

Design of Liquid Nitrogen Capsules for Forest Fire Suppression

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Abstract—

In recent years forest fires have become increasingly frequent, increasingly large and, hence, increasingly catastrophic. As these fires burn unchecked, firefighters strive to extinguish them by dropping water onto affected areas with aerial delivery methods, such as planes and helicopters. Past research at Northeastern University [1], [2] showed that direct application of liquid nitrogen is very effective at extinguishing fuel pool fires and, thus, research was initiated to explore the application of liquid nitrogen to forest fires. It is hypothesized that liquid nitrogen would be effective at suppressing forest fires, most likely as a two-part approach. Initial application of liquid nitrogen can suppress the flames and subsequent application of water can extinguish deep-seated fires in the pores of the wood [1]. Herein, as an initial step to realize this approach, a capsule was designed to deliver liquid nitrogen to forest fires. This capsule is designed to insulate the liquid nitrogen and minimize in-transit vaporization, whereas incorporation of exterior fins is expected to impart a controlled spin as the capsule falls from the helicopter. This spin will eject liquid nitrogen, which can create a sprinkling effect as it reaches a crown fire whereas any liquid nitrogen remaining in the capsule will be ejected upon impact and will affect the bottom fire. The capsule is made of a single injection molded piece to be cost-effective. Initial tests proved the insulating, spinning and spilling capabilities of the capsule. No fire tests have been conducted yet.

I. INTRODUCTION

Forest fires are becoming increasingly common around the globe as increasing population, water usage, droughts, and global climate change induce favorable conditions. From 2007 to 2011 an average of over 75,000 wildfires occurred each year costing a total of over \$8 billion [3], [4]. Currently, ground crews use a combination of water, fire, and trenches to contain a fire long enough that it can burn out [5]. Once a fire has spread to an area, it cannot be permanently extinguished, and the area cannot be saved. Airplanes and helicopters cannot carry enough water to effectively suppress forest fires, and much of the water evaporates before reaching the fire [5]. More acres of woodland were damaged from 2005-2009 than in the entire 1990's [4]. Current fire containment methods are failing to keep pace with the number and intensity of forest fires that are seen today, suggesting that additional research is required into more effective fire suppression methods.

Previous research at Northeastern University demonstrated the effectiveness of direct application of liquid nitrogen (LN_2) in extinguishing fuel pool fires [1], [2]. It was found that bringing the cryogen into contact with a pyrolysing/burning surface causes an abrupt phase change followed by a very large thermal expansion. LN_2 absorbs more energy to vaporize and heat up in a fire than water (H_2O), as it is colder and has a thermal expansion ratio of 1:694, and approximately 1:1,000 when exposed to flame temperatures [6]. The vaporizing cryogen forms a cloud over the pyrolysing/burning surface, thus cooling the surface and thereby reducing its pyrolysis rate. Therefore, the pyrolysis gases become inert and the fire is starved of air. These phenomena lead to expedient fire extinction. The pyrolysing surface is then blanketed for a considerable period of time with nitrogen gas and re-ignition is impeded.

Forest fires can be of considerable magnitude, and may require tremendous resources to suppress and, eventually, extinguish. Therefore, it is expected that the application of LN_2 to forest fires will be particularly challenging, due to (a) the very large size of such fires and (b) to the fact that fire enters the pores of wood as it burns. Hence, extinction of the burning pyrolyzates of wood can still leave smoldering embers burning behind. Regarding the size of the fire, it would be prudent to confine this technique in addressing only limited areas of critical need (nascent fires, important infrastructure, houses, etc.). Regarding the extinction of smoldering wood embers, a two-step approach is envisioned: application of LN_2 to suppress the flames followed by sequential application of water to quench the smoldering wood embers.

Overcoming the energy transfer as the cryogen approaches the fire is critical. The temperature of a forest fire is considerably high, rendering both convection and radiation as significant modes of energy transfer to the cryogen. Forest fires are, by nature, huge and difficult to extinguish. This means that any potential solution has to be implemented on a large scale and, more realistically, to a targeted area. This suggests the solution should be economical enough to be implemented on a large scale, scalable from a production and manufacturing perspective, and environmentally benign. In order for the proposed method to be acceptable, it would have to outperform or at least complement conventional fire suppression methods in all of the major categories stated above.

Extensive research did not yield a single solution, either using cryogen or with conventional methods, which could target all three phases of the forest fire. Furthermore, no cryogen

solutions found were economically feasible, as delivery costs were significantly higher than the proposed solution, with a significantly lower coverage.

The capsule solution proposed in this paper was developed by using an analysis-based approach validated by testing. Initially, the problem was approached from a thermal perspective, and a mathematical model was created of the thermal effects of a forest fire. This was based heavily on previous research [7], [8], [10]. This model was then expanded to include a droplet of liquid nitrogen descending to the fire below. Further expansion lead to a model that was based on the capsule approach presented herein. Testing was simultaneously conducted to validate this thermal model with steady state nitrogen vaporization. Additional testing was conducted to determine coefficients of drag and lift. Fluid ejection testing was conducted to validate the dispersion mechanism and the calculations for fluid coverage. Finally, the capsules were dropped to see all aspects of the design at work. Throughout this process, capsule parameters were changed and the capsule evolved from a purely theoretical design to a complex part with moldable geometry fit for mass production.

II. THERMAL CONSIDERATIONS

The first part of this problem was ensuring that LN_2 would reach the forest fire without vaporizing. While gaseous nitrogen can extinguish a fire, delivering nitrogen in a liquid state extinguishes more fire per unit of nitrogen. In theory, vaporized nitrogen would continue to descend due to its lower temperature and density, but the intense updrafts known to occur in forest fires, as well as potential wind conditions, make delivery of gaseous nitrogen undesirable. The nitrogen must also be transported to the drop location, and during transportation vaporization will occur.

