Ultrasonic Tape Lamination (UTL) Consolidation and Out-of-Autoclave Curing of Thick Composite Structures

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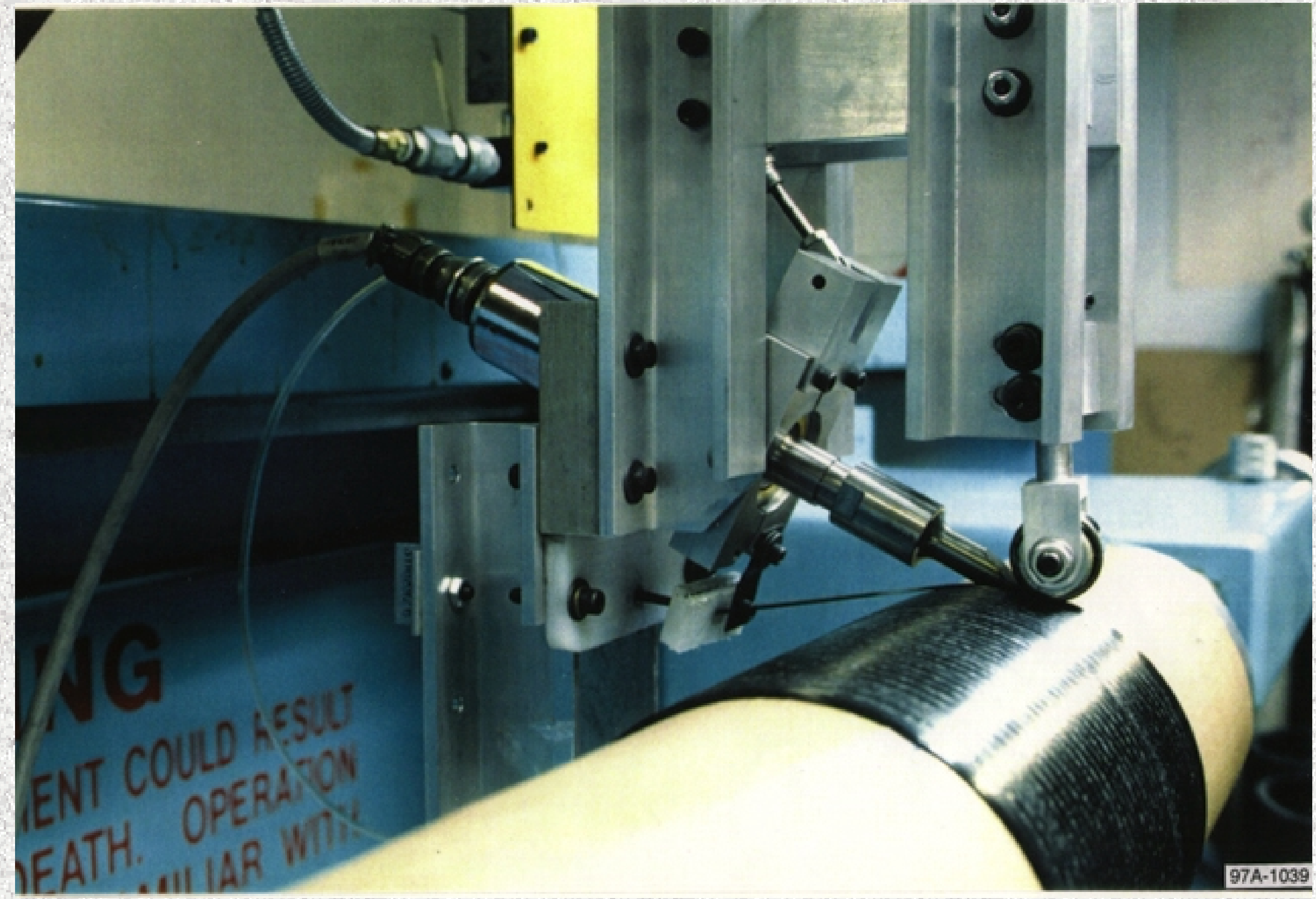
Ultrasonic Consolidation



