AEROJET
A GenCorp Company

Mitigation of Fuel Fire Threat to Large Rocket Motors by Venting

Kenneth J. Graham, Technical Principal
540-854-2182
ken.graham@aerojet.com

October 2010

The Problem

- 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.
  - AMRAAM TIVS
  - ARCAPS
  - 120mm Mortar with Ionomer-filled Vent
  - Many others

- The problem we are trying to solve is how to protect a large rocket motor, perhaps the size of Minuteman or Peacekeeper, while in the transportation mode.

- What is the critical vent size to prevent overpressurization and how is it determined ?

Large Motor Transport

Accidents Happen !

AEROJET
A GenCorp Company

Solution

- **The basic solution to mitigation by venting is to understand the competition between pressure rise rate and pressure decay rate.**
- **For Pressure Rise > Pressure Decay the system reacts violently**
- **For Pressure Rise = Pressure Decay the system is critically vented**
- **For Pressure Rise < Pressure Decay the system reacts mildly**
  - **This is what we want !**

Pressure Rise

- **From interior ballistics, the rate of pressure rise from combustion of an energetic material is given by:**

  dP/dt = RTB/V * dn/dt (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,**

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

  - **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**
  - **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**

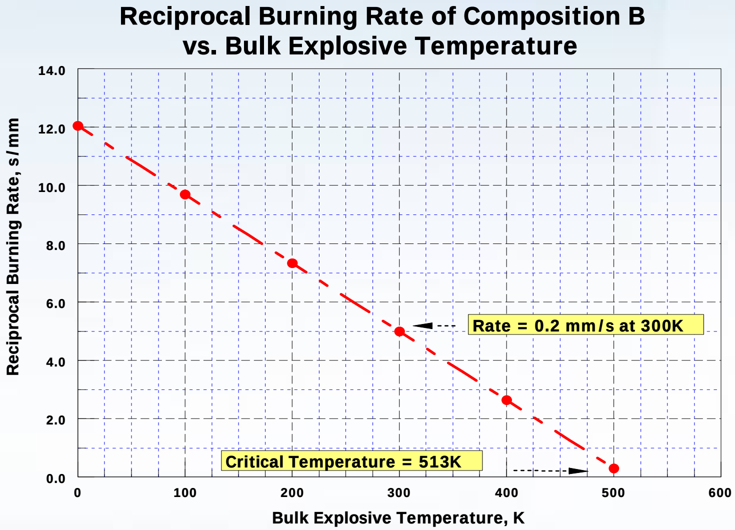
AEROJET
A GenCorp Company

Pressure Rise

- The term $[\alpha/(A - BT_0)]$ represents the variation in burning rate with bulk explosive temperature.

- Utilizing Andreev's method, we plot the reciprocal of burning rate against bulk explosive temperature.

- For Composition B explosive
  - $\alpha = 10^{-3}$ m/s-bar
  - A = 12.04
  - B = 0.0235/K
  - Thus: 1/burning rate = $12.04 - 0.0235T_0$



Pressure Decay

- **When the interior pressure exceeds the outside pressure by more than 0.8 bar, the flow velocity becomes sonic and a very simple expression for the pressure-decrease results (equation 3).**

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

  - **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**

- **Flow through a square-edged orifice results in a discharge coefficient of approximately 0.82 because of the *vena contracta* formed by the gases exiting the vent hole.**

Pressure Decay

- **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:**

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

- **a* is approximately 725 m/s for a nominal combustion gas mixture with:**
  - **T = 2500K**
  - **R= 8.31434 J/mol-K**
  - **M=0.028 kg/mol**
  - **k=1.27**

.

