Simple Balance Integral Model for Demise Tools

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Demise Material Modelling

- Standard ‘Equivalent Metal’ Model
  - Used in all tools for most materials
  - Heat up, melt with latent heat
  - Not everything demises like a metal
- Conduction Modelling
  - Bulk heating models (component based tools)
    - Can use 1D models (significant impact on runtime)
  - Full conduction models (panel based tools)
- Balance Integral Modelling
  - Considers heat on complete thickness of part
  - Uses thermal conductivity to impose a temperature profile
  - Heat Balance Integral (HBI) has been in SAMj for nearly 10 years
    - Some robustness issues

Simplified Balance Integral Model

- Objective
  - Provide a simple, robust model which accounts for temperature gradients
  - Provide a platform to allow alternative physics for demise
  - Applicable to component based, bulk heating models
  - Applicable to metals, glasses and composites

- Methodology
  - Start with HBI approach
  - Simplify generally cubic temperature profile to quadratic
  - Apply suitable surface conditions to capture surface temperatures and demise effects
  - Capture surface recession
    - Melt
    - Glass viscous material removal
    - Char removal

Simple Balance Integral Model

- Equation for bulk heating
  - Standard methodology
  - Total heat content

$$\Delta T_{bulk} = \frac{q_{in} A}{m c_p} \Delta t$$

- Assume temperature distribution (L thickness)
  - Simple quadratic approach
  - Provides approximation for heating or cooling
  - Relation between front, back and bulk temperatures

$$T(x) = nx^2 - 2nLx + T_0 \qquad n = \frac{T_0 - T_b}{L^2}$$

$$T_b = \frac{3T_{bulk} - T_0}{2}$$

- Equation for surface temperature
  - Energy balance between heat in and heat conducted to interior
  - Gives

$$\frac{dT}{dt} = q - \alpha \frac{d^2 T}{dx^2}$$

$$\Delta T_0 = \left(\frac{2q_{in}}{\rho c_p L} - \frac{2kn}{\rho c_p} \right) \Delta t$$

- Calculate bulk temperature, surface temperature
  - Infer back face temperature

Demise Considerations

- Heating is the same for all materials
- Demise behaviour is different
  - Different materials assessed differently
- Metals
  - Melt at front face only
  - Assess material above melt temperature
  - Integrate temperature profile gives average temperature above melt

$$\boldsymbol{L_m = L\left(1 - \sqrt{1 - \frac{T_0 - T_m}{T_0 - T_b}}\right)}$$

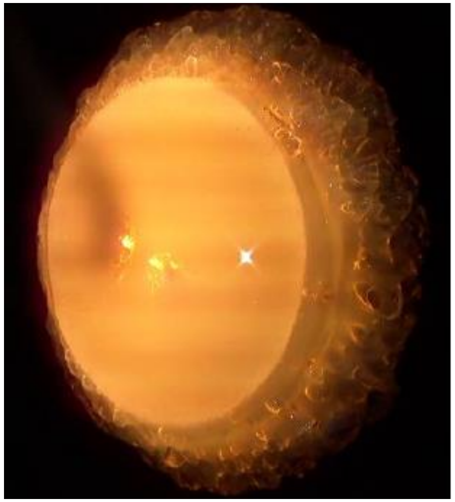
$$\Delta T = \left(\frac{nL_m^2}{3} - nLL_m + (T_0 - T_m)\right)\frac{L_m}{L}$$

  - Slightly underestimates melt against 1D predictions in very early stages of melt
    - Available energy for demise is then

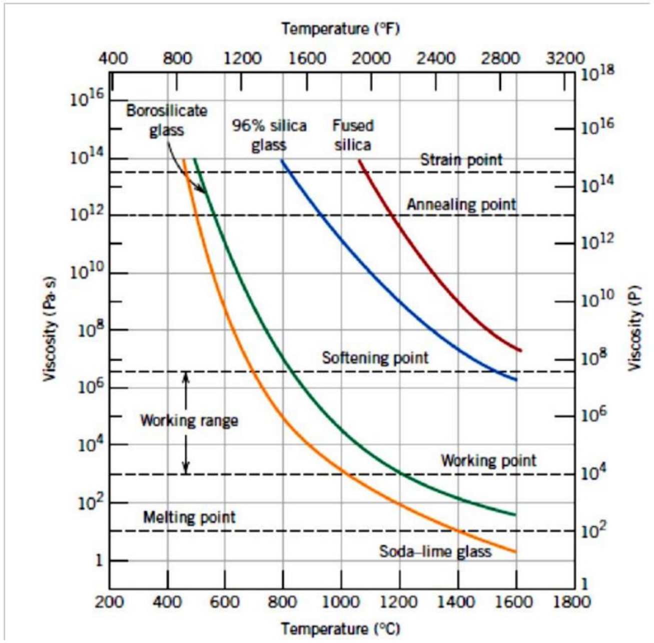
$$\Delta E = max\left(\Delta T, \frac{\Delta T_{bulk}}{3}\right) mc_p$$

