Mitigation of Fuel Fire Threat to Large Rocket Motors by Venting

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Introduction: Venting of a container such as a rocket motor or a warhead case is a well-recognized method to potentially reduce the violent response of the system to a fuel fire threat. There have been many proposed rocket motor or warhead venting systems. The thermally-initiated venting system (TIVS) on the AMRAAM rocket motor has been shown to reduce violent response, by cutting the case with a linear shaped-charge. Graham has demonstrated the ARCAPS system in which a small insert of secondary propellant having a lower temperature than the main propellant grain reacts to perforate the rocket motor case, reducing the system response in both fast and slow cookoff. In studying the response of a 120mm mortar in fast cookoff, a manufactured vent was filled with ionomer plastic that melted at a particular temperature leading to a mild reaction. There are many other designs that include stress-risers, thermite plugs or inserts, slotted overwrapped designs and so on.

Problem: The question that is generally overlooked is “what is the critical vent size to prevent overpressurization and how is it determined”. The problem we are trying to solve is how to protect a large rocket motor while in the transportation mode – typically truck and specialized trailer. This scenario provides the highest probability of a large rocket motor experiencing a fuel fire – whether from a rupture and ignition of the truck’s own fuel tanks in a crash, or running into some source of flammable fuel – from another truck, a car, or even a service station gasoline pump.

The basic solution to mitigation by venting is to understand the competition between pressure rise rate and pressure decay rate.

Pressure Rise Rate: Kinney and Sewell [1] determined, from interior ballistics, the rate of pressure rise from combustion of an energetic material. The basic form is given in Equation (1) below:

$$\mathbf{dP/dt = RT_B/V * dn/dt} \qquad (1)$$

where dn/dt is the time rate of change of the number of moles of product gases. This equation may be replaced with one in which the variables are more easily measurable. Thus,

$$\mathbf{dP/dt = RT_B/V * \rho/M * \alpha/(A-BT_0) * S_BP} \qquad (2)$$

where:
R = molar gas constant = 8.314×10^{-5} bar - m^3/mol - K
V = volume, m^3
T_B = flame temperature, K
M = formula mass product gas, kg/mol
ρ= density of explosive, kg/m^3

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T_0 = bulk temperature of explosive, K
α,A,B = energetic material constants (see below)
S_B = burn surface area, m^3
P = absolute pressure, bars

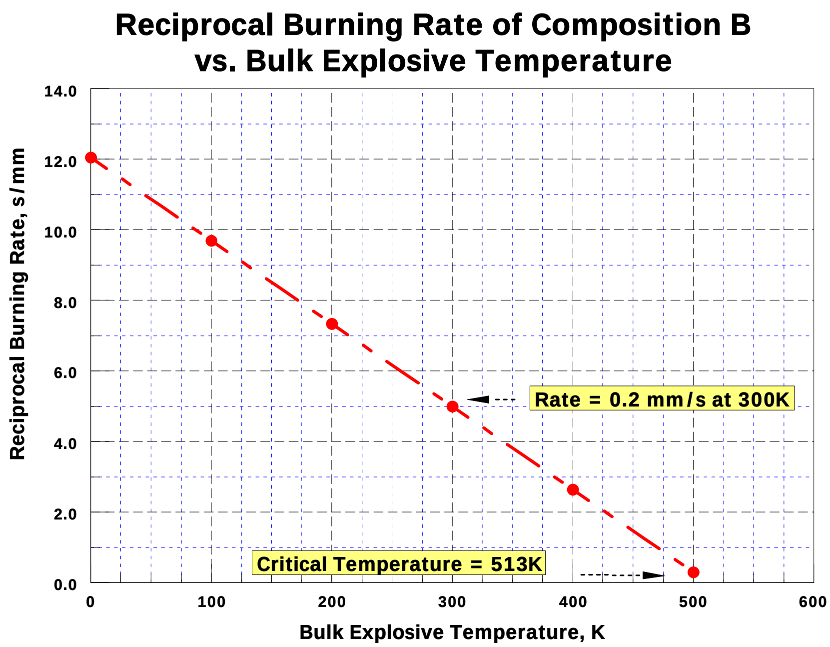
The term $[\alpha/(A - BT_0)]$ represents the variation in burning rate with bulk explosive temperature. In experiments with Composition B explosive, it was found that the burning rate at ambient was 0.2 mm/s [2] and from thermal analysis via DSC, violent decomposition occurs about 513K [3]. This is considered the critical temperature as the burning rate is assumed to be infinite at this point.