A. Anticipated Forest Fire Temperatures

The minimum safe distance from a forest fire was used as the minimum drop height. This was based on a review paper of several models used to calculate the safe distance based on radiation. A distance of four times the flame height was considered safe by all models in all conditions [7].

Eq. 1 below was used to calculate the temperature profile above a fire. This was developed in an analysis of the temperature distribution of the air above a burning house, and slightly modified for this application [8].

$$T_{air} = T_{\infty} + \sqrt[3]{\frac{q_{rad}^2 \times A_f^2 \times T_{\infty}}{C_{pair}^2 \times \rho^2 \times g}} \times \left(\frac{9.115}{P^{\frac{5}{3}}} \right) \quad (1)$$

Where A_f is the approximate area of the forest fire in m^2 , T_{air} is the temperature of the air at that height in $^{\circ}\text{K}$, T_{∞} is the temperature of the air far away in $^{\circ}\text{K}$, q_{rad} is the energy flux due to radiation in W/m^2 , C_{pair} is the specific heat of air in $\text{J}/\text{kg}^{\circ}\text{K}$, ρ is the density of the air in kg/m^3 , g is the acceleration

due to gravity in kg/m^3 , and P is the height for which the temperature is being calculated in meters.

This correlation in Eq. 1 approaches infinity as P approaches zero; therefore the maximum temperature of the air was set to equal the temperature of the fire. The temperature distribution has been plotted in Fig. 1. It was hypothesized that these elevated temperatures, even high above the fire, would impact vaporization during transport. Testing later validated this hypothesis. In response, a conceptual design of an insulated and automated capsule release device was developed.

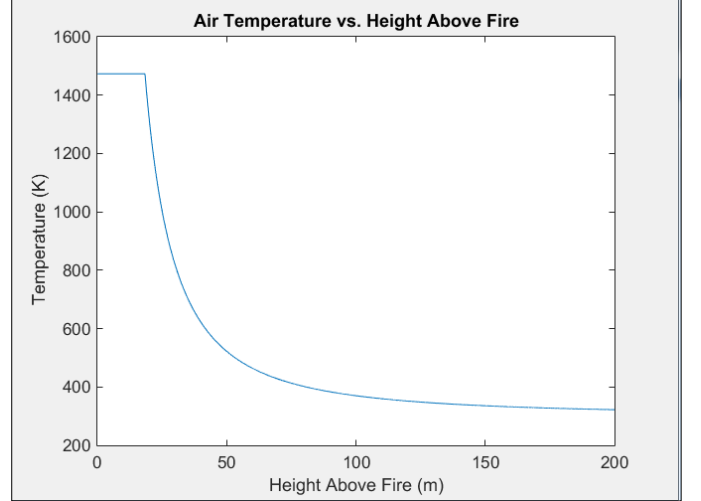


Fig. 1. Calculated temperature distribution at a given distance above a forest fire. Notice that the temperature at the capsule release point, 200 m above the fire, is still approximately 322 $^{\circ}\text{K}$ (120 $^{\circ}\text{F}$).

B. Anticipated Forest Fire Radiative Heating

Using a previous study on the radiative heat flux emitted by various types of fires as a starting point, the variation of the heat flux over a distance was found [9]. The magnitude of the radiation was determined based on research into radiative heating due to large-scale forest fires [10]. It has been reported that the maximum radiative energy flux given off by a forest fire was $300 \text{ MW}/\text{m}^2$ [10]. This energy flux was measured between the forest fire and a measuring device initially at room temperature [10]. Since radiative energy flux is known to vary according to the difference in temperature to the fourth power, the difference in temperature between the measurement probe used in the study and the LN_2 used in that application was accounted for [9]. The resulting expression for radiative heat flux at a given distance from the fire is given in Eq. 3. Notice that the variation of heat flux with respect to distance is approximately halfway between the inverse r^2 law and the temperature variation found by S. Yokoi in Eq. 1, which reinforces the plausibility of the result obtained herein [8], [9]. To calculate the energy transferred by radiation the view factor for an infinite plane on a spherical object (1/2) was used [9].

$$q_{rad} = \frac{300 \times 10^3}{P^{1.87}} \times \left(\frac{T_f^4 - 77^4}{T_f^4 - 300^4} \right) \quad (3)$$

Where q_{rad} is the energy flux due to radiation in W/m^2 , T_f is the temperature of the forest fire in $^{\circ}K$, and P is the height for which the energy flux due to radiation is being calculated in meters.

C. Calculation of Liquid Nitrogen Droplet Vaporization

This first simulation was run to determine how a droplet of LN_2 would behave as it descends into a forest fire. This information is important in the determination of an effective delivery method. This simulation uses energy balance to calculate the mass of LN_2 , which is vaporized as a droplet falls towards a forest fire. The basic energy balance is shown in Eq. 4.

$$(q_{rad} + q_{conv}) \times \Delta t = \Delta m \times H_{fg} \quad (4)$$

Where q_{rad} is the energy flux due to radiation in W/m^2 , q_{conv} is the energy transferred due to convection in W , A is the surface area of the liquid droplet in m^2 , Δt is the time step duration in s , Δm is the vaporized mass in kg , and H_{fg} is the heat of vaporization for N_2 in Joules.

