LaserComp

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Taking test
instruments
into the
21st century

- **Transient Heat Flow Probe for Quick Tests of Vacuum Panels Using Finite-Difference Method**
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Quick tests of Vacuum Panels using new Heat Flow Probe method

- VIP initially has room temperature T_0
- Heat Flow Probe is attached to a water-cooled (or – heated) metal heat sink at temperature $T_1 \sim 15^0$-20^0C lower (or higher) than VIP T_0
- After the Heat Flow Probe is placed on the VIP to be tested the panel's inner temperature T(x, t) starts to change, and signal of the Heat Flow Probe is recorded (x – coordinate, t –time)
- Thermal effusivity $\varepsilon = \lambda / a^{1/2}$ of the VIP is almost immediately determined -
  this can be the quickest VIP QC method

Thermal Conductivity Equation

$$\partial^2 T(x,t)/\partial x^2 = (1/a)\, \partial T(x,t)/\partial t$$

a - thermal diffusivity [m^2/s]

- Boundary conditions (B.C.):

$T(x=0, t)=T_1$ (heat sink's temperature) for all t

$T(x\rightarrow\infty, t)=T_0$ ("semi-infinite" sample)

- Initial conditions (I.C.) ($0<x<\infty$, $t=0$):
  $T(x, t=0)=T_0$ (sample has room temperature)

Analytical Solution of the Thermal Problem for Semi-Infinite Body:

- $[T(x,t)-T_1]/(T_0-T_1) = \mathrm{erf}\,[x/(4at)^{1/2}]$

  where **erf** is Gaussian error function

- Heat flux q/A [W/m²] at the surface (x=0):

  $$\mathbf{q/A(x=0,\,t)=\varepsilon\,(T_1 - T_0)/\,(\pi t)^{1/2}}$$

  where $\varepsilon=\lambda/a^{1/2}$ is thermal effusivity

  (Schneider, P.J.:"Conduction Heat Transfer," Addison-Wesley Publishing Company Inc., Reading, Massachusetts, 1955)

- **ε is proportional to the slope of the heat flux versus 1/sq.root(time) graph**

Analytical Formula Limits

- Analytical formula is not valid at initial moments of time t when the Heat Flow Probe's Fourier number
  $Fo' = a't/x'^2$ is not >>1
  (x'–probe's thickness, a'–it's thermal diffusivity)
- Analytical formula is not valid after the thermal disturbance reaches the back surface of the sample - when the sample's Fourier number
  $Fo = at/x^2$ is not <<1
  (x–sample's thickness, a–it's thermal diffusivity)

- I.e. the Analytical Formula is valid only during some time "window" between t_{min} and t_{max}:

  - For our 1 mm-thick Heat Flow Probe made of FR-4 resin ($a=1.037*10^{-7}$ m^2/s)
  t_{min} >~8 seconds

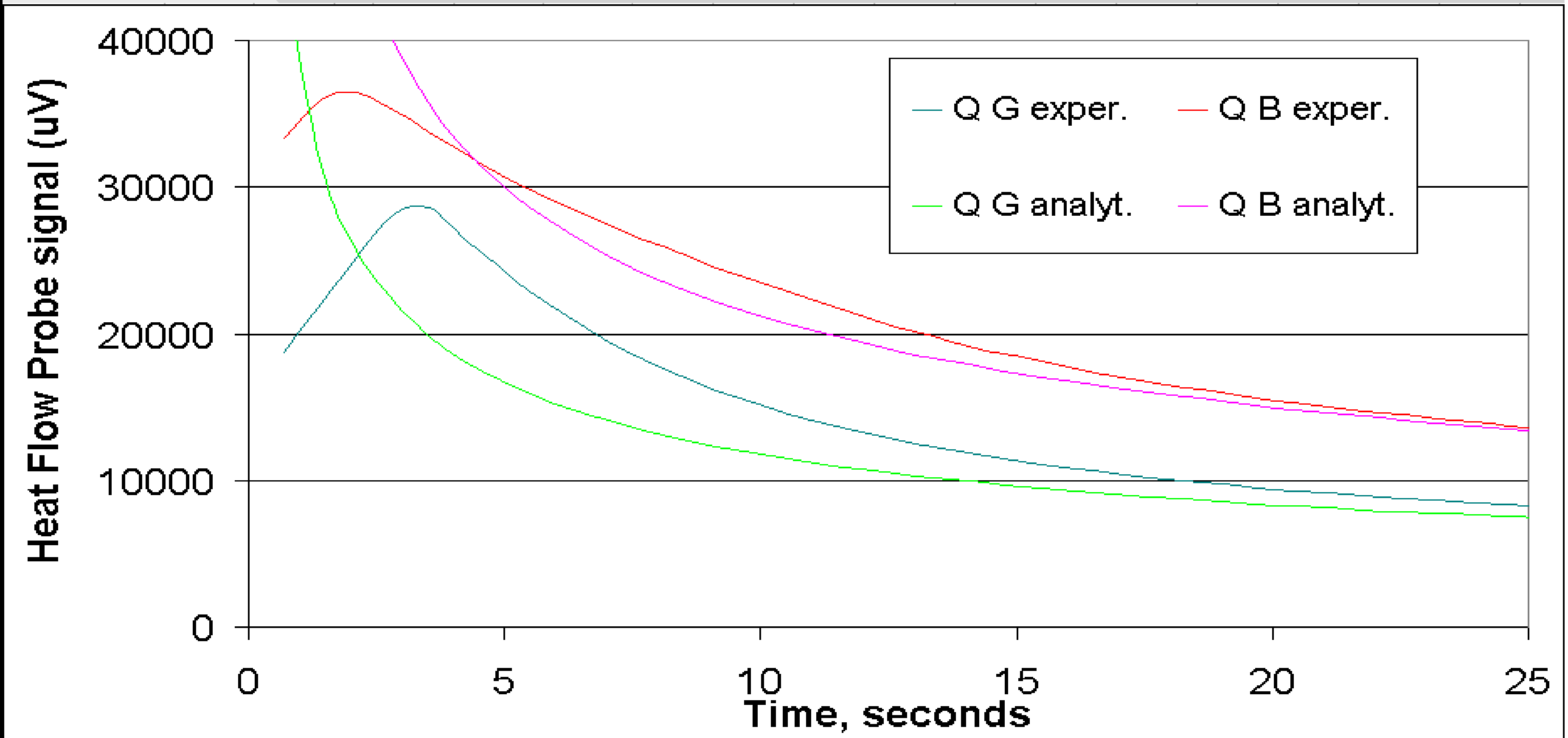
  - For 1"-thick "bad" VIP ($a\sim2.9*10^{-7}$ m^2/s)
  t_{max} < ~42 seconds

