The Goal:

Predict how long it takes an epoxy to cure at a given temperature.

The Problem:

Can’t test it directly.

The Problem:

In the process of heating the sample to the target temperature,

The cure advances at intermediate temperatures.

The Solution:

"Isoconversional" techniques.

Isoconversional:

The rate that the cure progresses depends only on:

(a) The current temperature and
(b) The current degree of cure (0% - 100%)

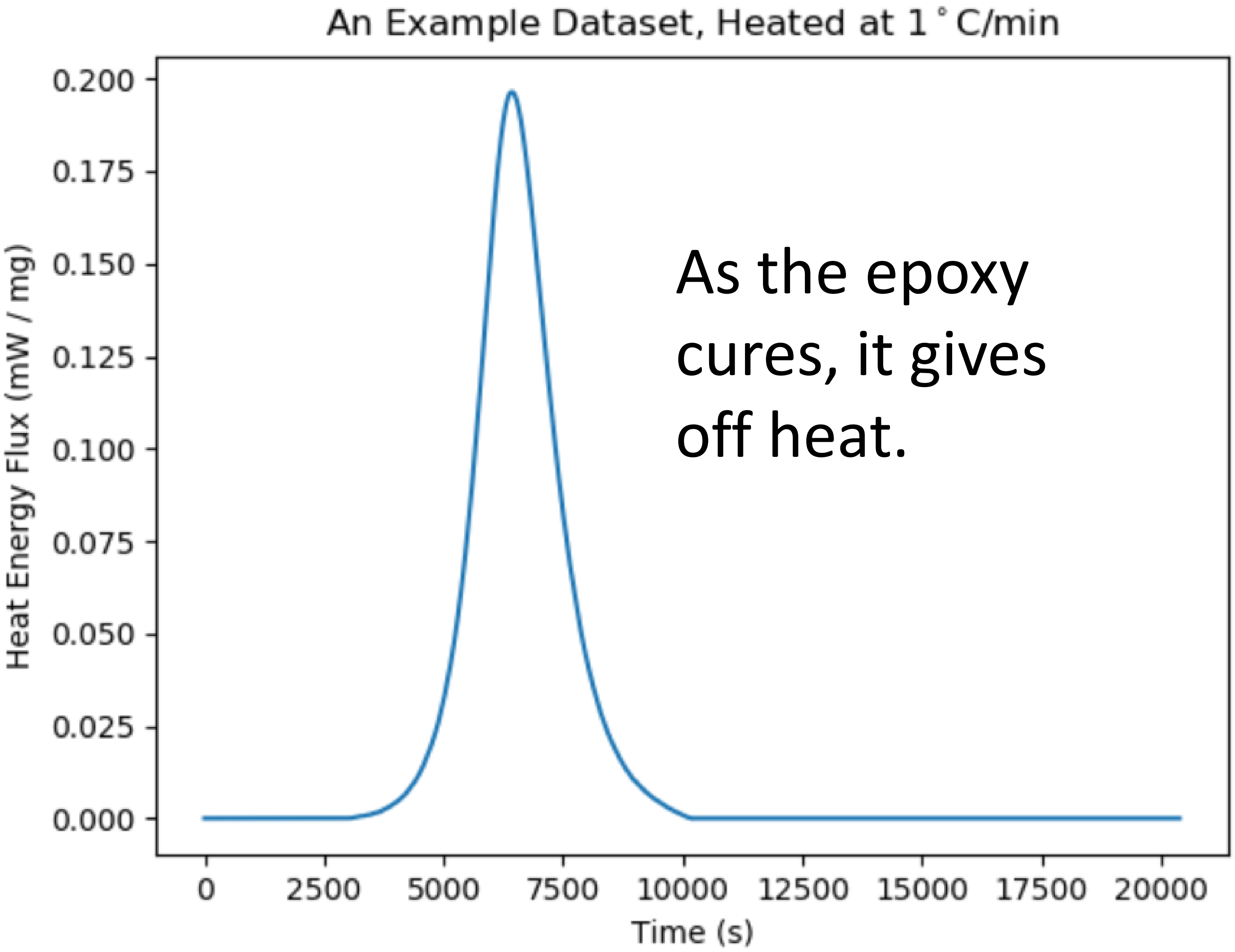
The Plan:

Heat the epoxy at a controlled temperature ramp.