Due to the complex nonlinear relationship between these variables, this equation was not solved. Instead, a time based numerical solution was used to find the amount of nitrogen vaporized during each time step. The position of a free-falling droplet is changing as a function of time due to gravity. The position is calculated from the velocity at the beginning of each time step, which is in turn calculated using its acceleration. The acceleration of the droplet at any instant can be calculated through Newton's second law, with gravity and drag considered. The drag force is calculated by using the drag coefficient correlations for a spherical object.

As can be seen from Fig. 2, a droplet would need to have an unrealistically large diameter to reach the fire with a reasonable efficiency. When a bucket of water is poured out, the water separates into smaller droplets during its descent. This was not taken into consideration in this model, due to its complexity, but is not significant because even a large initial volume would be inefficient. It was determined that convection was the dominant form of heat transfer.

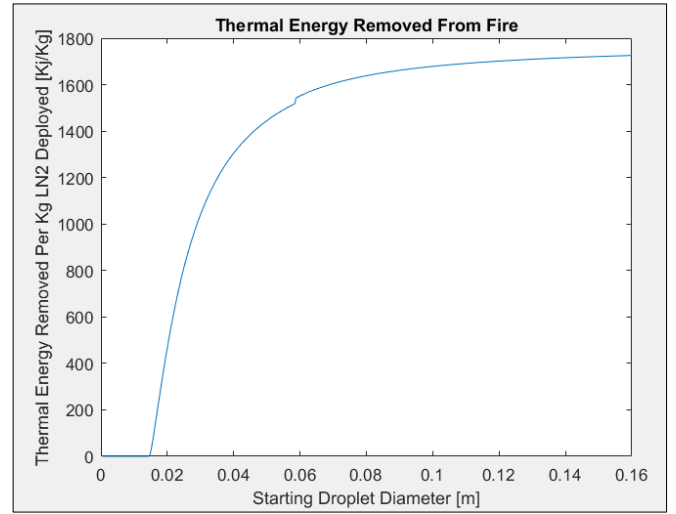


Fig. 2. Calculated thermal energy removed from the fire with different droplet starting diameters. Note that individual droplets would need to have a minimum diameter on the order of 2 cm, with a diameter closer to 10 cm being ideal. This is highly unrealistic, and prompted the development of a capsule based solution. The jump observed around 0.06 m diameter corresponds to a discontinuity in the drag correlations for a sphere near the Reynolds numbers observed.

D. Steady State Liquid Nitrogen Vaporization Testing

Steady state LN_2 vaporization testing was conducted to validate the model created to simulate the heat transfer effects through a capsule of various geometries and materials. This involved a series of experiments that included filling various cylindrical vessels and capsules of different volumes and materials with LN_2 . Materials, geometry, and volumes were selected so as to get multiple data points in all tested rows and columns of the testing matrix. Statistical analysis was used to extrapolate the effect of the relevant parameters. These parameters included thermal conductivity, wall thickness, surface area, volume, and relevant free convection coefficient. Rate of vaporization and overall time of vaporization was measured and compared to the predicted times. This allowed for verification of the heat transfer equations used in the model, and provided insight into desired material and geometric properties. The containers were tested after the temperature distribution within the container wall had reached steady state.

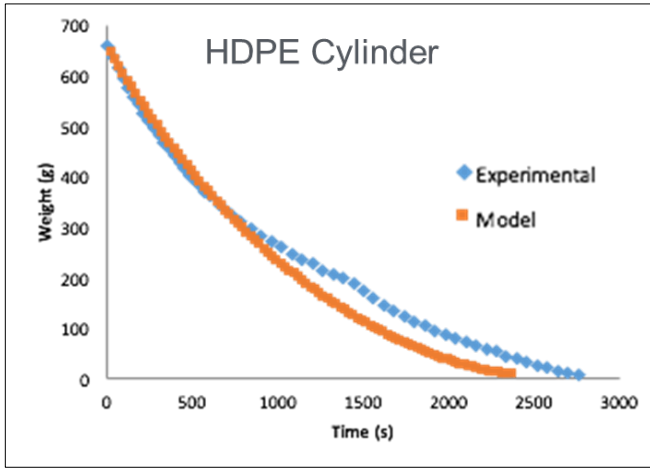


Fig. 3. A representative time series for cryogen vaporization at steady state conditions. This particular test corresponded to an HDPE cylinder. All model results were conservative like this figure shows. The major source of error in this model is the boiling equations, which had known errors of $\pm 100\%$ [11].

A representative cryogen vaporization time series is shown in Fig. 3. This is the predicted versus experimental data for a HDPE Cylinder filled with LN_2 . It can be seen that the model was found to be conservative. This was the case for every test run.

E. Falling Capsule Model

Upon extensive deliberations, it was decided that the most viable method for delivering the cryogen to the forest fire was a capsule. This resulted in a new model being developed, which calculated the heat transferred in three different regions: heat transferred to the capsule, heat transfer within the capsule, and heat transfer between the capsule and the LN_2 . Heat transfer in the first region was dominated by both convection and radiation, in the second region conduction was the only mode, and in the third region phase change (boiling) of the LN_2 was dominant. As the capsule design had an open or vented top, no pressure buildup was considered.

The first region, i.e., heat transfer into the capsule, was similar to the droplet model. The main differences being that the capsule outer diameter is constant, some heat transferred into the capsule is used to heat the capsule itself, thus, the temperature of the capsule was not assumed constant. The second region, heat transfer within the capsule, cannot be analyzed using traditional transient conduction. The difficulty is that this would have yielded a nonlinear result for temperature versus time [9]. Since the heat transfer equations used for boiling are highly temperature dependent, and nonlinear, this equation becomes unsolvable.

