potential vaporization.^{30,66,70} Under ideal conditions, methanol fuel could be stored for several years without significant degradation if it is stored in compatible and properly sealed containers with no exposure to air, moisture, or sunlight.^{24,30,66,70}

Short-term storage of methanol can be for several months to up to a year in properly sealed containers made from compatible materials (e.g., stainless steel, HDPE, and

FRP). During this time, the methanol remains relatively stable if stored in a cool, dry, and well-ventilated environment. Methanol stored in HDPE containers is suitable for short-term use, but over time, the material may degrade or allow some diffusion of the methanol, so usage within 6 months to 1 year is recommended.^{8–10,24,28,30}

Long-term storage of methanol can be 1–5 years in stainless steel containers depending on conditions such as temperature, contamination risks, and the presence of moisture. Properly sealed stainless steel containers are crucial for preventing both evaporation and contamination by water or air over longer storage durations. Methanol stored in large, vented tanks for longer durations must be monitored for any contamination or water absorption, which can compromise its quality. Methanol's corrosive nature over time may affect certain metals if not properly managed and monitored.^{8–10,24,28,30}

4.2.2 Ethanol

Ethanol is a domestically produced fuel that can be renewably sourced from fermentation of biomass, most commonly corn, and is used in more than 98% of U.S. gasoline to oxygenate the fuel. Ethanol has a specific energy of 29.7 MJ/kg (HHV, 26.7 MJ/kg LHV) (62% of JP-8's energy density) and can be combusted for power or used for electrochemical power in fuel cells and internal combustion engines. The most utilized gasoline–ethanol blend is E10 (10% ethanol, 90% gasoline) to reduce air pollution. Other available gasoline–ethanol blends are E85 for flexible fuel vehicles and E15 for use in newer, light-duty vehicles (model year 2001+).^{25,65,71} The Army allows the use of ethanol blends up to E85 (85% ethanol, 15% gasoline) in vehicles and equipment that are approved for its use.^{12,74}

4.2.2.1 State (Liquid/Gas)

Like methanol, ethanol is a liquid at room temperature and atmospheric pressure simplifying its storage and handling; however, special care must be taken due to its flammability. Ethanol storage regulations are controlled by OSHA and NFPA. Specifically, OSHA general industry standard § 1910.106, OSHA construction industry standard § 1926.152, and NFPA Code 30.^{8,9,75} OSHA classifies it as a Category 2 Flammable Liquid for having a closed-cup flash point below 23 °C (73.4 °F) and with a boiling point at or above 35 °C (95 °F). Also, due to its relatively low closed-cup flash point, NFPA classifies it as a Class 1B flammable liquid.^{8,9,74,76} The low flash point results in fast evaporation rates with dangerous levels of fumes if ethanol is not properly stored or handled, stressing the importance of storing ethanol in a cool, well-ventilated area and using exhaust fans.

Ethanol has a higher octane number than gasoline, which provides increased power and performance.^{25,77} Ethanol burns with a smokeless blue flame that is not always visible, so when ethanol burns, it is often referred to as an “invisible” fire. More than 20% of Brazilian cars can use 100% ethanol as fuel.⁷⁸ Ethanol was also originally used as a bipropellant rocket fuel early on in its application.

4.2.2.2 Pressures

Ethanol is not stored under pressure for regular commercial use. Large industrial tanks might require additional safety measures that include pressure-relief devices to manage vapor pressure during temperature changes. The flow rate of ethanol should be controlled to prevent excessive pressure, which can cause cavitation and damage to equipment. Ethanol should be injected into internal combustion engines at a pressure between 10 and 30 bar (145 and 435 psi) to ensure proper atomization and combustion.^{25,77}

4.2.2.3 Materials

Electrical equipment used in areas where ethanol is handled or stored should be designed to prevent ignition of vapors. Due to its flammability, ethanol must be stored in liquid-storage cabinets. Often made of steel and double-walled, these safety cabinets separate the ethanol from possible ignition sources.