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Process Model

- Ultrasonic heating

$$\frac{dT}{dt} = \frac{Q}{\rho c}, \qquad Q = f \cdot \pi E'' \varepsilon_0^2 + R_r \, \Delta H_r$$

- Dynamic modulus

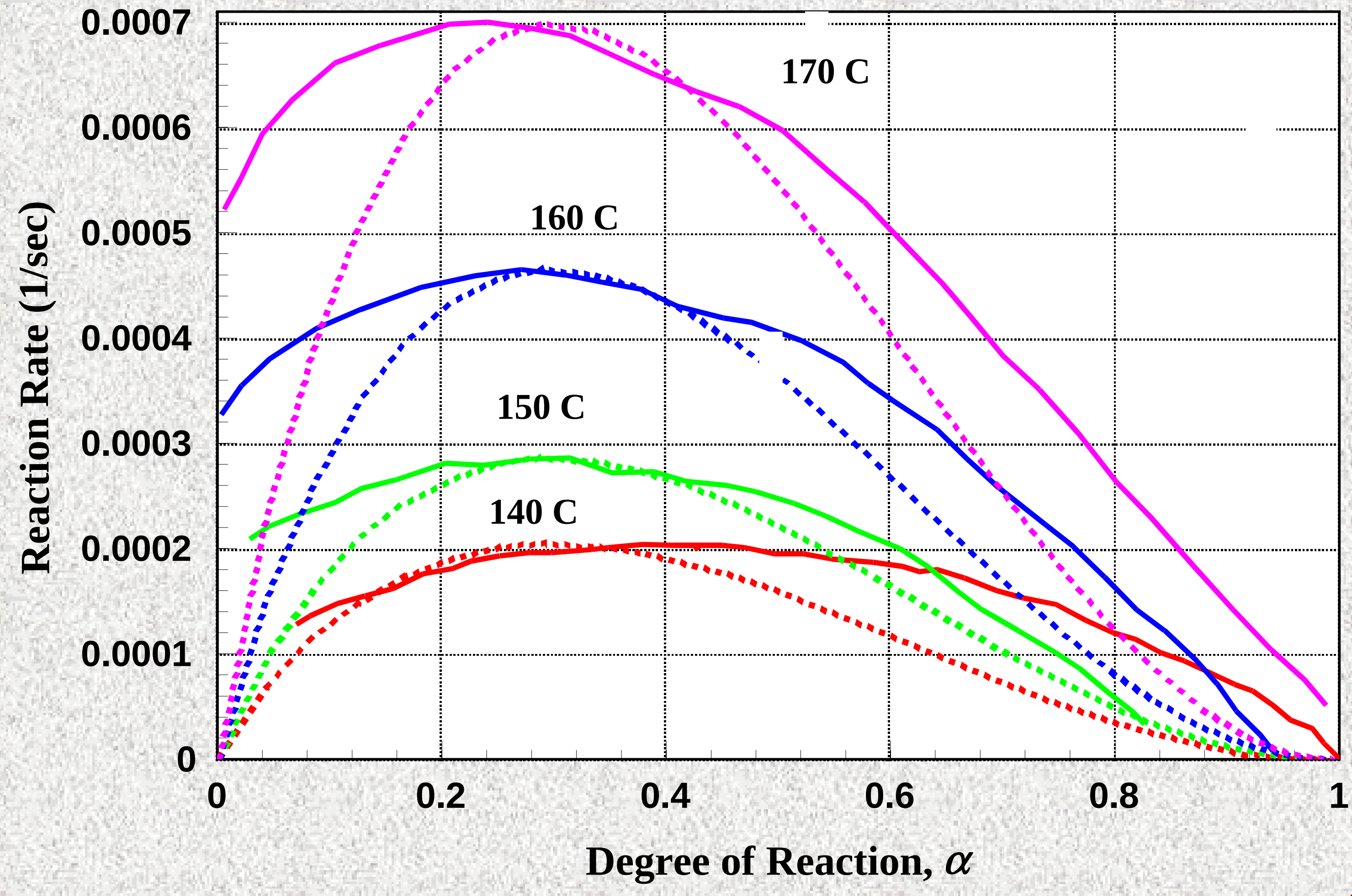
$$E' = k_0 + \sum_{j=1}^{N} \frac{k_j \left(\omega \tau_j\right)^2}{1 + \left(\omega \tau_j\right)^2}, \qquad E'' = \sum_{j=1}^{N} \frac{k_j \left(\omega \tau_j\right)}{1 + \left(\omega \tau_j\right)^2}$$