Utilizing the methodology of Andreev [2, 4, 5], we plot the reciprocal of burning rate against bulk explosive temperature. For Composition B, this gave the following energetic material constants:

$\alpha = 10^{-3}$ m/s-bar
A = 12.04
B = 0.0235/K

Thus:

1/burning rate = $12.04 - 0.0235T_0$



<u>Pressure Decay Rate:</u> If the volume under consideration is vented, the flow through the vent tends to decrease the pressure. When the interior pressure exceeds the outside pressure by more than 0.8 bar, the flow velocity becomes sonic [6] and a very simple expression for the pressure-decrease results (equation 3).

$$-dP/dt = (A_v C_D/V)\, a^* P \qquad (3)$$

where:

A = vent area, m^2
C_D = discharge coefficient, 0.6 to 1.0
V = volume, m^3
a* = flow velocity, m/s
P = absolute pressure, bars

In the generic equation, the discharge coefficient C_D was allowed to equal one, i.e., ideal flow. In actuality, flow through a square-edged orifice results in a coefficient of approximately 0.82 because of the *vena contracta* formed by the gases exiting the vent hole [7]. The sonic flow velocity of the gases through the vent hole, a*, is computed from the temperature of the products, and is also affected by compressible fluid flow. Thus:

$$\mathbf{a^* = (RT/M)^{1/2}\ [k * (2k/k+1)^{1/2} * (2/k+1)^{1/k-1}]} \tag{4}$$

For a nominal combustion gas mixture with

T = 2500K
R= 8.31434 J/mol-K
M=0.028 kg/mol
k=1.27

a* is approximately 725 m/s. This estimate can be improved by knowing the actual product composition of the gases, the specific heat as a function of temperature, the actual flame temperature, which, of course, are different for each explosive material.

<u>Critical Vent Area:</u> If the magnitudes of the pressure-decay and pressure-rise terms are equal, a critical condition results in which the pressure remains constant. This condition is met when the ratio of vent area to burning surface area is equal to a constant determined by the explosive constants and the initial temperature. The pressure-rise and pressure-decay equations can be combined. Thus:

$$\mathbf{dP/dt = [(RT_B * \rho/M * \alpha/(A\text{-}BT_0) * S_B) - (A_v C_D\, a^*)] * (P/V)} \tag{5}$$

If the vent-area to burn-surface-area ratio is less than the critical value, the pressure increases exponentially; if greater, the pressure decreases. Thus, the ratio is computed as:

$$\mathbf{A_v/S_B = (RT_B\ \rho\ \alpha) / [M\ C_D\, a^*(A\text{-}BT_0)]} \tag{6}$$

For the Composition B explosive cited above, and with an explosive density of 1700 kg/m^3, the predicted critical vent-area to burn-surface-area ratio as a function of bulk temperature is shown in Table 1.

Table 1. Critical Vent Area as a Function of Initial Explosive Temperature

T_0 K	Critical Ratio Av/S_B
273	0.002161
288	0.002305
334	0.002896

Experiments: In NWC experiments with vented burning of Composition B explosive, it was found that using the discharge coefficient of 0.82 gave a conservative prediction of the demarcation between quiescent burning and violent reaction (Figure 2). All of the violent burns lie below the demarcation line while the quiescent ones essentially lie on the predicted line.

