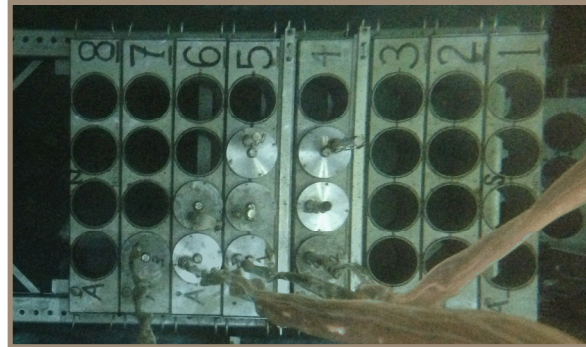


Exceptional service in the national interest



Nuclear Power Plant

Cable Aging at SNL

Sandia National Laboratories

Organic Materials Science Department

SNL's Core Polymer Aging Team

- Robert Bernstein
- John L. Schroeder
- Patricia S. Sawyer
- Derek J. Wichhart
- Guillermo A. Mata
- Amy Garner
- Kenneth T. Gillen (not shown)
- Greg White



Collaborators



National
Defence

Défense
nationale



SNL in Round Numbers

More than 9,400 full-time employees

1185 buildings, 6.5 M sq. feet

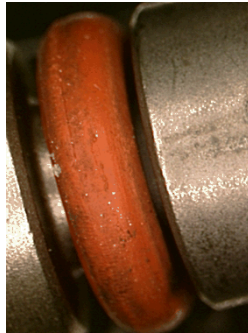
1,550 PhDs, 2,500 Masters

- Mechanical Engineering – 15%
- Electrical Engineering – 25%
- Other Engineering – 14%
- Other Fields – 11%
- Physics – 8%
- Chemistry – 7%
- Math – 3%
- Computing – 11%
- Other – 6%

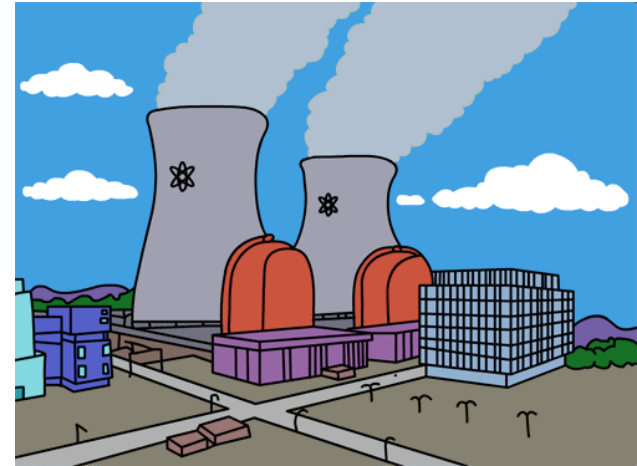
Annual budget ~ \$2.4B



Organic Materials Employed in Service for Decades in Critical High Reliability and Performance Applications



O-rings



Nuclear Power Plant Cable Insulation



Textiles/Fibers



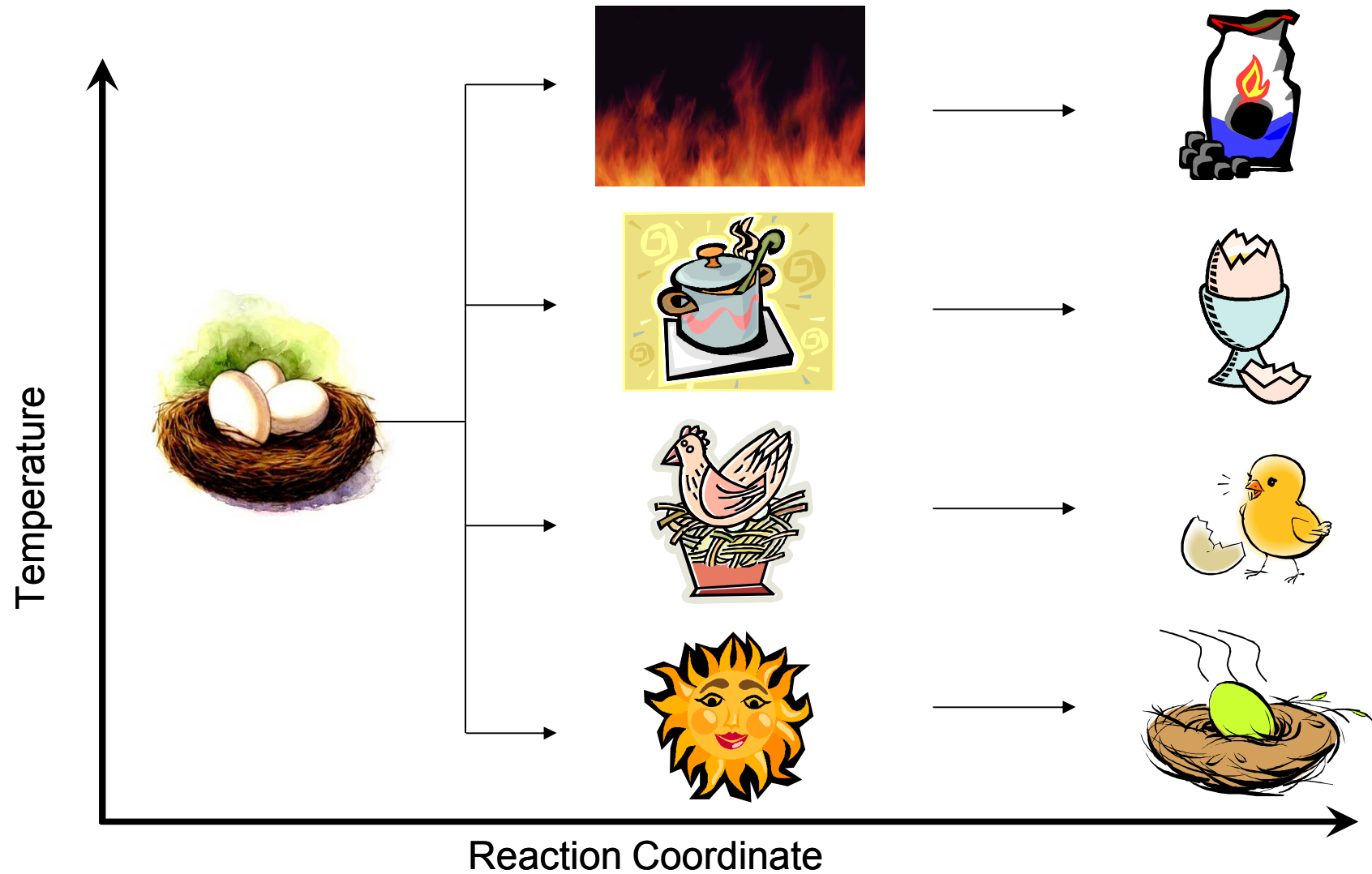
Glass Fiber Reinforced Epoxies

How do we accelerate time?

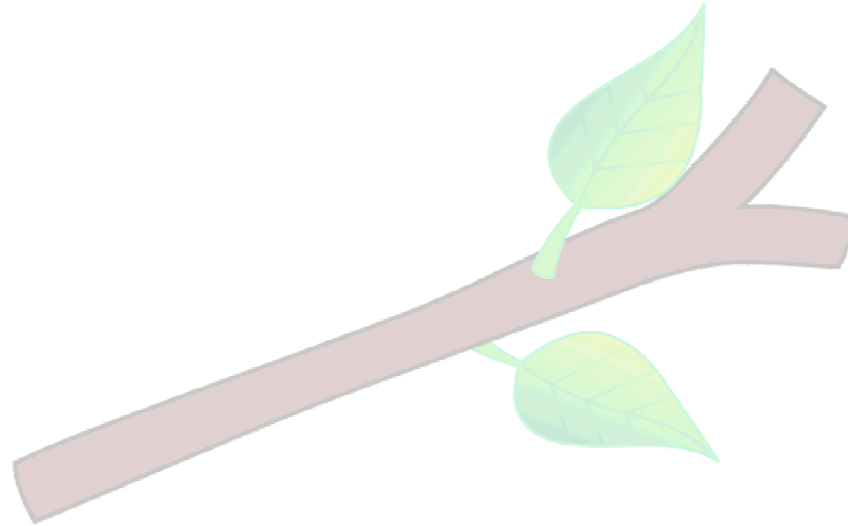


None of these are available or approved through **SNL suppliers!**

How do we accelerate time?



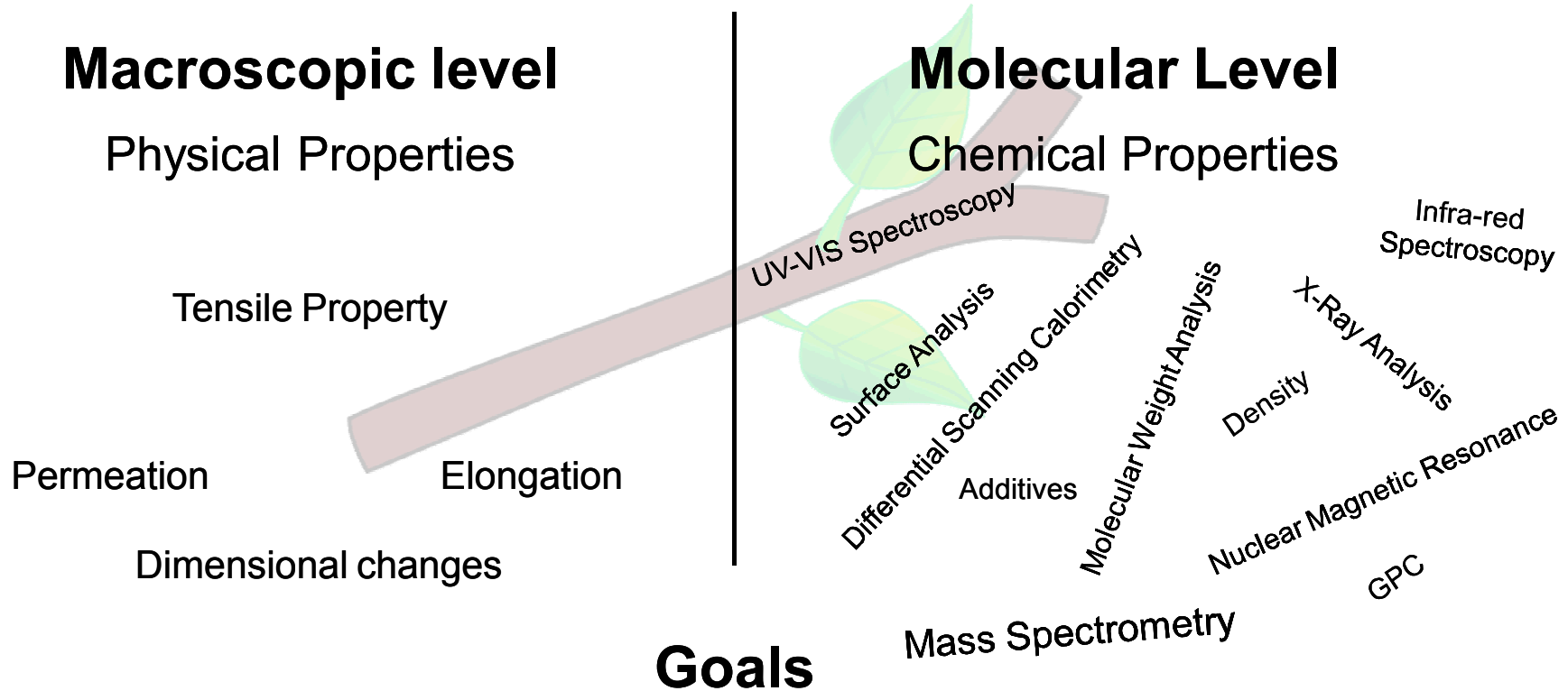
Polymer Aging - Approaches/Goals



Goals

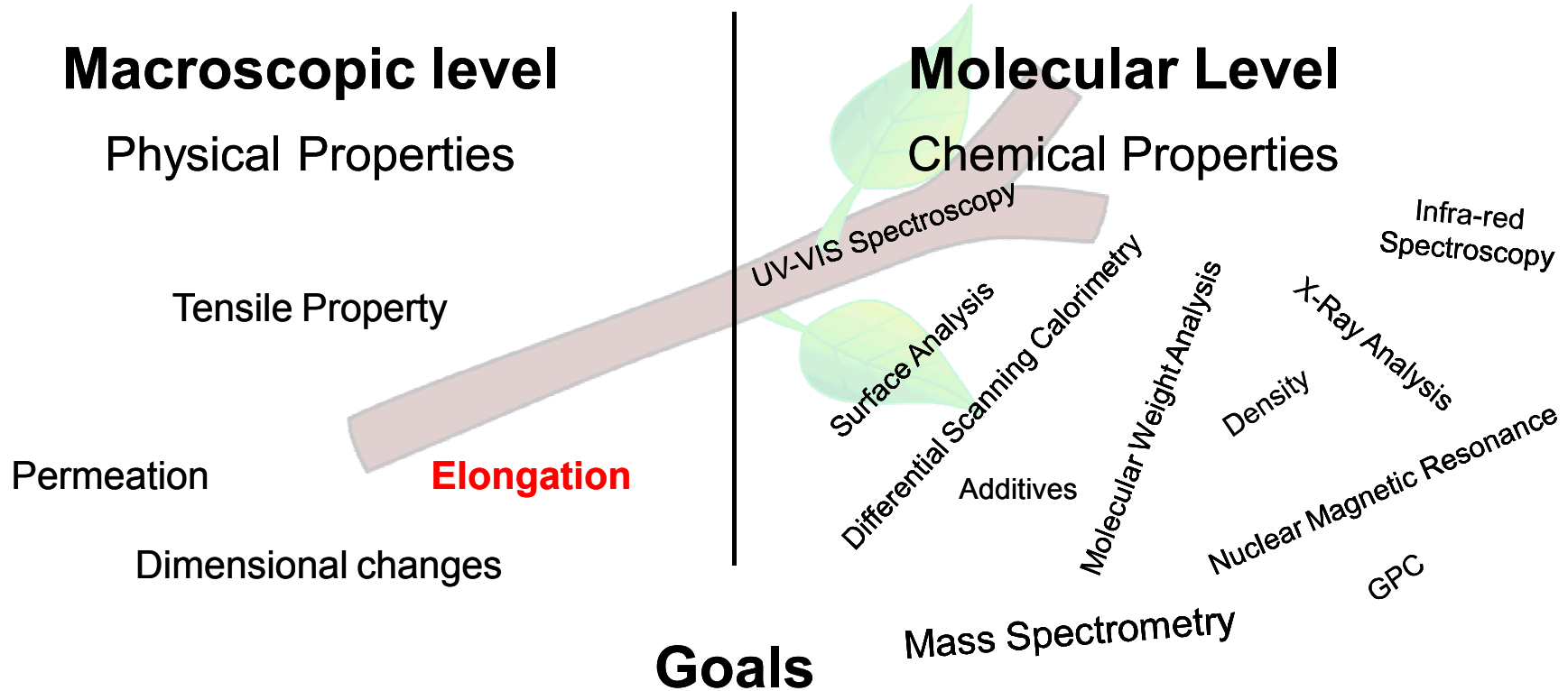
- Prediction of physical properties vs. time
 - Predict remaining physical properties of field materials
- Develop condition monitoring method

Polymer Aging - Approaches/Goals



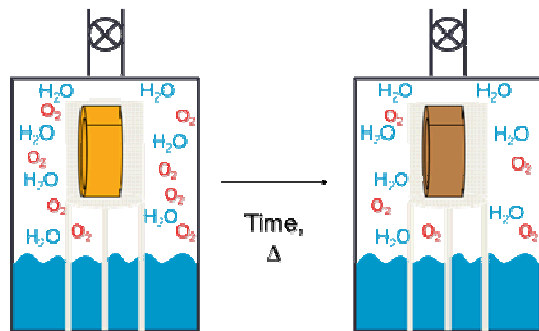
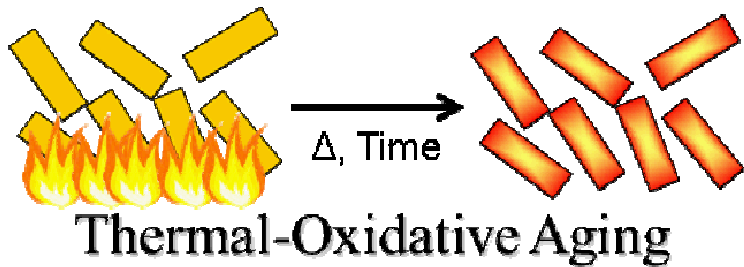
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Polymer Aging - Approaches/Goals

