Process Modeling of Susceptor Assisted Microwave Heating

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Ceralink Inc.

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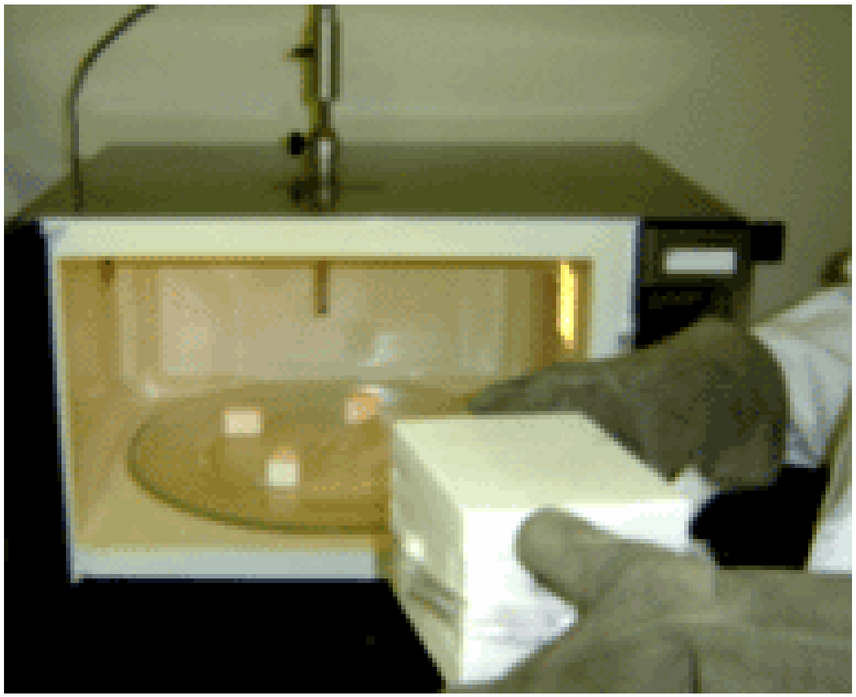
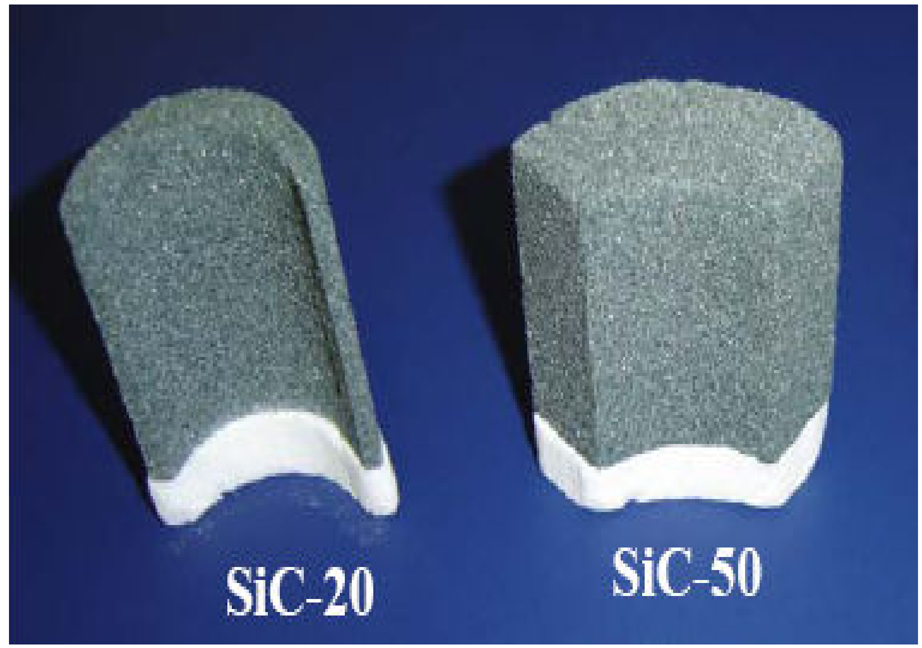
Outline

I. MW susceptors for materials processing
II. Variables and outputs of susceptor heating
III. Variable effects on microwave heating
IV. Calculation of heating profile models
V. Testing of model
VI. Conclusions

I. RMS ThermWave and Thermcept Susceptors





RMS ThermWave
1.3 kW, 2.45 GHz, water cooled

RMS Thermal Package
Zircar Ceramics Al-25/1700°C refractory
Standard sizes

RMS Thermcepts
SiC-25 – **25 g**
SiC-50 – **50 g**

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I. High Temperature Susceptors

- **Susceptors + Microwave Energy**
  - Microwave: volumetric heating (coupling)
  - Susceptor: radiant heating
  - Fast, reliable method for high temperature heating
- **Susceptors couple well at RT**
  - Provide initial heat transfer
  - Minimize temperature gradients
    - Inverse temperature profile
    - Thermal stress failure
- **Limited by power, heat loss, dielectric response**
- **Practical models for microwave users**

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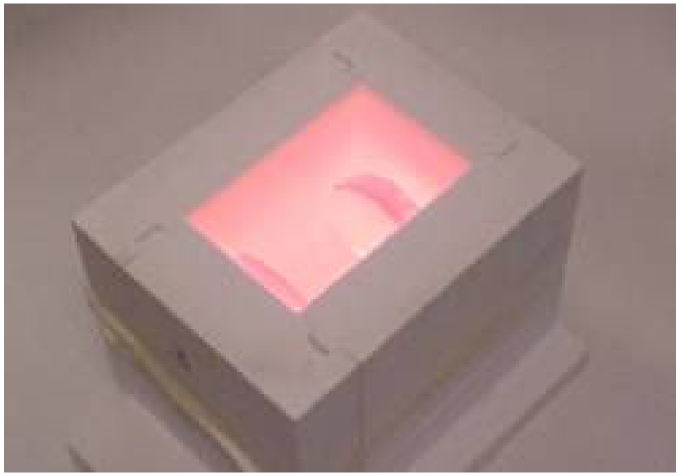
II. Model Components

