Process Control Diagram for Susceptor Assisted Microwave Heating

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Outline

- Introduction: The need for MW susceptors for materials processing
- Variables and outputs of susceptor heating
- Relationships of volume, mass, and power to temperature, heating rate, and energy consumption
- Calculated model of temperature
- Testing of model
- Summary

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High temperature microwave susceptors

- **Microwave Hybrid Heating = Susceptor + Microwave Energy**
  - Microwave : volumetric heating (coupling)
  - Susceptor: radiant heating
- **Susceptors couple well at RT**
  - Provide initial heat transfer
  - Decrease inverse temperature profile
- **Applied models will make susceptors more practical for experimental users and hobbyists**

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Pros and Cons of Susceptor Heating

- **Pros**
  - Radiant heat prevents thermal shock failures due to inverse temperature profile
  - Fast, reliable way to reach high microwave temperatures quickly
- **Cons**
  - Suscepting ability varies with temperature
  - Susceptor heating is not always a controlled process

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Model Components

- **Variables**

Susceptor type	**RMS Thermcepts**
Susceptor mass	$\mathbf{m}$
Thermal package volume	$\mathbf{V}$
Power input	$\mathbf{P}$
Time	$\mathbf{t}$

- **Outputs**

Temperature (T)	$\mathbf{T = f(m,V,P,t)}$
Heating Rate ($\partial T/dt$)	$\mathbf{(\partial T/dt) = g(m,V,P,t)}$
Energy Consumption (E)	$\mathbf{E = h(P,t)}$

Project Goal

- **Choose <u>susceptor mass</u> that's best for desired firing temperature!**
- There is an ideal susceptor mass for different firing temperatures
  - <u>due to</u> inverse between susceptor mass and max heating rate for constant microwave power
  - <u>resulting in</u>
    - Too much susceptor slows heating initially
    - Too little susceptor slow at high temp
    - Low temp use less susceptor mass; higher temps need more susceptor mass
  - <u>In addition</u>
    - Maximum heating rate gives minimum energy consumption
    - Smaller volume thermal packages have higher max heating rates

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Thermwave and Susceptors

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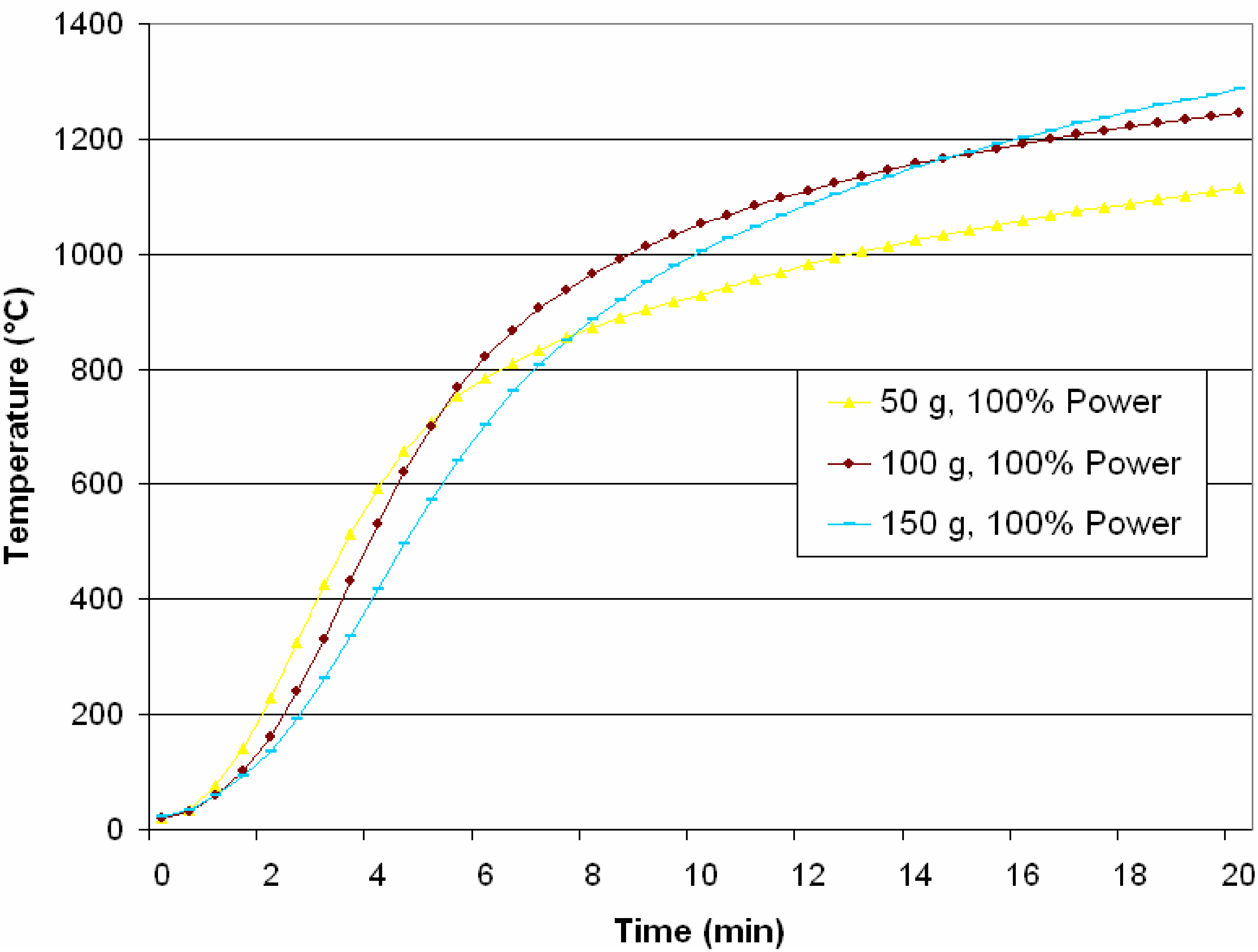
Mass Effect – Constant Power, Volume