The solution to this was to write a computer program, which divides the capsule into a series of elements, and calculates the heat transfer in each element using energy balance. This finite element method is more accurate as the number of elements increases and the time step decreases. However, due to the duration of the fall and the number of elements, this solution increases the computation time exponentially. In order to balance this, the elements are sized to be the largest possible elements for which the lumped capacitance method is valid.

While this finite element solution is different than the lumped capacitance method, the assumption for the lumped capacitance method is that the temperature within the wall is essentially constant. For sufficiently small elements this assumption is still valid.

The initial temperatures for the elements in the capsule are calculated using steady state equations. It is assumed that the capsule is filled and then, after an amount of time, the capsule is topped off to replace the nitrogen, which is vaporized cooling down the capsule.

The final heat transfer region is from the capsule walls into the LN_2 cavity. This is governed by boiling correlations based mostly on convection. The amount of heat transferred to the nitrogen via boiling then results in the mass of nitrogen lost. For each time step this mass is calculated, and the simulation ends when the capsule either runs out of nitrogen, or reaches the ground.

This model was run for a series of spherical capsules made of PTFE. It was found that the capsule solution is much more efficient. Fig. 4 shows the percent of the LN_2 , which reaches the forest fire for given dimensions of a capsule. The tradeoff of wall thickness and amount of remaining cryogen in the capsule undergoing a 200-meter drop can be noticed.

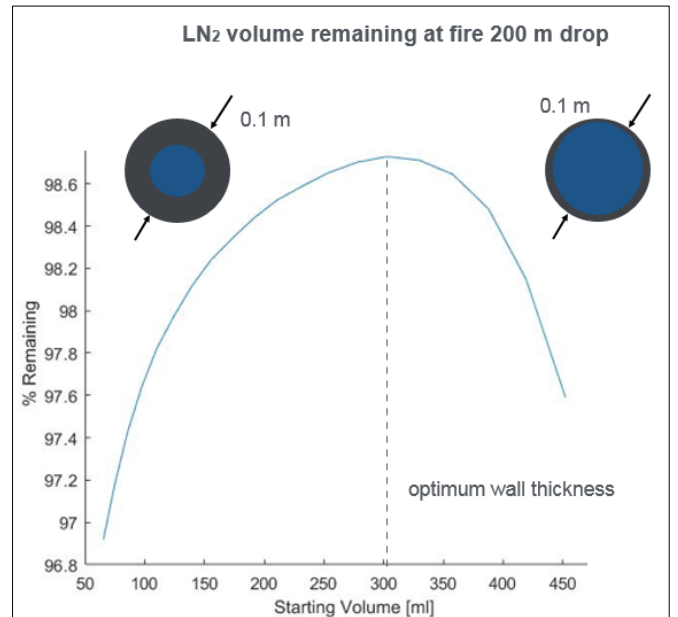


Fig. 4. Percent of original dropped volume remaining. The percent remaining reaches a peak value due to the combination of two factors. The first is that as the wall thickness decreases, any nitrogen vaporized corresponds to a smaller percentage of the nitrogen. The second is that as the walls become too thin they are no longer capable of insulating the nitrogen.

III. CAPSULE SPIN

At the desired forest fire location, the capsules will be released and will begin descending towards the fire. As a capsule starts falling, air will move across the fins on the outside of the capsule, which will impart a spinning force on the capsule. The inner wall of the capsule will exert a centripetal force on the nitrogen inside the capsule. This contact force, like all

elastic contact forces, is perpendicular to the surface of the capsule. Since the capsule geometry is semi-ellipsoidal, this force has a vertical component at all points on the inner surface. At low rotational velocities this force is balanced out by the gravitational force on the cryogen, but as the capsule starts spinning faster, the cryogen will start moving upward and will exit the capsule.

Since a certain rotational velocity is required for the nitrogen to leave the capsule, and the rotational velocity is a function of the lift force on the outside of the capsule, the capsule can be tuned to release the nitrogen at specific heights. This allows the capsule to target all three forest fire zones (crown, surface, and ground), while still insulating the nitrogen for the descent.

A. Capsule Descent Modeling

To perform an analysis of the drag force versus the lift of the body, the fins were approximated to be inclined at an angle tangent to the midpoint of the curved fin. The free body diagram in Fig. 5 shows the geometry for a falling capsule including the forces acting on it and the direction of those forces. The C_D and C_L values used were for a flat plate at a specific aspect ratio and angle of attack [12]. The velocity used to find the spin lift and drag components was approximated as the tangential velocity at the furthest distance from the fin tip to the central axis, in order to prevent integration, while ensuring a conservative estimate.

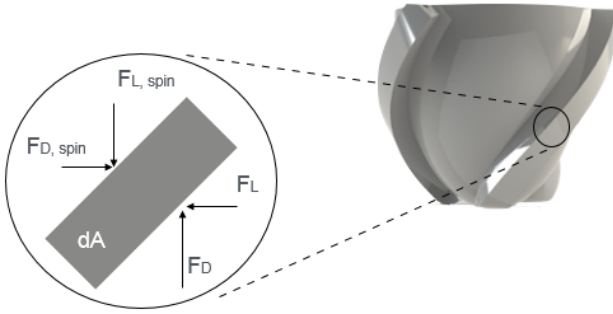


Fig. 5. Free body diagram of the fins on an early capsule design. The fins are the protrusions on the outside of the capsule. The capsule is hollow, with the liquid nitrogen residing within. From this diagram it can be seen that the drag on the fins reduces the capsule's velocity towards the ground, the lift on the fins causes the rotation of the capsule, the drag due to spinning opposes the rotation of the capsule, and the lift due to spinning propels the capsule downwards.