- **Variables**
  - Susceptor mass **m**
  - Thermal package volume **V**
  - Power input **P**
  - Time **t**



- **Outputs**
  - Temperature (T) **T = f(m,V,P,t)**
  - Heating Rate (∂T/dt) **(∂T/dt) = g(m,V,P,t)**
  - Energy Consumption (E) **E = h(P,t)**

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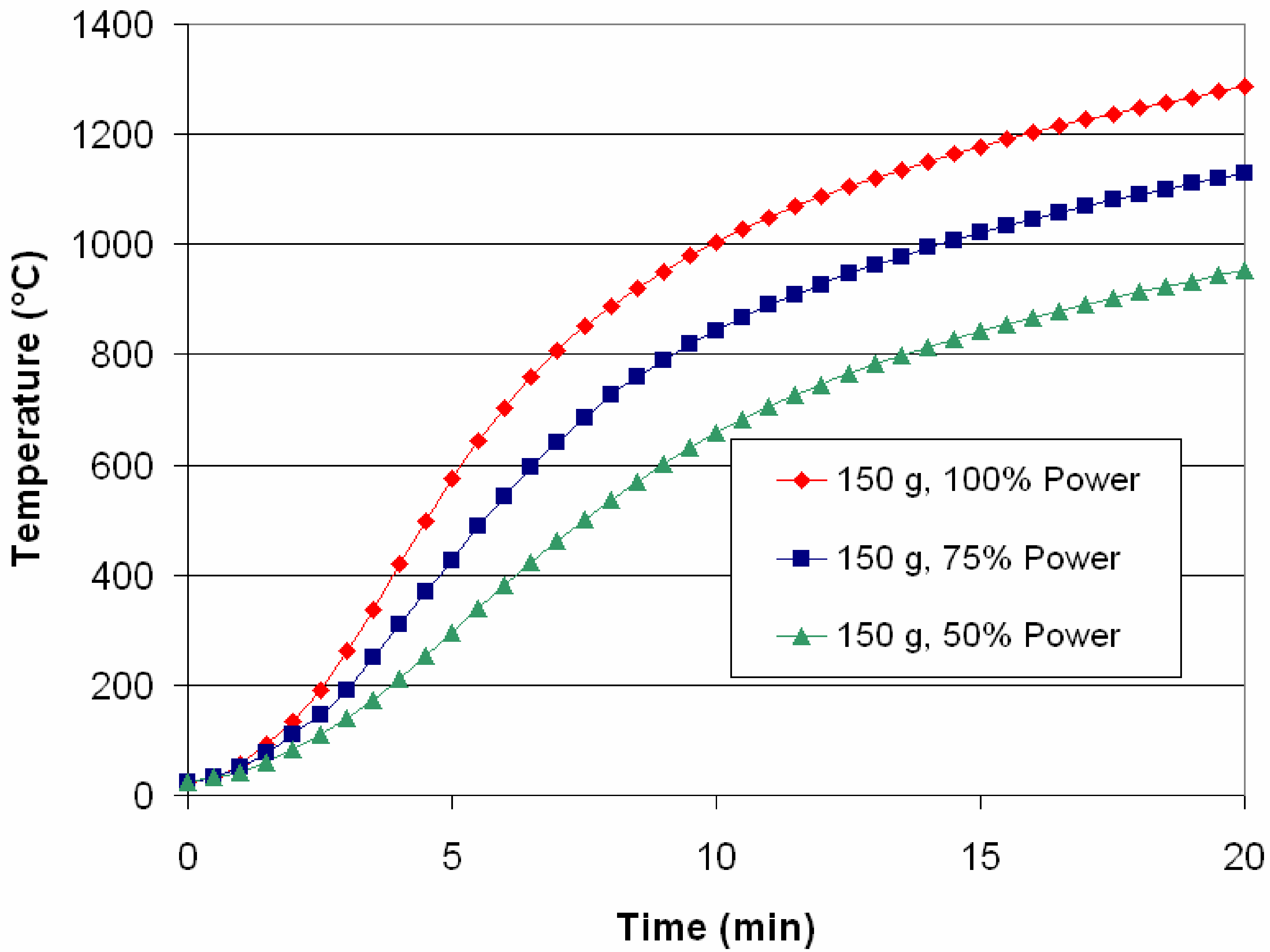
III. Power Effect – Constant Mass, Volume