Critical Vent Area

- **If the magnitudes of the pressure-decay and pressure-rise terms are equal, a critical condition results**

- **The pressure-rise and pressure-decay equations can be combined.**

$$dP/dt = [(RT_B * \rho/M * \alpha/(A-BT_0) * S_B) - (A_v C_D\ a^*)] * (P/V) \qquad (5)$$

- **Rearrangement gives the relationship of vent area to burning surface area**

$$A_v/S_B = (RT_B\ \rho\ \alpha) / [M\ C_D\ a^*(A-BT_0)] \qquad (6)$$

- **If A_v/S_B is greater than the critical value, pressure decreases.**
  - **This is what we seek!**

Critical Vent Area Ratio

- For the Composition B explosive cited previously, 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:

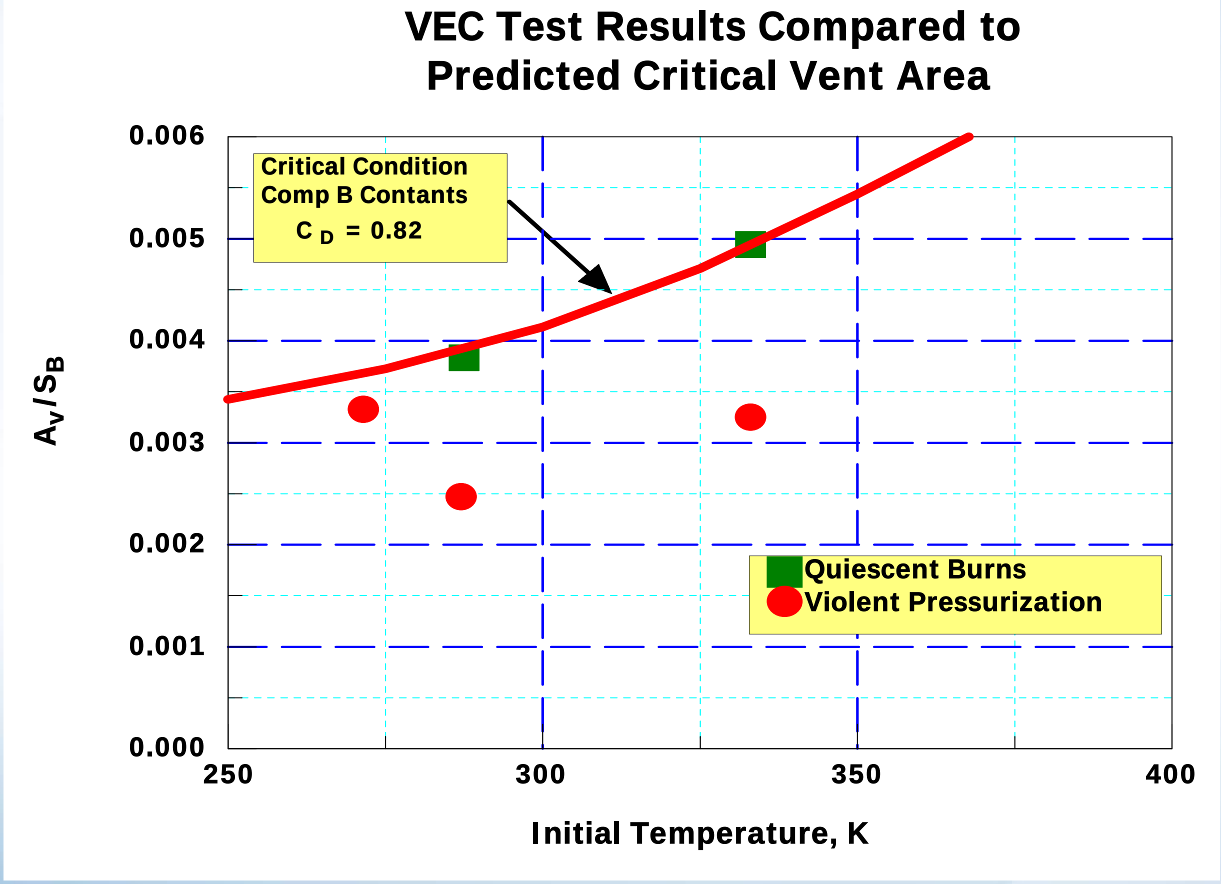
Table 1. Critical Vent Area as a Function of Initial Explosive Temperature

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

- It doesn't take much vent area to prevent pressurization !

