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Ignitability of Wood From Fragment Attack

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Ignitability of Wood From Fragment Attack

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Abstract

The U.S. Army Research Laboratory (ARL) has been funded by the Department of Defense Ammunition Logistics Agency (AMMOLOG) to develop technology for minimizing the effect of fires or hostile attacks on ammunition holding areas during combat operations. Historically, there are many examples of catastrophic fires and explosions in ammunition holding areas, including a recent example in Kuwait after Operation Desert Storm. These events normally involve a sequence of fires and explosions where each explosion spreads the fire to adjacent stacks, which then burn, explode, and propagate the reaction still further. Sometimes an entire stack will detonate, and sympathetic detonation of adjacent stacks may also occur. AMMOLOG would like to develop inexpensive and easy methods for minimizing these events. The concept is to use simple barriers, easily made from materials available on site, that will interrupt sympathetic detonation and stop low-trajectory fragments, and to use fire-resistant blankets to protect adjacent stacks from firebrands and small, high-trajectory fragments.

Much ammunition is packaged in wood crates and boxes, and stacked on wood pallets to facilitate handling and transportation. Fragments from exploding munitions can impact these materials and heat them to their ignition temperature, causing them to burn. If this happens, the munitions in or on them can be heated to their reaction point and, thus, further propagation. This report discusses the temperature of fragments from exploding ordnance.

Acknowledgments

Archibald Tewarson and Ron Alpert of Factory Mutual Research Corporation, and André Fournier, Aberdeen Proving Ground Fire Protection Specialist, provided interesting and informative discussions on flammability and time-to-ignition of combustible materials.

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Table of Contents

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1. Background

The U.S. Army Research Laboratory (ARL) has been funded by the Department of Defense Ammunition Logistics Agency (AMMOLOG) to develop technology for minimizing the effect of fires or hostile attacks on ammunition holding areas during combat operations. Historically, there are many examples of catastrophic fires and explosions in ammunition holding areas, including a recent example in Kuwait after Operation Desert Storm. These events normally involve a sequence of fires and explosions where each explosion spreads the fire to adjacent stacks, which then burn, explode, and propagate the reaction still further. Sometimes an entire stack will detonate, and sympathetic detonation of adjacent stacks may also occur. AMMOLOG would like to develop inexpensive and easy methods for minimizing these events. The concept is to use simple barriers, easily made from materials available on site, that will interrupt sympathetic detonation and stop low-trajectory fragments, and to use fire-resistant blankets to protect adjacent stacks from firebrands and small, high-trajectory fragments.

Much ammunition is packaged in wood crates and boxes, and stacked on wood pallets to facilitate handling and transportation. Fragments from exploding munitions can impact these materials and heat them to their ignition temperature, causing them to burn. If this happens, the munitions stacked on the pallets or within wooden boxes can be heated to the point where they react and thus propagate the event. Therefore, it was desired to learn more about the ignition of wood by fragments from exploding ordnance.

2. Ignition Temperature of Wood

Items that must be considered in developing the criterion for the fragment ignition of wood:

- Kindling temperature.

- Temperature of fragments as they impact wood (initial temperature and temperature change as they propagate through air).

$$\mathrm{TRP} = \Delta T_{ig}\,(\kappa\rho c_p)^{1/2},$$

and $\Delta T_{ig} = T_{ig} - T_a$,

T_a = ambient temperature,

- Critical and applied heat flux with respect to the wood impacted by the fragments.

- Adjacency of heat sources or reflectors for wood to continue burning.

- Potential modification of response for fragment penetration or intimate contact (little air available).

- Physical parameters defining munitions. Some fragments will be from thick-walled munitions, and others from thin-walled munitions. This will make a big difference in the amount of energy required to tear them into fragments—that energy being deposited in the fragments—and also in the rate of cooling as they propagate through the air.

2.1 Kindling Temperature. The following information was reported in a conversation with André Fournier (1996).

(1) There are two tests used to measure the ignition temperature of materials: the room test, and the time tunnel test. These tests may not always yield the same ignition temperature, but are usually rather consistent.

