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Particle Temperatures and Velocities in the Powder Flame Spray Process

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National Nuclear Security Administration

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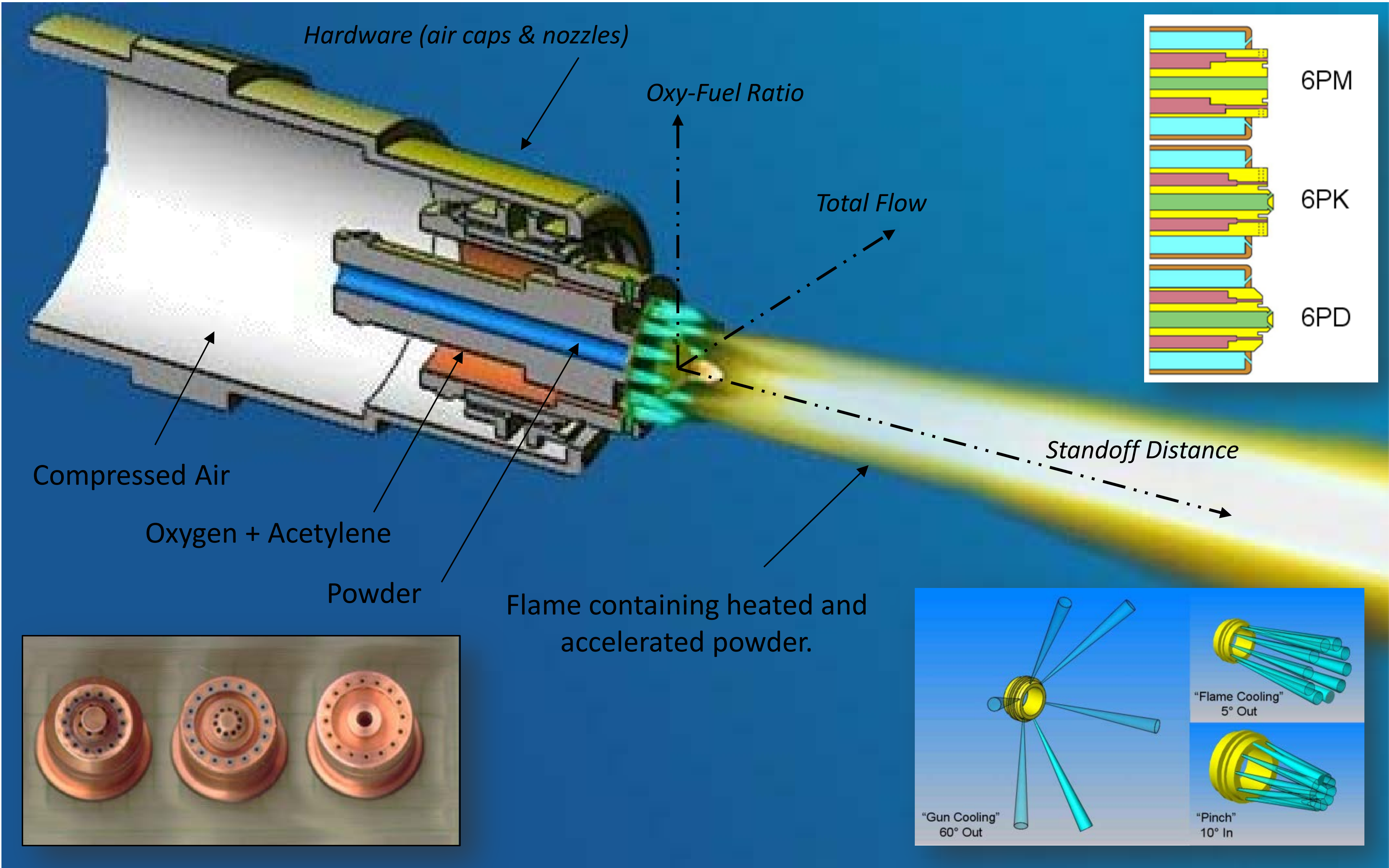
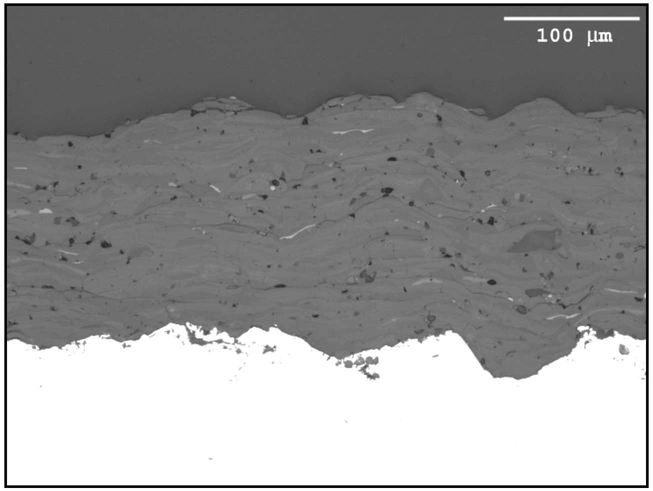
The Powder Flame Spray Process
(Sulzer-Metco 6P Torch)



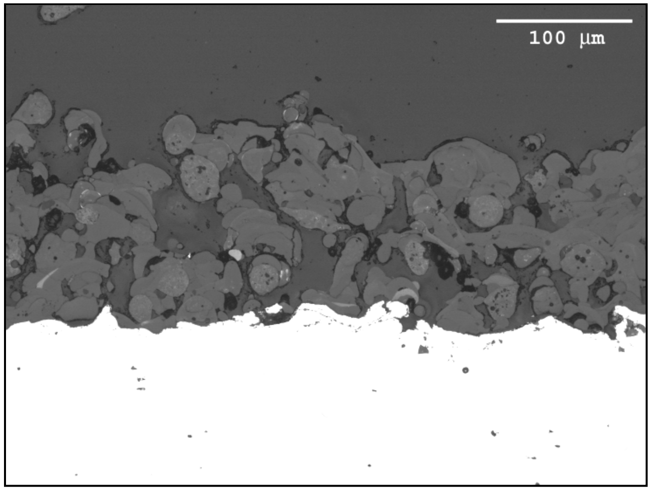
Particle Temperature (Tp) and Particle Velocity (Vp) directly affect coating microstructure and properties.

Tp and Vp:

- *Are controlled by how we set-up and use our spray torches*
- *Are measureable*
- *Are controllable*
- *Make sense*



vs.



Tp: Thermal energy of the particle

Vp: Kinetic energy of the particle

Increasing Tp or Vp

- Increases residual stress
- Increases deposition efficiency
- May increase substrate damage
- Reduces coating porosity

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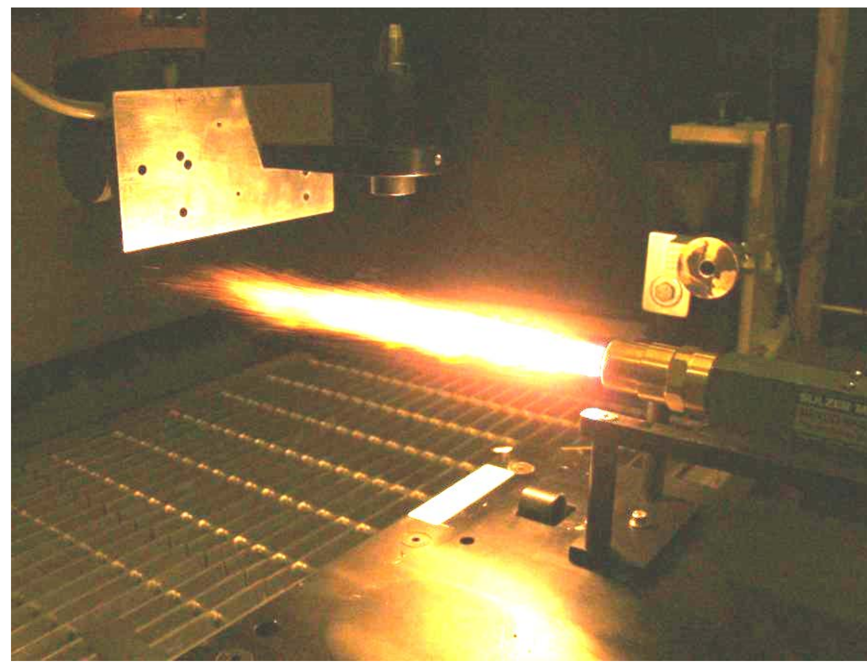
Experimental Set Up

T_p, V_p, d_p Measurement

- DPV-2000 sensor
  - Stäbuli RX60 Robotic Arm
  - Aligned with torch centerline
  - Fixed Trigger Level and Capture Depth