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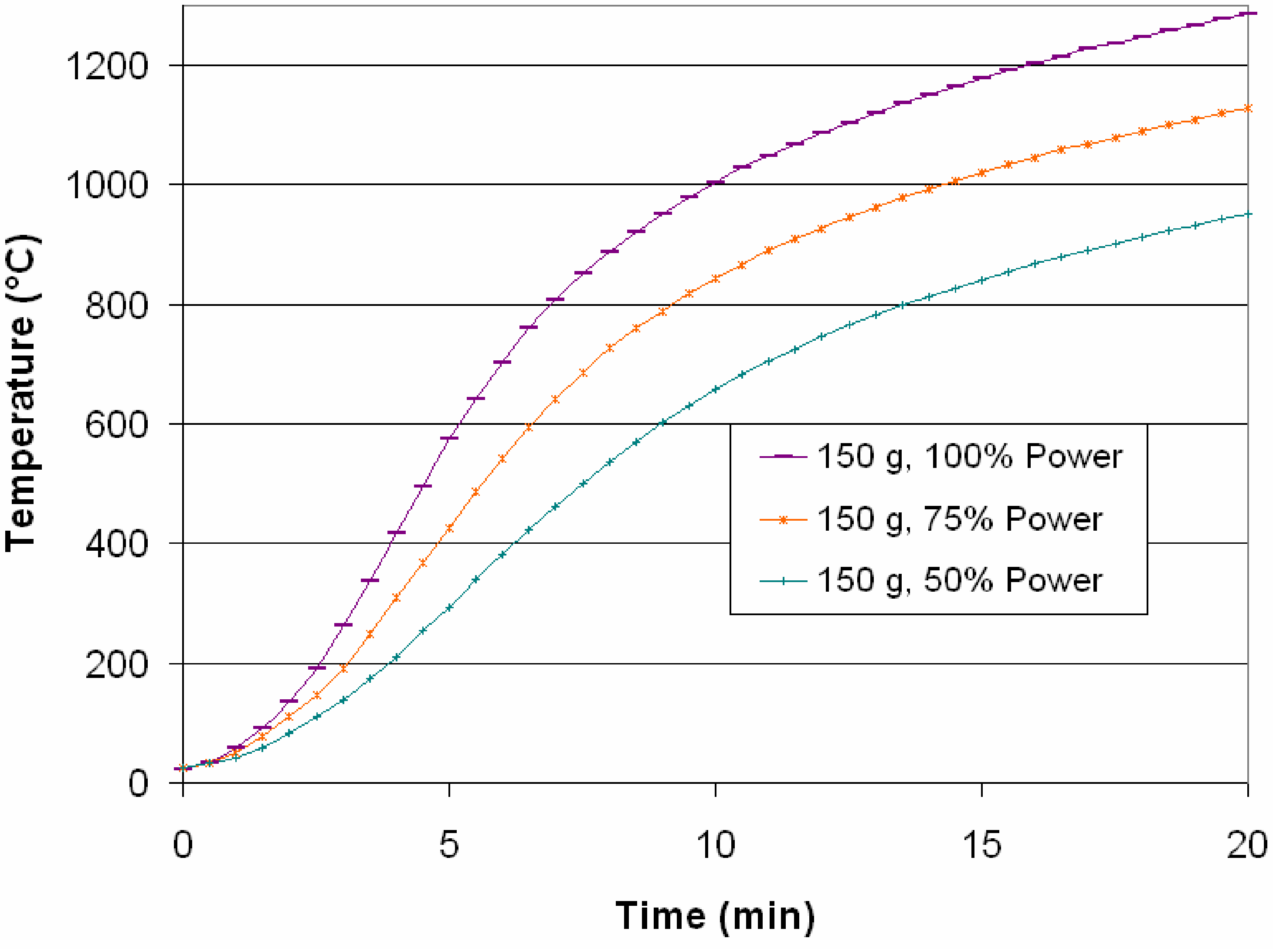
Power Effect – Constant Mass, Volume



