Thermoanalytical Characterization of Ethylene Vinyl Acetate Copolymer (EVA) for Lamination Process Simulation and Gel Content Determination in Photovoltaic Modules

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Introduction

A photovoltaic module consists of many jointly-connected solar cells. These solar cells are packaged between a polymeric backsheet on the bottom and a tempered-glass window on the top, and are typically encapsulated in a cross-linked polymer matrix. The encapsulant serves many functions – it provides mechanical support, electrical isolation, and protection against outdoor environmental elements of moisture, UV radiation and temperature stress. Many different materials can be used for encapsulation, but one commonly used is ethylene-vinyl acetate (EVA) copolymer.

As the encapusalant properties and performance are largely dependent on the degree of crosslinking of the EVA, it is important to accurately know the curing state of the thermoset matrix. Currently, the most popular method to determine the curing state of EVA is the xylene extraction gelcontent analysis. However, Differential Scanning Calorimetry (DSC) is an alternative, more efficient and convenient way to determine the curing degree of EVA.

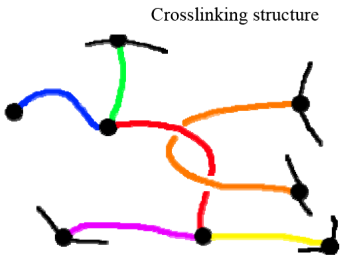
Normally a peroxide or peroxide mixture is the key component to initiate the curing reaction of the EVA encapsulant. As such, it is very important to know the dispensability of the peroxide in whole EVA film scroll. In this study, a sample of fresh EVA film (105cm wide, 165cm length, the same size of a real PV module), was evenly divided into 10cm x 10cm sections. A specimen from each section was analyzed by DSC (TA Instruments, model Q2000 with 50 position autosampler) from -90˚C to 250˚C at 10˚C/min under N2 purge. From this experiment, the curing enthalpy of the peroxide (which relates directly to the initial degree of EVA cure) can be determined automatically by the analysis software. Finally, a color map of the corresponding curing enthalpy for the fresh EVA film has been established that reflect the homogeneity of the peroxides that will have the influence on curing rate of EVA.

Alternate methods of determining the degree of curing were then compared. Each cured EVA sample with different crosslinking density was tested using the following three analytical techniques: (1) gel-content by xylene extraction; (2) curing degree by DSC and (3) viscoelastic properties by rheometer (TA Instruments, model AR-G2) or DMA (Dynamic Mechanical Analysis, TA Instruments, model Q800). The correlation between the xylene gel-content and DSC curing degree for cured EVA was built on the first step. Then the relationship between the xylene gel-content and tan delta (loss factor, the viscous modulus divided by the elastic modulus) will be established. DSC also can play a role as a mini-laminator to simulate the field laminator's actual temperature profile. The DSC could be operating according to the real laminator's measured temperature profiles following the control cooling for crystallization and control heating for melting and finally continue go on the full curing temperature on a DSC experiment run.

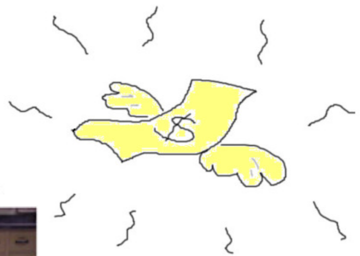
Finally, the EVA crosslinking properties could be developed to relating the viscoelastics behavior, ie., complex viscosity and tan delta value by means of DMA and Rheometer. The optimum curing degree of EVA also determined through the low temperature damping and high temperature creep properties. The Gel content by DSC (curing degree, crystallization, melting) was comparable with DMA and Rheometer results.

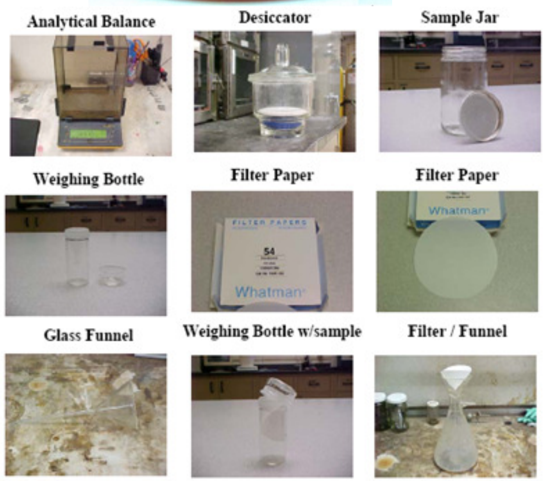
Gel Content Test of Cured EVA

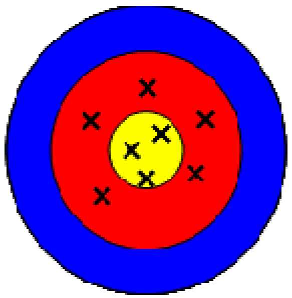
Gel content is very important parameter for setting up the condition of the lamination process – including heating temperature and time.

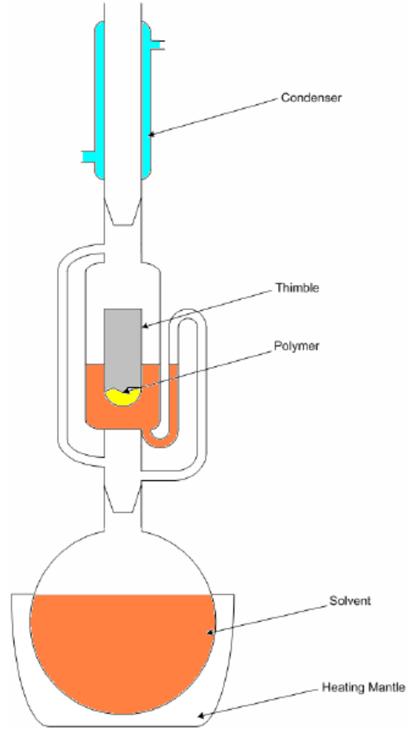


$$\text{Gel content}(\%) = \frac{\text{residual weight}}{\text{initial weight}} \times 100$$



