Defence Academy of the United Kingdom

Cranfield UNIVERSITY

Measuring Radiated Thermal Output from Pyrotechnics and Propellants

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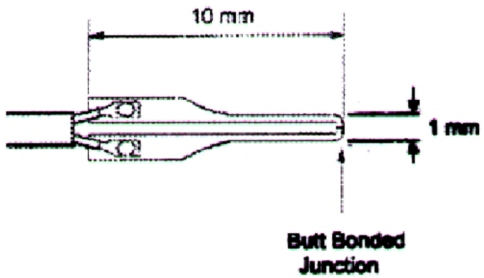
Topics

- Use of Surface Mounted Thermocouple heat flux gauges.
- Short and long duration heat flux.
- Estimating Fireball Surface Temperature.
- Estimating percentage of possible heat that is radiated.
- Blast wave perturbations.

Measuring Heat Flux with Surface Mounted Thermocouples

“Fast” response gauges are very thin (5 micron), butt-joined, thermocouples bonded flat to a ceramic surface (we use MACOR™).



No cooling is required. They are rugged and can be placed close to thermal event.

They can be calibrated for heating due to radiation but also report convection.

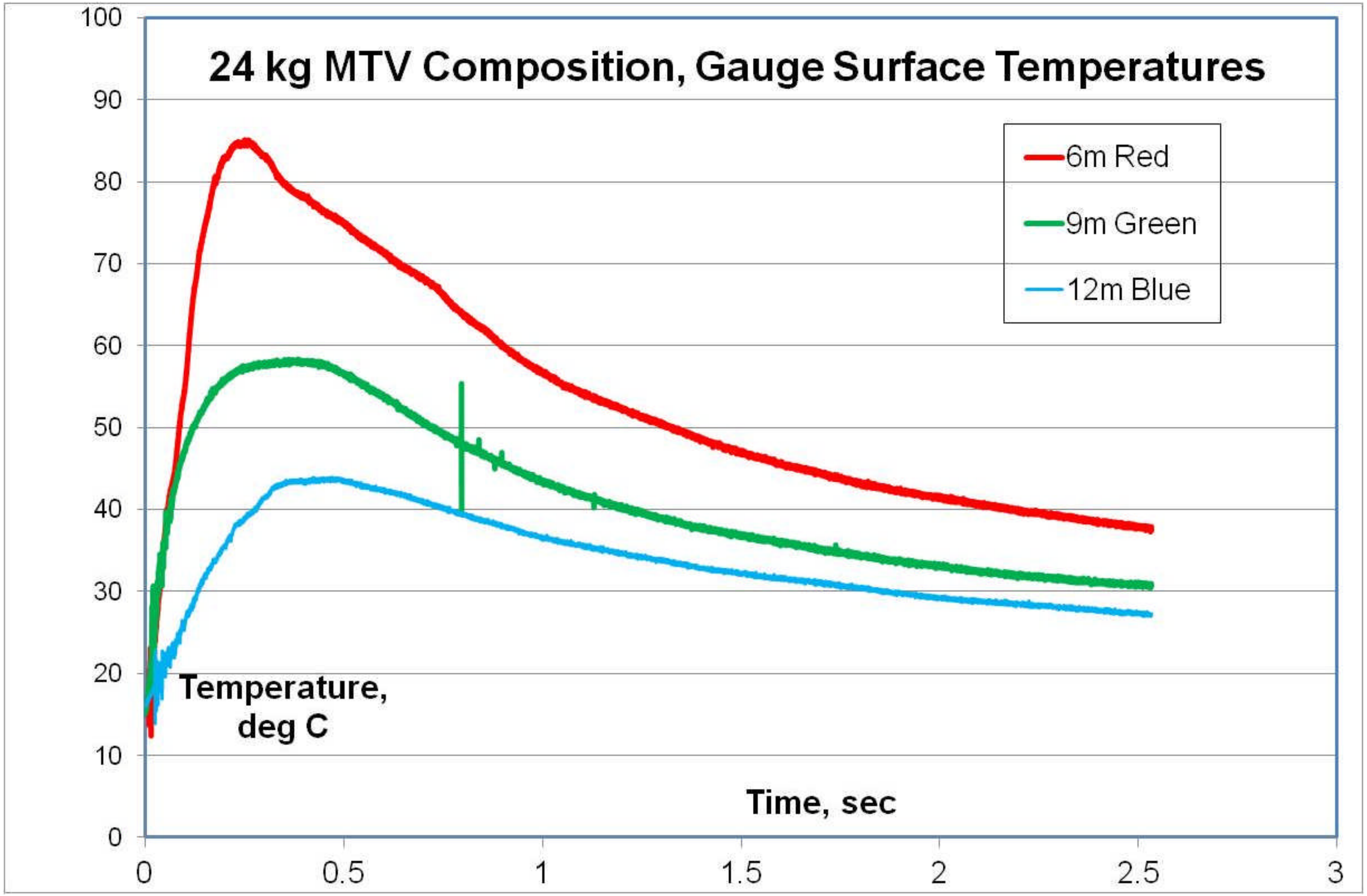
Broad band absorption – calibrated against 3 kW radiant heat source with steel surface.

Radiation Flux Gauges

Our Work

- MTV work based on paper to be published in Propellants, Explosives and Pyrotechnics (Wiley VCH). Work for Wallop Defence Systems.
  - MTV is a flare composition Magnesium/Teflon/ Viton.
- Propellant work for Roxel.
- Ignition composition work for BAE Systems.
- Other work sponsored in-house.

Surface Temperatures of Gauges



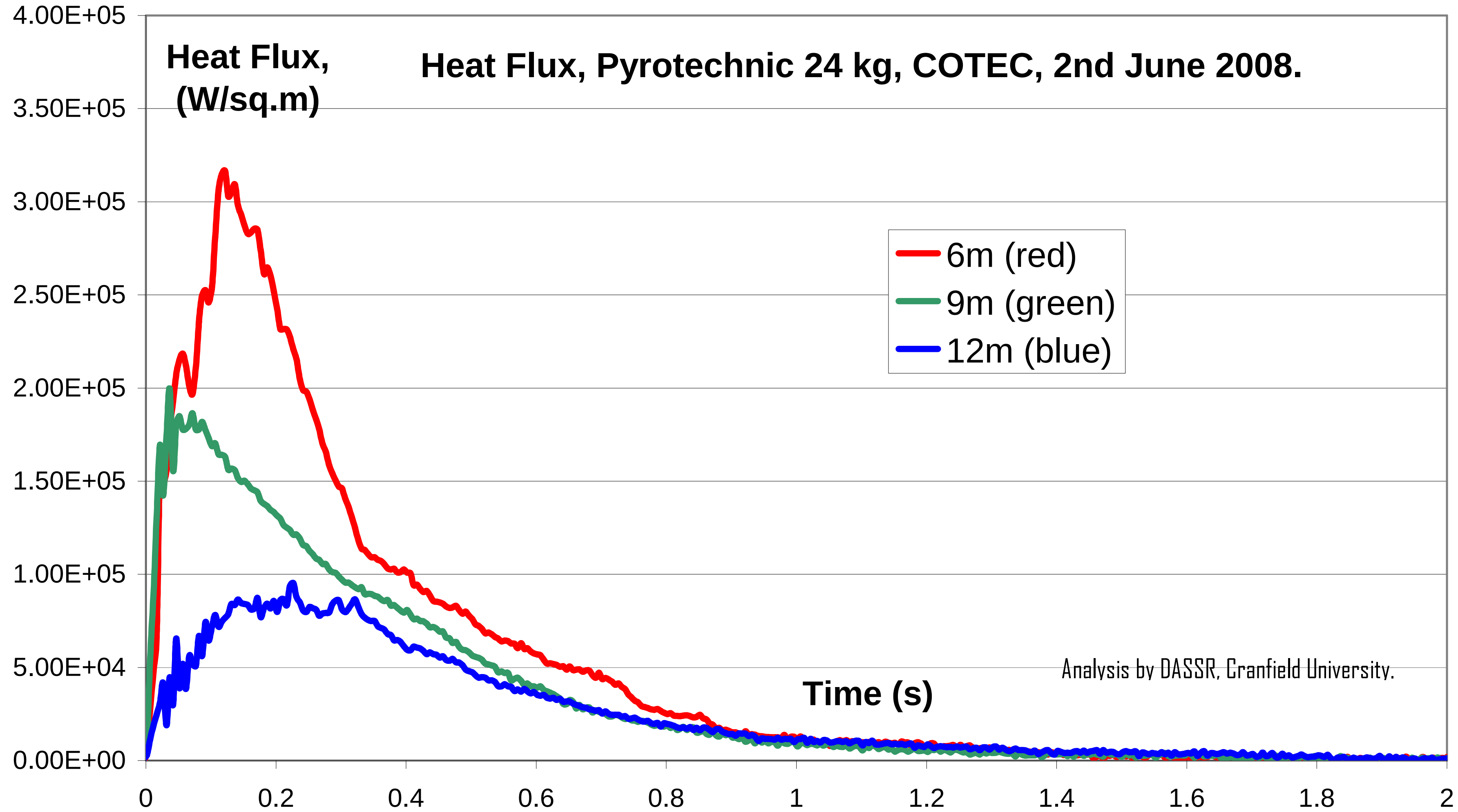
Calculating Flux

- Method of S.V. Patankar.
  - Heat flow into ceramic modelled using thermal conductivity, density and heat capacity. Temperature at depth assumed constant but temperature gradient adapted in “slices” as heat flow progresses
  - Calculation only valid for short durations of heat flow (a few seconds).

