

## EXECUTIVE SUMMARY

# Safety and Operational Aspects of Ammonia for Low-Carbon Power Generation

Ammonia ( $\text{NH}_3$ ) is gaining attention as a potential alternative energy carrier (AEC) for hard-to-decarbonize sectors, such as power generation, where fossil fuels have long been dominant due to their high energy density. While ammonia is primarily produced for fertilizers, its existing infrastructure for storage and transportation provides a logistical advantage over other AECs like hydrogen. Additionally, power plants already utilize ammonia for emissions control, giving personnel some familiarity with its handling. However, using ammonia as a direct fuel remains underexplored outside of limited work in Japan and Korea, with significant technical and safety challenges such as high nitrogen oxide ( $\text{NO}_x$ ) emissions, combustor stability issues, and acute toxicity risks. This report reviews the safety considerations of ammonia as a power generation fuel. By identifying knowledge gaps, synthesizing available safety information, and analyzing case studies, this report aims to establish a foundation for safely integrating ammonia into the power sector as a viable low-carbon fuel.

- **General Ammonia Safety Considerations:** Ammonia is a colorless gas with a pungent odor that can be stored as a liquid under pressure or refrigeration, presenting both safety advantages and challenges when used as a fuel. With a high ignition temperature ( $>849^\circ\text{C}$ ), narrow flammability limits (16–27% in air), and a minimum ignition energy significantly higher than hydrogen, ammonia has a relatively low fire risk; however, it can ignite in confined spaces with external heat sources. Material compatibility is a key concern, as ammonia can degrade certain elastomers and metals. While ammonia vapor generally disperses quickly, it can accumulate in humid environments, increasing exposure risks. Health hazards range from respiratory irritation at low concentrations to life-threatening pulmonary damage at higher exposures, with 300 ppm classified as immediately dangerous to life or health. Effective safety controls include engineered safeguards like double-walled storage tanks, ventilation systems, emergency shutdowns, and gas detection, alongside administrative measures such as training, risk assessments, and clear hazard markings. Personal protective equipment (PPE), including full-face respirators and flame-proof overalls, is essential for high-risk scenarios. Emergency response protocols must include rapid area isolation, coordination

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with local responders, and public notification measures, with evacuation distances varying based on spill severity. These considerations, primarily concerning leaks and toxicity, are applicable to all ammonia applications.

- **Ammonia Incidents:** Due to the novelty of ammonia as a power generation fuel, no incident reports exist for this application. However, safety incidents have been documented in other established ammonia industries such as agriculture, refrigeration, food processing, and transportation. Information and learnings pertaining to these incidents are relevant to all ammonia applications. Analyses of these incidents reveal that human error is the leading cause, followed by improper operation, inadequate maintenance, poor risk assessments, and equipment design flaws. Safety system failures, lack of training, and material defects also contribute to accidents, with human health consequences being the most frequently reported impact. Best practices to mitigate risks include robust alarm management, clear communication protocols, strict configuration management, proactive monitoring and maintenance, and adherence to regulatory standards. Organizations should also prioritize a strong safety culture, continuous risk assessments, and regular training on proper system operation and emergency response.
- **Lessons from Emissions Control Applications:** Ammonia is widely used in emissions control technologies, including selective catalytic reduction (SCR) and selective non-catalytic reduction (SNCR), to reduce NO<sub>x</sub> emissions in power plants and industrial facilities. Best practices from NH<sub>3</sub> emissions control are highly relevant to its use as a fuel in power generation, particularly in storage, handling, and vaporization processes. Anhydrous ammonia storage tanks are built to American Society of Mechanical Engineers (ASME) pressure ratings, with aqueous ammonia stored at lower pressures. Unloading systems utilize compressors or specialized pumps to prevent vapor lock and cavitation, while emergency water fogging systems mitigate accidental releases. Vaporization systems, often skid-mounted for easy installation, ensure controlled ammonia delivery using steam, hot water, or electric vaporizers, dilution air fans, and static mixers. Proper operation and maintenance practices address startup issues, routine inspections, and delivery logistics to enhance safety and reliability.
- **Ammonia Cracking:** Ammonia cracking, which decomposes ammonia into hydrogen and nitrogen over a catalyst at high temperatures, may be used to enable hydrogen-fueled power generation. While it enhances fuel stability, efficiency, and power loading while reducing direct NO<sub>x</sub> emissions from combustion, the process introduces unique safety challenges, including the handling of toxic ammonia, rapid phase transitions, and emissions of NO<sub>x</sub>, N<sub>2</sub>O, and ammonium compounds. Ammonia

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cracking involves material concerns such as nitriding and H<sub>2</sub> service risks, though insights from ammonia production may inform safer system designs. While studies indicate that ammonia import, storage, and transport can be conducted safely, the specific safety requirements for ammonia cracking remain under-researched, necessitating further study to develop comprehensive risk mitigation strategies.