(2) Both test protocols use the same type of sample, a 1.25-in × 1.25-in × 4-in block of wood. In the room test, the sample is placed into a closed container with a normal atmosphere, and it is slowly heated. A thermocouple, mounted on the sample, indicates a slowly rising temperature until combustion initiates, at which point the temperature increases rapidly. This transition temperature is noted as the ignition temperature. The ignition temperature of white pine by this test is 406° F (207° C).

(3) In the time tunnel test, the sample is passed through a 20-ft-long tube that is held at a fixed temperature. This passage requires 40 min. If ignition does not occur, the temperature is raised and the process repeated, most likely with a fresh sample, until ignition does occur. The temperature at which ignition first occurs is called the ignition temperature.

Thermal degradation of wood is defined as having four stages. For a certain unknown wood, they are (Beals 1986):

(1) **<392° F (200° C):** H_2O vapor, CO_2, and formic and acetic acids are evolved—all noncombustible gases.

(2) **392° F (200° C) to 536° F (280° C):** the endothermic phase; less water vapor, some carbon monoxide.

(3) **536° F (280° C) to 932° F (500° C):** the exothermic phase; flammable vapors and particulates; some secondary reaction from charcoal formed.

(4) **>932° F (500° C):** charcoal burning; notable catalytic action.

Phase 1 is also endothermic, but is not labeled as such. For this particular sample, the exothermic phase begins well above 406° F (207° C), the ignition temperature of white pine, so the sample must not be white pine.

There is a 5% reduction in ignition temperature for piloted (ignition initiated by a small pilot flame) vs. nonpiloted initiation (Fournier 1996).

The time-to-ignition for flammable materials is given by the following equations (Tewarson 1997).

$$(1/t_{ig})^{1/2} = \frac{(4/\pi)^{1/2}\,(\text{EHF} - \text{CHF})}{\text{TRP}},$$

where

$$\text{TRP} = \Delta T_{ig}\,(\kappa \rho c_p)^{1/2},$$

and $\Delta T_{ig} = T_{ig} - T_a$,

T_a = ambient temperature,

κ = thermal conductivity of the material,

ρ = density,

c_p = specific heat at constant pressure,

CHF = Critical Heat Flux,

EHF = External Heat Flux, and

TRP = Thermal Response Parameter.

2.2 Chemical Composition of Dry Woods. Since the ignitability of wood depends upon its composition, Table 1 is excerpted from Beals (1986).

Table 1. Chemical Composition of Dry Woods

Species	Constituents				
	Carbon (wt-%)	Hydrogen (wt-%)	Oxygen (wt-%)	Nitrogen (wt-%)	Ash (wt-%)
Oak	50.16	6.02	43.26	0.09	0.37
Ash	49.18	6.27	43.19	0.07	0.57
Elm	48.99	6.20	44.25	0.06	0.50
Beech	49.06	6.11	44.17	0.09	0.57
Birch	48.88	6.06	44.67	0.10	0.29
Pine	50.31	6.20	43.08	0.04	0.37
Poplar	49.37	6.21	41.60	0.96	1.86
Calif. Redwood	53.50	5.90	40.30	0.10	0.20
Western Hemlock	50.40	5.80	41.40	0.10	2.20
Douglas Fir	52.30	6.30	40.50	0.10	0.80

The composition of these woods is very similar throughout the table, but their densities vary greatly. Likely their conductivities and specific heat capacities are also dissimilar, which implies dissimilar Thermal Response Parameters (TRP). However, most wood ammunition packing is made from pine, so the parameters for pine can safely be used for the calculation and discussion in this report.

2.3 Temperatures of Explosively Driven Fragments. Almost all the thermal energy deposited into a fragment will be from the fragmentation process, not from the detonation products that produce the kinetic energy. In order to calculate the temperature of a fragment at the time of release from its munition, the following steps must be considered.

A shell explodes, and the shell casing expands. The chemical reaction products do work on the shell casing. The reaction products are contained within the shell casing until its volume roughly trebles its original volume, depending upon the properties of the shell casing—in particular, the tensile strength at very high strain rates. For this discussion, assume $V/V_0 = 3$ when comminution of the shell casing is complete.