Sensitivity Parameters

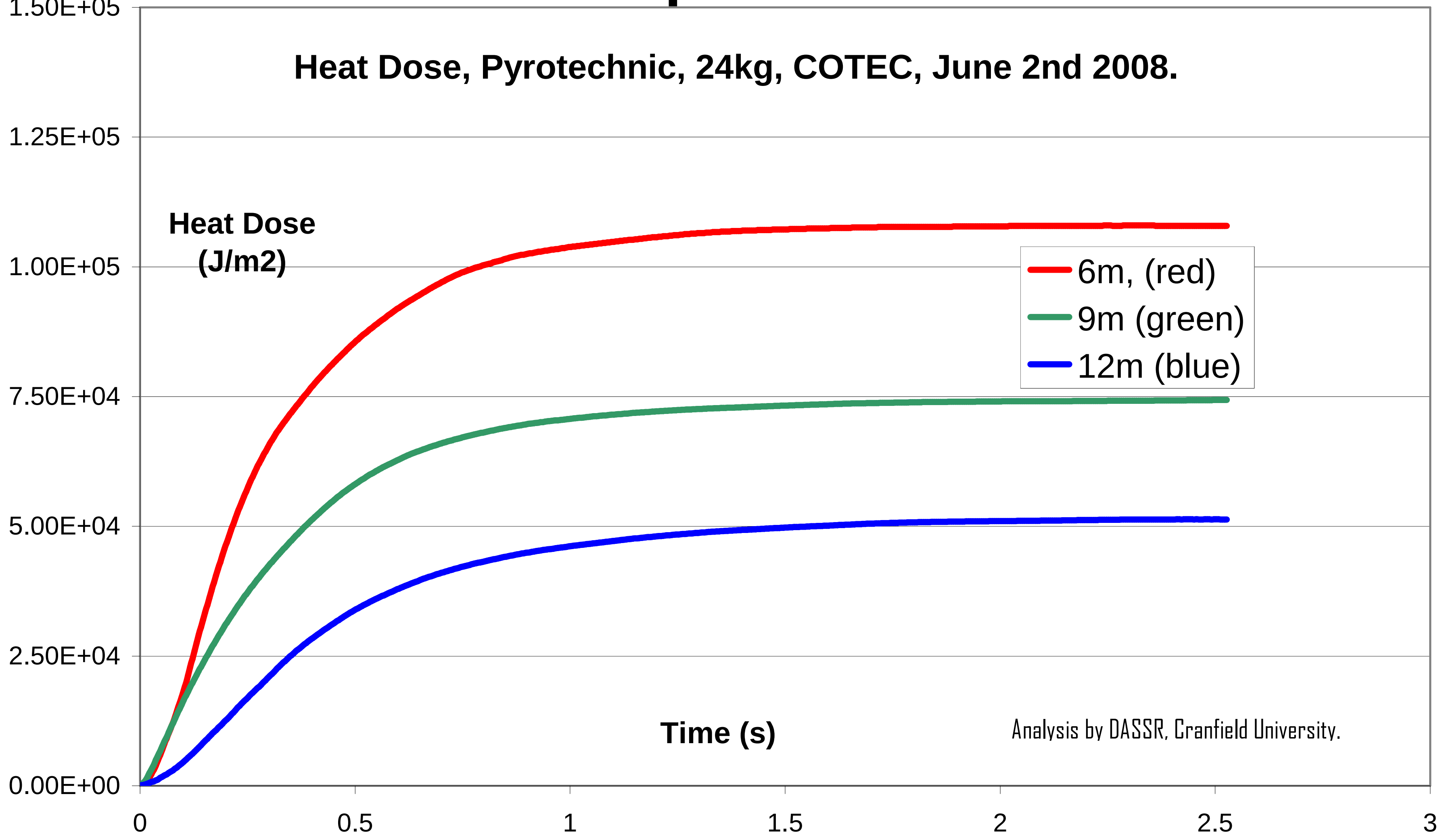
- Sensitivity Depends on:-
  - Absorptivity of surface
  - Thermal Conductivity, Density and Heat capacity of Substrate
- Calculation runs in “Basic” program. In essence
  - dT/dt produces flux (Q)
  - $\int Q \cdot dt$ over duration of flux produces dose
- Flux lines can be erratic, dose usually smooth

Heat Flux

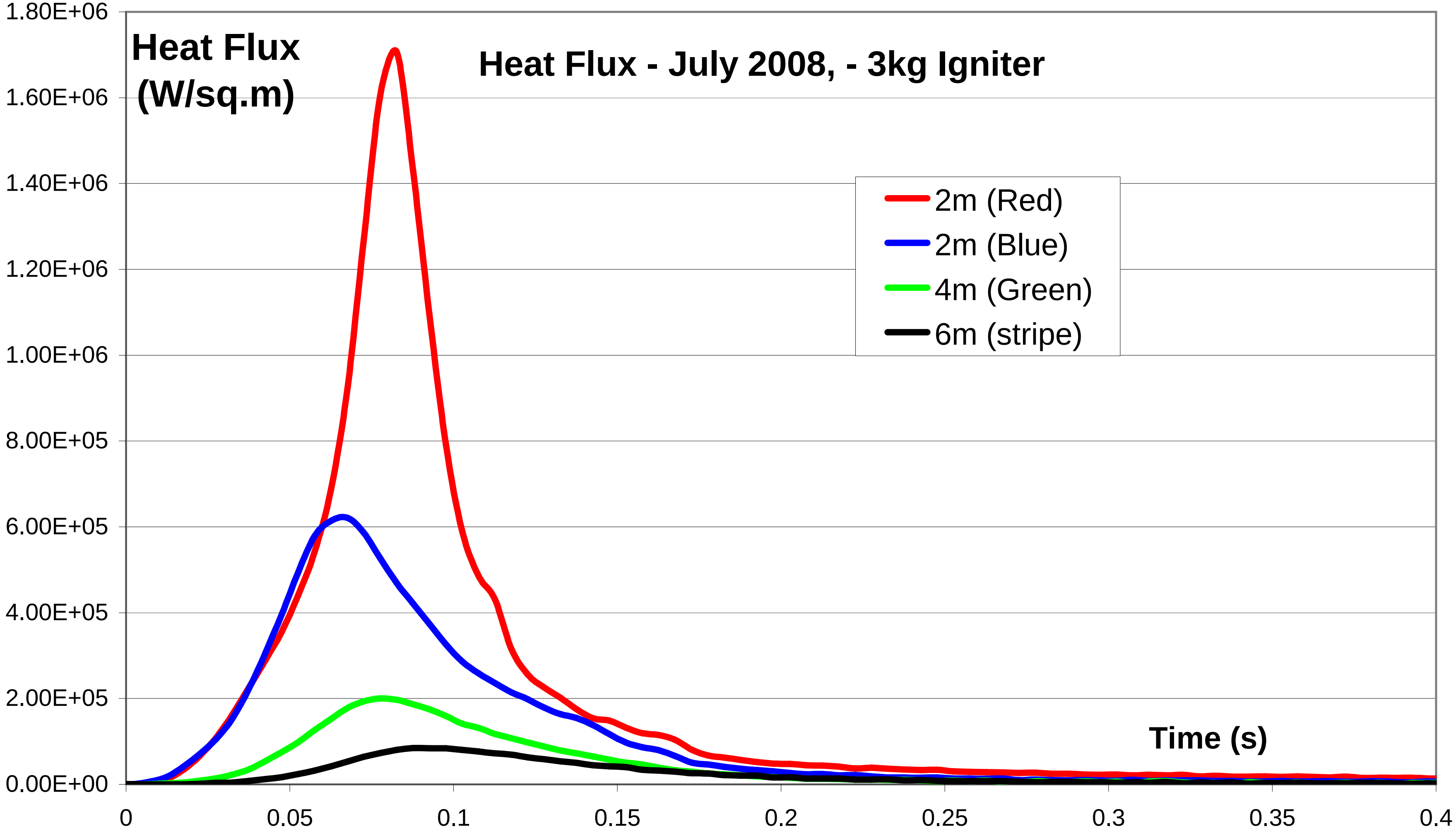


Heat Flux, Pyrotechnic 24 kg, COTEC, 2nd June 2008.
Heat Flux, (W/sq.m)
4.00E+05
3.50E+05
3.00E+05
2.50E+05
2.00E+05
1.50E+05
1.00E+05
5.00E+04
0.00E+00
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
Time (s)
6m (red)
9m (green)
12m (blue)
Analysis by DASSR, Cranfield University.