VEC Experiments

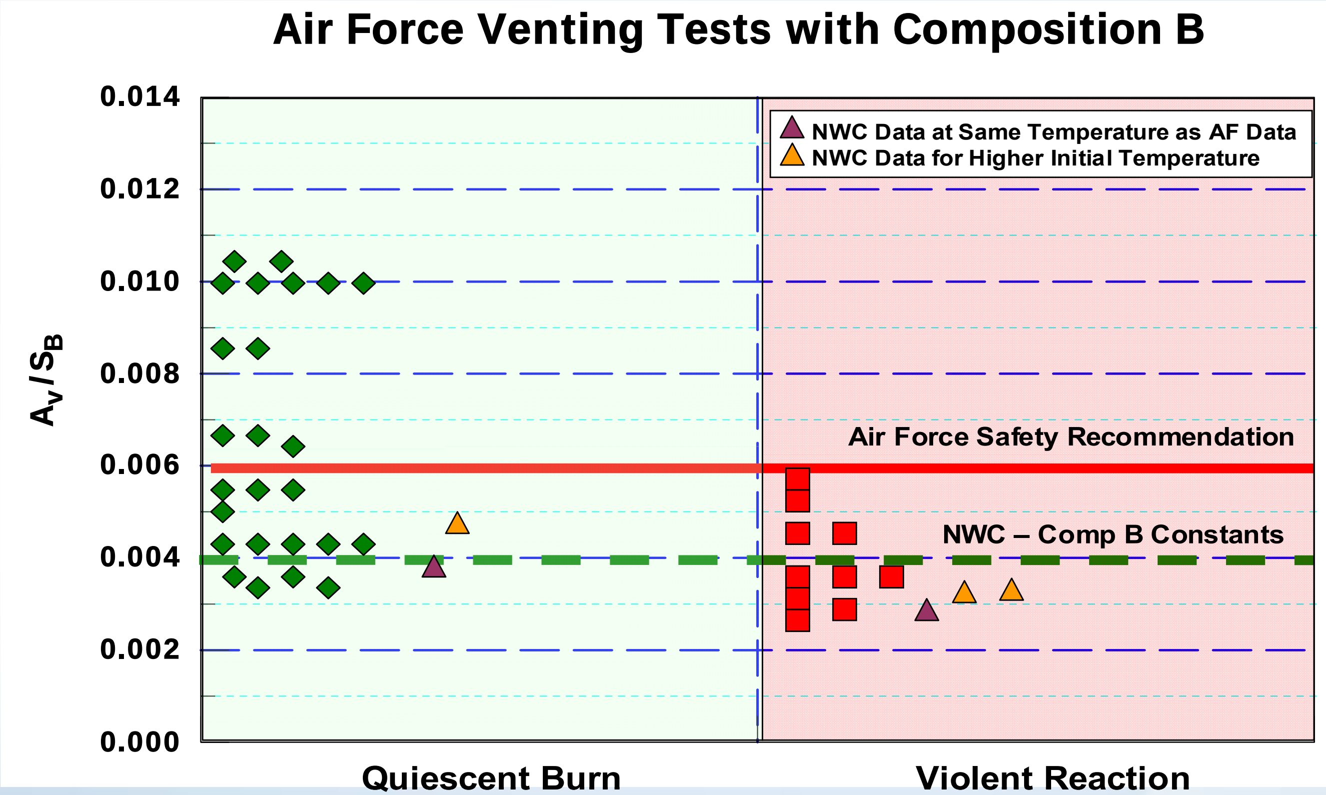
- NWC – Composition B



AEROJET
A GenCorp Company

VEC Experiments

- AFWL – Kirtland – Composition B



Summary of Experiments

- 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.
- Application to the fast cookoff scenario may be successful if the vent is created at a low enough energetic material bulk temperature.