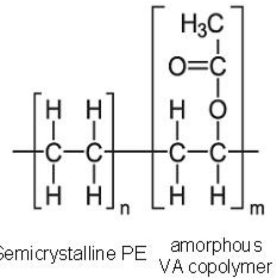


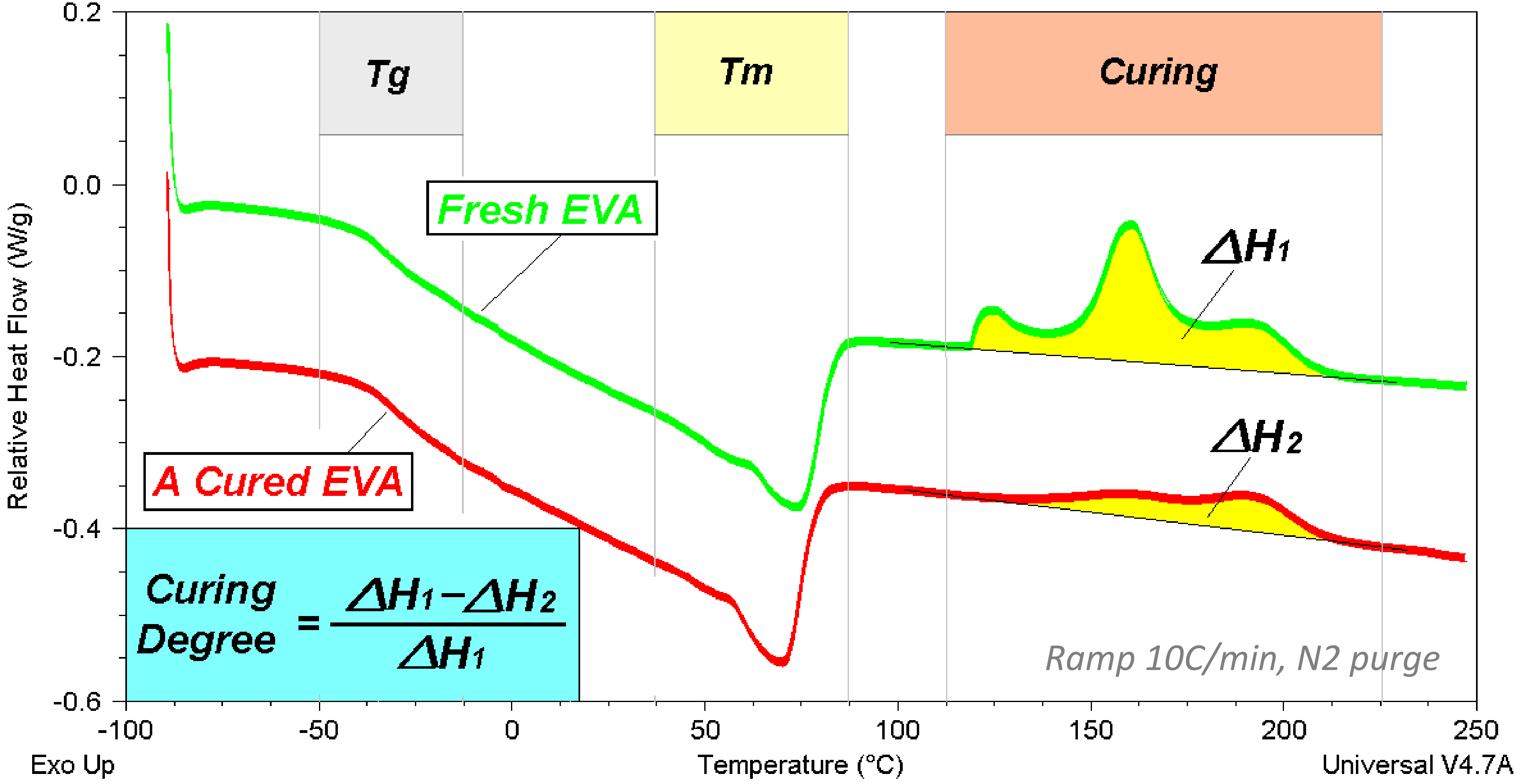




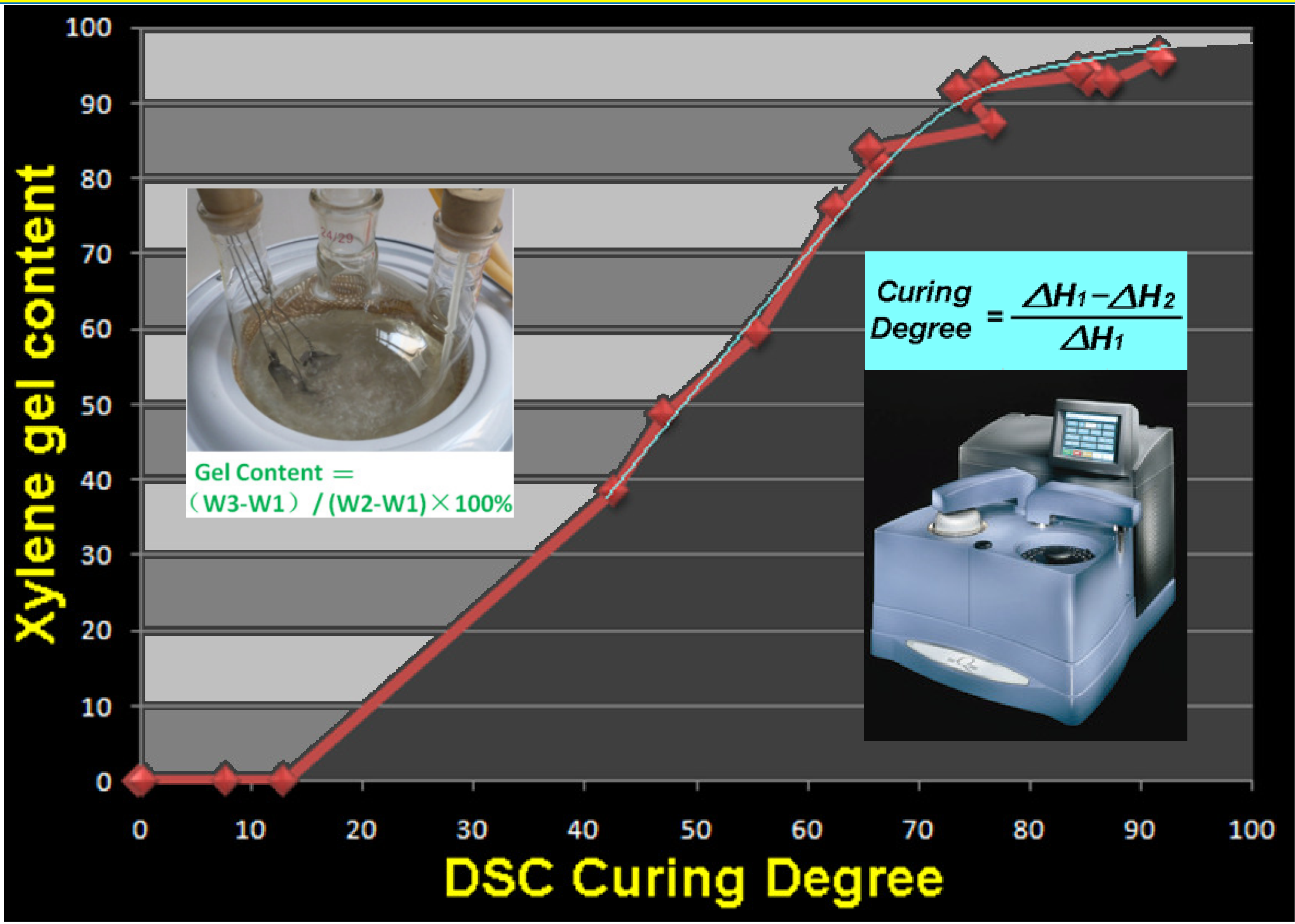
Soxhlet extraction apparatus

Determining EVA Curing Degree by DSC Method

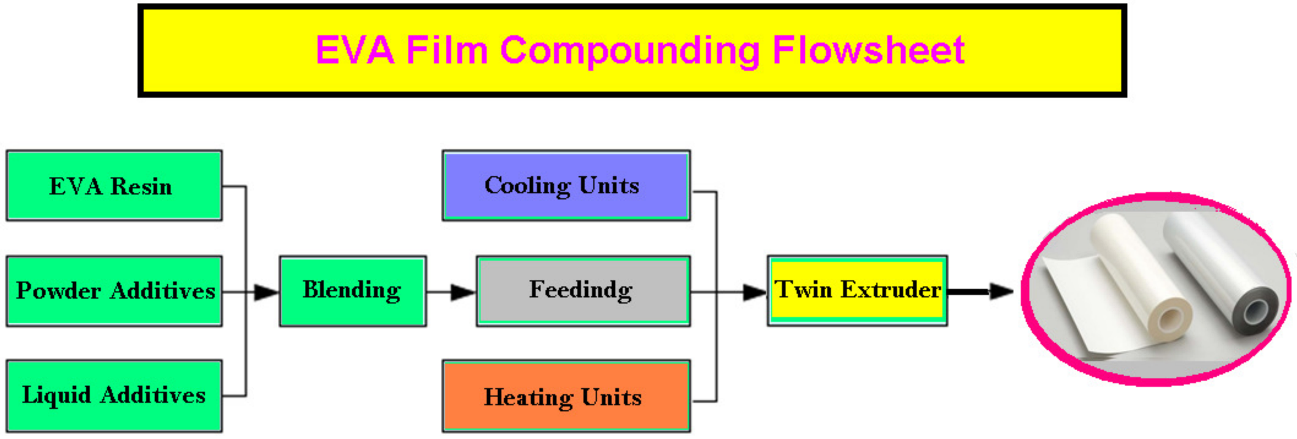


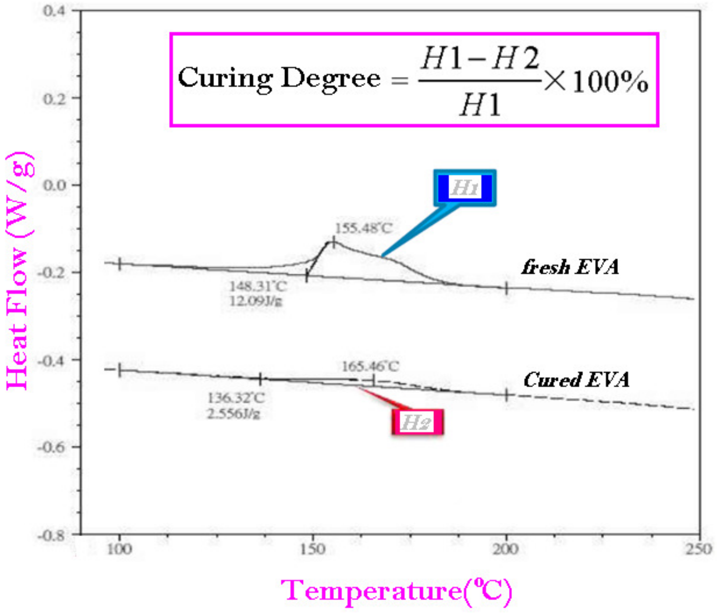


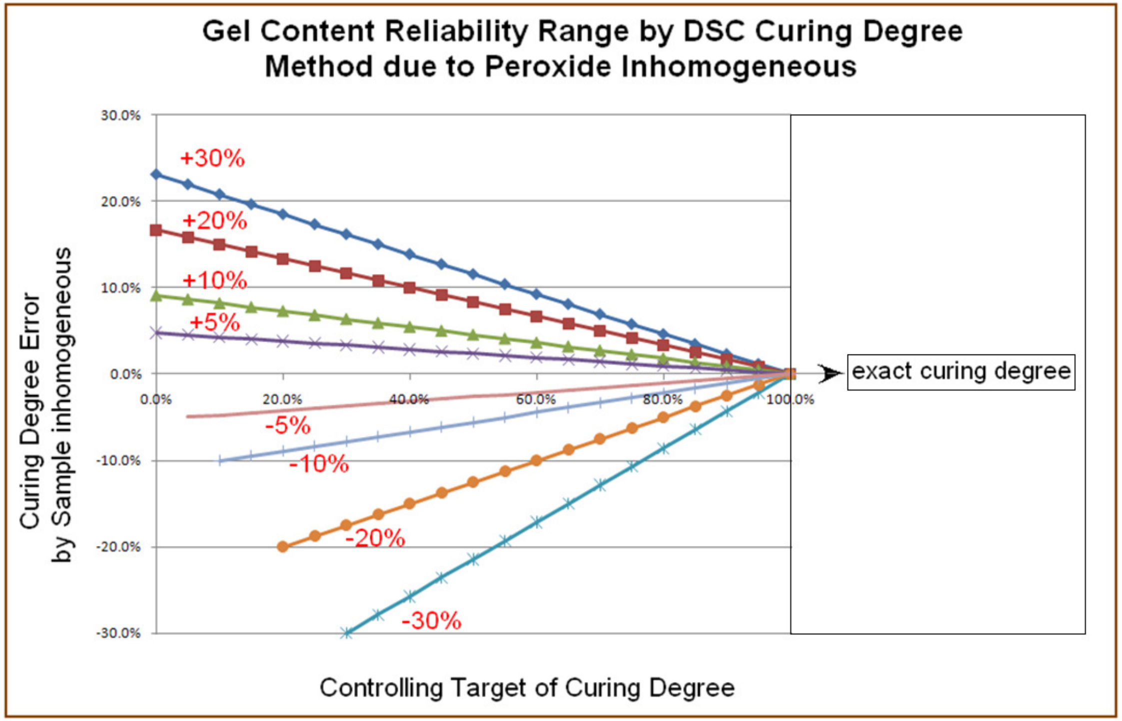
The Relationship between Gel Content and Curing Degree Should be Established for Every Type EVA



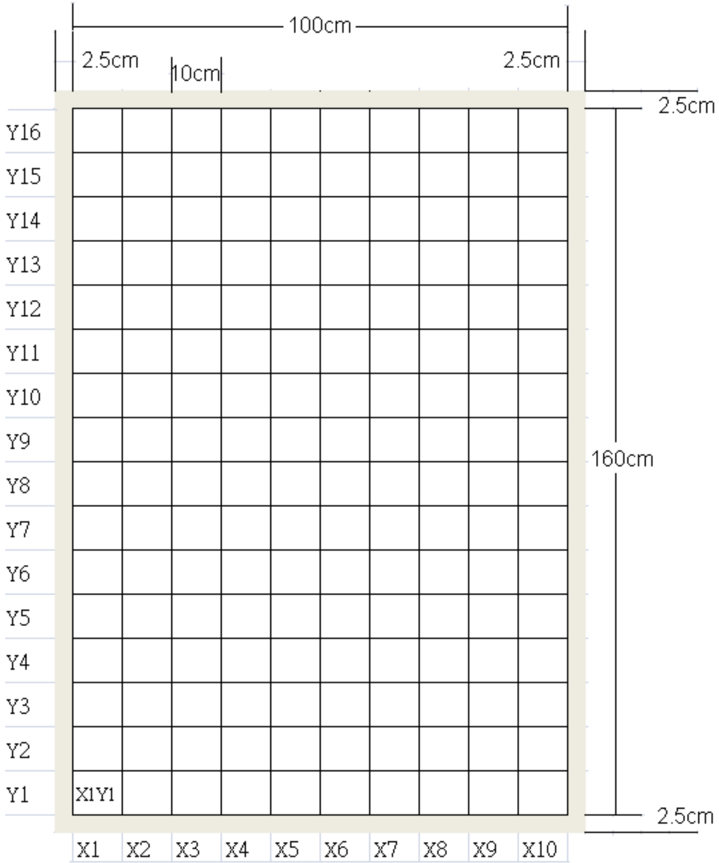
The uncertainty of EVA Curing Degree Calculation

