Liquid Nitrogen as a Fire Extinction Agent

Yiannis A. Levendis
Department of Mechanical and Industrial Engineering
Northeastern University
Boston, Massachusetts, USA

ABSTRACT

Results on fire extinction using direct dumping of the cryogen liquid nitrogen are presented. This technique is targeting challenging and dangerous fires, such as chemical fires, liquid pool fires, etc., where expedient extinction is paramount in order to prevent explosions, avoid release of toxic fumes and avert environmental disasters. Liquid nitrogen, although seemingly challenging to deliver, may provide firefighters with an expertise method for fire extinction in the most demanding situations. Directly application of this cryogenic liquid onto a pyrolyzing surface causes its vaporization and abrupt expansion. The pyrolyzing gases are inerted, the pyrolyzing/burning surface is cooled further reducing its pyrolysis rate, air is separated from the fuel and the fire extinguishes.

Liquid pool fire experiments have shown that as soon as small quantities of liquid nitrogen reach a burning surface they change phase and expand, forming a cylindrical cloud spreading over and near the surface. The following major fire extinction mechanisms apply simultaneously: (i) surface cooling because of the very low temperature of this cryogen and effective heat transfer by boiling; (ii) inerting of the surrounding atmosphere, which starves the fire from oxygen; (iii) rapid expansion (like a mild explosion) followed by gravity spread that results in blanketing of the surface with a cloud of condensed water, and possibly some fuel, vapors. This cloud also blocks radiation from adjacent flames to the pyrolyzing surface. As the temperature of liquid nitrogen is very low (77 K), these sequential processes are very expedient. Different examples of hydrocarbon pool fire extinguishment are discussed herein.

INTRODUCTION

Fire is one of the leading causes of loss of property and life around the world. There are inadequacies with current techniques for extinction of fires in power plants, chemical plants, fuel storage installations, warehouses, etc. Many such fires are difficult to control in a timely fashion and are often threatening to their surroundings. Fires at tire dumps have been reported to burn for months with environmental consequences. Thus, in cases where currently used extinction agents and methods are only partially effective, new techniques may find applications. This is also true in the case of some other warehouse or industrial fires where water may be applied, but where water damage needs to be prevented or minimized. Hence, along with the continuous development of fire prevention and early detection methods, new fire extinguishing agents and techniques are also needed.

This work aimed at exploring the beneficial effects of direct application (dumping) of liquid nitrogen in bulk in fires. The cryogen may also be applied (tossed) encapsulated in fires. The
capsules should be vented and be of a material that melts or shutters upon impact. In principle, the cryogen may be applied in many types of fires, both open and closed. Certainly, there are some obvious limitations, i.e., the cryogen should be applied to locations where no living beings are present, since it is both a freezing and asphyxiating agent, especially in closed compartments. The cryogen should also be handled carefully since skin contact may result in frostbite. Otherwise, mature technologies exist and installations are in place for the production, handling, distribution and storage of this cryogen at widespread locations. The cryogen is safe for the environment and it is relatively inexpensive (in the order of $1 per liter or per gallon, depending on the purchased quantity). Liquid nitrogen may provide firefighters with an expertise method for fire extinction in some most demanding situations. Various technologies are envisioned for delivering liquid nitrogen to fires, including delivery by an insulted hose, direct dumping (pouring) from a distance of the cryogen in bulk, or tossing cryogen in the fire in vented and insulated containers (e.g., styro-foam) that will open upon impact or burn in the fire. Application of liquid nitrogen may be used alone or in conjunction with other conventional methods, such as those using water in the form of sprinklers or direct water hose impingement. In this work the cryogen was delivered (dumped) in bulk.

By directly applying this cryogen onto a pyrolyzing/burning surface an abrupt phase change and a subsequent thermal expansion takes place. The vaporizing cryogen forms a cloud over the pyrolysing/burning surface, therefore, the surface is cooled thereby reducing the pyrolysis rate, the pyrolysis gases are inerted, the fire is starved from oxygen and it extinguishes. The pyrolyzing surface is then blanketed for a short period of time with nitrogen gas and re-ignition is impeded. It was calculated that a direct application of a small quantity of liquid nitrogen (at 77 K) on a pyrolyzing/burning horizontal surface initially causes rapid evaporation to gaseous nitrogen still at 77K, an expansion of 180 times, and then to gas at a higher temperature in the inner core of the flame, which is in the order of 1000 K. This would constitute an additional 13 times expansion, or a total expansion of 2000 times. If the expanding gases were to form a hemisphere over the flat surface, then a 1-milliliter quantity of liquid nitrogen (a teaspoon full) would form a cloud of 0.33 m in diameter. This was, indeed, the case observed in the initial laboratory experiments described herein. In reality, the cool vapor cloud is, actually, flatter than a hemisphere, more likely in the shape of a stubby cylinder (resembling a 'pancake') because of gravity. The key point here is that this expansion is typically very fast, like a mini-explosion, with a duration in the order of seconds. In cases where instantaneous evaporation is realized then the size of the flame that can be extinguished is maximum. In those cases where the evaporation of the cryogen is slower because of cooler surfaces, or if obstacles to the spreading of the cryogen exist, then additional quantities of cryogen need to be applied. This exploratory investigation focused on pool fires of various hydrocarbon fuels, however, other types of fires certainly merit future investigation.
RESULTS