  - Correct mass removed from front face; gives surface recession
  - Latent heat used is removed from bulk heat, bulk temperature updated

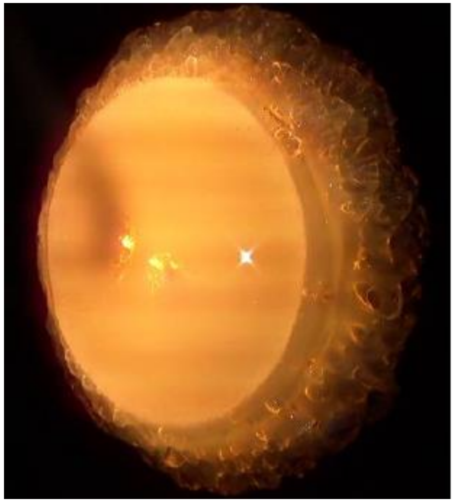
Glass Material Demise Modelling



- Viscosity-shear Model
  - Based on understanding of hot outer layer
  - Material shear
  - Zerodur test picture suggests this type of mechanism
- Requirements
  - Representation of viscosity-temperature curve
    - Implement VFT formula $\log(\eta) = A + \dfrac{B}{T - T_0}$
  - Require temperature profile through material
    - Implement simplified balance integral model
    - Bulk heat $$\Delta T_{bulk} = \frac{q_{in}A}{mc_p}\Delta t$$
    - Surface heat $$\frac{dT}{dt} = q - \alpha\frac{d^2T}{dx^2}$$
    - Assumed profile $$T(x) = nx^2 - 2nLx + T_0$$ $$n = \frac{T_0 - T_b}{L^2}$$



Glass Material Demise Modelling



- Material Demise
  - Sufficiently low viscosity

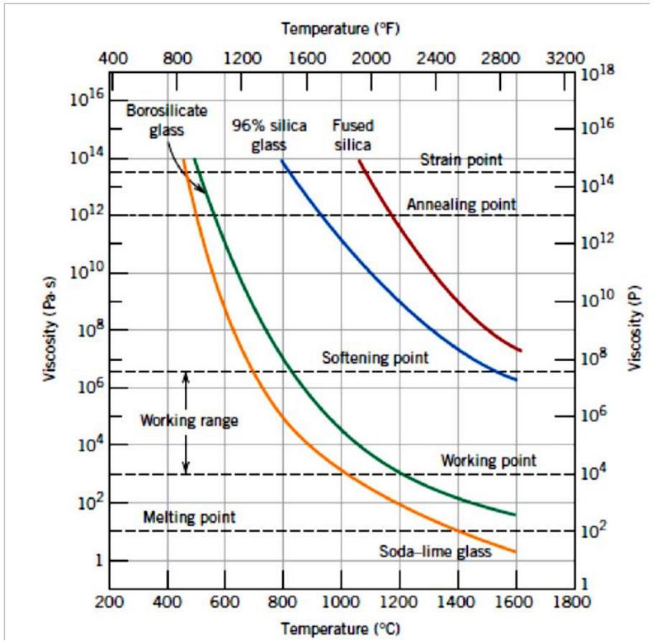
$$\log(\eta) = A + \frac{B}{T - T_0}$$

$$T_c = T_0 + \frac{B}{(3 - A)}$$

  - Find depth with profile
  - Require timescale for mass loss
    - Faster mass loss as viscosity reduces
    - Base on surface viscosity

$$\eta_s = 10^{A + \frac{B}{T_S - T_0}}$$

    - Timescale $t_m = 6\eta_s$
  - Adjust temperature profile for mass lost
    - Update bulk temperature for hot material loss
- Catalycity
  - Note also very low catalycity of glass surfaces
  - MUST be included in model