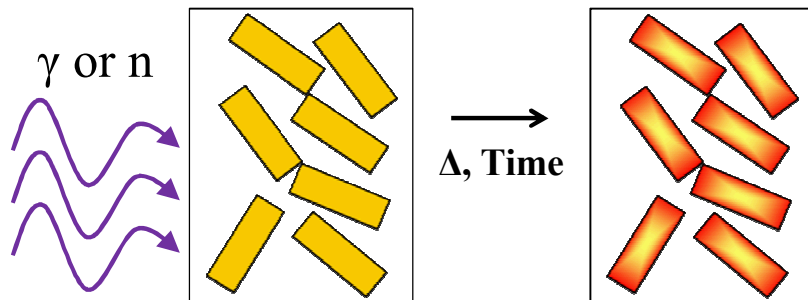


- **Prediction of physical properties vs. time**
 - **Predict remaining physical properties of field materials**
- Develop condition monitoring method

Methodologies

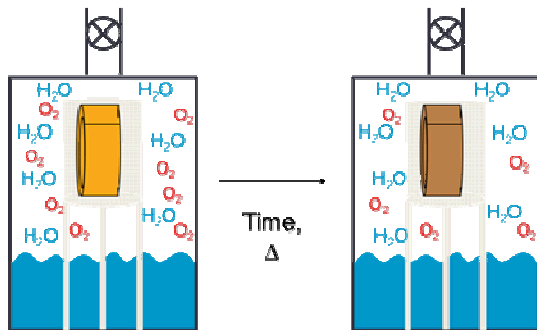
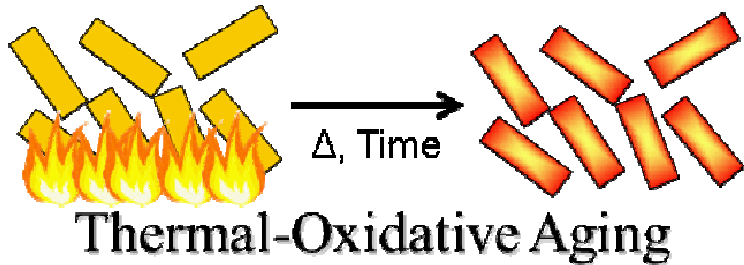


Humidity Aging

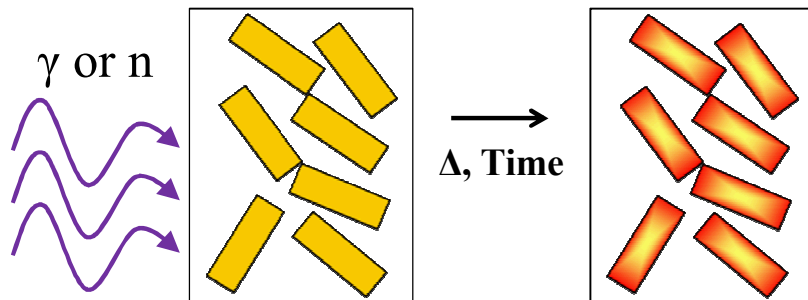


Radiation Aging

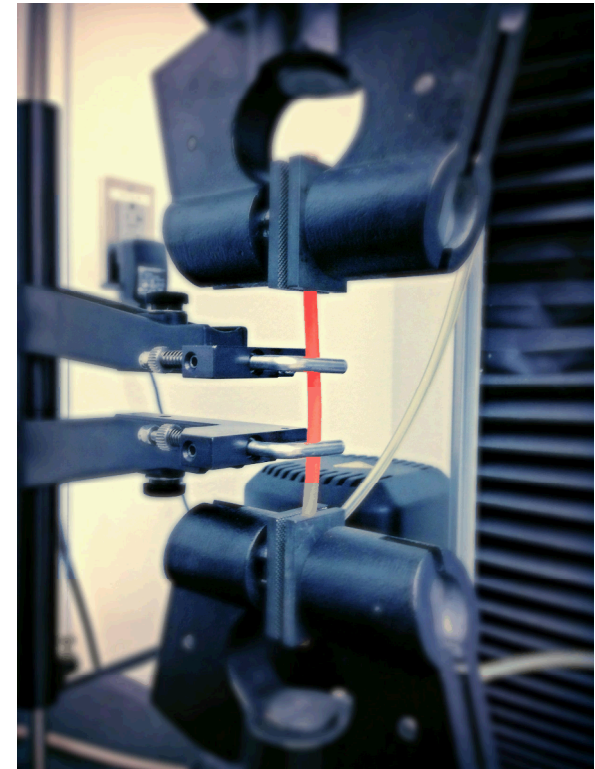
Methodologies



Humidity Aging

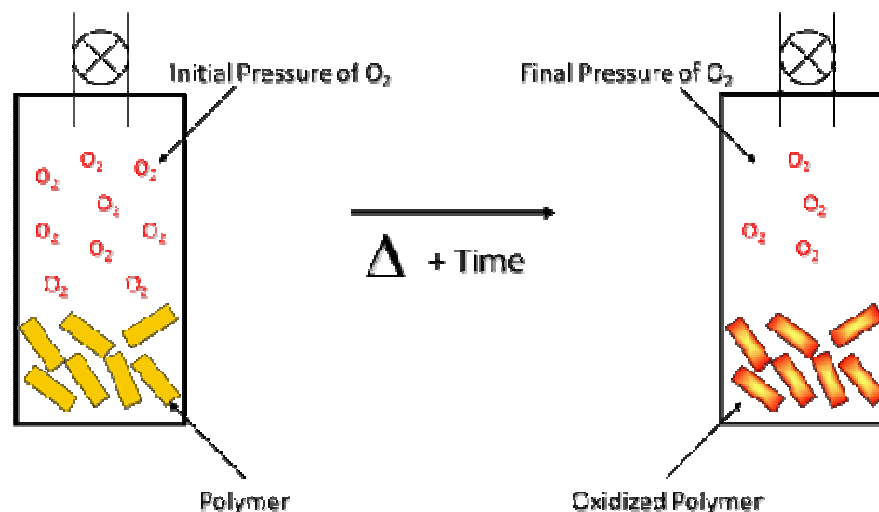


Radiation Aging

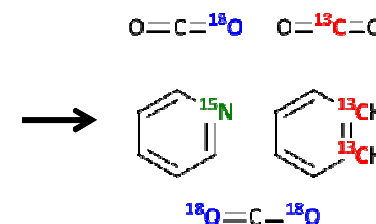
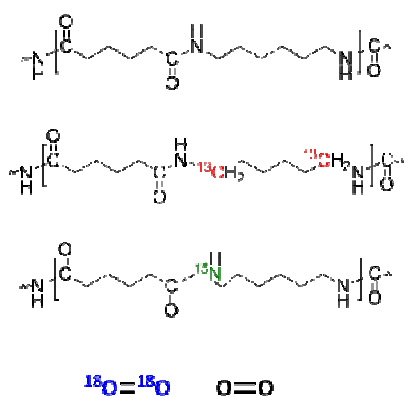


Tensile Testing

Methodologies



Oxygen Consumption



Proposal of Underlying Degradation Mechanisms

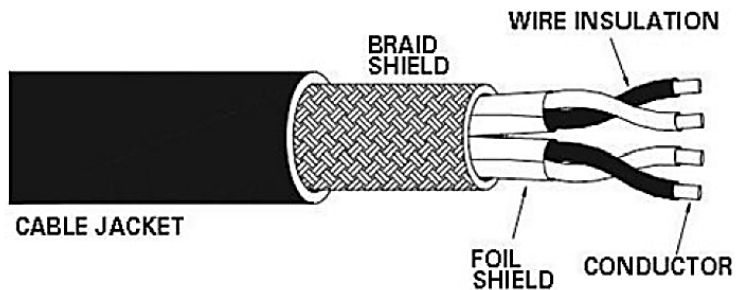
Power Plant Cables



Nuclear Power Plant Cable Insulation

One of the 5 critical concerns for license renewal of US Nuclear Power Plants (NPPs)

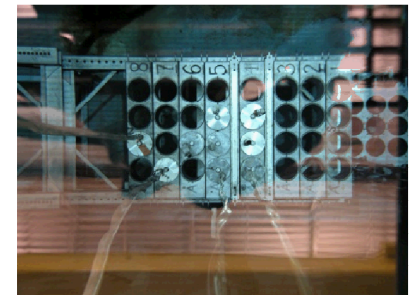
IEEE 383-1974: ~50 Mrad (500 kGy) in 40 years at 50 °C



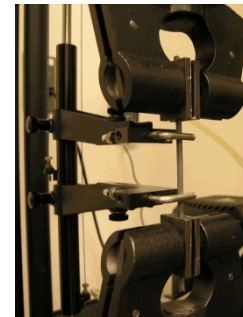
Hashemian, Nuclear Technology 2011, vol. 176, 414-429



Sample
Prep

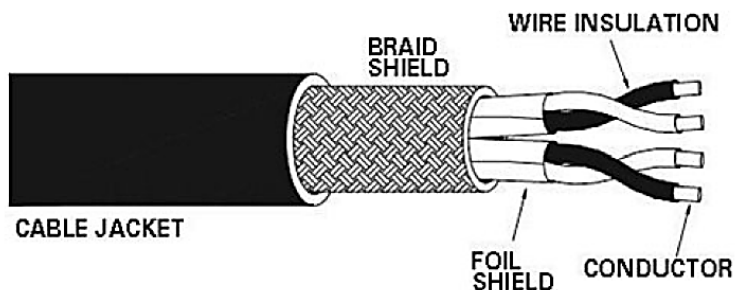


Aging



Tensile Testing

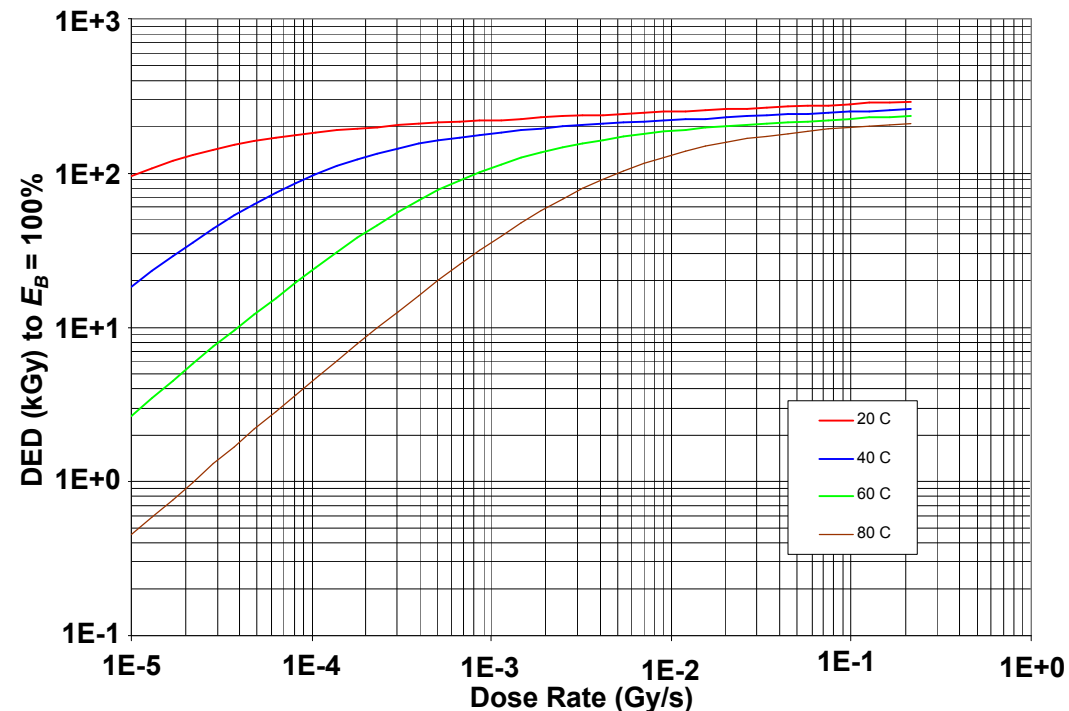
Power Plant Cables



Hashemian, Nuclear Technology 2011, vol. 176, 414-429

Nuclear Power Plant Cable Insulation

One of the 5 critical concerns for license renewal of US Nuclear Power Plants (NPPs)



IAEA Nuclear Energy Series "Assessing and Managing Cable Ageing in Nuclear Power Plants" IEAE No. NP-T-3.6

Dose-to-Equivalent Damage = DED

DED is assumed to be $E_B = 100\%$

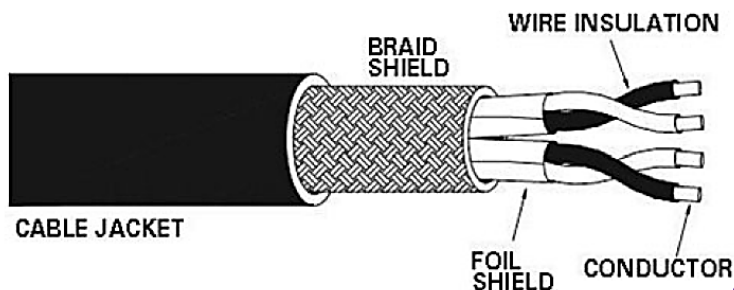
(IEEE Standards Define End-of-Life when a cable achieves $E_B = 50\%$)

Power Plant Cables



Nuclear Power Plant Cable Insulation

One of the 5 critical concerns for license renewal of US Nuclear Power Plants (NPPs)

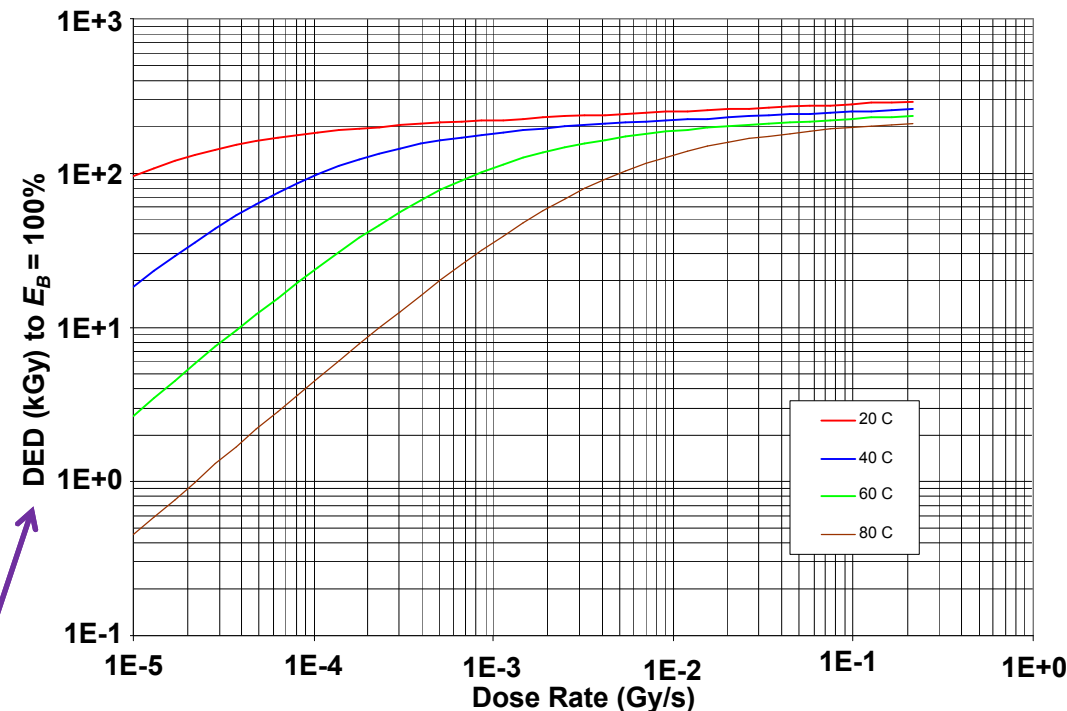


Hashemian, Nuclear Technology 2011, vol. 176, 414-429

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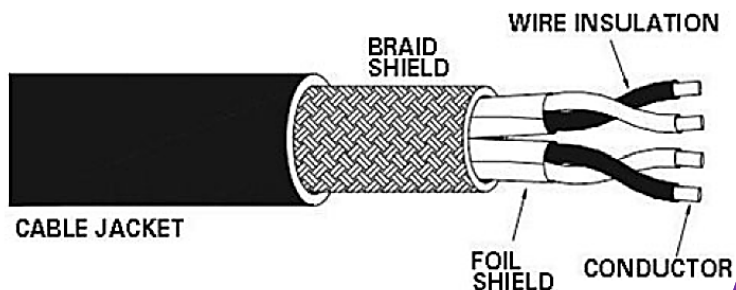
IAEA Nuclear Energy Series "Assessing and Managing Cable Ageing in Nuclear Power Plants" IEAE No. NP-T-3.6