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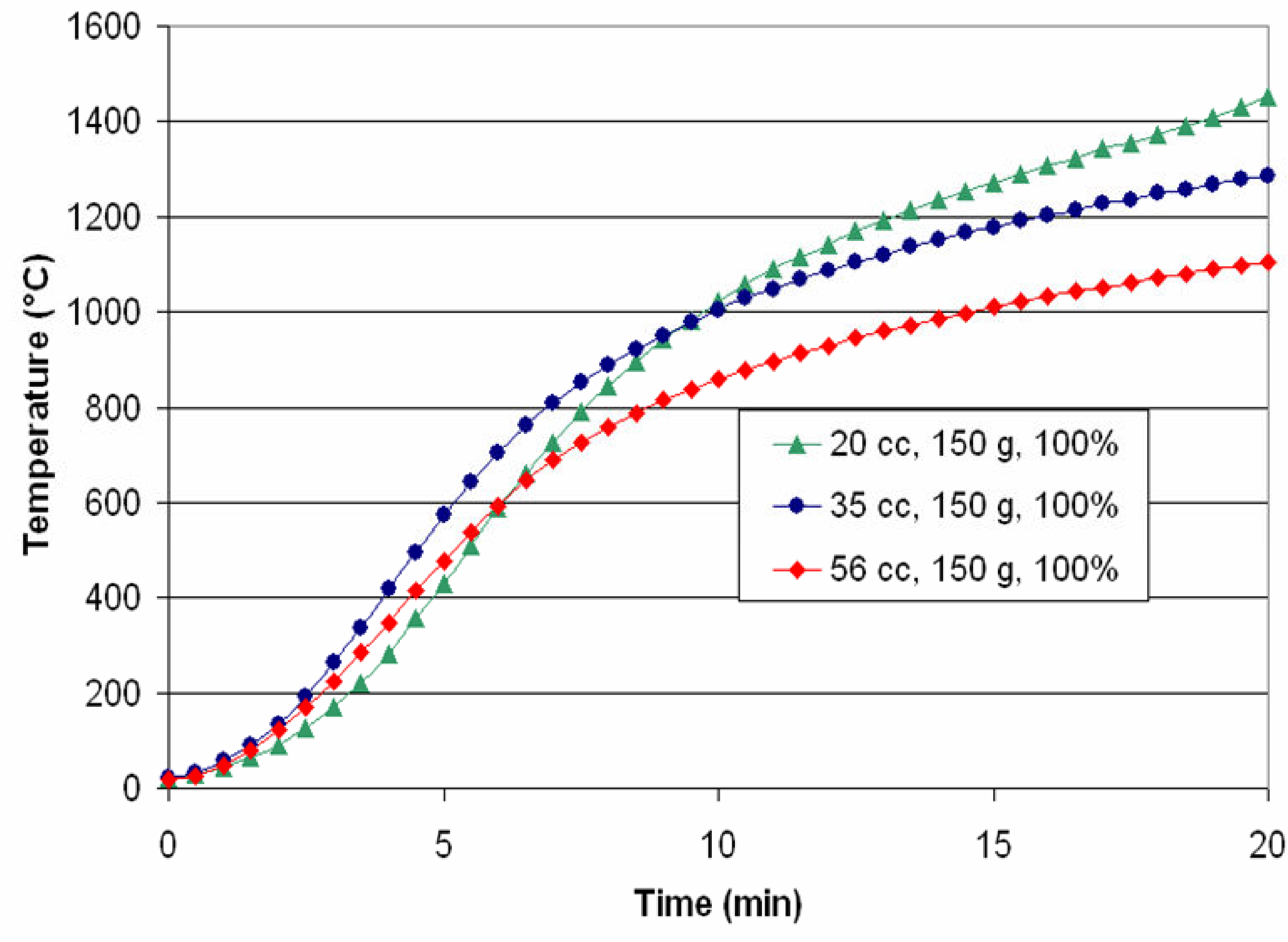
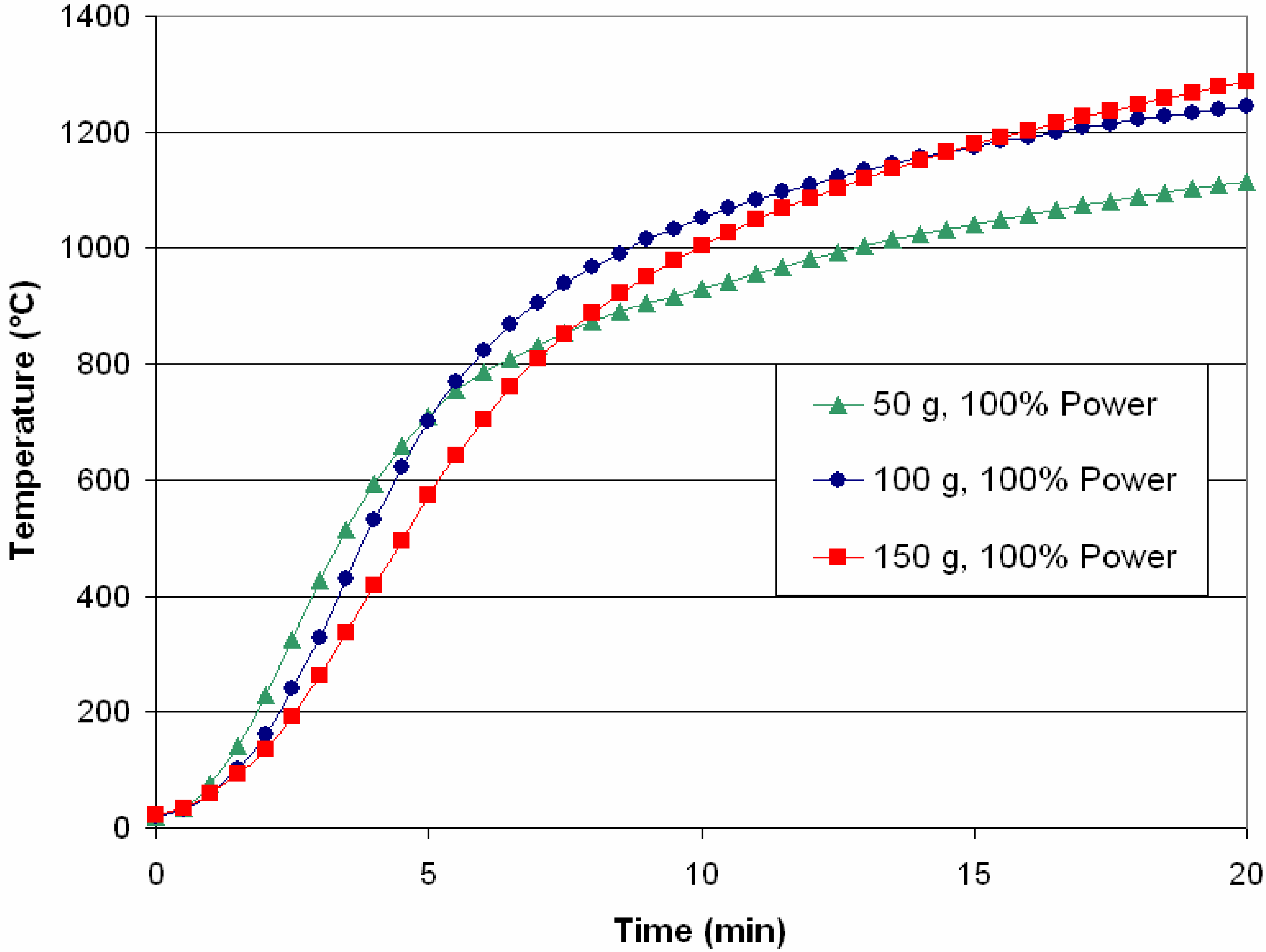
III. Volume Effect – Constant Mass, Power