  - For 1"-thick "good" VIP ($a\sim4.3*10^{-8}$ m^2/s)
  t_{max} < ~282 seconds (~5 minutes)

- This "window of opportunity" is ideal for quick VIP QC using the Analytical Formula

Experimental and Calculated using Analytical formula Heat Flow Probe signals (μV) vs. time (seconds). (T_0=21C;T_1=6C)

- "Good" VIP (G): ε_G ~25 W sec$^{1/2}$/(m^{2}K); λ_G =0.0056 W/mK;
- "Bad" VIP (B): ε_B ~45 W sec$^{1/2}$/(m^{2}K); λ_B =0.0320 W/mK;



Experimental and Calculated using Analytical formula Heat Flow Probe signals (μV) vs. 1/sq.root(time). ($T_0=21^0C$; $T_1=6^0C$)

- "Good" VIP (G): ε_G ~25 W sec$^{1/2}$/(m^{2}K); λ_G =0.0056 W/mK;
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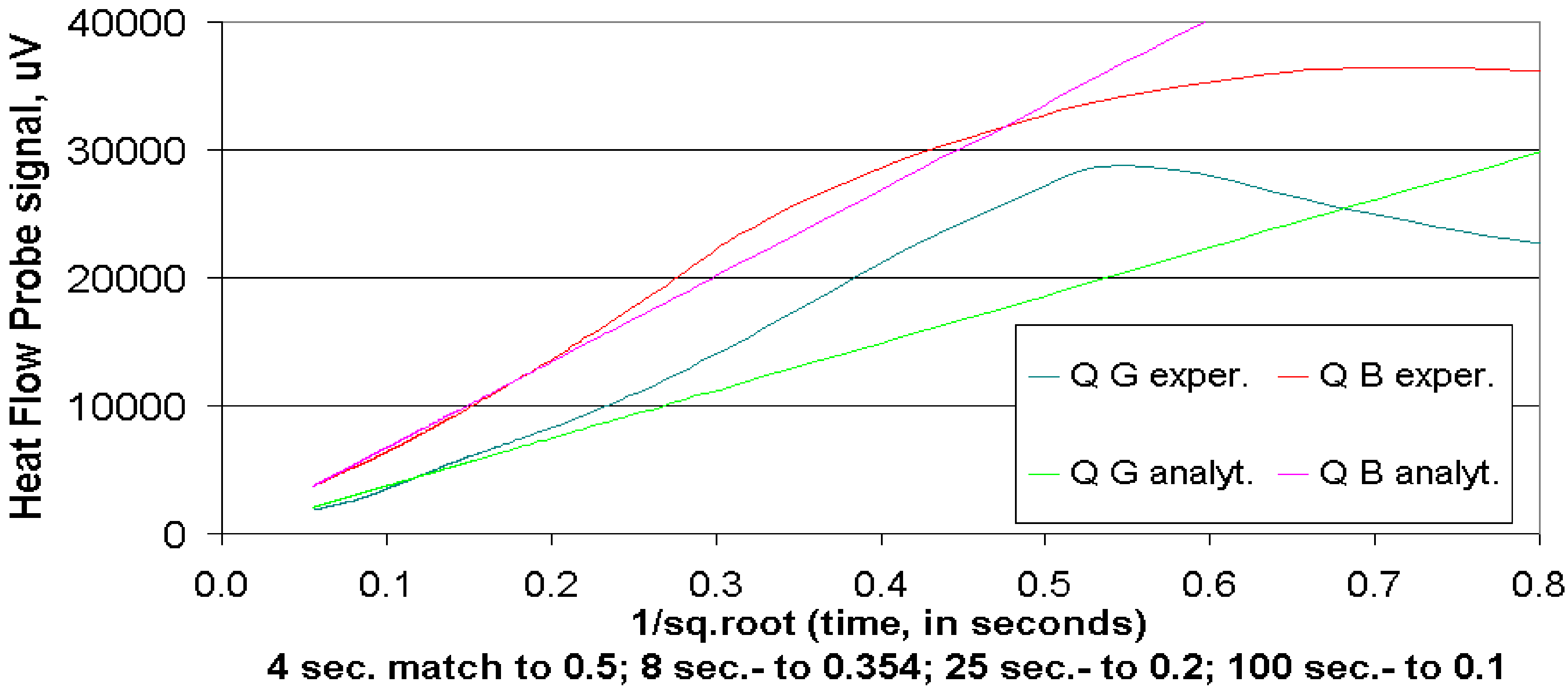
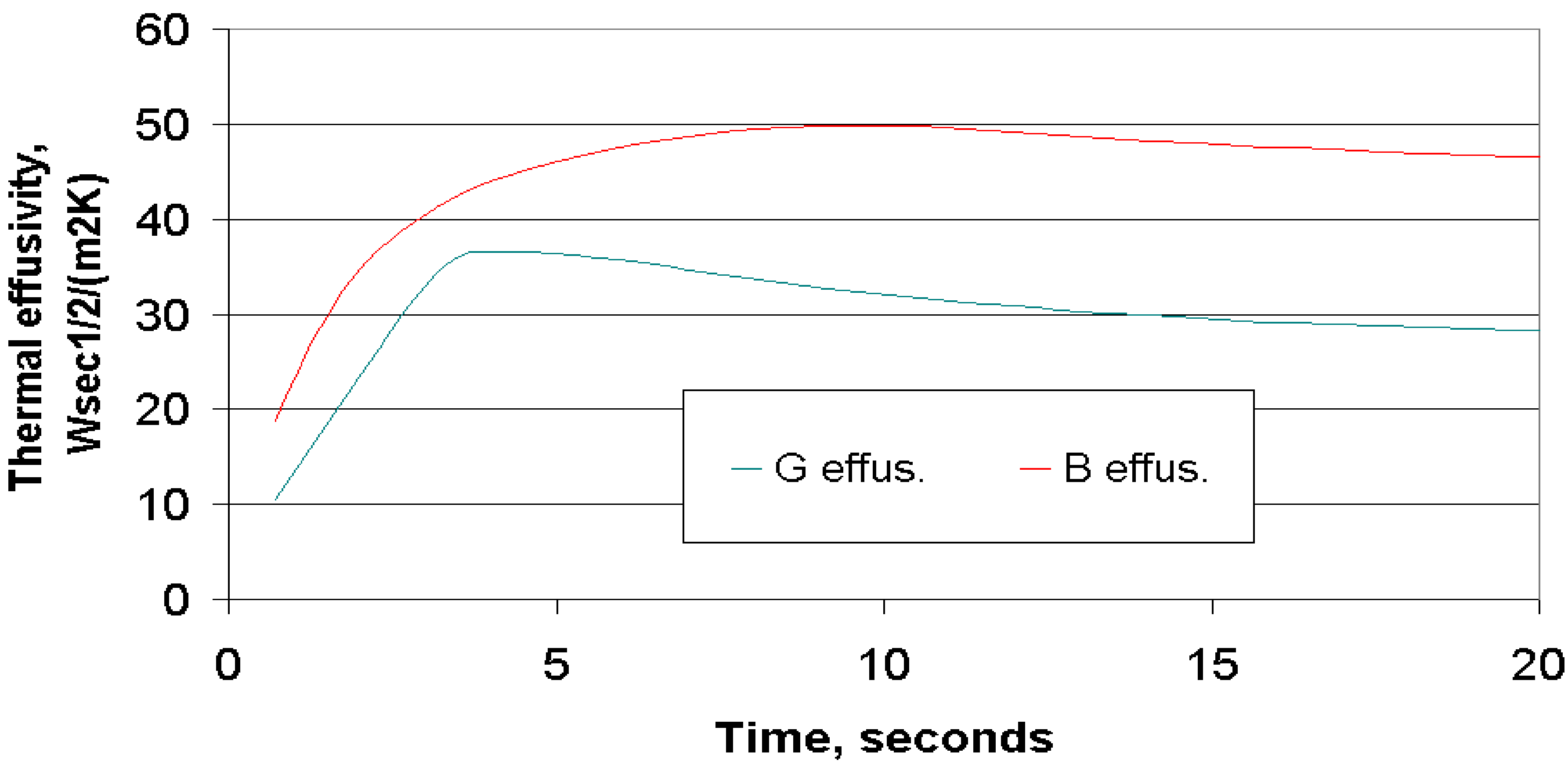


Thermal effusivity vs. time - determined using Heat Flow Meter Probe signal and the Analytical Formula. ($T_0=21^0C; T_1=6^0C$)

- "Good" VIP (G): ε_G ~25 W $sec^{1/2}/(m^2K)$; λ_G =0.0056 W/mK;
- "Bad" VIP (B): ε_B ~45 W $sec^{1/2}/(m^2K)$; λ_B =0.0320 W/mK;



- We see very satisfactory agreement between the experimental and the calculated (using the Analytical Formula) Heat Flow Probe’s signals for t>~8 seconds
- There is a deviation between them at the first moments of time when Fo’=a’t/x’ is not >>1 for t<~8 seconds (a’ – the probe’s thermal diffusivity, x’ - it’s thickness)
- To find a more adequate (for the initial moments of time) and <u>more informative</u> <u>numerical solution</u> of the thermal problem we will use the **<u>Finite Difference Method.</u>**

Thermal Conductivity Equation using Finite-Difference Method:

- $[T(x+\delta x, t) - 2T(x,t) + T(x-\delta x, t)] / (\delta x)^2 \cong$
  $\cong (1/a) [\underline{\mathbf{T(x, t+\delta t)}} - T(x,t)] / \delta t$
- Next moment temperature **T(x, t+δt)** for every point x can be calculated using previous moment temperatures T(x+δx, t),T(x,t), and T(x-δx, t) at the point x, and 2 adjacent points x+δx and x-δx
- Temperatures and heat flux at all co-ordinates and at all moments of time $T(x_i, t_i)$ can be calculated starting from the initial condition at t=0

Initial and Boundary Conditions

(x_N – probe/sample contact surface; \` means probe's)

- I.C. $T(\text{all } x_i > x_N, t) = T_0$ (sample at room temperature)
- B.C. $T'(x=0, t) = T_1$ is the heat sink's temperature;

  $T`(x_N, t) = T(x_N, t)$;

  $\lambda`[T`(x_N,t) - T`(x_N - \delta x, t)]/\delta x = \lambda[T(x_N,t) - T(x_N + \delta x, t)]/\delta x$

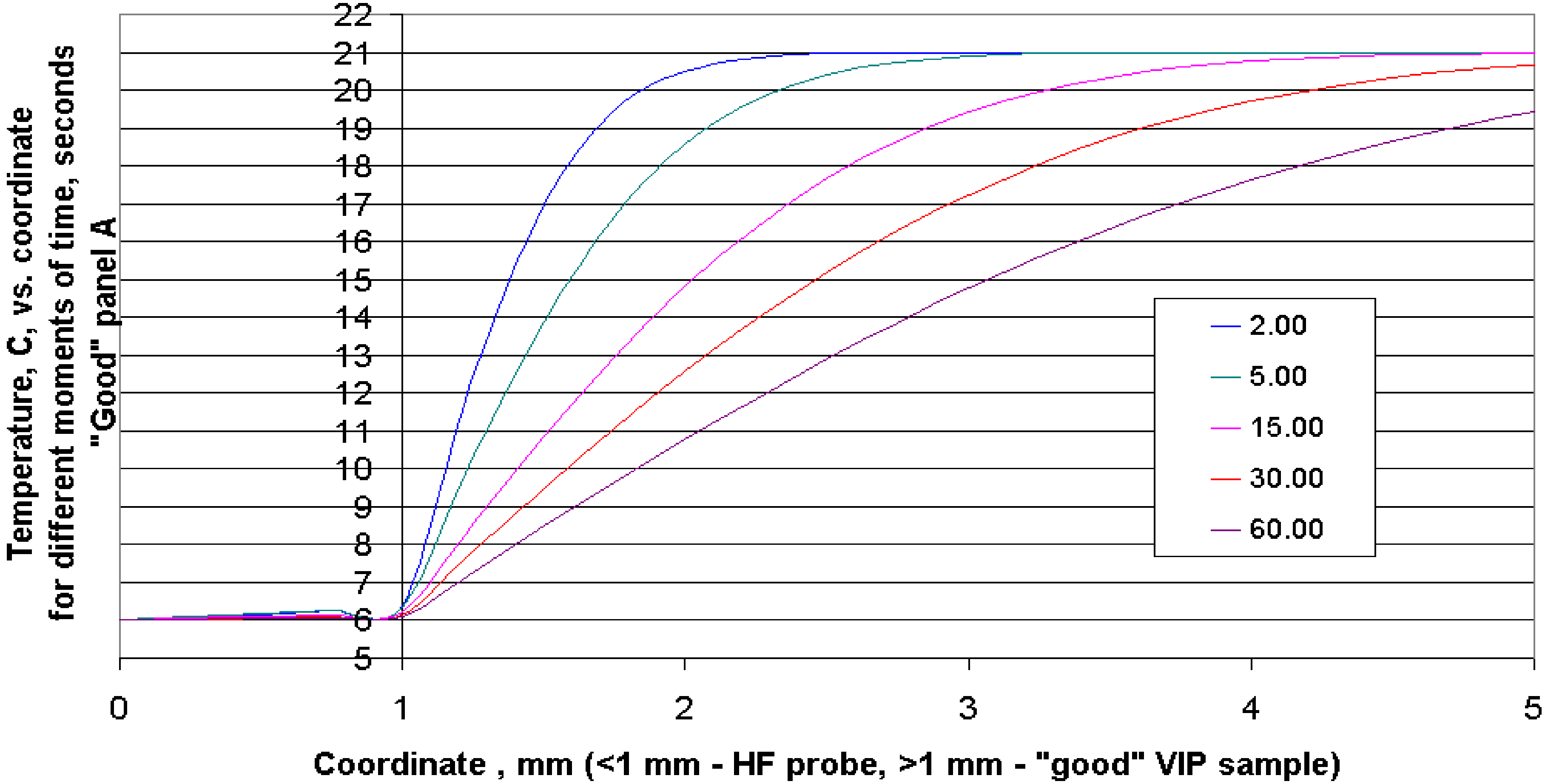
  i.e. the temperatures and heat fluxes are equal, which means and reflects a good thermal contact between probe and sample
- Probe's signal (μV) / temperatures relation:

  $Q(t) = \lambda`[T`(x_N,t) - T_1)] / x_N / S_{cal}$

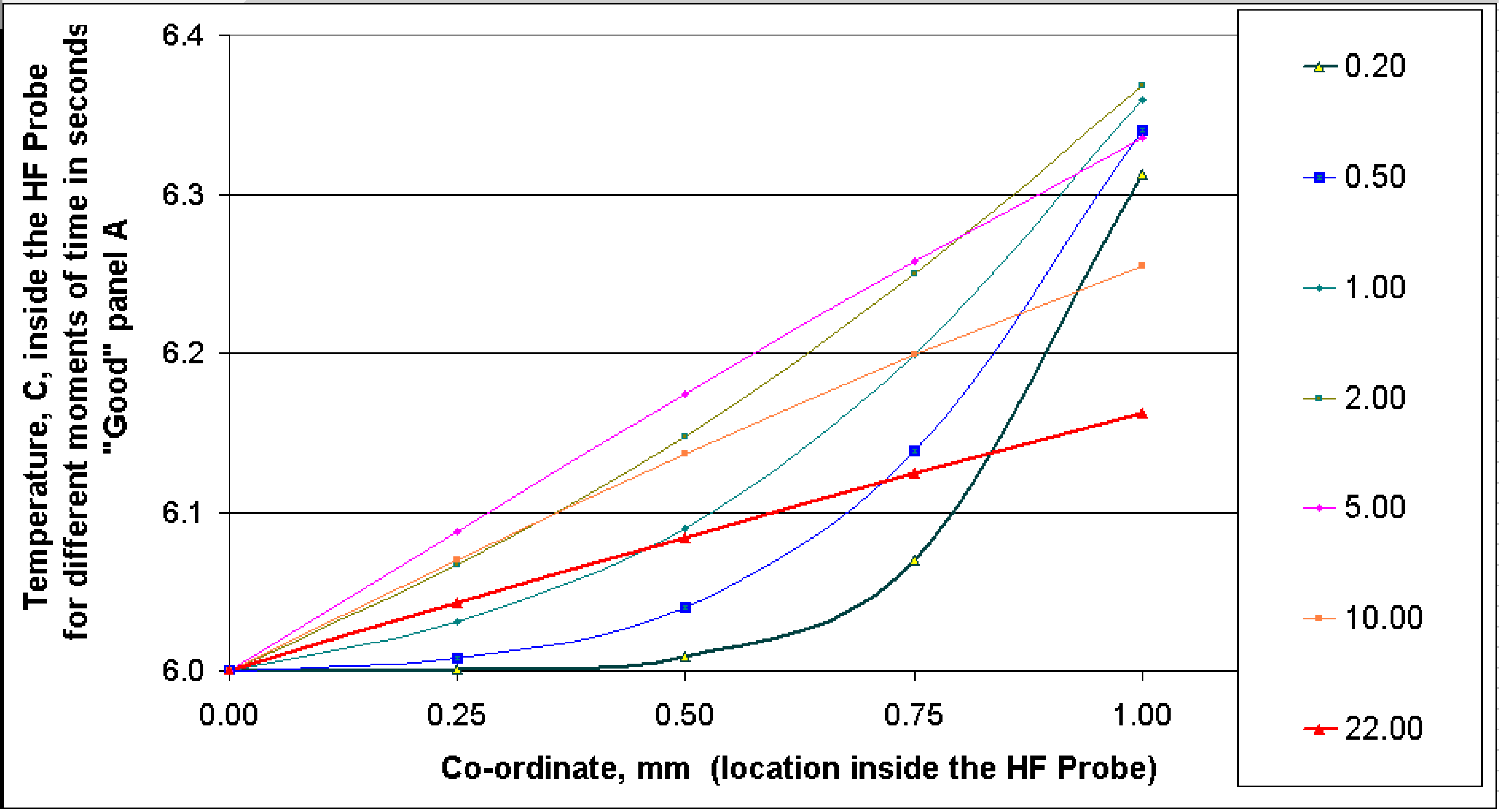
Temperature Evolution Calculated using the Finite Difference Method, part of the Microsoft Excel table (blue cells – T, ^{0}C inside the Probe)