Ethanol can cause corrosion of certain metals, such as aluminum, zinc, and brass. Internal combustion engines used for burning partial blends of ethanol with gasoline as a fuel should be constructed of corrosion-resistant components, such as stainless steel.²⁵ Ethanol can cause swelling, cracking, and degradation of certain rubbers, elastomers, and plastics, such as nitrile rubber and polyethylene (PE). Material corrosion is a concern due to its potential to contaminate ethanol fuel, which may adversely affect fuel system operation or cause component malfunction and lead to degraded performance.²⁹

4.2.2.4 Temperatures

Ethanol should be stored in a cool, dry, well-ventilated area, away from direct sunlight and heat sources to reduce the risk of vapor buildup. Ideal storage temperatures are below 38 °C (100 °F), as ethanol has a low flashpoint of 13 °C (55 °F), meaning it can form explosive mixtures with air at relatively low temperatures.^{61,77} Ethanol’s viscosity decreases and volatility increases with increasing temperature, which can impact fuel efficiency. High temperatures can increase the corrosion rate of metals and promote microbial growth in ethanol, which can lead to component degradation. Insulating ethanol fuel-storage tanks and

fuel systems can help minimize temperature fluctuations and reduce the risk of fuel degradation and contamination.^{25,29,65}

4.2.2.5 Form Factors

Guidelines and standards for aboveground ethanol storage tanks is essentially the same as that for gasoline and flammable-liquid feedstocks.^{9,24,25} The American Society of Mechanical Engineers (ASME) publishes standards for the design and construction of tanks used to store ethanol, including ASME Boiler and Pressure Vessel Code, Section VIII, Division 1.⁷⁹ ASTM has developed standard specifications (D4806 and D5798) for storage, handling, and use of ethanol as a fuel to be used in spark-ignition engines.²⁹ Ethanol must be stored in approved containers made of materials resistant to its corrosive nature, such as carbon steel, stainless steel (304 or 316), aluminum, or PE. Containers should be sealed to prevent evaporation and exposure to air, which can increase the risk of ignition. Special containers designed for flammable liquids, like Type I and Type II safety cans, offer fire and explosion protection with pressure-relief valves.⁷⁵

4.2.2.5.1 Size

Due to its flammability, OSHA requires that no more than 60 gal of ethanol can be stored in a single safety cabinet and that no more than three cabinets can be kept in any given facility.⁷⁵ For bigger production needs, fire-rated buildings can be used to keep larger quantities either less than 10 ft (U.S. Chemical Storage 4-h fire-rated buildings) or 10 to 30 ft away (2 h fire-rated buildings) from occupied buildings.^{80,81} Fire-rated buildings are made from fire-resistant gypsum board encased in hand-welded steel. For anything further than 30 ft, non-fire-rated buildings can be used. To be EPA-compliant, buildings must have secondary containment sump for spills or leaks.¹⁰

According to NFPA 30, the size limits are given for barrel (42 gal, 159 L), container (119 gal or less, 450 L), and intermediate bulk container (<3000 L, 793 gal).⁹ The maximum storage capacity for ethanol is typically limited to 50,000 gal (189,271 L) per tank, although larger tanks may be permitted with special approval.^{8,9}

4.2.2.5.2 Weight

The weight of ethanol stored in a tank is typically limited to 80% of the tank's capacity to allow for expansion and to prevent overfilling. Table 4 provides the weight and capacity information for a standard 55-gal open-top drum used to store ethanol for two common drum materials. According to OSHA regulation 29 CFR § 1910.120 and NFPA 30, the maximum weight of ethanol that can be stored in a single container is 13,000 lb (5900 kg).^{8,9}

Table 4. Common commercially available 55-gal drum of ethanol with weight and capacity for two common drum materials with “open top” configurations.