III. Mass Effect – Constant Power, Volume



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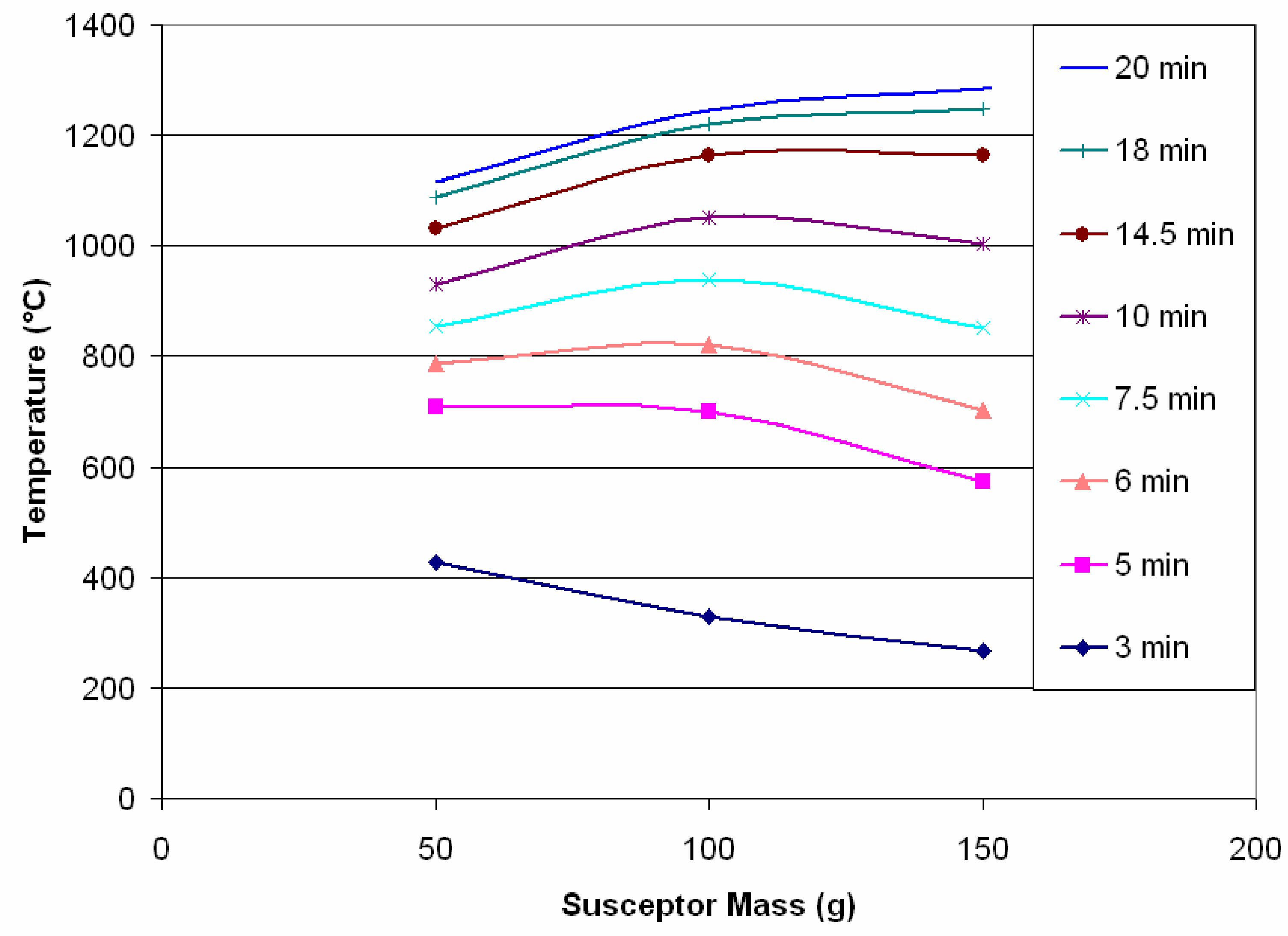
III. Mass and Time Interactions



IV. Curve Fitting T = F(m,V,P,t)

- Polynomial fitting

$$T = a + bx_1 + cx_2 + dx_3 \ldots nx_k$$

- Sigmoidal fitting (S-curve)

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

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IV. Sigmoidal Fitting

- Heating curve has S-shape
- Heating limited by microwave power
- Energy In = Energy Out → T plateau
- When t=0, F(t) = c2, ∴ c2 = T_O
- Linear regression for each T-t profile
  - c1 = F(m,V,P) $R^2 = 0.983$
  - c3 = G(m,V,P) $R^2 = 0.948$
  - c4 = H(m,V,P) $R^2 = 0.543$