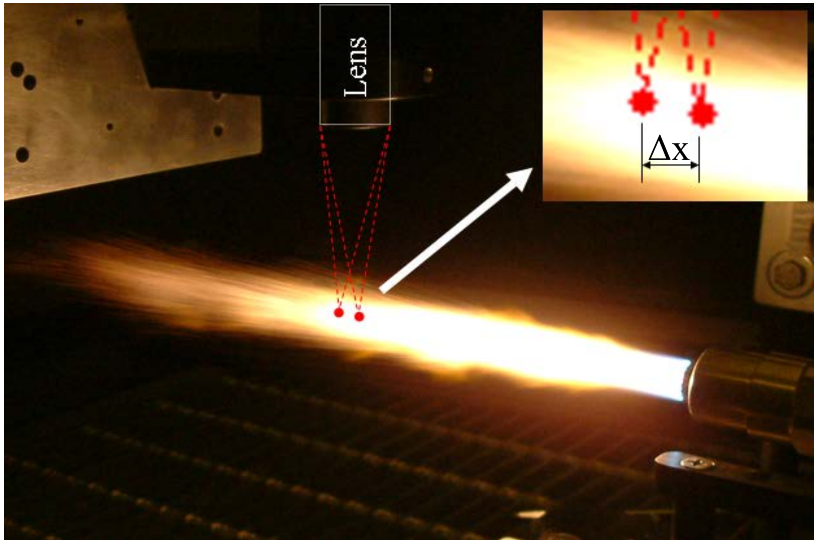


Spraying Coupons

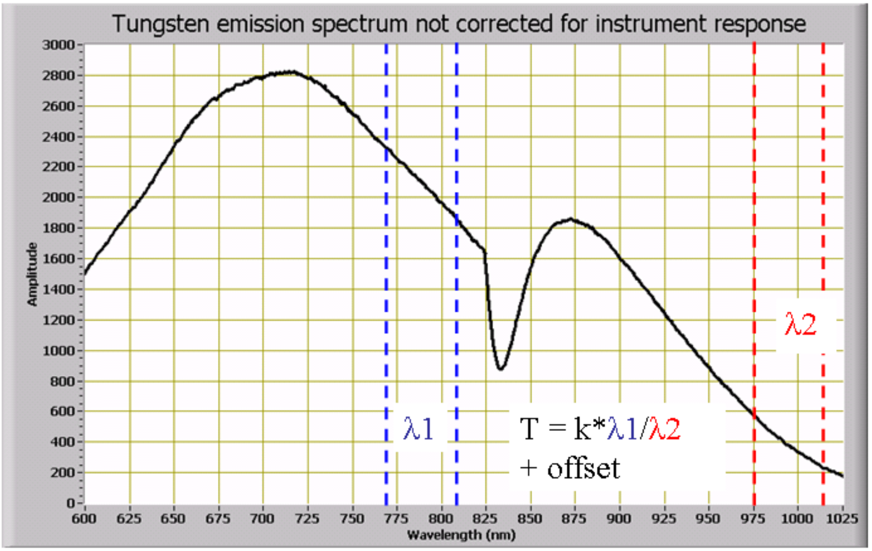
- Stäbuli RX60 Robotic Arm
  - Vacuum chuck
- 2” Square X 1/8” thick Al
  - Grit blast, acetone wash, methanol rinse, compressed air dry.

Sensor-Based Particle Measurement

- Particle Velocity (Vp)
  - Time of flight between two points separated by a known distance
  - Individual or groups of particles
  - Vp = Δx /Δt



- Particle Temperature (Tp)
  - Two color pyrometery: Tp is proportional to the ratio of measured intensity at two wavelengths (infrared colors)
  - Calibrated using a Tungsten strip lamp



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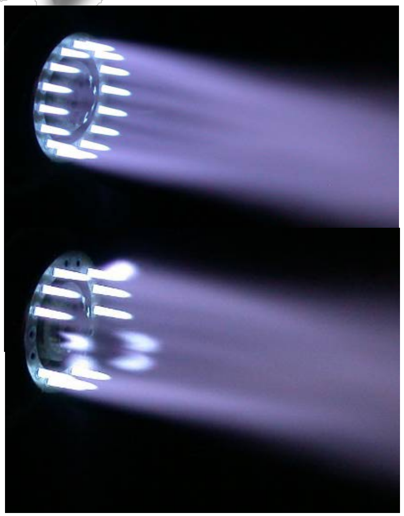
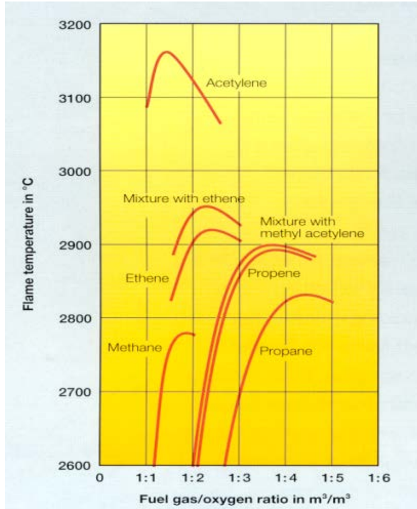
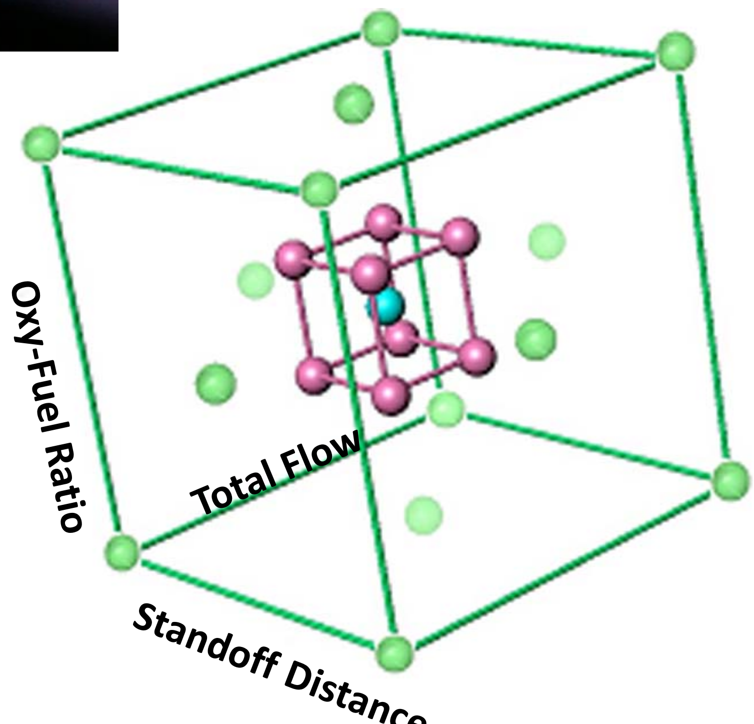
Designed experiments were used to creating process maps and identifying sources of variability.







Sequence Number	TFC	OFRC	SDC	TF	OFR	SD
1	0	0	0	85.00	2.00	6.50
2	-1.682	0	0	75.00	2.00	6.50
3	-1.682	1.682	1.682	75.00	2.50	7.50
4	1.682	0	0	95.00	2.00	6.50
5	1	-1	-1	90.95	1.70	5.91
6	0	0	0	85.00	2.00	6.50
7	1	-1	1	90.95	1.70	7.09
8	0	0	0	85.00	2.00	6.50
9	0	0	1.682	85.00	2.00	7.50
10	-1.682	-1.682	1.682	75.00	1.50	7.50
11	0	0	0	85.00	2.00	6.50
12	1.682	-1.682	1.682	95.00	1.50	7.50
13	0	0	-1.682	85.00	2.00	5.50
14	0	-1.682	0	85.00	1.50	6.50
15	-1	1	1	79.05	2.30	7.09
16	-1.682	1.682	-1.682	75.00	2.50	5.50
17	-1	-1	-1	79.05	1.70	5.91
18	-1	1	-1	79.05	2.30	5.91
19	0	1.682	0	85.00	2.50	6.50
20	-1	-1	1	79.05	1.70	7.09
21	1	1	1	90.95	2.30	7.09
22	1.682	1.682	-1.682	95.00	2.50	5.50
23	1	1	-1	90.95	2.30	5.91
24	0	0	0	85.00	2.00	6.50
25	1.682	-1.682	-1.682	95.00	1.50	5.50
26	-1.682	-1.682	-1.682	75.00	1.50	5.50
27	1.682	1.682	1.682	95.00	2.50	7.50
28	0	0	0	85.00	2.00	6.50

- *28 randomized experiments*
- *5 levels for each variable*
- *6 repeat points*
- *Used to analyze 8 hardware sets*

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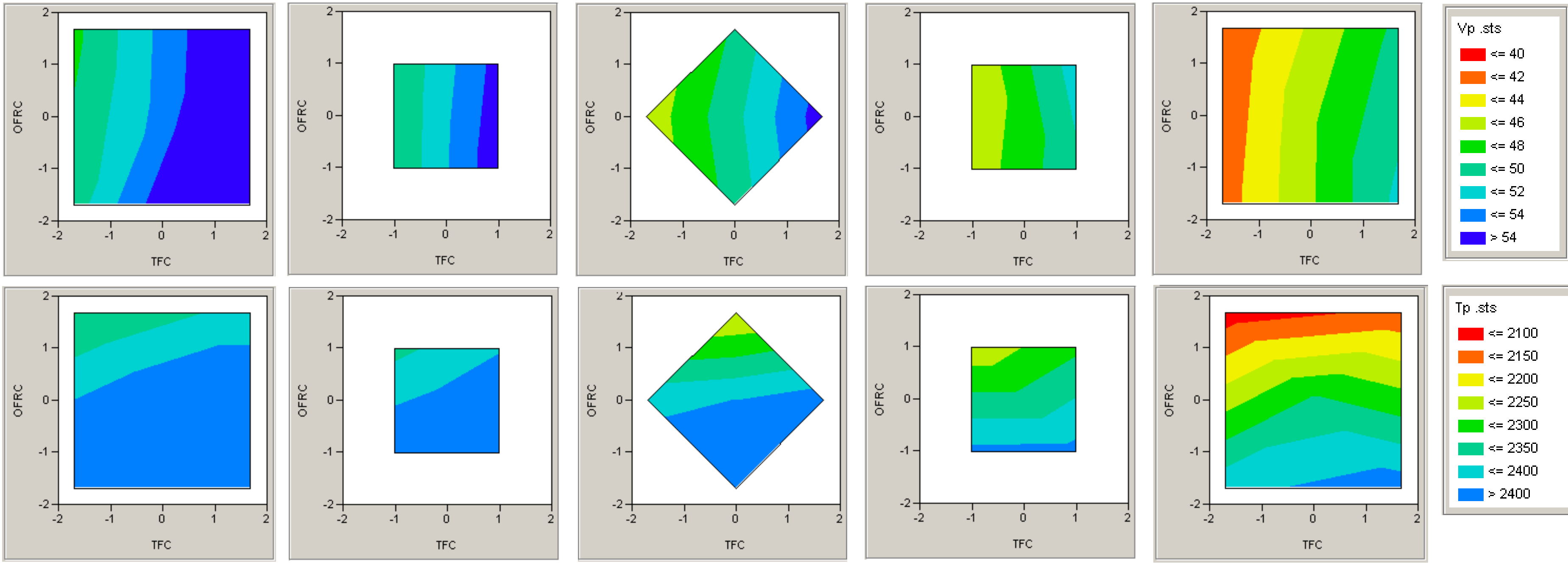
Tp, & Vp Contour Plots reveal very simple process vectors!