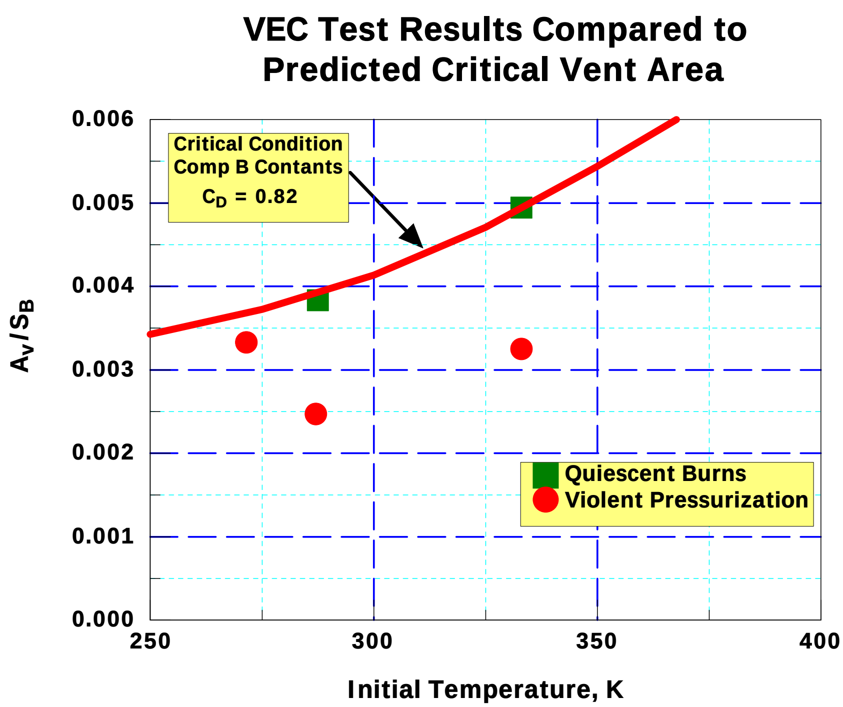


Figure 2. NWC VEC Test Results Compared to Predicted Critical Vent Area for $S_B = 11.04$ in^2.

The US Air Force Weapons Laboratory at Kirtland AFB performed experiments on Composition B explosive similar to those done by NWC but with a somewhat larger initial burning surface area [7]. Their data is shown in Figure 3. Their experiments are in qualitative agreement with the NWC experiments. They found quiescent burns in the range of 0.003 to 0.121 A_v/S_B and violent pressurizations from 0.0028 to 0.0058 A_v/S_B.

