**Ammonia Flare Testing for the Hydrogen Production Industry**

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**Introduction**

A global drive towards decarbonization for the purpose of reducing CO2 output has driven many companies to reduce carbon emissions by replacing hydrocarbons with hydrogen in their facilities. New hydrogen plants are being planned and built across the globe to support this effort. Synthesizing ammonia from N2 and energy-dense hydrogen for safer storage and transportation has resulted in 100% ammonia becoming a common gas case for industrial flare systems. Burning ammonia is difficult due to its slow flame speed and narrow flammability range, requiring some specific design considerations that many other gases do not necessitate. Although some previous ammonia flare testing had been completed in the 1980s and 90s, the scope of those tests was quite limited. This has created a need to perform further ammonia combustion testing to advance the industrial knowledge of ammonia combustion systems and provide the facilities with safe and well-designed equipment. This paper discusses some of those design considerations generated and validated at Zeeco’s Global Test Center, historical ammonia testing throughout the industry, and insights into future solutions for ammonia flaring. With this work, Zeeco hopes to advance the combustion industry’s knowledge of ammonia combustion.

**Background**

Flares have been used for the disposal of Ammonia vapors generated in tanks due to loading activities or normal breathing or boil off since the early 1970’s. The flares were usually small, 2” to 4” in size, as these generated Ammonia vapors were small design flow rates.

Little was known about the efficiency or effectiveness of flares for the destruction of Ammonia vapors. The testing that was available indicated that 100% pure Ammonia vapors could not be burned in a flare system effectively. Several engineering design guideline documents and books on Ammonia vapor in refrigeration process also indicated that 100% Ammonia would not burn unless it was premixed with air.

Flare vendors knew that low Btu gases, including Ammonia, were difficult to flare as entraining too much air would cause the flame to be extinguished. Until the early 1980’s, the basic design concept for flare these low Btu gases and Ammonia was approached in the same way.

1. Design the flare tip barrel diameter and exit area for the available pressure drop and resultant exit velocity at the tip.
2. Include in the design some type of gas assist injection ring at the flare tip exit to create a fire the vapors can pass through.

For Ammonia vapors, this approach has been proven to be ineffective through a couple different tests in the 1980’s. The following covers two of those tests and what we learned from this testing.

A major chemical company located near Houston, Texas, USA, was expanding their facility, and needed to modify their permit for flaring to increase total allowable emissions. The local authorities would not allow the increase in Ammonia emissions from the flare providing the chemical company with two options. They could install an incinerator for higher destruction efficiency or prove the destruction efficiency of Ammonia in the flare was higher than shown on the current permit.

The chemical company elected to contract with a Flare vendor to test the destruction efficiency of a 100% Ammonia flare varying different configurations. The installed flare at the facility was a standard Ammonia flare system for the time with a gas assist ring to create turbulence and to create a good combustion zone at the flare tip exit. For the testing, 100% Ammonia gas with varied flow rates to change exit velocity was flared in a 12” diameter utility flare with a full flame retention ring. With the varying exit velocities, the following equipment options were fitted to the tip.

* Extended large diameter windshield assembly that enclosed the discharge of the flare tip and the pilots.
* Assist gas injection ring at the tip exit to produce turbulence and increased air inspiration into the combustion zone.
* Multiple pilots (three maximum) were available to determine the impact of ignition flames on the combustion process.

The testing found the following conclusions:

* Ammonia will burn to technically complete combustion (99% or higher) if the exit velocity at the flare tip discharge point is kept very low. The acceptable velocity is a function of the nominal tip diameter.
* Higher flare gas exit velocities result in the inspiration of too much ambient air into the combustion zone, which dilutes the ammonia / air mixture to below the combustible limit. Ammonia has a lower explosive / combustible limit that is 16% in air. This is in comparison to most hydrocarbons that have LEL values that are from 1% to 3%.
* Ammonia needs to have a good source of ignition. This is typically provided by a very reliable pilot flame. For good destruction efficiency, a sufficient number of pilots around the perimeter of the flare tip are needed so the pilot flame can be ensured to contact the Ammonia. During the testing, if the ignition source was removed, the Ammonia would not sustain a stable flame.
* A windshield is very useful in limiting the amount of air inspirated by cross winds into the Ammonia flare gas stream to facilitate ignition of the gases.
* Burning of the Ammonia vapor eliminates any Ammonia smell.
* The temperature of combustion in an ammonia flame is much lower than a hydrocarbon flame. The lower temperature of combustion will also produce NOX as a mole of Ammonia will produce a mole of NOX (usually colorless NO and NO2).