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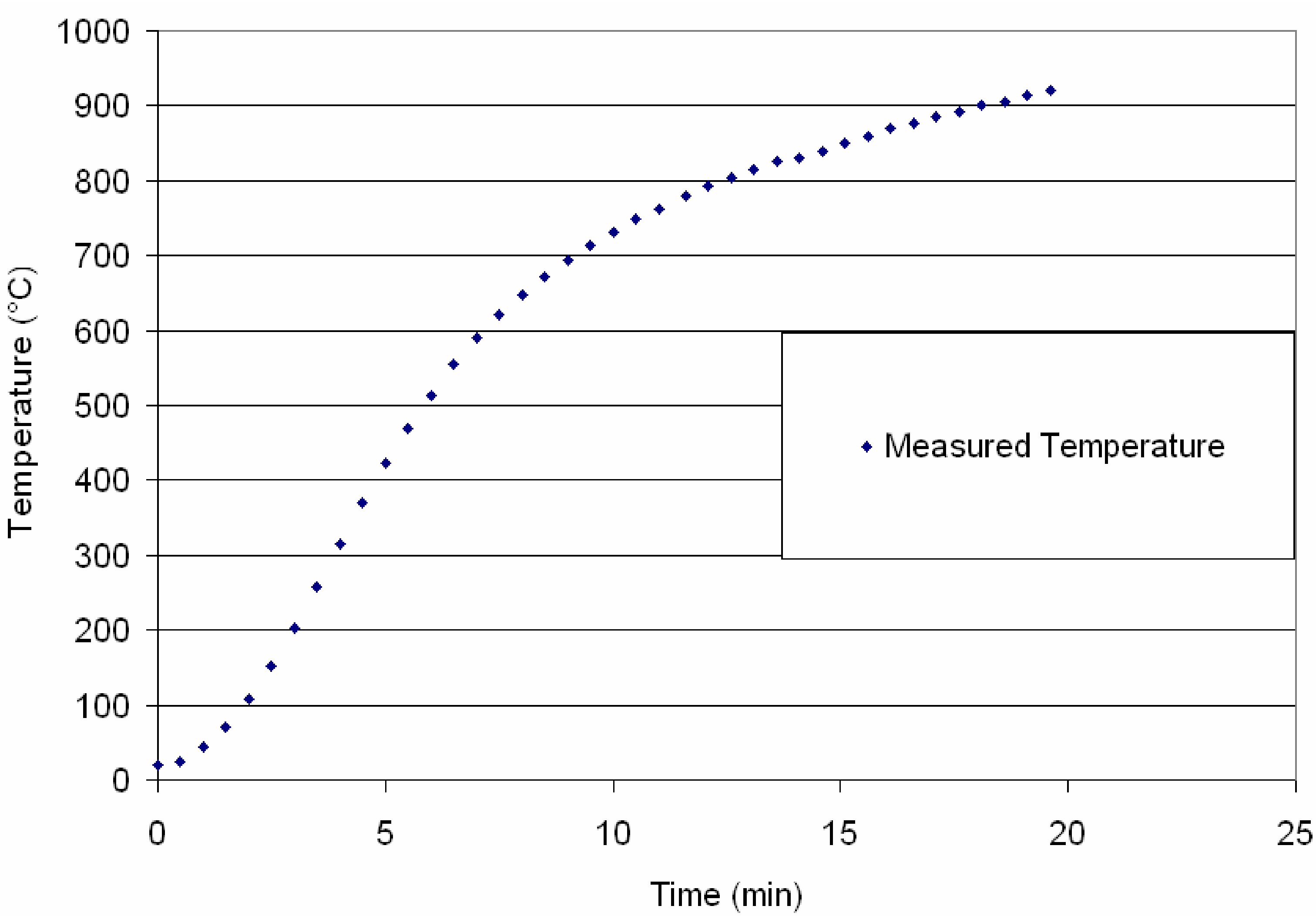
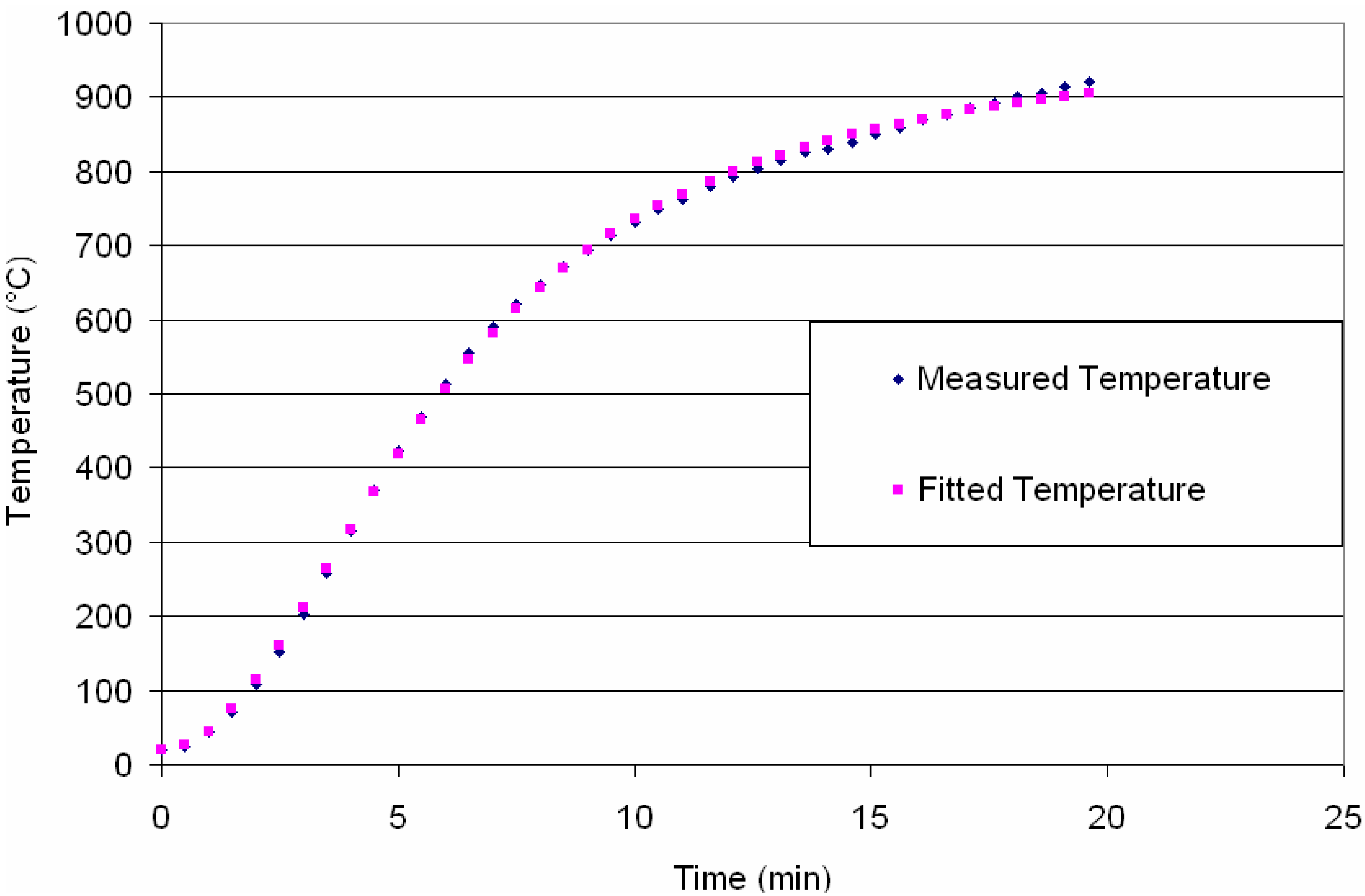
IV. Sigmoidal Fitting
100 g, 75%, 920 cc