Power Plant Cables



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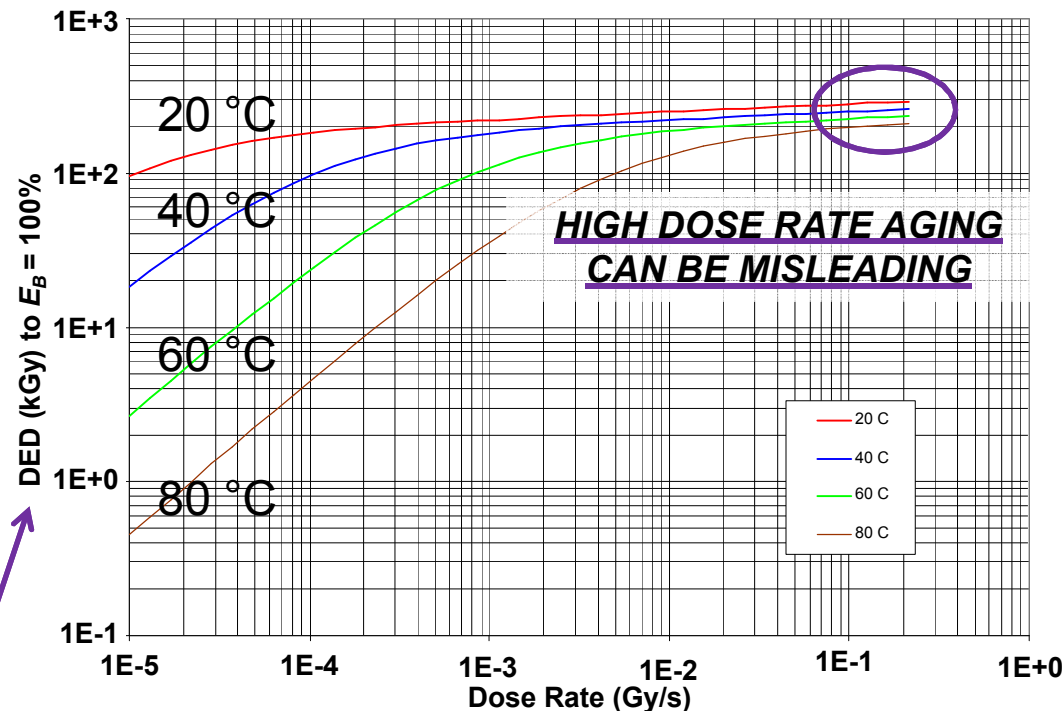


Hashemian, Nuclear Technology 2011, vol. 176, 414-429

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IAEA Nuclear Energy Series "Assessing and Managing Cable Ageing in Nuclear Power Plants" IEAE No. NP-T-3.6

Cables Insulation Types of Interest

Rank	Insulation Material	Entries	Percentage of total
1	XLPE	439	36
2	EPR	434	36
3	Silicone rubber	63	5
4	Kerite	61	5
5	Polyethylene	52	4
6	ETFE	39	3
7	Flame retardant	36	3
8	CSPE	28	2
9	Butyl rubber	20	2
10	Mineral	12	1
11	PVC	12	1
12	Polyimide	8	1
13	Polypropylene	3	0
14	XLN (cross-linked neoprene)	3	0
15	Neoprene	2	0
16	Industrite	2	0
17	Styrene	1	0
	Total	1215	

Cables Insulation Types of Interest

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	Total	1215	

SNL is actively studying XLPE, EPR, and SiR Cables of interest

What are expected accumulated doses and dose rates?

UTILITY ENVIRONMENTAL DATA

PWR At-Power Dose Survey: Summary and Conclusions

Presented at: ASTM D33 Committee Meeting
West Conshohocken, PA

Presented by: Tim Andreychek
Westinghouse Electric Co., LLC
andreyts@westinghouse.com
(412) - 374 - 6246

Date: June 11, 2001

June 11, 2001

PWR_At-Power_Dose_Summary

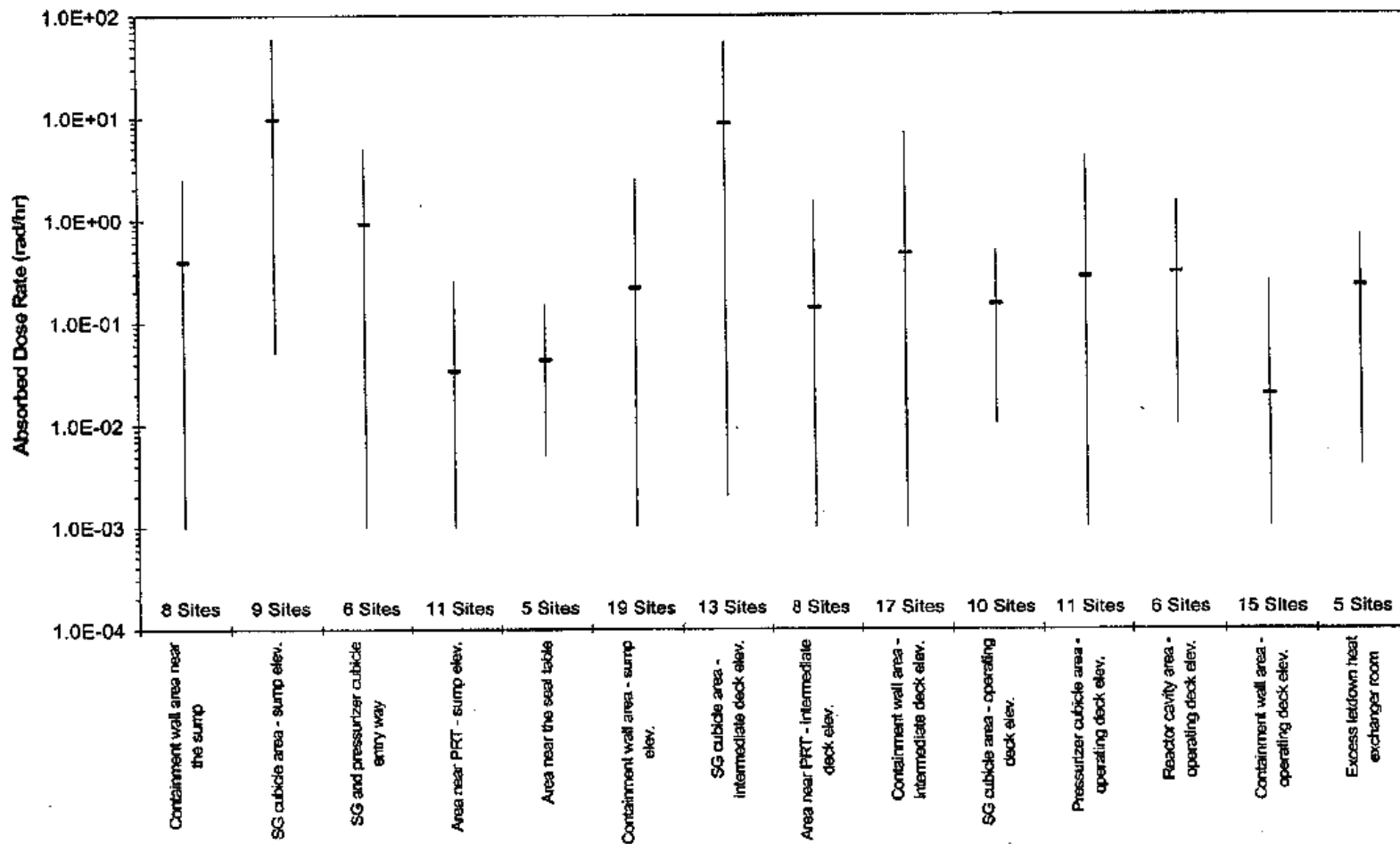
1

Thank you Drew Mantey and EPRI for passing this information onto our team!

Lots of Plants included in PWR Study...

- Beaver Valley
- Braidwood Units
- Callaway
- Comanche Peak
- Diablo Canyon
- Indian Point
- Kewaunee
- KRSKO
- Milestone
- North Anna
- Prairie Island
- Salem
- Crystal River
- Oconee
- TMI
- Waterford
- Sequoyah
- Shearon Harris
- South Texas Project
- Surry
- Turkey Point
- V.C. Summer
- Vogtle
- Wolf Creek
- ANO
- Calvert Cliffs
- Fort Calhoun
- Palisades
- Palo Verde
- St. Lucie
- SONGS

Gamma Dose Rates



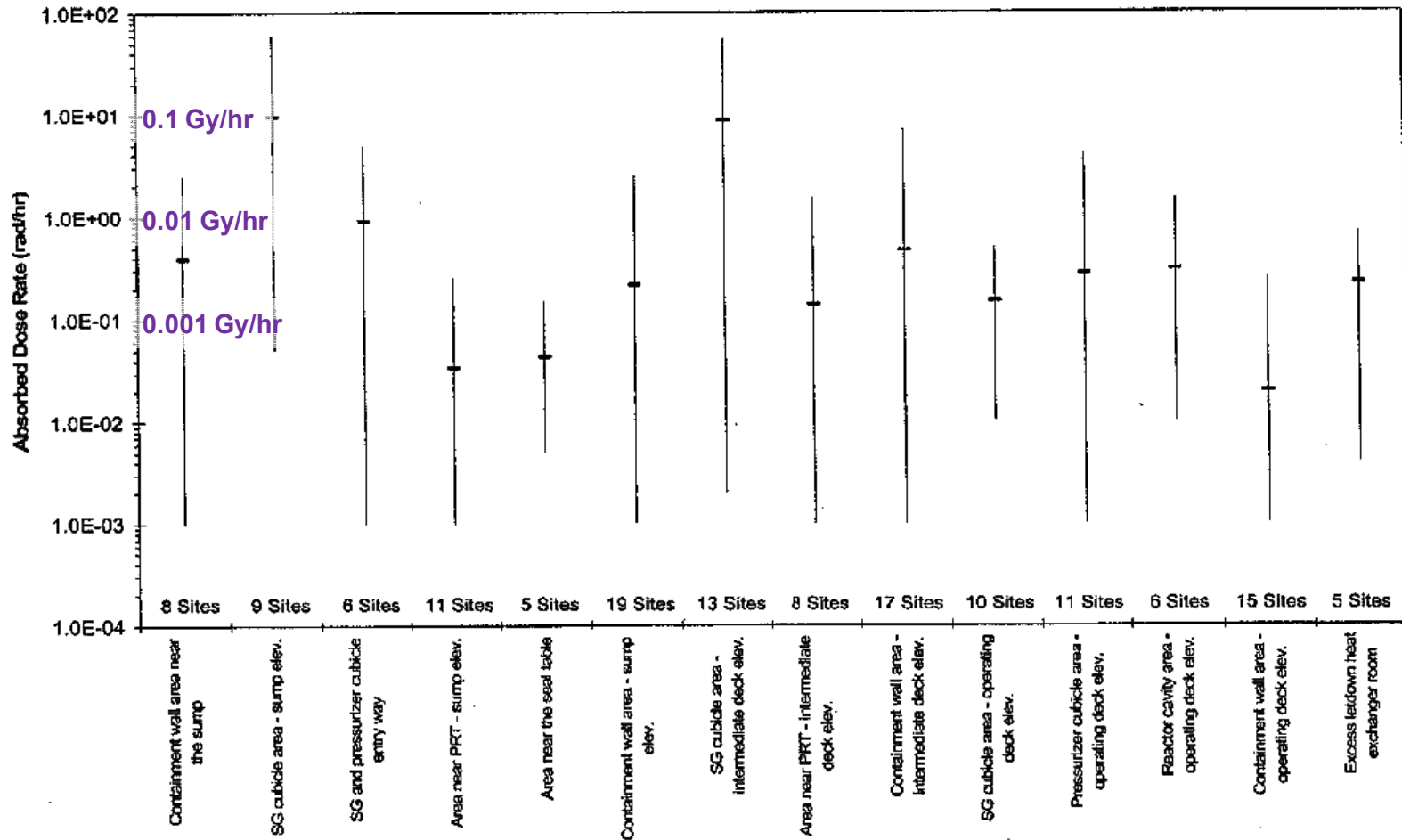
June 11, 2001

PWR_At-Power_Dose_Summary

11

Gamma Dose Rates

Measured dose rates are on average $< \sim 0.1$ Gy/hr



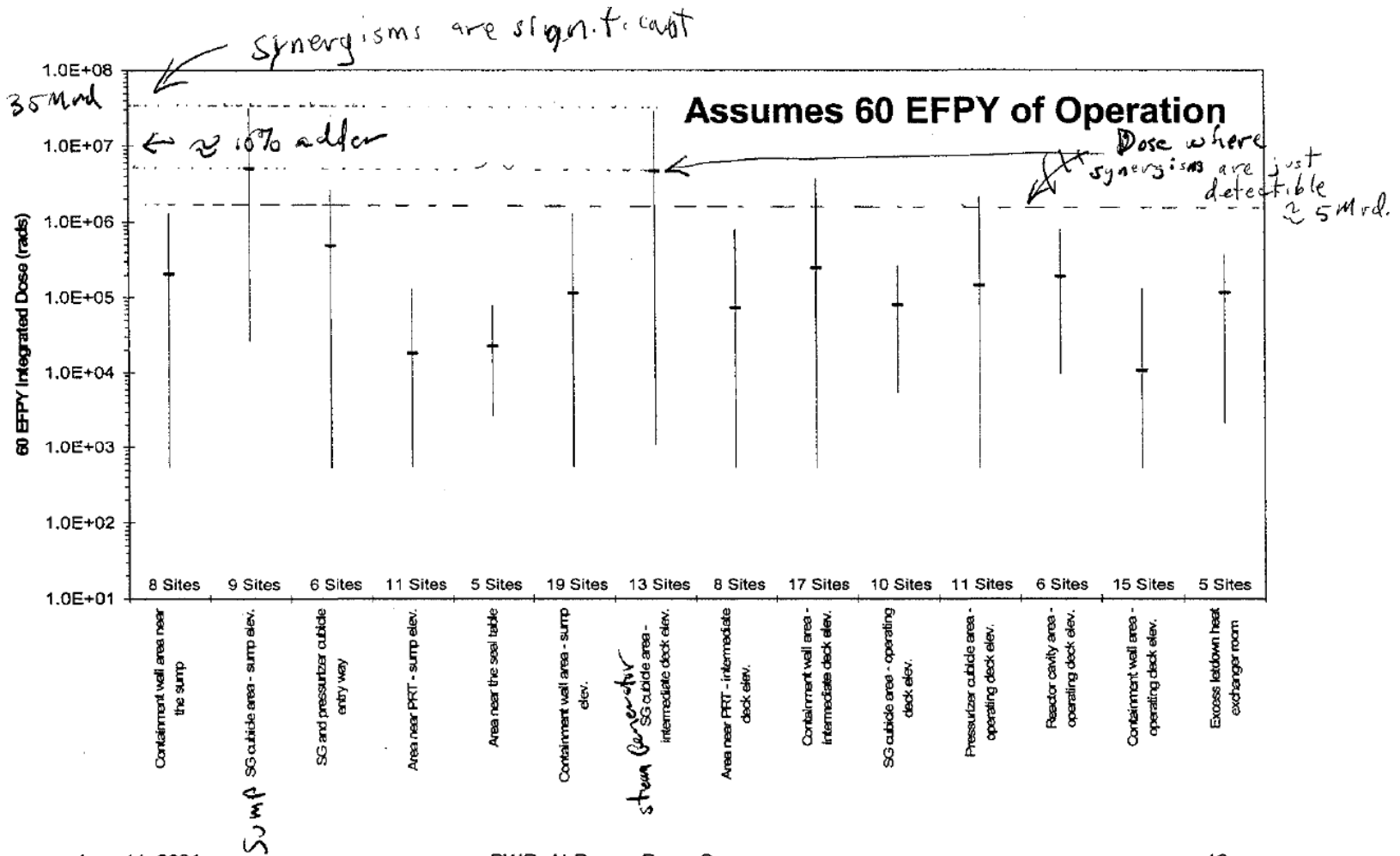
June 11, 2001

PWR_At-Power_Dose_Summary

11

Total Integrated Dose to 60 years

Reported dose rates were extrapolated to total integrated dose after 60 Effective Full Power Years.