$$\tau_j = \tau_{0j} \exp\left(\frac{E^{\tau}}{R_g T}\right)$$

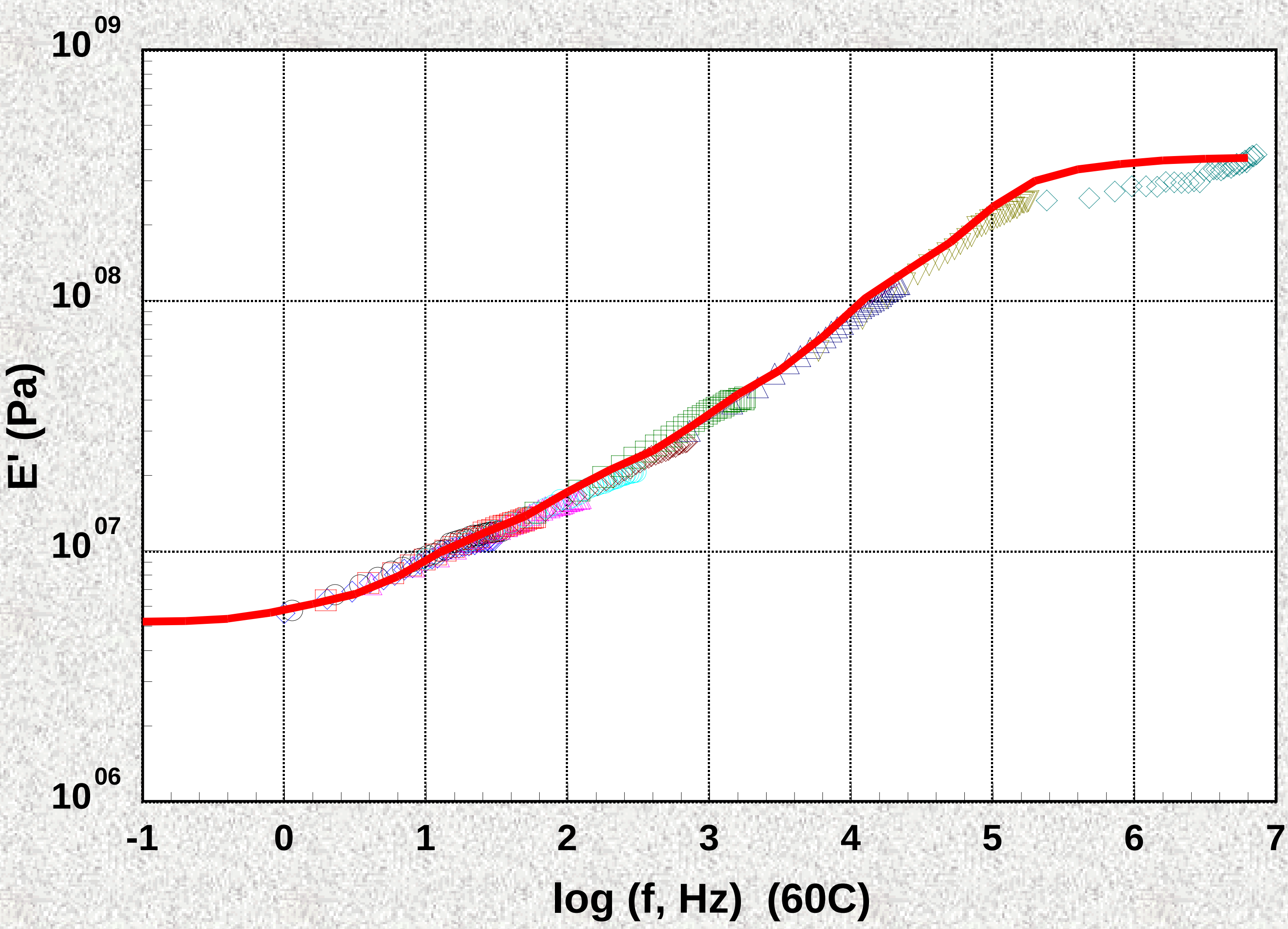
- Curing reaction

$$\frac{d\alpha}{dt} = k_0 \exp\left(\frac{-E^{r}}{R_g T}\right) \cdot \alpha^{m1} \left(1 - \alpha\right)^{m2}$$