AEROJET
A GenCorp Company

Ballistic Analysis

- **Minuteman III first stage motor was chosen as the example. The assumed propellant properties:**
  - **Outer grain surface area: 42,629 sq. in.**
  - **70°F Burning Rate: $r_b = 0.290 (P_c/1000)^{0.34}$**
  - **Temperature Coefficient: $\sigma_p = 0.001/^{o}F$**
  - **Characteristic Velocity: c* = 5172 ft/s**
  - **Density: $\rho = 0.0652\ lb/ft^3$**
    - **P_c = chamber pressure in psia**
    - **r_b is burning rate in in/s**

Minuteman III First Stage Motor

Ballistic Analysis

- 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.

- Assumptions:
  - The whole exterior surface of the propellant grain ignited instantaneously between the case and the grain
  - All gases exited through the square-edged orifice
  - The motor surface was all at the same temperature

- The Stage 1 weight is 50,550 lb_f

- The 702°F burning rate, $r_b = 0.546 (P_c/1000)^{0.34}$

MM III Ballistic Analysis

- First, compute the thrust using equation (7).

$$F = P_c A_t C_f \eta_F \qquad (7)$$

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

- Second, apply definition of the chamber pressure using equation (8)

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

  - 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

MM III Ballistic Analysis

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

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

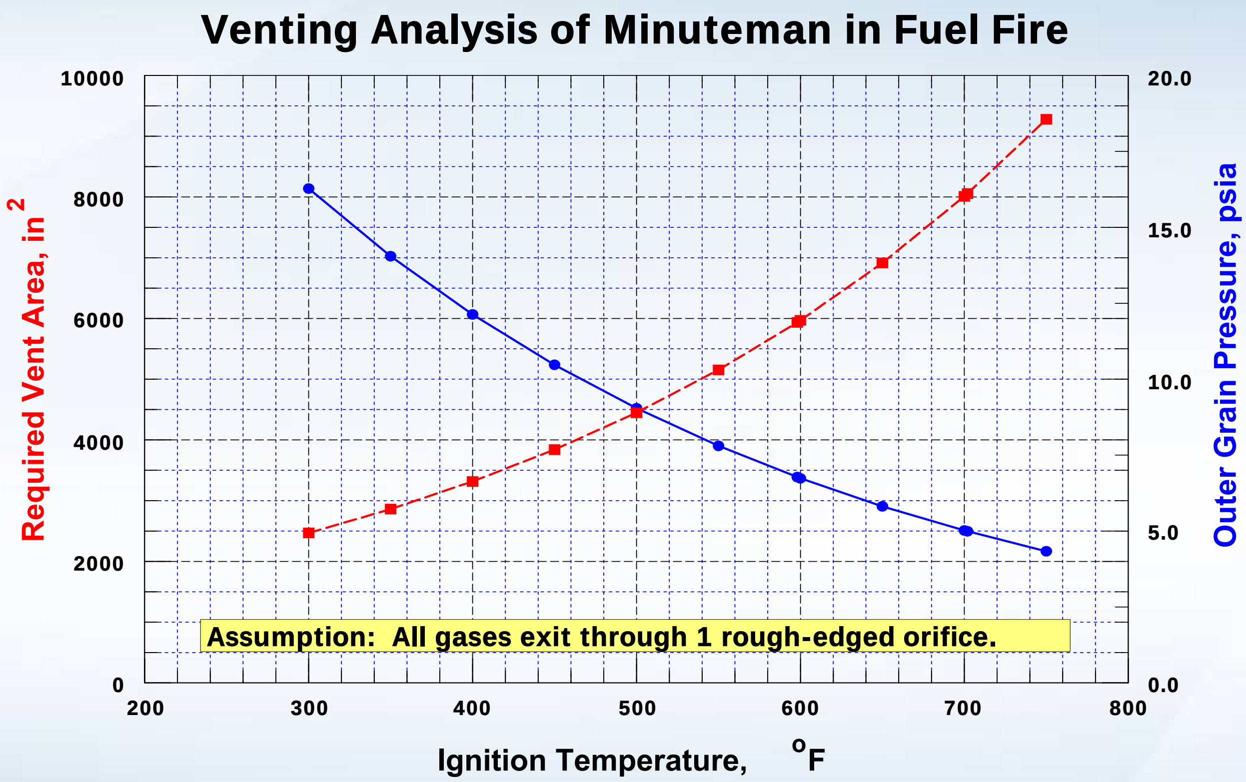
- Solving for Pc through the use of equation (8) gives (10):

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

- The solution: Outer grain pressure, P_c = 4.99 psia and a required vent area of A_t = 8053 sq. in.