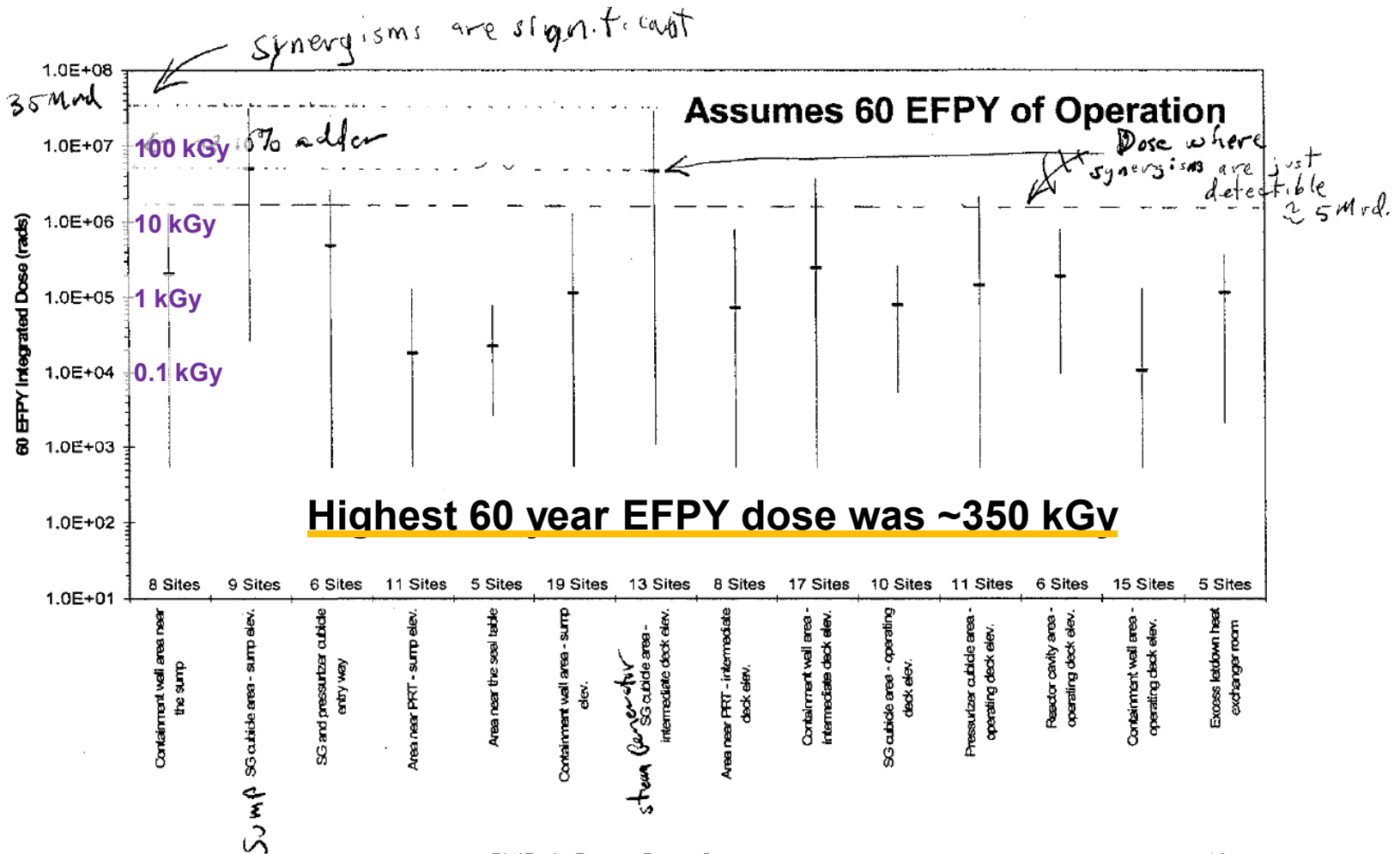
June 11, 2001

PWR_At-Power_Dose_Summary

12

Total Integrated Dose to 60 years

Reported dose rates were extrapolated to total integrated dose after 60 Effective Full Power Years.



June 11, 2001

PWR_At-Power_Dose_Summary

12

NEPO 51 – CSPE Jacket/EPR Insulation

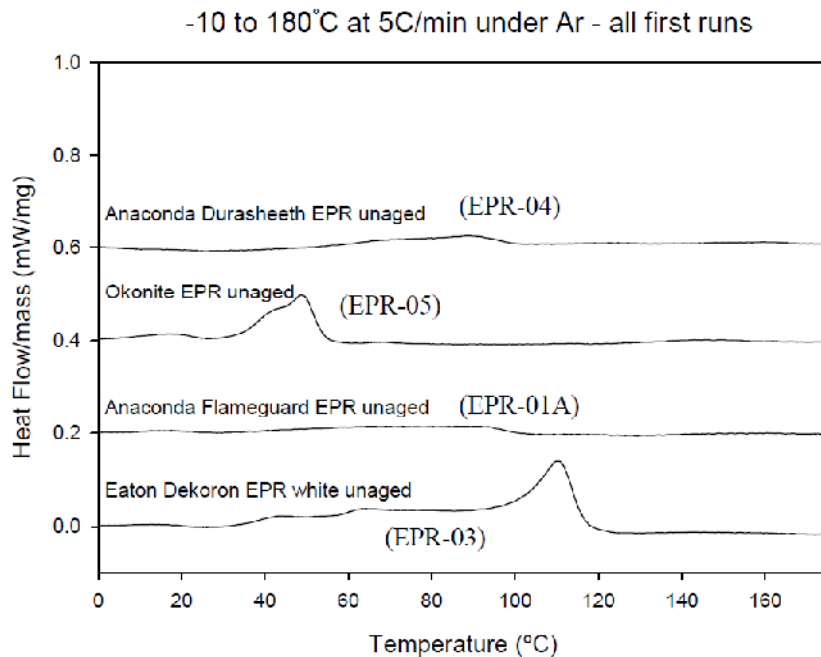
EATON DEKORON EPR



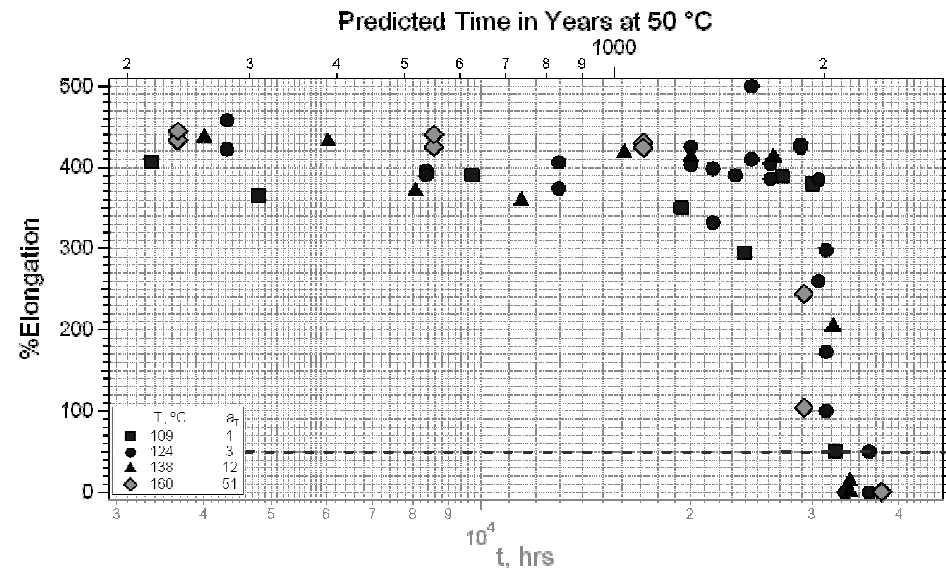
Ethylene Propylene Rubber (EPR)

Eaton Dekoron Elastoset EPR Cable Insulation

Highly crystalline polymer



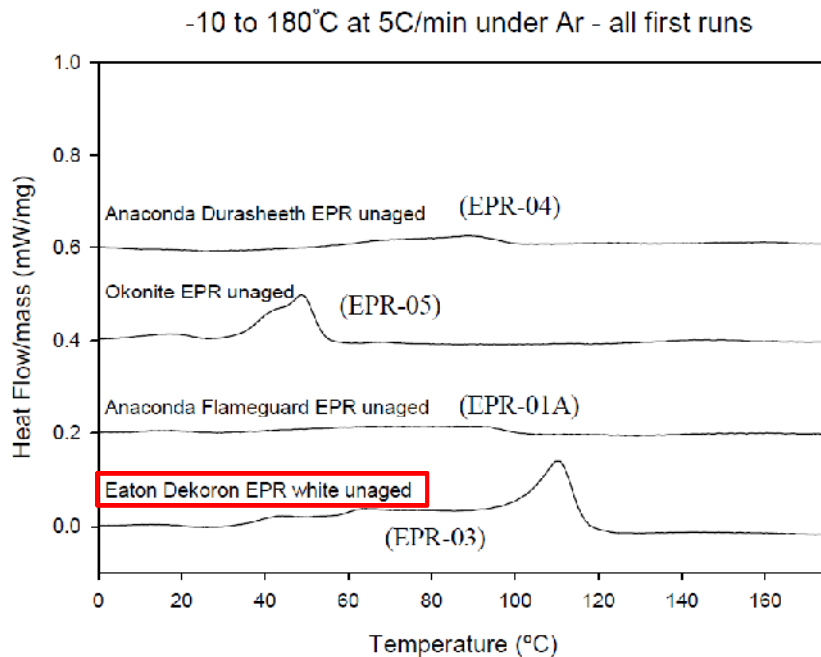
Exhibits Large “Induction Time”



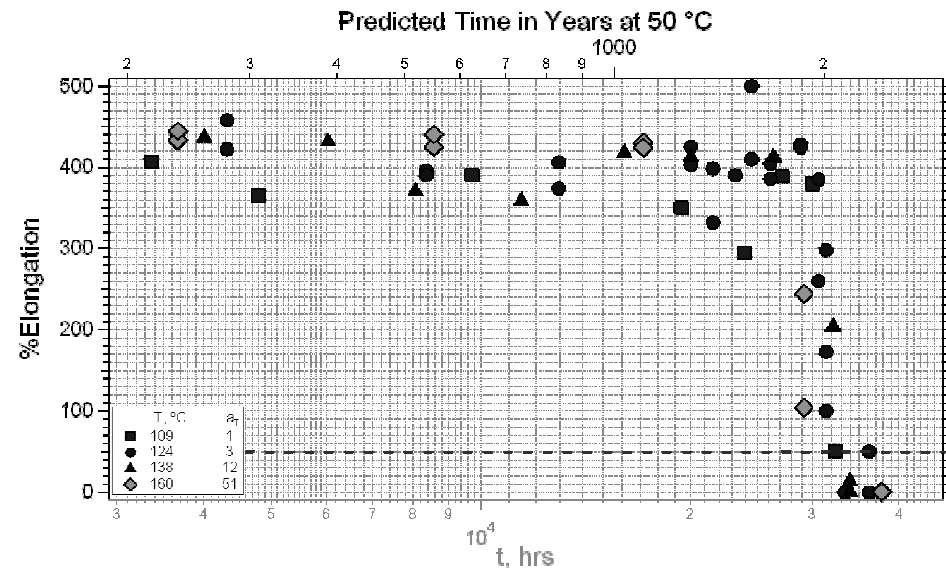
Ethylene Propylene Rubber (EPR)

Eaton Dekoron Elastoset EPR Cable Insulation

Crystalline polymer

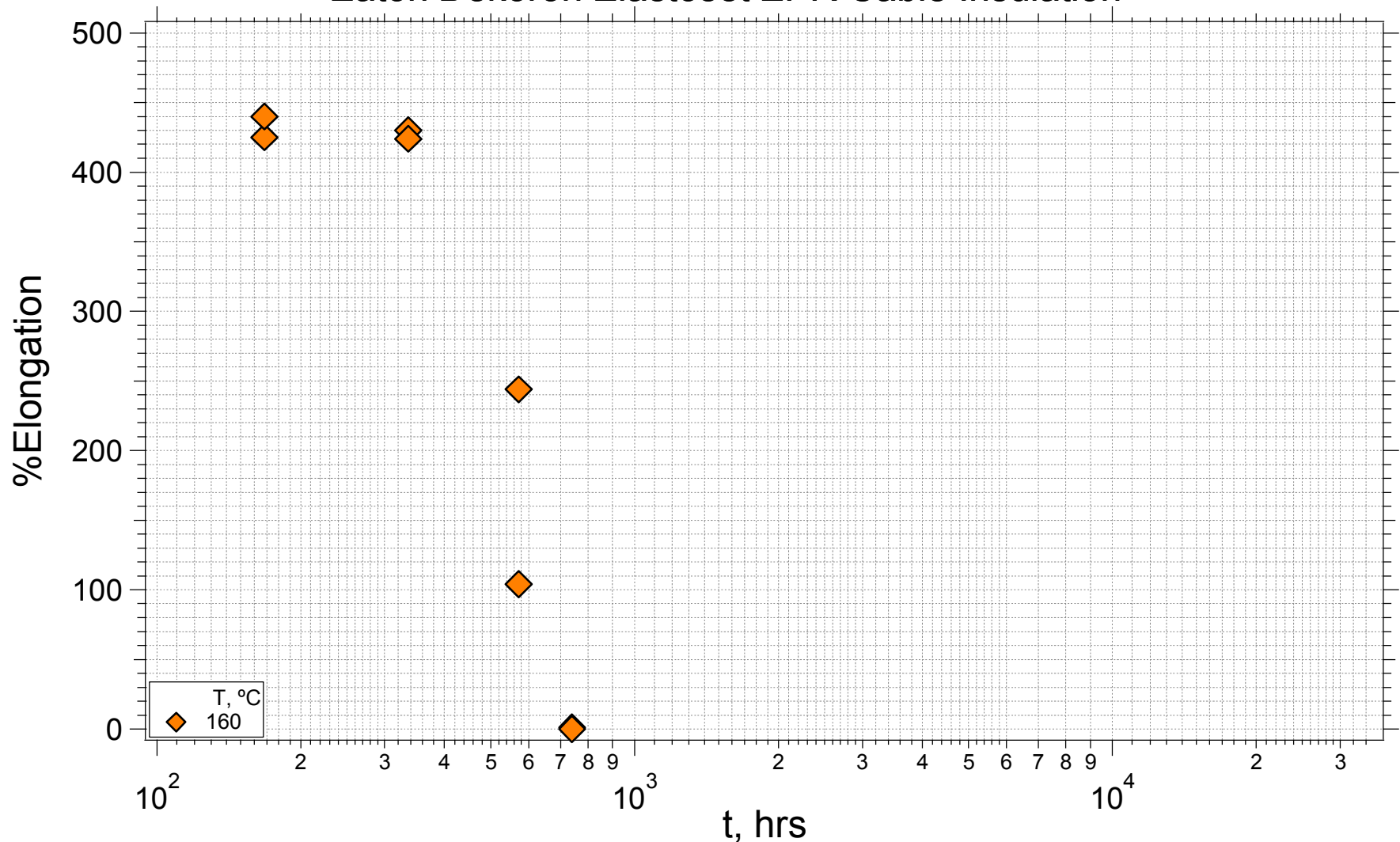


Exhibits Large “Induction Time”