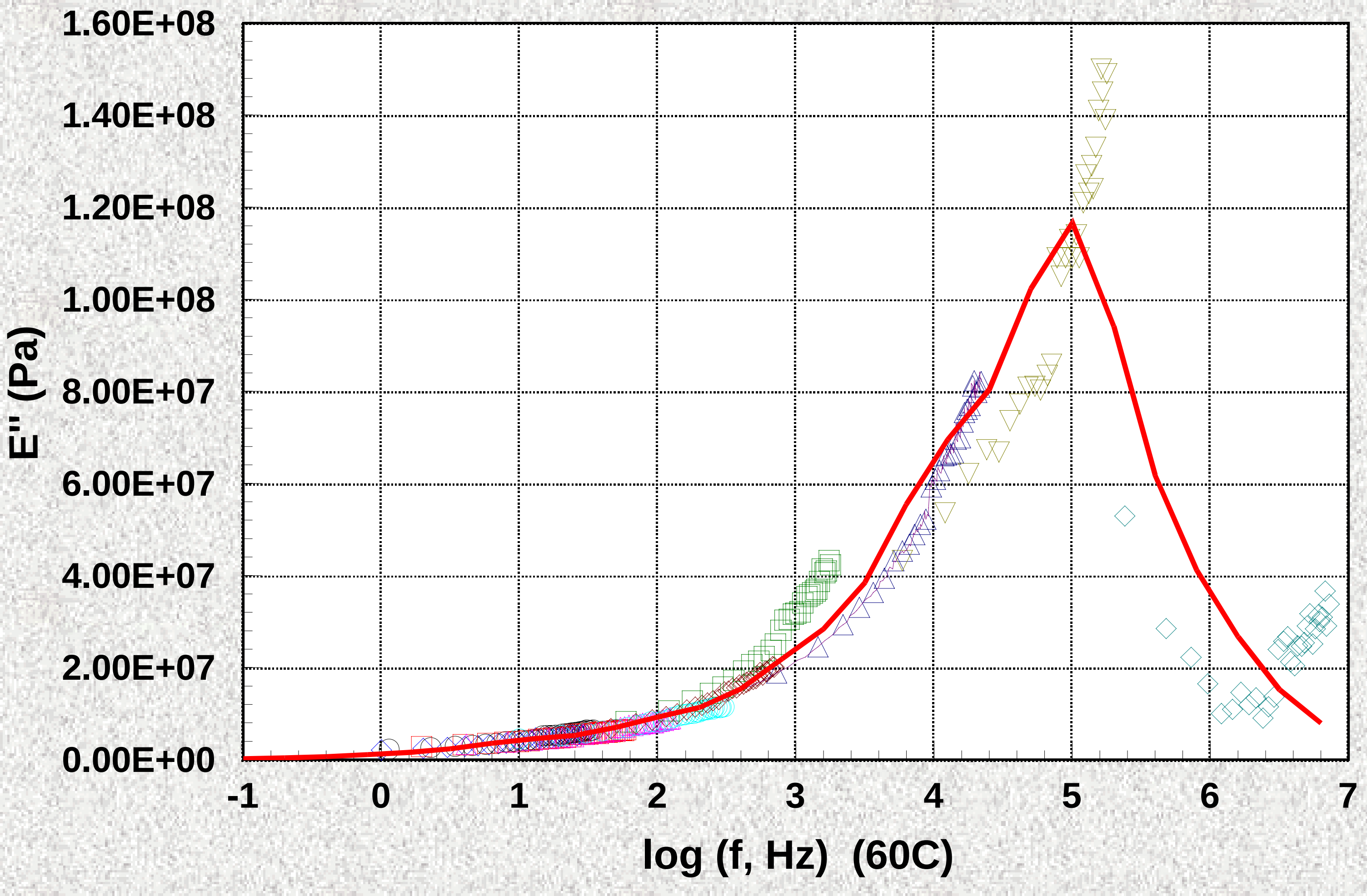
DSC Cure Scans and Model Fit



E' Master Curve and Model Fit



E'' Master Curve and Model Fit



