

Fuel pool ignition caused by a pyrotechnic device

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Abstract

Safety protocols on both military and commercial aircraft rely on our knowledge of fire dynamics, temperature distributions and thermal mass transfer of specific chemical components. Indeed, the temperature field associated within an incendiary flash has numerous implications, particularly in the aircraft survivability arena. Our present knowledge is limited when it comes to determining the local temperature field around a burning incendiary and although there are full-scale experimental facilities these are often too expensive to perform all the parameters that are necessary to understand this type of event. Furthermore, if a fire has been initiated due to the instigation of a short duration pyrotechnic event then the scenario is further complicated, and is even more so if the event is in close proximity to a pool of fuel. Indeed, the ignition of a fuel pool by an incendiary device, such as an armour-piercing incendiary (API), has not been exhaustively covered, and it is widely accepted that the energy is released uniformly and produces a homogeneous high temperature field. This work has shown that not only is the spectral energy released some 5 times greater than that of the actual fireball, but that the pyrotechnic charge has to be within a set distance from the surface of a pool of fuel, for a particular fuel temperature, before a fire may be initiated and sustained.

Keywords: pyrotechnic, fire, fuel pool ignition, temperature measurements.

1 Introduction

Safety protocols on both military and commercial aircraft rely on our knowledge of fire dynamics, temperature distributions and thermal mass transfer of specific chemical components. If a fire has been initiated due to a short duration



pyrotechnic event then the scenario is further complicated, and is even more so if the event is in close proximity to a pool of fuel. Indeed, the ignition of a fuel pool by an incendiary device, such as an armour-piercing incendiary (API), has not been exhaustively covered, and it is widely accepted that the energy is released uniformly and produces a homogeneous high temperature field.

As an example, consider the trajectory of a 12.7 mm diameter API passing through a 5 mm thick (target) panel. Such an API, as shown diagrammatically in fig. 1., may be considered to be composed of an inner steel core surrounded by an incendiary material and enclosed by a thin walled outer jacket, often referred to as the windscreen. Once fired, the API impacts against the panel and here the windscreen is effectively 'peeled' back as the API passes through the target. On doing so, the friction caused between the windscreen and the panel is sufficient to ignite the incendiary material, Fig. 2. This figure shows that the trajectory of this API (from left to right) produces a large area of visible spectral energy, some 355 mm in diameter but did not however, provide a near uniform temperature distribution throughout, as measured with a thermocouple grid, Dusina et al [1].

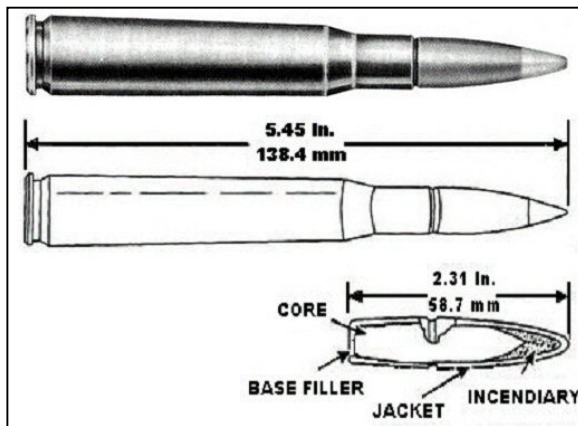


Figure 1: Details of a 12.7 mm Armour Piercing Incendiary.

The measurement of the high temperatures attained in this near instantaneous pyrotechnic event are difficult to determine and as such these temperatures within this type of fireball has not been measured with certainty and questions have recently arisen regarding the accuracy of such measurements. It is also widely accepted that the thermal energy is released uniformly and that it is considered to be similar in size to that of the emitted spectral energy in the visible wavelength range. It is this uncertainty in the understanding of such an event, especially in the case where an API functions in the vicinity of a fuel pool, that our knowledge of the ignition process of the fuel by the incendiary is far from complete.