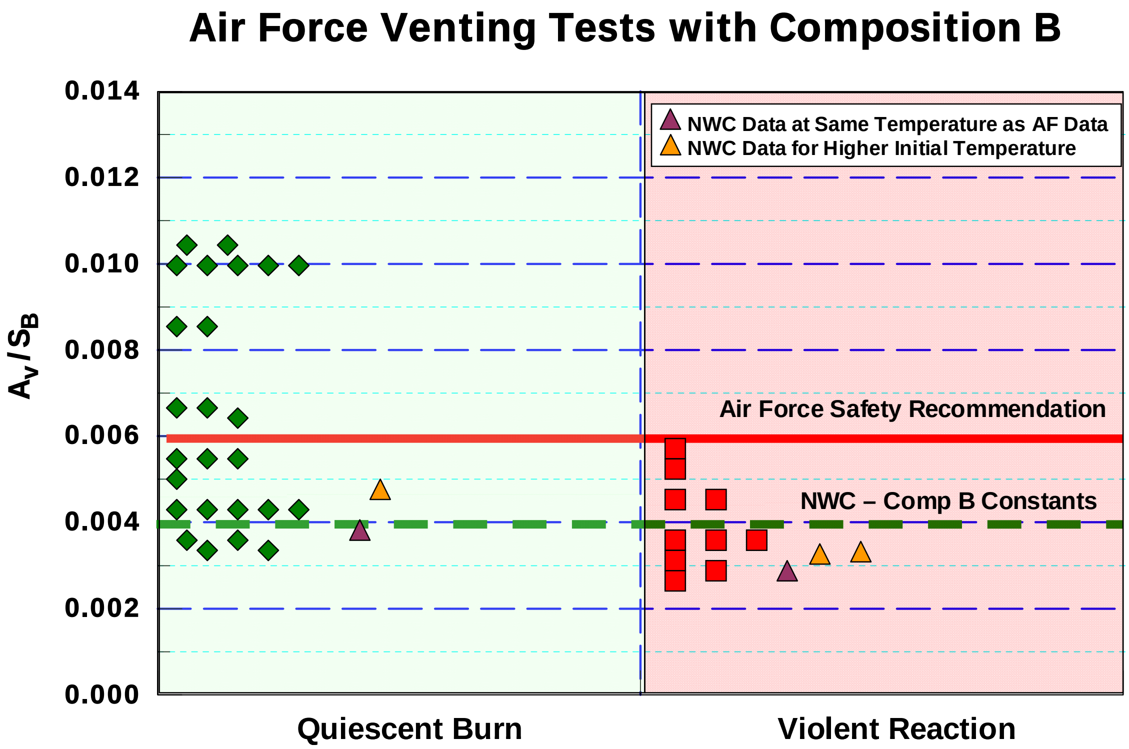


Figure 3. Air Force Vented Burning Studies with Composition B Explosive. Initial Bulk Temperature, T_o = 300K; S_B = 12.57 in^2. NWC Data (purple symbols) at T_o = 288K and S_B = 11.04 in^2.

<u>Summary of Experiments</u>: Vent areas to prevent pressurization and violent reaction in these tests are significantly less than 1% of the burning surface area. Tests were conducted with end-burning test items. This formalism works well for items with bulk temperatures near ambient – in particular, it works well in bullet impact of warheads where the bullet hole provides enough vent area to prevent overpressurization when the energetic material ignites and burns. Application to the fast cookoff scenario can be successful if the vent is created at a low enough energetic material bulk temperature.

<u>Ballistic Analysis Methodology</u>: Another method for estimating the required venting area to prevent violent reaction relies on classical ballistic analysis. For this exercise, the Minuteman III first stage motor was chosen as an example large rocket motor [8].

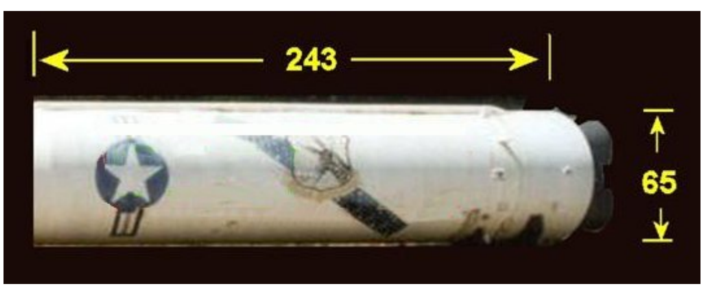


Figure 4: Minuteman III First Stage Motor

The following typical aluminized propellant properties were assumed in the calculations:

70°F Burning Rate: $r_b = 0.29\,(P_c/1000)^{0.34}$
Temperature Coefficient: $\sigma_p = 0.001/°F$
Characteristic Velocity: $c^* = 5172$ ft/s
Density: $\rho = 0.065\ lb/ft^3$

Where: P_c = chamber pressure in psia
r_b is burning rate in in/s

For the initial analysis, the burning rate was adjusted to a temperature of 702°F, and a single square-edged orifice was used as the vent. It was assumed that the whole exterior surface of the propellant grain ignited instantaneously between the case and the grain resulting in a burning surface area of 42,620 in^2; that all gases exited through the square-edged orifice; and that the motor surface was all at the same temperature.

<u>Analysis</u>:
The motor weight is 50,550 lb_m and at 702°F, the burning rate is calculated to be 0.546 $(P_c/1000)^{0.34}$.

