Nozzle Design Influence on the Supersonic Particle Deposition Process

by
Victor Champagne, Dennis Helfritch, Phillip Leyman,
Robert Lempicki and Scott Grendahl

U.S. Army Research Laboratory
Aberdeen Proving Ground, MD

presented at the
Cold Spray 2004 Conference

Purpose

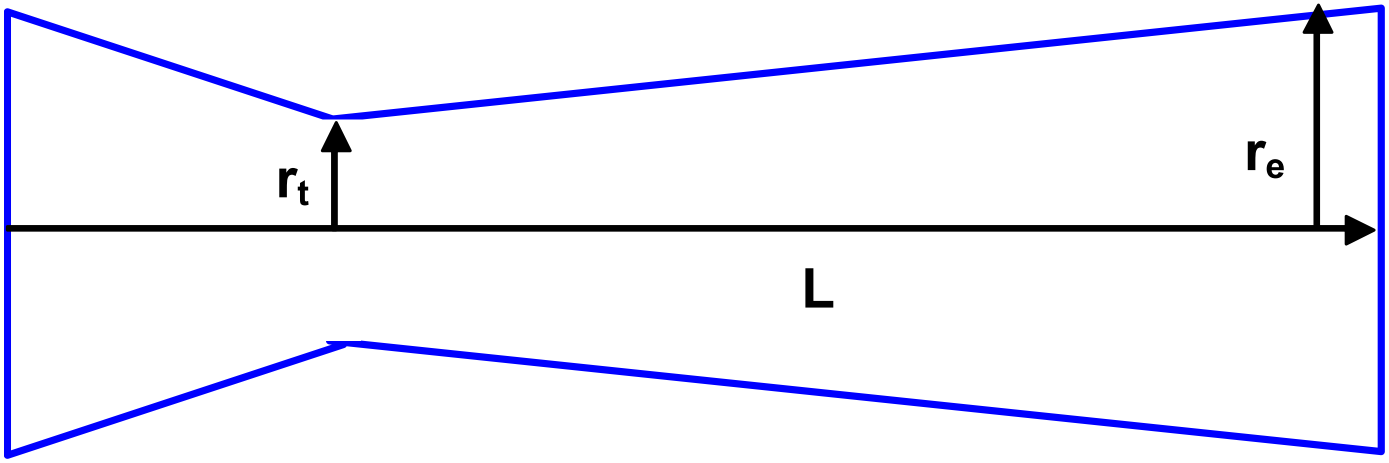
To improve cold spray deposition through the investigation of:

- Nozzle geometry
- Accelerating gas characteristics
- Particle characteristics

Outline

1. Calculate the gas flow and temperature in the nozzle
2. Calculate particle velocity and temperature through the nozzle
3. Calculate penetration depth and particle/substrate mixing
4. Calculate the deposition efficiency
5. Compare with experiment

Apply Gasdynamic Analysis to Simple Nozzle Geometry



- The gas obeys the perfect gas law
- There is no friction impeding the gas flow
- The gas flow is adiabatic
- No shocks or discontinuities
- Flow is one-dimensional
- Particles do not influence gas conditions

Particle Motion / Deposition

- Using the gas flow already calculated, employ solid rocket nozzle particle drag and heat transfer relationships* to calculate particle conditions.
- Particles are assumed to be spherical.
- Particle initial temperature = 293 degree K.
- Use empirical relationships between particle velocity and particle/substrate material characteristics to calculate deposition effects.