For the purpose of torque calculations, the distance where the spin drag and lift forces were applied at was two thirds of the way up the capsule, similar to the center of area of a triangle. The results from this model were later confirmed in wind tunnel testing.

These calculations were then integrated into a thermal finite element code. This resulted in a final model which calculated a list of variables including; position, linear and angular acceleration, linear and angular velocity, heat transfer in the form of convection and conduction into the capsule, conduction between elements within the capsule wall, heat

transfer in the form of convection into the nitrogen within the capsule, and mass of nitrogen removed. The equations of motion of the capsule are the following:

$$J\ddot{\theta} = D(F_{lift} - F_{Drag, spin}) \quad (5)$$

$$a = g - F_{Drag, Fin} + F_{Lift, Spin} - F_{Drag, Capsule} \quad (6)$$

Where J is the mass moment of inertia of the capsule in kg m^2 , D is the effective distance in m, F_{lift} is the lift on the capsule fins from the vertical velocity in N, $F_{Drag, Fin}$ is the drag on the fins due to the vertical velocity in N, $F_{Drag, Capsule}$ is the drag on the capsule due to the vertical velocity in N, $F_{Drag, spin}$ is the drag on the fins due to the rotational velocity in N, m is mass in kg, g is the gravitational acceleration in m/s^2 , and $F_{lift, spin}$ is the lift on the capsule fins due to the rotational velocity in N.

B. Wind Tunnel Testing

The paper used for lift and drag correlations had a wide range of values [12]. Since this was the governing parameter in nitrogen release, the team conducted wind tunnel testing to determine actual values. Airspeed measurements were taken on a Pitot tube, and a Go-Pro was used to record the position of the capsule.

After testing, the video recordings from the Go-Pro were used to calculate the angular speed for the three different wind speeds that were used. The data can be seen in the graph in Fig. 6 where the predicted values were close to the experimental data for capsules S-1 and S-2, but capsule S-3 was shifted about 2 m/s . This is acceptable because the wind speeds that the capsule would see would not be constant and a variation of this magnitude is small enough where it would not significantly affect the rotation.

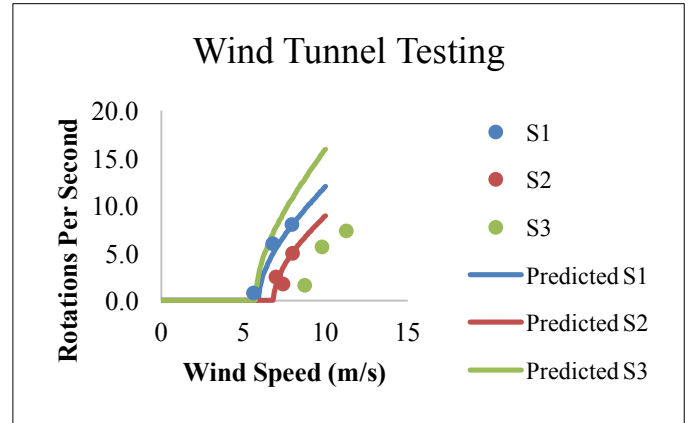


Fig. 6. Wind tunnel testing data for three experimental capsules. These capsules were an early design that was scaled down for testing purposes.

Based on these results final values for the lift and drag coefficient were chosen. Values of 0.9 for C_D and 1.5 for C_L were used. These are within the ranges provided in the paper.

C. Fluid Ejection Testing

Fluid ejection testing was performed to determine the minimum angular velocity that the LN_2 would be ejected from the fin channels and the dispersion radius of the capsule. Water was used for this testing because it is easier to handle and has a similar density and viscosity to LN_2 . Video recording was used to ensure accuracy.

The minimum release velocity was found to be 2.65 revolutions per second or 159 revolutions per minute. Fig. 7 shows the actual dispersion of the water from the capsule. The dispersion radius was found to be approximately 40 inches for this design.



Fig. 7. Spin testing with an early capsule design. This design had small channels for fluid dispersion, which were later modified to allow the more dramatic release seen in subsequent drop testing of the capsule.

D. Fluid Ejection Modeling

Due to the complex nature of the fluid dynamics inside the capsule, it was much easier to perform the testing previously outlined than to create a CFD model for every capsule geometry required. As such, the critical angular velocity measured in testing was used as the angular release velocity, and then the area covered by the capsule as it fell was calculated using ballistic motion.

The angle of the helical flow channels will be the initial release angle of the fluid, due to contact forces. The tangential velocity can be calculated using the rotational velocity and the distance at the tube exit, and then using the height and gravity, the radius of dispersion can be calculated. This was integrated into the model so that when a set of parameters were run, the fluid dispersion area could be calculated. This was particularly important for ensuring the capsules could be scaled up to reasonable sizes and quantities. The results of this model can be seen in Fig. 8.

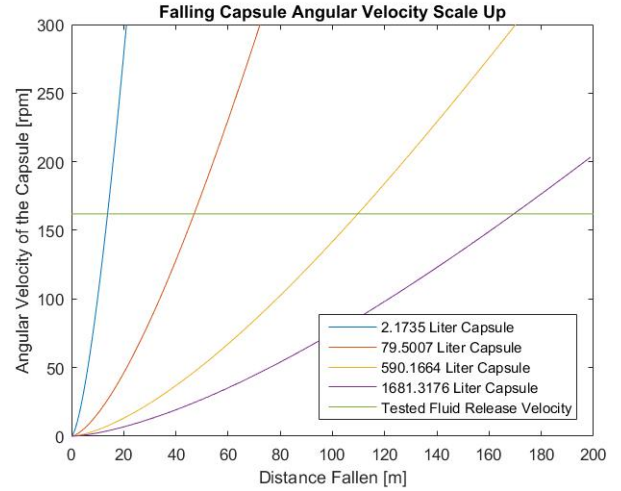


Fig. 8. Plot showing how capsule scale up affects the fluid release height. Plots of this nature were generated for multiple different capsule designs to determine which would perform best, and to inform design decisions. Variables like fin size can be varied to shift these curves.