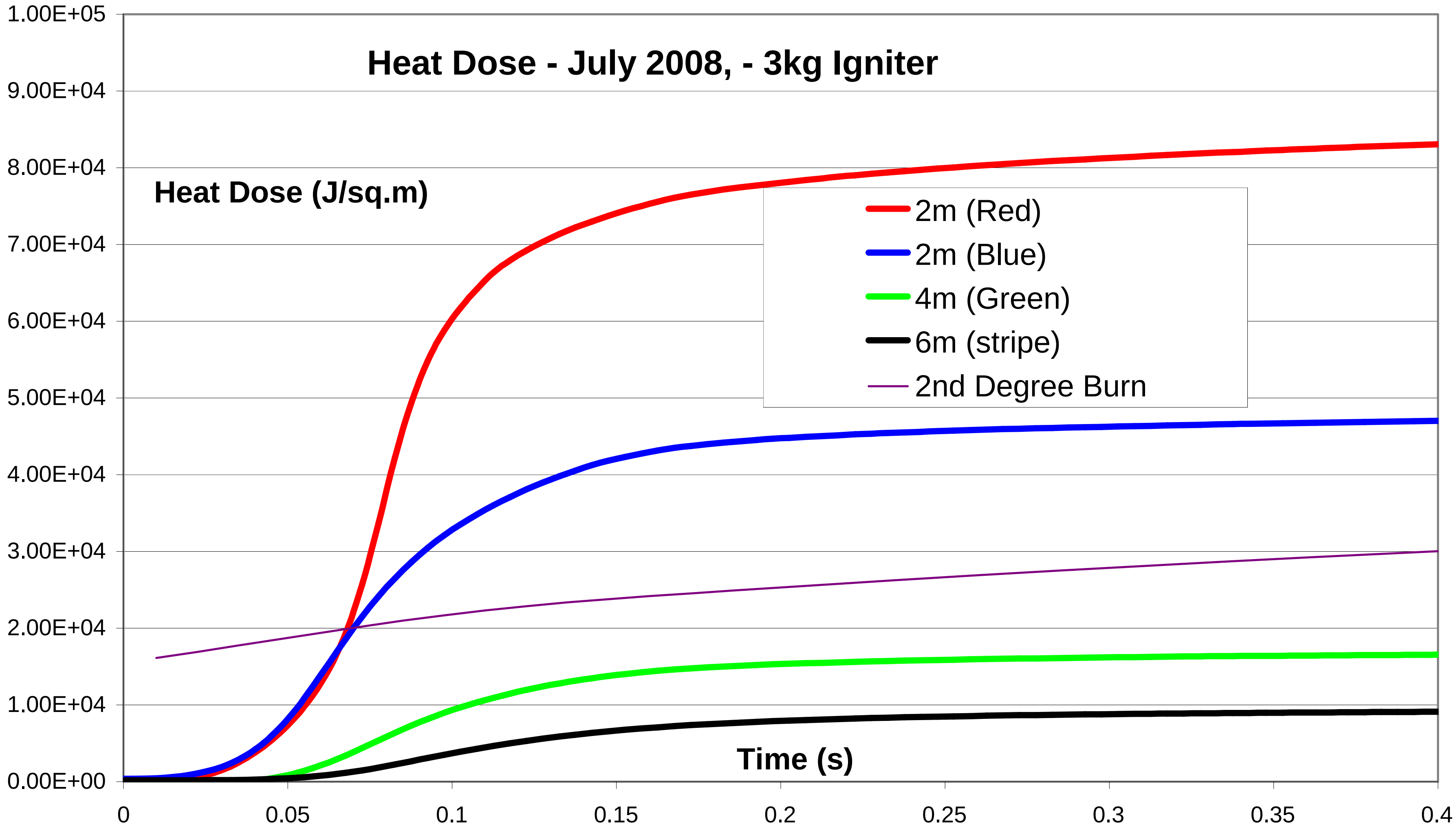
Heat Dose - medium fast composition



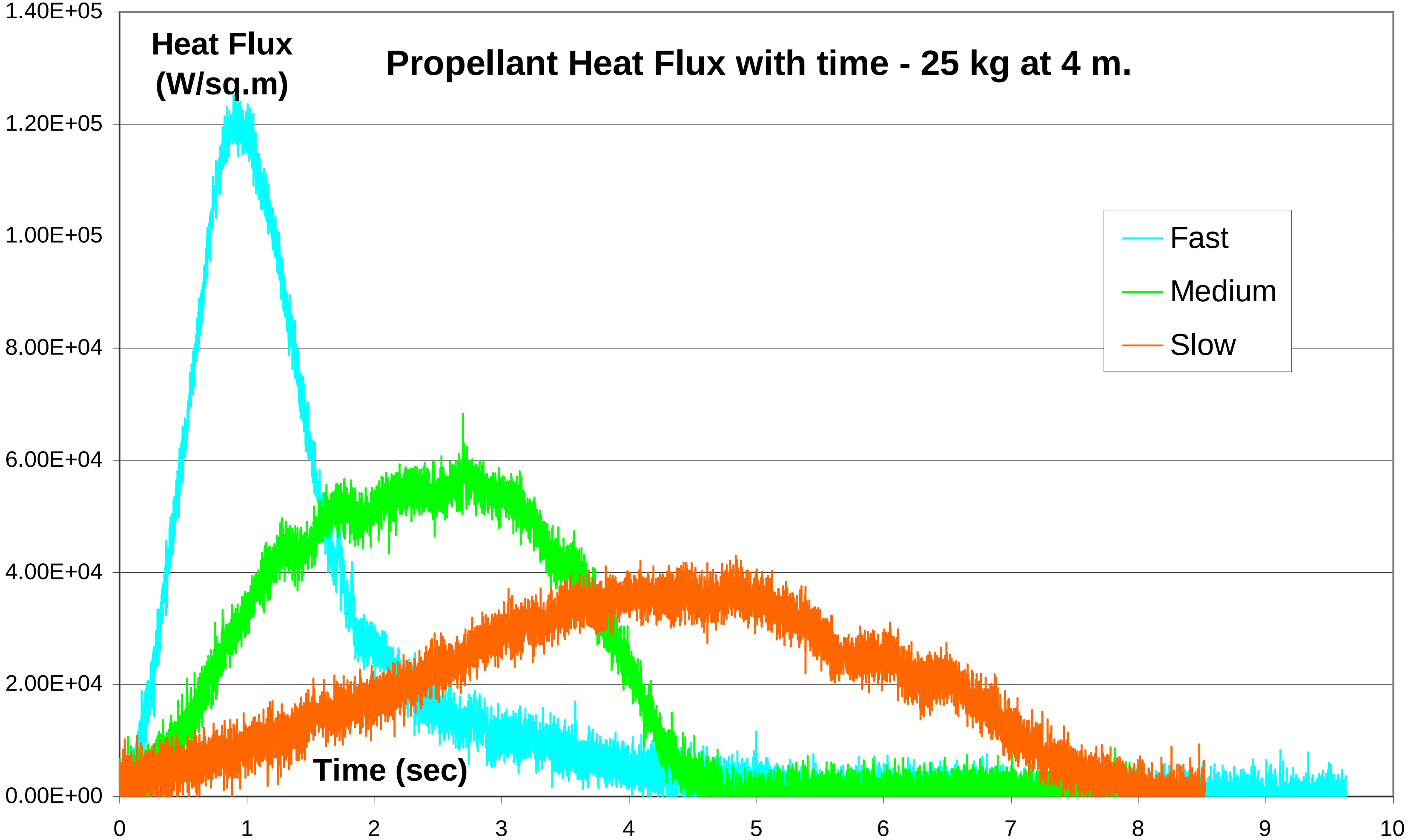
Fast Burning Composition



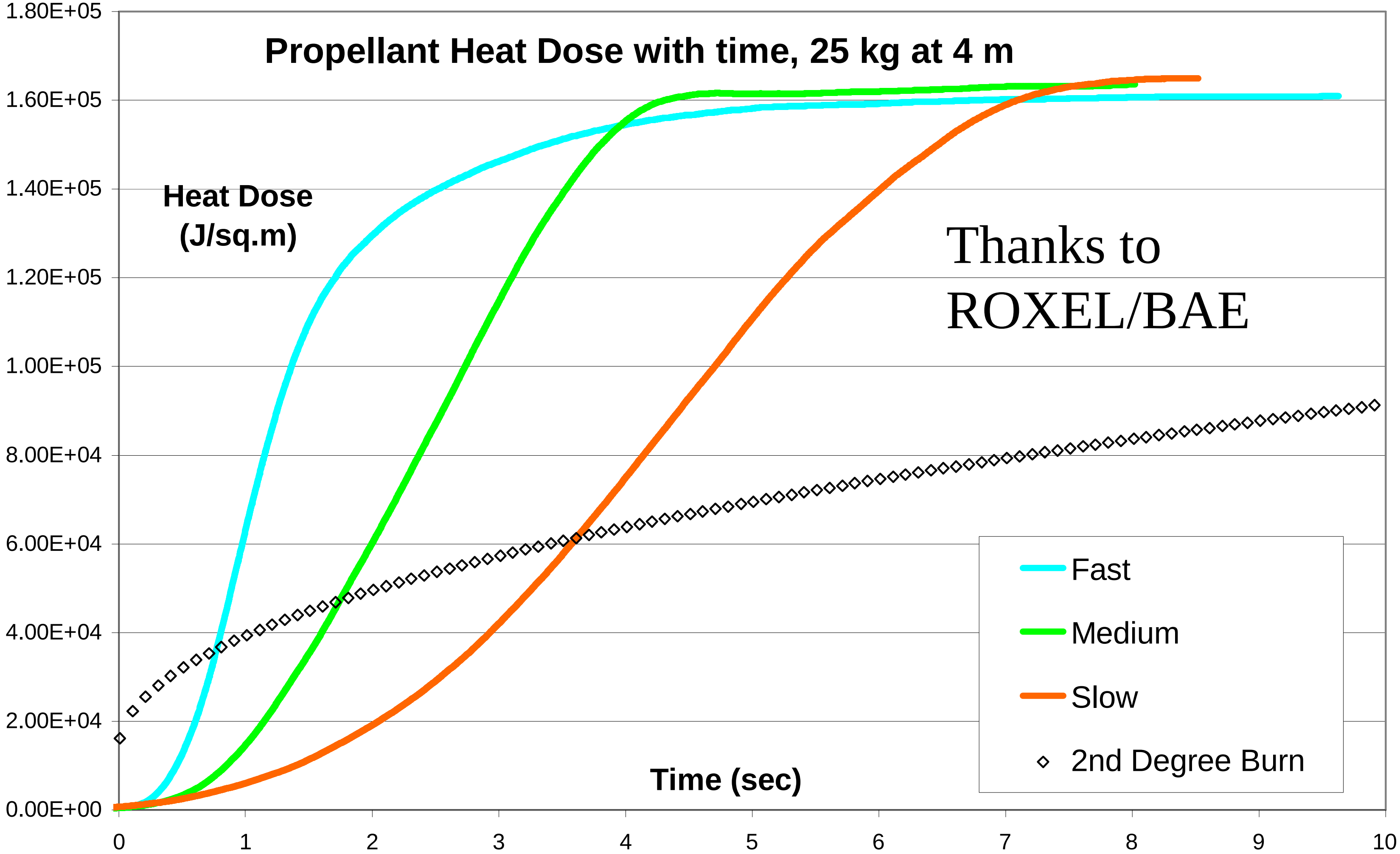
Dose from Burning Composition



Propellant – Three Speeds

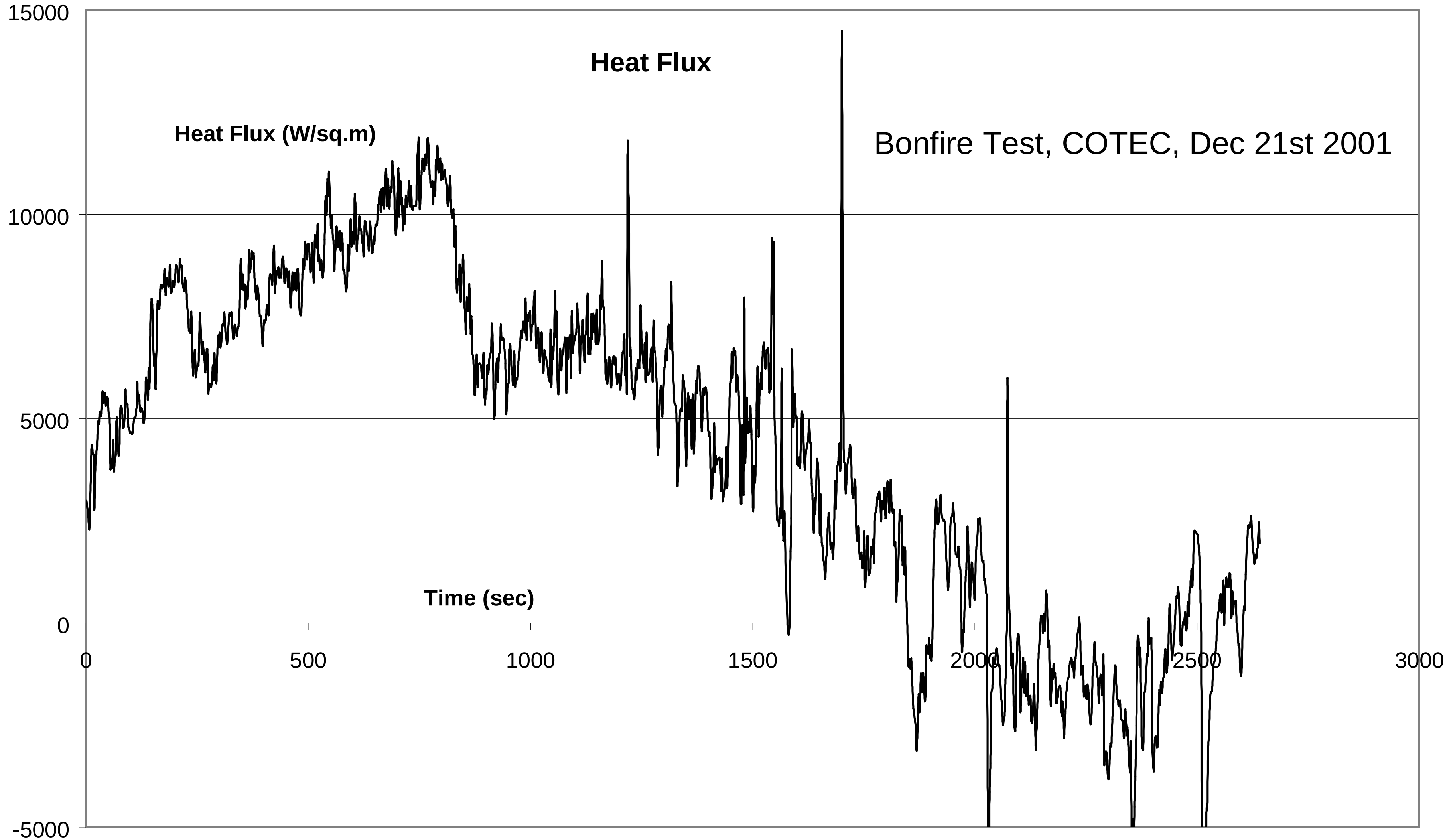


Propellant – Doses



Fuel Fire Test

IM Fuel fire test

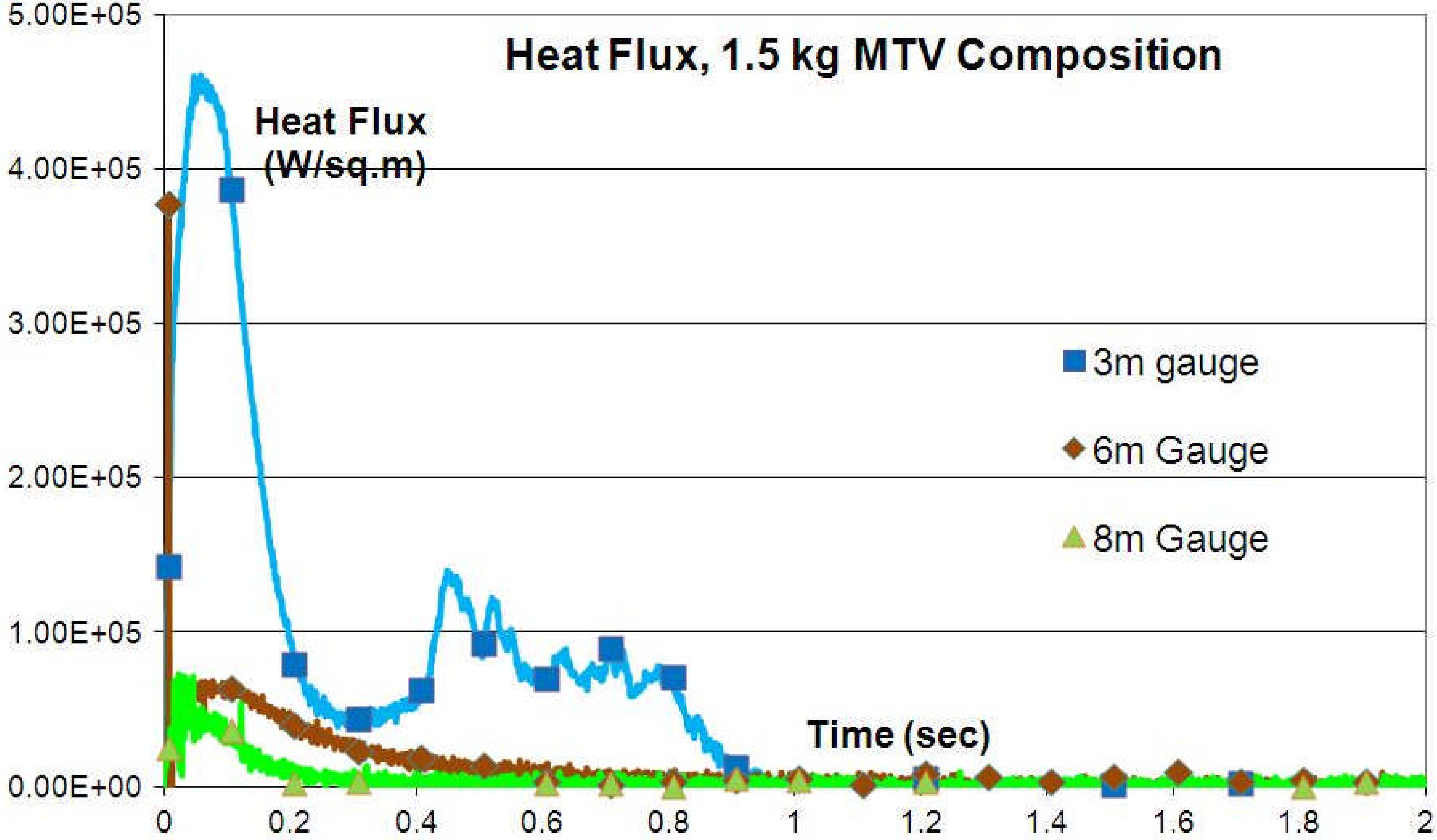