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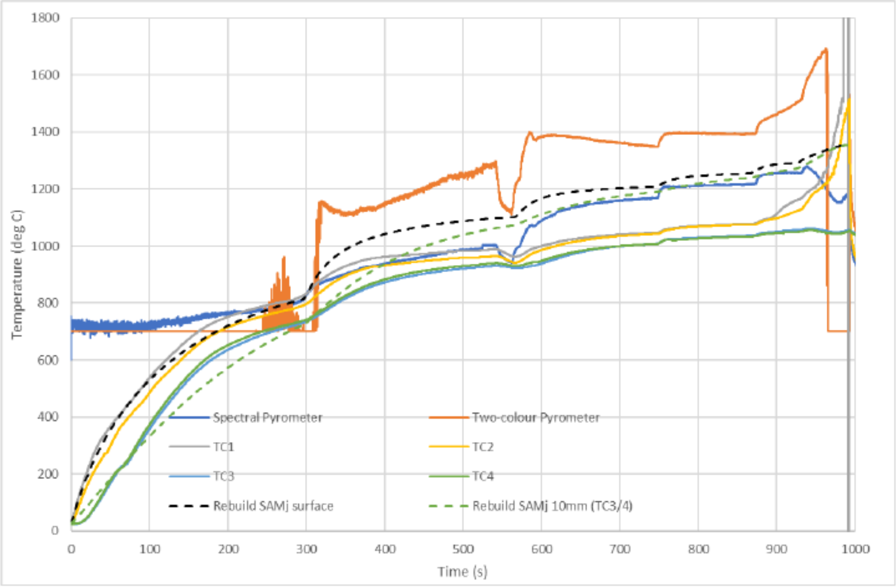
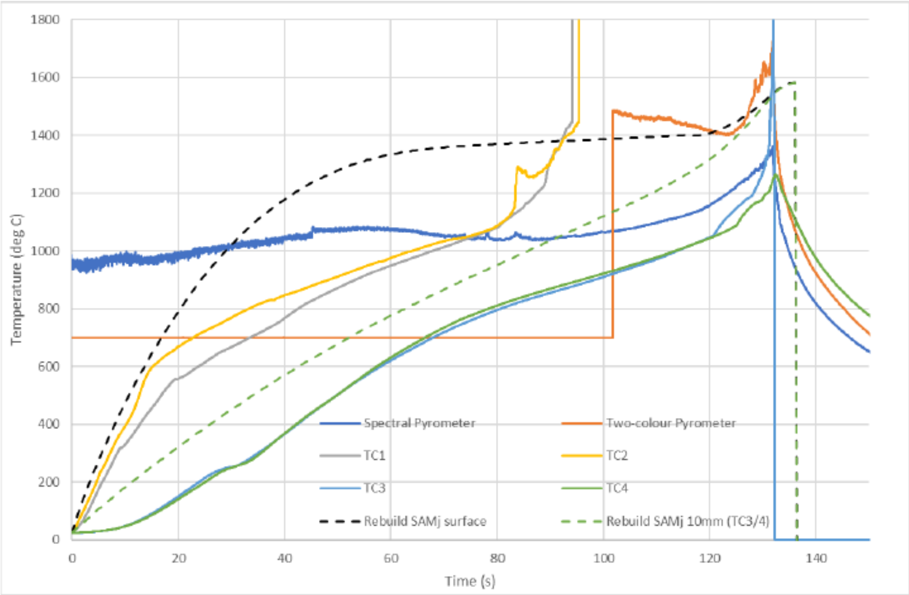
Glass Modelling

- Simplified Balance Integral Model
  - 0D approach, so computationally efficient
  - Surface energy balance
  - Captures representative temperature gradient
  - Surface and bulk temperatures reasonably captured
  - Material removal by surface viscosity
  - Mass loss well captured across Zerodur tests
- Materials Available
  - Zerodur (test data)
  - Fused Silica (test data)
  - Borosilicates (viscosity data)
  - GFRP (test data)





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CFRP Modelling

- Driven by matrix behaviour
  - Low char yield allows fibres to be removed
- Material removal driven by surface recession
  - Removal of layers
- Allow for pyrolysis and blowing
  - Char progression
  - Endothermic reaction removes heat from material
  - Blowing reduces heating at surface
- Assess recession as function of temperature
  - Threshold (recession starts)
  - Gradient (recession approximately linear with temperature)
    - Simplification – can be improved with more data