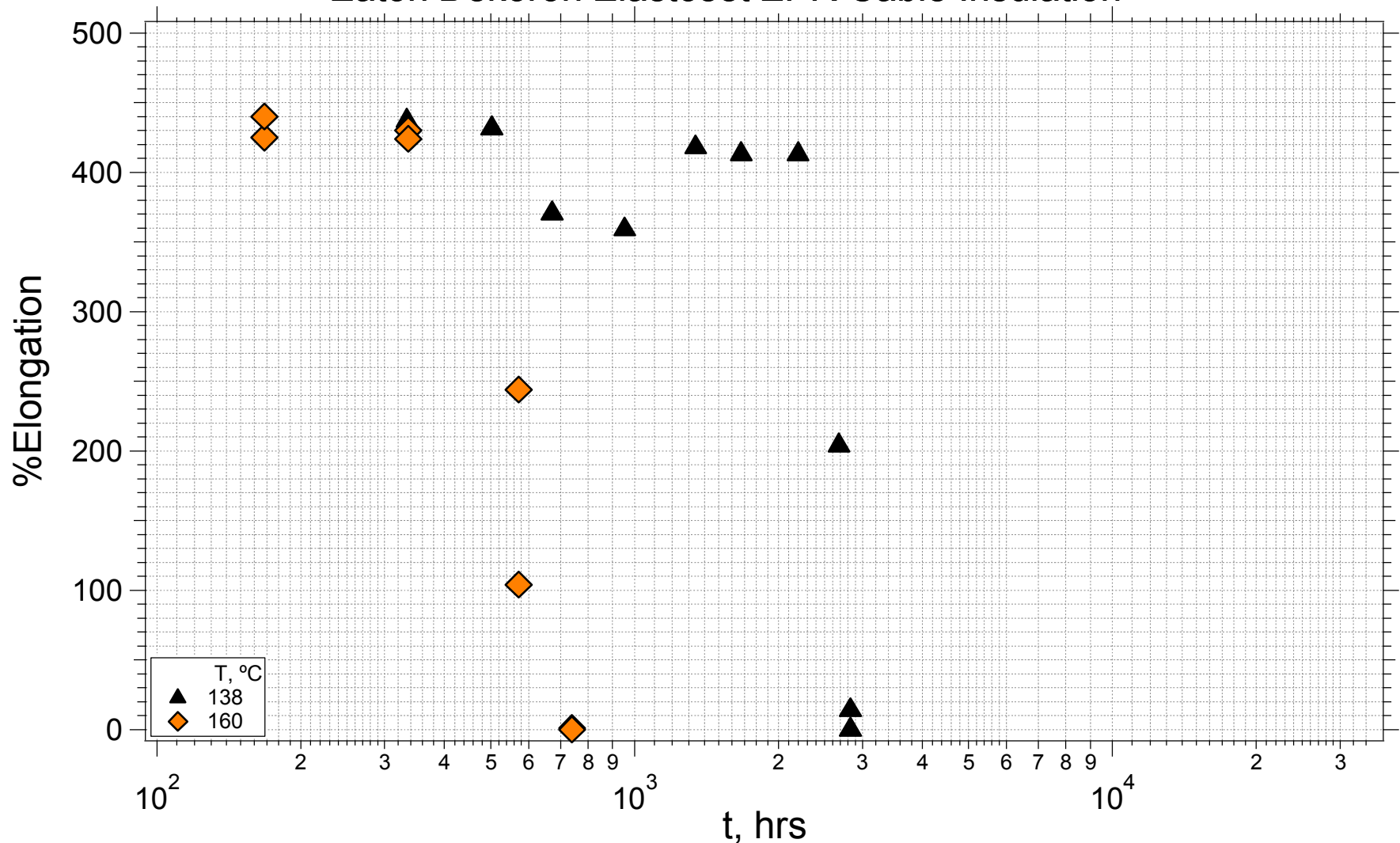
Tensile Properties – Thermal Aging

Eaton Dekoron Elastoset EPR Cable Insulation



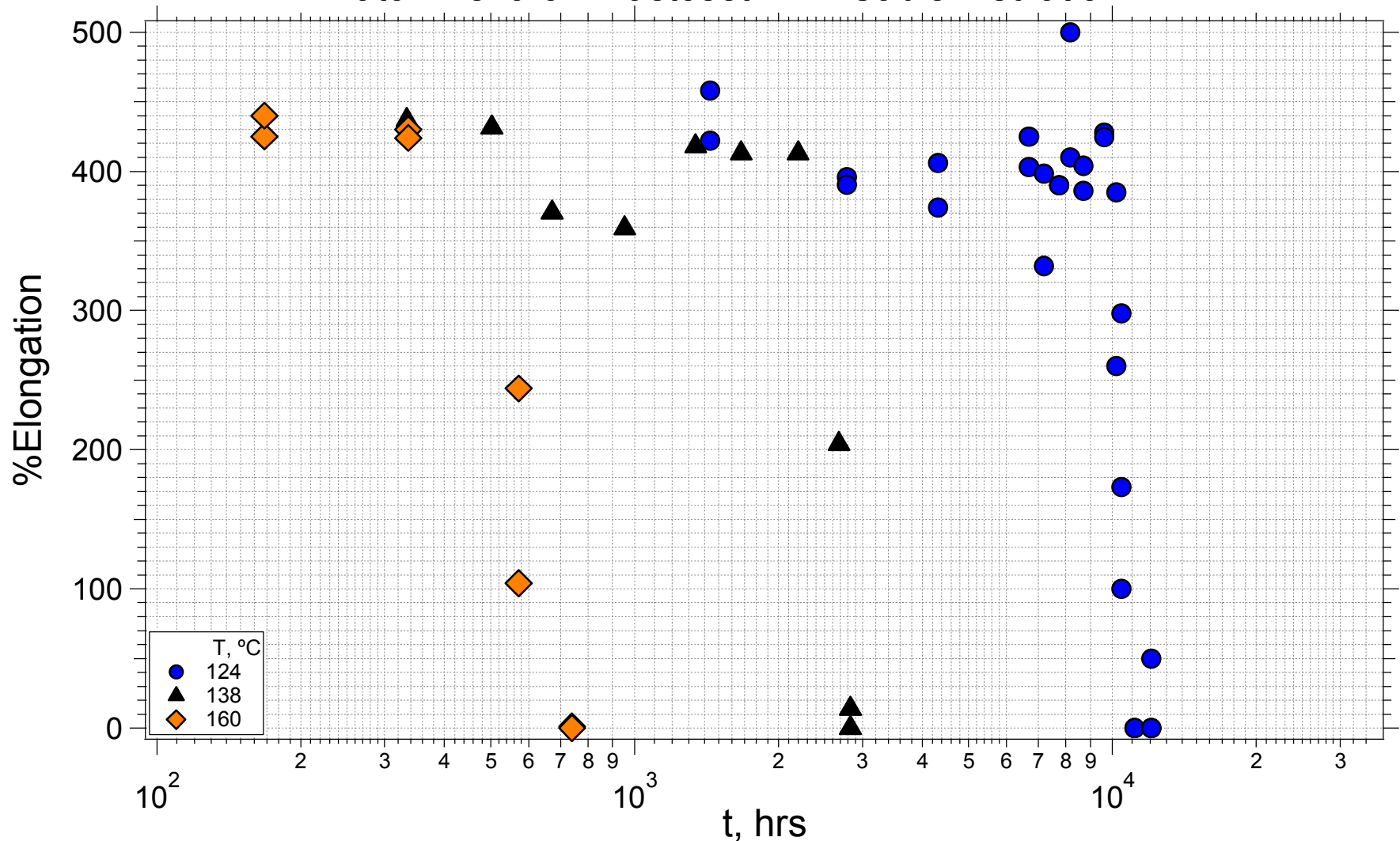
Tensile Properties – Thermal Aging

Eaton Dekoron Elastoset EPR Cable Insulation



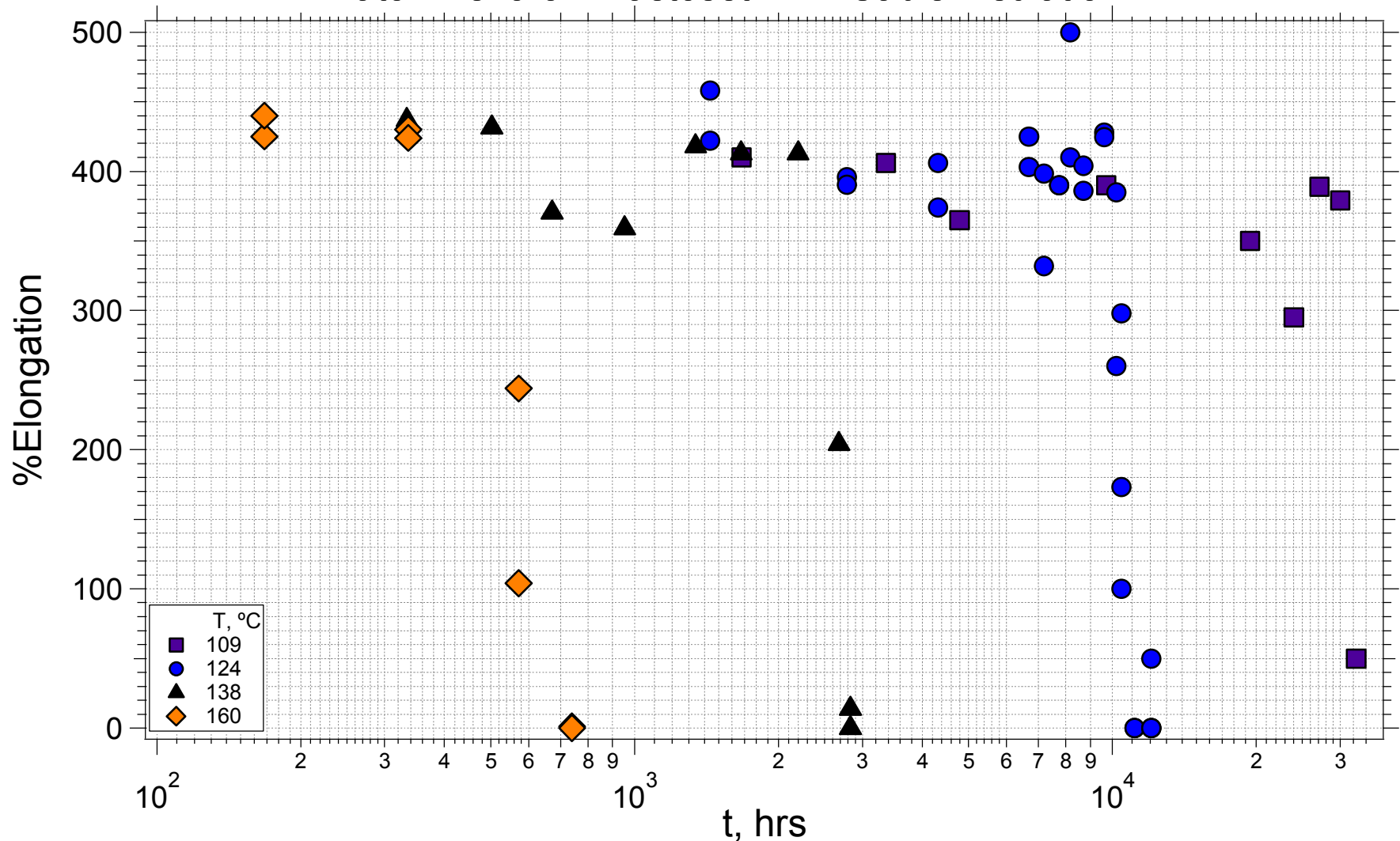
Tensile Properties – Thermal Aging

Eaton Dekoron Elastoset EPR Cable Insulation



Tensile Properties – Thermal Aging

Eaton Dekoron Elastoset EPR Cable Insulation



Time-Temperature Superposition

Does mechanism change as a function of temperature?

If same mechanism:

- same shape (log graph)
 - should be constant acceleration (multiple)
1. Pick a reference temperature
 2. Multiply the time at each temperature by the constant that gives the best overlap with the reference temperature data
 3. Define that multiple as ' a_T ' ($a_T = 1$ for ref. temp.)
 4. Find a_T for each temperature

Plot $\log(a_T)$ vs $1/T$ linear if Arrhenius

Gillen, K. T.; Celina, M.; Clough, R. L.; Wise, J. *Trends in Polymer Science*, Extrapolation of Accelerated Aging Data -Arrhenius or Erroneous? 1997, 5, 250-257.

Arrhenius equation:

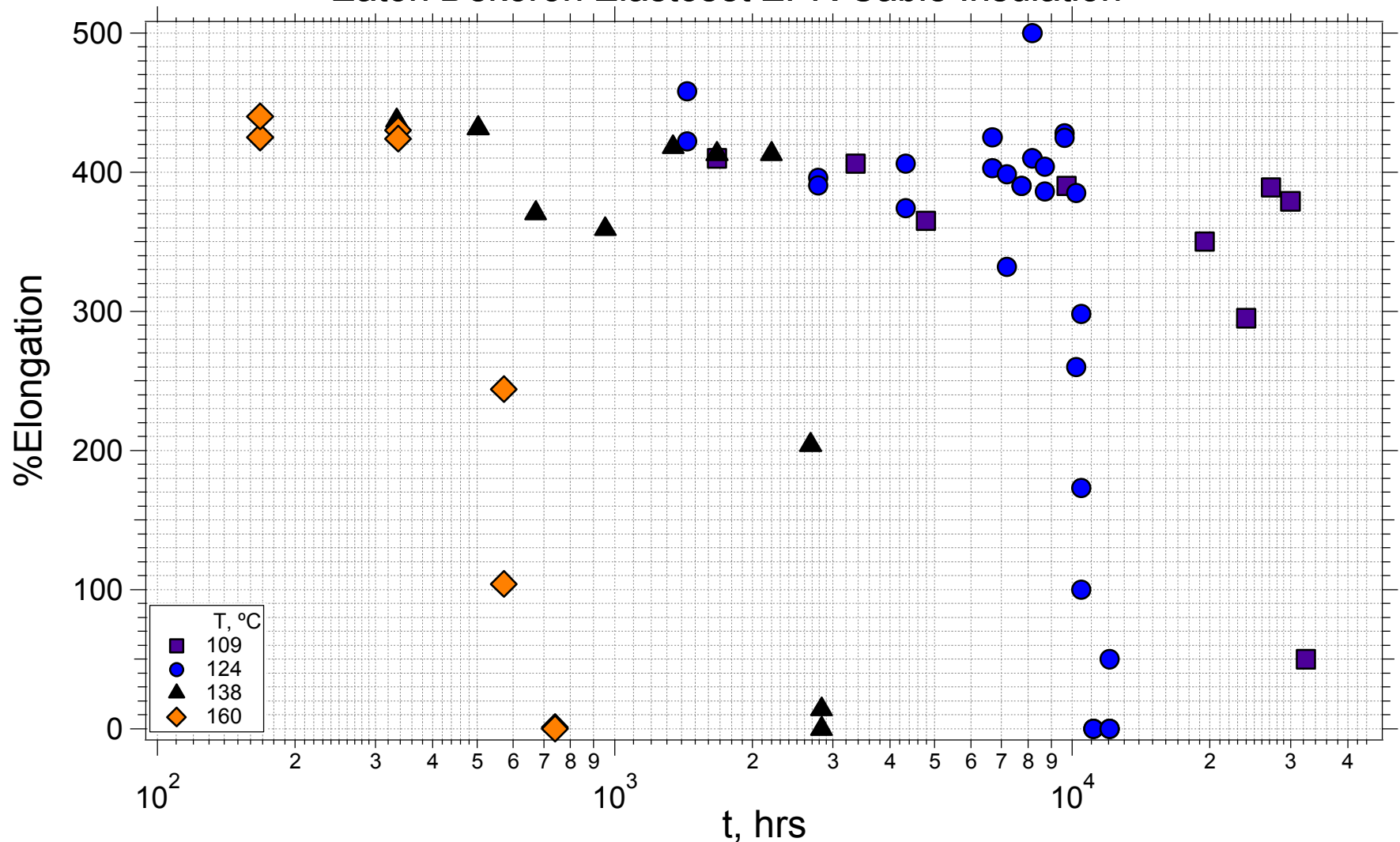
$$k = Ae^{-E_a/RT}$$

Empirical equation

$$\ln(k) = \ln(A) - E_a/RT$$

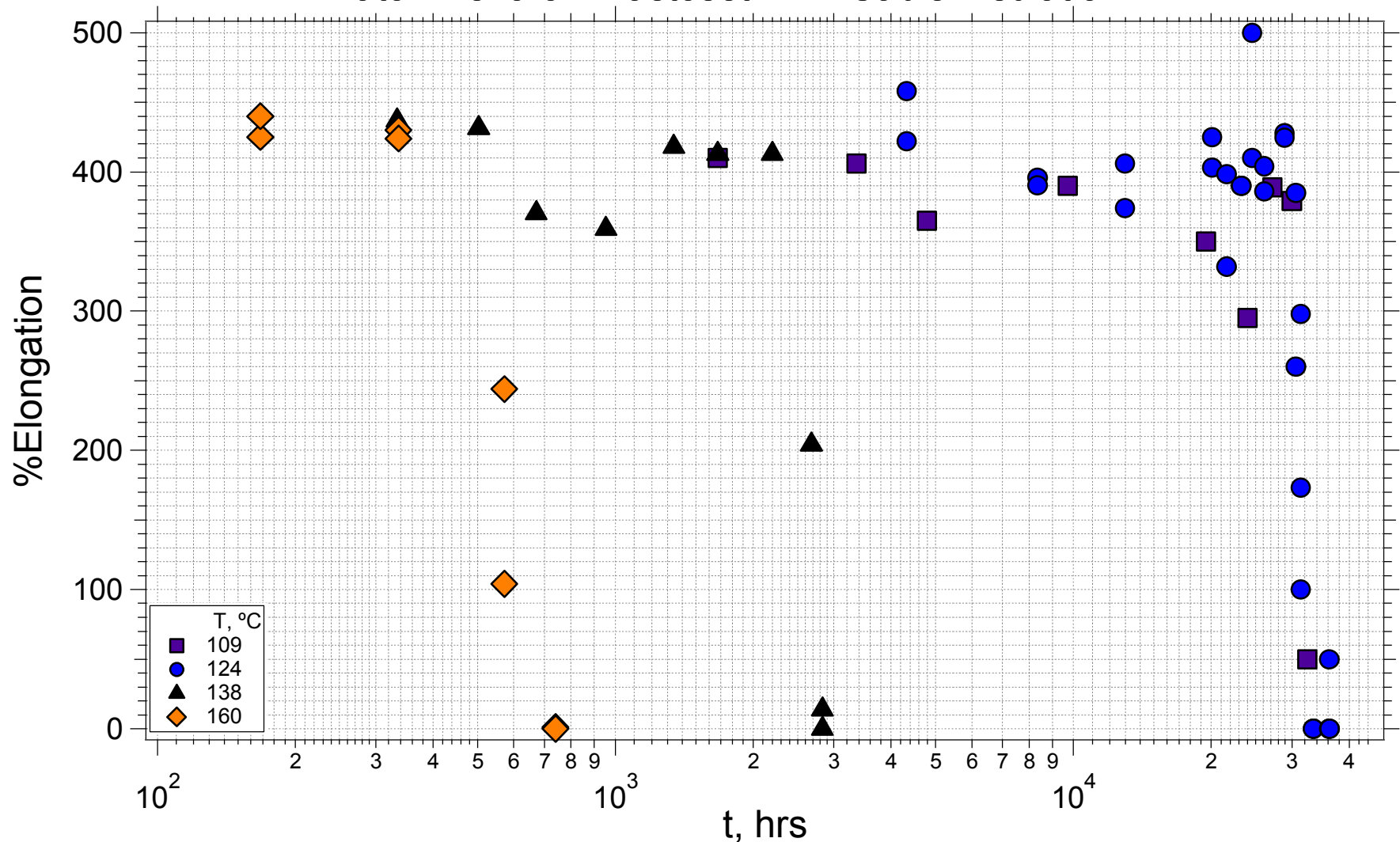
Time-Temperature Superposition

Eaton Dekoron Elastoset EPR Cable Insulation



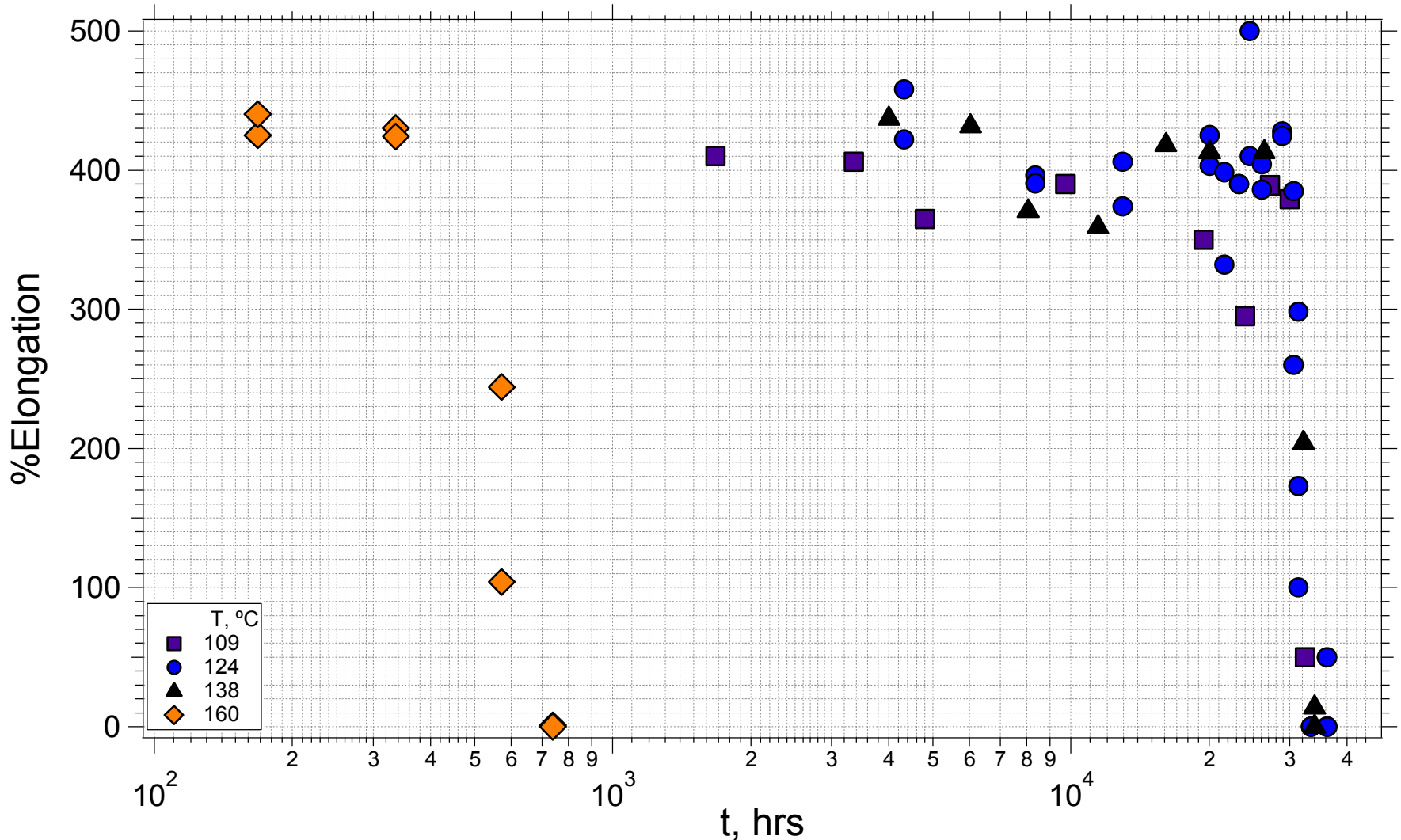
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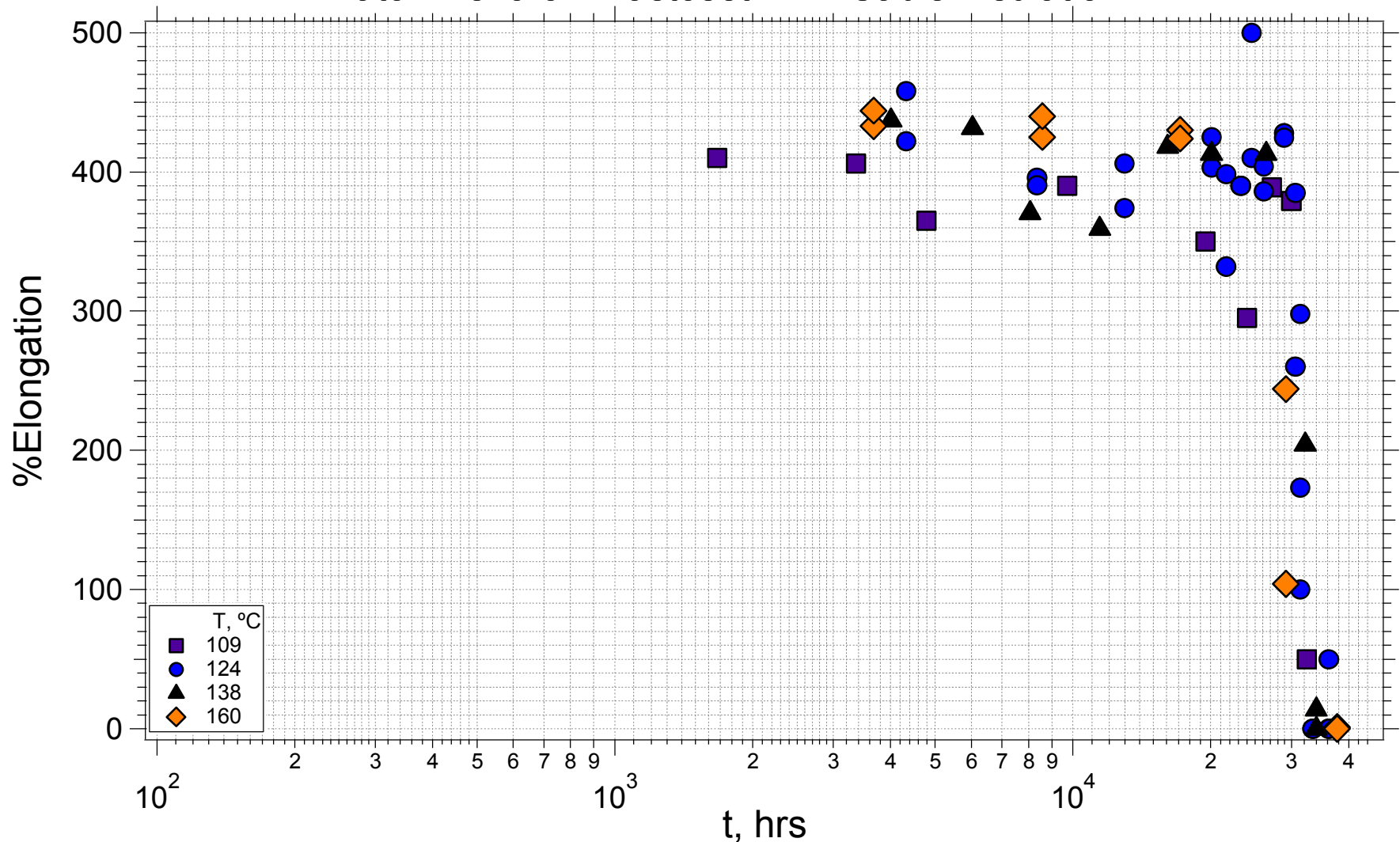
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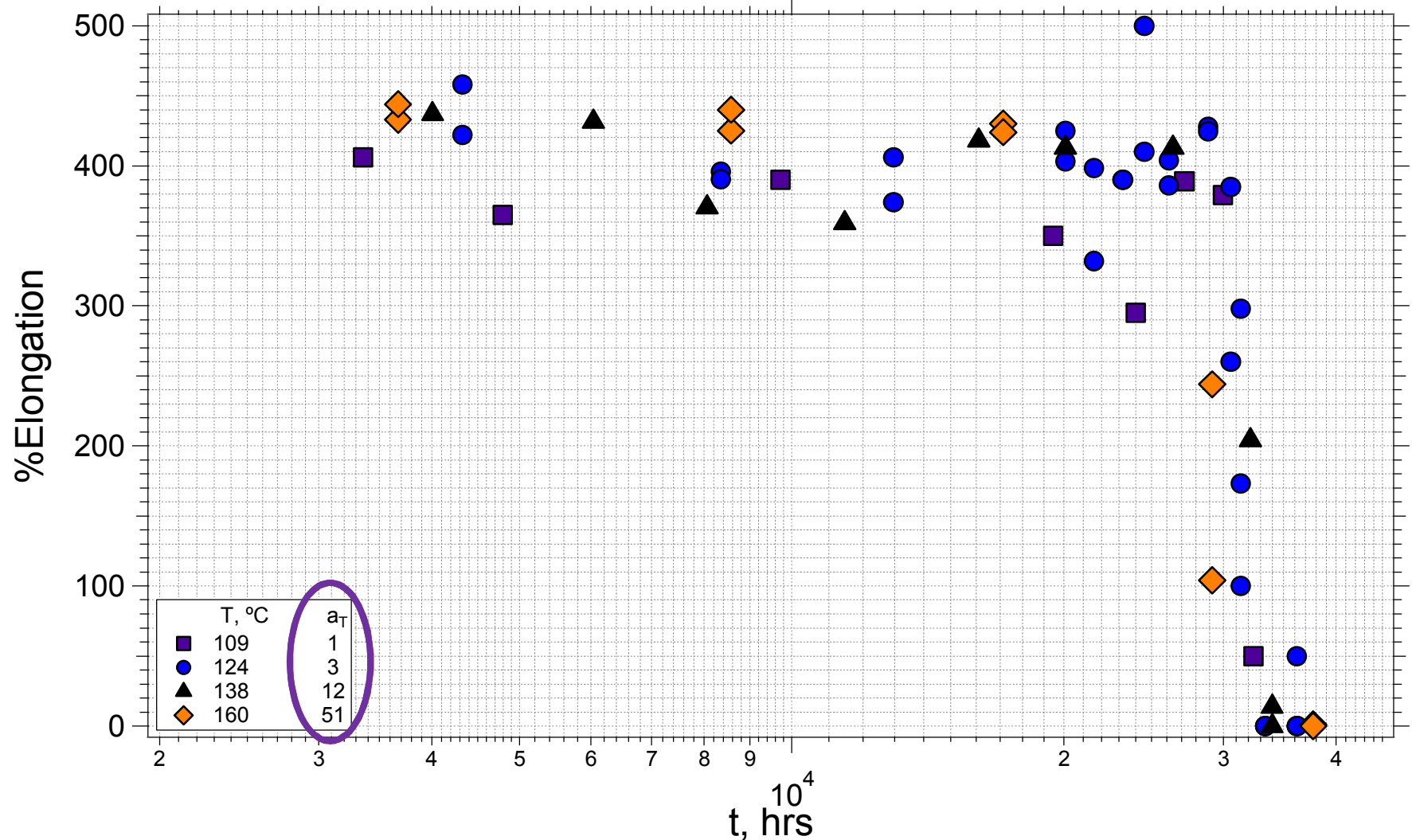
Time-Temperature Superposition