- **Ammonia as a Power Generation Fuel:** Direct ammonia combustion presents unique material and operational challenges due to its distinct properties and combustion byproducts, which differ significantly from traditional fuels. High temperatures, gas compositions, and flow stresses impact combustor materials, requiring resistance to degradation from hydrogen embrittlement, nitriding, and exposure to acids and bases. Research has shown promising resistance in materials like Inconel alloys, while thermal coatings such as yttrium and zeolites enhance durability. Ammonia combustion in gas turbines has seen renewed interest, with companies like Mitsubishi and IHI advancing commercial-scale demonstrations. Similarly, ammonia's application in internal combustion engines has been explored, with historical studies confirming material compatibility for engine components, excluding copper-based materials. In boiler applications, ammonia co-firing with coal is being pursued as a pathway to decarbonization, with demonstrations in Japan, China, and South Korea. Ammonia is also being explored as a co-firing additive with hydrogen to improve combustion safety, flame stability, and visibility, while mitigating hydrogen's detonation risks.
- **Codes and Standards:** Few regulations specifically govern ammonia as a fuel for power generation due to the novelty of this application. However, hundreds of existing codes and standards apply to ammonia across various industries. Compliance with jurisdictional codes is mandatory, but additional guidance from other regions can enhance safety practices. Key U.S. regulations include OSHA's Process Safety Management program and the EPA's Risk Management Program (RMP), which require hazard analyses, system documentation, and emergency preparedness for facilities handling over 10,000 pounds of ammonia. The RMP mandates offsite consequence analyses to assess potential ammonia release impacts, modeling worst-case and alternative scenarios. International standards, such as ISO 21343 for ammonia-fired boilers, establish benchmarks for emissions control, performance testing, and environmental compliance. Recent updates in Dutch PGS-12 guidelines address large-scale ammonia storage and safety measures.

In conclusion, ammonia as a fuel for power generation presents both opportunities and challenges, requiring a comprehensive understanding of safety, material compatibility, emissions, and regulatory frameworks.

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### KEY TAKEAWAYS

- Human error is the leading cause of NH<sub>3</sub>-related incidents, underscoring the need for robust training, procedural adherence, and risk management.
- While ammonia is less flammable than traditional fuels, it poses toxicity risks and requires careful storage and handling.
- Material compatibility is a concern, with ammonia-resistant metals and elastomers needed to prevent corrosion and stress cracking.
- Gas turbine and internal combustion engine applications show promise but require further optimization for NO<sub>x</sub> emissions, flame stability, and operational safety.
- With respect to ammonia co-firing with coal in boilers, advancements in combustion technology are necessary to address scaling, slagging, and efficiency challenges.
- Ammonia-hydrogen blends offer potential benefits for flame stability and explosion resistance but introduce material and emissions complexities.
- The regulatory landscape lacks dedicated standards for ammonia combustion, relying on existing guidelines for industrial applications.
- Key knowledge gaps include large-scale safety data, ammonia cracking risks, material degradation in high-temperature environments, and emissions reduction practices.
- Next steps include facility visits, expanded demonstrations, emissions optimization, material research, and the development of comprehensive safety guidelines to support ammonia adoption in power generation.



## THE LOW-CARBON RESOURCES INITIATIVE

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### LCRI CONTACT

Alex Gupta, PhD  
Low-Carbon Fuel Safety  
Specialist  
505.709.5787  
[algupta@epri.com](mailto:algupta@epri.com)

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For more information, contact:

EPRI Customer Assistance Center  
800.313.3774 • [askepri@epri.com](mailto:askepri@epri.com)



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3420 Hillview Avenue, Palo Alto, California 94304-1338 USA • 650.855.2121 • [www.epri.com](http://www.epri.com)

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