IV. Sigmoidal Fitting
100 g, 75%, 920 cc



f1 = 982

f3 = 5.93

f4 = 2.04

IV. Master Fit for T = F(m,V,P,t)

Coded Variables	m	P	V
	-1	-1	-1
	0	0	0
	1	1	1.4

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

c1 c2 c1

$$T = (1171 + 84m + 111p - 129v + 21mp) + \frac{(T_O - 1171 + 84m + 111p - 129v + 21mp)}{(1 + (\frac{t}{5.92 + 1.47m - 1.3p - v + 0.32pv + 0.73v^2})^{2.14 - 0.091v + 0.045v^2 m - 0.085m^2}}$$

c3 c4

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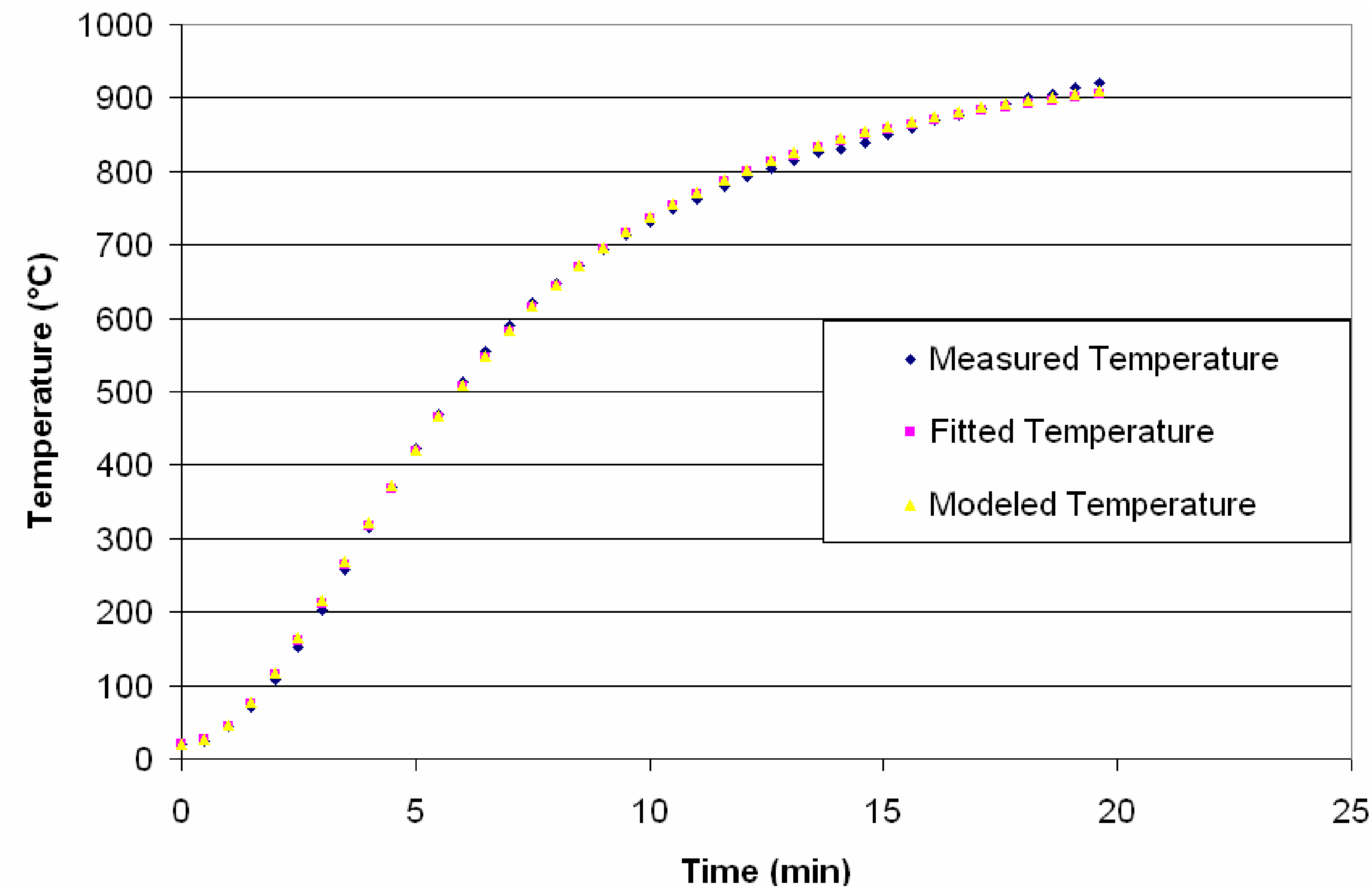
IV. Sigmoidal Fitting
100 g, 75%, 920 cc