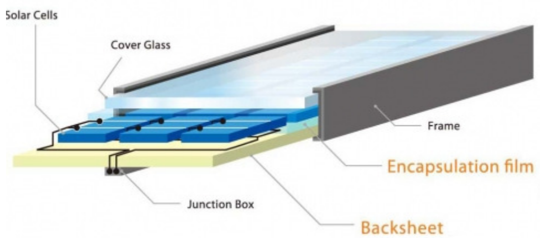






Mapping Study of EVA ΔH_1 Curing Heat Deviation on Real PV Module Scale



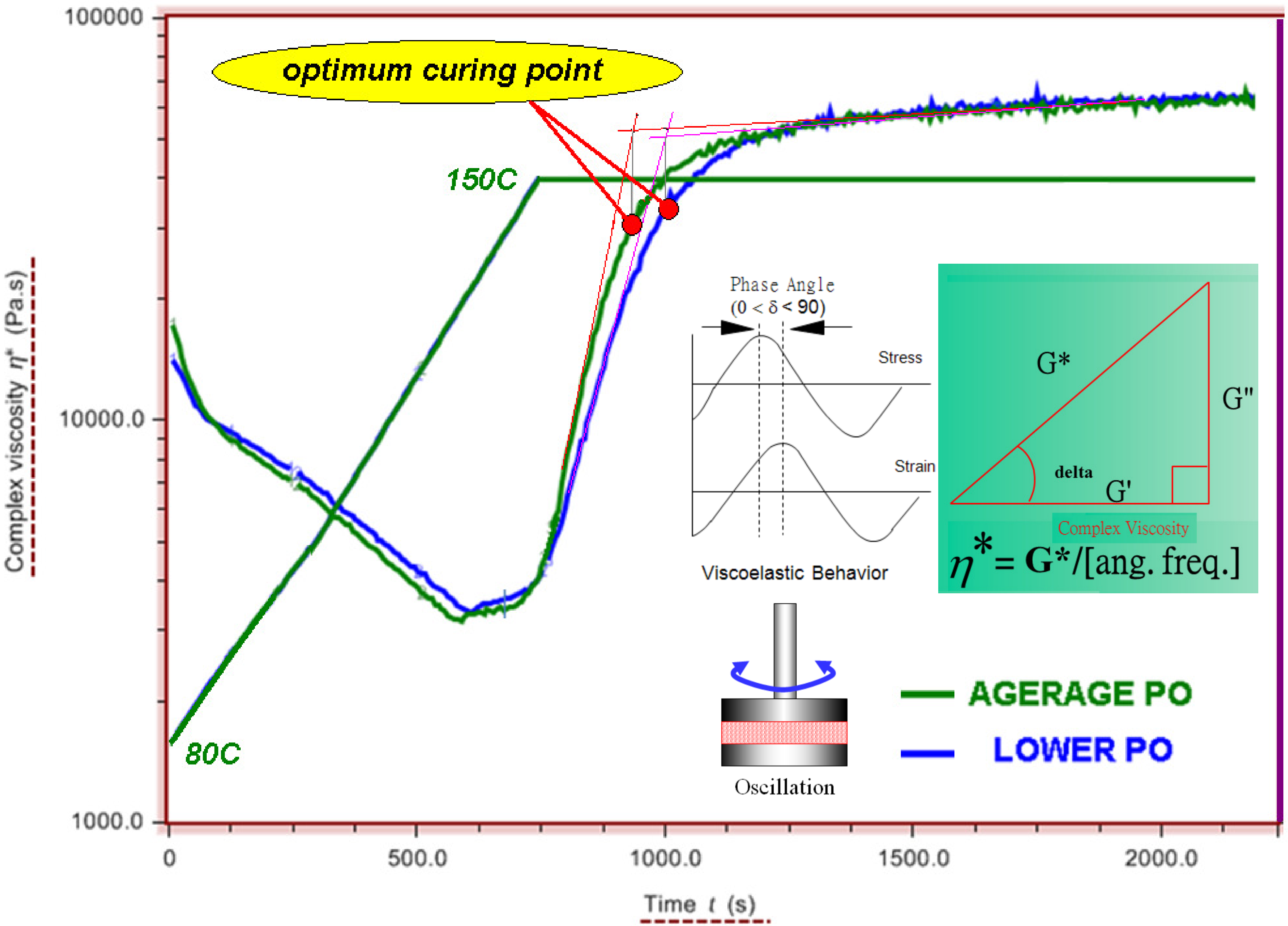


	X1	X2	X3	X4	X5	X6	X7	X8	X9	X10	
	26.7	29.2	29.6	30.0	30.1	30.5	29.9	30.4	29.9	29.2	29.55
Y16	27.9	30.5	32.0	30.9	28.3	31.7	30.7	31.1	30.8	32.5	30.64
Y15	27.9	29.5	30.3	31.0	30.1	29.2	27.8	30.1	29.0	27.3	29.22
Y14	27.1	29.8	30.4	30.6	31.6	31.5	29.8	30.7	29.4	28.3	29.91
Y13	26.5	30.1	30.6	29.7	32.4	30.6	29.9	29.6	29.6	27.2	29.60
Y12	29.1	31.0	30.4	30.8	31.3	30.7	30.1	32.7	28.0	28.7	30.27
Y11	26.5	29.1	30.1	30.4	30.4	31.0	30.2	30.5	29.4	29.4	29.72
Y10	29.0	30.2	29.4	30.0	27.0	31.2	30.6	30.5	29.5	28.5	29.60
Y9	29.6	31.7	28.4	29.7	32.2	31.0	31.0	30.0	29.6	30.0	30.31
Y8	27.6	28.6	30.6	31.8	30.4	31.5	31.7	31.0	30.8	30.9	30.49
Y7	25.4	28.0	28.2	29.3	29.1	29.9	29.5	28.9	29.6	27.8	28.57
Y6	26.5	29.0	28.8	30.6	31.5	32.0	31.0	30.9	31.3	30.5	30.21
Y5	25.5	28.3	29.0	28.9	30.6	31.0	29.5	30.5	29.8	30.0	29.30
Y4	24.3	28.7	28.2	29.4	30.8	28.2	29.9	30.4	31.0	30.1	29.09
Y3	27.4	29.1	30.1	32.2	31.3	31.2	30.8	32.3	30.6	30.8	30.58
Y2	23.6	28.1	29.2	26.7	27.5	30.1	29.8	30.1	30.0	29.5	28.44
Y1	23.9	26.1	28.5	27.4	27.4	27.3	26.4	26.5	29.3	26.3	26.89

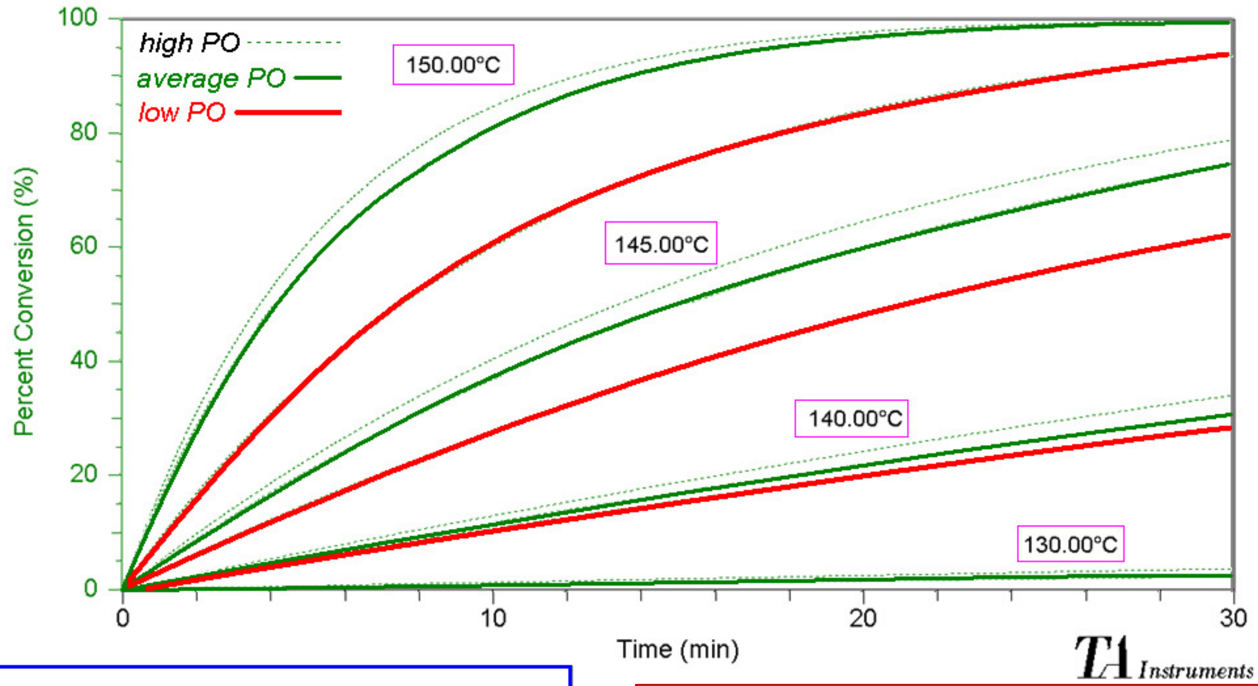
legend

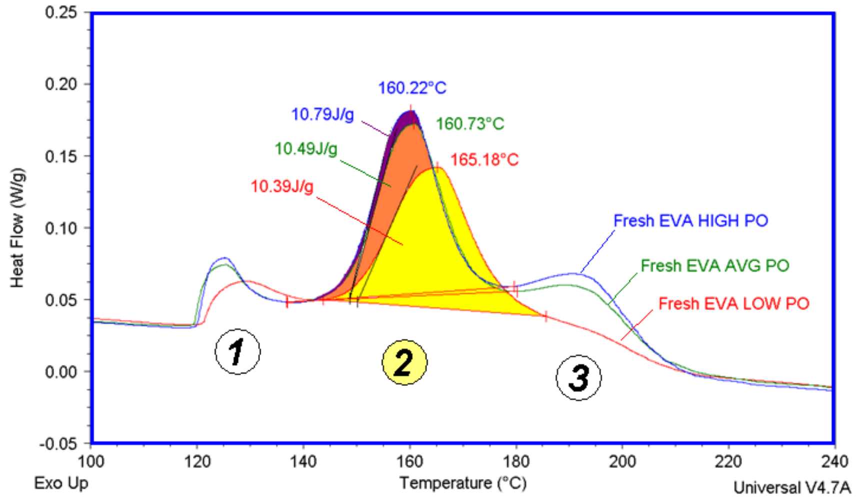
ΔH_1	+/-%
>33	>+12.0%
32.1~33.0	+8.6~11.9%
31.1~32.0	+5.0~8.5%
30.1~31.0	+1.8~5.0%
29.1~30.0	+/-1.7%
28.1~29.0	-1.8~5.0%
27.1~28.0	-5.1~8.1%
26.1~27.0	-8.2~11.5%
25.1~26.0	-11.6~14.9%
<25	<15.0%