Drum material	Drum capacity (L)	Drum weight (kg)	Ethanol volume (L)^a	Ethanol weight (kg)	Total weight (kg)	Fuel-to-storage weight ratio
Lined steel ⁸²	208.2	20.4	166.6	131.4	151.8	6.4
HDPE – plastic ⁸³	208.2	11.8	166.6	131.4	143.2	11.1

^a Assuming liquid ethanol density (0.789 g/mL) and maximum capacity of 80%; the remaining head space allows for vapor expansion.

4.2.2.6 Storage Time

Ethanol can be stored for a maximum of 12 months, although it is recommended to store it for no more than 6 months to minimize degradation and contamination. The storage of ethanol is relatively more favorable compared to other emerging fuels because it has a higher volumetric energy density and can be stored in conventional containers at ambient temperatures and pressures, like gasoline. However, ethanol is highly hygroscopic and can absorb water from the air, which can lead to phase separation and engine corrosion. This implies that to move stored ethanol energy, relatively smaller volumes are required compared to other emerging fuels like H₂, but specialized storage and handling equipment may be necessary to mitigate the risks associated with water absorption.

4.3 Ammonia

The Haber–Bosch process has been instrumental in making ammonia one of the most widely produced chemicals in the world, with over 150 million tons produced annually. The high efficiency and low costs of the Haber–Bosch process has enabled ammonia to become a cornerstone of the agriculture industry for decades, serving as a vital fertilizer and plant nutrient. Recently, ammonia is emerging as a promising fuel owing to its high energy density of approximately 18.6 MJ/kg (HHV) and 17.6 MJ/kg (LHV) (41% of JP-8’s energy density), ease of storage and transportation, and existing infrastructure.^{84–87} Ammonia’s high energy density and lower production costs make it an attractive option. As the agriculture industry continues to evolve, ammonia’s dual role as a fertilizer and fuel is poised to play a significant part in shaping the future of energy production and consumption.⁸⁸

4.3.1 State (Liquid/Gas)

Ammonia is a gas at standard temperature and pressure (STP; 0 °C, 1 atm). However, at low temperatures or high pressures, the gas becomes a liquid, and at more extreme conditions, a solid.⁸⁹ Ammonia is typically stored in one of two ways:

- **Gas (Anhydrous Ammonia):** Stored under pressure in cylinders, tanks, or refrigerated systems. Storage tanks can have a maximum capacity of 85% (CFR 1910.111(b)(11)(i)); the remaining head space allows for vapor expansion. Small lecture bottles can store 170 g of compressed ammonia and have a storage to empty weight ratio of 0.22.⁹⁰⁻⁹³
- **Liquid (Anhydrous Ammonia or Ammonia Solution/Aqua Ammonia):** Stored in bulk tanks or smaller containers for industrial use or agricultural fertilizer.^{84,85} Like gas ones, anhydrous liquid ammonia storage tanks can have a maximum capacity of 85% (CFR 1910.111(b)(11)(i)); the remaining head space allows for vapor expansion.⁹⁰⁻⁹³ For ammonia solution, the allowed capacity increases to 95% as less head space is needed.⁹⁰⁻⁹³ The storage weight to empty tank weight ratio for ammonia solution (35 wt%, remainder water) is 0.52 for 111-gal tanks.^{90,94,95}

OSHA requires the use of appropriate PPE when handling anhydrous ammonia, including respirators, chemical-resistant gloves, and face shields due to its corrosive and toxic properties. Facilities storing or using anhydrous ammonia must provide employees with access to first aid, such as eyewash stations and safety showers, in case of direct exposure.^{8,84,88,96-99}

Anhydrous ammonia must be stored in cylinders and tanks in well-ventilated areas, away from incompatible materials, such as chlorine, sources of heat, and ignition. Caution must be exercised even with residual gas in empty containers. All lines and equipment must be grounded to prevent static sparks. Due to an autoignition temperature of 651 °C and a risk of ignition with significant preheating, containers should not be pressurized, cut, welded, brazed, soldered, drilled, grinded, or exposed to heat, flames, sparks or other sources of ignition.^{98,99}