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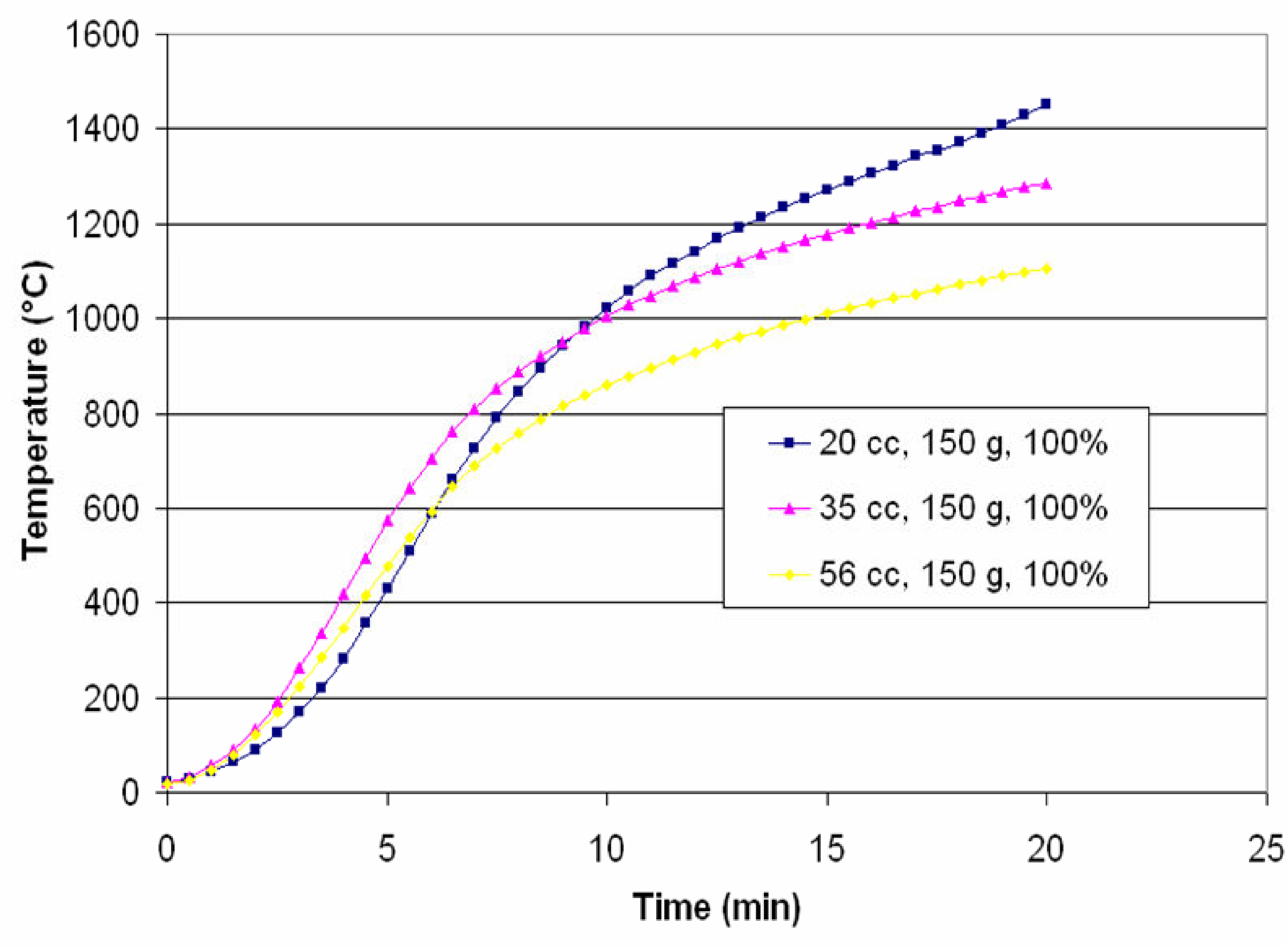
Volume Effect – Constant Mass, Power



