

Recent Findings in the Development of Solid Propellant Inert Gas Generator Fire Extinguishing Systems for Occupied Space Uses

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Introduction

Solid propellant-based fire extinguishing systems offer many advantages for numerous fire protection applications. Since their by-products (which act as their effective extinguishing agents) are inert gases, they pose no environmental hazards and comply with all international legislation, as well as not decomposing into acid gases when exposed to a fire that can harm occupants and property. By being stored in a very dense solid form until being activated, such devices are much smaller in size compared to other extinguishing agent systems (and in fact can be comparable to Halon systems in size for equivalent firefighting performance), and without the requirement for a pressurized vapor space as is needed for liquefied extinguishants (to maintain a minimal pressure during discharge), further space savings are realized. Such solid-based systems are not vulnerable to leakage nor require heavy, high pressure equipment to store or transmit the extinguishant. They have been used to date successfully in aircraft dry bay applications on several recently fielded aircraft, including the U.S. Navy F-18 E/F and V-22 tilt rotor aircraft. While such applications have been very successful, the inert gas-only generator systems have been limited to date for unoccupied areas (and in fact are listed in the U.S. Environmental Protection Agency Significant New Alternatives Program (SNAP) as being suitable for only unoccupied areas), due to the high content of carbon dioxide in currently available systems.

Recently, a new patented concept and design of a solid propellant gas generator system for occupied areas has been demonstrated, and is in advanced development. The output gases of the device are water vapor with nitrogen, and are a blend suitable for use in occupied areas. These devices have been designed to be packaged in a multiple-cartridge N₂ Tower design, which permits the use of individual in-room towers, each of a given firefighting capacity to protect a given volume of the compartment. This design precludes the use of on-site engineered networks and flow calculations, the installation of extensive piping networks, or high-pressure bottles that are prone to leakage and must be stored and take up considerable space, and with minimal other maintenance required. These systems are predominantly targeted to provide the ideal solution for the commercial “total flood” fire protection industry, although other key applications have been identified, including aircraft engine and cargo bay systems, as well as the marine industry. Testing to date has shown a high efficiency and rapid fire knockdown in room-sized fire tests, with heptane fires at both ground level and at a six foot elevation extinguished using four generators comprising a total of forty lbs. of propellant (a portion of which converted to and was discharged as agent), in a 1000 cubic foot chamber. In addition to the aforementioned technological advantages which justify this performance, the ability to discharge a moist, fully saturated inert gas atmosphere at elevated temperatures into a protected compartment provides

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unique opportunities for performance enhancements in fire extinguishment which have not been characterized in published work to date, and which will be the subject of exploration of this paper.

Discussion of Advantages of Moist, Saturated Inert Atmospheres at Elevated Temperatures, and Other Facets of Gas Generator-Derived Systems and Performance

Gas generator systems such as the N₂ Tower design generate the desired extinguishant on an “on demand” basis when activated, when the presence of a fire in the protected area is detected. The solid propellant is electrically or otherwise “jump-started” to initiate a chemical reaction within the material, rapidly converting its mass to gaseous by-products. For the N₂ Tower design, the by-products are nitrogen gas and water vapor, with trace amounts of other combustion by-products within acceptable exposure limits. This exothermic process of gas generators also generates large quantities of excess heat. This heat is typically absorbed with external coolant beds (such as residing within the overall system) or radiated outwardly from the exterior of the container. Since water vapor is a significant component of the extinguishing agent generated with the system, some of this water vapor will condense onto the surfaces of the internal cooling bed, leaving within the gaseous effluent a mass proportion of water vapor equal to the saturation humidity ratio at the local temperature (the higher the temperature, the higher the mass proportion). National Fire Protection Association (NFPA) 2010 published guidelines for pyrotechnic aerosol generators (which also generate hot gas and other heat in addition to solid particulate aerosols) recommend a limit exhaust gas temperature of 75 C (167 F), to assure the safety of persons in contact with such gases. In accordance, even though the N₂ Tower systems generate clean extinguishing gases (unlike aerosol systems) designed for use in occupied areas, this limit was adopted as the maximum temperature for gaseous extinguishing effluent exiting the N₂ Tower device into the protected area.