The yield stress for a representative steel (1080) is $\sigma_y = 125$ ksi, a figure that may be used to represent the yield stress for artillery shells. The strain is given by the stress-strain relationship, which can be derived from the V/V_0 ratio at shell breakup that was assumed. Integrating this stress-strain product around the shell perimeter will yield the energy per unit volume deposited into the fragments. This is more understandable when one considers an infinitely long, hollow cylinder as representing a shell. The infinite length enables one to ignore end effects on a small-length element, of length L. Let the wall thickness be τ. Initial values of the parameters are represented by the subscript "0," and final values by subscript "F." Thus, the volume

$$V_0 = \pi\, r_0^2\, L,$$

where r is the radius of the cylinder. The circumference is

$$C_0 = 2\, \pi\, r_0.$$

$$V_F = 3\, V_0 = 3\, \pi\, r_0^2\, L = \pi\, r_F^2\, L, \text{ and } r_F = \sqrt{3}\, r_0.$$

Thus, this annular ring of steel has stretched from length C_0 to length C_F under a yield stress of σ_Y. If $r_0 >> \tau$, the energy, E, deposited under this process is given approximately by

$$E = \int_{C_0}^{C_F} \vec{F} \cdot \vec{ds}.$$

$\vec{F}$ is the hoop stress and so is parallel to $\vec{ds}$. Thus, the vector dot product, $\vec{F} \cdot \vec{ds}$, becomes the simple product, F ds.

$$F = \left(\frac{F}{A}\right) A = \sigma_Y \, A,$$

but

$$A = L \, \tau,$$

where τ is the thickness of this cylinder, so

$$F = \sigma_Y \, L \, \tau \quad \text{and} \quad ds = dC.$$

Therefore,

$$E = \int_{C_0}^{C_F} \vec{F} \cdot \vec{ds} = \sigma_Y L \tau C \Big|_{C_0}^{C_F} = \sigma_Y L \tau \left(C_F - C_0\right),$$

$$C_F - C_0 = 2\pi \, r_F - 2\pi \, r_0 = 2\sqrt{3} \, \pi \, r_0 - 2\pi \, r_0 = 2\pi \, r_0 \, (\sqrt{3} - 1),$$

and

$$E = \sigma_Y \, L \, \tau \, 2 \, \pi \, r_0 \, (\sqrt{3} - 1).$$

This energy from the fragmentation process goes into heating this length element, and can thus be expressed as,

$$E = m \, c_p (\Delta \, T),$$

where m = mass of the annular ring,
c_p = specific heat, and
ΔT = change (increase) in temperature.

$$m = \rho_0 V_2 = \rho_0 2\pi r_0 \tau L,$$

where V_2 = volume of the length element, L, of the shell casing.

Equating these two expressions for energy yields

$$\sigma_Y L \tau 2\pi r_0 (\sqrt{3} - 1) = \rho_0 2\pi r_0 \tau L c_p (\Delta T),$$

and

$$\Delta T = \frac{\sigma_Y (\sqrt{3} - 1)}{\rho_0 c_p}.$$

The yield stress for 1080 steel is ~125 ksi (*Horace T. Potts Steel Catalog and Reference Book* 1985); for very high strain rates, this at least doubles (Gregory 1997) to ~250 ksi. Converting to MKS units, this becomes,

$$\sigma_Y \approx 1.72 \cdot 10^9 \text{ N/m}^2.$$

Also,

$$\rho_0 = 7.88 \text{ g/cm}^3 = 7.88 \cdot 10^3 \text{ kg/m}^3$$

and

$$c_p = 0.107 \frac{\text{cal}}{\text{g - °C}} = 4.48 \cdot 10^2 \frac{\text{J}}{\text{kg - °C}}.$$

Therefore,

$$\Delta T = \frac{1.72 \cdot 10^9 (\sqrt{3} - 1)}{7.88 \cdot 10^3 \cdot 4.48 \cdot 10^2} = 357° \text{ C}.$$

But $T = T_0 + \Delta T$, so for 20° C ambient temperature, T = 377° C or 711° F.