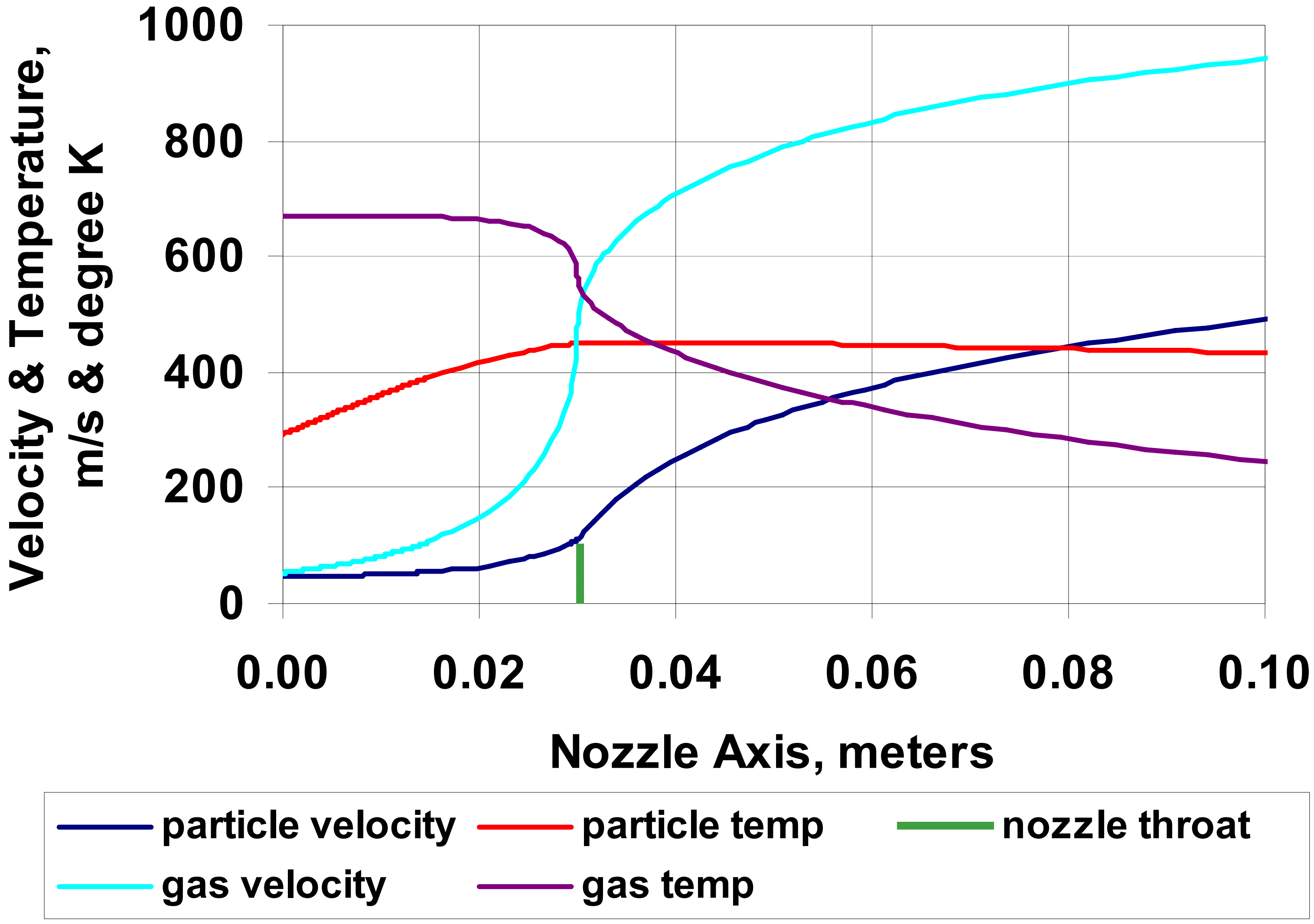
*D. Carlson and R. Hoglund: "Particle Drag and Heat Transfer in Rocket Nozzles," *AIAA Journal,* 1964, *2*(11), pp. 1980 -1984.

Conditions of Calculations

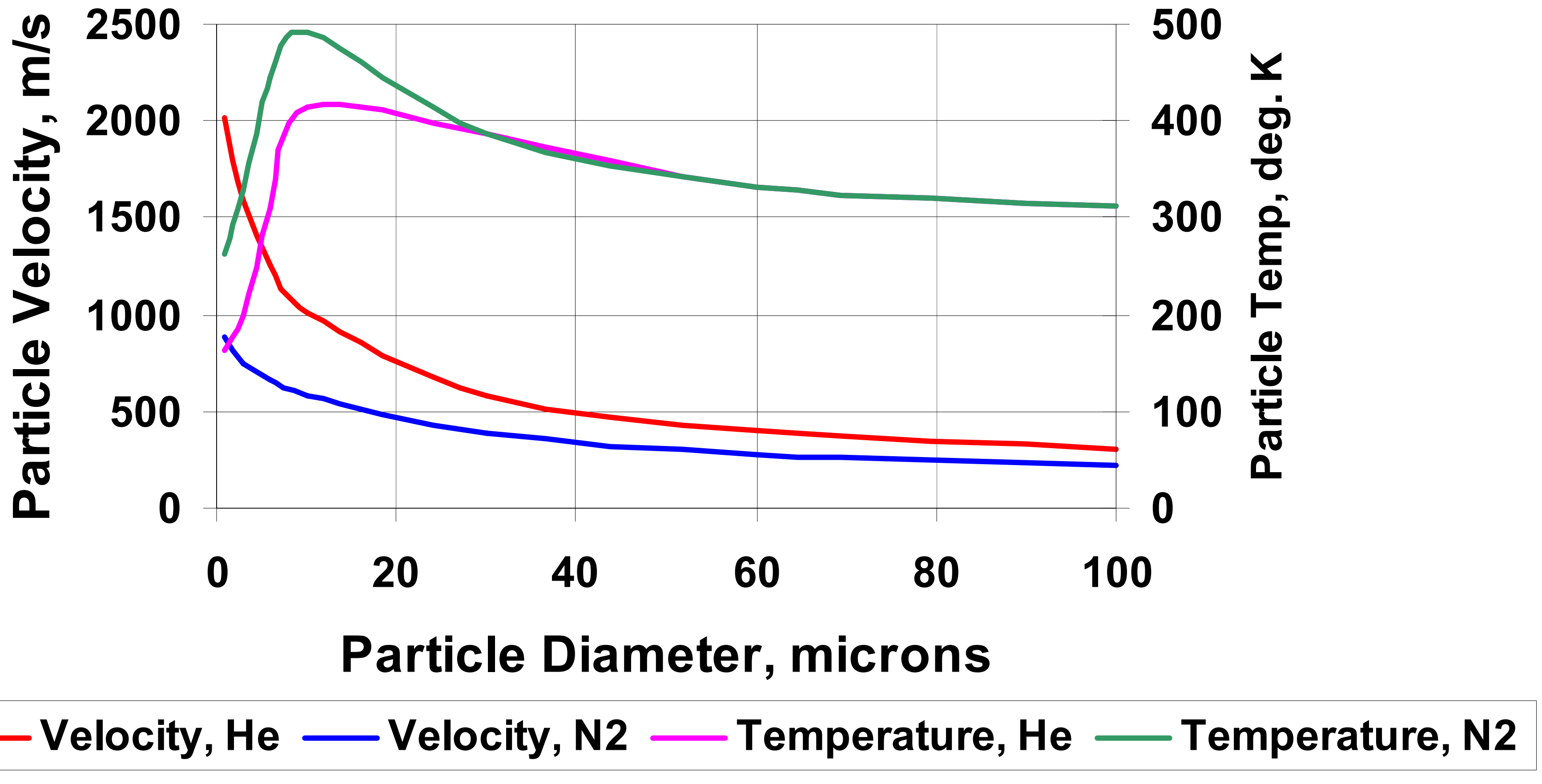
Unless otherwise stated, all calculations are carried out for the following conditions:

- Area ratio = 4, Length = 0.1m
- Nitrogen accelerating gas
- 2.76 MPa, 673 degree K stagnation conditions
- Copper particles
- Mass mean diameter 20 microns
- Log-normal distribution, SD = 1.5

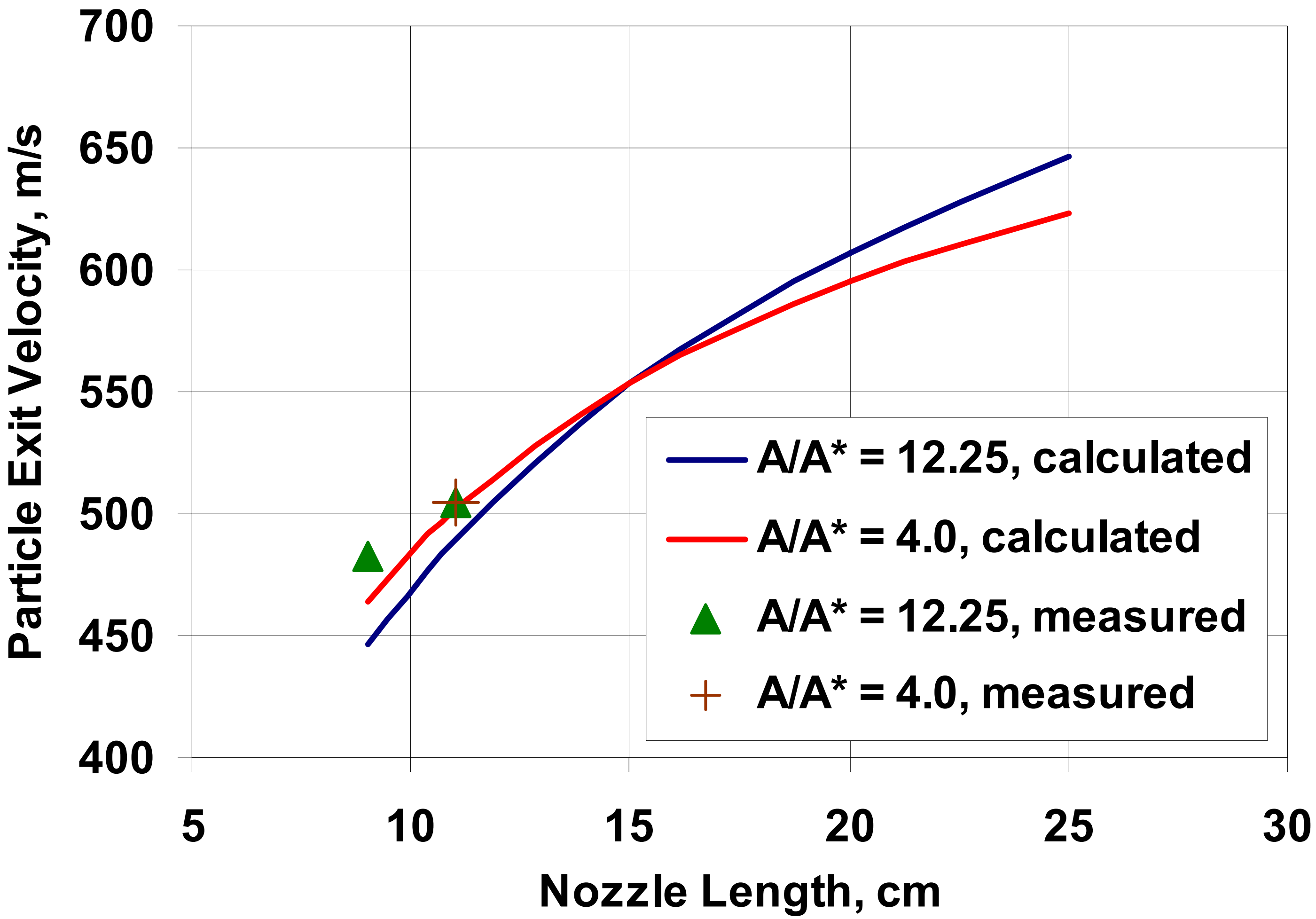
Typical Calculation



Particle Exit Conditions as a Function of Diameter and Accelerating Gas



Effect of Nozzle Length on Particle Velocity



Deposition Calculations
Particle / Substrate

Empirical micrometeorite penetration into spacecraft*

$$\text{Volume} = \frac{\left(4x10^{-5}\right)E}{B}$$

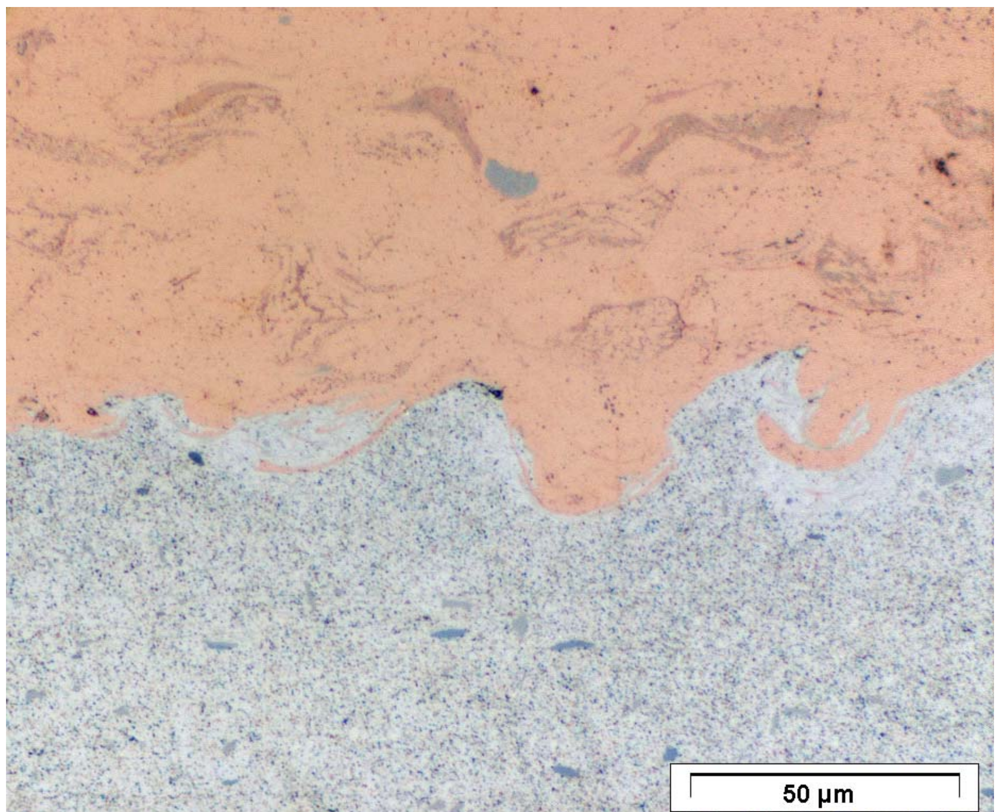
Substituting 1/2mV^2 for energy, with volume = 2rπr^2

$$V = \left[\left(7.5x10^{4}\right)\left(\frac{B}{\rho}\right)\right]^{0.5}$$