Eaton Dekoron Elastoset EPR Cable Insulation



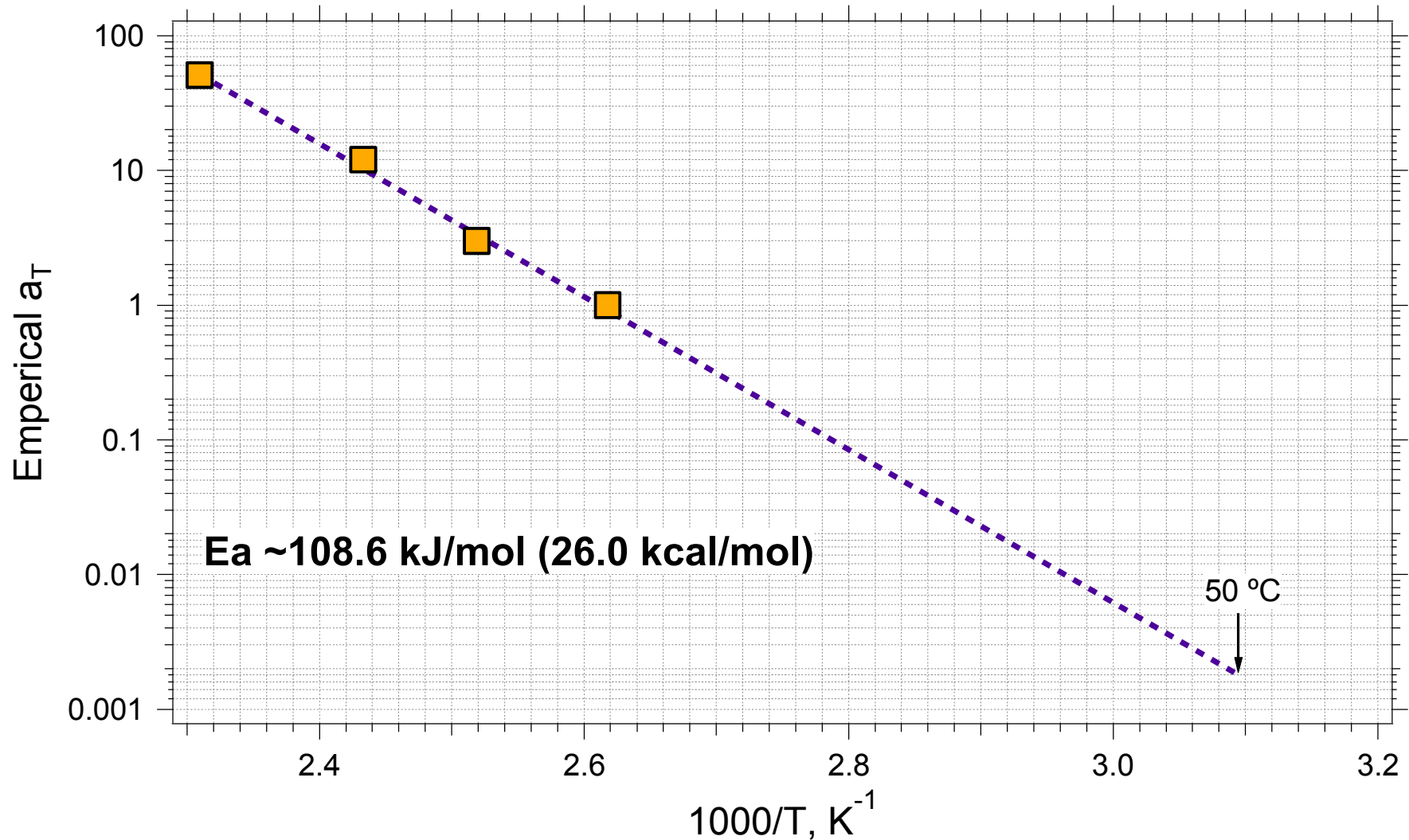
Arrhenius Plot

Eaton Dekoron Elastoset EPR Cable Insulation



Arrhenius Plot

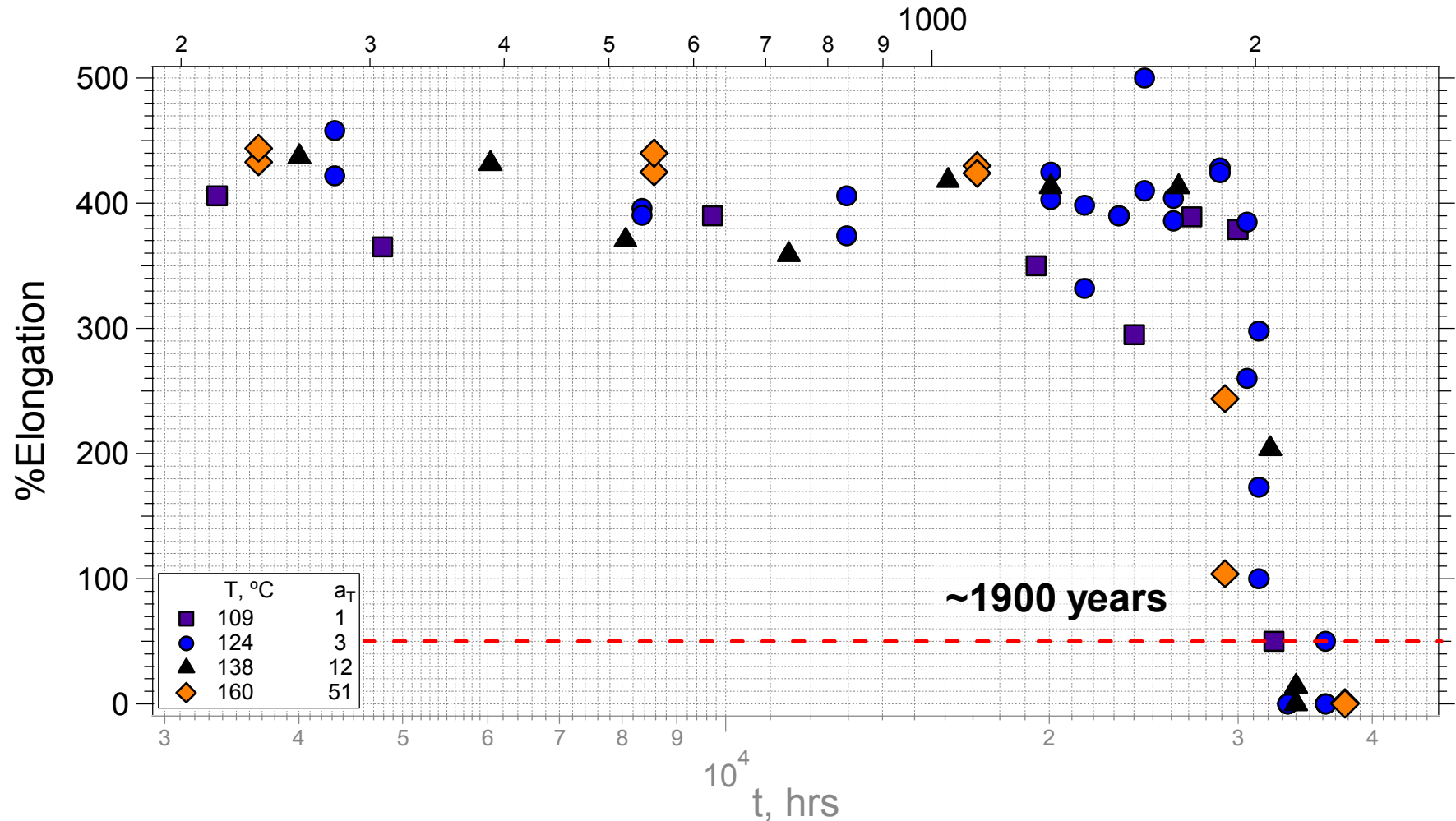
Eaton Dekoron Elastoset EPR Cable Insulation