MM III Ballistic Analysis

- This methodology was applied over a wide range of temperatures.



- Clearly, lower temperature venting is advantageous!

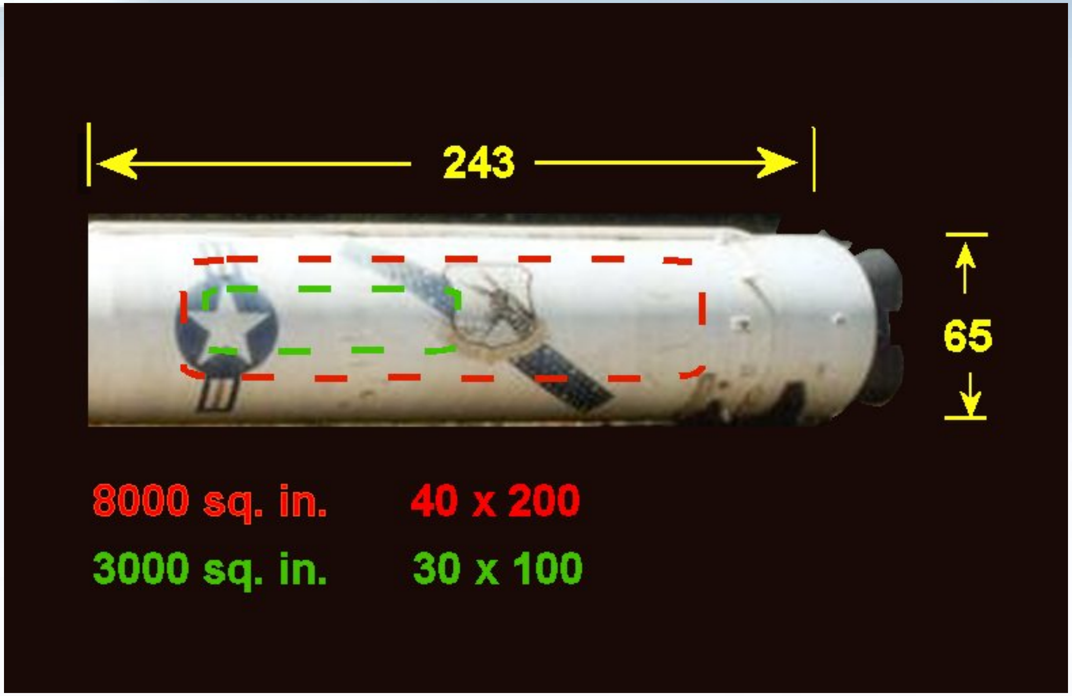
AEROJET
A GenCorp Company

Vent Area Ratio for MM III Stage 1

Table 2. Vent Area to Burn Surface Ratio as a Function of Temperature for MM III Propellant in MM III Case.