The selection of this maximum exhaust temperature of the moist inert nitrogen gas is important, because it dictates the proportional (and total) amount of water that remains in the effluent in a gaseous state and is guaranteed to be discharged into the protected area, “total flooding” everywhere as a gas. Figure 1 is a plot of the saturation humidity ratios of atmospheres (the ratios of water vapor mass to dry air mass) at various elevated temperatures. This data [1] reveals that the mass of water that can be retained in a vapor state in atmospheres increases exponentially, rather than linearly, with temperature, and at temperatures above normal ambients it can be quite considerable. In fact, it reveals that at 167 F (the maximum design temperature of effluents from an N₂ Tower system), 0.386 lbs. of water can be retained in vapor state for every pound of dry air discharged – far more than the 0.016 lbs. possible at ambient (70 F) conditions. A large proportion of water vapor is desired in the extinguishing gas blend, not only because it was originally produced by the unit and not desired to be wasted, but the specific heat of water (and hence its heat extraction and physical extinguishing capabilities) is higher than that of the nitrogen component (66.19 KJ/mol versus 51.54 KJ/mol), and with a smaller molecular weight than nitrogen (18 versus 28) results in an even more effective heat extraction medium on a per unit mass basis (3.68 KJ/gram versus 1.84 KJ/gram). In addition to the effective heat extraction capabilities of water, its large heat storage and subsequent release capabilities over small temperature changes also provides benefits to the process by facilitating a significant temporal rise in the compartment temperature during suppression, thereby increasing the amount of water vapor remaining in gaseous state, as well as increasing the agent and room air specific volume which reduces extinguishing quantity requirements, as will be shown in subsequent analysis.