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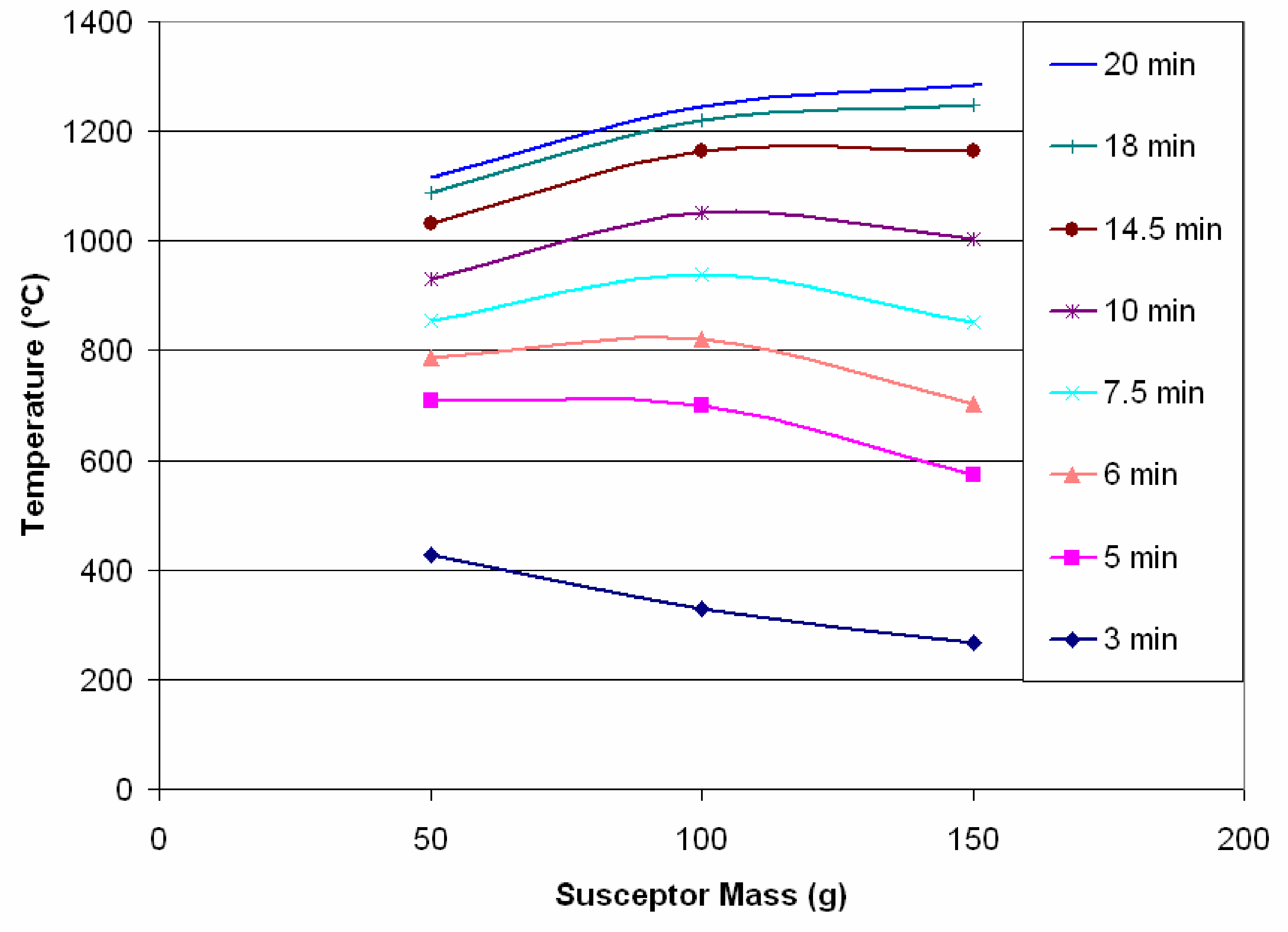
Interaction of Mass with Time



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Curve Fitting T = F(t,m,p,v)

- Sigmoidal fitting (S-curve)

$$F(t) = c1 + \frac{(c2 - c1)}{\left(1 + \left(\frac{t}{c3}\right)^{c4}\right)}$$