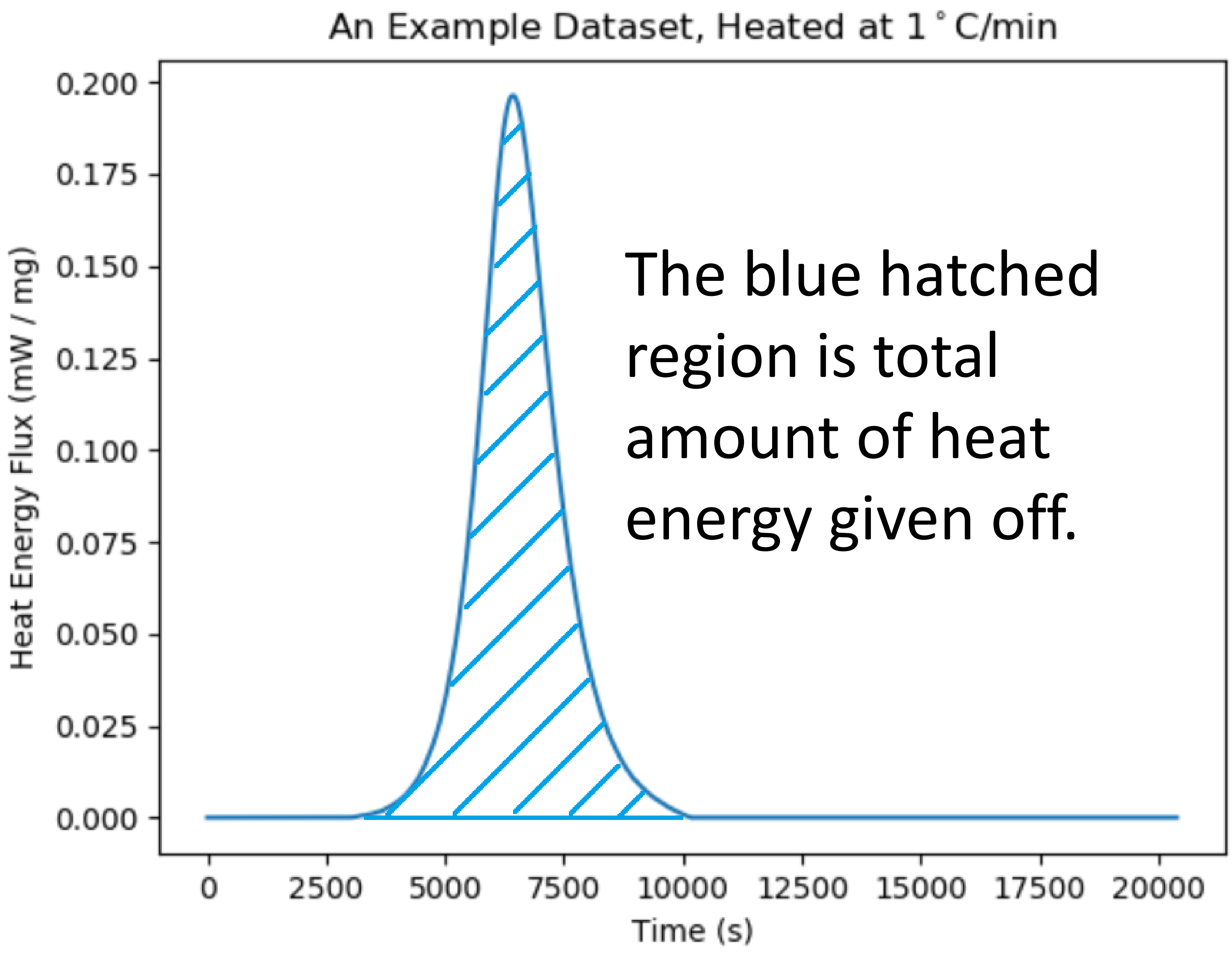
Record the temperature and information about cure.

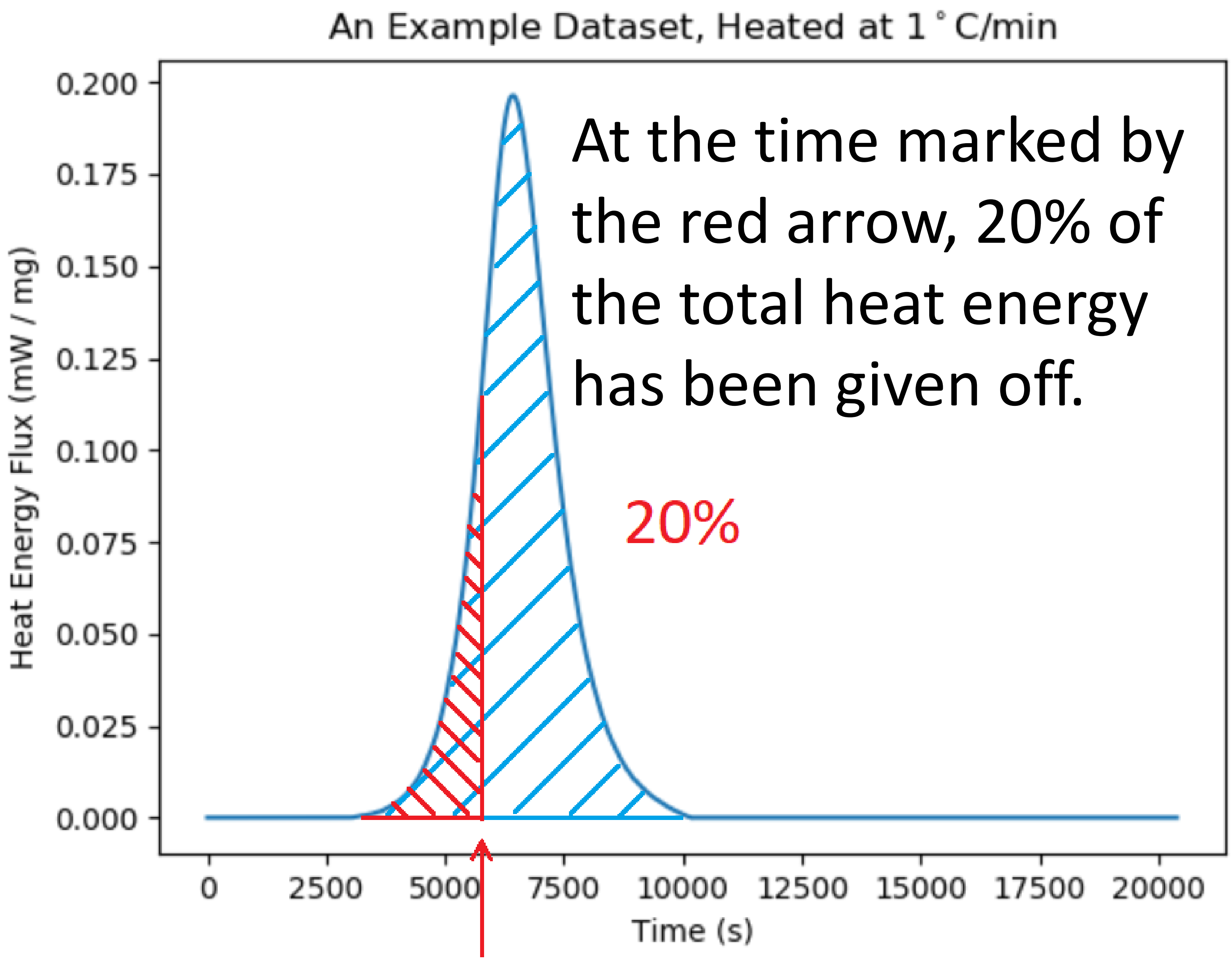
The Data:

The following slides show pre-processing of the data.