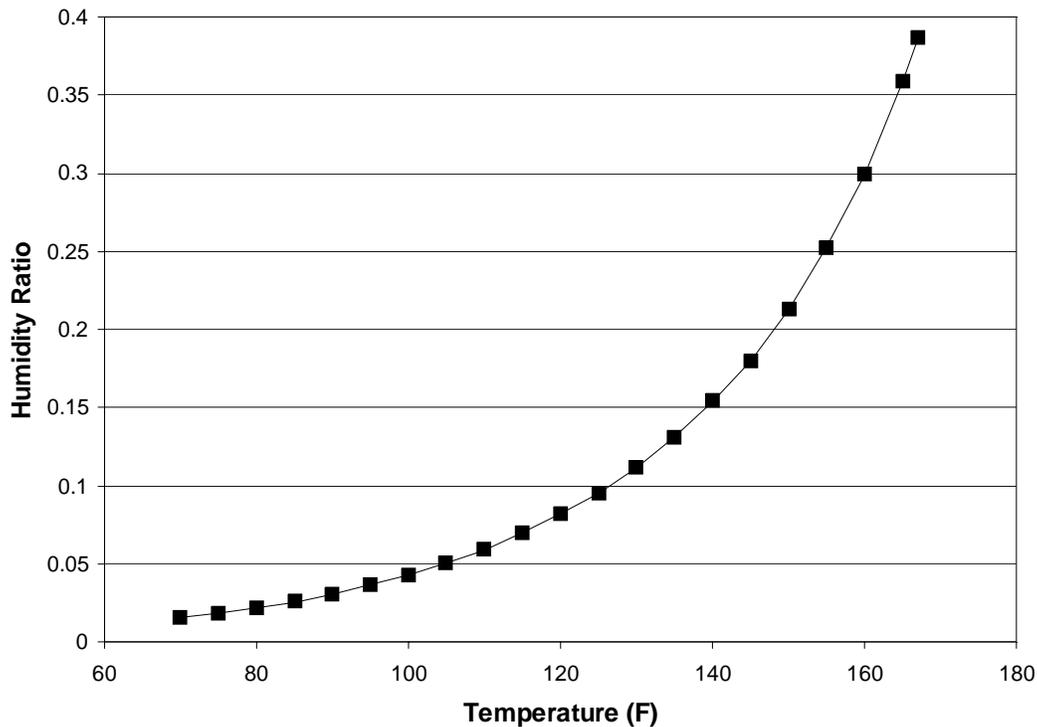


Figure 1. Atmospheric Humidity Ratios At Various Temperatures (data courtesy of the *ASHRAE Handbook – 1985 Fundamentals*)

Some of additional water beyond that entrained in the effluent at discharge may condense into an ultra-fine liquid aerosol that does not collect onto the cooling bed surfaces prior to discharge, and may be entrained to some degree (and possibly to an overwhelming extent) into the compartment as well, thereby adding some, or even a considerable degree of additional firefighting effectiveness. This excess water may vaporize further when mixed with dry air in the protected compartment, and provide additional extinguishing capability via phase change cooling (and the large amount of heat extraction associated with this process) at the fire site as this ultra-fine aerosol is dispersed and then entrained into the fire region. However, for this very conservative analysis, only the gaseous water vapor component known to exit the extinguisher unit at its exhaust temperature is considered further here, although it may significantly under-predict actual performance of these systems under actual conditions, which to otherwise characterize would require additional rigorous analysis and possibly extensive experimental data.

System Sizing Estimates, Comparisons to Existing Alternatives and Behavior Impacting Performance Limits

The author is not aware of any officially approved or universally accepted “cup burner” extinguishing concentration values published in the literature for water vapor, with this experimental criterion being the most widely accepted technique for adopting formal required extinguishing concentration standards for extinguishing agents approved for various total flood applications, such as standard NFPA 2001 for the design of clean agent fire extinguishing

systems [2]. The lack of this widely accepted concentration standard could impede any further analysis of the use of water vapor in whole or as a part of a clean agent option for total flood fire extinguishing. However, Dr. Joseph Senecal of Kidde Fenwal, Inc. recently published a paper [3] outlining a fundamental analysis and subsequent theoretical criterion developed to both explain and reproduce the published experimental cup burner results of inert gases based upon their purely physical heat extraction mechanisms, and to serve as a predictive tool of the anticipated cup burner values expected for inert gases and blends based upon their heat transfer properties. In fact, Dr. Senecal was able to theoretically reproduce the cup burner values for a number of inert gas blends now available for use in the marketplace, by pro-rating the heat transfer properties of each blend component based upon their volumetric, or molar, proportions in the blend. This mathematical criterion formula was further simplified for the consideration of heptane flames, as is used in a standard cup burner, resulting in the following expression:

$$X_G = (0.0415h_G + 1)^{-1} \quad (1)$$

where X_G is the predicted cup burner extinguishing concentration, and h_G is the enthalpy change per mole of the inert gas from 1871 K (the expected flame extinction temperature when using nitrogen as a representative gas in a cup burner) to a reference value of 298 K.

This tool and criterion, which was shown to accurately predict values in the range of published cup burner data for a number of inert gases based upon a fundamental heat transfer property, provides a means of accurately estimating theoretically the expected cup burner concentration for water vapor, based upon its relevant enthalpy properties in a vapor state. As was shown in this previous cited work with other inert gases, it can be used to estimate cup burner values for various proportional blends of nitrogen and water vapor, as is exploited by the N₂ Tower system. This tool was used to evaluate nitrogen/water vapor blends at a range of temperatures from 70 F to 167 F, since their relative proportions in gaseous form are dictated by the humidity ratios at saturation at a given temperature. These ratios are converted to volumetric or molar proportions, and then a pro-rated molar enthalpy difference can be calculated, and inserted into Equation (1). It was found that, due to the range of water vapor/nitrogen ratios over the temperature range, and the relative volumetric superiority of water vapor over nitrogen in physic fire suppression, that predicted blend cup burner values ranged from 31.7 percent to 29.7 percent (at the highest temperature), versus 31.9 percent predicted for nitrogen (it should be noted that for a “pure” water vapor blend at 167 F, a cup burner value of 26.7% would be predicted, if such an atmosphere could be created at that temperature). This improvement appears quite modest, and is largely due to the smaller proportions of water vapor present, and the small enhancement in heat extraction by water vapor over nitrogen on a volumetric basis.