From this testing, it was concluded that Ammonia can be burned in a flare system with very high efficiency when the flare system is designed correctly.

During the mid-1980’s, the US EPA wanted to understand additional aspects to the destruction efficiency of Ammonia. They wanted to how low the Btu value of flared gases, including Ammonia, could go and have good destruction efficiency in an open flame flare system. The used CO2 and Nitrogen to dilute these gases. The testing showed that Ammonia could be diluted to 200 Btu/scf and still be combusted to a high efficiency. If the gas stream was lower than 200 Btu/scf, the stream had to be enriched using assist gas in the flare header.

**EPA Emissions – TCEQ NSR Emissions Calculation - 2021**

Ammonia can be up to 99% DRE1 per TCEQ. This 1 is *on a case-by-case review.* Ammonia being very difficult to burn, can easily oxidize below the minimum requirement of the 99% DRE if not properly controlled.

**ZEECO 2024 Enclosed Flare Ammonia Testing**

**Foreword**

Combustion testing was performed on June 25, 2024 by Zeeco, Inc for a client in the Asian market. The objectives of this performance test were to demonstrate the flare flame ignition, stability, and destruction removal efficiency (DRE). Pretesting was conducted in the months leading up to the client testing. Two testing mixtures were investigated. 100% ammonia at close to ambient conditions as well as an ammonia-nitrogen mixture to reach 300 Btu/SCF LHV.

**Setup and Safety**

**Setup**

One (1) utility style flare tip was fired with specialized stability mechanisms within the scope of the arrangement. The flare was mounted vertically in the center of the test enclosure as seen in Fig. 1. The flare tip was outfitted with three (3) standard Zeeco HSLF pilots using propane as a fuel to match project requirements. A sample probe was inserted near the top of the flare stack exit which was used to collect the flue gas sample. The sample was conveyed to a third-party mobile trailer where the ammonia content was measured and recorded. Flare ignition and flame stability was monitored visually via video streaming from a camera mounted on the side of the flare stack near the flare tip exit elevation. An orifice flow meter was used to meter and measure the flowrate of ammonia and another orifice flow meter was used for nitrogen when applicable. The orifice flow meters were adjusted to achieve the specified test fuel mixture and flowrate.

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Figure 1 - Testing Setup and P&ID

**Safety**

Safety was paramount in the approach to testing this equipment and gas mixtures. A summary of the general safety related considerations is listed below:

* NFPA Hazard Diamond. Range 0-4
	+ Blue Health Hazard 3: Extreme Danger
	+ Red Fire Hazard 1: 200°F preheat required
	+ Yellow Instability Hazard 0: Stable
	+ White Specific Hazard None
* The *Blue Health Hazard 3: Extreme Danger* relates specifically to poisonous gas and great efforts were made to protect the health and well-being of test participants and individuals in the surrounding campus and community.
* Emergency response personnel were equipped with self-contained breathing apparatuses (SCBAs) and were at the testing site during all testing events.
* Escape respirators were required for all personnel involved.
* All personnel involved were required to participate in Zeeco’s ammonia specific safety training created by the HSE staff for this testing or provide training records that show they have been trained at an equivalent level
* Prior to testing, emergency action plan was conveyed to all personnel involved
* Prior to testing, company wide notifications were issued detailing large regions of the Global Test Center to be off-limits to personnel not involved in the testing.

**Time, Temperature, and Turbulence?**

Obtaining high destruction efficiencies while flaring depends on the basic principles of combustion. The 3 T’s: Time, Temperature, and Turbulence. Depending on the type of gas these 3 factors need to be adjusted to create the optimum mixture for high DRE without undue cost or negative performance issues.

Time is gained by reducing the velocity of the flared gas and combustion products. Reducing the air into the unit can produce poor DRE due to the lack of oxygen in the chamber. Increasing the volume of the unit would result in a higher cost to the manufacturer and end user. If not properly designed, an improper height to diameter ratio can result in matching a harmonic frequency of the chamber to a node of the combustion frequency and low frequency, high intensity, noise will develop from the combustion. This testing stayed within the typical 0.5 – 1.0 s residence time for enclosed flares.