Time interval, sec.		HFM thickness, meters =			0.0010	T chiller=	6.0	ThC. A=	0.00566	ThEff.A=	25	ThDiff.A=	5.13E-08	CpRo A=	1.10E+05		S cal =	0.00568
0.02	No of nodes in HFM			4		T room=	21.0	ThC. B=	0.0320	ThEff.B=	45	ThDiff.B=	5.06E-07	CpRo B=	6.33E+04			
	Step	0.00025	meters					ThC.HFM	0.293	ThEff.HF	910	ThDiff.HF	1.04E-07	CpRo HF:	2.83E+06			
Time, sec	0.00	0.25	0.50	0.75	1.00	1.25	1.50	1.75	2.00	2.25	2.50	2.75	3.00	3.25	3.50	3.75	4.00	4.25
	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
0.00	6.00	6.00	6.00	6.00	6.00	21.00	21.00	21.00	21.00	21.00	21.00	21.00	21.00	21.00	21.00	21.00	21.00	21.00
0.02	6.00	6.00	6.00	6.00	6.28	20.75	21.00	21.00	21.00	21.00	21.00	21.00	21.00	21.00	21.00	21.00	21.00	21.00
0.04	6.00	6.00	6.00	6.01	6.28	20.52	21.00	21.00	21.00	21.00	21.00	21.00	21.00	21.00	21.00	21.00	21.00	21.00
0.06	6.00	6.00	6.00	6.02	6.29	20.29	20.99	21.00	21.00	21.00	21.00	21.00	21.00	21.00	21.00	21.00	21.00	21.00
0.08	6.00	6.00	6.00	6.03	6.29	20.08	20.98	21.00	21.00	21.00	21.00	21.00	21.00	21.00	21.00	21.00	21.00	21.00
0.10	6.00	6.00	6.00	6.03	6.30	19.87	20.96	21.00	21.00	21.00	21.00	21.00	21.00	21.00	21.00	21.00	21.00	21.00
0.12	6.00	6.00	6.00	6.04	6.30	19.66	20.95	21.00	21.00	21.00	21.00	21.00	21.00	21.00	21.00	21.00	21.00	21.00
0.14	6.00	6.00	6.00	6.05	6.30	19.46	20.93	21.00	21.00	21.00	21.00	21.00	21.00	21.00	21.00	21.00	21.00	21.00
0.16	6.00	6.00	6.01	6.06	6.31	19.27	20.90	21.00	21.00	21.00	21.00	21.00	21.00	21.00	21.00	21.00	21.00	21.00
0.18	6.00	6.00	6.01	6.06	6.31	19.08	20.88	21.00	21.00	21.00	21.00	21.00	21.00	21.00	21.00	21.00	21.00	21.00
0.20	6.00	6.00	6.01	6.07	6.31	18.90	20.85	20.99	21.00	21.00	21.00	21.00	21.00	21.00	21.00	21.00	21.00	21.00
0.22	6.00	6.00	6.01	6.08	6.32	18.73	20.82	20.99	21.00	21.00	21.00	21.00	21.00	21.00	21.00	21.00	21.00	21.00
0.24	6.00	6.00	6.01	6.08	6.32	18.56	20.79	20.99	21.00	21.00	21.00	21.00	21.00	21.00	21.00	21.00	21.00	21.00
0.26	6.00	6.00	6.01	6.09	6.32	18.40	20.76	20.99	21.00	21.00	21.00	21.00	21.00	21.00	21.00	21.00	21.00	21.00
0.28	6.00	6.00	6.02	6.09	6.32	18.24	20.72	20.98	21.00	21.00	21.00	21.00	21.00	21.00	21.00	21.00	21.00	21.00
0.30	6.00	6.00	6.02	6.10	6.32	18.08	20.68	20.98	21.00	21.00	21.00	21.00	21.00	21.00	21.00	21.00	21.00	21.00
0.32	6.00	6.00	6.02	6.10	6.33	17.93	20.65	20.97	21.00	21.00	21.00	21.00	21.00	21.00	21.00	21.00	21.00	21.00
0.34	6.00	6.00	6.02	6.11	6.33	17.79	20.61	20.97	21.00	21.00	21.00	21.00	21.00	21.00	21.00	21.00	21.00	21.00
0.36	6.00	6.00	6.02	6.11	6.33	17.64	20.57	20.96	21.00	21.00	21.00	21.00	21.00	21.00	21.00	21.00	21.00	21.00
0.38	6.00	6.00	6.03	6.12	6.33	17.51	20.53	20.96	21.00	21.00	21.00	21.00	21.00	21.00	21.00	21.00	21.00	21.00
0.40	6.00	6.00	6.03	6.12	6.33	17.37	20.48	20.95	21.00	21.00	21.00	21.00	21.00	21.00	21.00	21.00	21.00	21.00
0.42	6.00	6.01	6.03	6.12	6.33	17.24	20.44	20.94	21.00	21.00	21.00	21.00	21.00	21.00	21.00	21.00	21.00	21.00
0.44	6.00	6.01	6.03	6.13	6.34	17.12	20.40	20.94	21.00	21.00	21.00	21.00	21.00	21.00	21.00	21.00	21.00	21.00
0.46	6.00	6.01	6.04	6.13	6.34	16.99	20.35	20.93	20.99	21.00	21.00	21.00	21.00	21.00	21.00	21.00	21.00	21.00
0.48	6.00	6.01	6.04	6.14	6.34	16.87	20.30	20.92	20.99	21.00	21.00	21.00	21.00	21.00	21.00	21.00	21.00	21.00
0.50	6.00	6.01	6.04	6.14	6.34	16.76	20.26	20.91	20.99	21.00	21.00	21.00	21.00	21.00	21.00	21.00	21.00	21.00
0.52	6.00	6.01	6.04	6.14	6.34	16.64	20.21	20.90	20.99	21.00	21.00	21.00	21.00	21.00	21.00	21.00	21.00	21.00
0.54	6.00	6.01	6.04	6.15	6.34	16.53	20.16	20.89	20.99	21.00	21.00	21.00	21.00	21.00	21.00	21.00	21.00	21.00
0.56	6.00	6.01	6.05	6.15	6.34	16.43	20.12	20.88	20.99	21.00	21.00	21.00	21.00	21.00	21.00	21.00	21.00	21.00
0.58	6.00	6.01	6.05	6.15	6.34	16.32	20.07	20.87	20.99	21.00	21.00	21.00	21.00	21.00	21.00	21.00	21.00	21.00
0.60	6.00	6.01	6.05	6.15	6.35	16.22	20.02	20.86	20.98	21.00	21.00	21.00	21.00	21.00	21.00	21.00	21.00	21.00
0.62	6.00	6.01	6.05	6.16	6.35	16.12	19.97	20.85	20.98	21.00	21.00	21.00	21.00	21.00	21.00	21.00	21.00	21.00
0.64	6.00	6.01	6.06	6.16	6.35	16.02	19.92	20.84	20.98	21.00	21.00	21.00	21.00	21.00	21.00	21.00	21.00	21.00
0.66	6.00	6.02	6.06	6.16	6.35	15.93	19.87	20.82	20.98	21.00	21.00	21.00	21.00	21.00	21.00	21.00	21.00	21.00
0.68	6.00	6.02	6.06	6.17	6.35	15.84	19.83	20.81	20.98	21.00	21.00	21.00	21.00	21.00	21.00	21.00	21.00	21.00
0.70	6.00	6.02	6.06	6.17	6.35	15.74	19.78	20.80	20.97	21.00	21.00	21.00	21.00	21.00	21.00	21.00	21.00	21.00
0.72	6.00	6.02	6.06	6.17	6.35	15.66	19.73	20.78	20.97	21.00	21.00	21.00	21.00	21.00	21.00	21.00	21.00	21.00