However, the enhancement is more clearly seen when considering its efficiency on a mass basis. To consider this, the protocol used by NFPA 2001 for clean agents is applied, such as when designing a total flood extinguishing system for an application. In accordance with this standard, these concentrations (presuming that they were the officially accepted cup burner values) are increased by 30% to provide protection for Class B fuels. They are then adjusted for the increased proportions relative to the compartment to be protected beyond the cup burner concentration due to some agent leakage during discharge as it builds up to the design concentration (a “free efflux” model), and then adjusted downward for higher final compartment temperatures due to the increased specific volume of both the compartment and agent gas (which

fills up a higher proportion of the fixed room volume for a given mass). These volumes are converted into system agent masses for a given compartment size, which varies based upon the final room temperature, both due to the specific volume of the gas, and the proportion of water vapor that remains in a vapor state after discharge. This same protocol was applied to a conventional Halon replacement, HFC-227ea, and the masses of both, sufficient to protect a 1000 cubic foot enclosure, for a range of final room temperatures, are shown in Figure 2.

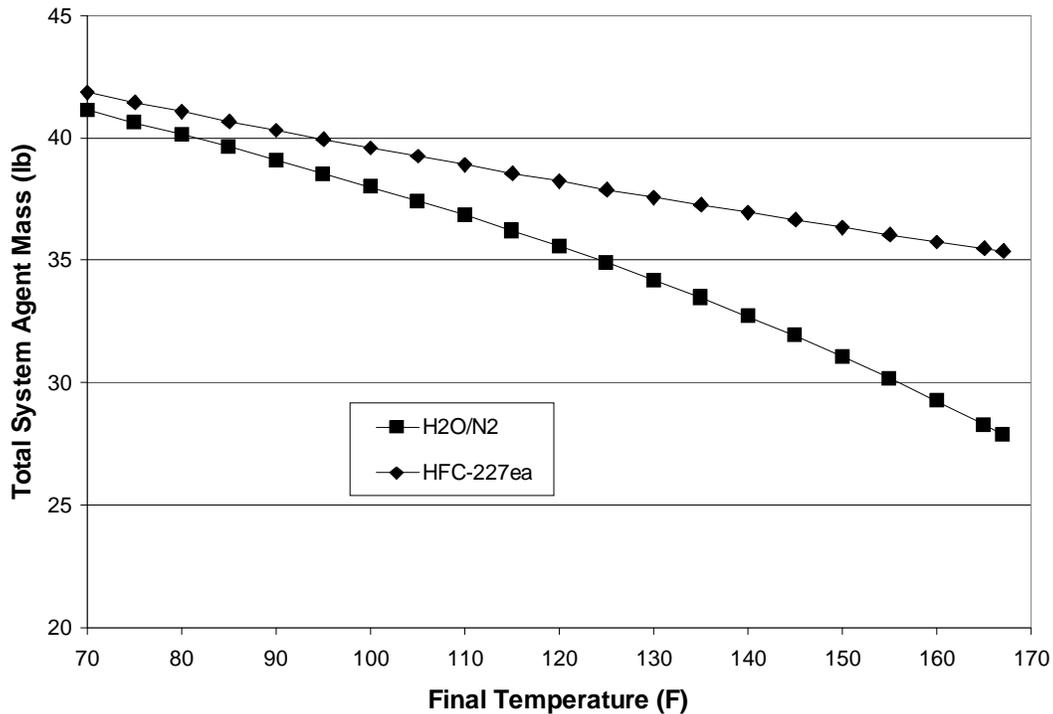


Figure 2. Agent Requirements for 1000 Cubic Foot Enclosure – Various Temperatures