*R.J. Eichelberger and J.W. Gehring: “Effects of Meteoroid Impacts on Space Vehicles,” *ARS J.*, 1963, *32*(10), p. 1583.

Copper Deposited on Aluminum

Particle/substrate equation predicts a velocity of 500 m/s needed for full penetration. Photograph below shows this condition.



Deposition Calculations
Particle / Particle

The empirical relationship for the critical velocity is given by Assadi* as:

Critical Velocity = $667 - 14\rho + 0.08T_m + 0.1\sigma_\mu - 0.4T_e$

ρ = particle density

σ_μ = particle UTS

T_m = particle melting point

T_e = particle exit temperature

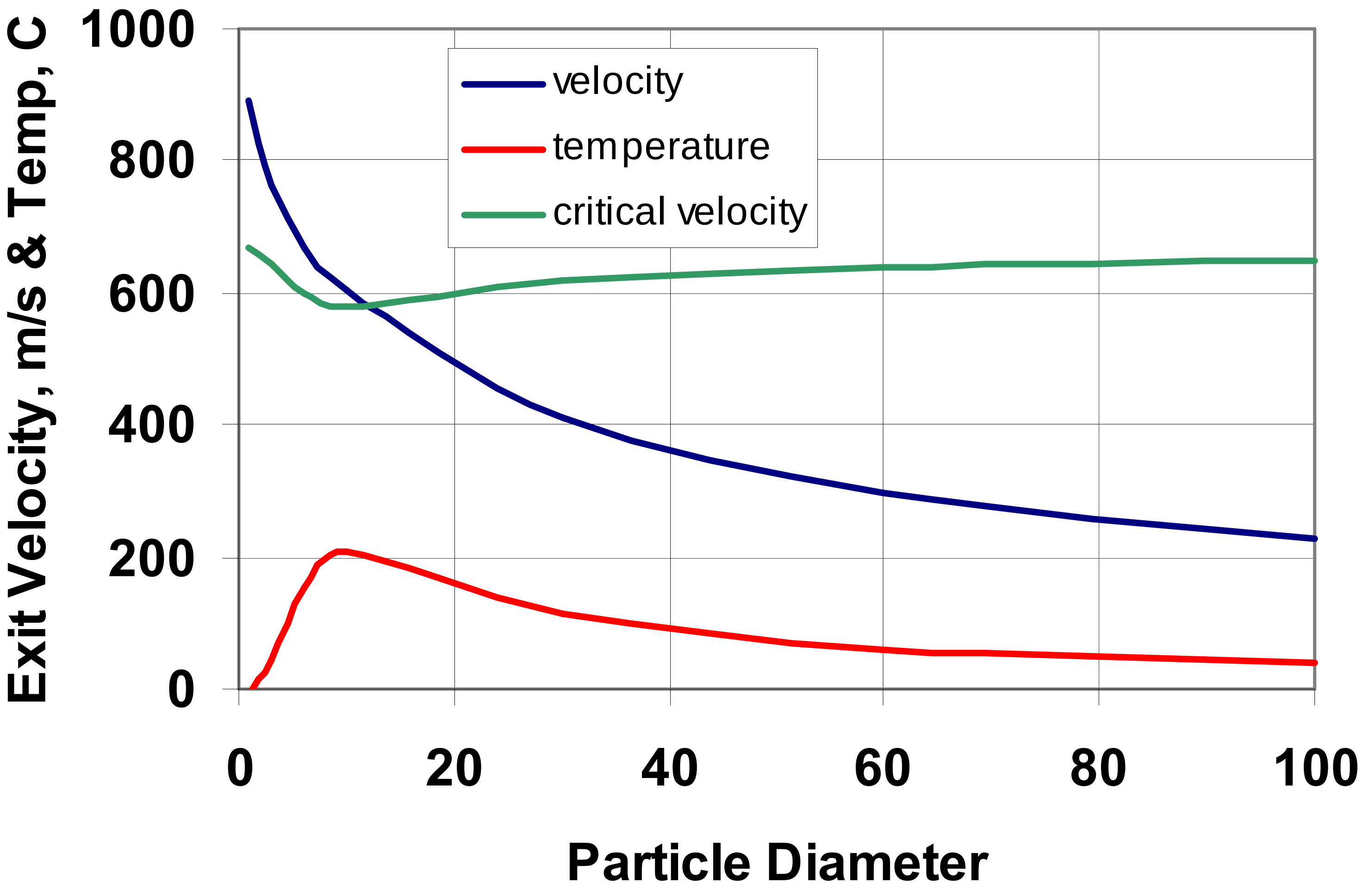
All particles smaller than that exiting with the critical velocity will deposit