Effect of 25g Explosive on Fire

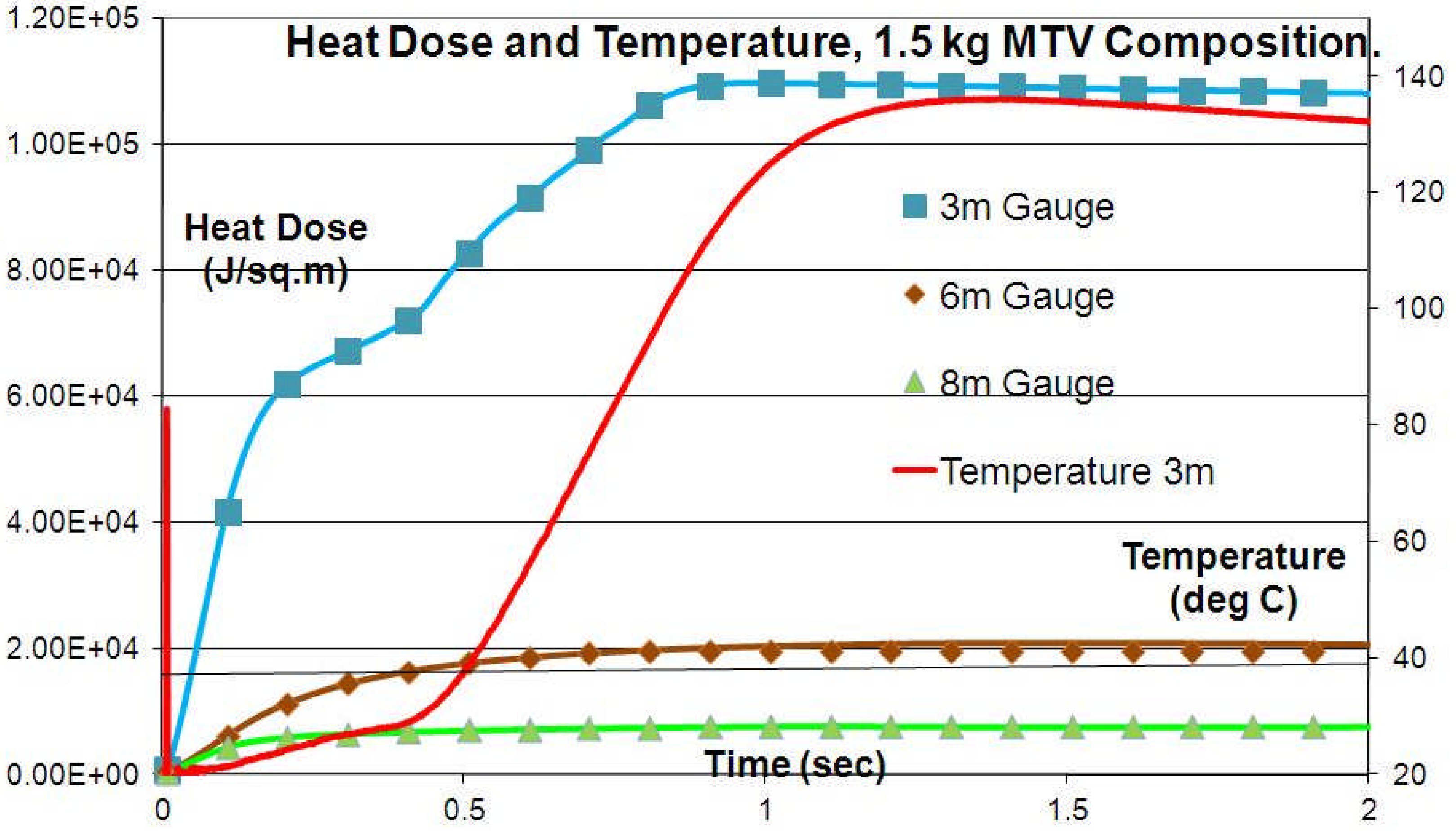
Convection

- Not easy to predict.
- Can more than double heat dose.
- Need to Consider:-
  - Reynolds number
  - Prandtl number
  - Expansion number
  - Four variables determined by experiment!
    - See Lawton and Klingenberg, “Transient Temperature Measurement in Engineering”