Identify the Peroxide Enthalpy will Impact the EVA Curing Rate by Rheology



Identify the Peroxide Enthalpy will Impact the EVA Curing Rate by DSC Kinetics Software





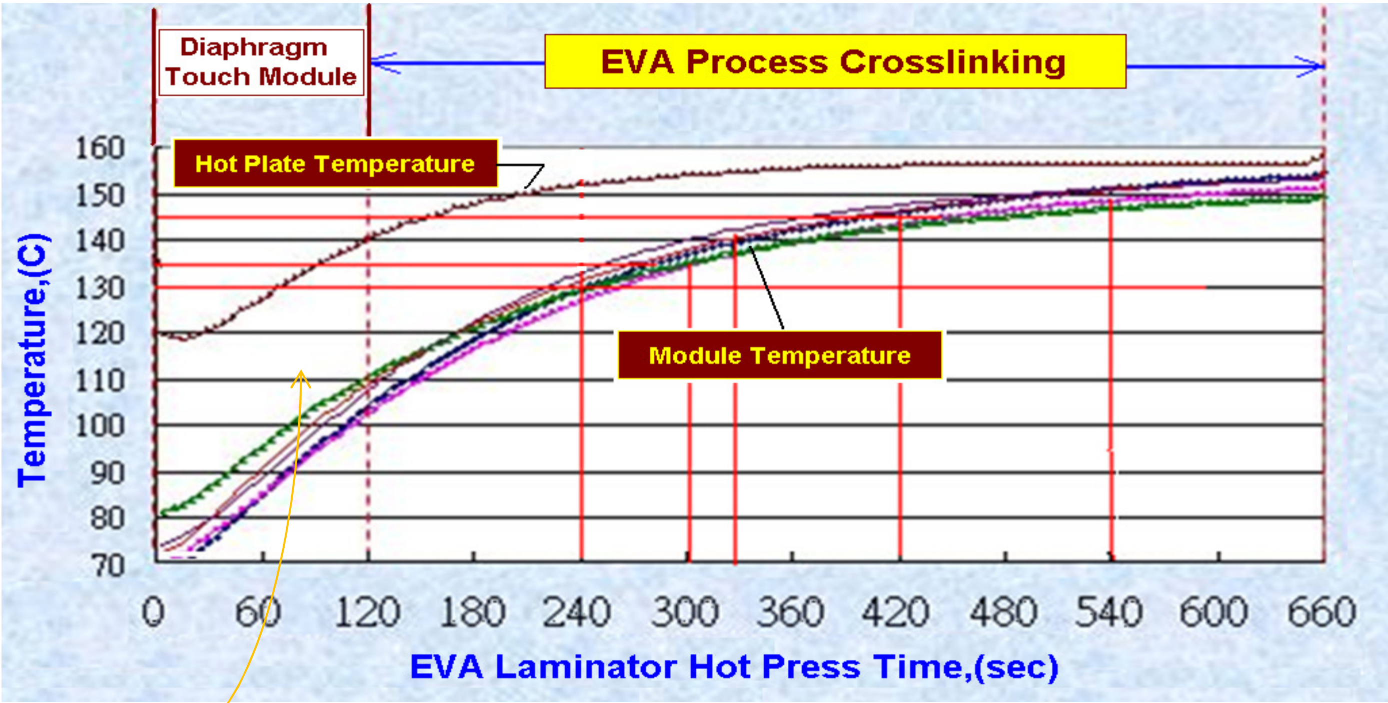
Borchardt and Daniels (B/D) kinetics

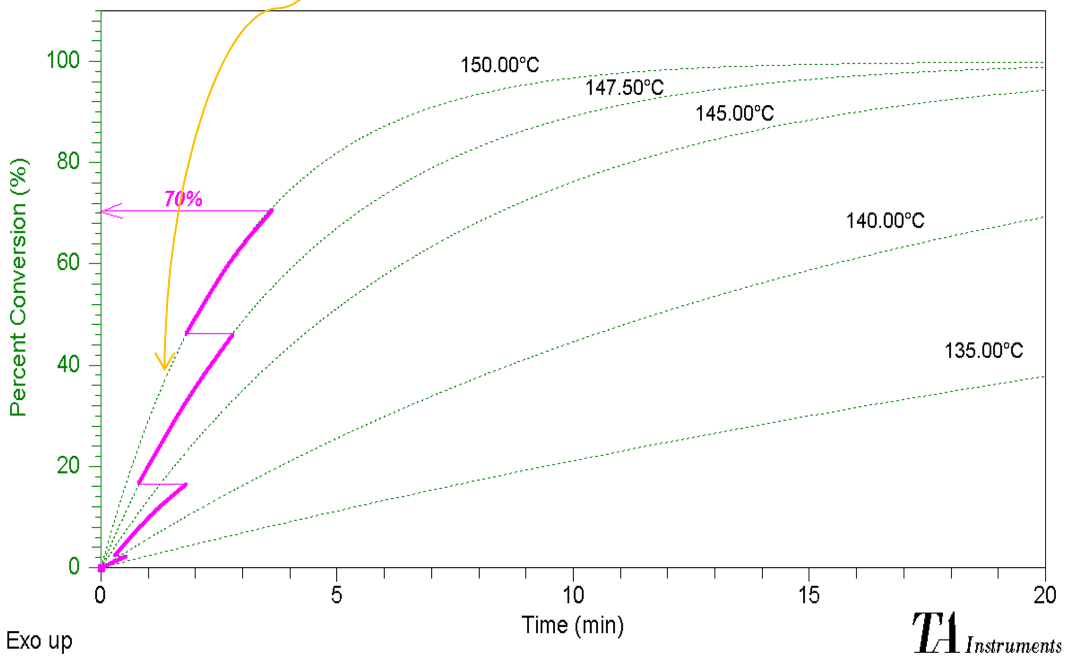
$$k(T) = Z\, e^{-Ea/RT}$$

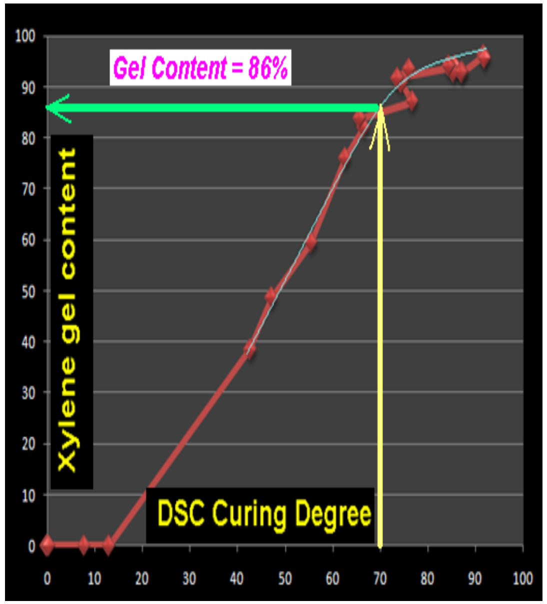
$$d\alpha/dt = Z\, e^{-Ea/RT}\, [1-\alpha]^n$$

$$\ln (d\alpha/dt) = \ln (Z) - Ea/RT + n \ln [1 - \alpha]$$

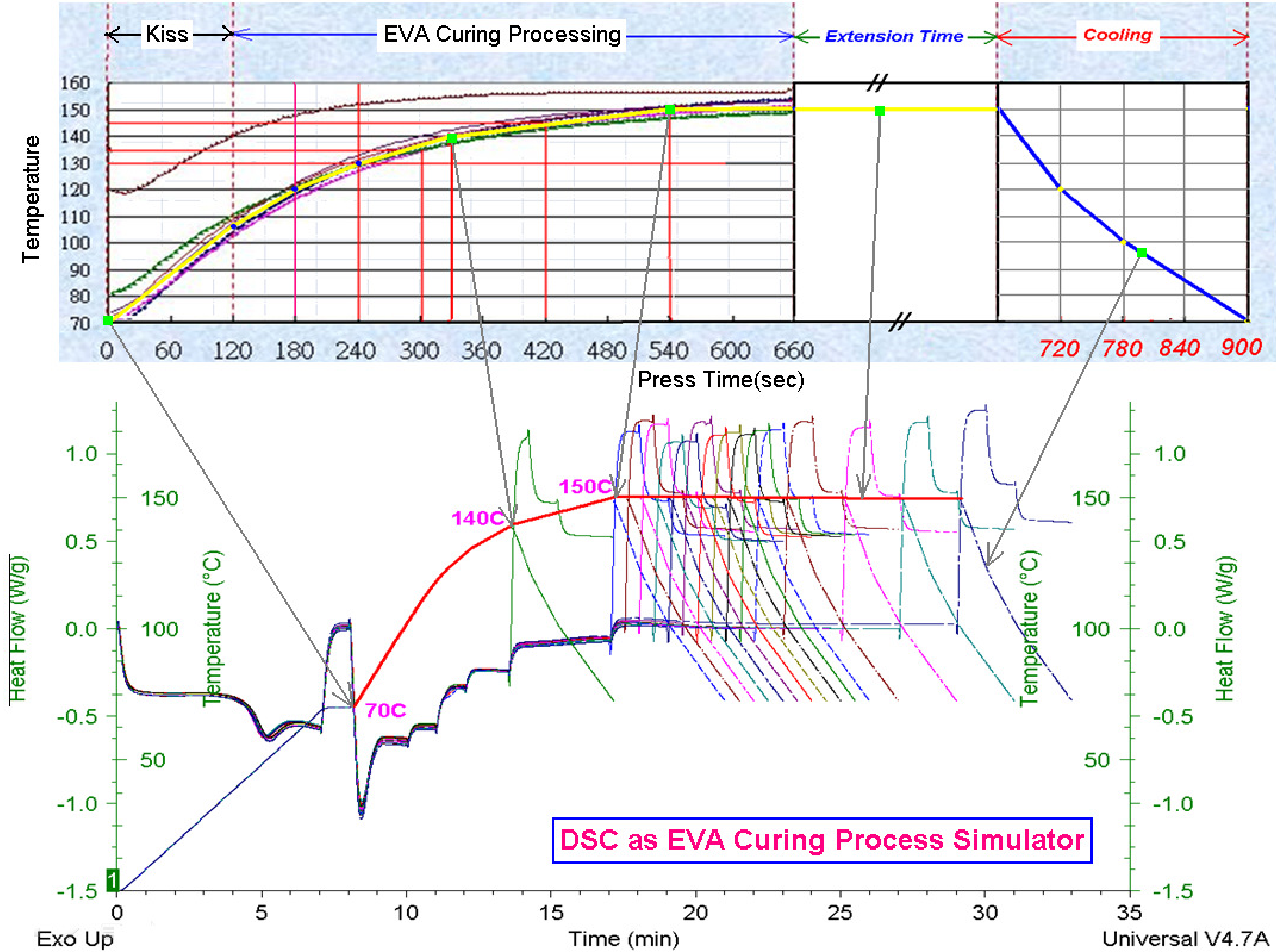
Simulation the Curing Degree of the Real EVA Lamination Process by DSC Kinetics Software