4.3.2 Temperature–Pressure Relationship

Ammonia should ideally be stored as a liquid under ambient temperatures (at or below 20 °C [68 °F]) in sufficiently pressurized containers (typically 100–200 psi). It is commonly stored at temperatures below 20 °C (68 °F) to minimize vapor pressure and remains a liquid under pressure at higher temperatures. At atmospheric pressure and –33 °C (–27 °F), ammonia is at its boiling point and can be stored as a liquid. Figure 3 shows the pressure–volume–temperature (pVT) phase diagram for ammonia.¹⁰⁰ If moisture is kept to a minimum, ammonia is treated as anhydrous

ammonia regardless of what side of the pressure–temperature (P–T) line its phase is found in. At standard conditions (15 °C or 59 °F), ammonia exhibits a vapor pressure of approximately 6.2 bar (90 psi), rising to 8.6 bar (125 psi) at 20 °C (68 °F) for liquefaction. Tanks typically maintain pressures ranging from 100 to 200 psi to keep ammonia in its liquid form. If the temperature rises, pressure in the tank will also increase, necessitating the use of pressure-relief valves.^{8,9,84,89,96,97}

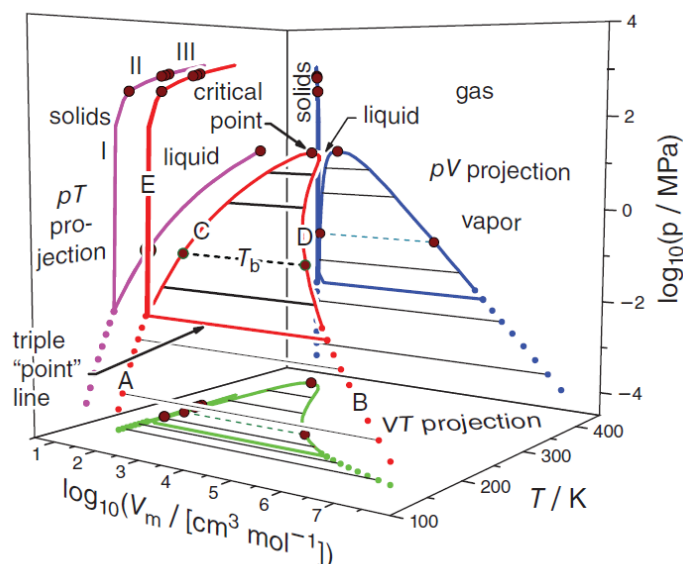


Figure 3. Perspective 3D pVT phase diagram for ammonia. Generated in Glasser.¹⁰⁰

The freezing point at atmospheric pressure is approximately -77.7 °C . Ammonia is used in refrigerant systems due to its thermal properties. For further information, reference the ANSI/IIAR 2-2021, *American National Standard for Design of Safe Closed-Circuit Ammonia Refrigeration Systems* and CGA G-2.1-2023, *Requirements for the Storage and Handling of Anhydrous Ammonia*.^{33,101}

Facilities often employ temperature and pressure monitoring systems for ammonia tanks to ensure that conditions remain within safe ranges. Automated systems may trigger alarms or release controls if temperature or pressure exceed safe limits. While ammonia is not highly flammable, NFPA guidelines cover the precautions necessary in case of fire incidents, such as the need for water-spray systems to mitigate toxic fume exposure.⁹

4.3.3 Materials

Storage containers must be made of materials like carbon steel or stainless steel, especially for anhydrous ammonia. Carbon steel is widely used because it provides good resistance to ammonia when stored as a liquid under pressure, and stainless steel is often preferred for its added corrosion resistance, especially in environments