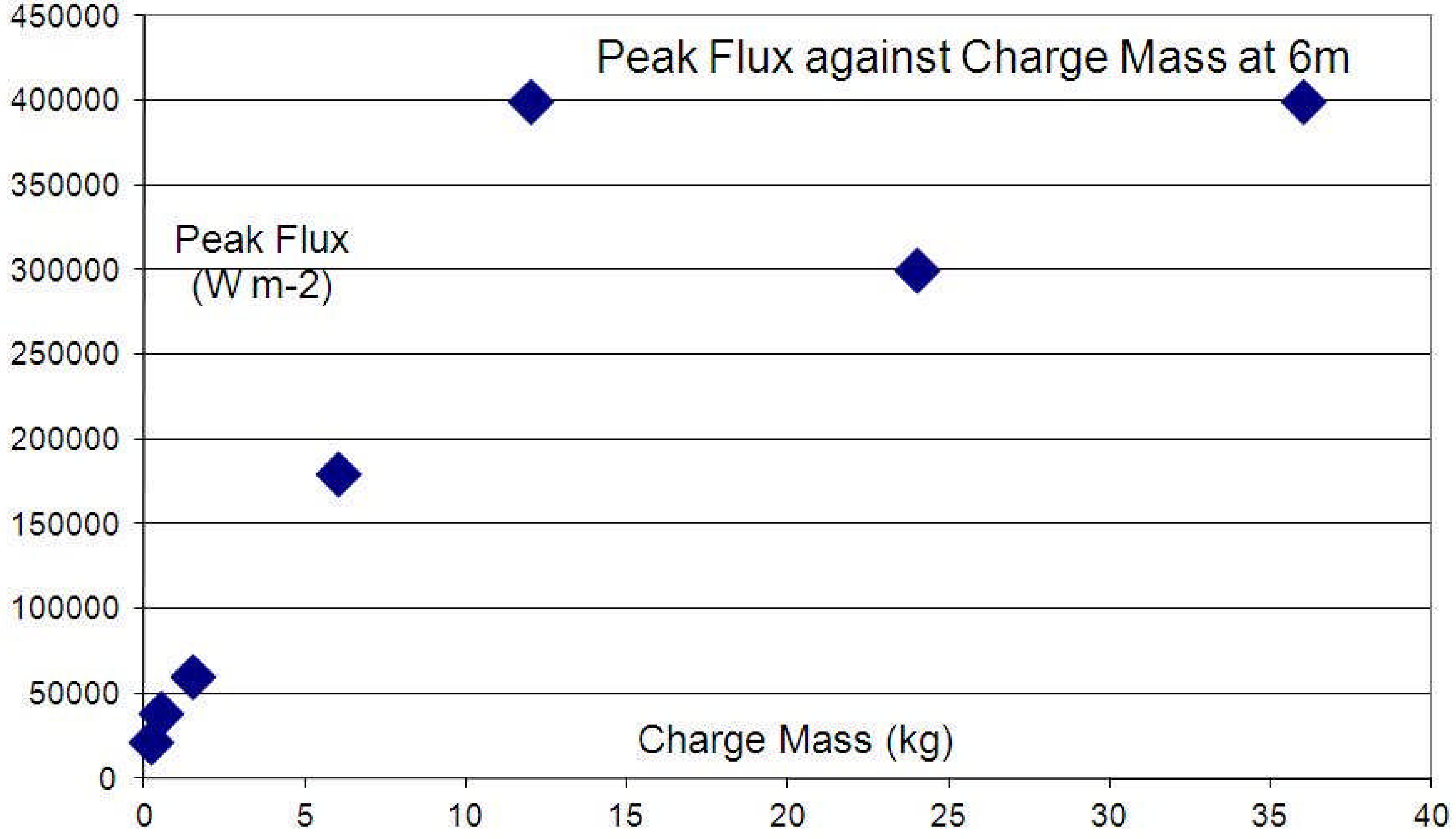
Flux with Convection



Dose with Convection



Peak Flux – MTV Composition



Heat Transfer from Optically thick Flames and Hot Surfaces

$$M = \varepsilon_T \,.\, \kappa.\, T^4$$

M = Rate of Heat transfer (Watts m^{-2})

ε_T = Temperature dependant emissivity (a number ≤1)

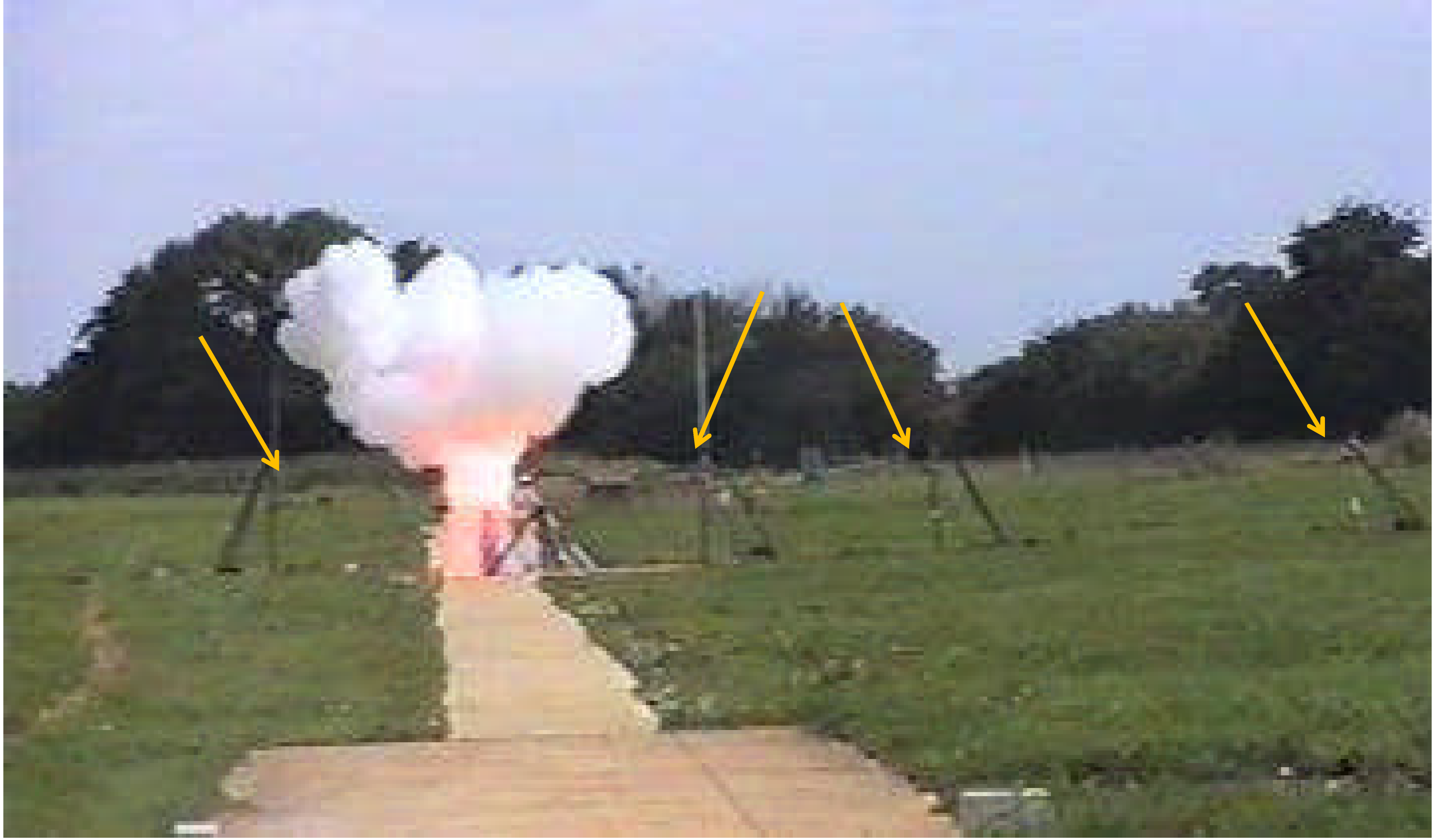
κ = Stefan Boltzmann constant = 5.67×10^{-8} W m^{-2} K^{-4}

T is Emitting Surface Temperature (in Kelvin).

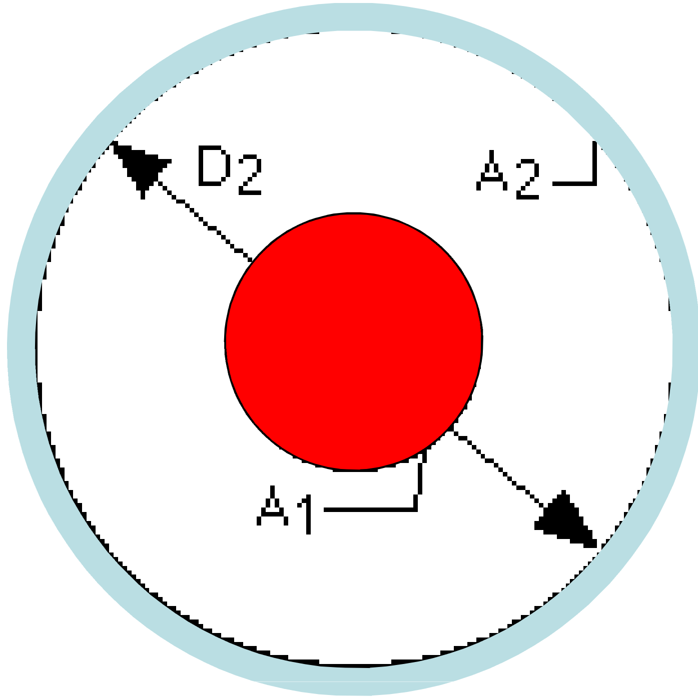
Using ε_T = 0.85 and assuming maximum flux fills field of view of gauges

	Maximum M	Surface Temperature
Propellant	0.12 MW m^{-2}	1260 K
MTV	0.5 MW m^{-2}	1800 K
Igniter	1.7 MW m^{-2}	2440 K

Effect of Distance and View Factor



Simple View Factor



For Infinitely long coaxial cylinders. $F_{1\text{-}2} = 1$

All of the heat emerging from the inner cylinder must pass through the outer one. Concentric Spheres are the same – assumption of point source model.