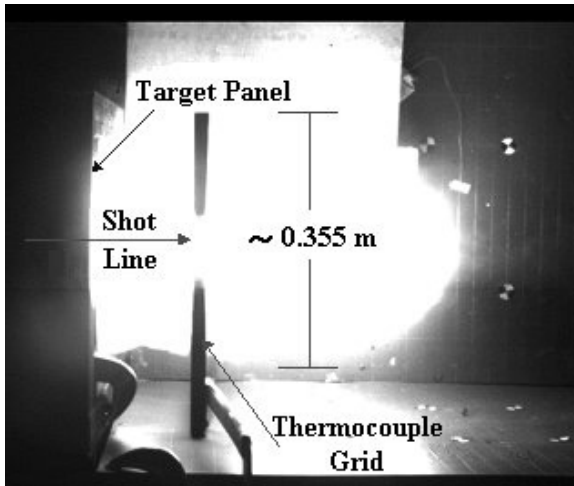


Figure 2: Shot line of an API passing through 5 mm thick target panel.

A number of methods have been used to measure the temperature of this type of dynamic radiant field. Such methods have ranged from the simple thermocouple thermometry to pyrometry with varying degrees of success. For instance, in the case of optical pyrometry, where the brightness of a flame has been compared to the brightness of an incandescent filament in order to determine the flame temperature, Shidlovskiy [2], only the average temperature across a steady flame region could be determined. Other types of pyrometers have also been used, but have been equally unsuccessful in determining point measurements, for example, photoelectric and color photometers, Shidlovskiy [2]. This same author has also measured the temperature fields with relation to flame height using a cinephoto pyrometer, but detailed temperature distributions were unattainable since this method could not provide measurements at intervals under 10 mm. In contrast to this steady flame analysis, the temperature region within non-uniform temperature zones in a complex combustion process has been determined successfully using a line-reversal methodology, but it is dependent upon the emission of characteristic spectral lines from the flame as viewed by a spectroscope, Strong et al [3]. But once again, the temperature measurements only accounted for the average temperature across a flame region and not within the inner zones. Unlike the non-contact methodology of pyrometry, high-speed thermocouples have been used with varying degrees of success, on different pyrotechnic material but usually at single fixed positions. For example, Birnbaum [4] investigated the Pd/Al mixture whereas Beck [5] studied the reactions of Sb/KMnO₄. Even for such high temperatures above 2000°C, where only W-Re thermocouples may be used with any success, such as in W/KClO₄/BaCrO₄ material, Lao and Wang [6] and in Mo/KClO₄ material, Gongpei et al [7], only temperatures at fixed positions were measured. These measurements were further hampered because of the nature of the W-Re

thermocouples since although they are capable of measuring temperatures in excess of 2000⁰C they are very prone to oxidation leading to large errors due to the reaction of the Tungsten (W) with Oxygen and therefore they have to be used within inert environments to prevent the Tungsten from burning out.

For the purposes of the present study, and given the complications of the reviewed systems, it was decided to measure the temperature distributions within the proposed pyrotechnic events using R and K type thermocouples.

These point temperature measurements were further enhanced using digital video analysis of the pyrotechnic event to observe the area of the spectral radiation. It was also found that this methodology could be improved by using optical filters to suppress a significant portion of the visible wavelength region thereby allowing the hotter zones of the event, in the near infrared region, to be captured. Given these two different methodologies, the temperature distributions could be obtained quantitatively, while the video analysis provided qualitative support by differentiating between the fireball and the photon flash.

2 Experimental methods

The incendiary mixture of an API was checked and a laboratory mixture containing similar ingredients was prepared. Table 1 provides a comparison of the chemical constituents between the API and the Labmix and the heat released from such mixtures. It may be noted that the heat released from the Labmix was well within 0.01%.

Table 1: Formulations of an API and the Laboratory pyrotechnic mixture.