-1.682 -1 0 1 1.682

Standoff Distance

- Tp is controlled by Oxy-Fuel Ratio
- Vp is controlled by Total Flow
- Both Tp and Vp decrease with Standoff Distance

Parabolic Model

$$Tp = a(TFC) + b(OFRC) + c(SDC) +$$

Linear Terms

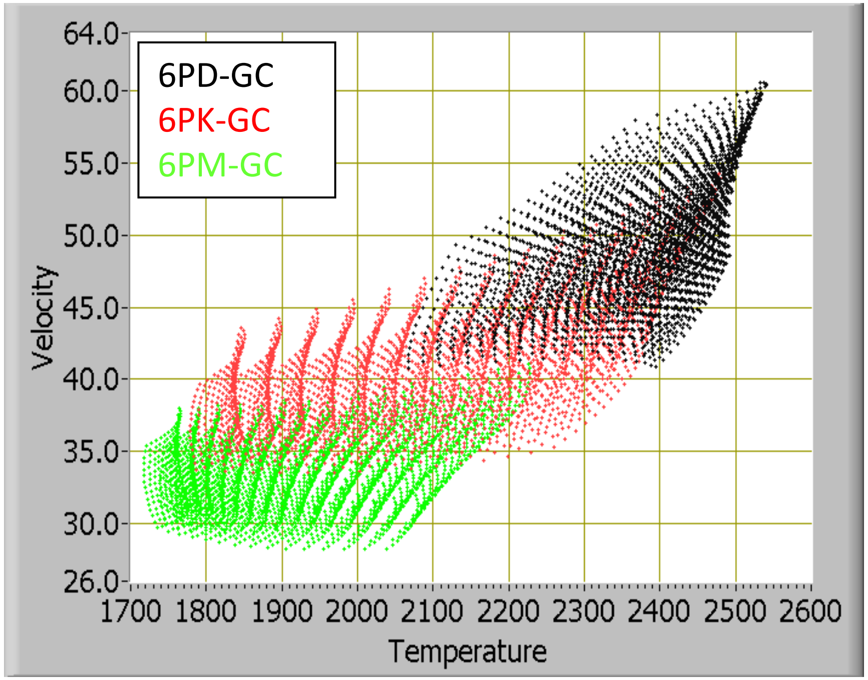
$$d(OFRC)(TFC) + e(SDC)(TFC) + f(SDC)(OFRC) +$$

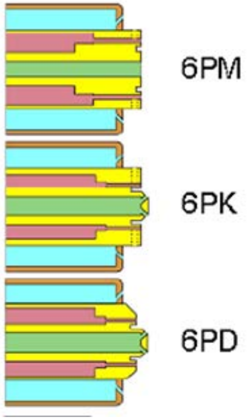
Cross Terms

$$g(TFC)^2 + h(OFRC)^2 + i(SDC)^2$$

Quadratic Terms

- Experimental Data from each DOE is fit to a model.
- Coded variables allow relative importance of each parameter to be determined.
- Three separate models (T_p, V_p, d_p) were created for each 28 point DOE.





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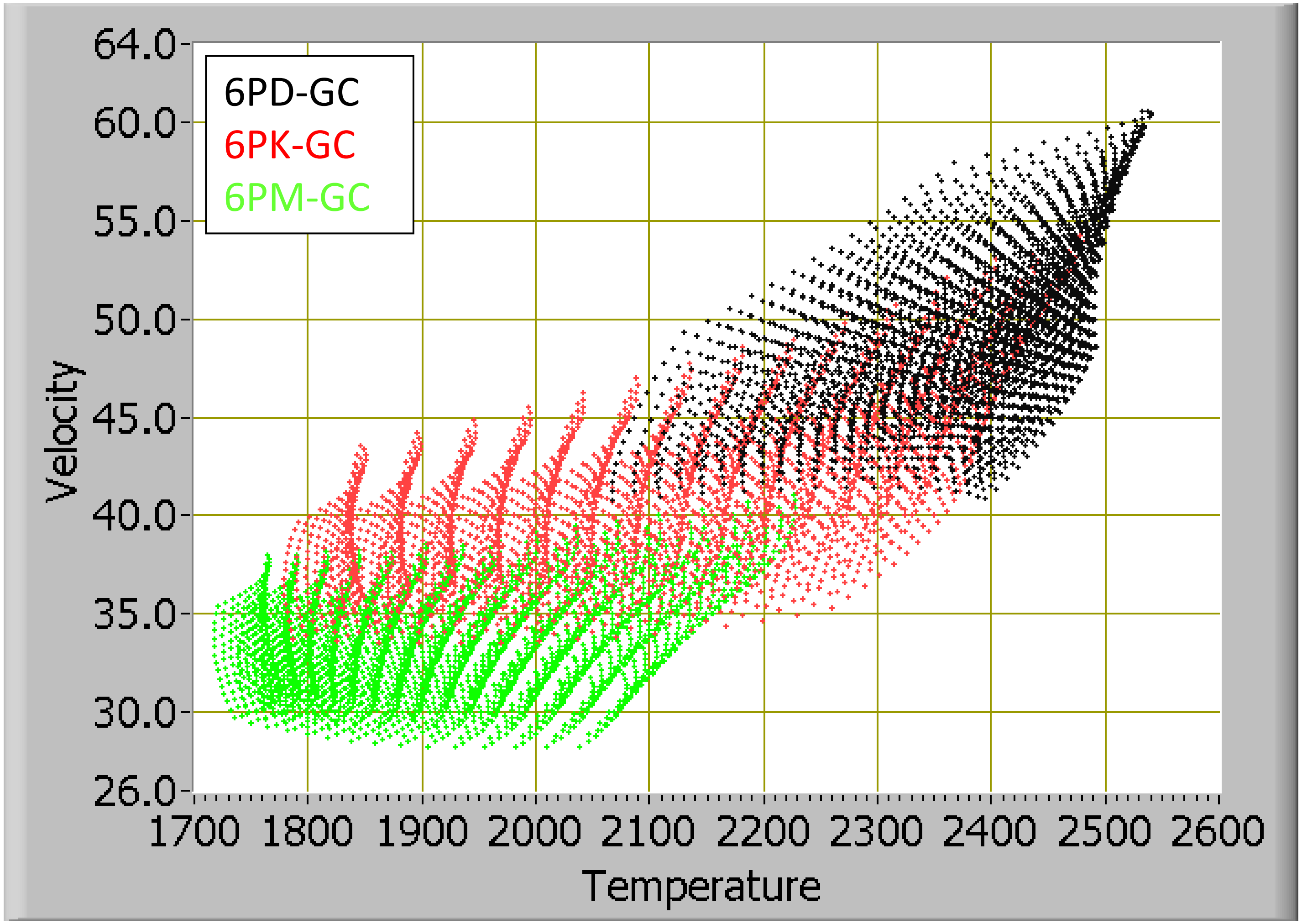
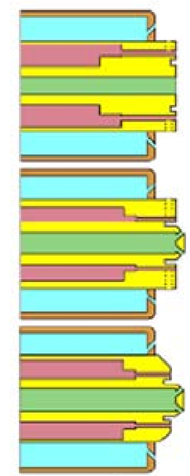
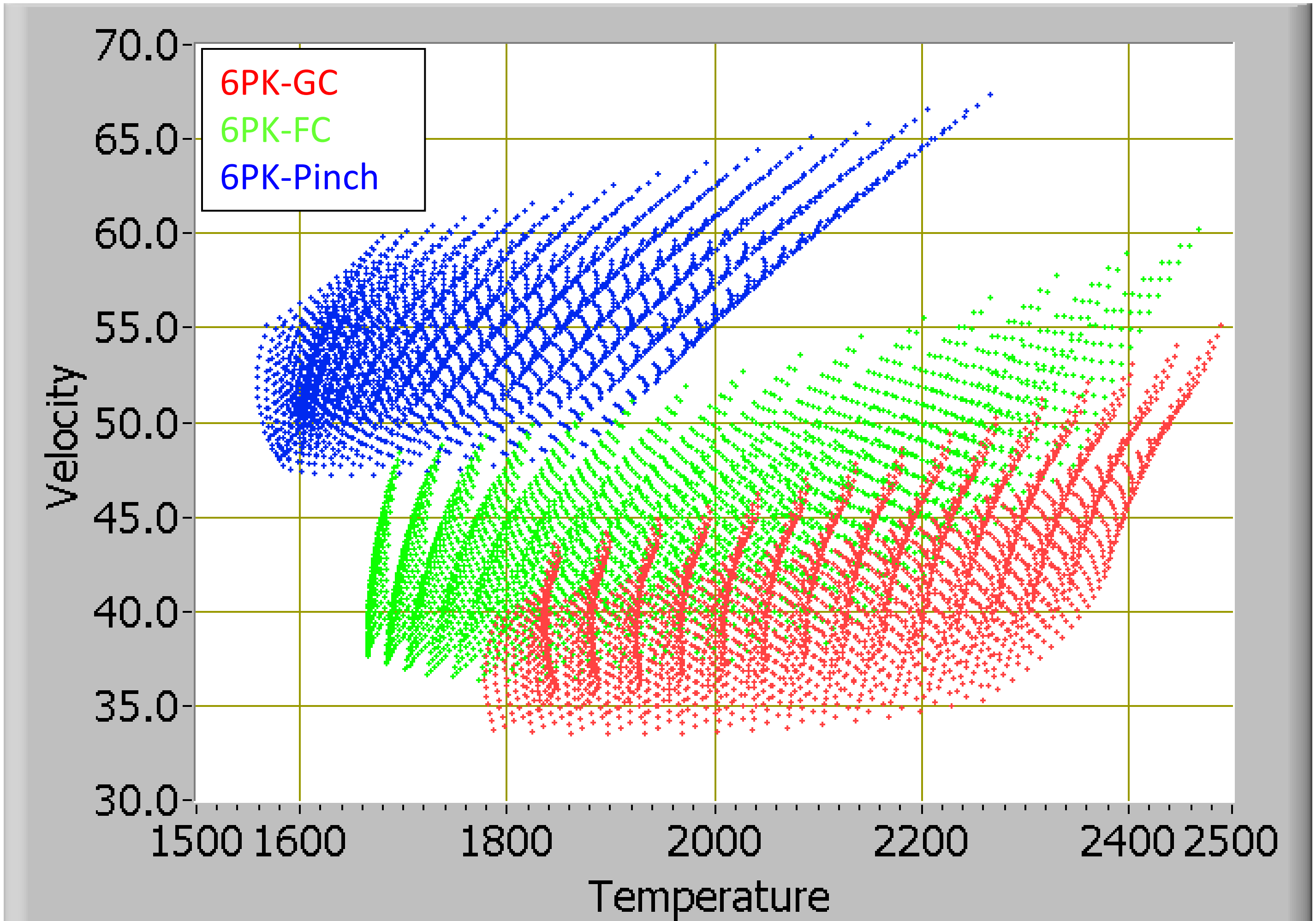
6P Available Operating Space