f1 = 982

f3 = 5.93

f4 = 2.04

↓

Linear regression

↓

m1 = 991

m3 = 5.96

m4 = 2.01

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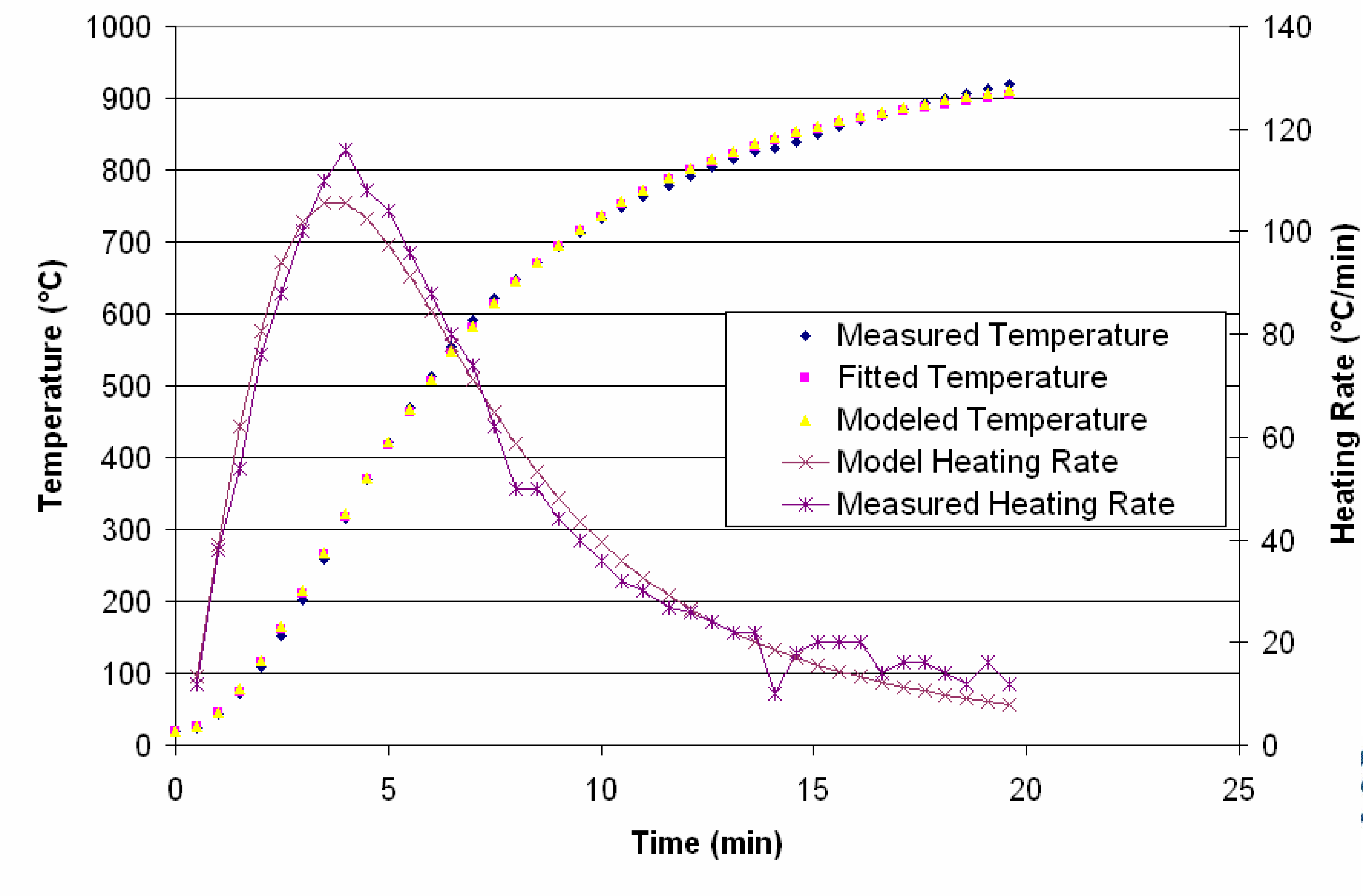
IV. Master Fit of Heating Rate

$$\frac{\partial T}{dt} = -\frac{c4(c2-c1)t^{c4-1}}{c3^{c4}\left(1+\left(\frac{t}{c3}\right)^{c4}\right)^{2}}$$