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Spreadsheet Model

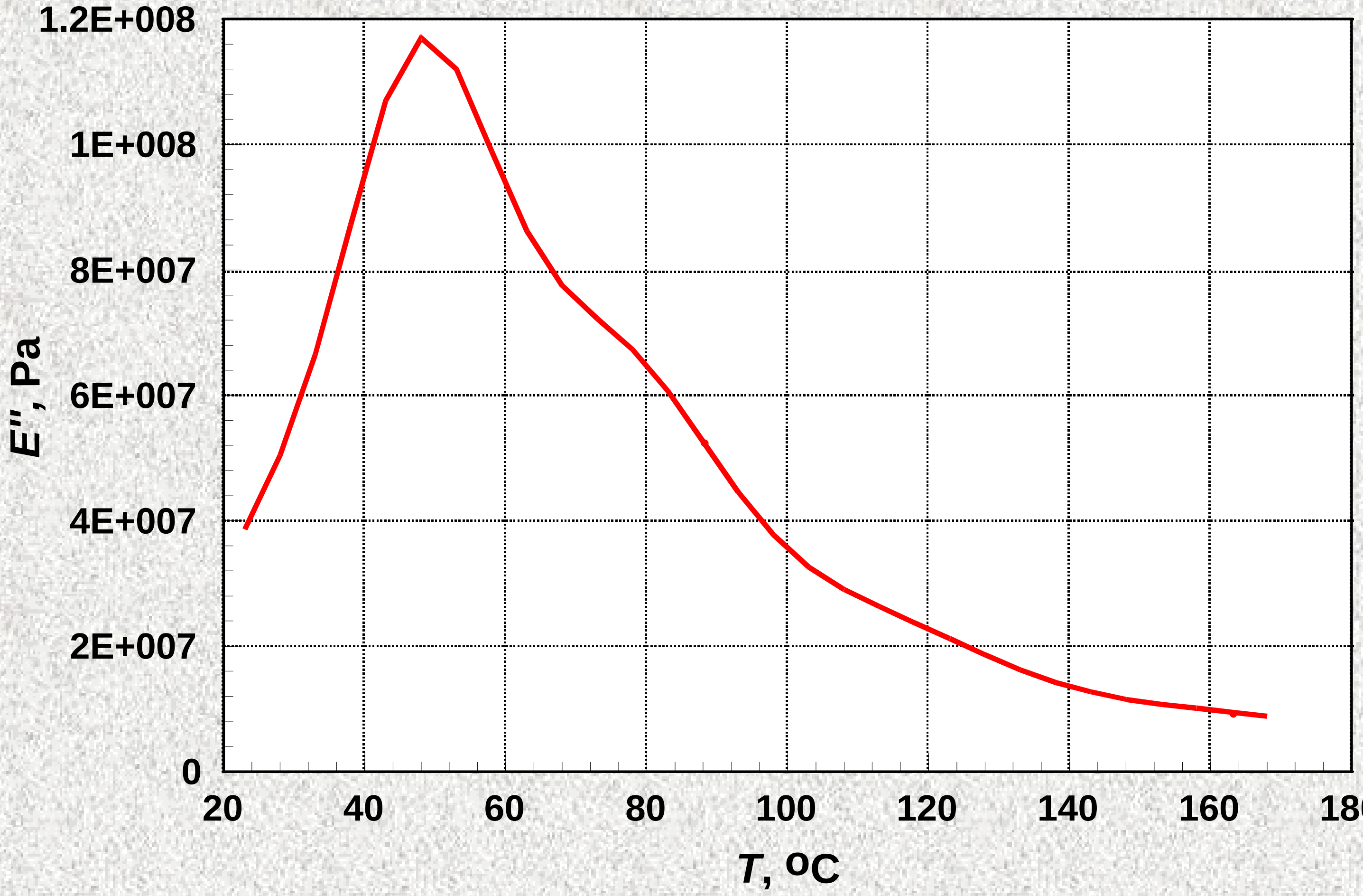
Microsoft Excel - kinetic model (zukas).xls