Effect of Air Cap on 6P Operating Space



Fitting the data to a parabolic model reveals the effect of hardware on operating space.

Tp = *a(TFC) + b(OFRC) + c(SDC) +*

Linear Terms

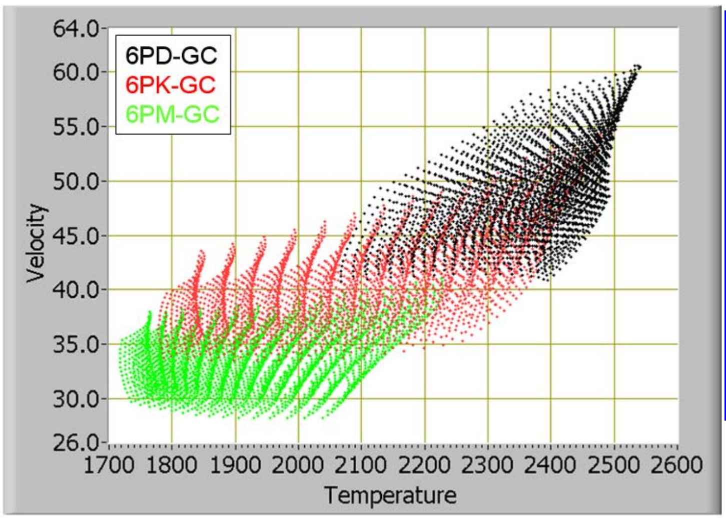
d(OFRC)(TFC) + e(SDC)(TFC) + f(SDC)(OFRC) +

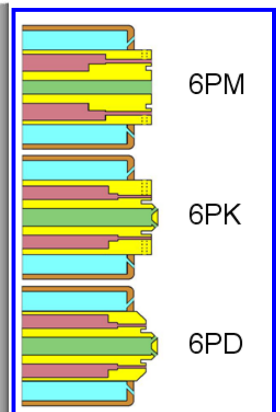
Cross Terms

g(TFC)² + h(OFRC)² + i(SDC)²

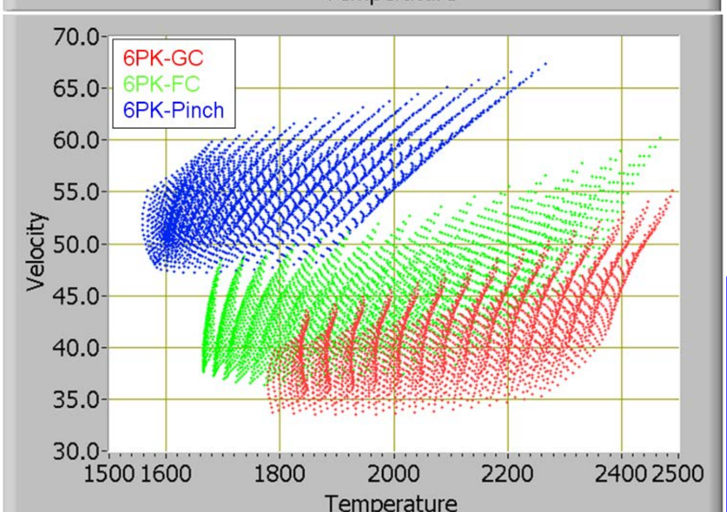
Quadratic Terms

$$Tp = a(TFC) + b(OFRC) + c(SDC) + d(OFRC)(TFC) + e(SDC)(TFC) + f(SDC)(OFRC) + g(TFC)^2 + h(OFRC)^2 + i(SDC)^2$$

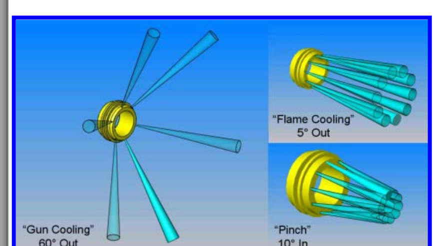


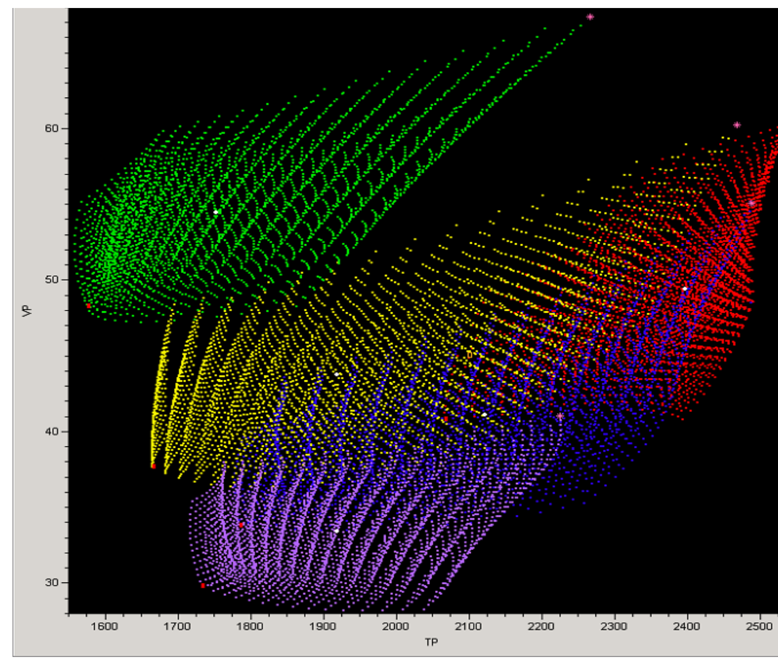


Nozzle Choice



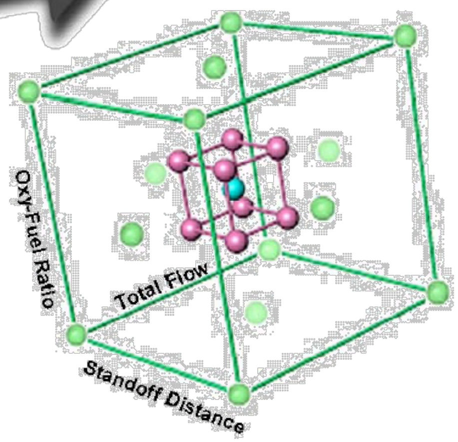
Air cap Choice with “K” nozzle





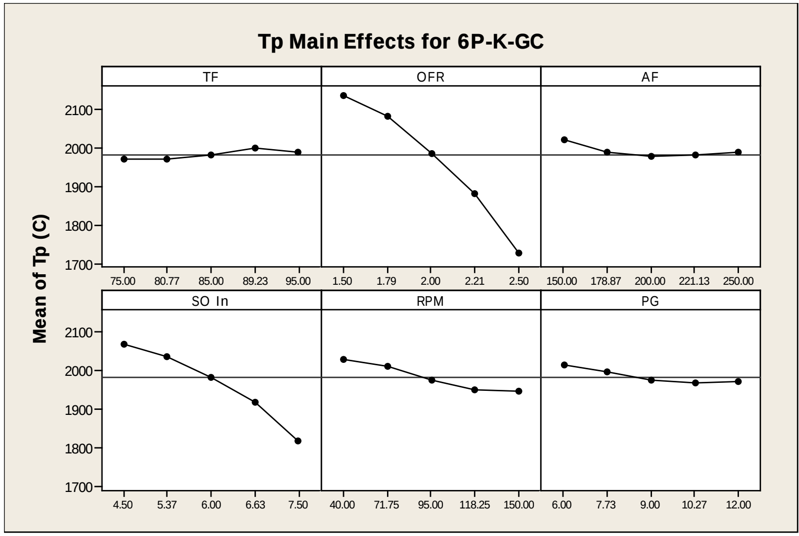
A broad range of Tp, Vp space is accessible!

What about Powder Gas Flow, Cooling Air Flow, and Powder Feed Rate ?



TF: 75-95 SCFH
OFR: 1.5-2.5
AF: 50-250 SCFH
SD: 5.5-7.5”
PFR: 6-16 g/min
PG: 6-12 SCFH

An augmented CCD with 6 factors requires 90 experiments. The half factorial design required 54 experiments.



Tp affected significantly by all factors except TF, AF and PG.