*H. Assadi, et al: "Bonding Mechanism in Cold Gas Spraying," *Acta Materialia, 2003, 51,* pp. 4379 – 4394.

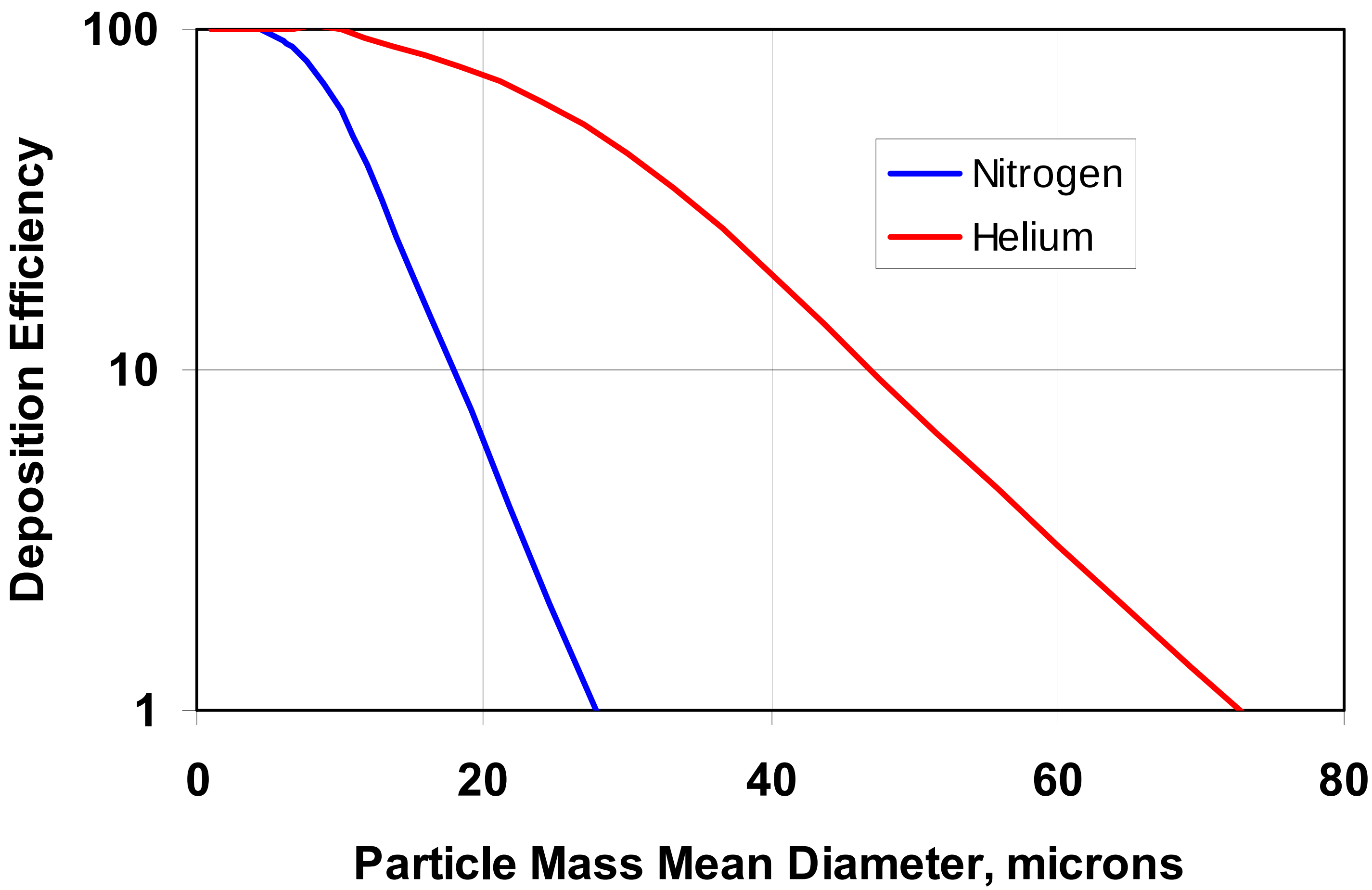
Deposition Efficiency Calculation

1. Calculate table of particle exit velocities and temperatures vs. particle diameter.
2. Calculate critical velocities based on the particle exit temperatures.
3. Find the critical particle size that has an exit velocity equal to the critical velocity.
4. Integrate the log normal particle size distribution from the critical diameter to 1/infinity.