Chemical	Barium Nitrate	Aluminum	Magnesium	Binder (Dextrin)	Heat Release
Formulae	Ba(NO ₃) ₂	Al	Mg	(C ₆ H ₁₀ O ₅) _n	(Kcal/gm)
API	50%	24%	24%	2%	3.13
LabMix (Experimental)	50%	24%	24%	2%	3.11

The Labmix was then formed into cylindrical charges on stainless steel support rods, with an electrical initiator to facilitate ignition. The charge was approximately 4 mm in diameter and 16 mm in length, Fig. 3.

In order for the charge to be ignited a primary igniter was constituted from Potassium Chlorate, Lead Thiocynate and a Binder in the proportions given in table 2. This primary charge was ignited by passing a current through a 2.73 Ohm Nickel wire resistor embedded in the mixture during manufacture. The heat released from this initiator was sufficient to ignite the main charge.

Temperature distributions between 20 and 30 mm of the surface of the charge were measured using R and K type thermocouples. These thermocouples have a response time of approximately 50 ms and maximum temperatures of 1450 and 1250 respectively.

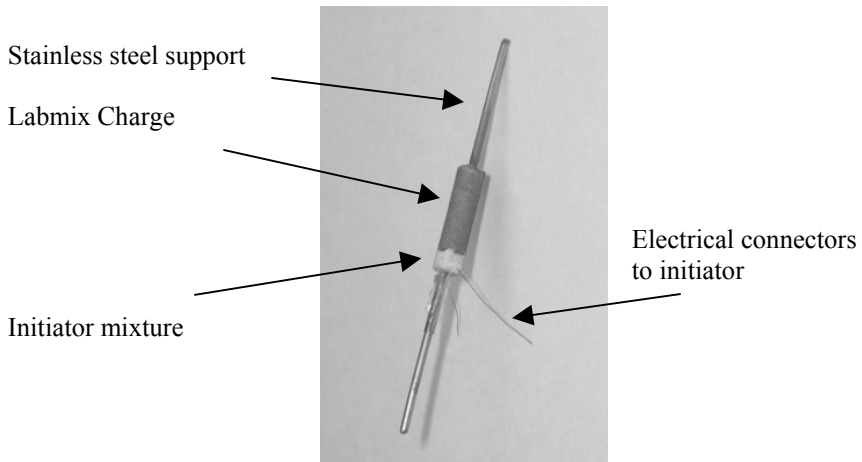


Figure 3: Laboratory designed pyrotechnic charge.

Table 2: Formulation of the Main charge and the Ignition initiator.

Charge	Main Charge			Initiator		
Chemical	Barium Nitrate	Magnalium	Binder (Dextrin)	Potassium chlorate	Lead thiocyanate	Binder (Dextrin)
Formulae	$\text{Ba}(\text{NO}_3)_2$	Mg-Al	$(\text{C}_6\text{H}_{10}\text{O}_5)_n$	KClO_3	$\text{Pb}(\text{SCN})_2$	$(\text{C}_6\text{H}_{10}\text{O}_5)_n$
Quantity (by wt)	50%	48%	2%	55%	44%	1%
Mesh size	<200	200	<200	<200	<200	<200

In addition to the quantitative measurements supported by the thermocouples, video-imaging analysis was performed on the resulting image of the burning charge. This was achieved by observing the pyrotechnic event using a 3-CCD Panasonic WV250B series NTSC color video camera and recorded using a Panasonic AG-7750 SVHS recorder. Camera setting was typically set to a 10 ms shutter speed with an aperture of 2.8. However, even with these setting, the high intensity flash from the charge saturated the camera and spectral filters were used to reduce this intensity. The filter chosen had to be within the very small 'window' of the visible energy range of 390 – 760 nm, as shown in fig. 4., and the most appropriate filter selected was one that cut off 95 % of the visible radiation below 600 nm, fig. 5. This resulted in an 80% transmission reduction over the wavelength range.

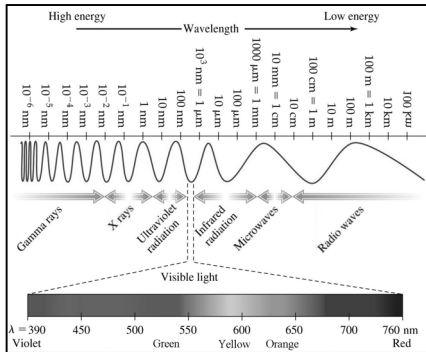


Figure 4: Spectral energy diagram.