Effect of distance = $1/d^2$

Point Source Model

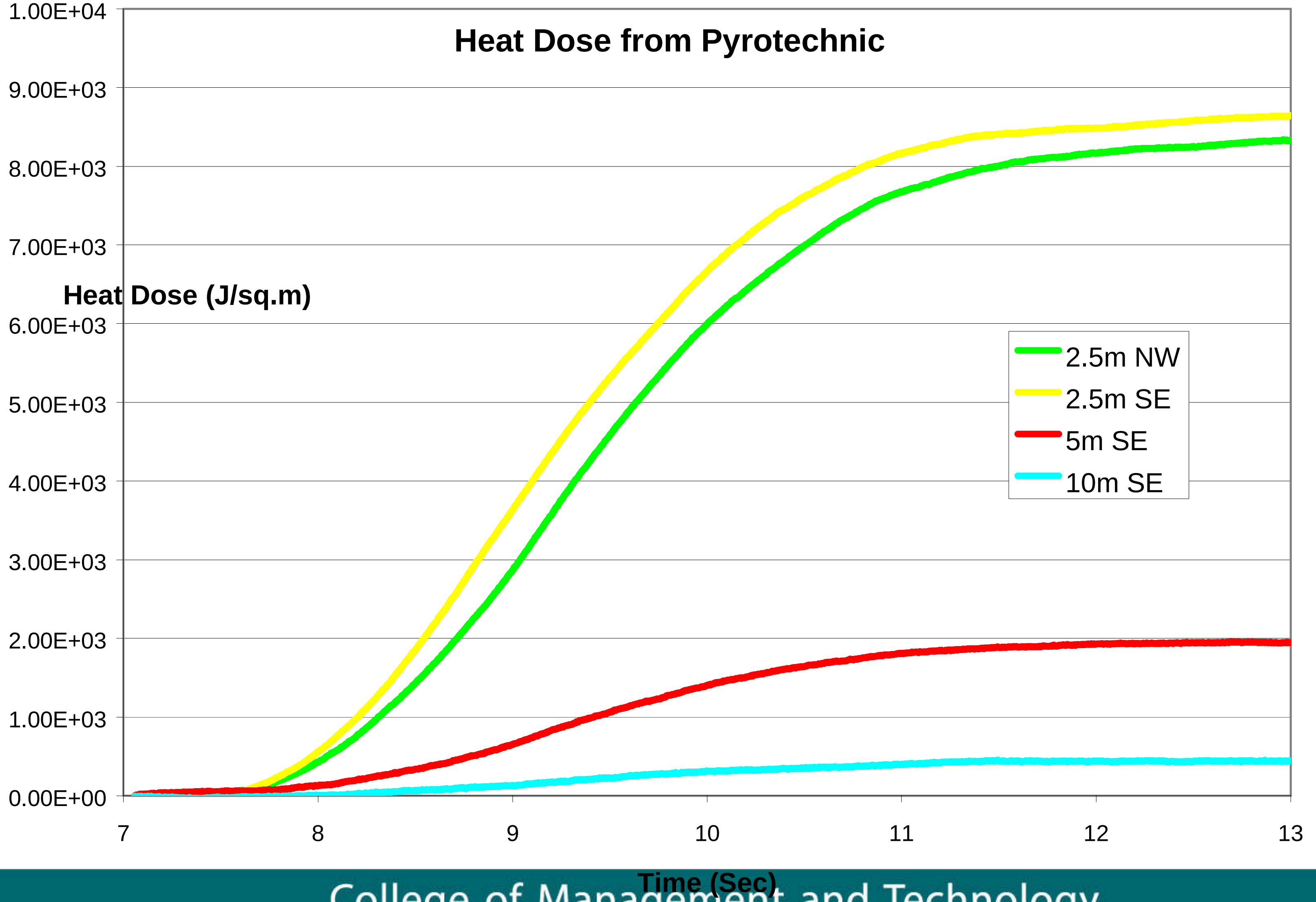
Assumes all radiated heat comes from a fixed point.

Assume view factor = 1.

Work back from measured J m^{-2} to total Joules using surface area of a sphere at the distance of measurement.

This will give an output in J kg^{-1} that can be compared with thermochemistry of material to estimate an effective emissivity.

Heat Dose



Heat Dose from Pyrotechnic
Heat Dose (J/sq.m)
1.00E+04
9.00E+03
8.00E+03
7.00E+03
6.00E+03
5.00E+03
4.00E+03
3.00E+03
2.00E+03
1.00E+03
0.00E+00
7
8
9
10
11
12
13
Time (Sec)
2.5m NW
2.5m SE
5m SE
10m SE

Effect of Distance – Polythene Pyrotechnic

Distance (m)	Heat Dose ($J\ m^{-2}$)	Total Heat $MJ\ kg^{-1}$
2.5	8400	1.64
5	1950	1.53
10	430	1.35

$$\text{Dose} = K/(d^{2.14})$$

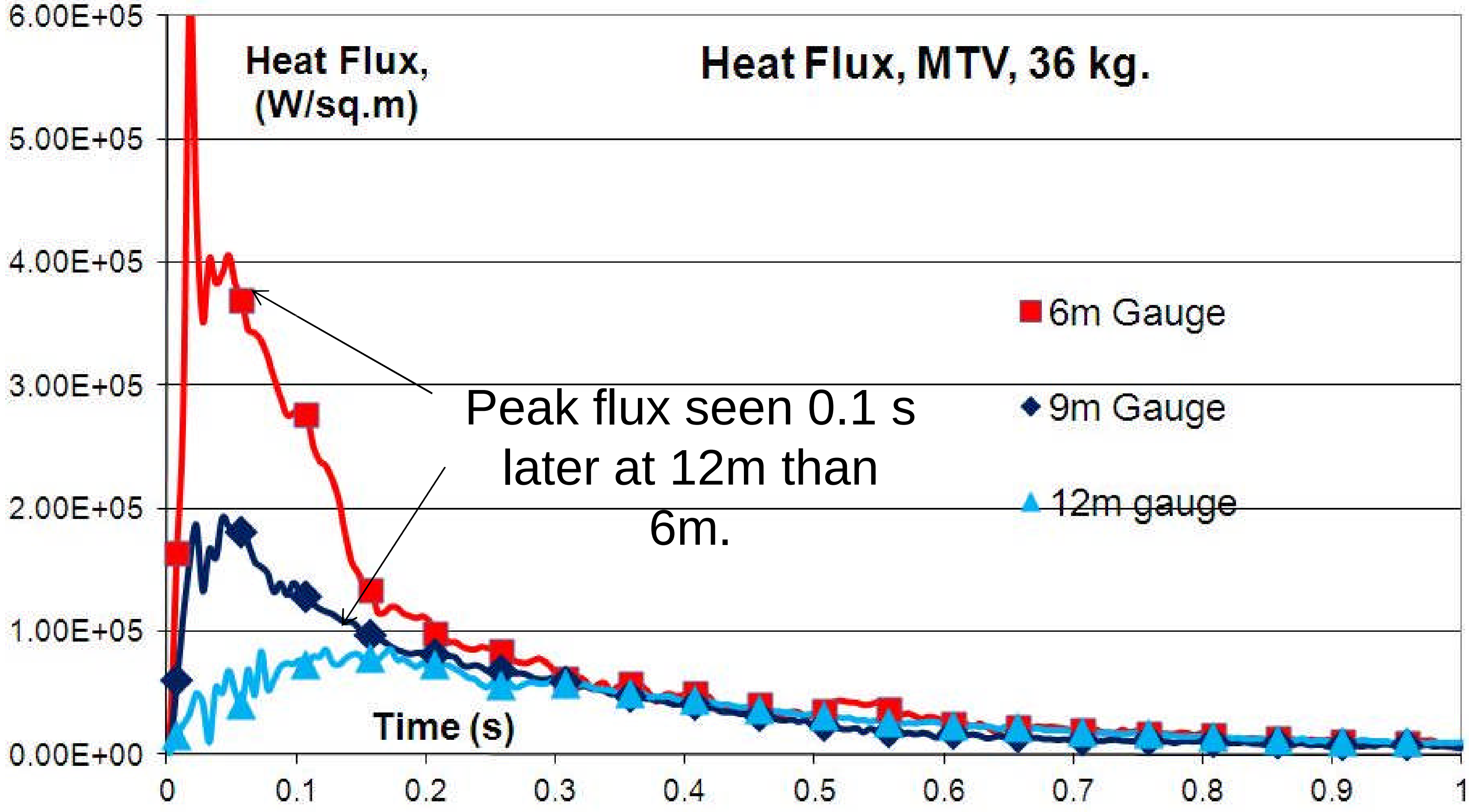
The fact that the exponent in the distance term is >2 is probably due to atmospheric attenuation as the fireball was stable.