- Polynomial fitting

$$\mathbf{T = a + bx_1 + cx_2 + dx_3 \ldots nx_k}$$

Sigmoidal Fitting

- Heating curve has sigmoidal shape
- Eventually system exhausts heating power
- When Energy In = Energy Out → T plateau
- When t=0, F(t) = c2 = T_O → *true constant*
- Solve c1, c3, and c4 for each T-t profile (27 runs)
- Linear regression to determine c1, c3, and c4 as F(m,p,v), G(m,p,v), H(m,p,v)

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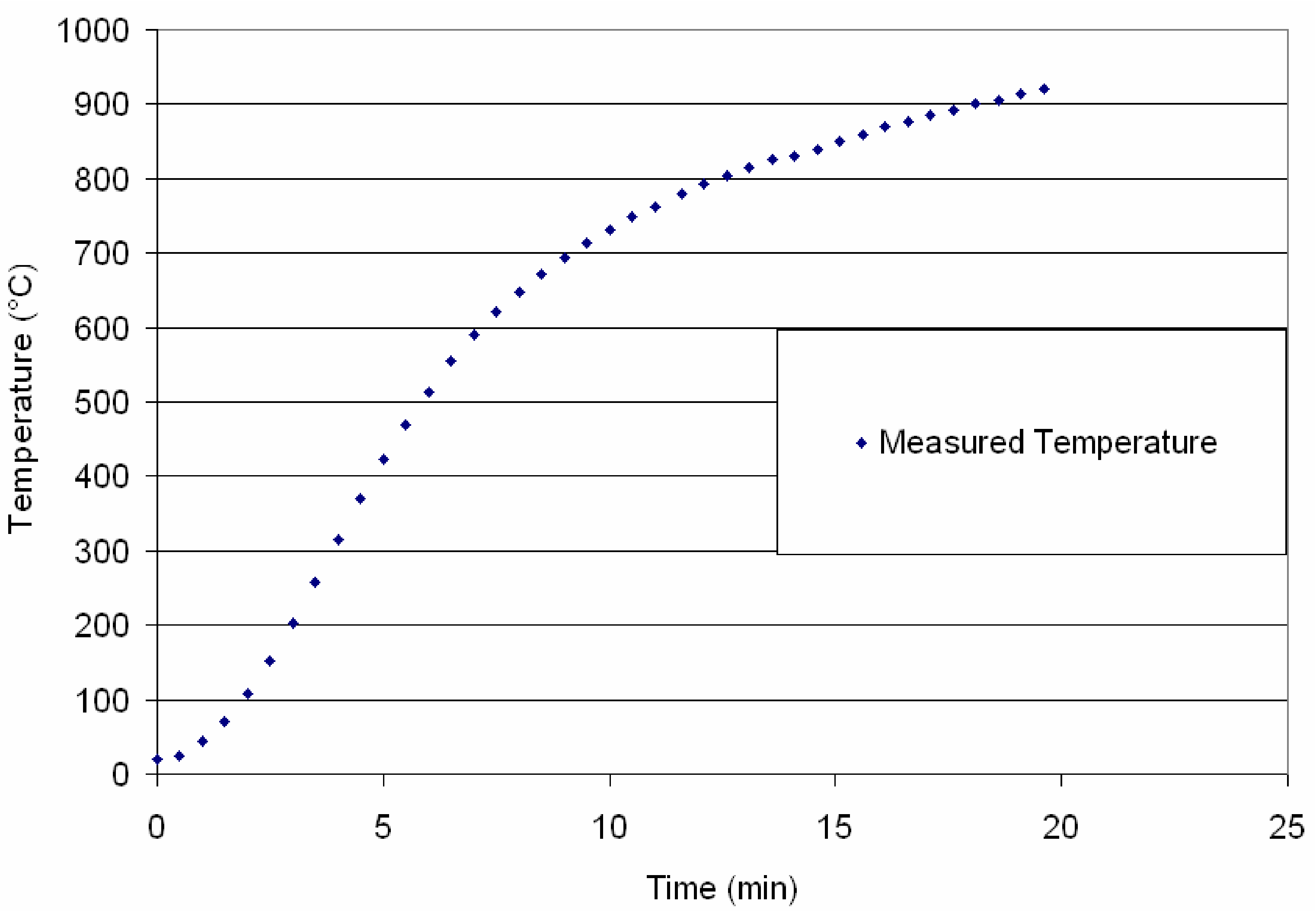
Sigmoidal Fitting