O13 = =k_4*Dp*t_4*EXP(Ev*120.3/(273+$B13))/(1+(Dp*t_4*EXP(Ev*120.3/(273+$B13)))^2)

	A	B	C	D	E	F	G	H	I	J
1	**Ultrasonic cure, simple model, 8552 resin**									
2	Dissipation from Zukas data, SLS model									
3	no spatial variation, heating from viscous dissipation and reaction									
4	exotherm, less convective cooling									
5										
6		Z(1/s)=	1.27E+05	E(J/mol)=	6.34E+04	n=	0.9			
7		T_a(C) =	100	H_r(J/g)=	483			G0(Pa)=	1.18E+08	
8		depth(mm)=	0.360	ampl(mm)=	0.005	f(Hz)=	4.00E+04	tau0(s)=	9.09E-16	
9		c(J/kg-K)=	2000	rho(kg/m^3)=	2000	w(rad/s)=	6.37E+03	Ev(kJ/mol)=	69.1	
10		h(J/m^2-K)=		E"(N/m^2)=	7.00E+04	strain=	0.014			
11										
12	t (s)	T (C)	α	alpha_dot	tau (s)	E" (Pa)	q_d (W/m^3)	q_r (W/m^3)	h (W/m^2)	T_dot (C)
13	0.000	23	0.010000	1.30E-08	1.42E-03	3.86E+07	9.37E+08	1.26E+01	0.00E+00	2.34E+02
14	0.021	28	0.010000	2.00E-08	8.92E-04	5.04E+07	1.22E+09	1.93E+01	0.00E+00	3.05E+02
15	0.038	33	0.010000	3.02E-08	5.68E-04	6.65E+07	1.61E+09	2.92E+01	0.00E+00	4.03E+02
16	0.050	38	0.010000	4.51E-08	3.67E-04	8.72E+07	2.11E+09	4.36E+01	0.00E+00	5.28E+02
17	0.060	43	0.010000	6.65E-08	2.41E-04	1.07E+08	2.60E+09	6.42E+01	0.00E+00	6.49E+02