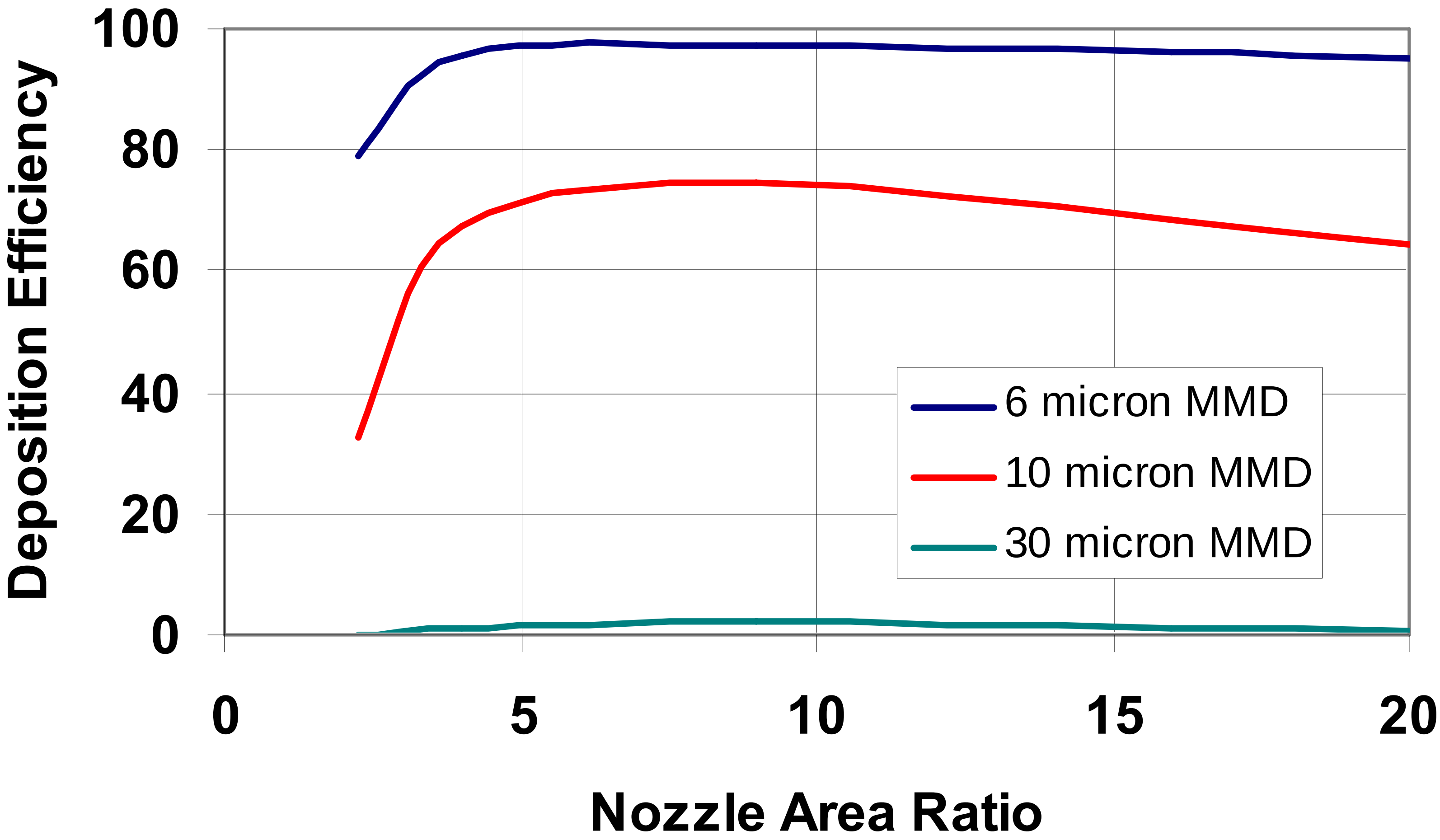
Critical Particle Diameter



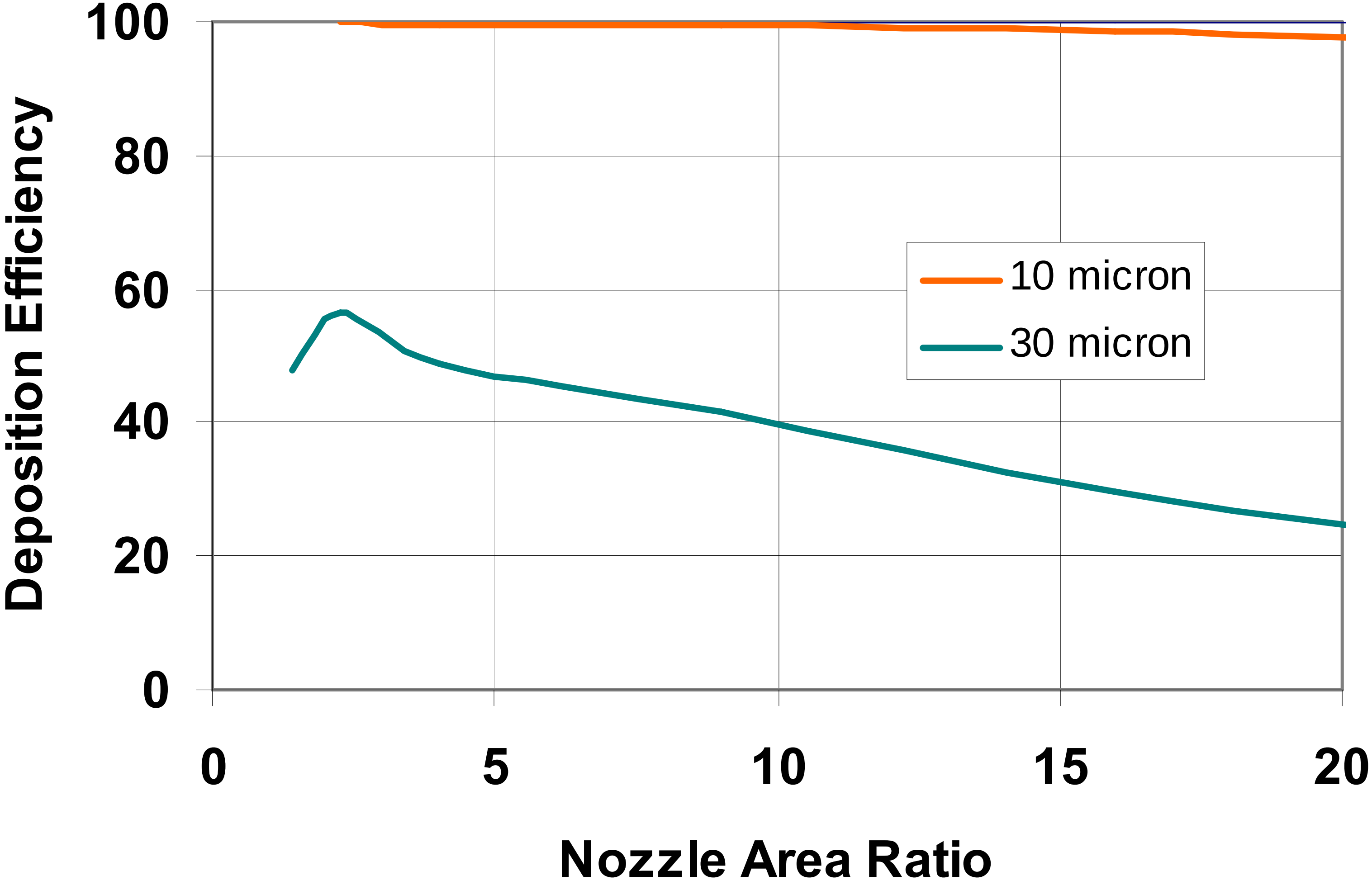
Effect of Particle