Fireballs

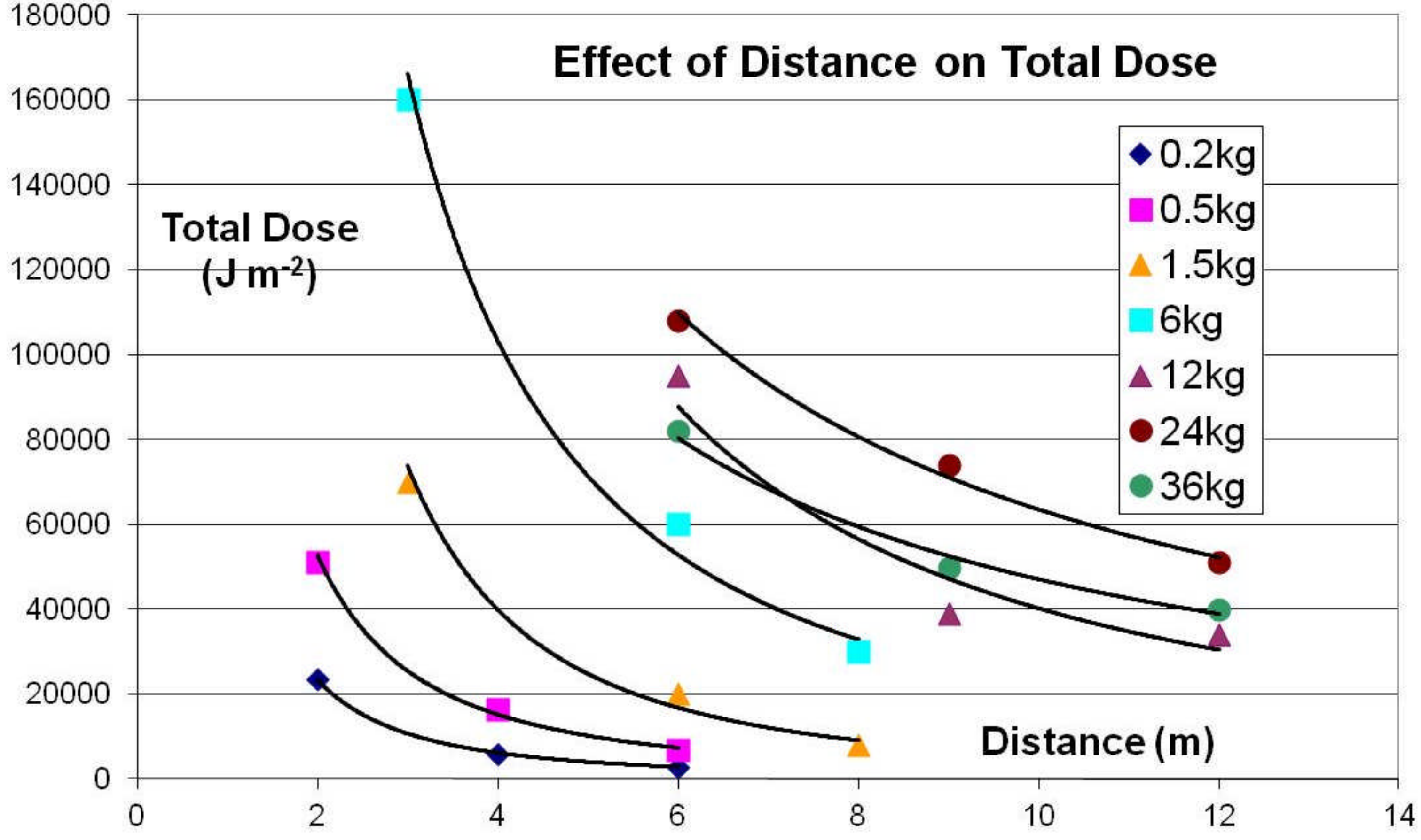
- Most fireballs are not well behaved – tending to be buoyant. View factor is dynamic as fireball rises.
- Assael and Kakosimos (Fires, Explosions and Toxic Gas Dispersions, CRC Press, 2010) have a formula linking

Height/radius	Effect of distance
0.5	$1/d^{2.4}$
1.0	$1/d^{1.98}$
5.0	$1/d^{1.19}$
10.0	$1/d^{1.08}$

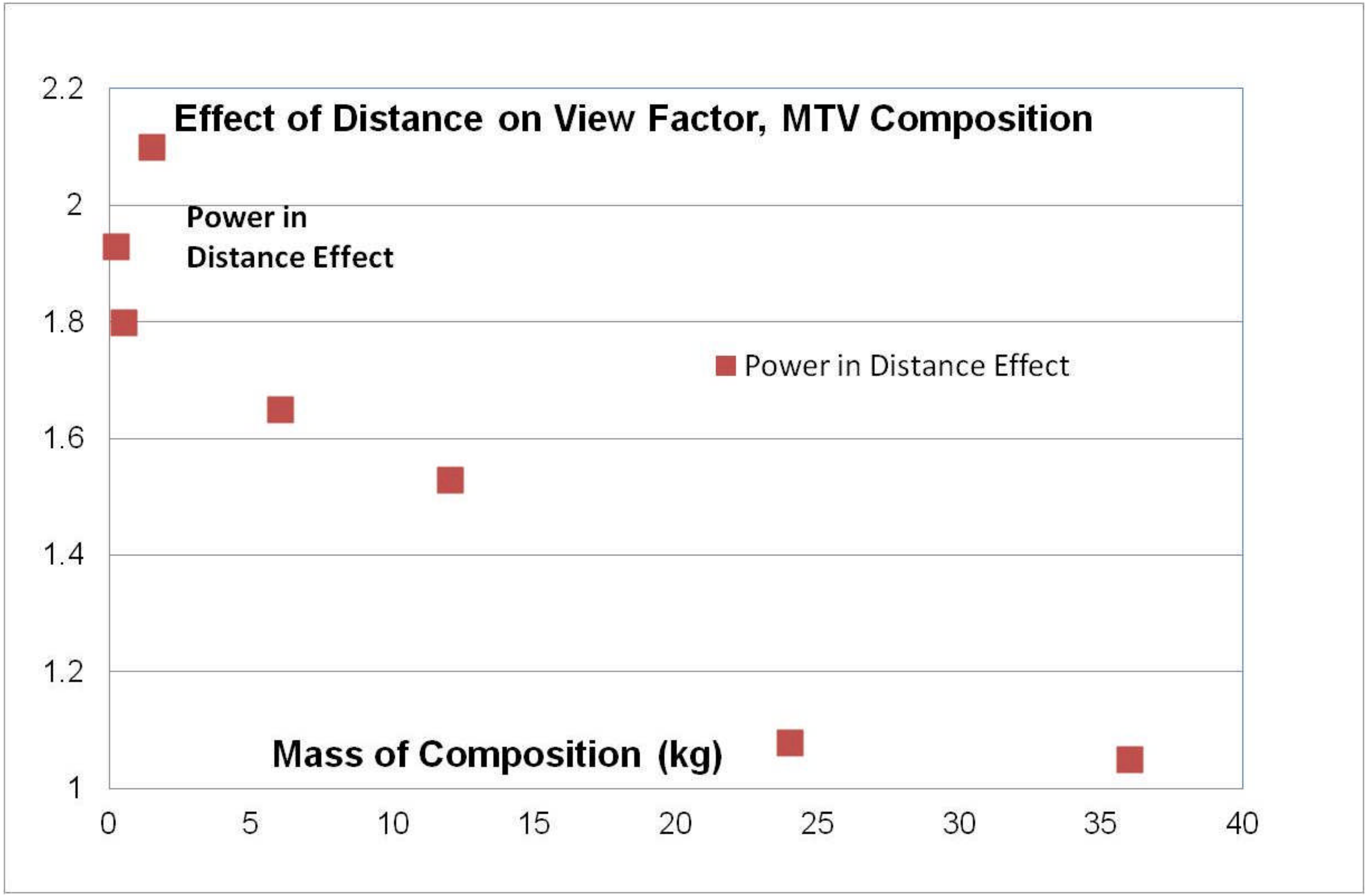
Rising Fireball Effects?