IV. CAPSULE DROP TESTING

The capsule drop testing that the team conducted was done to determine how well the capsule spins and disperses LN_2 in a real life situation. After determining that the capsule would spin from the wind test and that the fluid would eject from the stationary spin test, the drop test was the last step needed to conclude that the design was promising.

The drop testing was conducted from the rooftop of a local parking garage. This gave a drop height of approximately 17 meters, much lower than the 200 meters the capsules were designed for. However, it was the highest point available at the time of testing. Testing was performed at the presence of a university police detail.

A. Procedure

The setup for the drop test consisted of a support structure to extend the capsule over the edge of the parking garage and control the drop of the capsule. In order to compensate for the reduced fall time, the fixture had the capability to spin the capsules prior to releasing them. This better simulated the angular speed of the capsule if it had been dropped from the proper height. Several capsules were dropped into large cardboard boxes filled with packaging to prevent them from breaking. The capsules tested can be seen in Fig. 9.

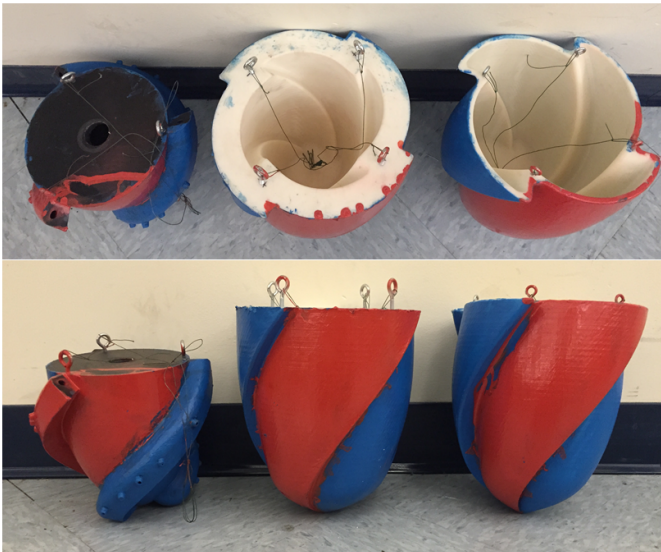


Fig. 9. Capsuled drop tested. On the left is an old version of the capsule design, which had internal fluid channels and could only be 3-D printed. On the right were two capsules of a newer, moldable design. One panel of the capsules was painted red in order to better visualize the rotation during the drop testing.

B. Results

Without being spun on the test stand prior to release, the capsules started spinning slightly before impact, with minimal water dispersion. This was expected based on the low drop height. The maximum radius for the capsule dropped with pre-spin was approximately eight feet.

Overall, the drop testing proved that the capsules were able to spin and disperse water as they were falling through the air. This test was able to prove the effectiveness of the design of the capsule for both spin capacity and fluid dispersion. An image of the capsule dispersing water during the pre-spin period and during the drop of the capsule can be seen in Fig. 10.



Fig. 10. Capsule releasing die water. On the left the capsule can be shown early in the descent, just as the liquid begins to release the water. The dispersion is more visible on the right.

This test was a culmination of all the testing and design that had been done on the capsule and proved that the design works and can be effective.

V. COST MODELING

One of the final steps to validate this method of firefighting was to perform a cost analysis in conjunction with the heat transfer modeling. The results of this model showed that utilizing a two-phase process of dropping the LN_2 capsules to suppress the fire followed by a load of water to extinguish the fire would cost approximately \$9,869 and could extinguish 2 acres in about thirty minutes. This is compared to the standard method of dropping water from a helicopter, which would cost approximately \$7,910 and take four hours and thirty minutes to extinguish the same area. The material used for this analysis was SMMA copolymer due to the favorable mechanical and thermal characteristics, as well as very low cost.

A. Material Cost

The maximum weight that could be carried by a representative helicopter was found through research. Using material costs for the capsule and the nitrogen, and a rough calculation of the injection molding manufacturing cost, the team was able to determine the material cost of a helicopter load.

Then, the thermal analysis was implemented to determine the efficiency of the LN_2 during transport and drop to assess how much LN_2 was delivered to the fire. An impact analysis of the falling capsule was performed in the software package MATLAB, which showed that the gas would rise to a height that is about one third of its diameter as it expands. From this, the area of fire suppressed from a single capsule was determined. When combined with the cost of the liquid nitrogen and capsule, this calculation was used to determine the cost of materials per acre extinguished: \$4,614. This value proved to be reasonable enough to make the LN_2 suppression method an economically viable option to replace helicopter loads of water.

B. Time and Operational Cost

In order to find the costs of fighting with water, research found from the Camping and RVing British Columbia Coalition dictated the quantity of water required to extinguish a fixed fire size [13]. After LN_2 proved to cover more area than water, the authors contacted CalFire Aviation and communicated with the Chief of Aviation, Bill Payne. Chief Payne is an expert in managing aerial vehicles for the purpose of fighting large forest fires. He offered valuable information regarding the operational costs of these pieces of equipment. The scenario of dropping a single load of LN_2 filled capsules, followed with a load of water was compared to current methods. It was determined that it would take more than 26 helicopter loads of water to cover that same area as one load of LN_2 followed by a load of water.