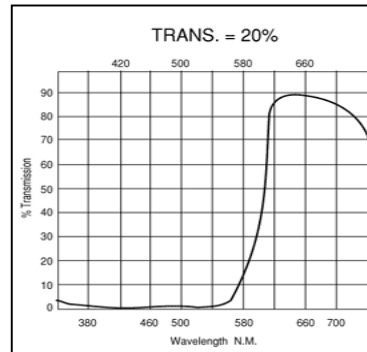


Figure 5: Optical filter used for determining the difference between the flash and flame diameters.

3 Results and discussion

Temperature distributions were obtained for three different locations around a 4 mm diameter charge: at the top, the bottom and to the side of a horizontally mounted specimen. Due to the transient nature of the event these three measurements had to be taken simultaneously and the results are shown in fig 6. Here it is shown that the temperature distributions from these three locations are similar in form but markedly different in value, being some 400 °C between the top and the bottom of the test charge. This alone is remarkable given that the burning of this charge is completed within approximately 2 seconds and that there would be little time for a convection type response to have occurred in this time interval. Furthermore, the temperature field as recorded at the point of measurement is travelling along the burning charge and the thermocouple is responding to this increasing, and then decreasing, temperature fluctuation. First impressions of such an event would suggest a uniform temperature distribution around the charge but this is clearly not the case, and although measurements below 20 mm were unable to be made for fear of destroying the thermocouples, temperatures fell by about 600°C between 20 and 30 mm for all three locations, with temperatures of 200°C being recorded at the bottom of the charge and as high as 600°C at the top.

An analysis of the video recordings of the burning charges provided further insight into the complexities of this event. In this case the camera was set to view the pyrotechnic event along the axis of the charge. The optical filter allowed the flame diameter to be recorded whilst recordings without a filter allowed the overall flash diameter to be determined. Fig. 7. shows how the flash diameter is some 5 times greater in extent to that of the actual flame diameter.

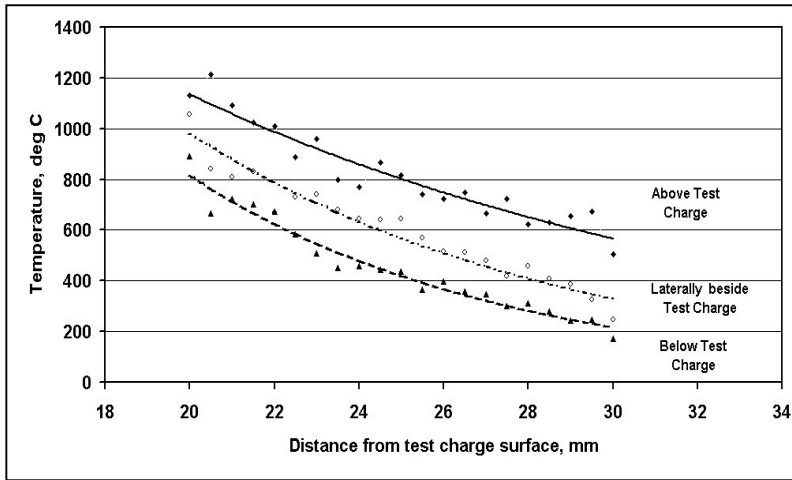


Figure 6: Temperature distribution around the LABMIX pyrotechnic material.