Diameter on Deposition Efficiency



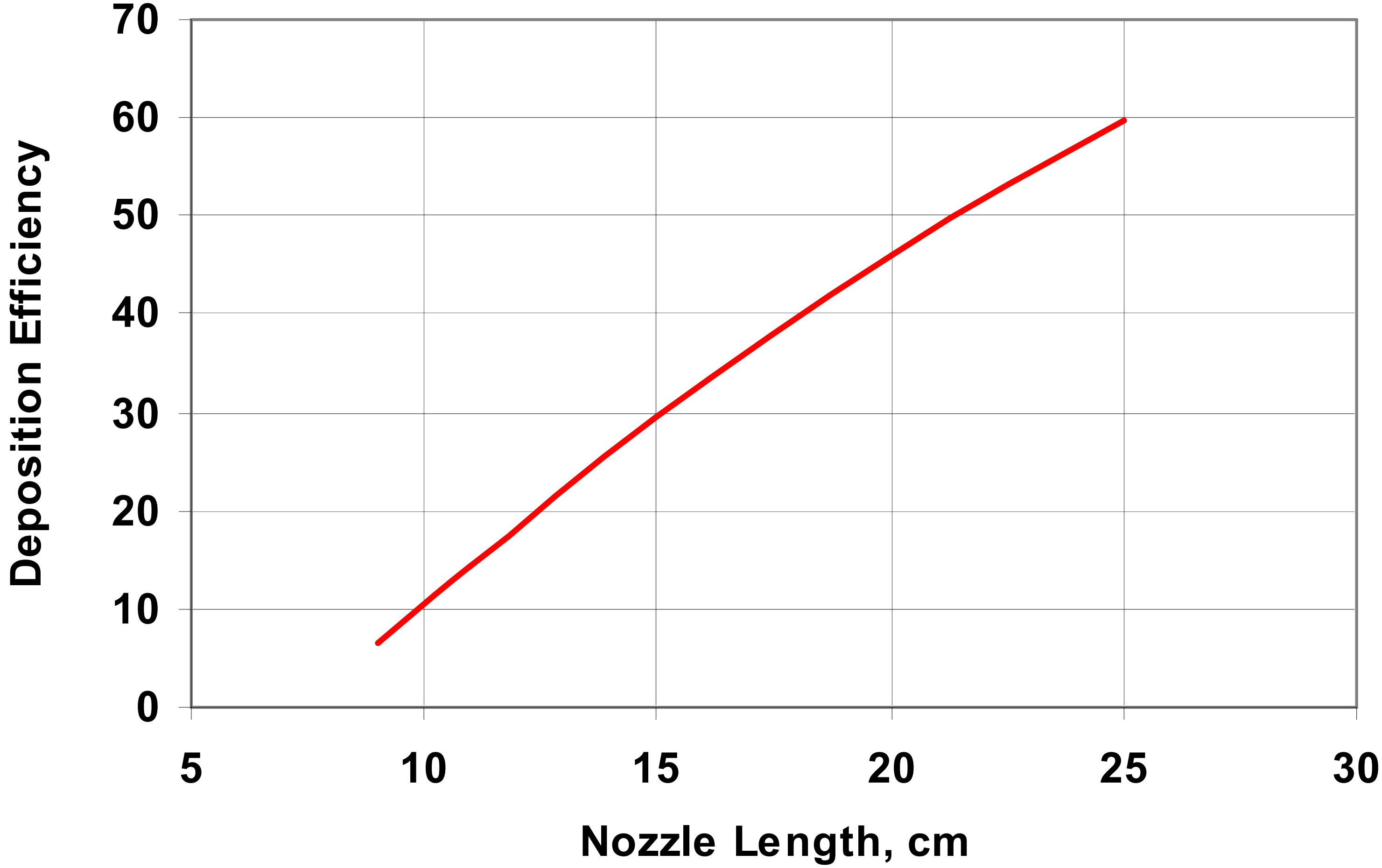
Effect of Nozzle Area Ratio on Deposition Efficiency