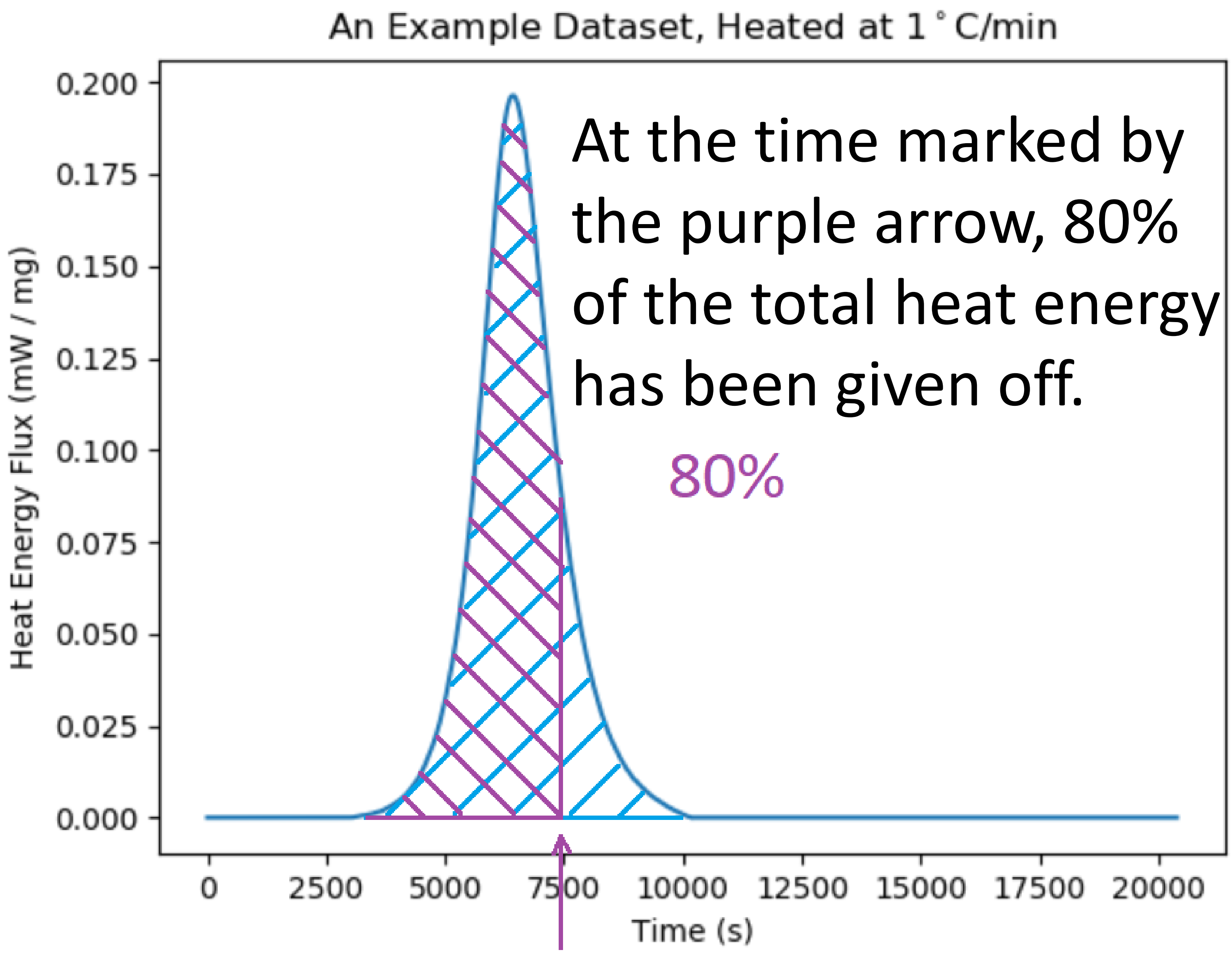


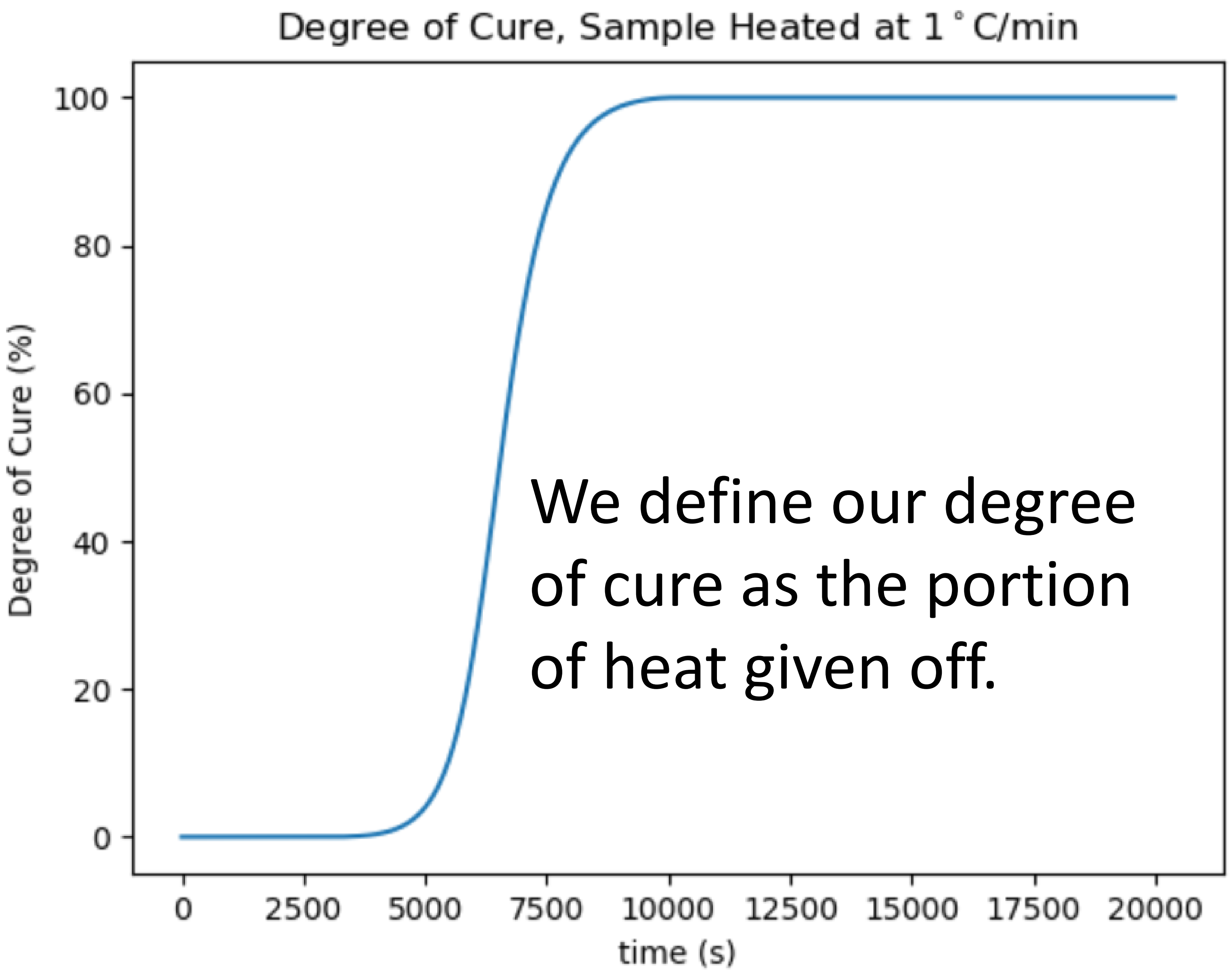
As the epoxy cures, it gives off heat.


An Example Dataset, Heated at 1 ° C/min
Heat Energy Flux (mW / mg)
0.200
0.175
0.150
0.125
0.100
0.075
0.050
0.025
0.000
0
2500
5000
7500
10000
12500
15000
17500
20000
Time (s)
The blue hatched region is total amount of heat energy given off.