First, compute the thrust using equation (7).

$$\mathbf{F = P_c\, A_t\, C_f\, \eta_F} \qquad \textbf{(7)}$$

Where: F = Thrust, lb_f
A_t = Throat area, in^2 (This is the vent size)
C_f = Thrust coefficient = 1.25 (exit cone with no expansion)
η_F = Thrust efficiency = 80% (square-edged orifice)

Secondly, determine chamber pressure using equation (8).

$$\mathbf{P_c = [(S_B\, \rho\, c^* a)/(A_t\, g_c)]^{(1/1-n)}} \qquad \textbf{(8)}$$

where:
S_B = the surface area, in^2
a = burning rate coefficient in the equation aP^n, in/s
g_c = gravitational constant, 32.174 lb_m-ft/lb_f/s^2
n = burning rate exponent in the equation aP^n

We wish to keep thrust to < 80% of stage weight to prevent propulsion. Applying this to equation 7 we get equation (9):

$$\mathbf{40{,}202 = P_c\, A_t\, (1.25)(0.8)} \qquad \textbf{(9)}$$

Solving for P_c through the use of equation (8) gives (10):

$$P_c = [(42629)(0.06519)(5172)(0.0521)/A_t(32.174)]^{1.515} \quad (10)$$

Which gives the solution: Outer grain pressure, $\mathbf{P_c}$ **= 4.99** psia and a required vent area of $\mathbf{A_t}$ **= 8053 sq. in.**

This analysis was applied over various temperatures to assess the required vent area. Figure 5 illustrates. **It can be seen that early, lower temperature venting is definitely advantageous.**

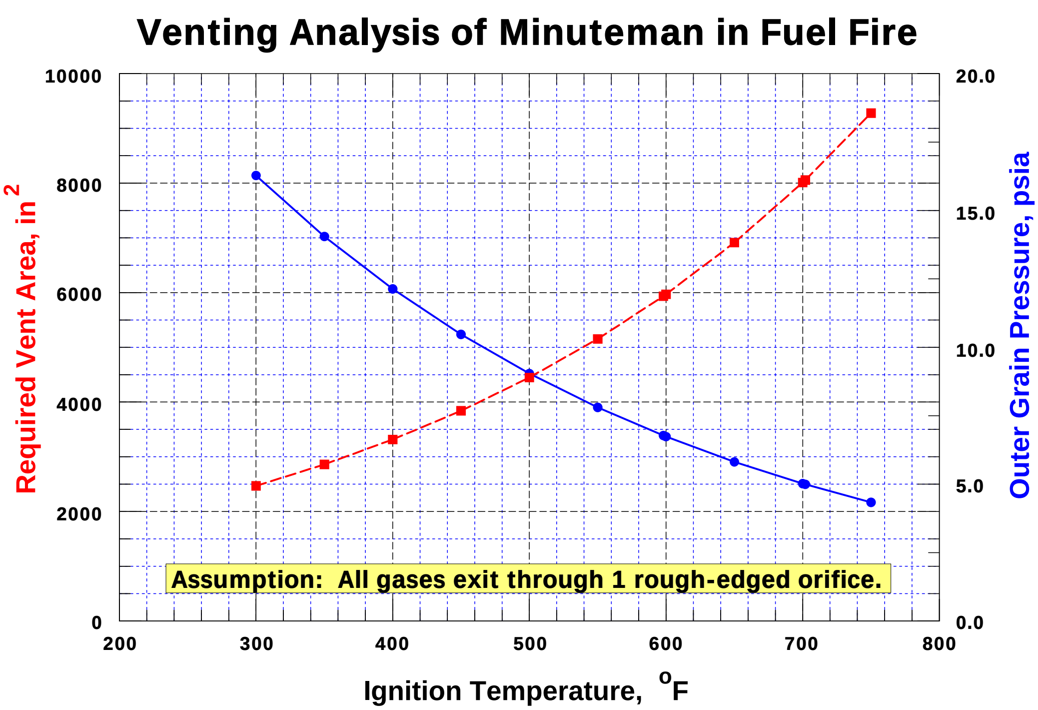


Figure 5. Effect of Ignition at Various Temperatures on Required Vent Area and Outer Grain Pressure.

In terms of our original ratio of vent area to burning surface area ratio, A_v/S_B at various temperatures is shown in Table 2.