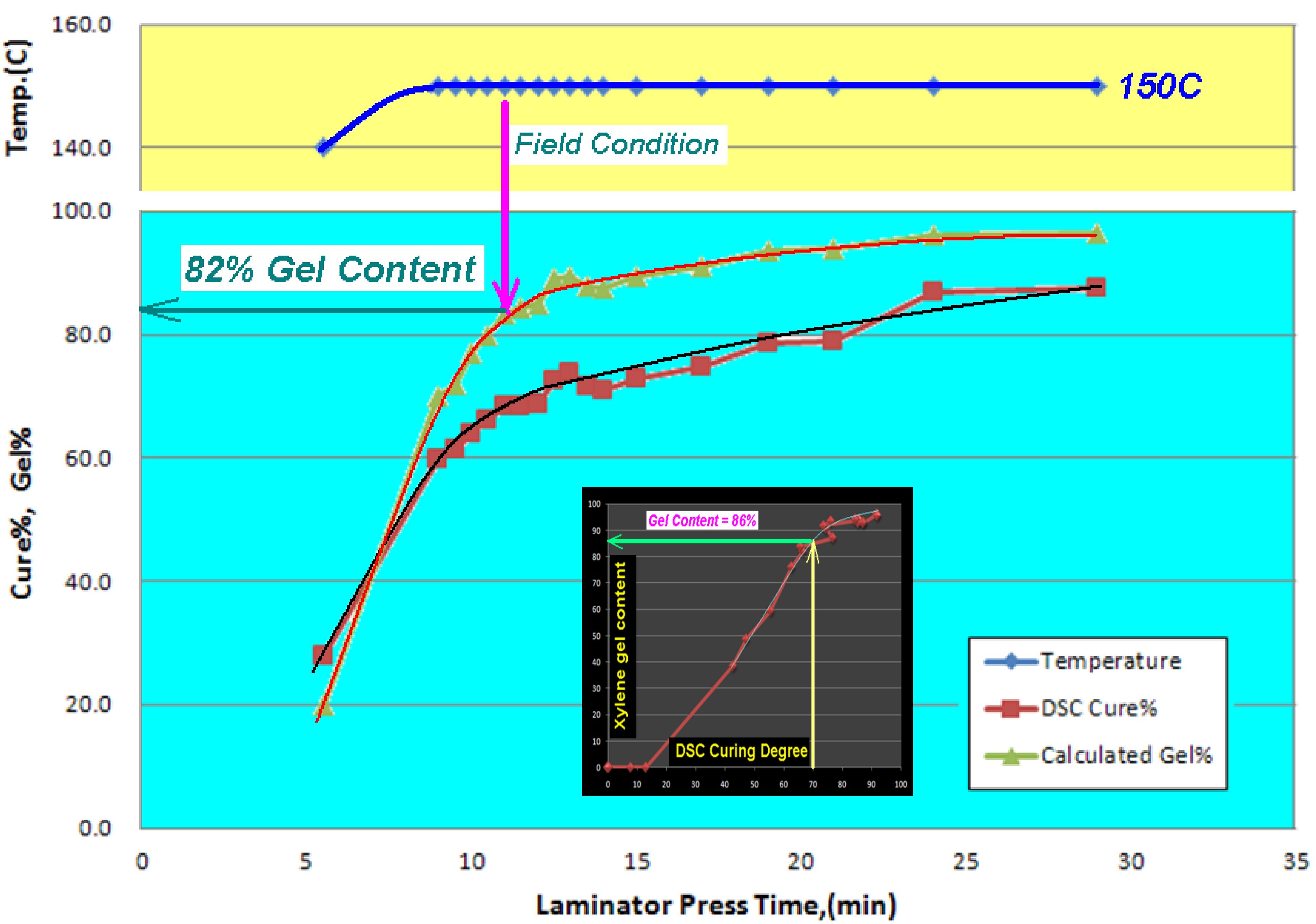




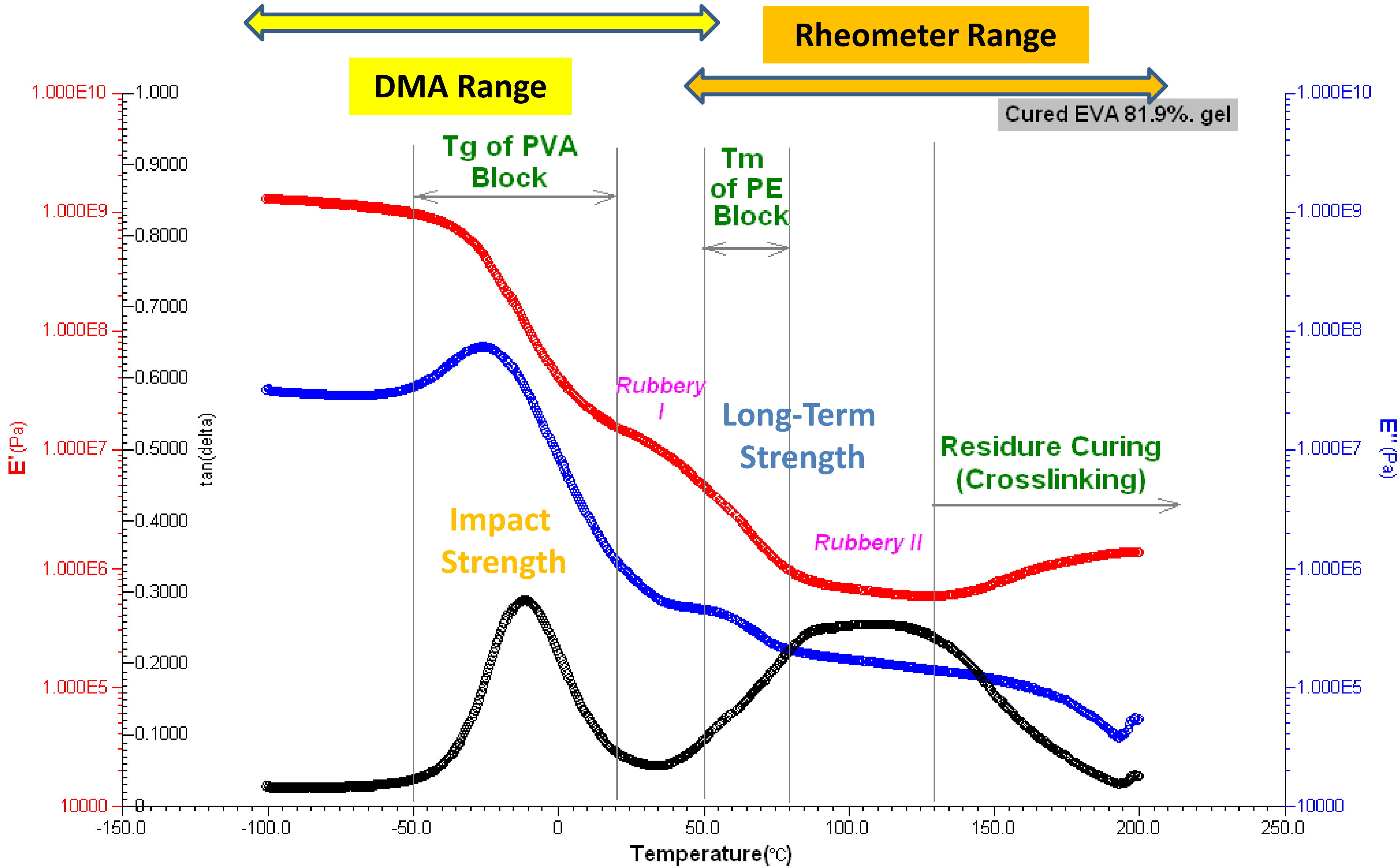
Simulation the Curing Degree of the Real EVA Lamination Process by Direct DSC Furnace Heat Treatment



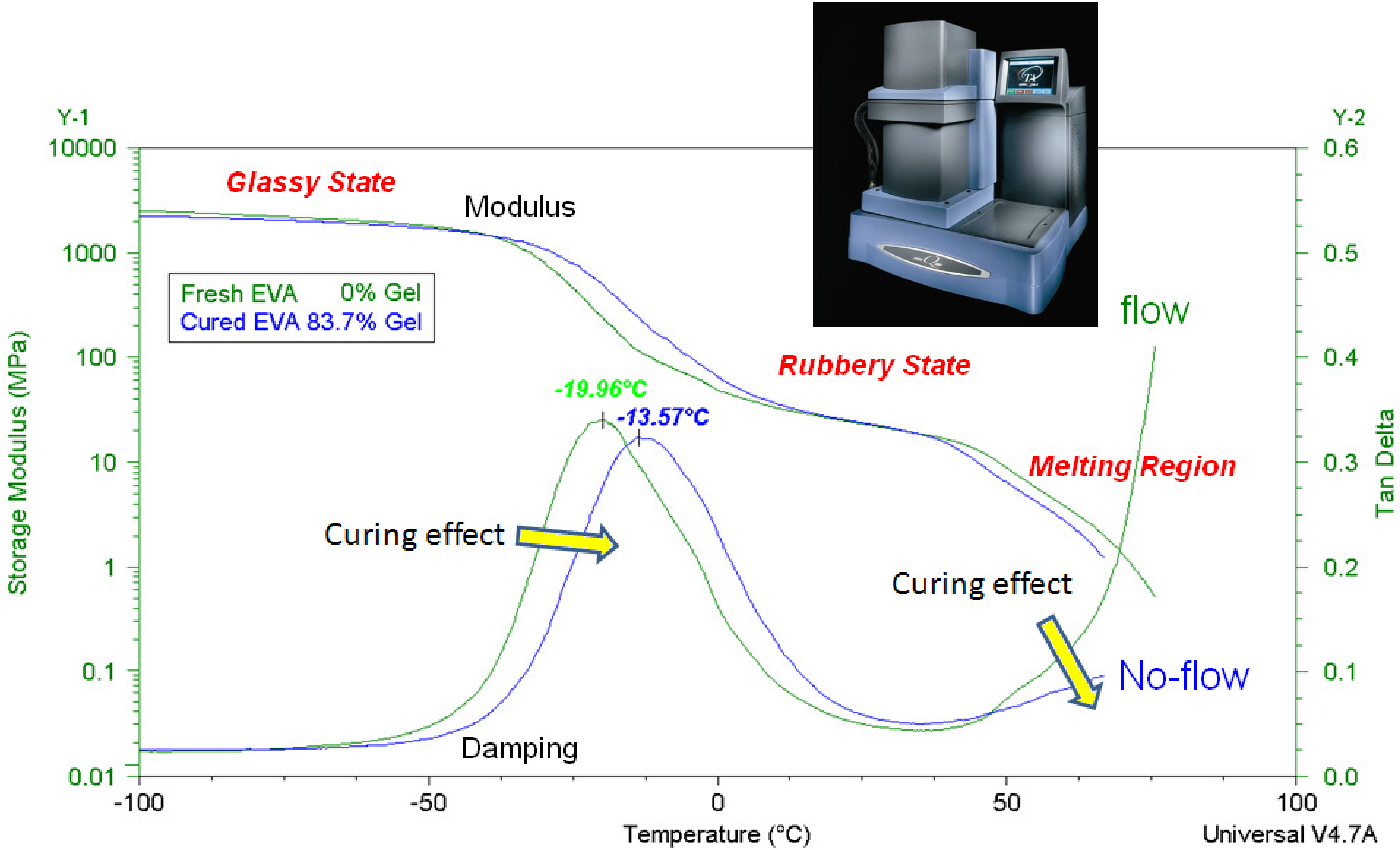
Simulation the Curing Degree of the Real EVA Lamination Process by Direct DSC Furnace Heat Treatment (Cont.)