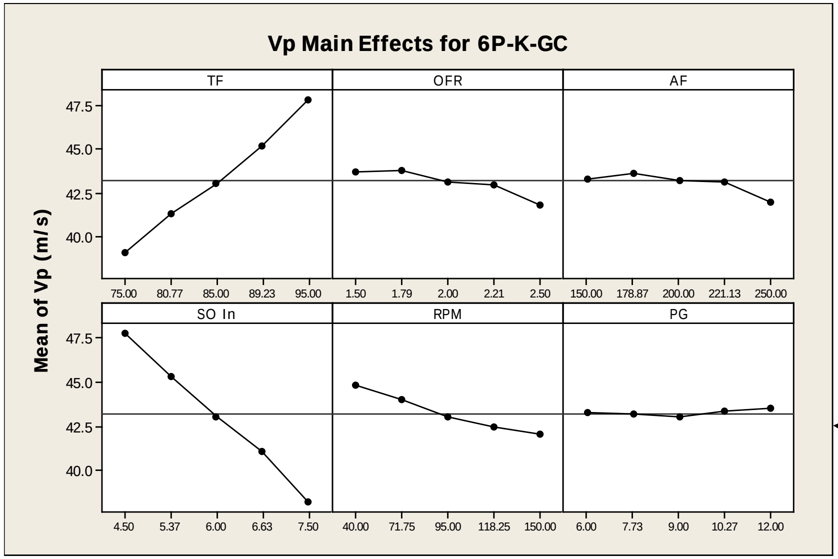
@ TF=85 SCFH, OFR=2, SD=6”, & AF=200 SCFH:

PG: 6-12 SCFH

- 4-5 SCFH: Intermittent feed
- 13+ SCFH: Unmelted powder

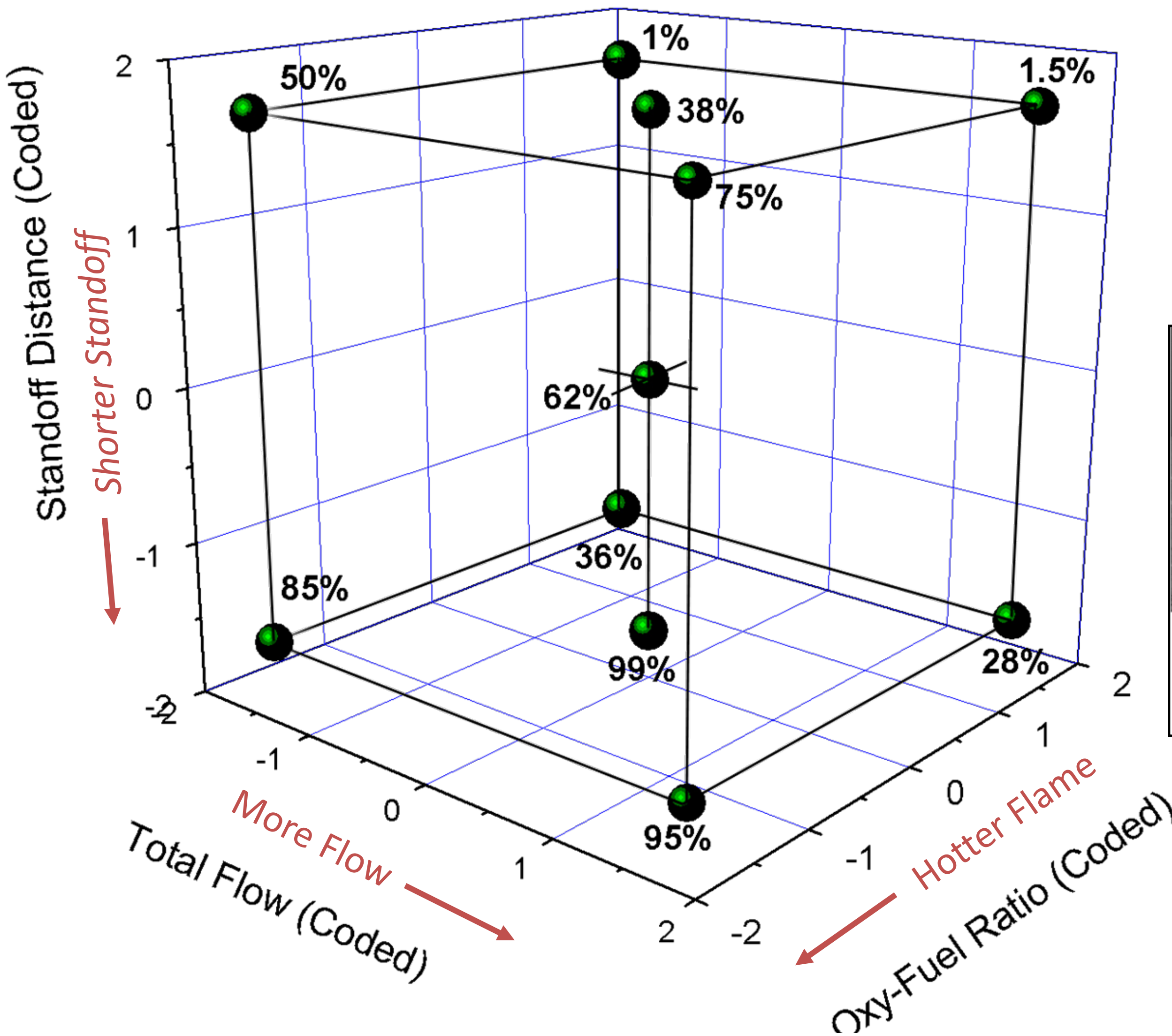
PFR 6 - 16 g/min

- 30 RPM: Intermittent feed
- 160+ RPM: Unmelted powder



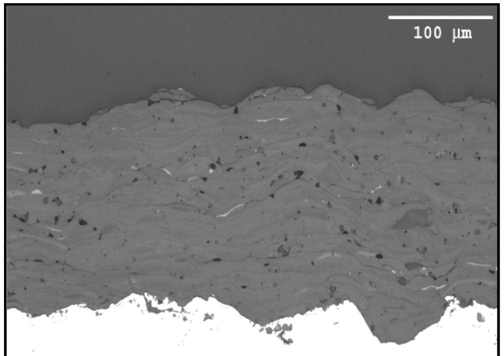
Vp affected significantly by all factors except PG.

Tp and Vp affect Deposition Efficiency, Microstructure, & Properties: DE vs Torch Conditions for the 6P-K-GC

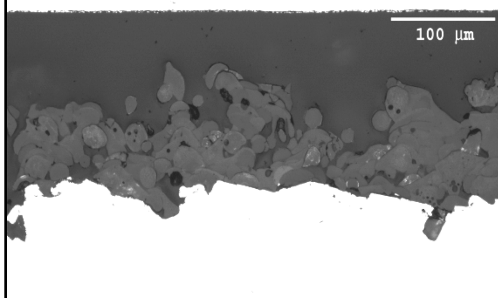


DE = 19.09 TFC -17.73 OFRC - 10.58 SDC + 61.41

Hotter, faster particles = higher DE & Denser Coating



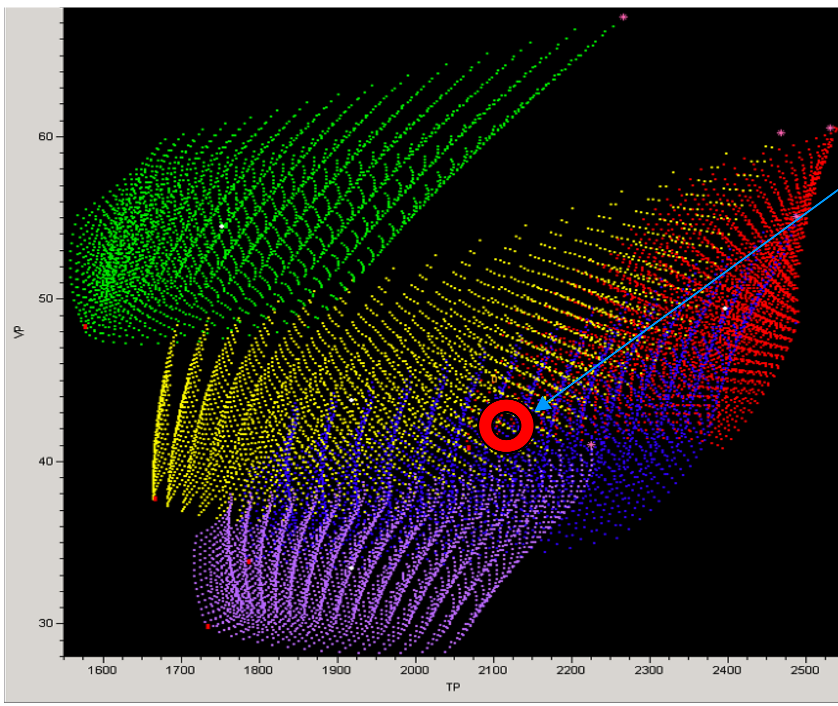
4.5” Stand off Distance



6.5” Stand off Distance

A simple exercise reveals that this data should be used with caution!