Table 2. Vent Area to Burn Surface Ratio as a Function of Temperature

Temperature, F	Temperature, K	A_v/S_B
300	422	0.059
400	477	0.077
500	533	0.106
600	589	0.141
700	644	0.189
702	645	0.190

Figure 6 illustrates the rectangular vent area for the MM III first stage at two extremes of surface temperature – 700°F (8000 in^2 area required) and 360°F (3000 in^2 vent area).

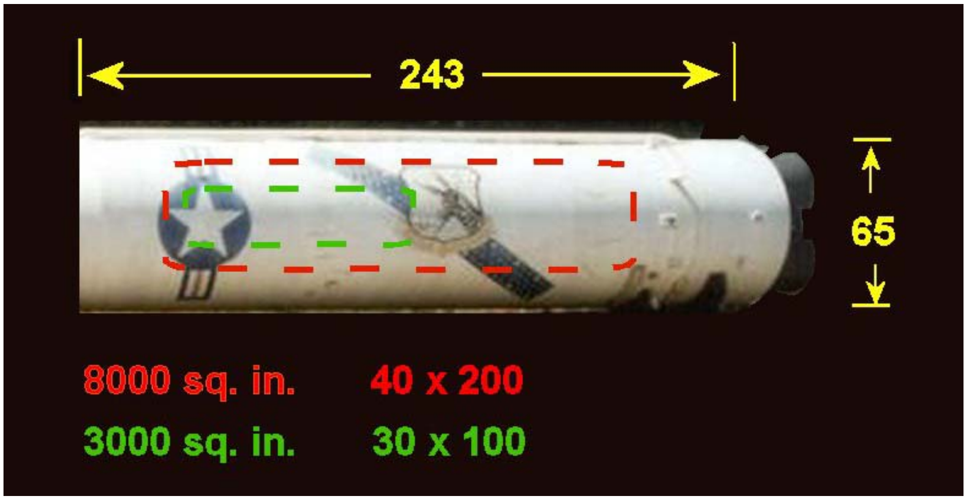


Figure 6. Vent area requirements as function of surface temperature

Figure 7 illustrates the difference between the two cases studied in this paper.

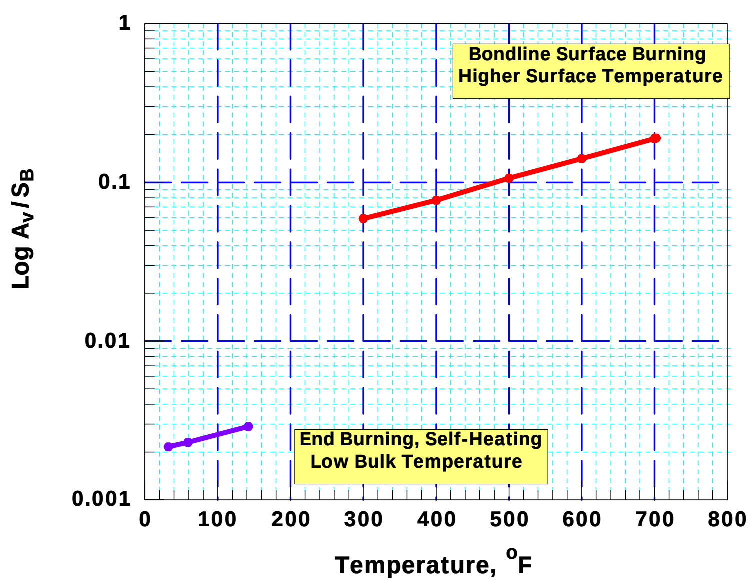


Figure 7. Comparison of required vent area to burning surface area ratios

<u>Discussion</u>: It can be seen that it is imperative to vent a cased energetic material subjected to fuel fire threat at as low a temperature as possible, consistent with its operational requirements and some margin of safety. Required vent areas are dramatically increased as temperature rises.

It should be noted that if the grain has a significant bore area and the flame reaches the bore, then increased vent area will be required.

It is anticipated that the vent area should be on the side of the motor case rather than on the end to prevent launching the motor. Attempts at neutral thrust (vent in front, nozzle in the rear) have been successful but require an exceptionally uniform fuel fire.

References

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