Temperature is important to promote the oxidation of the compounds into the final products. Higher DRE is gained from higher temperatures and a relation between Time and Temperature above the auto-ignition point exists. Ammonia has a high auto-ignition temperature (AIT) at 1204°F compared to hydrocarbons. Higher AIT typically results in requiring higher temperature or increased residence time for very high DRE. This was not the case for the testing conducted by Zeeco which had a unit temperature nominally characteristic of EGFs. As an added anecdote, there exists a functional limit to the allowed temperature within the enclosed flare. Typical allowed temperatures for this type of combustion device is between 1600-2000°F. The walls of the enclosed flare are protected by insulated ceramic blanket. Traditional blanket is refractory ceramic fiber (RCF) and is being replaced in many markets with Alkaline-Earth-Silicate (AES) due to the post-firing carcinogenic properties of RCF. AES is not as durable as RCF which limits the allowed temperature in the unit. In either case, RCF or AES, above 2000°F unit temperature refractory brick would need to be used to protect the exterior of the shell in much the same was it is used in thermal oxidizer equipment. This is typically not selected due to expense, challenges to constructability, and difficulties in thermal growth allowance.

Turbulence or the rate of mixing the stoichiometric air with the flare gas was found to be the most important controlling factor of the 3 T’s to achieve high DRE. This was primarily due to the small flammability range of ammonia with a UEL of 27% and LEL of 15.5%. From a volumetric standpoint this is between 4-7 volumes of air per volume of ammonia. In comparison, methane can allow between 7-20 volumes of air per volume of methane. The range of allowed air before over-aeration is much smaller as a result the combustion zone and more importantly the flame boundary will lack stability to anchor the flame to the flare tip. Unstable flames that are not well anchored to the flare tip gain additional air as the transient flame boundary and associated flare gas travels farther into the chamber. The air entrained into the gas increases with the distance traveled and can easily push the mixture past the LEL resulting in lower DRE. Multiple past tests have also found the rate of air entrainment decreases at the point of the flame boundary further giving purpose to the need of a strong stability mechanism at the flare tip exit. Initial testing did not take these principles well into account and found the need to limit flow through the flare tip much lower than the expectation. Once the air velocity was well controlled, stability at the flare tip was achieved, and high DRE was gained. Most other gases combustion engineers design to oxidize require high rate of mixing to prevent smoke and limit emissions. Not so with ammonia. Rethinking Turbulence and the need to reduce it, is a unique feature of flaring enclosed ammonia.

**Results**

These are the final results from months of testing and design iterations. Hundreds of man hours were used in multiple rounds of designing, building, and testing flare arrangements to understand the required nuances of the system. The ammonia testing conducted by Zeeco found very good DRE of ammonia as can be seen in Figure 2. When the EGF system has heated up to above 1600°F under non-variable inlet flow and burner flame stability conditions, the combustion found 99% DRE. Increasing the EGF temperature further continued to achieve higher and higher DRE as the temperature continued to rise. As the unit temperature stabilized, the DRE continued to climb reaching above 99.99% before the test ended. Testing is a short duration process on the scale order of minutes. EGFs take many minutes to reach full temperature on the interior walls of the unit which have low velocity and comparatively poor mixing with the heat produced during the combustion process. It is very possible continued testing would have resulted in even higher DRE as illustrated in Figure 4. The result is an amazing DRE considering the type of equipment is not a Thermal Oxidizer, natural draft using no blowers, and used no automation to control the inlet air and prevent fluctuations due to wind. The 99.995% DRE achieved at the end of the testing shows for each 100,000 molecules of ammonia entering the unit only 5 escape.

Figure 2 - DRE vs Temperature

Figure 3 - DRE & Temperature plotted against Testing Data Point Acquisition Time

Figure 4 - DRE & Temperature plotted against Testing Data Point Acquisition – End of Testing Period - Greater than (4) "9's" of Destruction Efficiency

**Future Testing**

Increasing the range of compositions mixed with ammonia will give greater clarity on performance. Ammonia – hydrogen – nitrogen mixtures inside an enclosed flare and outside on a typical elevated flare will ensure stable performance no matter the equipment condition. Facilities which employ the use of ammonia as a storage and transport vector for energy will need to crack the ammonia into hydrogen before use in most current combustion equipment. This presence of ammonia, hydrogen, and the byproduct nitrogen in a single facility necessitates the need for greater understanding of how these mixed compounds perform during combustion.

**Conclusions**

The testing and growth we as an industry achieve builds on itself over years and decades. We have been supported by the testing of the 1980’s but now need to meet the challenges of a more demanding future and continue to explore the bounds of the combustion industry. The growth of ammonia facilities and the need to limit emissions necessitates the expansion of the performance envelope of current enclosed flares to include ammonia as a common fuel. The recent testing by Zeeco proves to not take the knowledge we’ve gain for granted but to be grateful for the ability and drive to continue testing where no one has tested before.