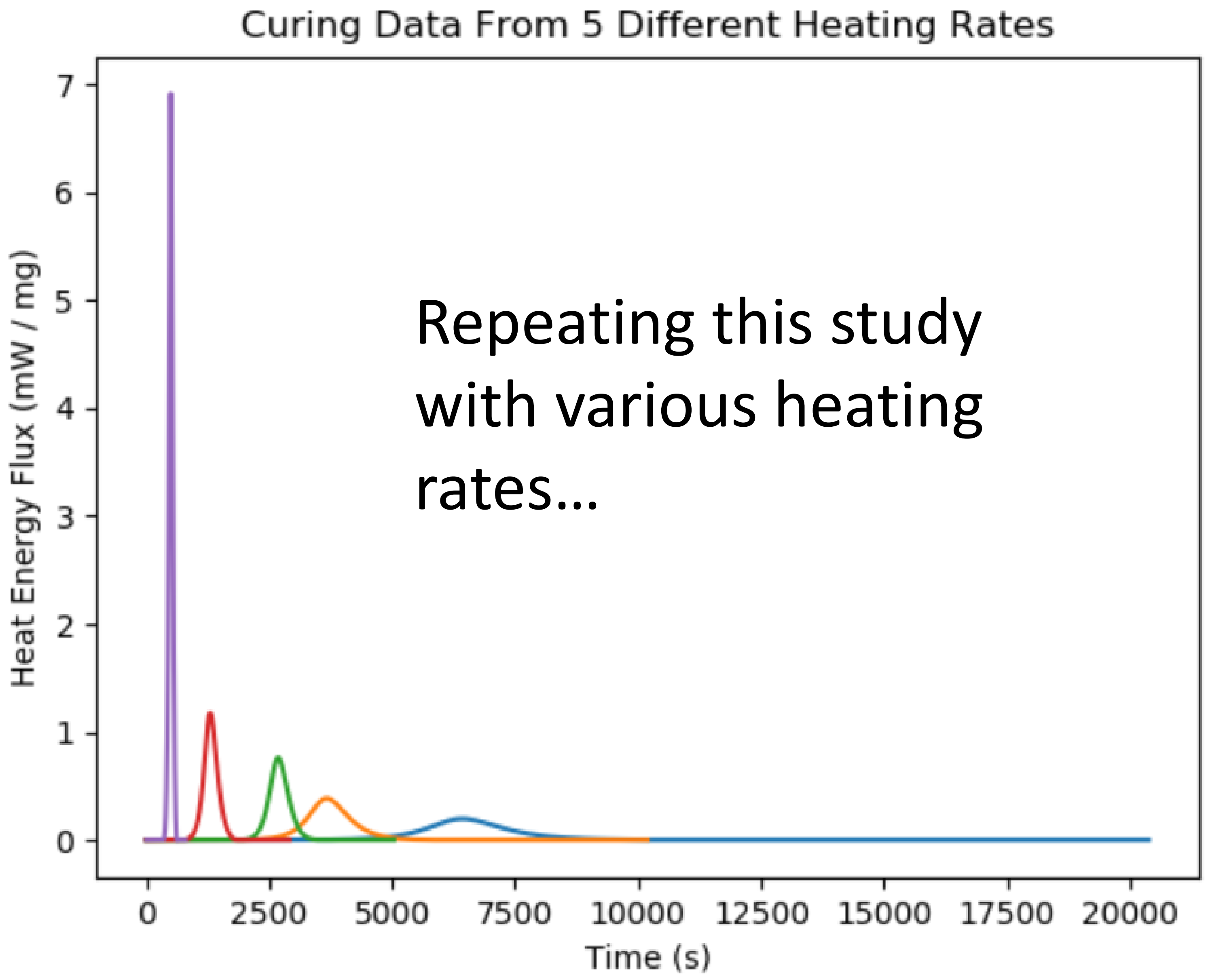


An Example Dataset, Heated at 1 ° C/min
Heat Energy Flux (mW / mg)
0.200
0.175
0.150
0.125
0.100
0.075
0.050
0.025
0.000
0
2500
5000
7500
10000
12500
15000
17500
20000
Time (s)
At the time marked by the red arrow, 20% of the total heat energy has been given off.
20%

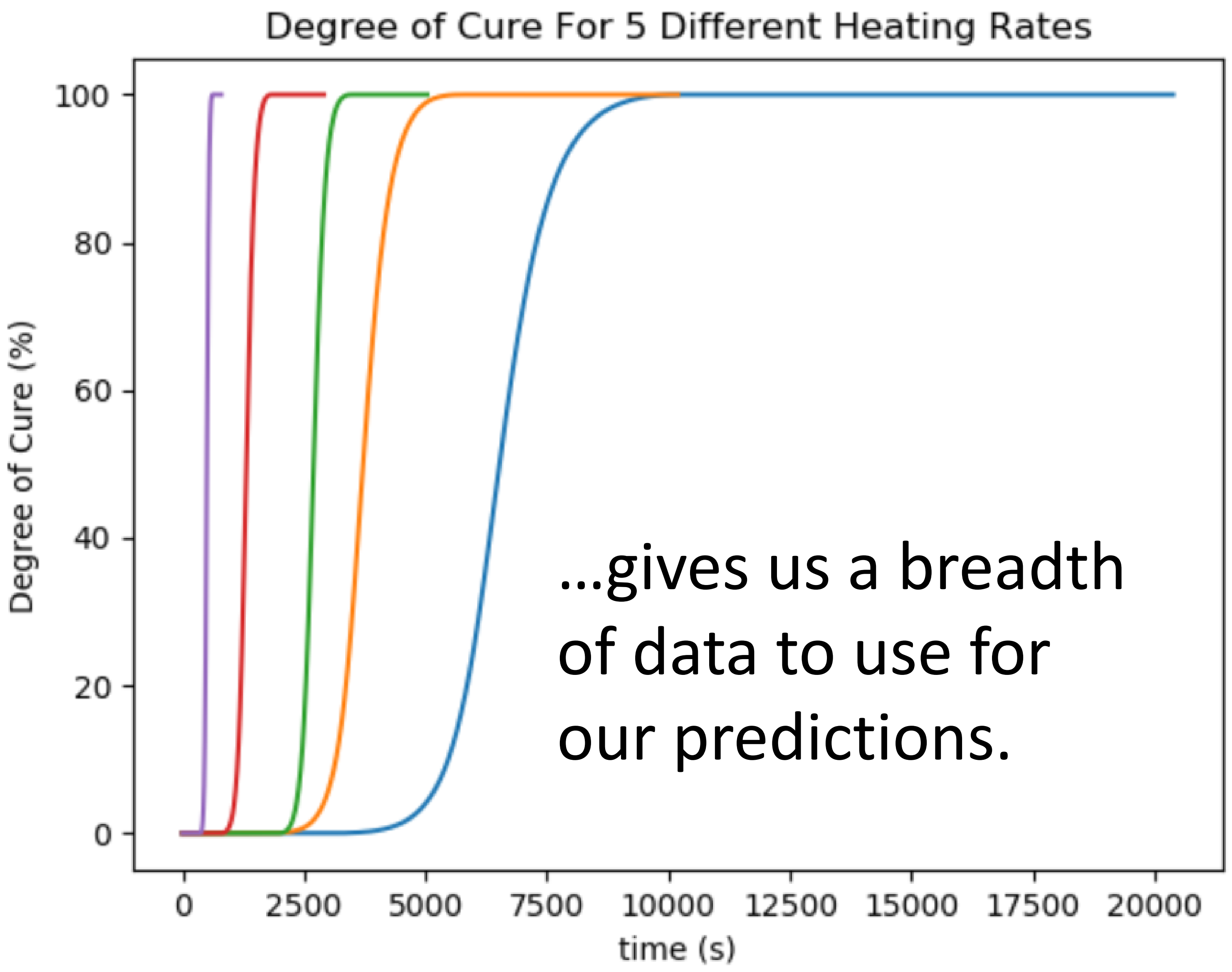

An Example Dataset, Heated at 1 ° C/min
Heat Energy Flux (mW / mg)
0.200
0.175
0.150
0.125
0.100
0.075
0.050
0.025
0.000
0
2500
5000
7500
10000
12500
15000
17500
20000
Time (s)
At the time marked by the purple arrow, 80% of the total heat energy has been given off.
80%



Degree of Cure, Sample Heated at 1 °C/min
Degree of Cure (%)
0
20
40
60
80
100
0
2500
5000
7500
10000
12500
15000
17500
20000
time (s)
We define our degree of cure as the portion of heat given off.