Methodology

- Material Properties
  - Char front temperature based on TGA (reasonably consistent)
    - Char depth calculated from temperature profile

$$L_c = L\left(1 - \sqrt{1 - \frac{T_0 - T_c}{T_0 - T_b}}\right)$$

  - Heat of ablation consistent across tested materials
    - Material charred in step based on movement of char front

$$m_g = (\rho_v - \rho_c)A\Delta L_c$$

    - Mass from different in virgin and charred densities (no reaction zone)
    - Endothermic pyrolysis requires reduction in bulk temperature

$$\Delta T_{bulk} = -\frac{m_g \Delta H_{abl}}{m c_p}$$

- Focus on three materials
  - C01 – LY556 matrix (baseline)
  - C02 – L20 matrix (demisable)
  - C10 – EX1515 matrix (cyanate ester – most robust)
  - (Kevlar also tested/modelled)

	C1	C2	C10
Fibre	T300	T300	M55J
Matrix	LY556	L20	EX1515
Density (kg/m^3)	1580	1580	1580
Char Density (kg/m^3)	1265	1250	1240
Char Front Temperature (K)	700	700	700
Heat of Ablation (J/kg)	1300000	1300000	1300000
Emissivity	0.9	0.9	0.9

Methodology

	C1	C2	C10
Fibre	T300	T300	M55J
Matrix	LY556	L20	EX1515
Recession Threshold (K)	1187	915	1273
Recession Gradient (m/sK)	2.33e-8	6.6e-8	1.17e-8

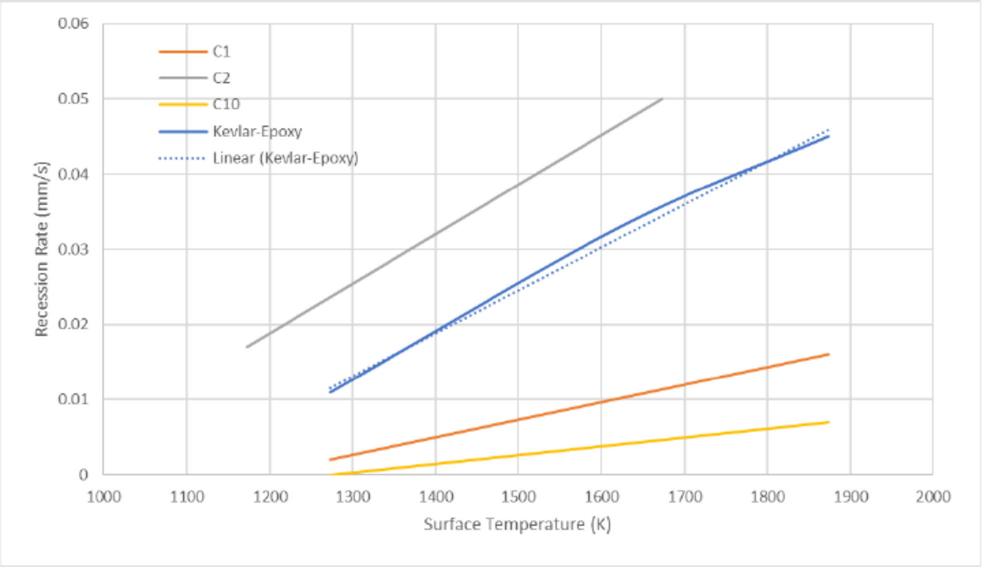
- Recession Rates
  - Function of temperature
  - Tentatively linear
    - Test data is only current method for inference of recession rate
  - Material removed from simulation

$$m_c = \rho_c A \Delta L$$

  - Char front depth reduced
  - Surface temp to recession depth
    - Hot surface removed
    - No oxidation heat