Sheet1 Sheet2 Sheet3

Temperature Dependence of E’’ at 40MHz



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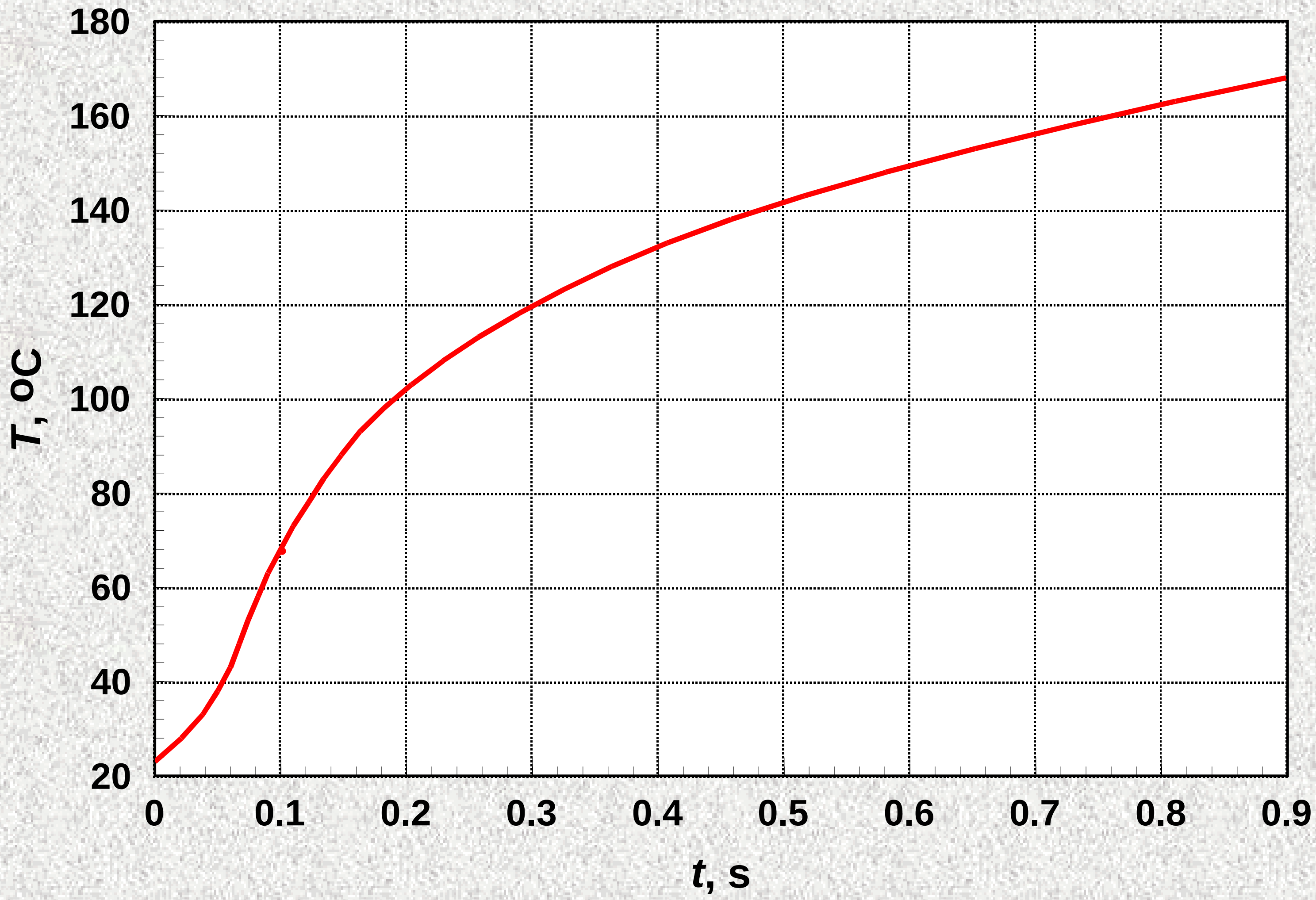
Carbon/8552 composite, ε_o = 1.4%, f = 40 kHz.