Effect of Nozzle Area Ratio on Deposition Efficiency - Helium



Effect of Nozzle Length on Deposition Efficiency



Conclusions

- Particle exit conditions are principally determined by nozzle length and particle diameter.
- Particle/surface interaction can be characterized by particle velocity and surface hardness.
- Particle velocity and deposition efficiency are relatively insensitive to nozzle area ratio.
- Large improvements to deposition efficiency are possible through the use of smaller particles and longer nozzles.

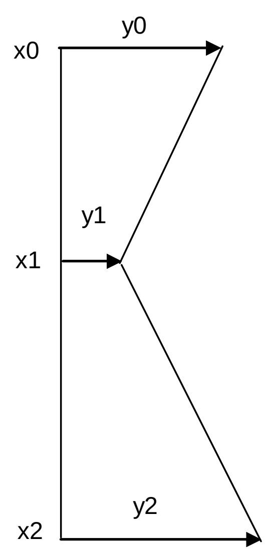
Parameters for Calculation

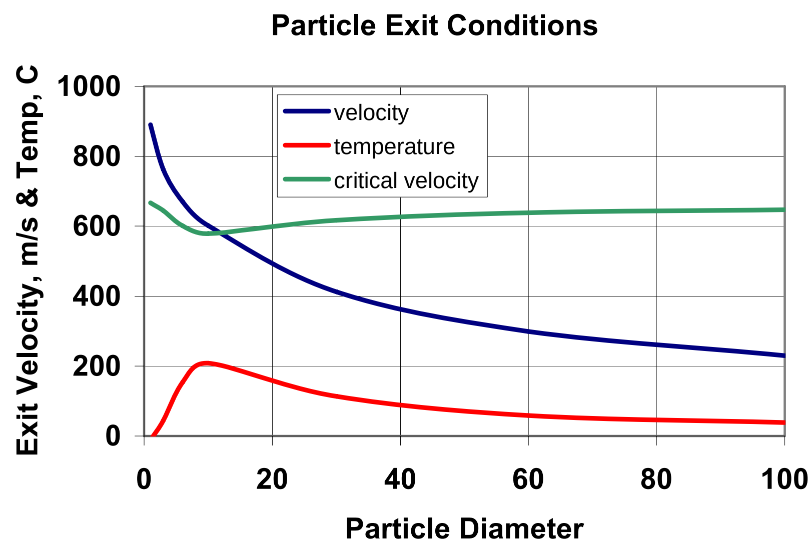
0.1	M0	
0.001	delM, M<1	
0.05	delM, M>1	
673	T0 degK	
400	P0 psia	
2758000	P0 pascal	
28	MW	
8314	R	
1.4	gamma	
0.9	Vp0/Vg0	
0.001	throat radius m	
Fn(M0)	y0	
0.001	y1	
0.002	y2	
0	x0	
0.03	x1	
0.1	x2	
4.00	Ae/A*	
1.00E-05	reference diameter m	
9	material density g/cc	
7.85E-11	particle area m^2	
4.71E-12	particle mass kg	
2.00E-05	viscosity kg/m-sec	same N2-He
293	Tp0 K	
390	particle Cp J/kg-K	
0.03	gas cond. Kg-m/s^3-K	.03N2-.15He
1084	melting Point, C	
345	particle UTS, Mpa	
12.00	critical diameter	
1.5	std dev	
1	ERF sign	
0.3180	ERF argument	

microns	Vp, m/s	Tp, C	Vc, m/s	Tp critical	critical dia
1	890	-11	667		
3	762	44	645	0	0
6	670	153	601	0	0
10	602	208	579	0	0
30	412	113	617	199	12
60	299	58	639	0	0
100	230	39	647	0	0

10 MMD

67.35 Deposition Efficiency





Effect of Feeder Gas Mixing