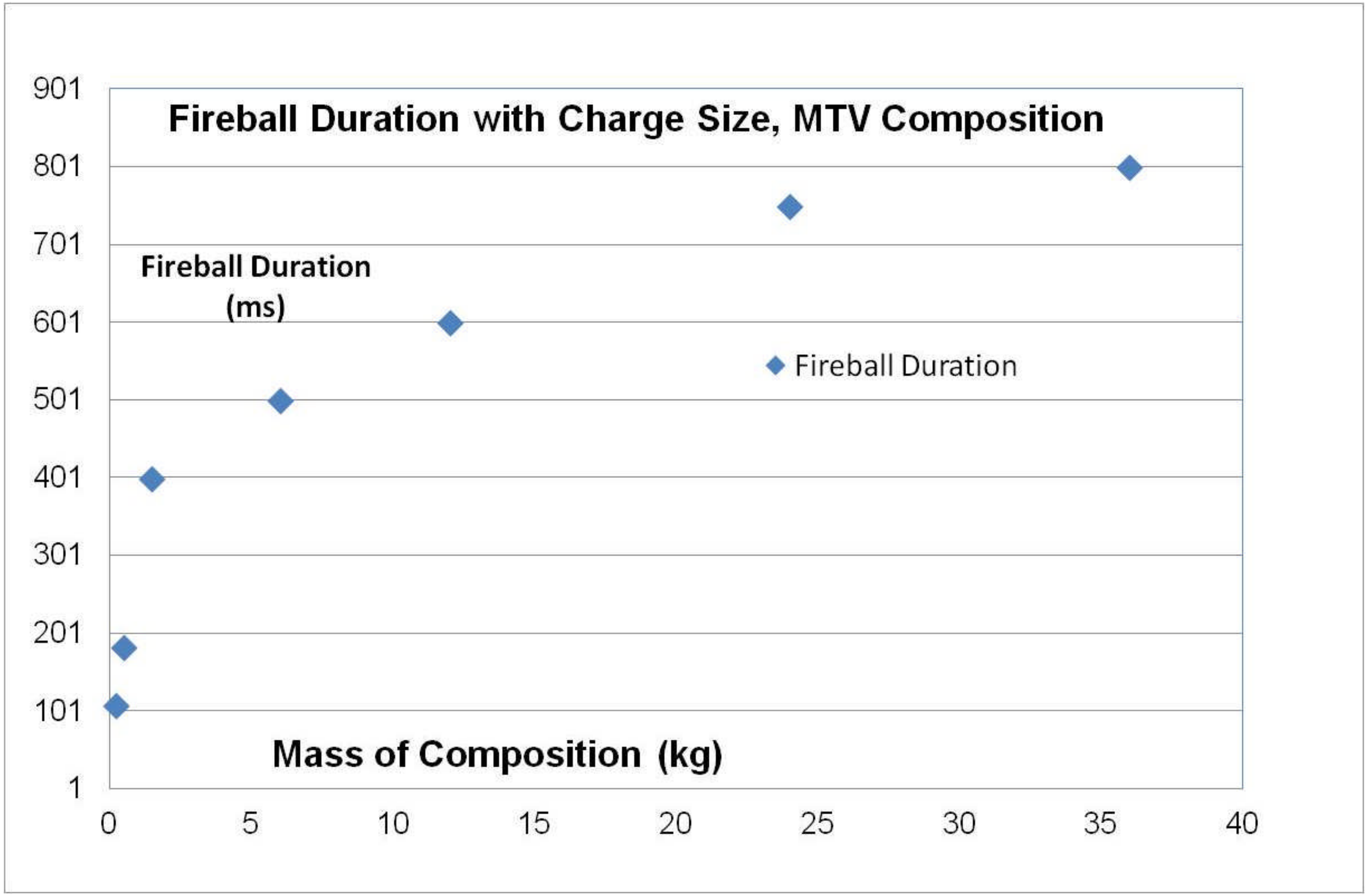
Effect of Amount and Distance
MTV Flare



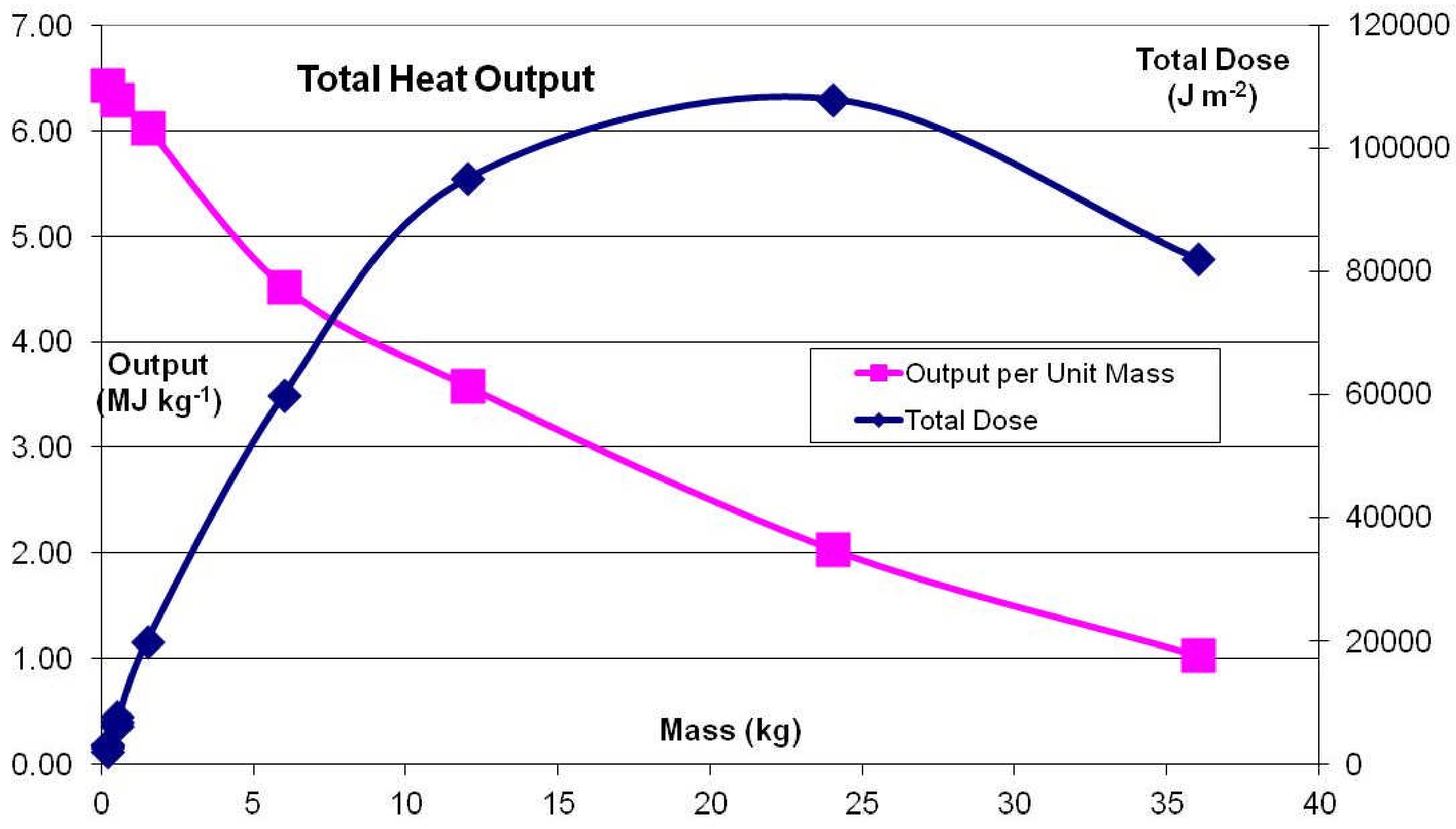
Effect of Amount on View Factor



Effect of amount on Fireball Duration as Radiant Source



Bigger Fireballs – 6m data

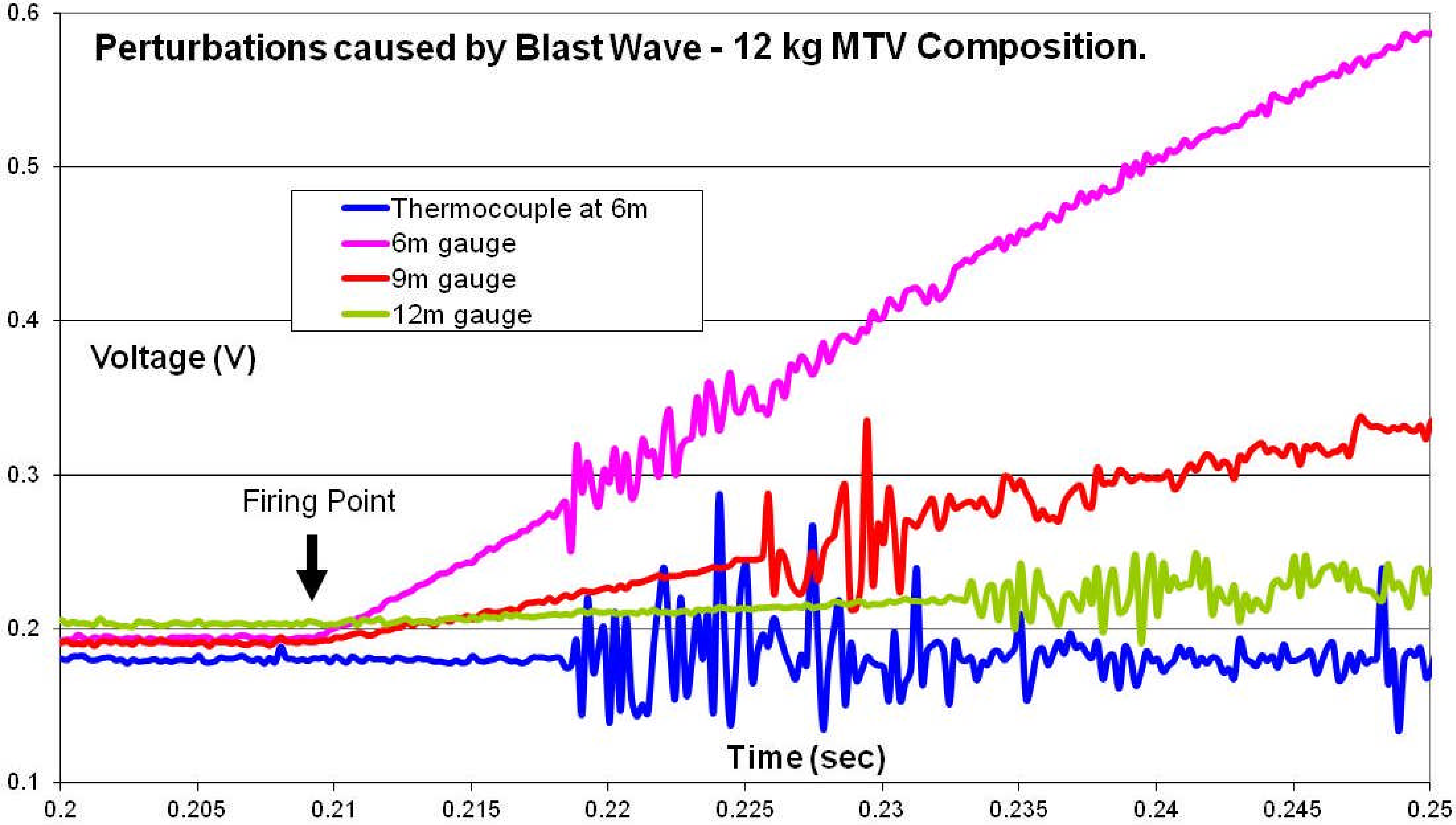


Output and Effective Emisivity

• Pyrotechnic	1600 kJ/kg	20%
• Fuel Fire Test	8000 kJ/kg	20%
• Propellant	1500 kJ/kg	30%
• MTV Flare	6000 kJ/kg	30%

E-C Koch (Metal Fluorocarbon Based Energetic Materials, Wiley-VCH, 2012) calculated MTV effective emissivity as 23% from measured radiation between 1.8 and 4.8 microns. Koch also measured the surface temperature of the fireball as 1940 K based on 1.6 to 1.7 microns.

Blast Wave Effects



Speed of Perturbation Effect

Distance (m)	Time of Arrival	Overall Speed (m s^{-1})	Speed between Points (m s^{-1})
6	0.0086	698	750
9	0.0158	570	417
12	0.0234	513	395

Conclusions

- Surface Mounted Thermocouple Heat Flux gauges can be used to calculate radiated heat flux and dose from relatively rapid thermal events.
- They can be used to estimate fireball surface temperatures.
- They can be used to estimate effective emissivity for compositions – which can then be used in hazard calculations.
- They respond to but do not quantify convection.
- All thermocouples respond to fast pressure fluctuations.