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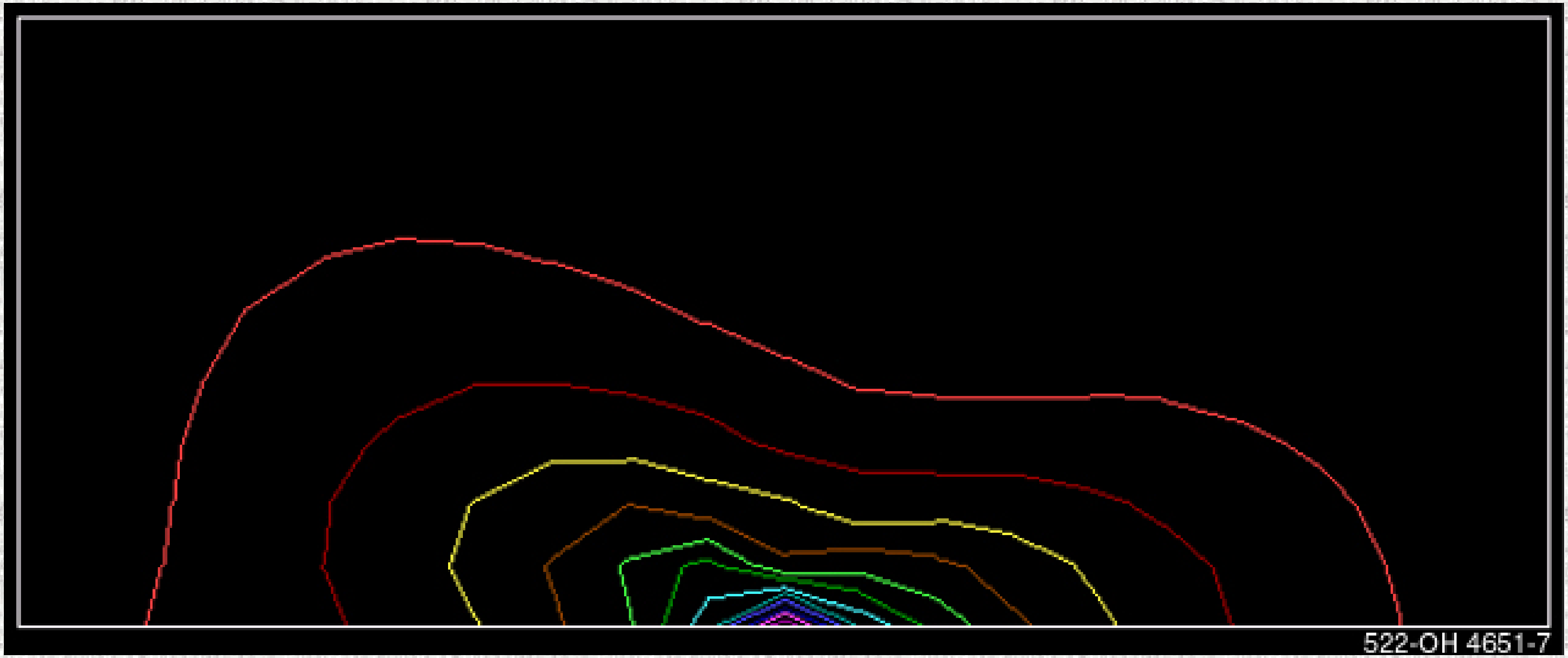
Finite Element Analysis (FEA)

$$\rho\left[\frac{\partial u}{\partial t}+u\nabla u\right. = -\nabla p+\nabla\left(\eta\nabla u\right)$$

$$\rho c\left[\frac{\partial T}{\partial t}+u\nabla T\right]=Q+\nabla\left(k\nabla T\right)$$

$$\left[\frac{\partial C}{\partial t}+u\nabla C\right]=R+\nabla\left(D\nabla C\right)$$

FEA - Displacement (u_x) Contours



FEA - Temperature Contours