IV. Sigmoidal Fitting
100 g, 75%, 920 cc



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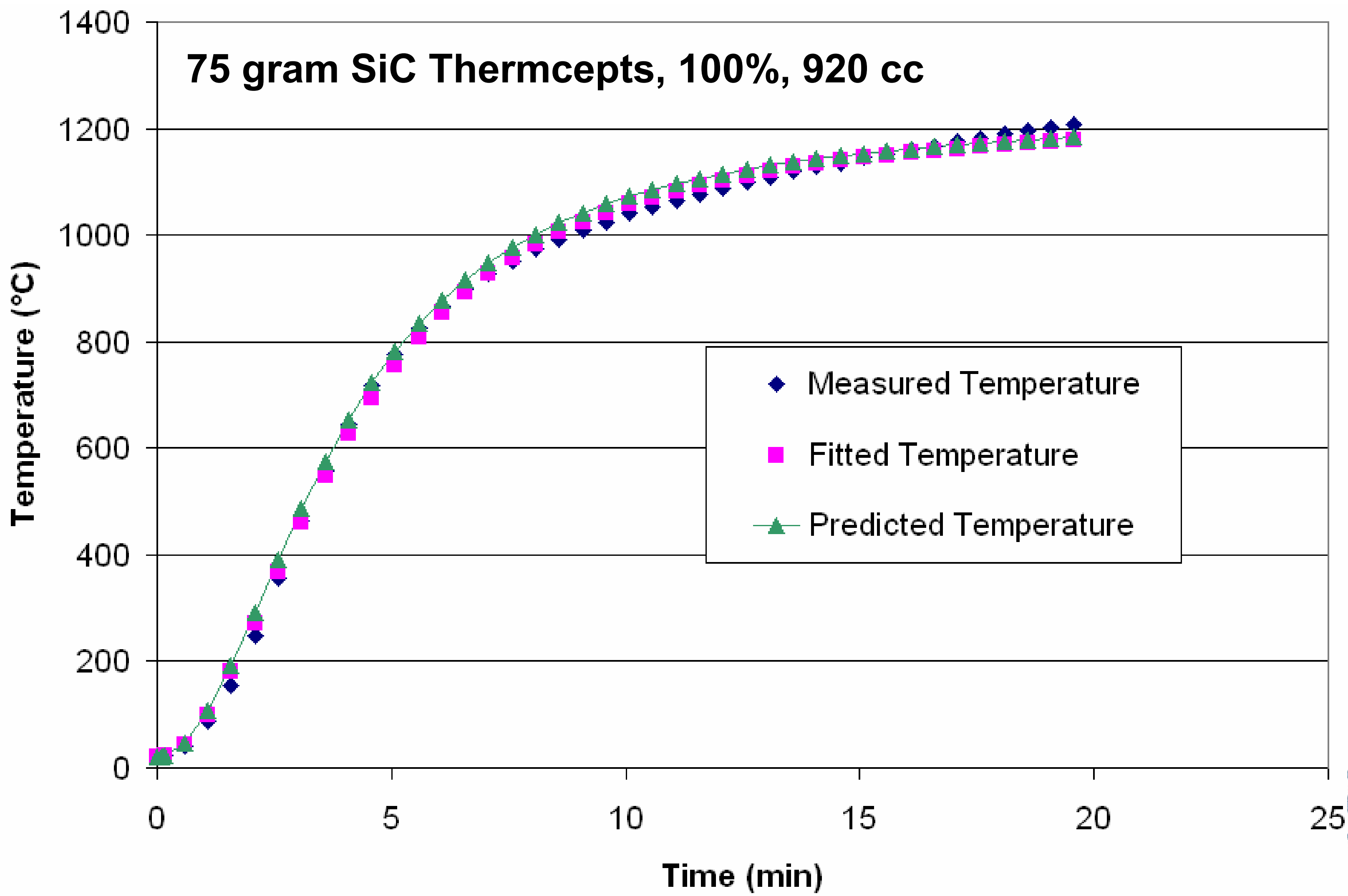
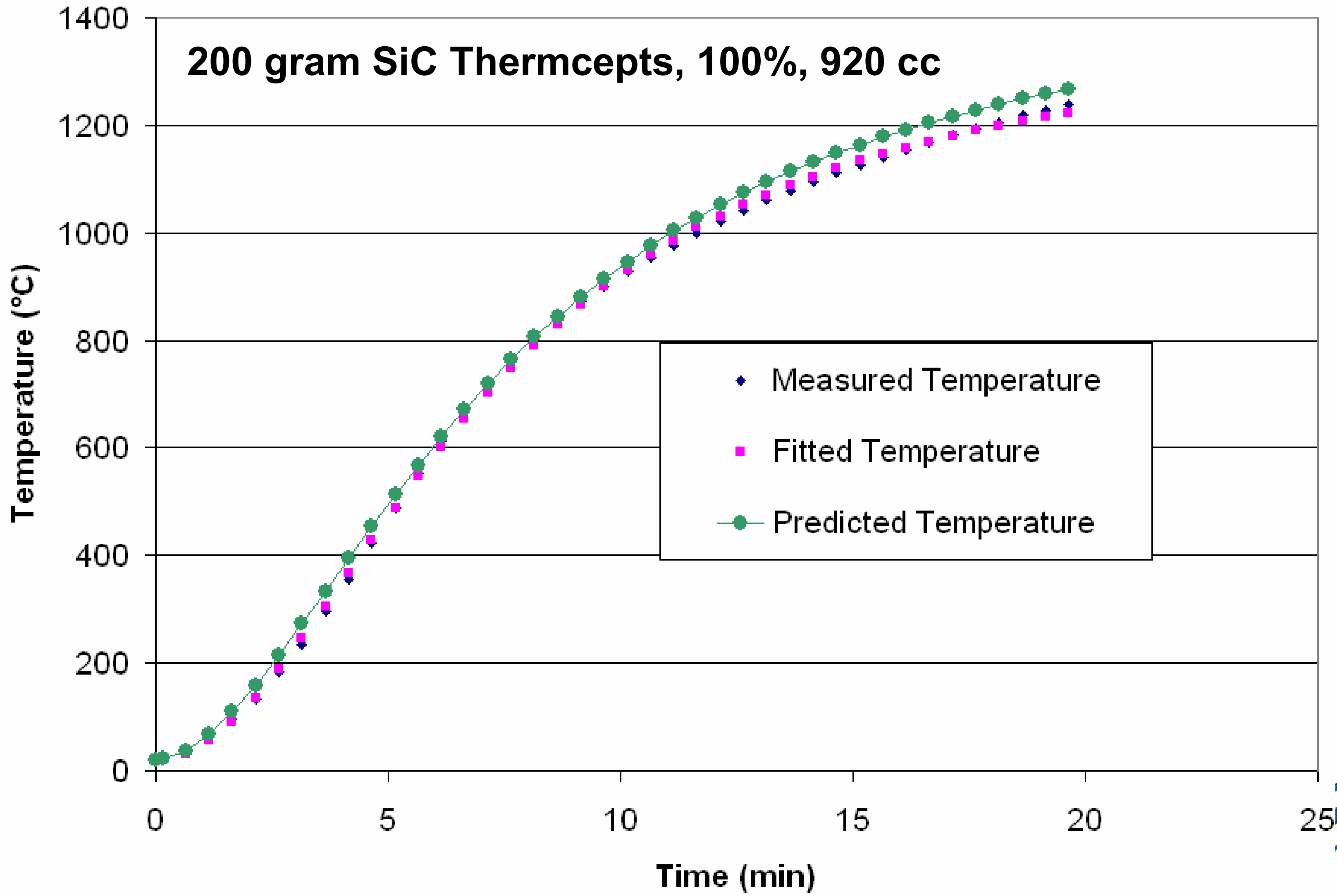
V. Testing the Model: Interpolation of Master Fit



V. Testing the Model: Extrapolation of Master Fit



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VI. Conclusions

- Empirical models can be applied to standardized high temperature susceptor assisted microwave heating
- Fit of model indicates reproducibility of susceptor assisted heating data
- Model can be used to predict heating profiles
- Method for modeling other susceptor systems
- Coefficients provide links to physical models

Acknowledgements

- Dr. Timothy Keith
- John Byrnes

Questions?