The differences in mass requirements between the conventional HFC-227ea and water vapor/nitrogen blend are shown again to be modest with both at ambient room temperatures, but as the room temperature rises, the differences are more significant. This is due to the rapid increase in the amount of efficient water vapor that resides in air if the final room temperature after discharge is higher. The most important point to note is that gas generator-based systems like the N₂ Tower system can “artificially” raise the room temperature temporarily after discharge to increase its performance, since the agent discharged is significantly higher in temperature than the initial compartment temperature. Therefore, the most relevant comparison in Figure 2 is between the HFC-227ea value at ambient temperatures, since most discharges of such agents will even cool the compartments to some degree, and the nitrogen/water vapor blend values at elevated temperatures, due to the warm agent discharge in the enclosure. As an example, the 41.83 lbs. of HFC-227ea agent required can be reduced down to as much as 27.87 lbs. of nitrogen/water vapor required if the room temperature rises as much as agent discharge temperature, a decrease of 33% over the state-of-the-art. Final room values cooler than this extreme will reduce this performance enhancement – the challenge is to determine the actual final enclosure temperatures expected to be observed when appropriately designed systems are discharged.

Estimates can be made of the expected final enclosure temperature by performing a heat loss and gain balance between the warmer agent discharged into enclosure, and the cooler gas originally residing in the enclosure. A temperature at which the heat liberated by the agent volume and the heat gained by the remaining enclosure gas are equal becomes a final equilibrium temperature that both the agent gas and enclosure atmosphere reach. Figure 3 is a plot of such a heat balance between the original compartment air and the discharged agent air, for a range of possible final room temperatures, for agent amounts appropriate for the final compartment temperature. The final water mass remaining in the room is adjusted for the final enclosure temperature and the fact that the original enclosure gas can retain additional water vapor rather than letting it condense. The heat lost by the agent is a result of the enthalpy difference between the discharge temperature (167 F) and the final enclosure temperature, with contributing heat loss quantities from the respective volume portions of both the water vapor and nitrogen. The heat gained by the portion of the original enclosure volume that remains after discharge is determined by the enthalpy change between original enclosure temperature (70 F) and the final enclosure temperature. Figure 3 shows that the balance of heat loss and gain to a final equilibrium temperature occurs at approximately 115 F, which the extinguishing system should be sized for. At this temperature, a minimum weight reduction of 13.4% over an HFC-227ea system of similar performance is observed.