Repeating this study with various heating rates…



…gives us a breadth of data to use for our predictions.

The Math:

At the end of the day, we want the time it takes to reach a degree of cure.

The Math:

$$t_{\alpha} = [\exp(-E_{\alpha}/RT_{iso})]^{-1} \sum_{0}^{\alpha} \int_{t_{\alpha-\Delta\alpha}}^{t_{\alpha}} \exp(-E_{\alpha}/RT(t))dt$$

(Please forgive the calculus)

The Math:

$$t_\alpha = \sum_0^\alpha [\exp(-E_\alpha/RT_{iso})]^{-1} \int_{t_{\alpha-\Delta\alpha}}^{t_\alpha} \exp(-E_\alpha/RT(t))dt$$

Time to reach α

Gas constant

Isothermal temperature
For prediction

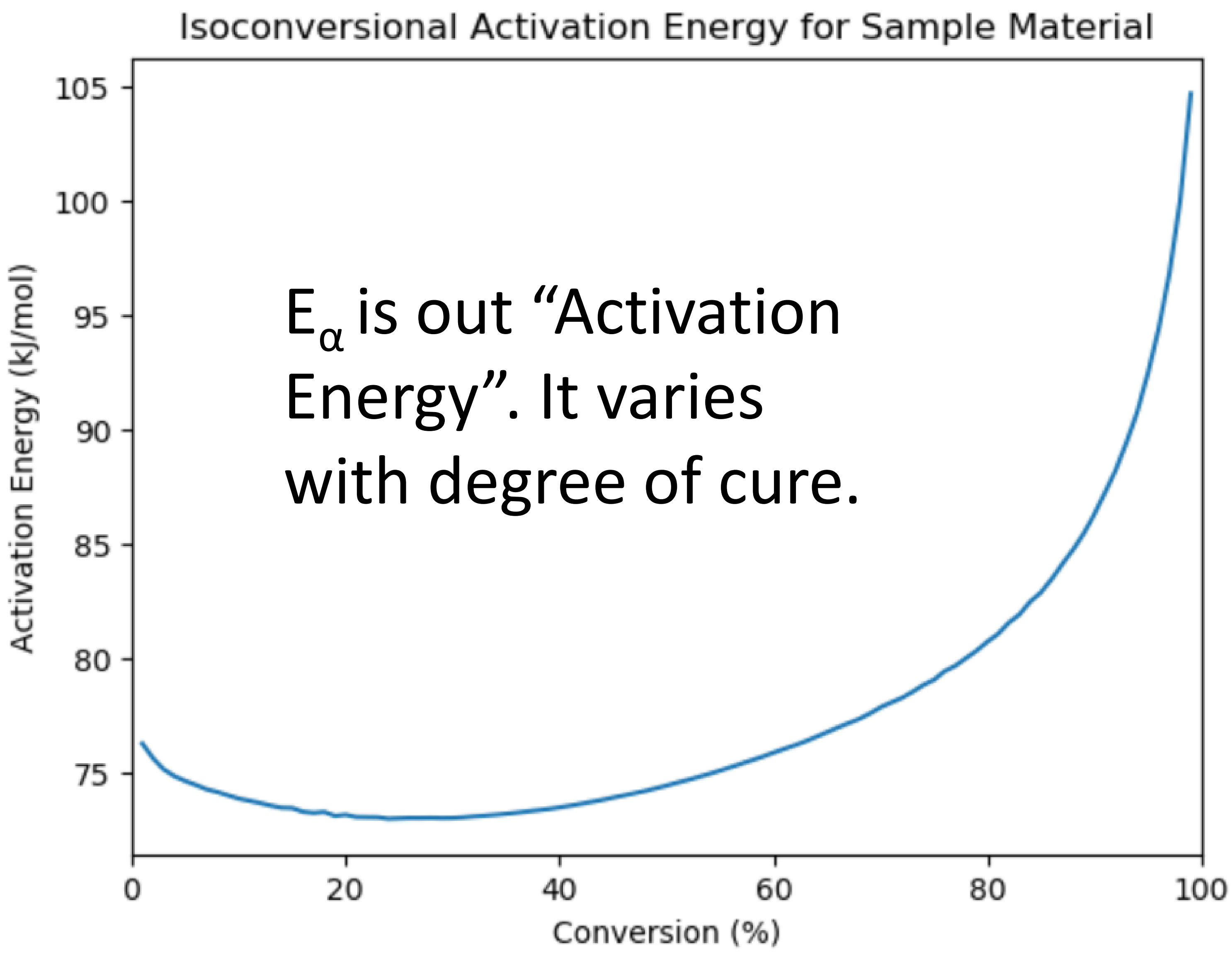
Temperature and
time from
experimental data

Something else altogether… we need to calculate this.