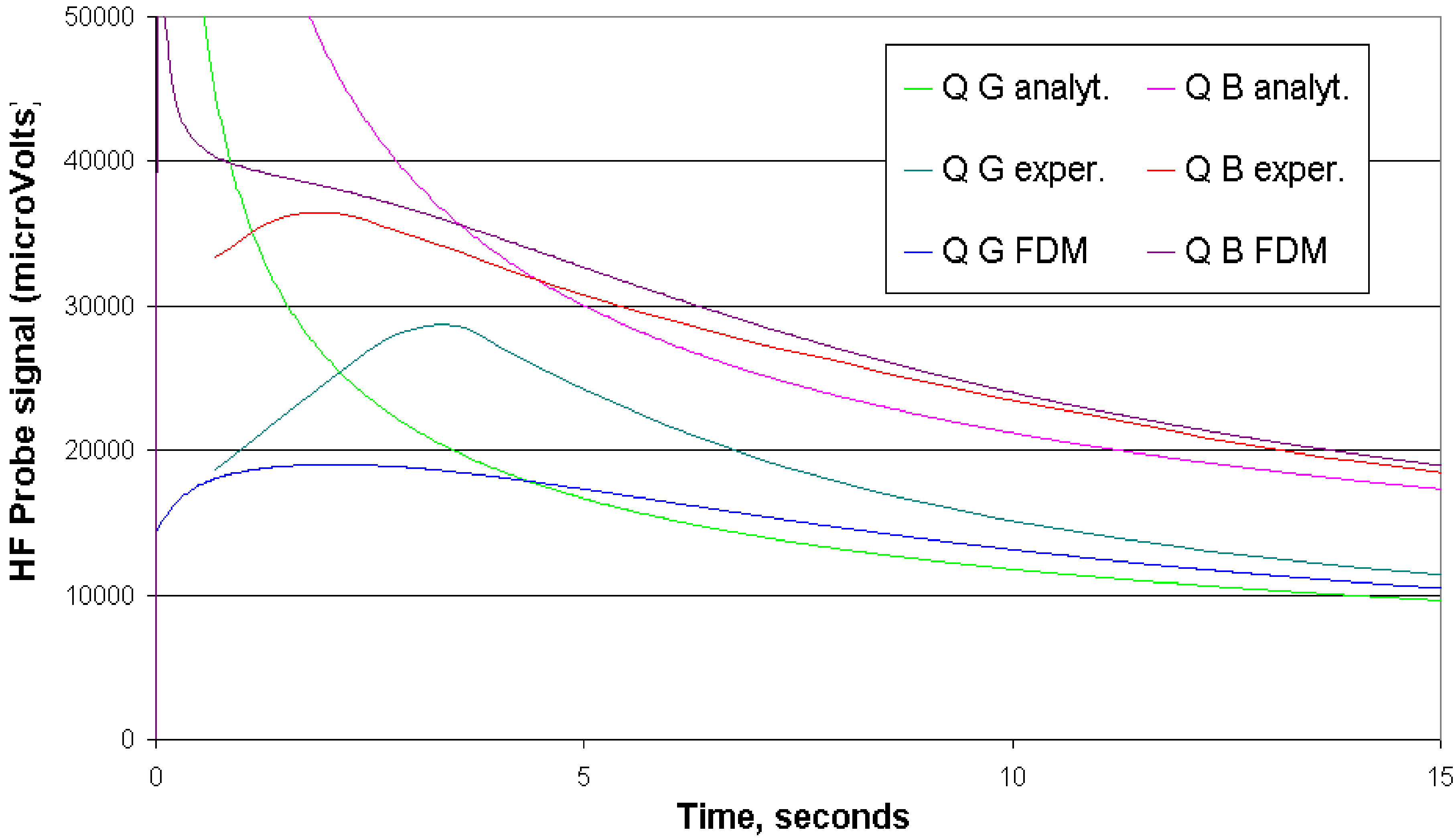
Temperature inside the “good” VIP vs. co-ordinate (mm) calculated for different moments of time (sec) using the Fin.Diff.Method