100 g, 75%, 56 cc



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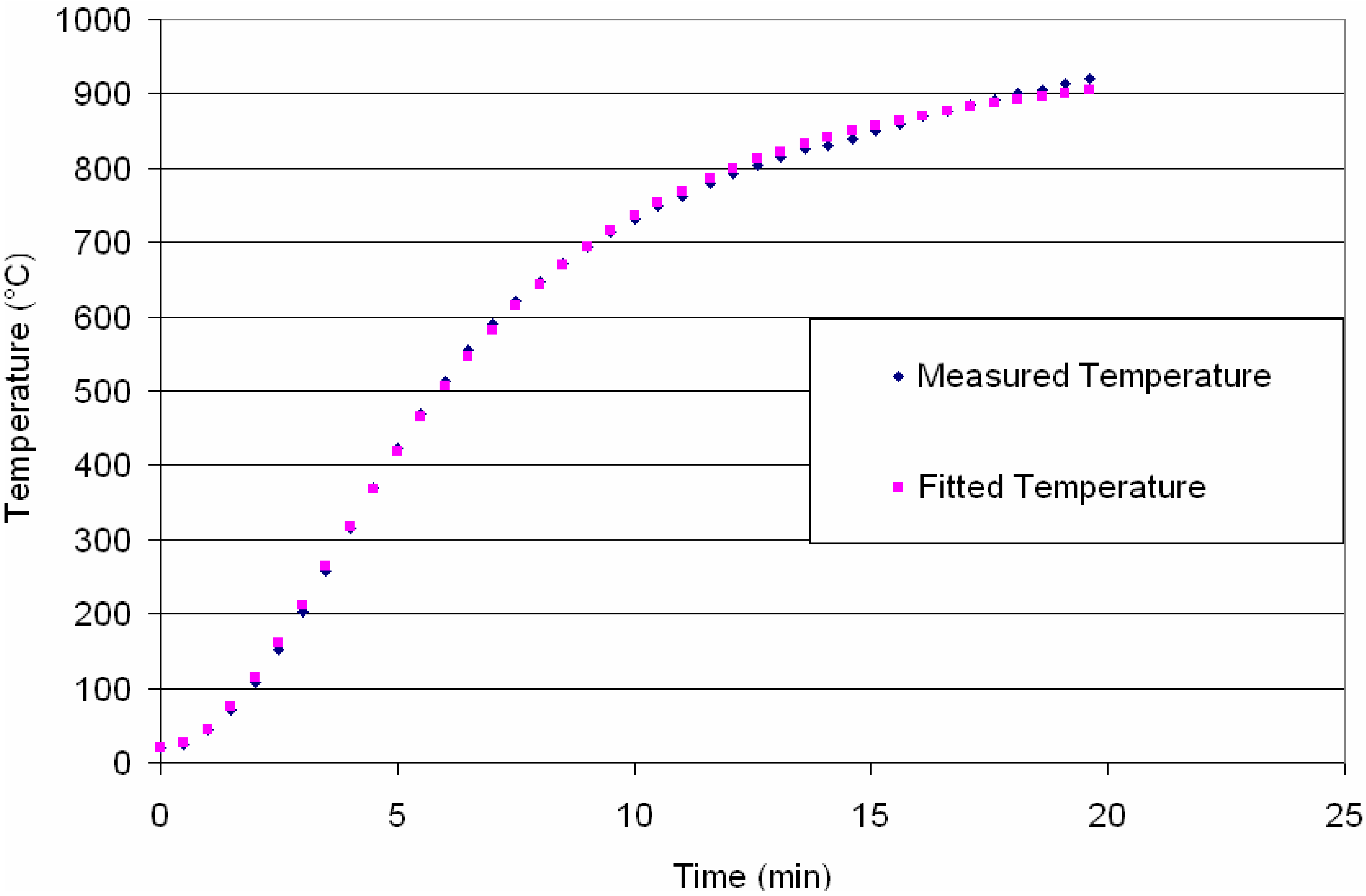
Sigmoidal Fitting