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

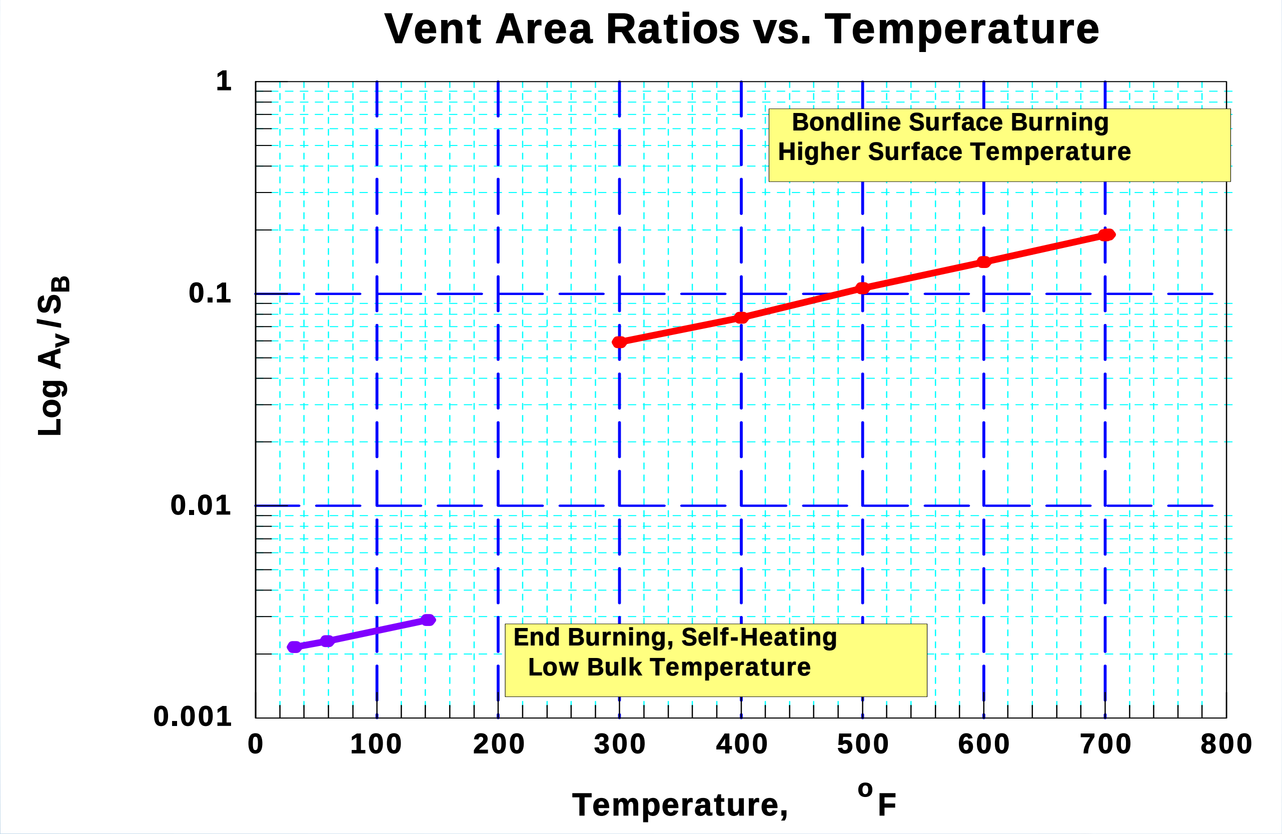
Effect of Surface Temperature at Time of Venting



- **700°F -- 8000 in^2 vent area required**
- **360°F -- 3000 in^2 vent area required**

Comparison of Methodologies

- Comparison of required vent area to burning surface area ratios for end burning and surface burning cased energetic grains



AEROJET
A GenCorp Company

Summary

- It is imperative to vent a cased energetic material subjected to a fuel fire threat at as low a temperature as possible, consistent with its operational requirements and a margin of safety.
  - Required vent areas increase dramatically as the temperature rises
- If the grain has a significant bore area and the flame reaches the bore, then increased vent area will be required.
- Grains that burn “cigarette fashion” and slowly self-heat require less vent area than those exposed to an engulfing fuel fire where the whole outer surface area is heated.
- 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.
- A ballistics-based methodology has been presented to predict the critical vent area for a motor exposed to a fuel fire.

AEROJET
A GenCorp Company

Acknowledgements

- This work was supported by the JIMTP program
  Contract No. FA9300-06-D-0008 Task Order 0005

- Government sponsor:
  Air Force Research Laboratory
  Solid Motor Branch
  Edwards AFB, CA 93524