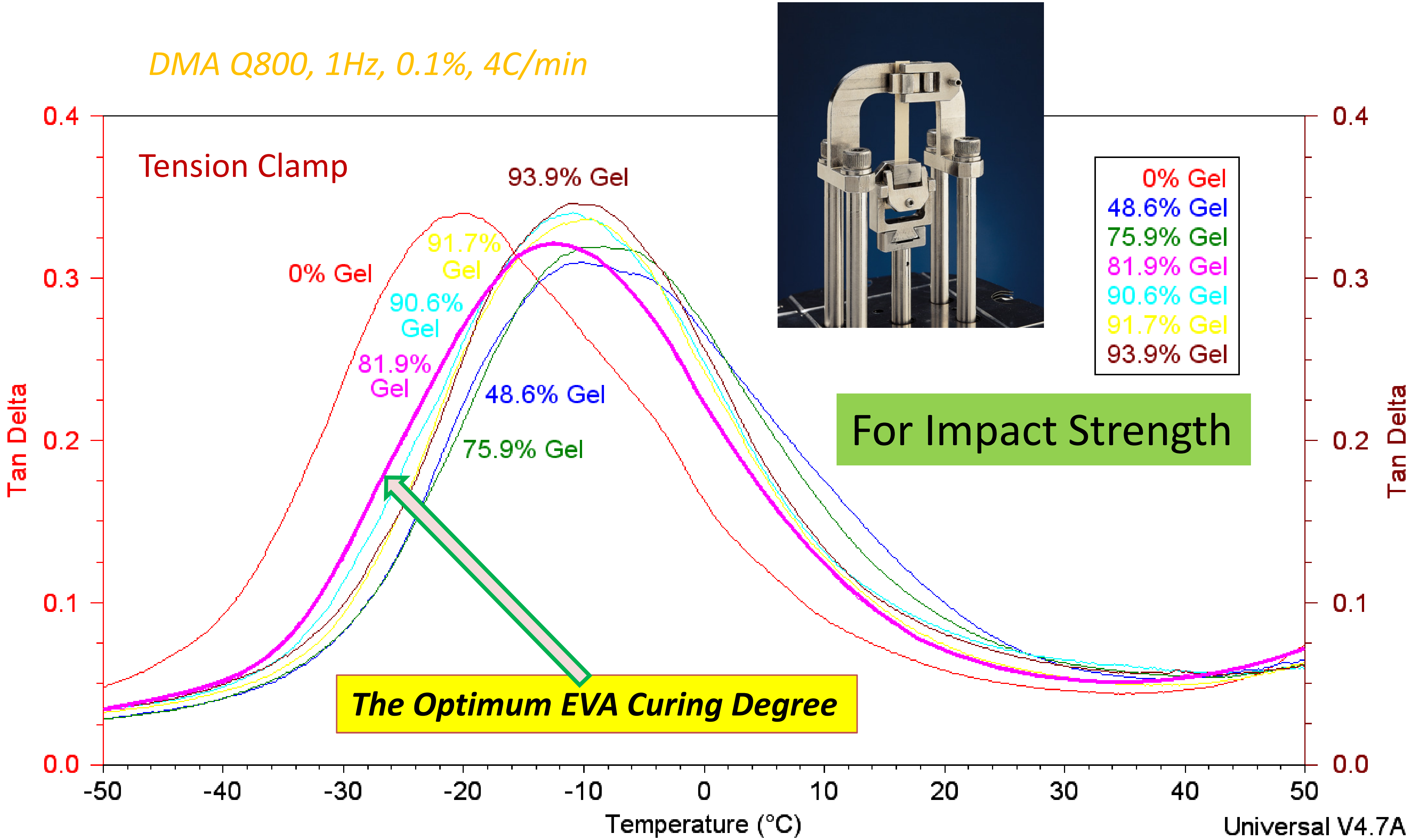
Use the Viscoelastic Properties to Evaluate What's the Optimum EVA Gel Content ?



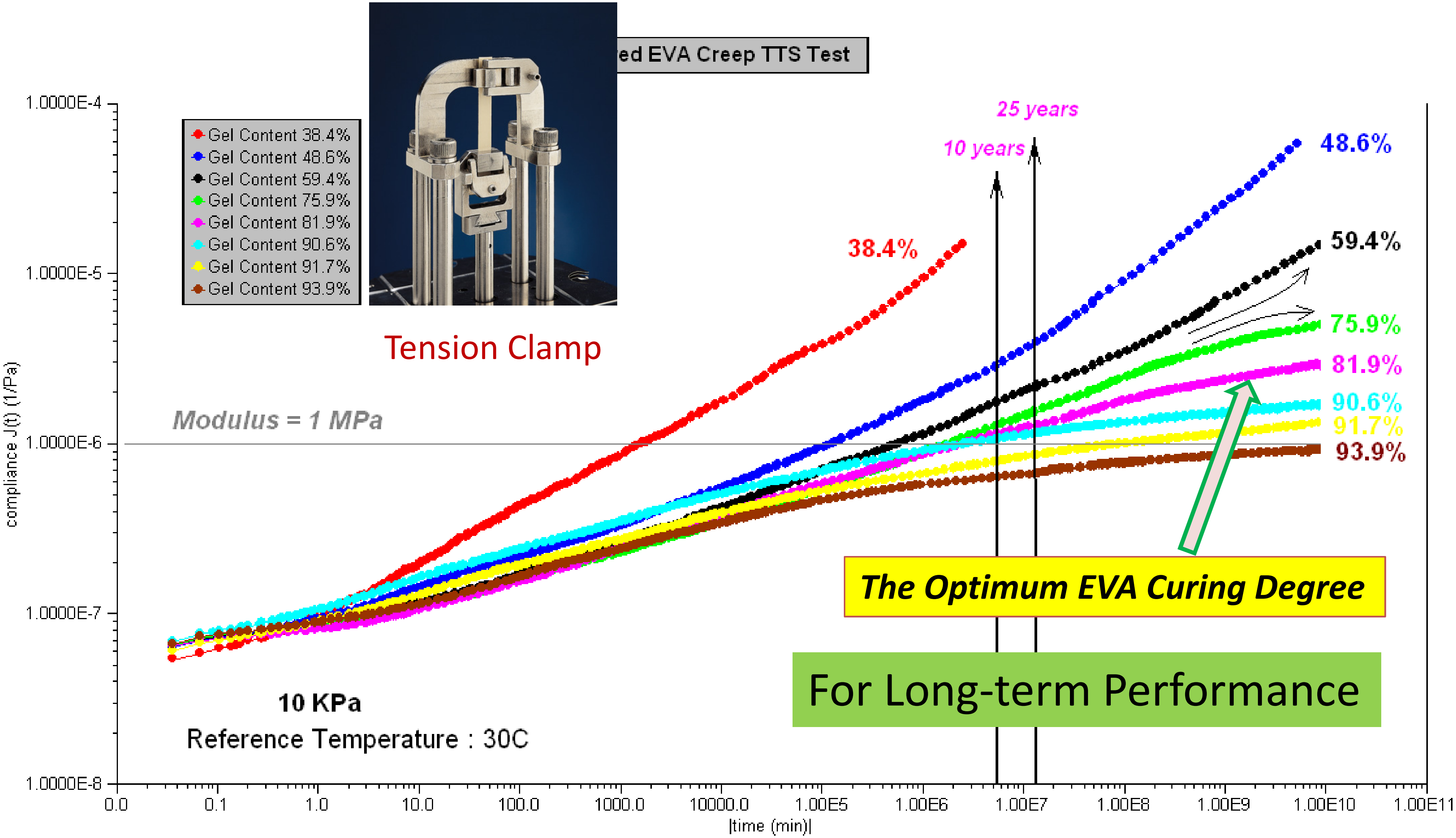
DMA Test to Get the Viscoelastic Properties Response for Fresh and Cured EVA Laminated



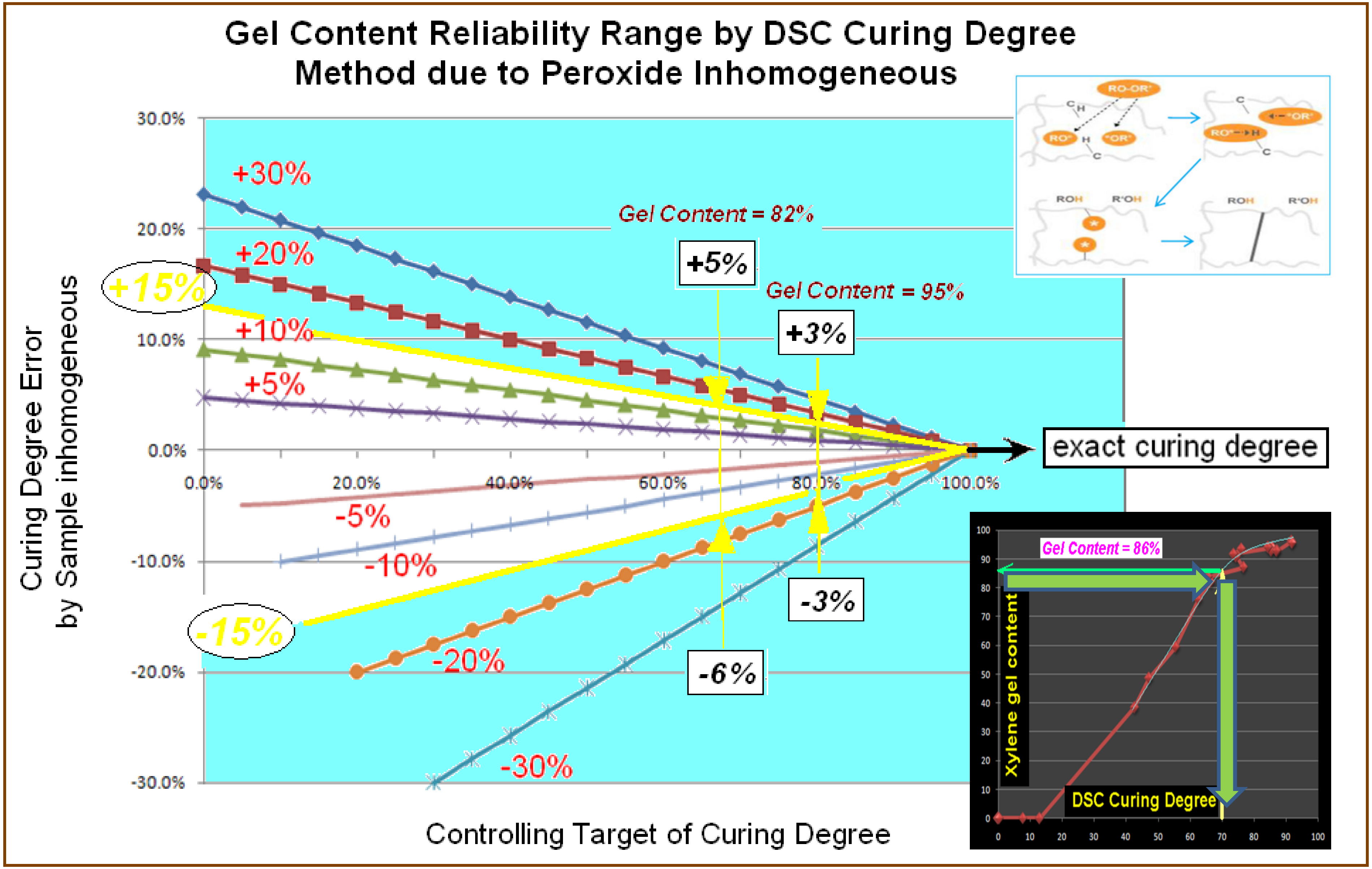
DMA Test : From the Tan Delta Low Temperature Damping Behavior to Get the Optimum EVA Curing Degree