100 g, 75%, 56 cc



f1 = 982

f2 = 5.93

f3 = 2.04

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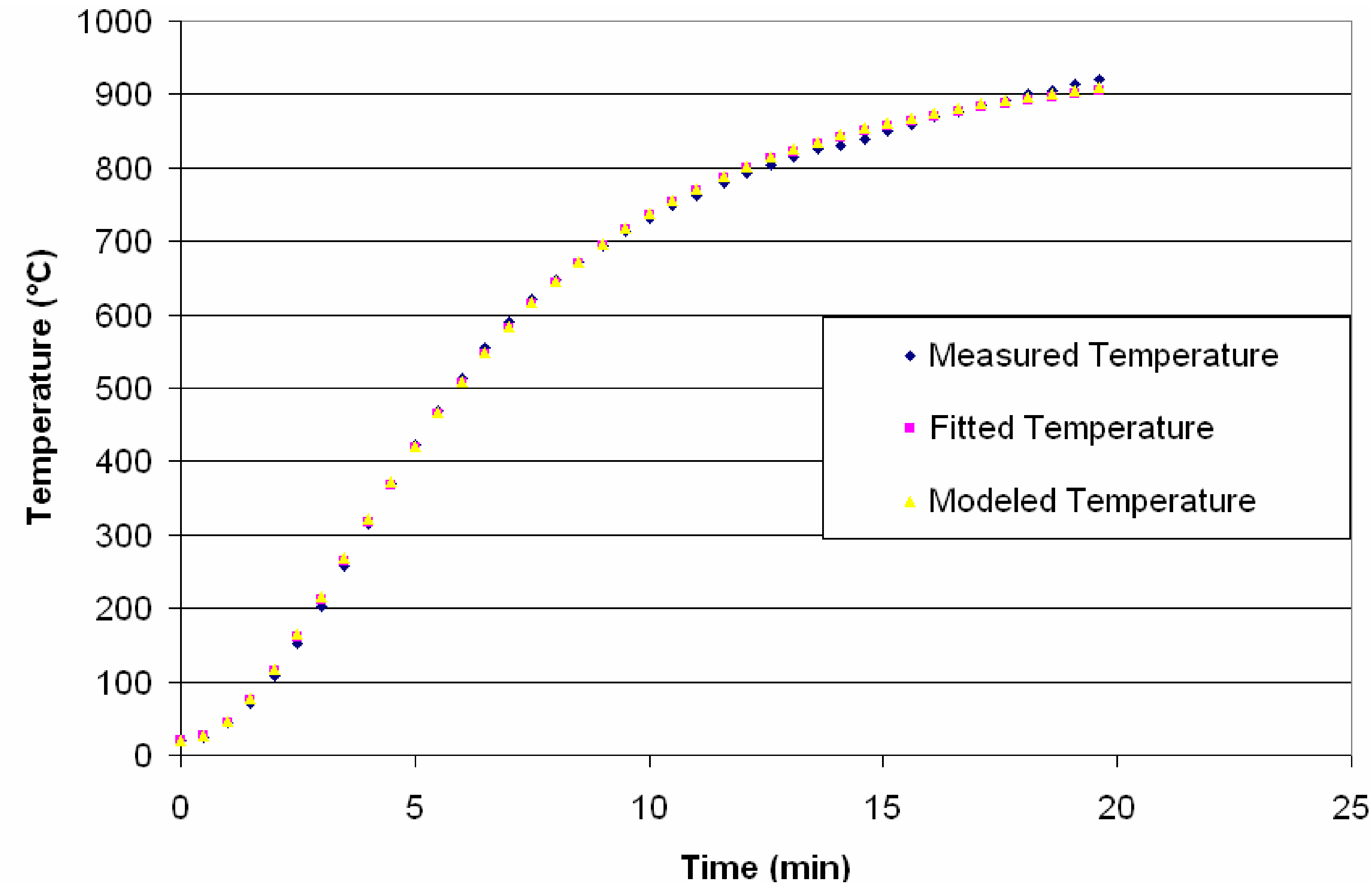
Sigmoidal Fitting