The results of these calculations showed that a two-phase LN_2 implementation plan would cost an extra \$1,960, but save four hours. This translates to a significant savings in avoided damages making it a preferred firefighting method when a fire is moving at a fast rate and may create thousands of dollars of damages in a small amount of time.

VI. CONCLUSIONS

The problem of suppressing forest fires with LN_2 is extremely unique and challenging. This topic required significant research into the properties of both forest fires and LN_2 . Based on this research, it is hypothesized that a two-stage process, using water as a second agent, is needed to fully extinguish the fire beyond re-ignition.

The proposed solution is to carry LN_2 in a high capacity capsule. It needs to be effectively insulated to maintain nitrogen in its fully liquid state, and to incorporate a series of spiraled fins with internal grooves for fluid rise flow. The spiraled fins can induce a spin on the capsule as the airspeed of the capsule increases, causing the LN_2 in the capsule to move outwards and disperse to the fire.

In order to understand the vaporization process, mathematical models were developed for the nitrogen's descent to the fire below. A model was then developed for the proposed capsule solution. From this model it was concluded that less nitrogen would vaporize during the descent of a properly designed capsule than in the lengthier transportation to the fire. A steady state vaporization model was developed to evaluate this conclusion, and testing was done to validate the model. This model allowed optimization of the geometry for insulation under a certain temperature given a capsule of a certain material.

An analytical model was constructed to predict the expected angular speeds of the capsule for different drop heights. This was verified with a wind tunnel test that simulated expected wind speeds encountered at different heights. This was incorporated into the thermal model to account for second order effects on the capsules position, velocity, and convection values as the capsules fell.

Then, the area covered by the nitrogen as it left the capsule had to be determined. This was done experimentally, by spinning a 1.9-liter capsule and measuring the spread of water. The area coverage was determined to have increased from 5 m^2 merely from impact, to a conservative 8.7 m^2 from preliminary fluid ejection calculations.

The capsule was then dropped from the rooftop of a university building to evaluate the capsule in action. The capsule rotated and the coverage area from the drop testing was found to be approximately 23 m^2 .

Finally, an economic analysis was conducted to determine if this solution was cost effective. Through research and collaboration with Cal Fire Aviation, the costs of current methods and the proposed solution were estimated. This showed that a helicopter filled with 400 LN_2 capsules (25 liters each) could extinguish two acres of fire in approximately thirty minutes, while existing methods using water would require four hours and thirty minutes to extinguish the same area. Using LN_2 would cost \$9,870 where a method of fighting with just water would cost \$7,910.

Further research still needs to be conducted to develop and design the release mechanism required to optimally release the capsules on critical areas of the fire. This would require sufficient cooling or insulation to protect the nitrogen on its journey, while keeping the pilots concentration of the operation of the vehicle as opposed to the payload. This work can serve as a foundation for the development of this solution.