DMA Test : From the Creep Time-Temperature-Superposition Method to Get the Optimum EVA Curing Degree

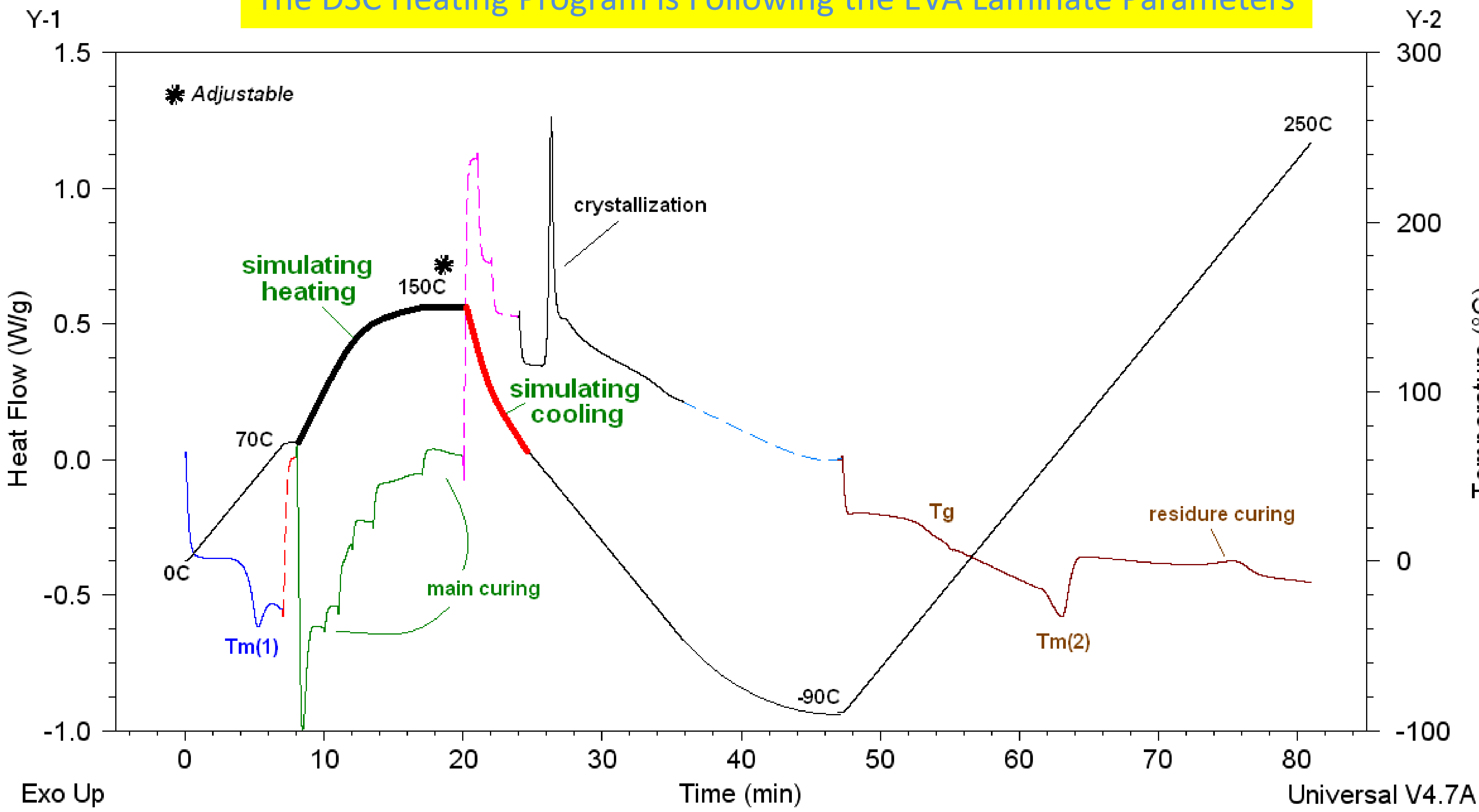


To Estimate the Possible Deviation For the EVA Gel Content Transformation From the DSC Curing Degree Method on the Optimum Control Position

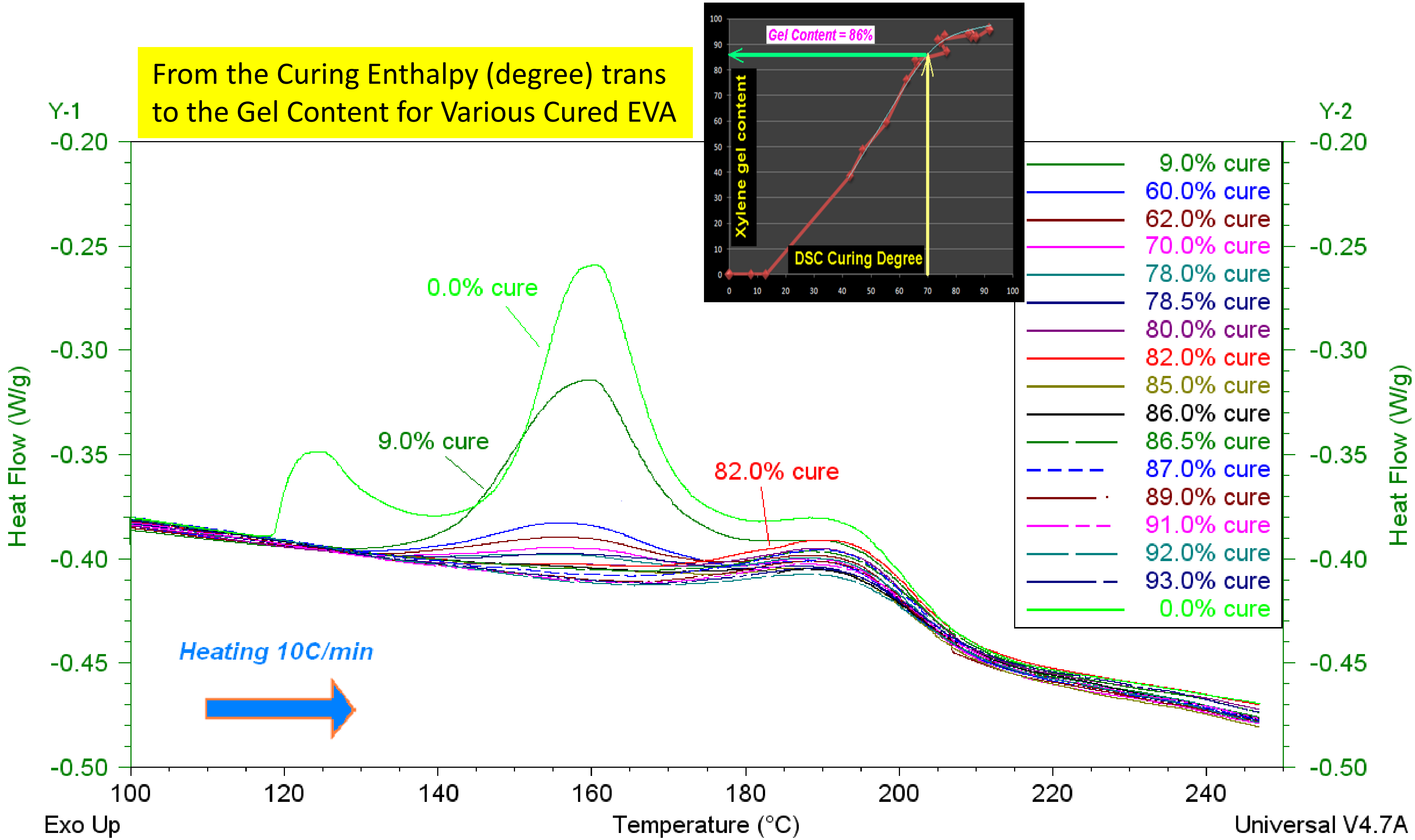


Double Check To Confirm the DSC Curing Degree Method through the Cooling Crystallization Way for Cured EVA