Experiments with small alcohol pool fires.
The effectiveness of liquid nitrogen was first demonstrated in a bench-scale experiment at Northeastern University (NU) in Boston. These preliminary experiments dealt with a fire over a shallow (1 cm) pool of iso-propyl alcohol, 20 cm in diameter, see Fig. 1a. It was first attempted to extinguish this fire with a milliliter (teaspoon quantity) of water thrown to the fire in bulk from a one-meter distance, directly above the flame. This attempt was not successful. It was found that sequential dumping of several milliliters of water had no permanent effect on the fire. To the contrary, a single milliliter of liquid nitrogen, thrown from the same distance, successfully extinguished the fire. The extinction of the flame appeared to be nearly instantaneous. This striking effect is documented in the pictorial sequence of Fig. 1 (a-d).

![Figure 1](image1.png)

Figure 1. Photographs from the exploratory experiments at Northeastern University (a) a 20-cm diameter fire over a 1 cm deep pool of iso-propyl alcohol, initially; (b) after a one milliliter (a teaspoon-full) quantity of liquid nitrogen was dumped in the fire, the fire was extinguished instantaneously; (c-d) photographs of the blanketing nitrogen cloud upon extinguishment of the pool fire.

Experiments with large Diesel oil pool fires.
Demonstrations were subsequently performed at the Boston Fire Department's Training Academy. In these experiments a sizable pool-fire of diesel oil and gasoline was ignited on a thick layer of water (5 cm). The tank size was 1 square meter. The tests were conducted outdoors, at the presence of a strong wind (20-40 mph). A bulk quantity (1 liter) of liquid nitrogen was manually distributed over the fire, using a bucket attached to the tip of a horizontal pole. The fire was quickly extinguished.
Systematic large-scale experiments were conducted at CSIRO's laboratory at Sydney, Australia and the other series was conducted at the laboratories of Mutual Factory Research at Norwood, Massachusetts, USA.

The work at CSIRO involved fires of two different fuels (propanol and diesel oil) ~1 square meter pools, 2.5 cm deep. The pan containing fuel was placed inside a bigger pan containing water. One liter quantities of the cryogen were gently poured from a small height (15 cm above the fire) at different locations, such as: (a) at one corner of the fuel pool (inside pan); (b) along the floor, outside of both pans. The first type of experiments were remarkably successful; as the cryogen was poured at one corner of the fuel pool it spread all over the fuel pool and extinguished the fire instantaneously (in the order of 1 sec.). The cloud of nitrogen then spread over the outside water pool and subsequently over the laboratory floor, covering an area of approximately 3 meters in diameter. The height of the cloud was only 15-20 cm, because of gravity. The coverage of that area by the nitrogen vapors, upon extinguishment of the flame, lasted for approximately 2 minutes. This technique was also successful at the presence of wind, generated by a fan blowing on the flame, the cryogen being poured at a corner upstream of the flame. The second type of experiments was not successful in most cases, with one notable exception. Successful extinguishment was accomplished with the cryogen poured outside of the pool of fuel, at the presence of wind. The cryogen was poured upstream of the fire. The cryogen vapors were effectively carried by the wind over the fire, mixed with the burning gases and inerted them. Thus, the experimental series at CSIRO revealed that flames of 1 square meter may be successfully extinguished with 1 liter of cryogen poured at one corner of the flame. Both gasoline and diesel oil fires were extinguished.