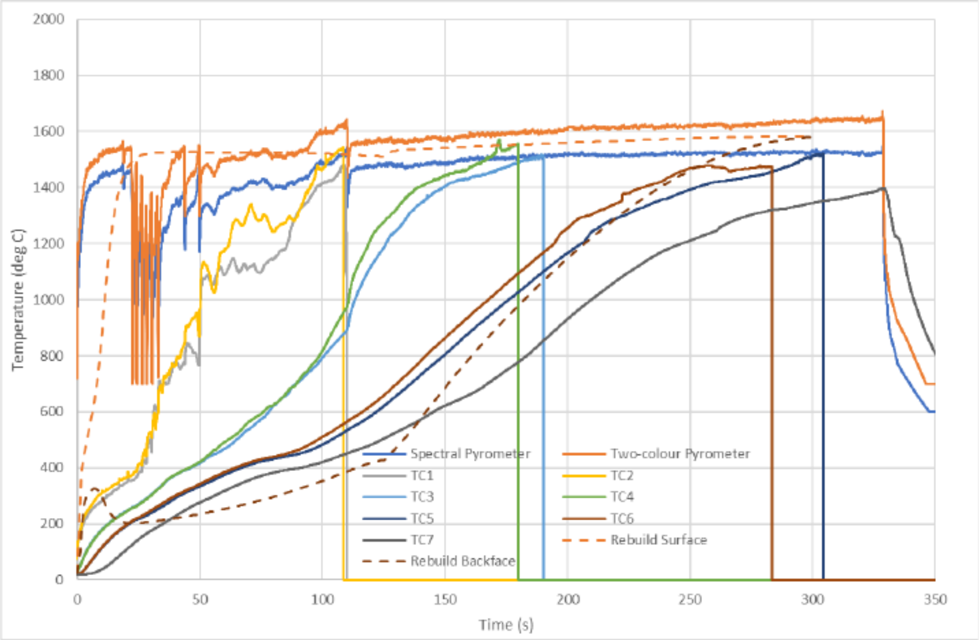
$$T_{0,new} = n\Delta L^2 - 2nL\Delta L + T_0$$

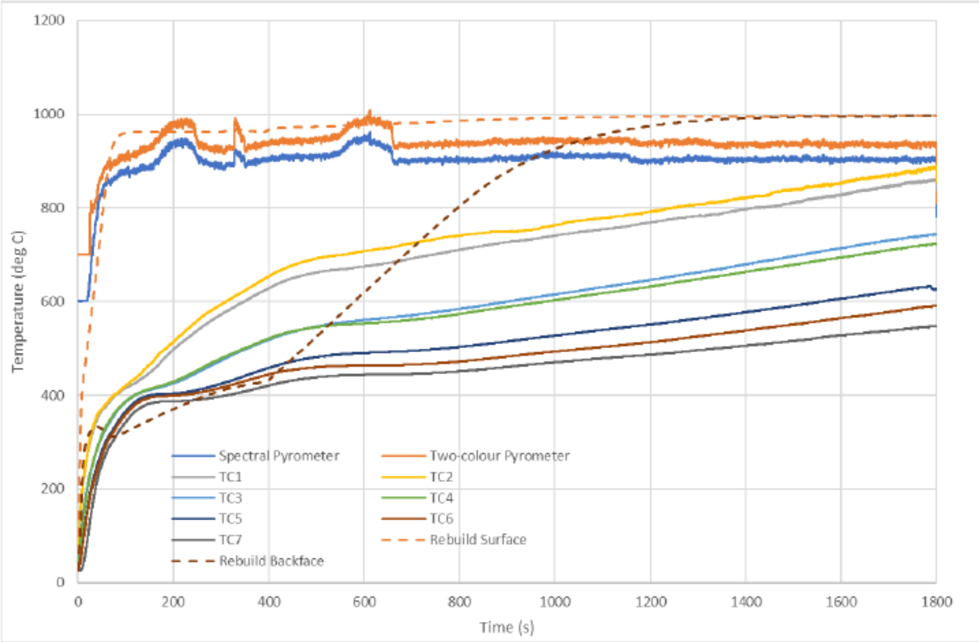
  - Bulk temperature updated



Test Rebuild

- C01
  - High flux, low flux
  - Reasonable temperatures
    - Low flux increase after 400s
    - High flux is good
  - Reasonable recession (fit)