Additional thermal energy is derived from axial strain and shear, as well as from intimate contact with the very hot reaction products. However, the interval during which the reaction products can impart thermal energy to the fragments is so brief that the energy transfer can be neglected.

However, axial strain is not negligible. If one assumes locally isotropic strain (which is a reasonable assumption) within a shell casing as a detonation takes place, then the axial strain energy will be roughly equivalent to that from the circumferential strain. However, strain-to-failure was already assumed, so the present calculation accounts for axial as well as circumferential strain.

Additional heating occurs from plastic work upon impact, for both the fragment and the impacted material—in this case, wood. Also, as the fragment moves through the air, it is heated by air friction and cooled by conduction. These tend to offset each other, but not completely.

3. Discussion

With reference to the four stages of thermal degradation of wood (section 2.1), one can see that this calculated fragment temperature is more than adequate to bring most types of wood to the kindling point, especially white pine at 406° F. Wood is a poor thermal conductor while steel is a good thermal conductor, so the temperature of the wood at the fragment-wood interface would closely approximate that of the fragment; thus, with the presence of air, the wood would ignite.

After the explosion or detonation of a steel-encased explosive, one can find some of the resulting fragments. They display a wide range of colors, depending on their history after they were explosively launched. The fragments must impact a hard material for them to acquire the rich, deep purple to bright blue colors often found in fragments at high-explosive experimental facilities (Kineke 1996). Colors found on fragments after an explosive shot are indicative of the highest temperature achieved by the fragment during this event. Up to ~1,000° F, the colors are produced by the oxide layers formed on the surfaces of the fragments, and these colors persist even after cooling; beyond this temperature the colors are caused by black-body radiation, but do not remain once the fragment has cooled. Several references document the relationship between the highest temperature achieved and the resulting color of the fragment (Dixie Gun Works 1997; *Machinery's Handbook* 1992; Glover 1991). The relevant section of Dixie Gun Works (1997) is quoted here as Table 2.

Table 2. List of Temperature Colors on Polished Steel

Color	Temperature (°F)
Very Faint Yellow	430
Pale Straw Color	450
Golden Yellow	470
Brown	490
Brown With Purple Spots	510
Purple	530
Violet	540
Dark Blue	550
Bright Blue	565
Grey Blue	600
Black Red in Dull Light or Darkness	800
Very Black Red in Room Light	900
Blood Red	1,050
Dark Cherry Red	1,075
Medium Cherry Red	1,250
Bright Cherry Red	1,550
Salmon	1,650
Orange	1,725
Lemon	1,825
Light Yellow	1,975
White	2,200
Sparkling White	2,350

Since some of these fragments can strike wood in an ammunition stack, it is important to know the temperature of the fragments after they strike. If they have a sufficiently high temperature for a sufficiently long interval of time, they will ignite the wood. Fragments can acquire heat energy from their propinquity to the reaction products of the explosion that launched them, from the plastic work of tearing loose from the munition, from friction with the atmosphere, and from impact, in which they trade kinetic energy for thermal energy. These impacts can be both intermediate and final—i.e., the impact in which the fragment comes to rest. Fragments can also lose thermal and kinetic energy (KE) to the air during passage, and they can lose KE through inelastic collisions.

An important mechanism for cooling is conductivity from the fragment to the wood in which it is embedded. The rate at which the heat flows from the fragment into the wood is determined by the TRP, which is defined previously.

Once ignited, the wood may not continue to burn. It is almost impossible to have a sustained fire with only one piece of wood; two or three pieces in the immediate neighborhood are required so that the radiant energy of one piece can be reflected back onto itself, and this energy, combined with that arriving from the adjacent pieces, can then maintain its surface temperature above the kindling temperature. However, if a fragment has sufficient energy, it cannot only kindle the flame, but maintain it until adjacent wood surfaces have been ignited, and then these can provide the energy required to maintain combustion.

The bottom line is that fragments from exploding munitions will frequently possess sufficient energy, at a sufficiently high temperature, to ignite wood and support continued combustion. Blankets that protect ammunition from such fragments should be able to survive temperatures of at least 380° C.

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