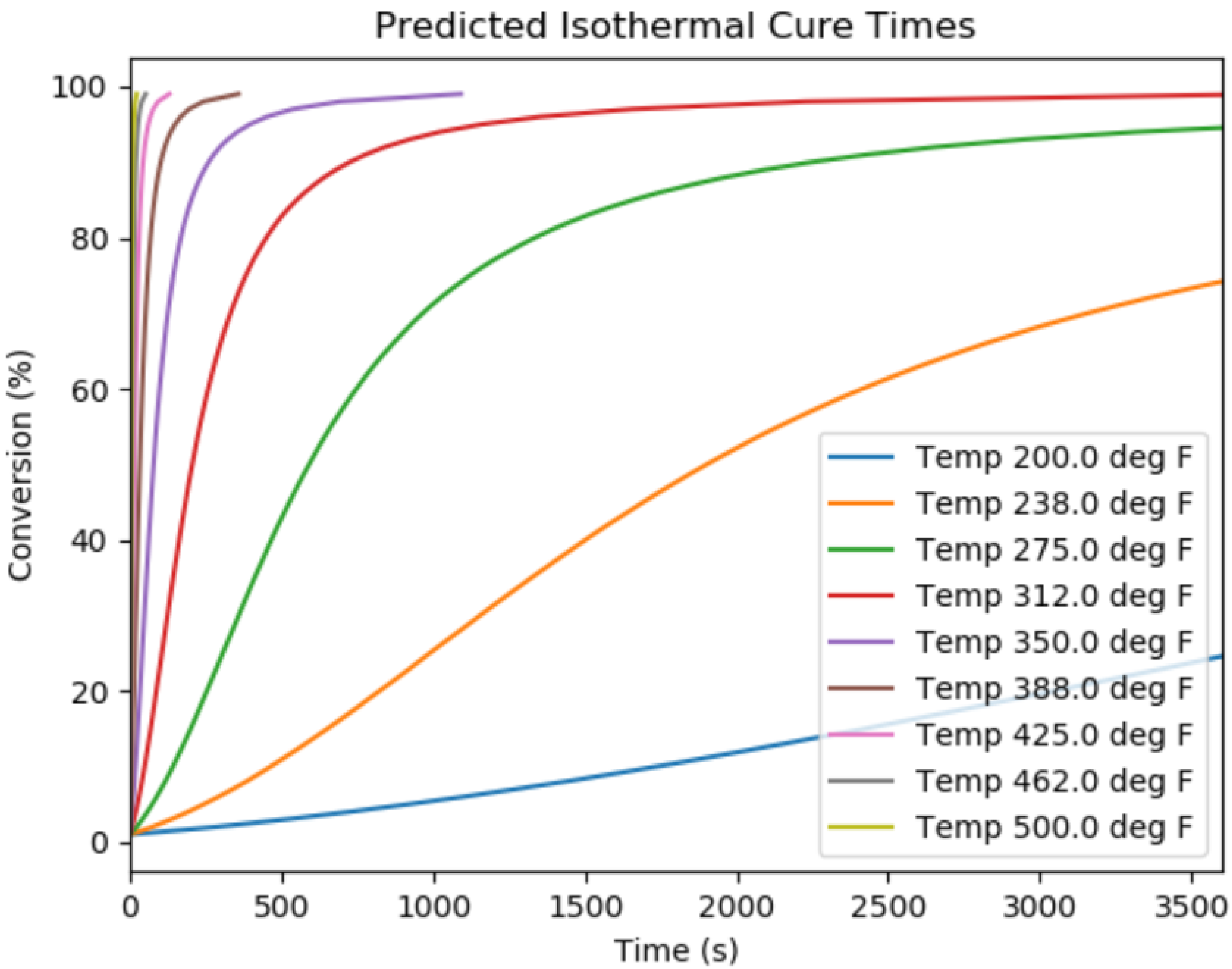
The Math:

$$\Phi(E_\alpha) = \sum_i \sum_{j \neq i} \frac{\int_{t_{\alpha-\Delta\alpha}}^{t_\alpha} \exp(-E_\alpha / RT_i(t_\alpha))dt}{\int_{t_{\alpha-\Delta\alpha}}^{t_\alpha} \exp(-E_\alpha / RT_j(t_\alpha))dt}$$

We'll calculate E_α by minimizing this cost function.
(Find the value of E_α for which ϕ has the lowest value.)



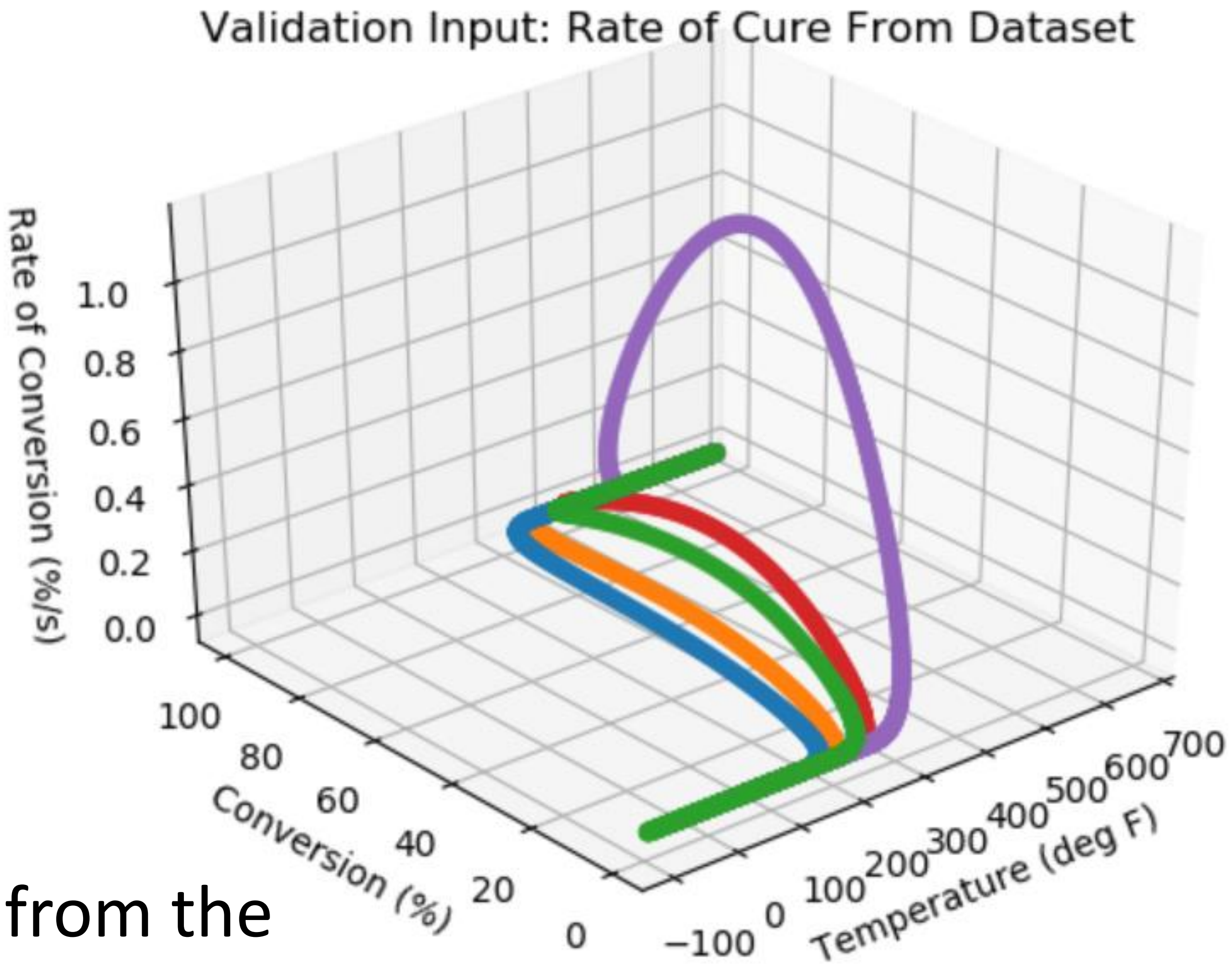
E_α is out “Activation Energy”. It varies with degree of cure.