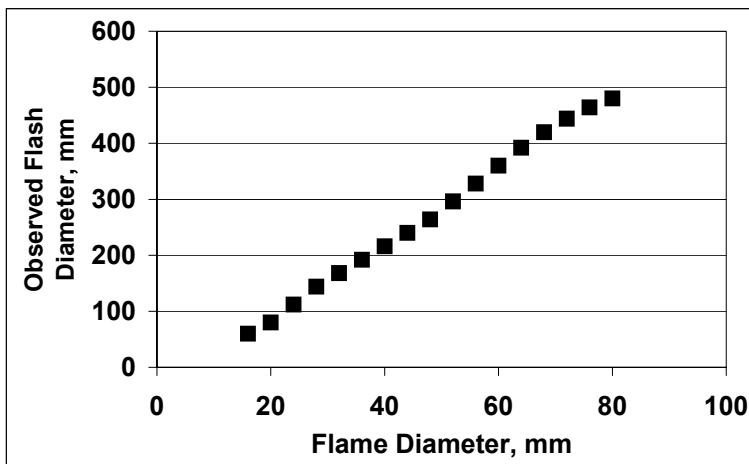


Figure 7: Observed flash diameter to that of the measured flame diameter.

3.1 Ignition of fuel pool by a pyrotechnic

The ignition of fuel in a pool by a short duration pyrotechnic event is far from obvious. Such questions concerning the location of the charge from the fuel surface, fuel temperature, flashpoint, and the evaporation rate of the fuel, and thereby its fuel-air ratio is of direct relevance if the fuel ignition sequence and its sustainment is to be understood. In order to examine how a fuel pool may be

ignited and the subsequent fire sustained, a preliminary study has been initiated using video analysis. This has been achieved by observing the pyrotechnic event using a set-up as shown diagrammatically in fig. 8. Here, the camera is again set to observe the charge along its axis and the charge is mounted on a traversing mechanism such that it may be located at a set distance (H) from the surface of a small pool of Kerosene.

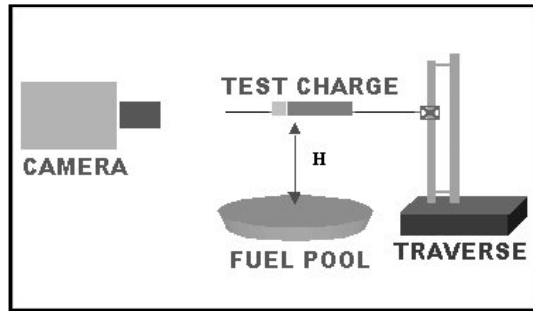


Figure 8: Diagrammatic representation of the test rig for the fuel ignition tests.

The evaporation rate of the fuel, Kerosene, for different temperatures was determined in the first instance. Since the flashpoint and auto ignition temperature of Kerosene is 105°C & 210°C respectively, four temperatures below this value were chosen, that is, 25°C , 50°C , 75°C and 100°C . The evaporation rate was determined by first measuring the weight of fuel in the container at a given fuel temperature and then recording its change over a time interval, giving 0.026 gm/min, 0.045 gm/min, 0.17 gm/min, and 0.24 gm/min for each of the respective temperatures.

Once the evaporation rates were established for each of the fuel temperatures, video recordings of the events of the discharge of a pyrotechnic, set at a known distance above the fuel pool, was undertaken. The following fig. 9. demonstrates the sequence of events that occurred when a charge was ignited 25 mm above the surface of a 25°C fuel pool. In this case, the charge appears to have completely engulfed the fuel and its container throughout the period, (a) – (d). However, the actual fireball emanating from the charge was not close enough to overcome the surrounding heat loss and provide sufficient heat for the pool to maintain a significant fuel evaporation rate sustaining a fuel burn scenario (e). Although the fuel vapour above the pool did ignite, this fire was extinguished once the initial vapours had burned (f).

By analysing the video's of whether a fire was sustained or not depending on the temperature and evaporation rate of the Kerosene and the location of the charge above the fuel pool, it was possible to determine an ignition and sustainment scenario, fig. 10.