Tp	Vp	Tp	Vp	GUN	TF	OFR	SD	DE
target		actual						
2100	45.0	2108.32	45.15	K-FC	79.000	1.92	5.64	64.02
2100	45.0	2100.93	44.88	D-GC	95.000	2.00	7.35	36.83
2100	45.0	2109.10	44.54	K-GC	95.000	1.80	5.50	75.20

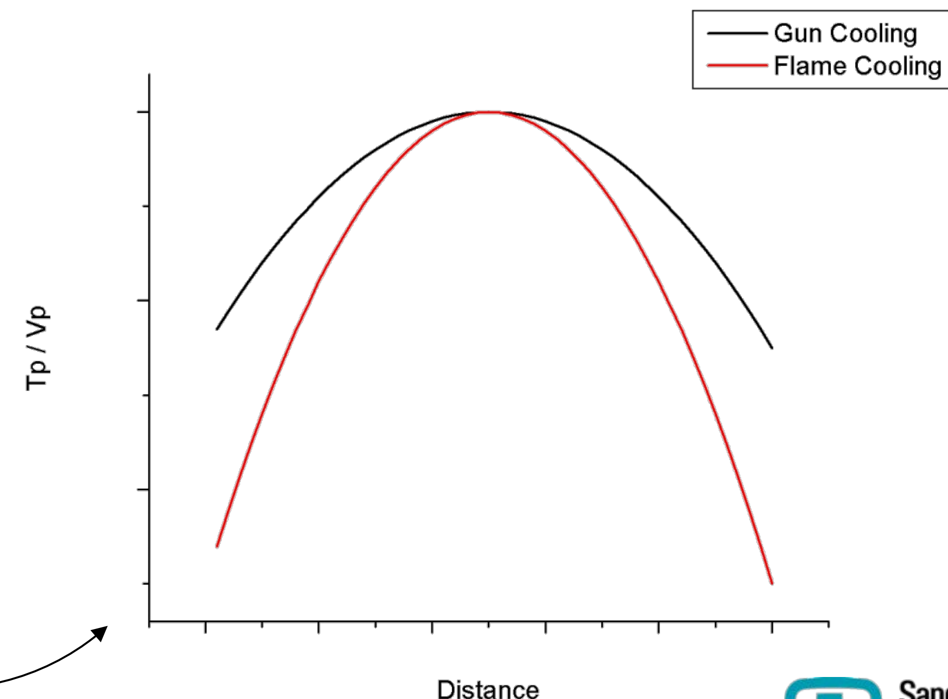


Driving different hardware sets to the same Tp, Vp should produce similar DE?

“the rest of the story….”

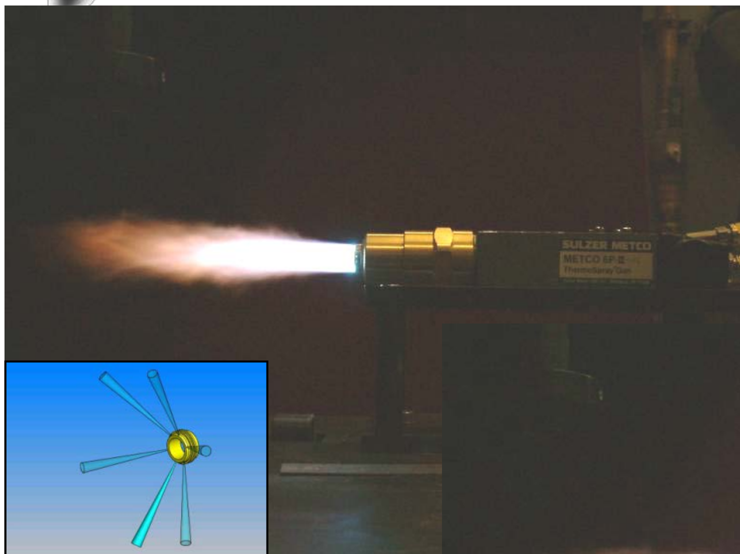
Tp	Vp	Tp	Vp	GUN	TF	OFR	SD	DE
target		actual						
2100	45.0	2108.32	45.15	K-FC	79.000	1.92	5.64	64.02
2100	45.0	2100.93	44.88	D-GC	95.000	2.00	7.35	36.83
2100	45.0	2109.10	44.54	K-GC	95.000	1.80	5.50	75.20

- Centerline T_p, V_p indicates trends well *and can identify sources of variability.*
- Complete understanding requires consideration of Tp, Vp *distributions within the spray plume.*
- *Hardware can be chosen for process stability just as operating conditions can.*

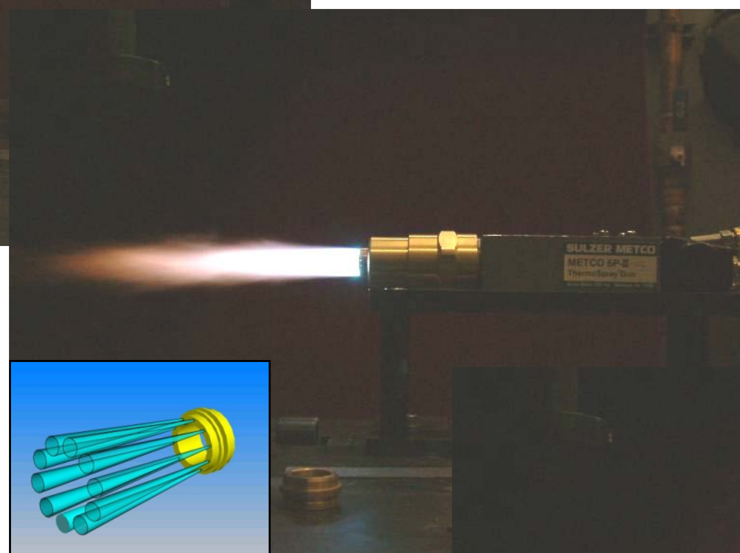


Effect of Air Cap on 6P-K Plume Cross Section

Plume cross sections were made by using the DPV-2000 to measure Tp and Vp every 5 mm within ±15 mm of the torch centerline at stand off distances of 13.97 cm (5.5”), 16.51 cm (6.5”), and 19.05 cm (7.5”)

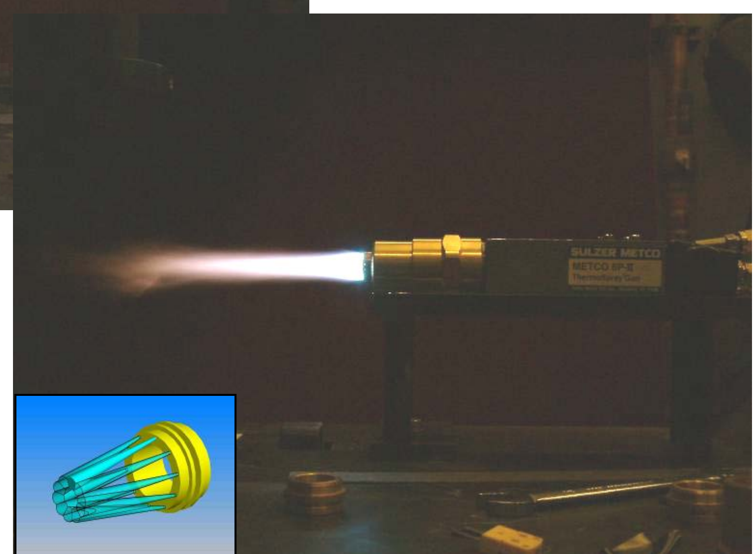


Gun Cooling (GC)



Flame Cooling (FC)

Torch Conditions: TF= 85 SCFH, OFR= 2.0 OFR, Air Flow (AF)= 400 SCFH, Powder Gas (PG)=10 SCFH, and Powder Feed Rate (PFR)= 10 g/min



Pinch

6P-K flame comparison for different air caps

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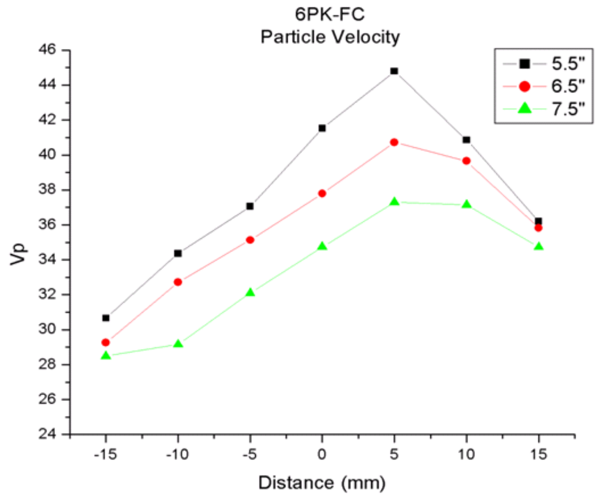
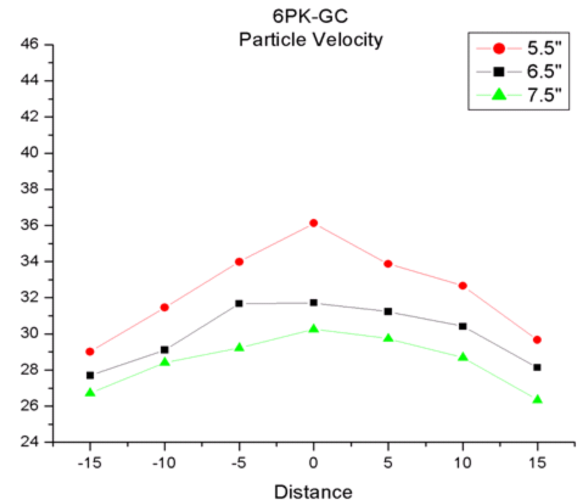
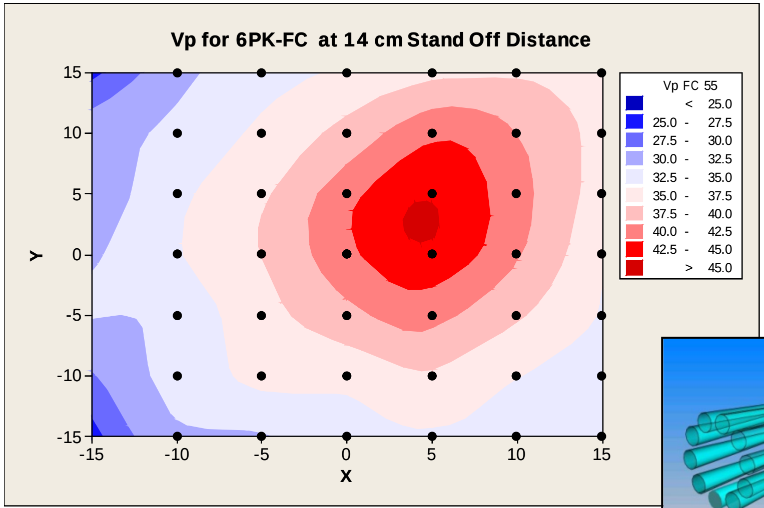
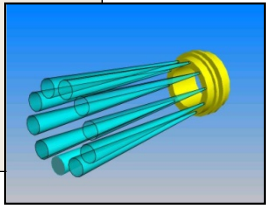
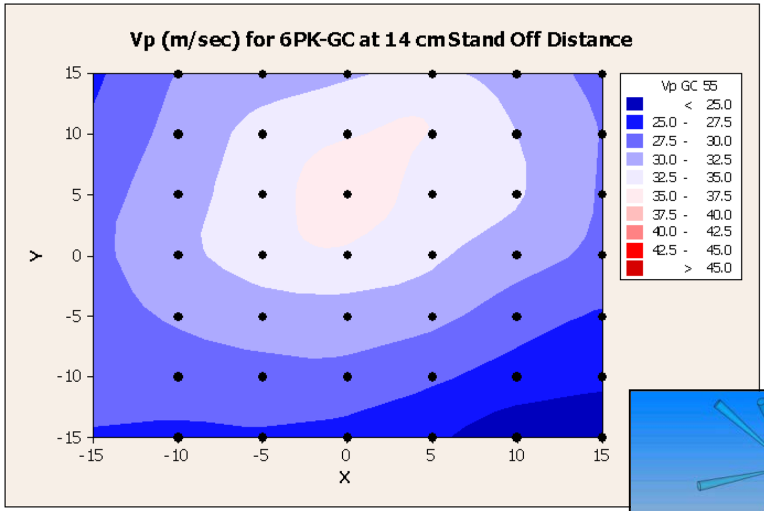
Effect of Air Cap on Vp Cross Section