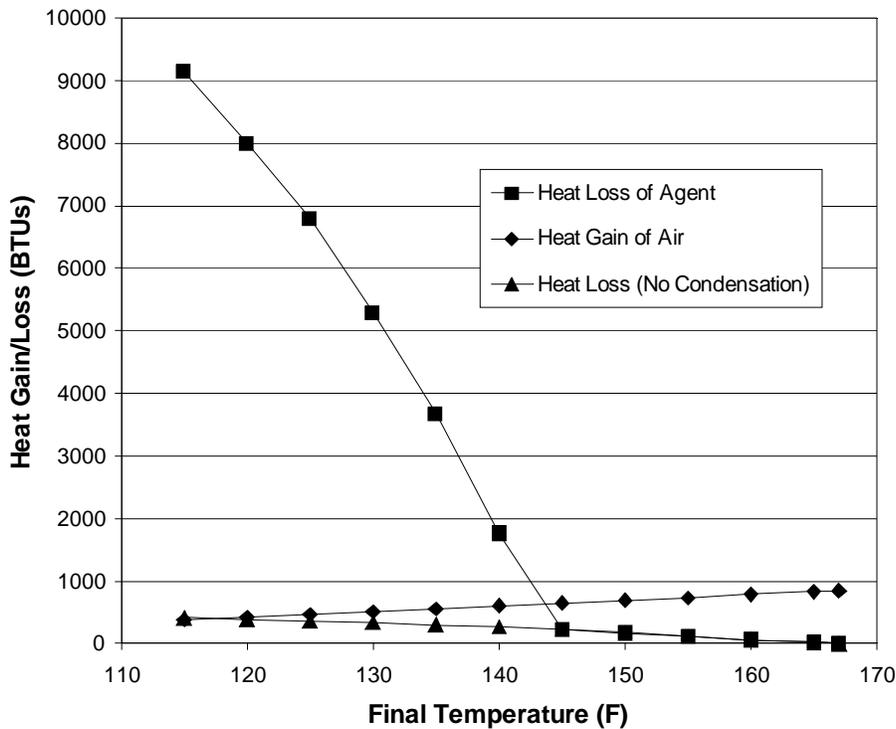


Figure 3. Heat Release and Loss Balance During Agent Discharge

However, one can also estimate that some of the excess water vapor will condense as the room cools from the discharge temperature, and in the process will liberate additional heat during condensation, with the excess heat thereby increasing the inherent final temperature of the enclosure. This heat release can also be estimated and added by considering the heat of vaporization (or condensation) of the excess water vapor until it reaches equilibrium, which can be a considerable quantity due to the large values for water phase change. This additional graph,

adding the sensible and latent heat releases, is also added to Figure 3, and it reveals that this excess heat source results in a much higher final equilibrium temperature, near 145 F in this instance. This results in a much more efficient system and lower agent mass that is 23.7 percent lower than a comparable HFC-227ea system. It should be noted that the discontinuity in the curve with the condensation-based heat release is due to the fact at this temperature and above, all of the vapor released from the unit at 167 F remains in vapor state even as it cools, due to the additional enclosure volume that can absorb the additional vapor at cooler temperatures, leaving no excess vapor to condense and liberate additional heat. The expanded atmosphere, including the original room volume remaining, in effect provides additional capacity for vapor residence, and if one presumes that some condensed aerosol is discharged from the extinguisher without totally collecting inside (as has been observed in test), than higher concentrations of water vapor are possible, also with additional excess liquid aerosol thermal ballast at high temperature to raise the overall room equilibrium temperature. Although one might consider a “pure water vapor” atmosphere at the discharge temperature of 167 F as an upper asymptote of performance, with a corresponding 48.9% reduction in agent weight over an HFC-227ea system, additional cooling of the fire by the remaining water aerosol (if present) may push the performance limits even further, although such complex mechanisms can only be confirmed further by experiment.

Summary

The capability of providing improved performance of inert gas-based agents by using gas generator devices to both generate them, raise their discharge temperature and effective specific volume, while also generating water vapor as an additional highly effective inert that remains in vapor state to a higher degree at elevated temperatures, provides additional engineering optimization opportunities not seen heretofore. The exploitation of the excess temperatures available with these units to use water vapor effectively as a gas for the duration of discharge provides a breakthrough in performance and design. The analysis of the water vapor and nitrogen gas agent components alone in this study reveals significant agent mass reductions are possible over state-of-the-art hydrofluorocarbon-based systems available today, as well as other benefits in toxicity and environmental traits. Additional water-aerosol by-products released can also provide additional performance enhancements, but must be characterized further. The encouraging results to date with full-scale gas generator breadboard systems, which have not been optimized in performance to date, suggest that such additional experiments are warranted.

References

1. ASHRAE Handbook – 1985 Fundamentals, American Society of Heating, Refrigerating and Air Conditioning Engineers, Inc., Atlanta GA, 1985.
2. *NFPA 2001 Standard for Clean Agent Fire Extinguishing Systems*, 2000 edition, National Fire Protection Association, Quincy, MA.
3. Senecal, Joseph A., “Flame Extinguishing Concentration by the Cup Burner Method: Inert Gas Theory, Performance & Advancing the Method”, 2003 Halon Options Technical Working Conference, Albuquerque, NM., May 2003.