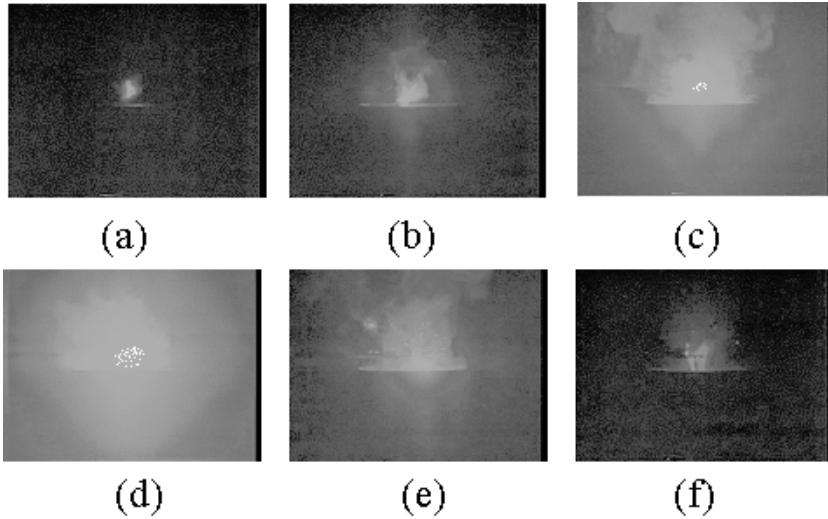


Figure 9: Sequence of events as a pyrotechnic is ignited 25 mm above a pool of Kerosene.

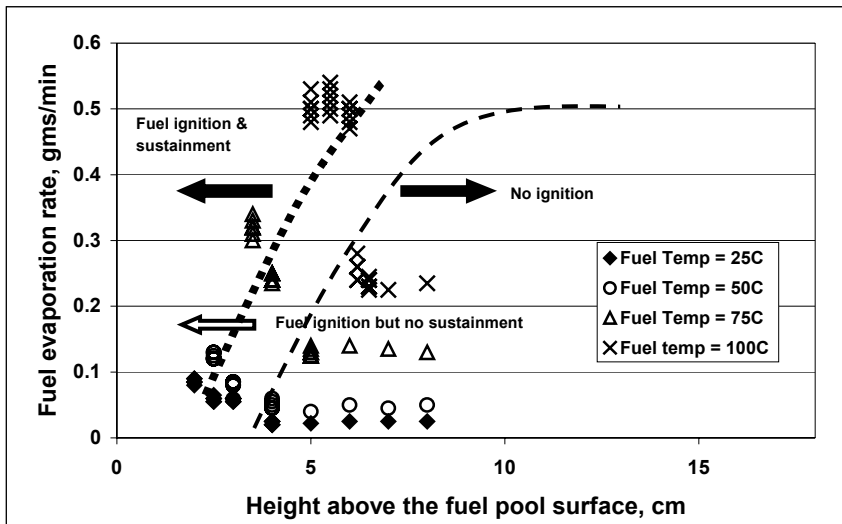


Figure 10: Fire ignition and sustainment relationship to charge location.

This figure shows a family of four data sets, one for each fuel temperature where the charge has been located at set distances, between 20 and 80 mm, from the surface of the fuel pool. The two dotted lines show the approximate position

of the edges of a band that stretches across the four sets of data, and depicts the boundary of three different circumstances. To the left of the boundary, the fuel will be ignited by the pyrotechnic device and is capable of providing sufficient heat to the fuel surface to encourage further evaporation and sustain the fire until all the fuel is spent. Within the two boundaries, the fuel may be ignited by the charge but due to insufficient heat and therefore low fuel evaporation rate from the surface making a fuel fire unsustainable. To the right of the boundary, there are insufficient levels of thermal energy to even ignite the fuel.

4 Summary

This work has started to determine how fuel ignition processes are developed when a threat of a pyrotechnic charge is made to a fuel pool. Without a clear understanding of the physics of the possible 'cause and effects' of such an event safety measures cannot be devised or undertaken. It has been shown that

- The fireball diameter and photon flash diameter differ in size.
- The high temperature associated with a charge is limited to the flame diameter and not the flash diameter.
- Initial temperature of a fuel pool, and therefore its evaporation rate, is important to fire sustainment.
- Height of a charge above a fuel pool is important to fuel ignition and fire sustainment.

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