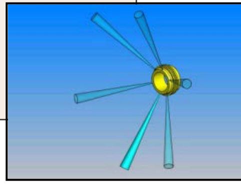






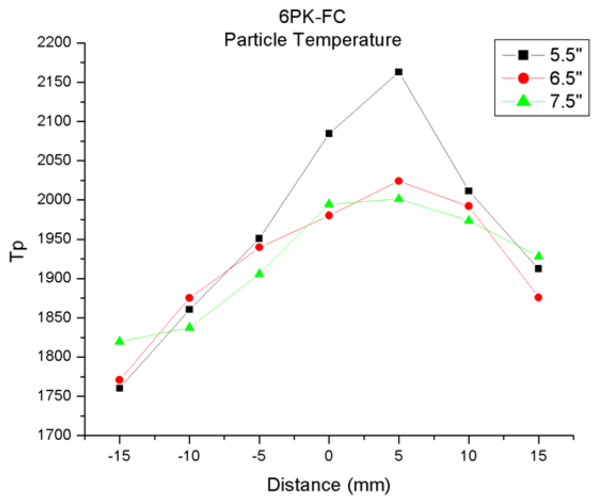


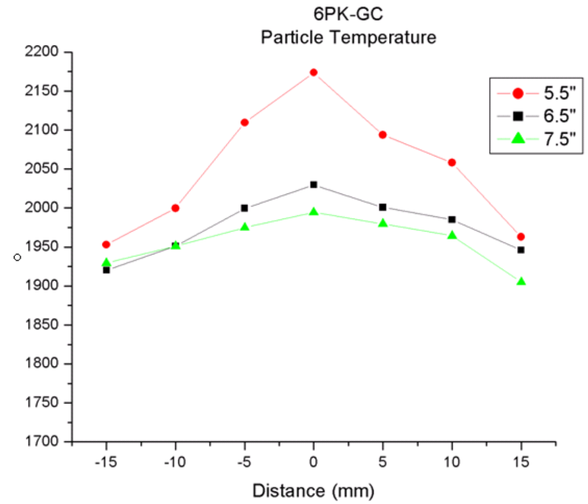


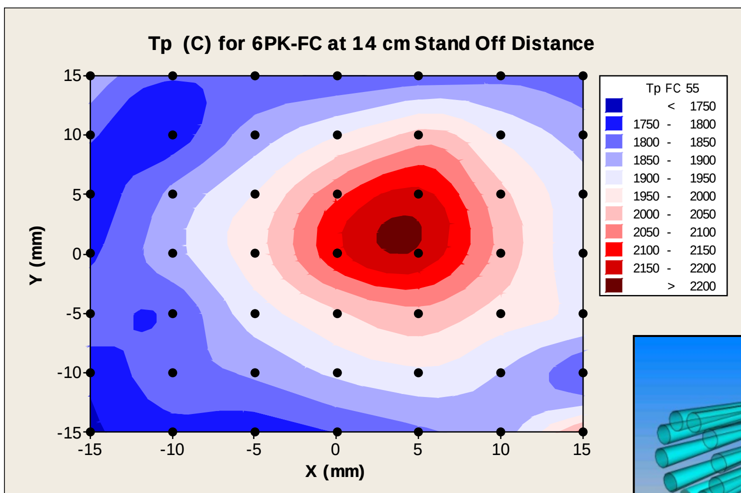


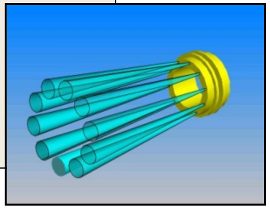
FC air cap produces more variation in Tp cross section than the GC air cap.
Variation decreases as standoff distance increases.

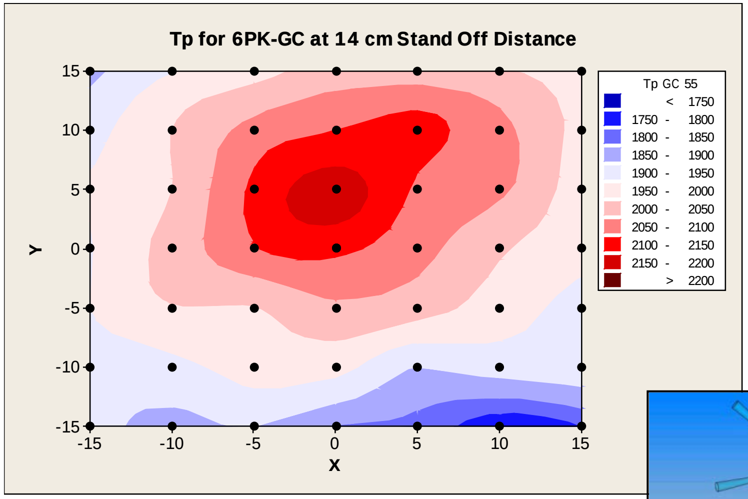
Effect of Air Cap on Tp Cross Section

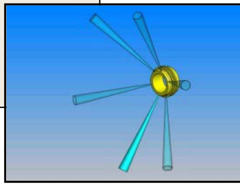












FC air cap produces more variation in Tp cross section than the FC air cap.
Variation decreases as standoff distance increases.

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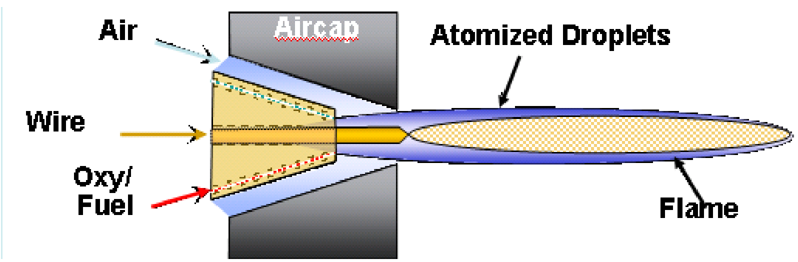
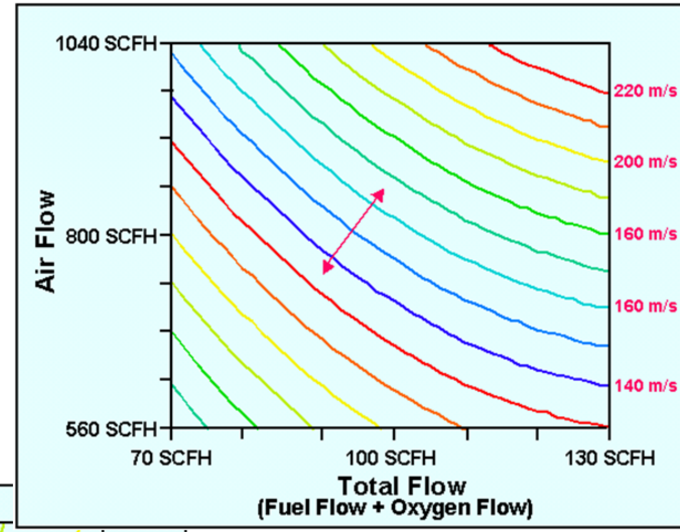
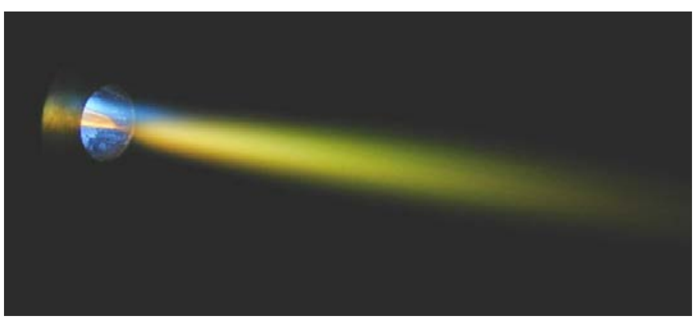
Wire Flame Spray