The experiments at the Factory Mutual Research laboratories were performed with 1 cm or 5 cm deep, 45 cm in diameter, heptane pool fires on a layer of water. Remote control equipment was specially constructed for delivering one-liter quantities of cryogen, see Fig. 2a. An insulated container (thermos) carrying the cryogen was pulled with a cable directly above the targeted area and then it was capsized to empty its contents on the pool fire. This was done from a height of 2-4 meters over the pool. In most cases dumping of liquid nitrogen splashed some the burning fuel out of the pans, spread it to the floor and resulted in a very wide fire, which was not always successfully extinguished. To remedy this problem liquid nitrogen was poured through a perforated metallic hemisphere (strainer), which spread many narrow streams of liquid over the flame. The observed results were as follows:

The 1 cm deep fires were successfully extinguished when 1 liter of liquid nitrogen was dumped from heights up to approximately 2 meters. Dumping the same quantity of cryogen from higher elevations did not extinguish these fires, because of the evaporation loss of the cryogen and because some of the cryogen fell outside the flame. The 5-cm deep fires could not be extinguished by dumping 1-liter quantities of the cryogen. It is possible that the extinguishment of the shallower (1 cm) pool fires was possibly aided by the deeper lip of the emptier pan, which helped confine more of the cryogen vapors over the fire.

An important observation during the experiments was that upon dumping liquid nitrogen into the 5 cm deep heptane pool fire, the fire would increase in height by approximately a factor of 1.5-2 and it would also increase in diameter. The increase in diameter was readily explained,
because of spilling of the fuel outside of the pan. Such spilling was minimized when the
dumping was not in bulk but it was more distributed, as was the case when the strainer was
used or when the cryogen was manually distributed close to the surface. The initial intense
flare-up of the fires of this particular fuel, with the notable increase in height, was evident in
most experiments. This behavior was rather unexpected, as it was never noticed before in the
other fuel pool fires, such as those involving propanol, diesel fuel (mixed with some gasoline).
Those fires did not flare up and were readily extinguished with application of smaller
quantities of cryogen, in relation to the fires of heptane.

It appears that this important difference in behavior on putting out fires of heptane in one hand
versus fires of propanol, gasoline or diesel fuel on the other hand relies in the specific gravity
of the fuel in the pool, in relation to that of the cryogen. Liquid nitrogen has a specific gravity
of 0.8; propanol (0.804), and diesel fuel (0.84-0.88) have comparable or higher values, hence,
liquid nitrogen stays mostly on the surface of the pool, where it evaporates and extinguishes
the fire. On the other hand, heptane has a specific gravity of 0.68. The liquid nitrogen sinks
below the surface of this fuel pool. The cryogen then evaporates inside the body of the warm
fuel and nitrogen vapors bubble back to the surface. Such bubbles create an effervescence
effect (like a carbonated beverage in a glass), which brings fuel vapors and tiny liquid drops to
the surface. This effect flares up the fire. Evidence for this hypothesis was provided by close
up photographs taken during the tests. A deep pool can exacerbate this effect because it allows
more time for effervescence. This was the case in some tests. Moreover, the hotter the pan and
the contained fuel, the more this effect was pronounced. Therefore, it may be concluded that
the specific gravity of the fuel is another parameter of importance in pool fires. Under certain
circumstances, this fire extinguishment technique appears to be more effective in the case of
liquid fuels with higher specific gravity than the cryogen or in the case of flammable
devolatilizing solids. In such cases the liquid cryogen will spread, vaporize and cover a large
surface area. In the case of liquid fuels with lower specific gravity than the cryogen, such as
heptane, the cryogen should be applied in fine dispersion, perhaps as drops, to be effective.

In conclusion, this last set of experiments showed that there is a minimum amount of cryogen
needed for a given fire size, there is a maximum height from which the cryogen may be
delivered, and that a good distribution of the cryogen over the fire may not be always
necessary. In deep pool fires abrupt dumping of cryogen in bulk may induce splashing of
burning fuel to a large area. The specific gravity of the liquid fuel appears to be an important
parameter. The existence of wind may be used to an advantage if the cryogen is applied
upstream of the fire. Then the wind may carry and spread the nitrogen vapors over the fire and
blanket it.

ACKNOWLEDGEMENTS
The author would like to acknowledge help and support in all levels of this work by Dr.
Michael Delichatsios. Help from Hong-Zheng Yu and Hsiang-Cheng Kung at Factory Mutual
Research is also acknowledged. The enthusiastic participation of the staff at the Boston Fire
Department's Training Academy at Moon Island, Massachusetts is appreciated.
Figure 2. A 1 cm-deep, 45 cm in diameter pool fire of heptane is extinguished by dumping 1 liter of liquid nitrogen from a height of 2 m. The test was conducted at the laboratory of Factory Mutual in Norwood Massachusetts.