with significant moisture. Containers made from these materials are commonly used in large-scale storage applications, such as tanks and pipelines. Copper, zinc, and their alloys (including brass) must be avoided because ammonia forms metal-ammonium complexes that weaken these metals over time and can cause stress-corrosion cracking in these materials. Galvanized steel, which is coated with zinc, should not be used because ammonia can strip the zinc layer, compromising corrosion protection and potentially causing tank or pipe failure. This can lead to structural failure in equipment containing or connected to copper, zinc, or alloyed components, like fittings or pipelines, especially under stress. Ammonia can react with aluminum and magnesium alloys, leading to surface corrosion and weakening of structural integrity. While not as reactive as copper, ammonia exposure can still degrade aluminum, especially in moist environments where ammonia may dissolve into water and accelerate corrosion. For aqueous ammonia (ammonia dissolved in water), compatible plastic linings like PE and polyvinyl chloride are sometimes used in storage tanks, especially in applications where corrosion-resistant liners are necessary. Containers must be constructed following ASME standards, which include specific guidelines on material thickness and resistance to ammonia corrosion. For outdoor storage, tanks are often insulated to reduce temperature fluctuations, which helps maintain consistent pressure and reduces the frequency of pressure-relief venting.^{29,84,96,97,102}

Ammonia must be stored separately from oxidizing agents, acids, and halogens, as it reacts violently with these substances. Mixing ammonia with chlorine or hypochlorites (e.g., bleach) creates toxic chloramine vapors or potentially explosive nitrogen trichloride. This reaction can occur in industrial settings or even at a smaller scale in cleaning products. These gases pose severe inhalation risks and should be avoided in confined spaces. Strong acids (e.g., hydrochloric acid, or sulfuric acid) react exothermically with ammonia and can cause dangerous pressure buildup in enclosed containers with risk of chemical splashing or thermal injury. Ammonia is incompatible with strong oxidizers, such as nitric acid, hydrogen peroxide, or bromine. These reactions can produce intense heat and, in some cases, hazardous decomposition products, creating a fire or explosion risk. Trace-levels of oxidizers can catalyze these reactions, so careful separation is necessary in storage and transport. Ammonia reacts with halogens to form halogenated nitrogen compounds, which are generally unstable and can be explosive under certain conditions. For example, ammonia reaction with iodine can produce nitrogen triiodide, a sensitive explosive.^{84,97}

Mercury is uncommon in ammonia applications but can form an unstable and hazardous ammonium product that can produce flammable H₂ gas. Ammonia should not be stored with some flammable organic materials (e.g., alcohols or

ethers) due to the risk of creating flammable mixtures or explosive atmospheres under certain conditions. While not a material safety incompatibility, ammonia readily dissolves in water to form ammonium hydroxide, a caustic solution that can corrode various metals and concrete over time. This reaction is also exothermic, and in enclosed environments, it can cause a dangerous rise in pressure or lead to structural damage in tanks or pipes. To minimize this, anhydrous ammonia should be kept away from moisture sources, especially in confined or closed systems.^{78,87}

Ammonia storage and handling requires proper materials selection and segregation of reactive or incompatible chemicals. Following OSHA and NFPA guidelines further ensures safe storage, minimizes risks associated with reactive chemicals, and provides reliable safety practices.^{8,9,28}

4.3.4 Form Factors

In agriculture, anhydrous ammonia is commonly stored in nurse tanks, which are pressurized, portable tanks designed for field use. These tanks can be transported on trailers and are built to withstand high pressure and protect against leakage. Underground storage tanks can also be used for long-term ammonia storage to reduce the risk of accidental release and exposure. Underground storage provides insulation from temperature fluctuations, reducing pressure changes within the tank, and may be more secure against tampering. For portable or smaller-scale applications in industrial and agricultural settings, anhydrous or aqueous ammonia is stored in stainless steel cylinders or drums for transportation and storage.^{84,85,96,102}

Facilities storage for large quantities of ammonia require bulk tanks equipped with venting and pressure-relief systems as safety precautions, and may use secondary containment systems, such as berms or catchment areas, to contain spills. In some cases, storage tanks are equipped with level indicators, pressure gauges, and temperature sensors for monitoring and maintaining safe storage conditions.^{84,85,96,102} NFPA 400 provides detailed guidelines for the safe storage of ammonia.²⁶ It specifies proper distances between ammonia storage containers and occupied buildings or boundaries, ensuring that containers are located away from potential ignition sources or populated areas.