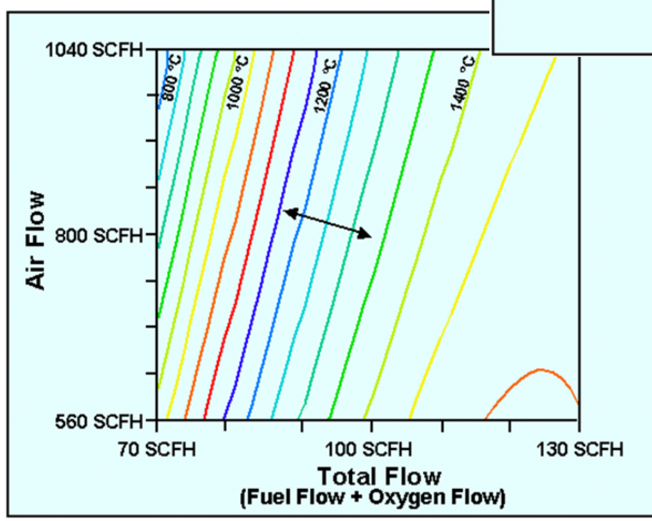
- **Similar to Powder Flame Spray, but different because we are atomizing the feedstock**
- **Tp strongly controlled by OFR and atomizing air flow**
- **Vp strongly controlled by Total Flow and Atomizing air flow**





Particle Velocity





Particle Temperature

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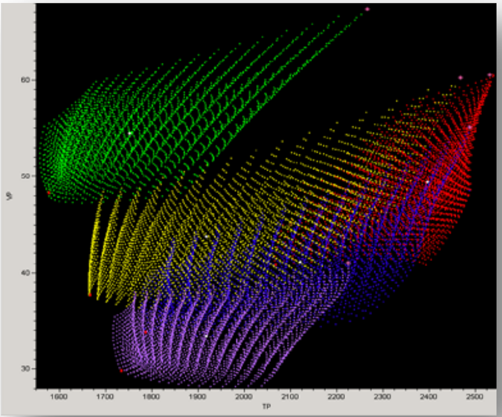
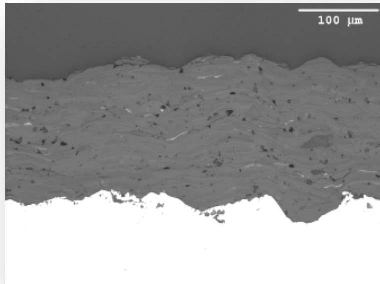
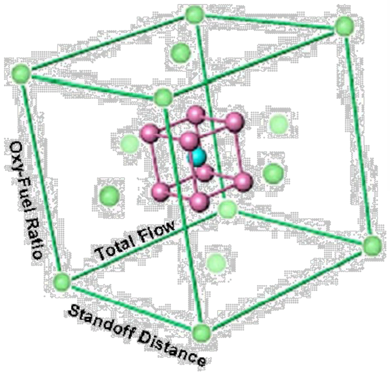
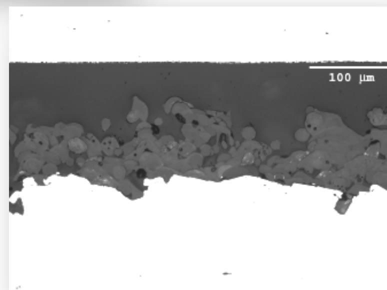
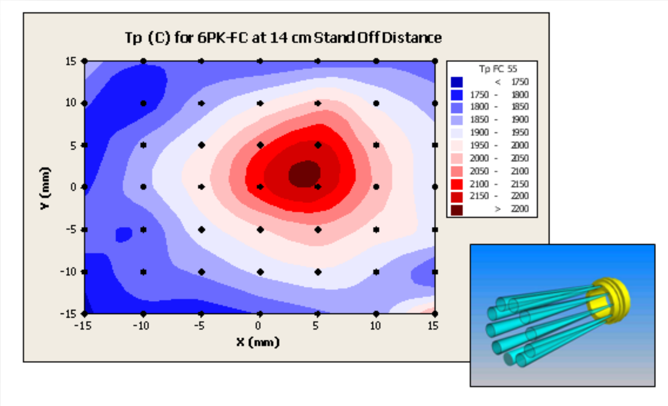
Summary

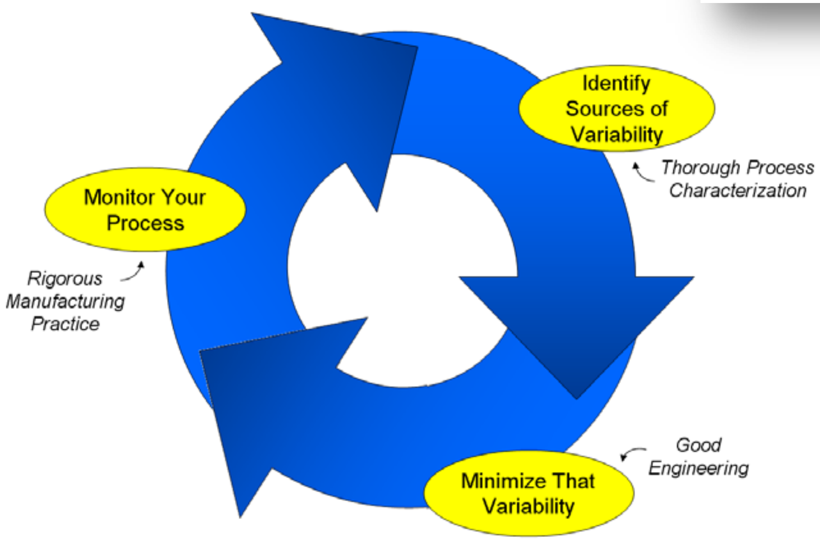


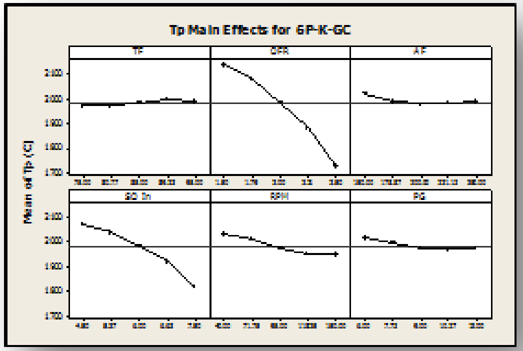












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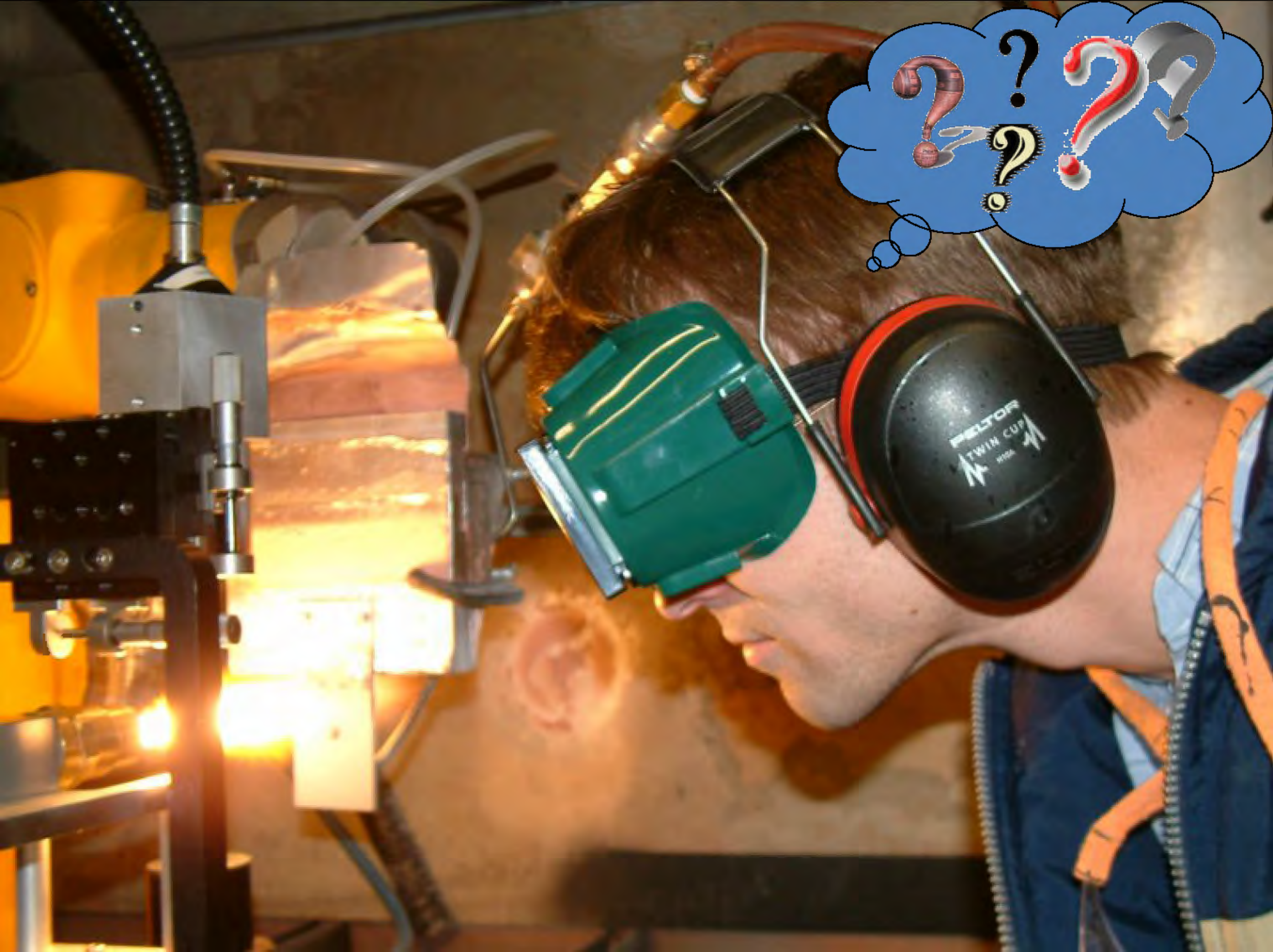
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TWIN CUP