100 g, 75%, 56 cc



f1 = 982

f2 = 5.93

f3 = 2.04

↓

Linear regression

↓

m1 = 991

m2 = 5.96

m3 = 2.01

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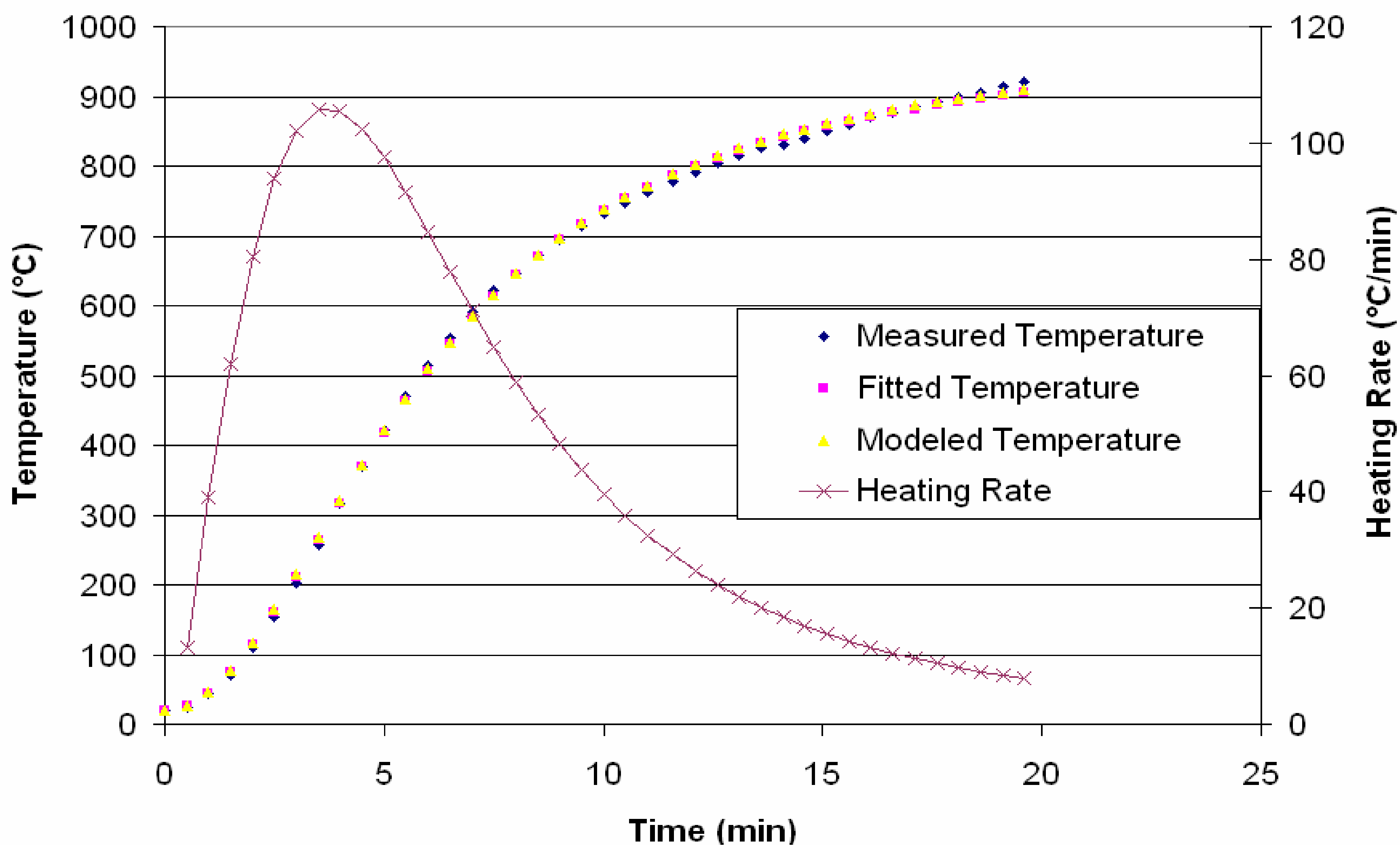
Sigmoidal Fitting

100 g, 75%, 56 cc



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Master Fit for T = F(t,m,p,v)

Coded Variables	m	p	v
	-1	-1	-1
	0	0	0
	1	1	1.4

$$T = (1171 + 83.8m + 110.6p - 128.5v + 21.2mp) + \frac{(T_O - 1171 + 83.8m + 110.6p - 128.5v + 21.2mp)}{(1 + (\frac{t}{5.92 + 1.47m - 1.3p - v + 0.32pv + 0.73v^2})^{2.14 - 0.091v + 0.045v^2 m - 0.085m^2}}$$

Master Fit for T = F(t,m,p,v)

$$T = \overset{\textbf{c1}}{(\mathbf{1171 + 83.8m + 110.6p - 128.5v + 21.2mp})} + \frac{(\overset{\textbf{c2}}{T_O} \overset{\textbf{c1}}{\mathbf{- 1171 + 83.8m + 110.6p - 128.5v + 21.2mp}})}{(1+(\underset{\textbf{c3}}{\frac{t}{5.92+1.47m-1.3p-v+0.32pv+0.73v^2}})^{\underset{\textbf{c4}}{2.14-0.091v+0.045v^2m-0.085m^2}}}$$

Interpolation of Master Fit

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Next Steps

- Modeling with heating load (alumina, zirconia, zinc oxide)

- Empirical modeling of other susceptor systems
  - Zirconia
  - Zinc oxide

- Transition from empirical model to physical model
  - Specific Heat
  - Activation Energy
  - Dielectric Properties

•Conductivity
•Convection
•Radiation

Conclusions

- Empirical models can be applied to high temperature susceptor assisted microwave heating
- Fit of model indicates reproducibility of susceptor assisted heating data
- Model can be used to predict heating profiles

Acknowledgements

- Dr. Timothy Keith
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Questions?

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