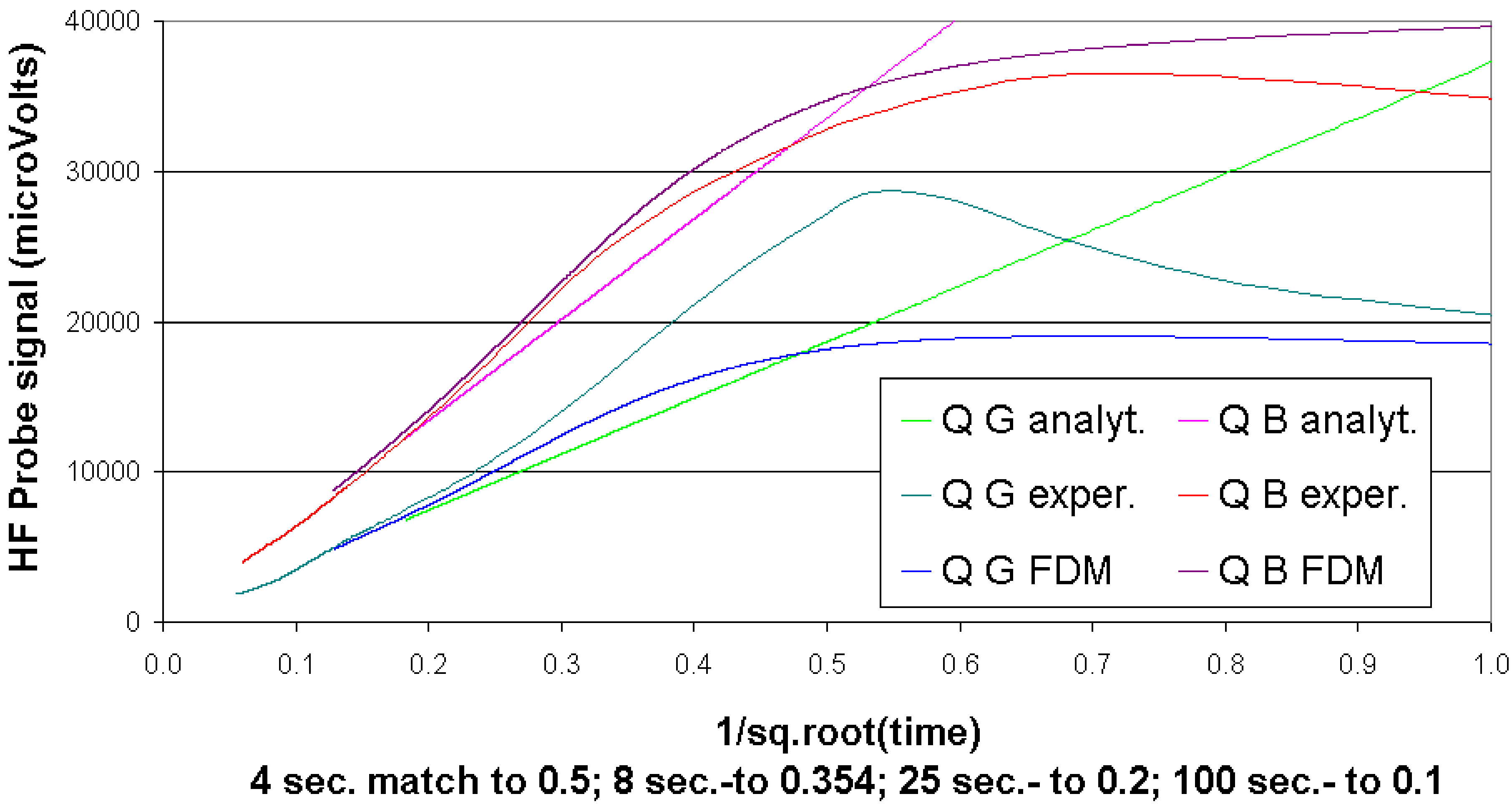
Temperature inside the HF Probe vs. co-ordinate (mm) calculated for different moments of time (sec) using the Fin.Diff.Method ("good" VIP)



Heat Flow Probe signal vs. time (FDM - calculated using the Finite Difference Method)



Heat Flow Probe signal vs.1/(√time) (FDM - calculated using the Finite Difference Method)



Analytical formula vs. Finite Difference method calculations

- Analytical Formula can be used only for thermal effusivity calculations when the Heat Flow Probe is thermally “thin” (i.e. when $Fo`=a`t/x`^{2}>>1$).

- Finite Difference method in theory has information about all 4 thermal properties of the sample (2 of them are independent) starting from the very first moments of time - when the Heat Flow Probe is thermally “thick”. Least-Squares method should be used for calculations to minimize the residual. Properties of the Probe are assumed to be known.

New transient method for quick VIP QC was developed and checked

- Thermal effusivity $\varepsilon=\lambda/\sqrt{a}$ of the VIP (or other insulation material) can be determined within a few seconds after touching the Heat Flow Probe to the surface of the sample.
- No waiting time or pause is necessary between the tests because the Probe does not need to return to cooler temperature. This enables thousands of VIPs to be tested during one working day using only one Heat Flow Probe.
- Thermal resistance (if sample's thickness is known) and all other thermal properties can be determined within a few minutes as well (provided the thermal properties of the Probe's material are known).

Prospective

- The new Heat Flow Probe method will be used in a new LaserComp's device for quick VIP QC.
- The new Heat Flow Probe method will be used in the existing LaserComp's FOX Instruments to accelerate tests of thick samples of insulation materials, and to make possible to test all thermal properties in addition to thermal conductivity (see our VIA-2002 Symposium report).