The DOT classifies ammonia as a hazardous material. Regulations under 49 CFR govern the transportation of ammonia, requiring specific tank cars or trucks designed to withstand high pressures.¹⁰³ Anhydrous ammonia is stored for transportation in ISO tanks that are standardized, pressurized containers designed for international transportation requirements for intermodal shipping by truck, rail, or ship. Containers over 125 gal must be equipped with pressure-relief devices.^{11,23,96}

4.3.4.1 Size

Generally, above-ground storage tanks for anhydrous ammonia can be up to 12,000 gal (~45,400 L) in capacity. When used for industrial or agricultural purposes, large bulk tanks are common, ranging from 2,000 to 30,000 gal (7,600–113,500 L).^{23,96,97,102} Table 5 details the dimensions, weight, and capacity of different sizes of standard high-pressure stainless steel cylinders used to store anhydrous ammonia, taking into account an 85% fill limit for vapor expansion as per CFR 1910.111(b)(11)(i).⁸

Table 5. Standard high pressure industrial cylinder dimensions, weight, and capacity calculated for commercially available stainless steel cylinders of anhydrous ammonia.¹⁰⁴

Cylinder size	20	40	60	80	125	150	200	300
Tare weight (kg)	5.0	10.9	13.2	21.3	26.3	27.7	53.1	63.0
Height (cm)	35.6	43.2	58.4	81.3	109	119	129	139
Diameter (cm)	12.7	17.8	17.8	17.8	17.8	17.8	22.9	22.9
Water capacity (L)	3.5	7.8	10.3	15.4	21.6	23.4	43.2	49
Ammonia capacity (L) ^a	3.0	6.6	8.8	13.1	18.4	19.9	36.7	41.7
Ammonia weight (kg)	1.8	4.0	5.3	8.0	11.2	12.1	22.4	25.4
Filled tank weight (kg)	6.8	14.9	18.5	29.3	37.5	39.8	75.4	88.4
Fuel to storage weight ratio	0.36	0.37	0.41	0.37	0.43	0.44	0.42	0.40

^a Assuming liquid ammonia density (0.609 g/mL) and maximum ammonia fill capacity at 85% of the vessel volume, the remaining head space allows for vapor expansion.⁸

4.3.4.2 Weight

In the U.S., systems that exceed 4540 kg (10,000 lb) of anhydrous ammonia are subject both to OSHA's regulation 29 CFR § Part 1910.119 and the EPA's 40 CFR § Part 68.^{105,106} For ammonia at concentrations of 20% or greater, the threshold is 9080 kg (20,000 lb). In both cases, because it is mandated by Congress, and it is on the extremely hazardous substances list as having a vapor pressure of 10-mm Hg or greater.¹⁰⁶

Ammonia is regulated under the EPA's Risk Management Program (RMP) due to its potential for creating toxic release incidents. Facilities storing more than 10,000 lb of anhydrous ammonia are required to submit an RMP to the EPA. Under the Clean Air Act, releases of more than 100 lb of ammonia must be reported to the National Response Center.^{10,84,97,102}

4.3.5 Storage Time

According to OSHA regulation 29 CFR § 1910.111, NFPA 59, and the EPA, anhydrous ammonia can be stored for a maximum of

12 months.^{8–10,23,96,97,102,105,106} However, OSHA recommends that anhydrous ammonia be stored for no more than 6 months to minimize degradation and contamination. The storage of ammonia is challenging due to its high reactivity and toxicity, requiring specialized containers and handling equipment. Ammonia is typically stored as a liquid under pressure, which can lead to significant energy losses and safety risks. However, ammonia has a higher energy density than H₂ and can be stored at lower pressures, making it a more practical option for long-distance transportation and storage. This implies that to move stored ammonia energy, specialized infrastructure and handling equipment are required to mitigate the risks associated with its storage and transportation.^{8–11,23,84,96,97,102,105,106}