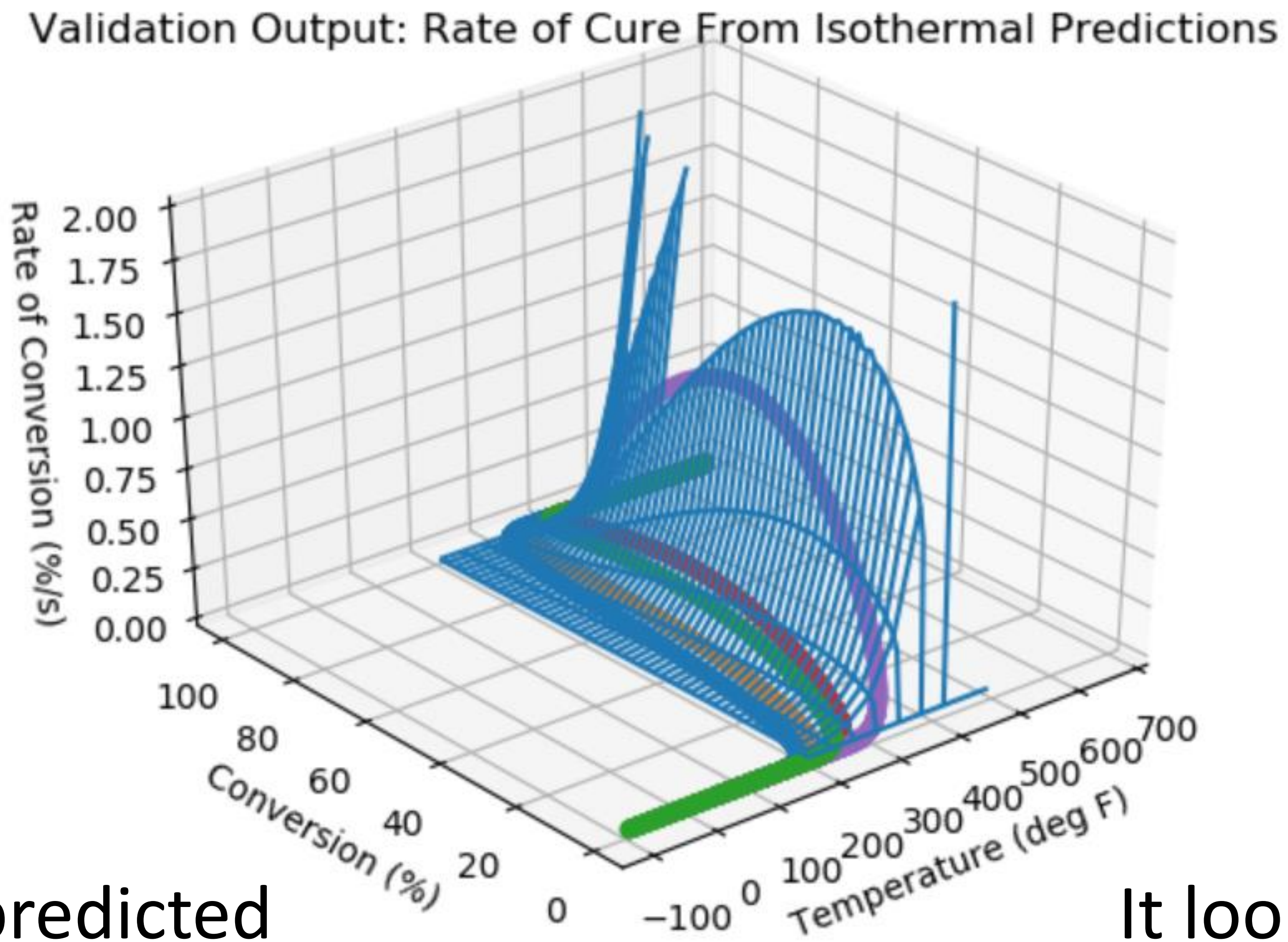
Now we can predict cure time for any isothermal temperature!

Validation:

…but is it right?



This is data from the experimental runs.



Now with predicted results on top.

It looks good!