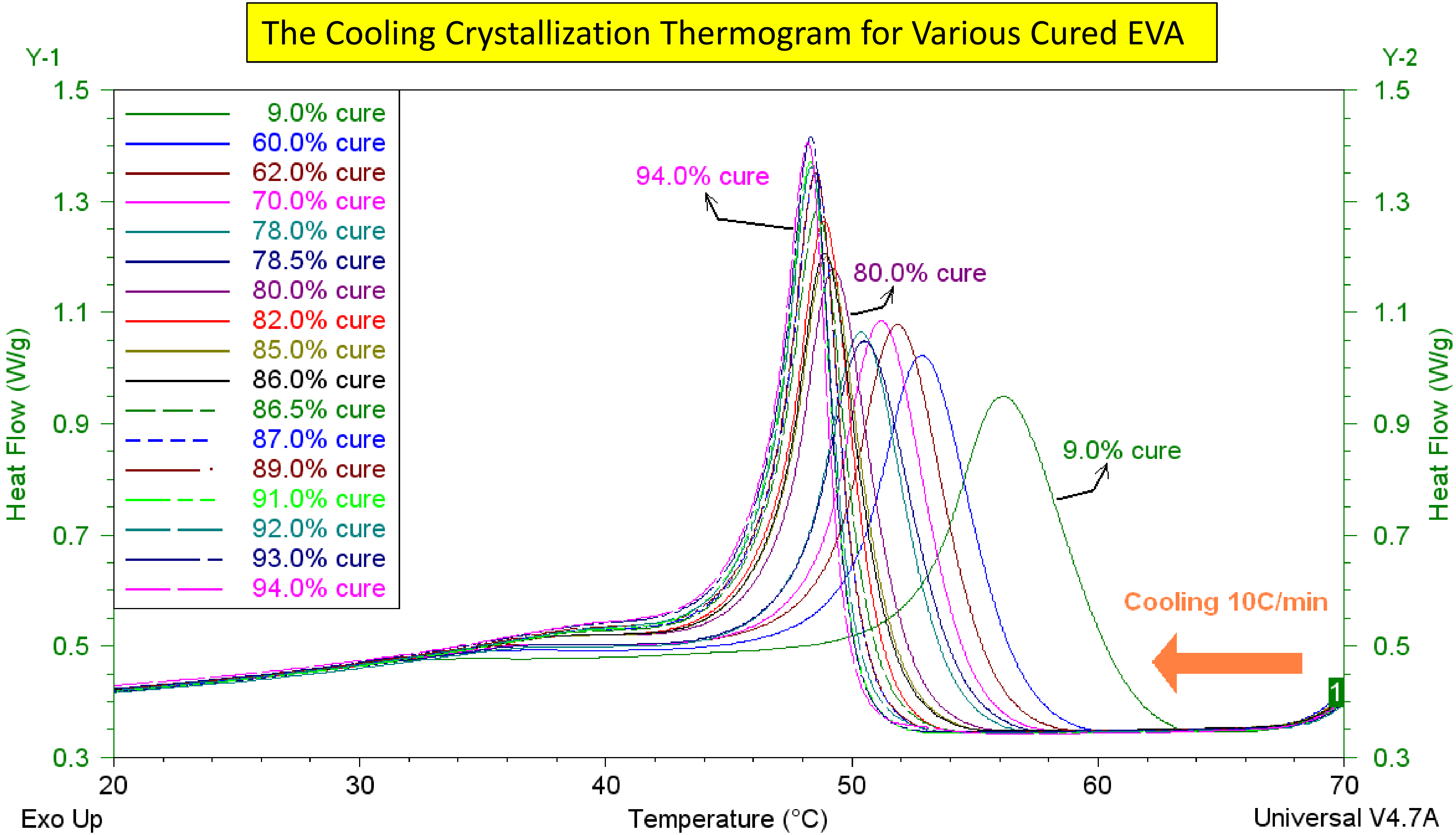
The DSC Heating Program is Following the EVA Laminate Parameters



Double Check To Confirm the DSC Curing Degree Method through the Cooling Crystallization Way for Cured EVA (Cont.)

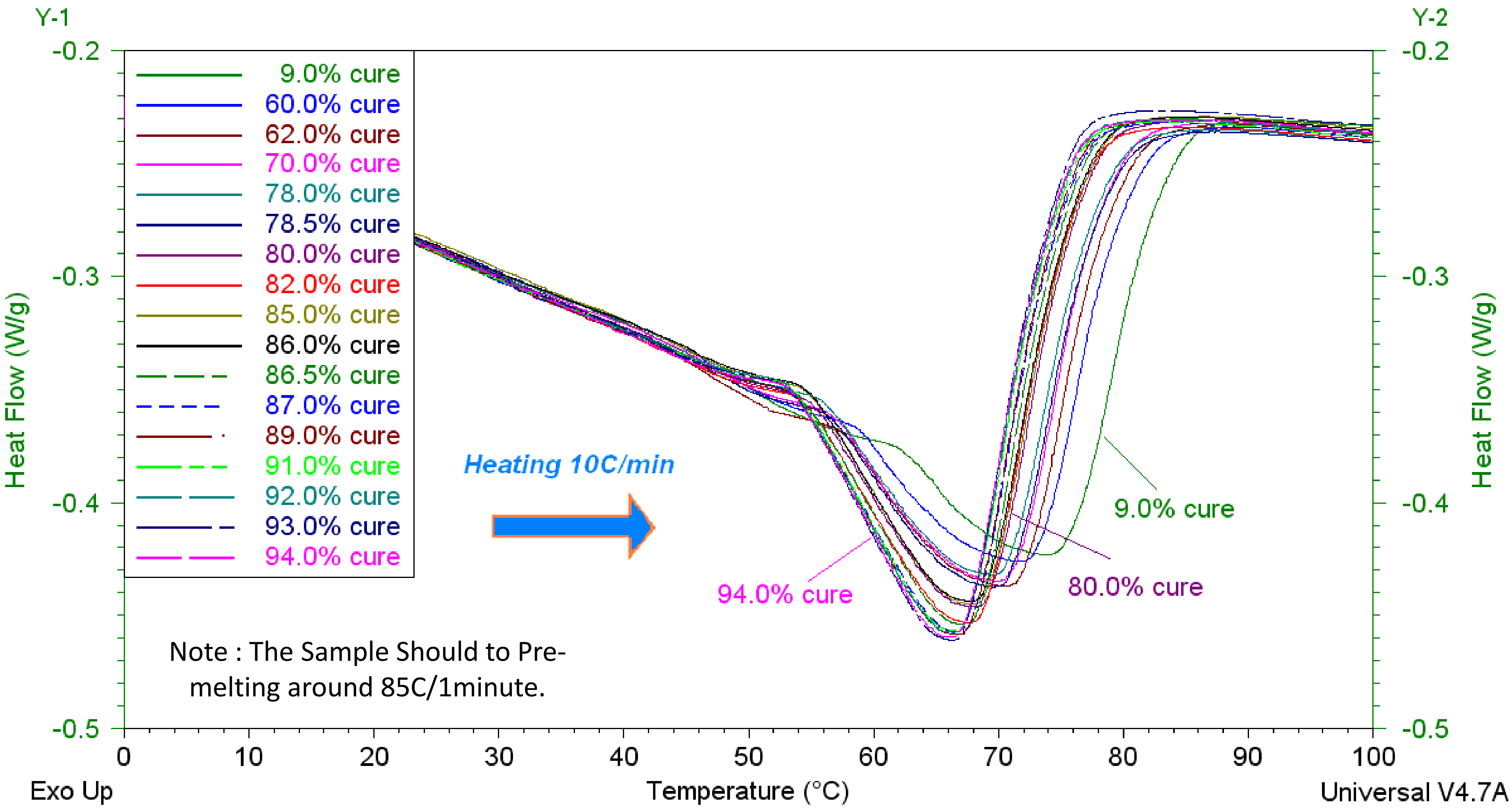


Double Check To Confirm the DSC Curing Degree Method through the Cooling Crystallization Way for Cured EVA (Cont.)

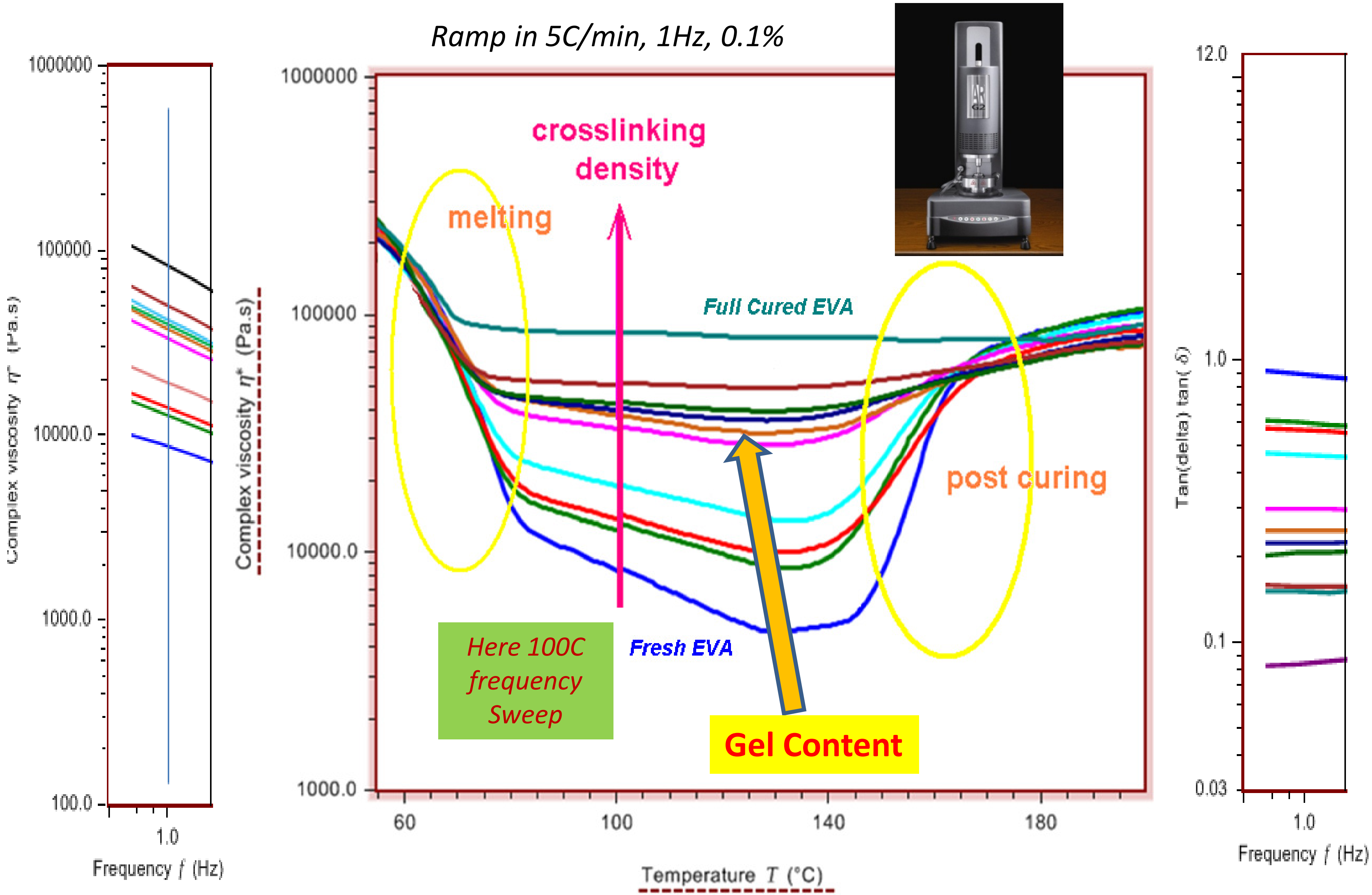


Triple Check To Confirm the DSC Curing Degree Method through the Heating Melting Way for Cured EVA

The Heating Melting Thermogram for Various Cured EVA



Rheology Method To Confirm the Gel Content for Cured EVA



Discussion

1. The DSC Curing Degree could trans to the Xylene Gel Content for Cured EVA in PV module.
2. The Materials Income Properties Stability of EVA for PV Module Purpose could be Studied by DSC Method.
3. The Cooling Crystallization and Re-heating Melting Behavior can ensure the Gel Content Calculation Results.
4. The Viscoelastic Properties of Cured EVA could Direct Related to its Gel Content or Crosslinking Structure better than DSC's Indirect Relationship.
5. DMA (Dynamic Mechanical Analyzer) and Rheology should be the More Important Measurement Tools for EVA Materials in the Future.