5. Conclusion

As the Army modernizes, emerging fuels provide an opportunity to create transformative shifts in power generation and sustainment for various use cases. The future operating environment is expected to be more distributed with more vulnerable supply chains. To lower this risk, energy diversification, coupled with point of need fuel synthesis, is a path to winning the future fight. This report provides a comprehensive overview of the regulations, guidelines, and best practices for the storage of the most promising of these emerging fuels: H₂, methanol, ethanol, and ammonia. Compliance with relevant regulations from the DoD, other government agencies, and industry associations is critical to minimize risks to Soldiers and maintain assured future operations. Unique properties, storage materials, storage temperatures and pressures, electrical guidelines, fire safety guidelines, and container designs were all identified for each fuel to provide a comprehensive reference for future designs of emerging fuel applications. Key findings from the study included:

- H₂ has a high specific-energy density but when the weight of the storage container is included, the energy density is similar to other emerging fuels.
- Methanol and ethanol are liquids at standard temperature and pressure conditions and can be stored in a wide variety of materials, but their flammability requires closely following safety guidelines.
- Ammonia has specific material considerations for storage and distribution, especially avoiding zinc and copper, but can be liquified at much lower pressures than H₂.
- Small-scale power demands of Soldiers and medium-to-small autonomous systems are most likely to benefit from the use of emerging fuels.
- The storage vessel has a large impact on the system level metrics for fuel energy density and specific energy density. Table 6 shows the comparison

between emerging fuels in their storage container if used as hydrogen carriers.

Table 6. Some specific and volumetric storage densities of emerging fuels in units of equivalent hydrogen weight.

Fuel	Storage phase	H₂stored/kg_{vessel} (kg/kg)	H₂stored/L_{vessel} (kg/L)
	Gas	0.075–0.18	0.015–0.018
Hydrogen	Liquid	0.05–0.11	0.015–0.022
	Hydride	0.01	0.025–0.05
Methanol	Liquid	0.81–1.40	0.08–0.08
Ethanol	Liquid	0.84–1.45	0.08–0.10
Ammonia	Liquid ^a	0.06–0.07	0.09

^a Anhydrous ammonia is usually shipped and stored in its liquid form despite it being a gas at STP so only values for the liquid phase are reported.

Recommendations for the U.S. Army include the following:

- **Investigate the potential impact for emerging fuels** to be used in a variety of potential U.S. Army tactical applications, including vehicles, Soldiers, autonomy, and installations.
- **Provide training and education** to personnel on the safe handling and storage of emerging fuels.
- **Continuously monitor and evaluate** the safety and efficiency of emerging fuel storage and handling procedures to identify areas for improvement.

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List of Symbols, Abbreviations, and Acronyms

3D	three-dimensional
ANSI	American National Standards Institute
APC	Army Petroleum Center
API	American Petroleum Institute
AR	Army Regulation
ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing and Materials
CFR	code of federal regulations
CGA	Compressed Gas Association
DC	direct current
DoD	Department of Defense
DoE	Department of Energy
DOT	Department of Transportation
EPA	Environmental Protection Agency
FRP	fiberglass-reinforced plastic
H ₂	hydrogen
HDPE	high-density polyethylene
HHV	higher heating value
HMR	hazardous materials regulations
ISO	International Organization for Standardization
LHV	lower heating value
LN ₂	liquid nitrogen
NFPA	National Fire Protection Association
OSHA	Occupational Safety and Health Administration
PE	polyethylene
PHMSA	Pipeline and Hazardous Materials Safety Administration
PPE	personal protective equipment
P–T	pressure–temperature

PV	photovoltaic
pVT	pressure–volume–temperature
RF	radio frequency
RMP	Risk Management Program
SAF	synthetic aviation fuel
STP	standard temperature and pressure
UAS	unmanned aerial system
UGV	unmanned ground vehicle
UL	Underwriters Laboratories
UV	ultraviolet

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