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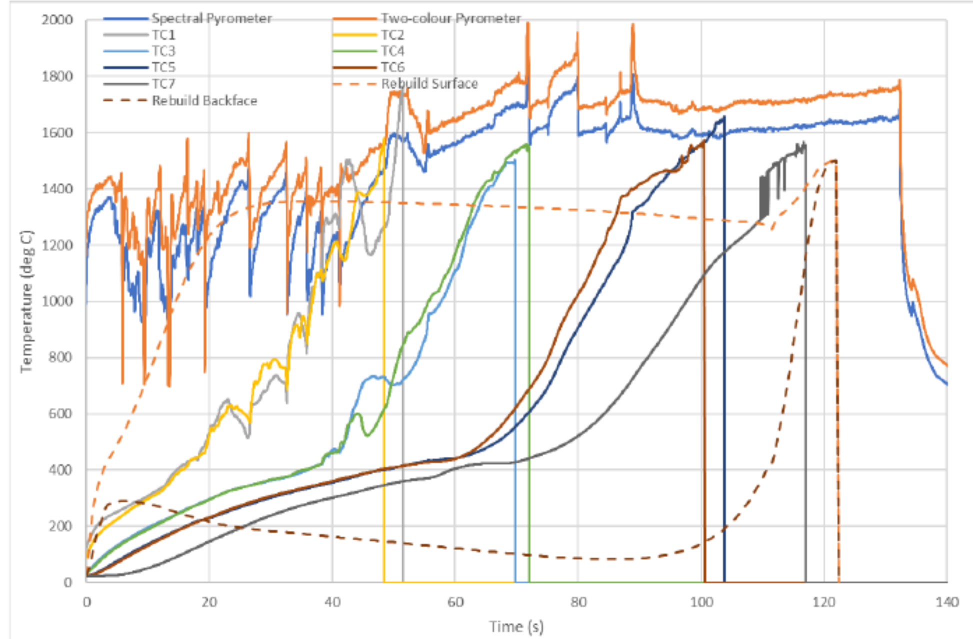
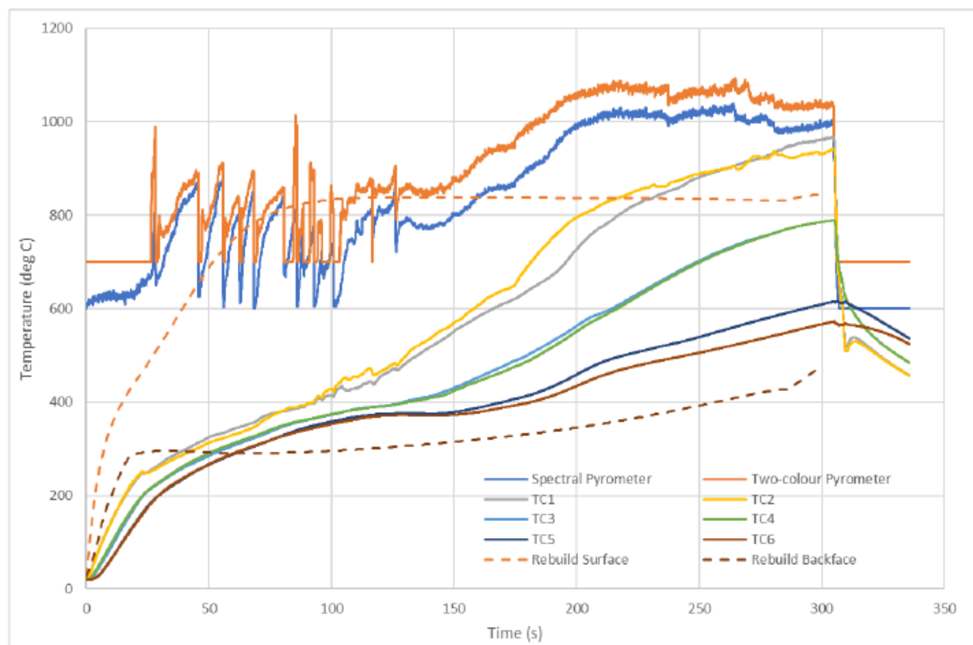
Test Rebuild

- C02
  - High flux, low flux
  - Less good temperatures
    - Low flux good
    - High flux is underpredicted
  - Reasonable recession (fit)
- C10
  - Good temperature fit
  - Little recession





Conclusions

- Simplified Balance Integral Model
  - Applicable to codes at DRAMA level
  - Bulk heating, component based
- Applicable to Various Materials
  - Metals
  - Glass (soon to be available in DRAMA)
  - CFRP
- Required Data
  - Glass models require viscosity-temperature curve to be measured
    - Can potentially be implemented without specific demise test
    - Currently require verification test
  - CFRP models require dedicated test at (minimum) 2 conditions to infer recession
- No Noticeable Impact on runtime