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REFERENCES

- [1] Y. Levendis and M. Delichatsios, "Cryogenic Suppression of Liquid Pool Fires and Wooden Crib Fires", in National Fire Protection Association Suppression and Detection, Orlando, FL, 2011.
- [2] K. Miyazaki, S. Inoue, and H. Horiike, 'Small-scale Experiments of Nitrogen Injection Effects on Sodium Fire Extinguishment', Journal of the Atomic Energy Society of Japan / Atomic Energy Society of Japan, vol. 41, no. 10, pp. 1084-1091, 1999.
- [3] U.S. Administration, 'U.S. fire statistics', [Usfa.fema.gov](http://www.usfa.fema.gov), 2015. [Online]. Available: <http://www.usfa.fema.gov/data/statistics/#tab-4>. [Accessed: 16- Aug- 2015]
- [4] Nifc.gov, 'National Interagency Fire Center', 2015. [Online]. Available: http://www.nifc.gov/fireInfo/fireInfo_statistics.html. [Accessed: 16- Aug- 2015]
- [5] Coloradofirecamp.com, 'Colorado Firecamp, Wildland Fire Suppression Tactics Reference Guide', 2015. [Online]. Available: <http://www.coloradofirecamp.com/suppression-tactics>. [Accessed: 16- Aug- 2015]
- [6] Y. Levendis, A. Ergut and M. Delichatsios, 'Cryogenic extinguishment of liquid pool fires', Process Safety Progress, p. NA-NA, 2009.
- [7] B. Butler, Wildland Firefighter Safety Zones: A Review of Past Science and Summary of Future Needs, 1st ed. Missoula, MT: US Forest Service, 2015 [Online]. Available: https://www.firescience.gov/projects/07-2-1-20/project/07-2-1-20_http_www.publishcsiroau_actview_filefile_idWF13021.pdf. [Accessed: 16- Aug- 2015]
- [8] W. Bert, International Symposium on the use of Models in Fire Research. Washington DC: National Academy of Sciences - National Research Council, 1961, pp. 198-204.
- [9] Ortiz, Xavier, David Rival, and David Wood. "Forces and Moments on Flat Plates of Small Aspect Ratio with Application to PV Wind Loads and Small Wind Turbine Blades." Energies (2015): 2438-453.
- [10] B. Gabbert, 'At what temperature does a forest fire burn?', Wildfiretoday.com, 2011. [Online]. Available: <http://wildfiretoday.com/2011/02/26/at-what-temperature-does-a-forest-fire-burn/>. [Accessed: 16- Aug- 2015]
- [11] C. Bergman, Intro to Heat Transfer. Wiley C, 2014.
- [12] K. Taira, W. B. Dickson, T. Colonius, M. H. Dickinson, and C. W. Rowley, Unsteadiness in Flow over a Flat Plate at Angle-of-Attack at Low Reynolds Numbers', 45th AIAA Aerospace Sciences Meeting, 2007.
- [13] "The Proven World Standard in Aerial Firefighting." Bambi Bucket – Precision Helicopter Fire Fighting Tool. SEI Industries, 2015. Web. 29 Nov. 2015.
- [14] Borealforest.org, 'Science and Innovation - Forest Fires', 2015. [Online]. Available: http://www.borealforest.org/world/innova/forest_fire.htm. [Accessed: 16- Aug- 2015]
- [15] Airproducts.com, 'Safetygrams', 2015. [Online]. Available: <http://www.airproducts.com/Company/Sustainability/environment-health-and-safety/product-safety-safetygrams.aspx>. [Accessed: 16- Aug- 2015]
- [16] R. Ghosh, Cryogenic Nitrogen Gas Cooling for Thermal Spray Coatings, 1st ed. Air Products and Chemicals, Inc, 2015 [Online]. Available: <https://www.airproducts.com/~media/Files/PDF/industries/metals-cryogenic-nitrogen-gas-cooling-thermal-spray-coatings.pdf>. [Accessed: 16- Aug- 2015]
- [17] Liquid Nitrogen Cryosurgery, 1st ed. Hadsund, Denmark: Cortex Technology, 2015 [Online]. Available: <http://www.cortex.dk/files/manager/documents/info-flyer.pdf?viewer=true>. [Accessed: 16- Aug- 2015]
- [18] Needhamag.com, 'Stream Bars for Uniform Liquid Fertilizer Application - Needham Ag Technologies, LLC', 2015. [Online]. Available: http://www.needhamag.com/innovative_product_sales/stream_bars_for_uniform_liquid_fertilizer_application.php. [Accessed: 16- Aug- 2015]
- [19] Ehs.research.uiowa.edu, 'Liquid Nitrogen Handling | Environmental Health and Safety', 2015. [Online]. Available: <http://ehs.research.uiowa.edu/liquid-nitrogen-handling>. [Accessed: 16- Aug- 2015]
- [20] Ehs.neu.edu, 'Cryogenic Liquids', 2015. [Online]. Available: http://www.ehs.neu.edu/laboratory_safety/fact_sheets/cryogenic_liquids/. [Accessed: 16- Aug- 2015]
- [21] D. An, P. Sunderland and D. Lathrop, 'Suppression of sodium fires with liquid nitrogen', Fire Safety Journal, vol. 58, pp. 204-207, 2013.
- [22] Z. Fu-bao, S. Bo-bo, C. Jian-wei and M. Ling-jun, 'A New Approach to Control a Serious Mine Fire with Using Liquid Nitrogen as Extinguishing Media', Fire Technol, vol. 51, no. 2, pp. 325-334, 2013.
- [23] M. Paczkowski and A. Kukuczka, 'Use of Liquid Nitrogen for Extinguishing Fires in Mines', Przegl Gorn, pp. 375-380, 1978.
- [24] H. McBay, "Fire Extinguishing Capsule", U.S. Patent no. 5590717, January, 1997.
- [25] P. Edwards and G. Ruebusch, "Fire Retardant Delivery System", U.S. Patent no.7083000, August, 2006.
- [26] B. Ivarez and L. Maria, "Method for Acting on Forest Fires, Pests or Atmospheric Phenomena from the Air", U.S. Patent no.7690438, April, 2010.
- [27] F. Cicanese, "Oil Well Fire Suppression Device", U.S. Patent no. 666278, December, 2003.
- [28] W. Reed, "Heat-Absorbing Gel material", U.S. Patent no. 6776920, August 2004.
- [29] V. Sridharan and R. Vairavan, "Fire Extinguishing by Explosive pulverisation of Projectile Based Frozen Gases and Compacted Solid Extinguishing Agents", U.S. Patent no. 7478680, Jan. 2009.
- [30] A. Ozment, "Method for Fighting Fire in Confined Areas Using Nitrogen Expanded Foam", U.S. Patent no. 7104336, September, 2006.
- [31] F. White, Fluid mechanics. New York, N.Y.: McGraw Hill, 2011.

- [32] Sadraey, M., and Dr. Müller. "Drag Force and Drag Coefficients." Web. 28 Sept. 2015.
- [33] R. Barron, Cryogenic Heat Transfer. CRC Press, May 1, 1999.
- [34] "The Original Bambi Bucket." SEI Industries 22 Aug. 2013. Web. 29 Nov. 2015.
- [35] Arney, Donald Brian, Peter Leighton Brooke, and Norman Carter Wagner. "Patent US5829809 - Multi-dump Fire Fighting Bucket." Google Books. USPTO, 3 Nov. 1998. Web. 29 Nov. 2015.
- [36] "Bambi Bucket Quick Repair Guide." SEI Industries, June 2014. Web. 29 Nov. 2015.
- [37] "Campfires in British Columbia | How To Camp." The Camping and RVing British Columbia Coalition. Camping and RVing BC Coalition, 2015. Web. 27 Nov. 2015.
- [38] Cost Estimator. Computer software. [Http://www.custompartnet.com/estimate/injection-molding/](http://www.custompartnet.com/estimate/injection-molding/). CustomPartNet, 2009. Web. 11 Nov. 2015.
- [39] "Aerial Firefighting." Wikipedia. Wikimedia Foundation, 21 Nov. 2015. Web. 27 Nov. 2015.
- [40] Fan, Karen. "Price of Liquid Nitrogen." Price of Liquid Nitrogen. The Physics Factbook, 2007. Web. 27 Nov. 2015.