Thermal-Oxidative Prediction

Eaton Dekoron Elastoset EPR Cable Insulation

Predicted Time in Years at 50 °C

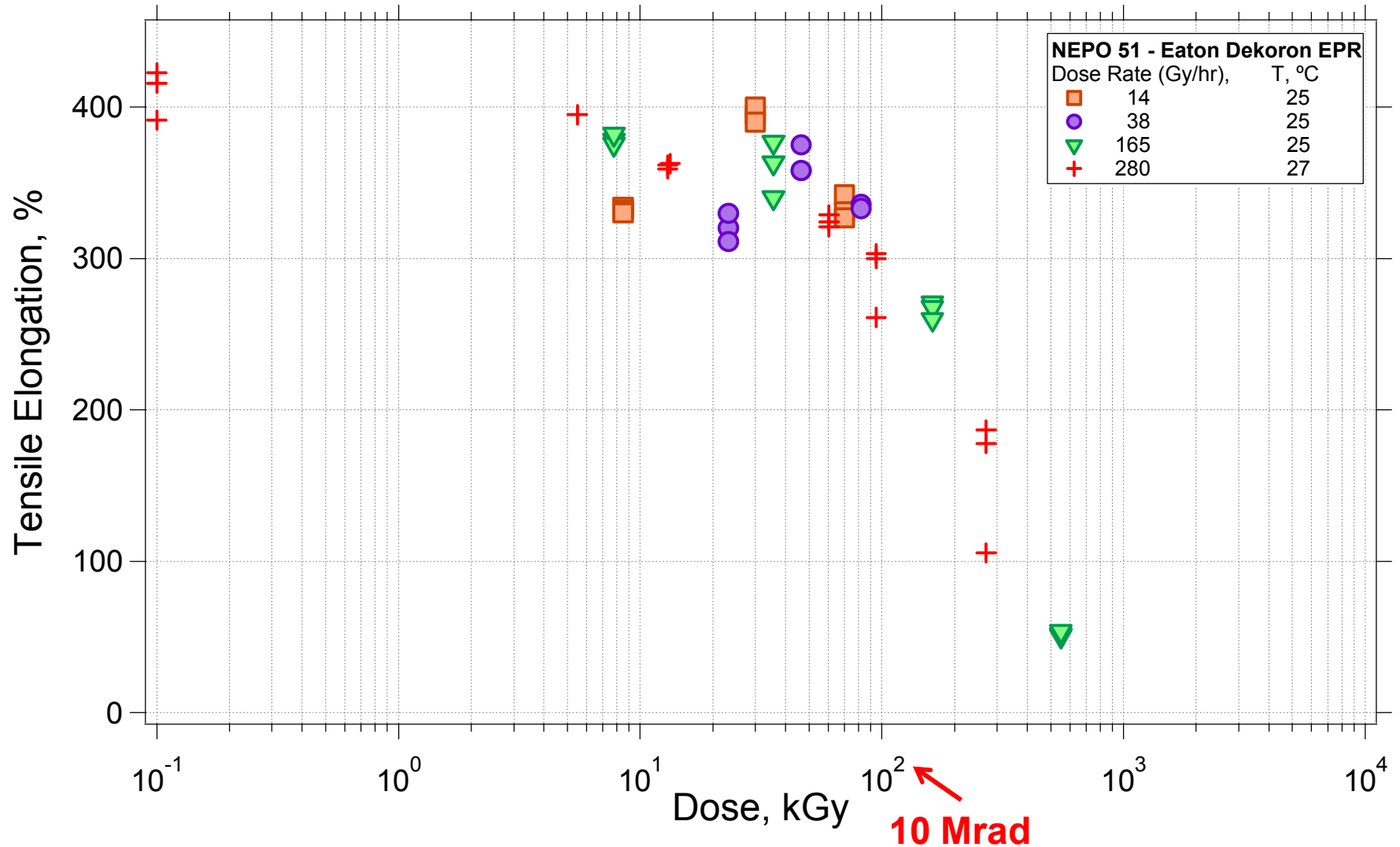


Simultaneous Radiation and Thermal Aging

ENVIRONMENTAL SYNERGIES

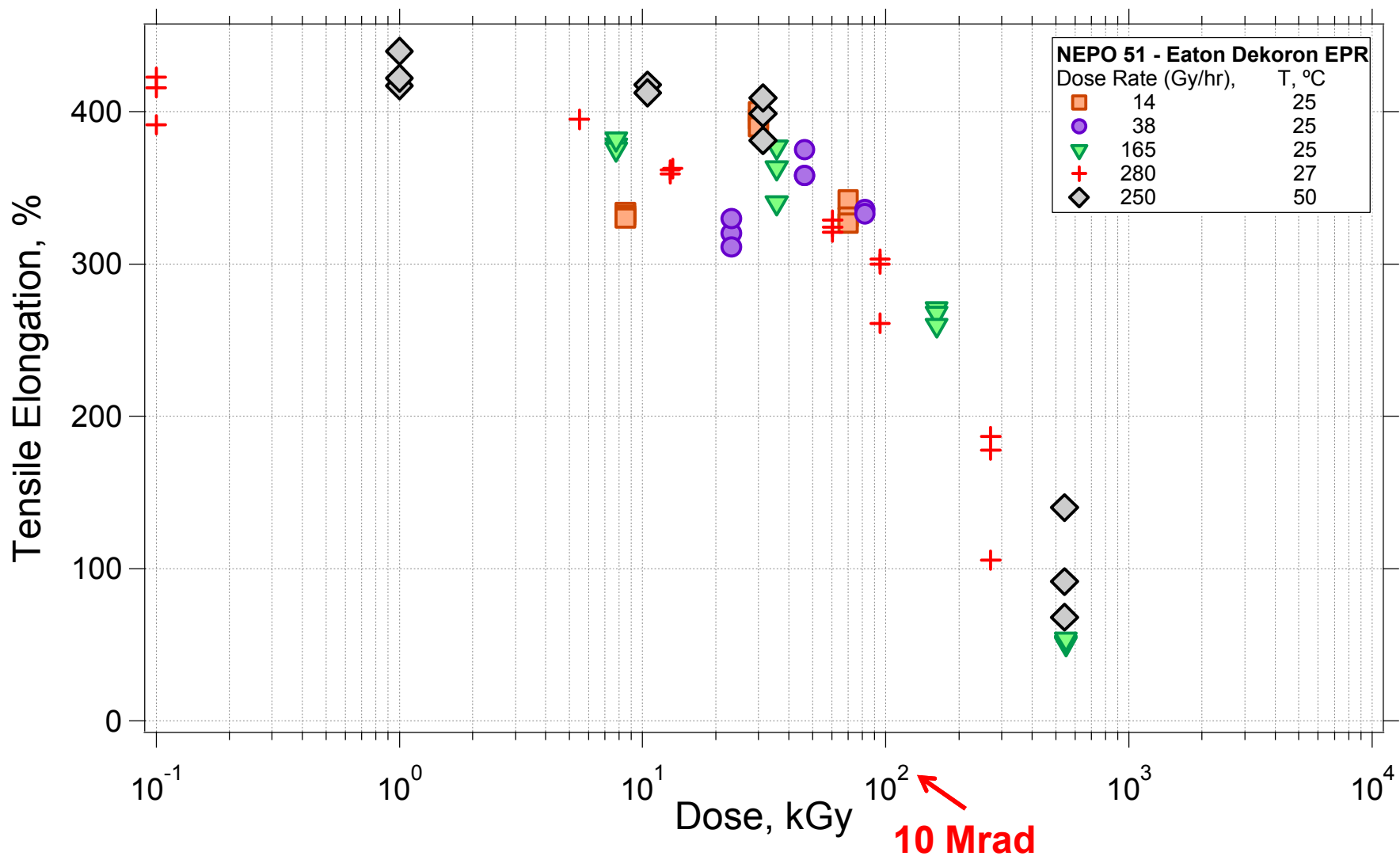
NEPO 51 – Eaton Dekoron EPR

Thermal/Radiation Synergy



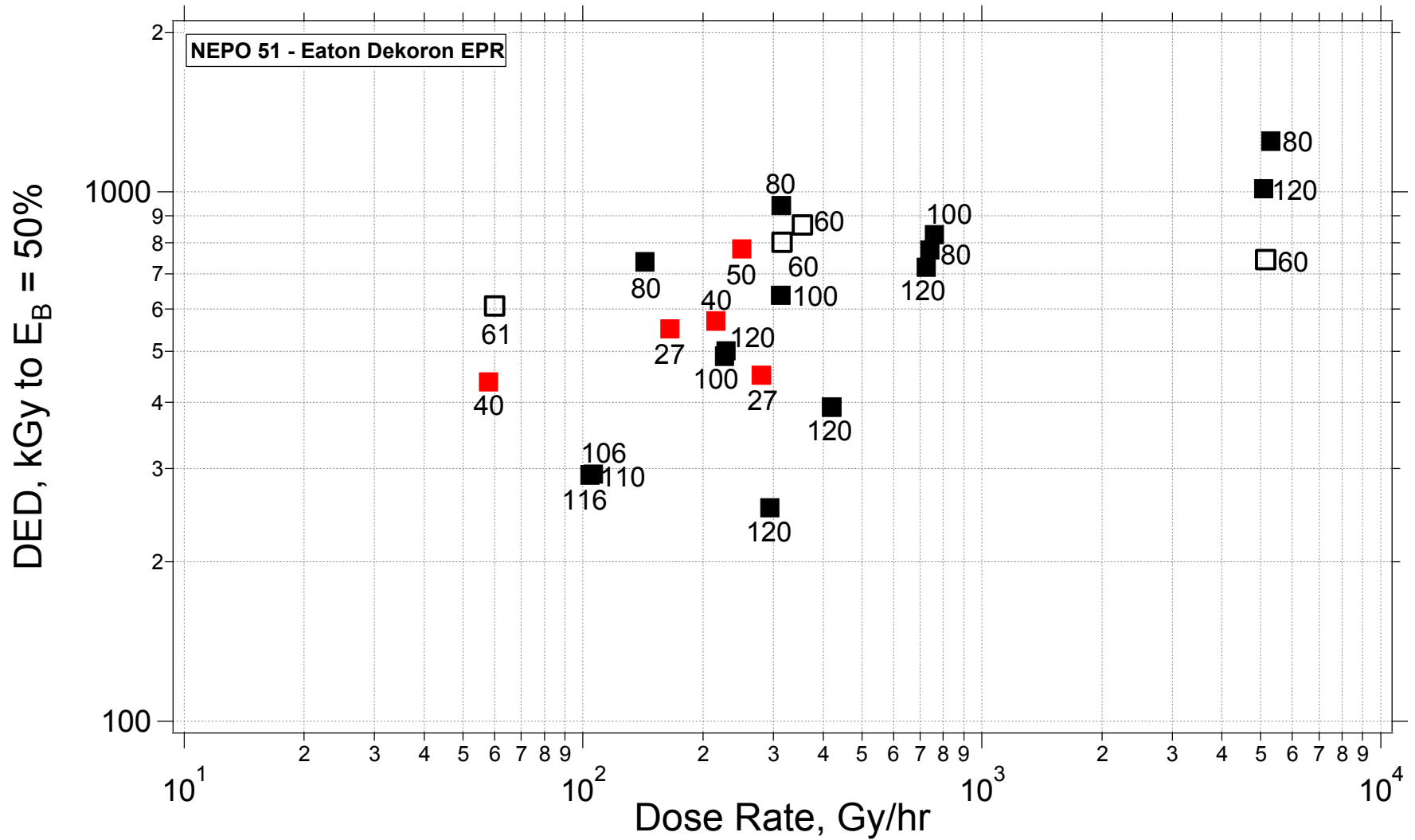
NEPO 51 – Eaton Dekoron EPR

Thermal/Radiation Synergy



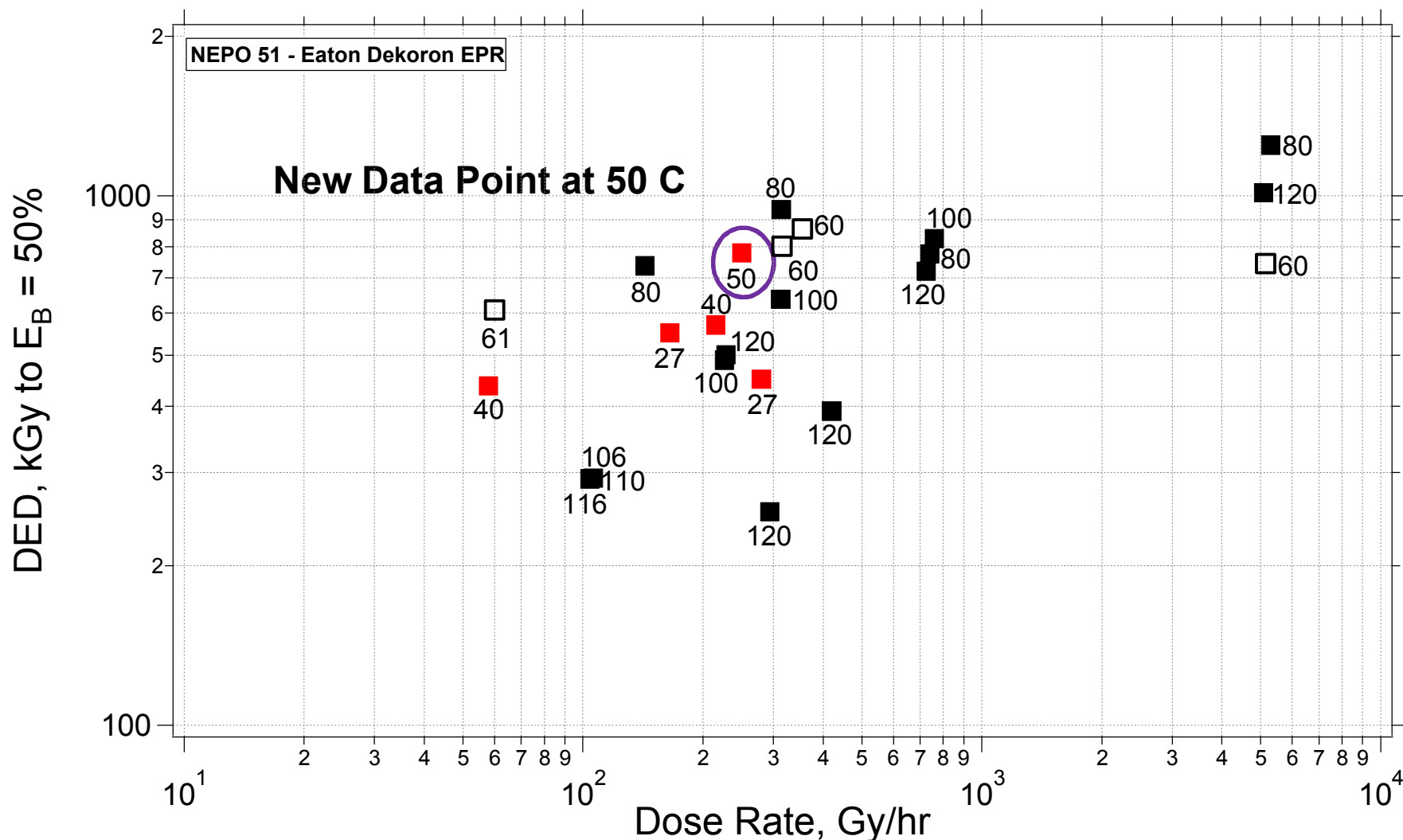
NEPO 51 – Eaton Dekoron EPR

Thermal/Radiation Synergy



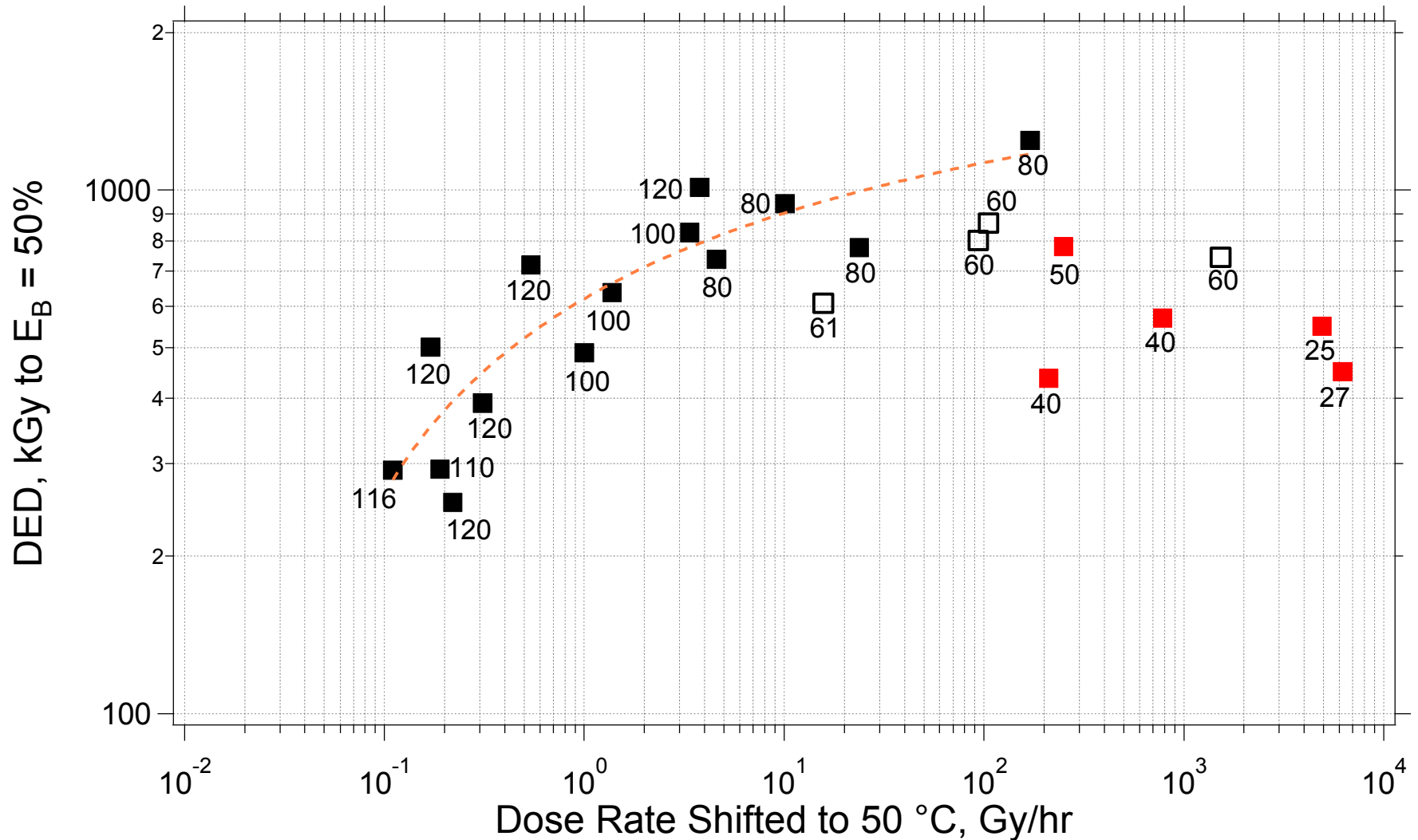
NEPO 51 – Eaton Dekoron EPR

Thermal/Radiation Synergy



NEPO 51 – Eaton Dekoron EPR

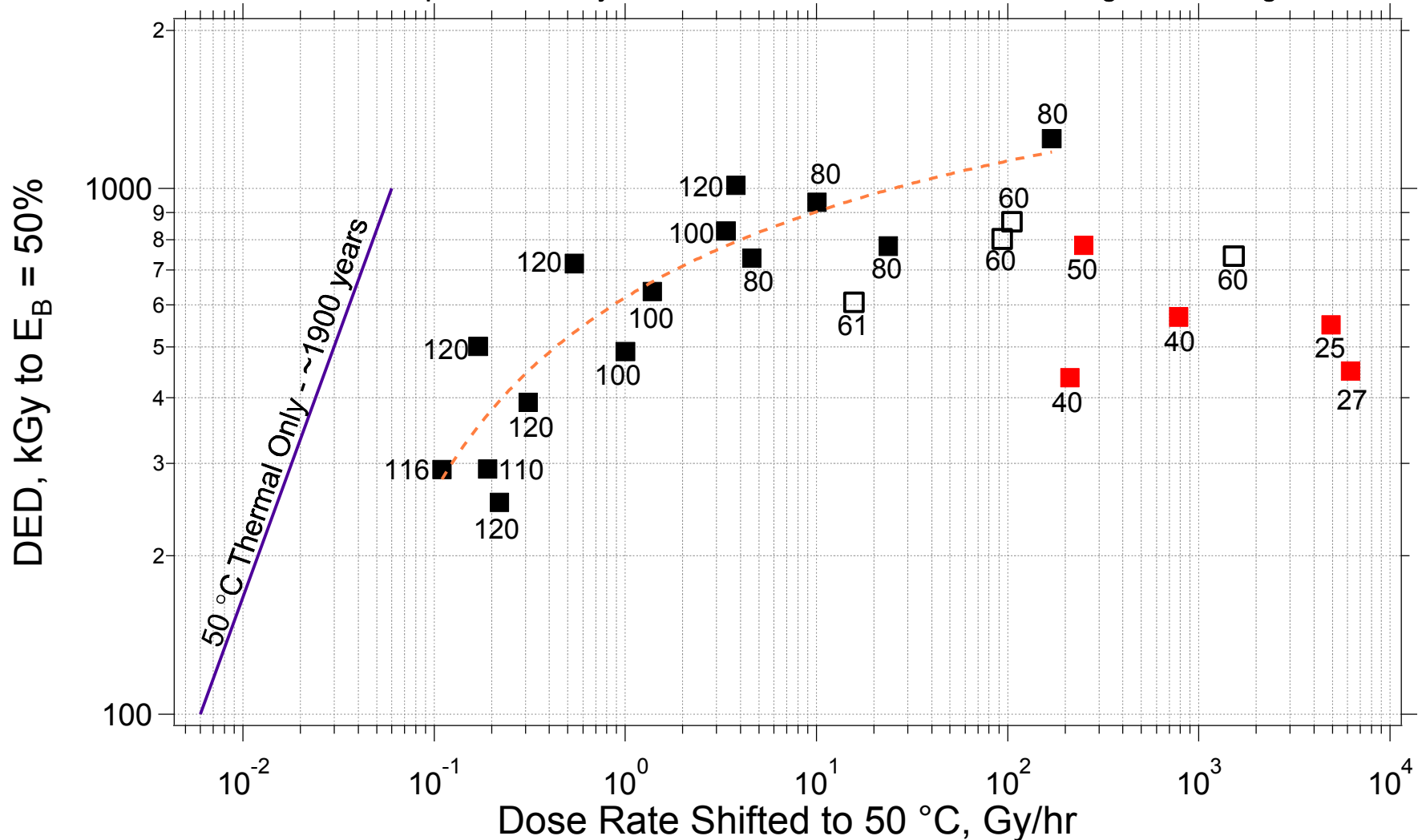
Thermal/Radiation Synergy



NEPO 51 – Eaton Dekoron EPR

Per PWR Environmental Data:

Eaton Dekoron EPR cables are predominantly in the thermal-oxidative dominant degradation regime



NEPO 9 – CSPE Jacket/XLPO Insulation

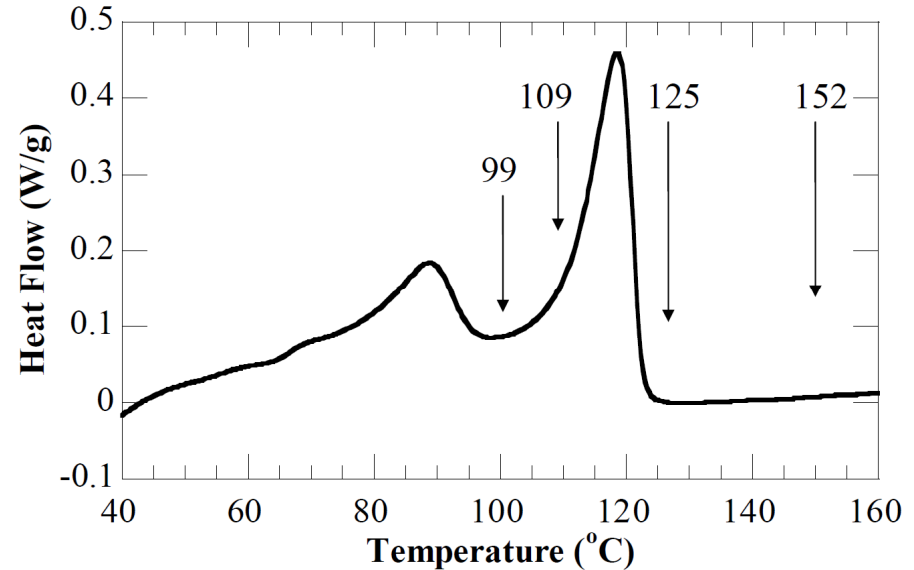
BRAND-REX XLPO



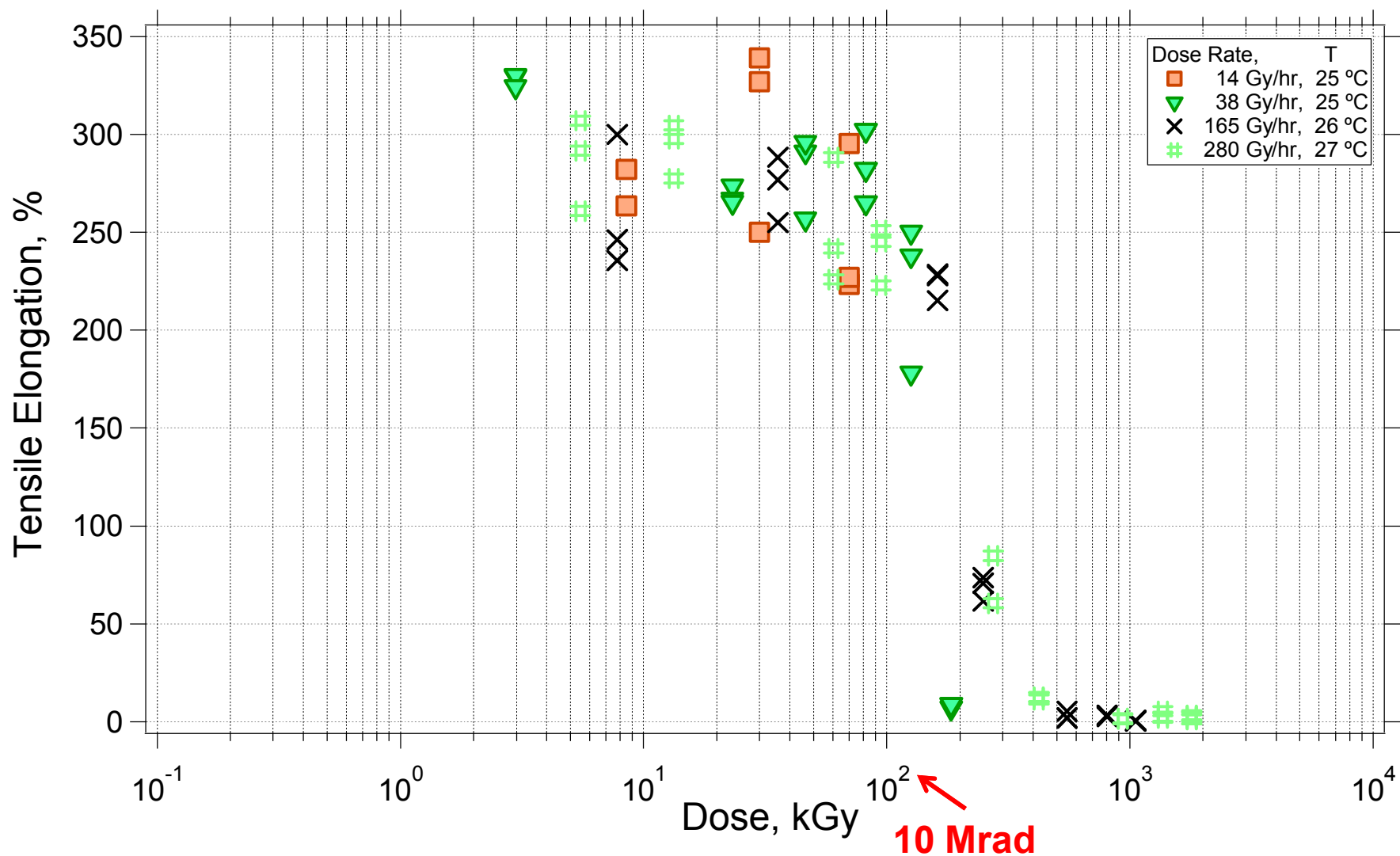
BRAND-REX XLPO

Crystalline Polymer

- Cross-linked medium to high density ethylene-vinylacetate co-polymer
- Melting region between ~ 89 and 119 °C
- Obvious mechanism change when aging at elevated temperatures

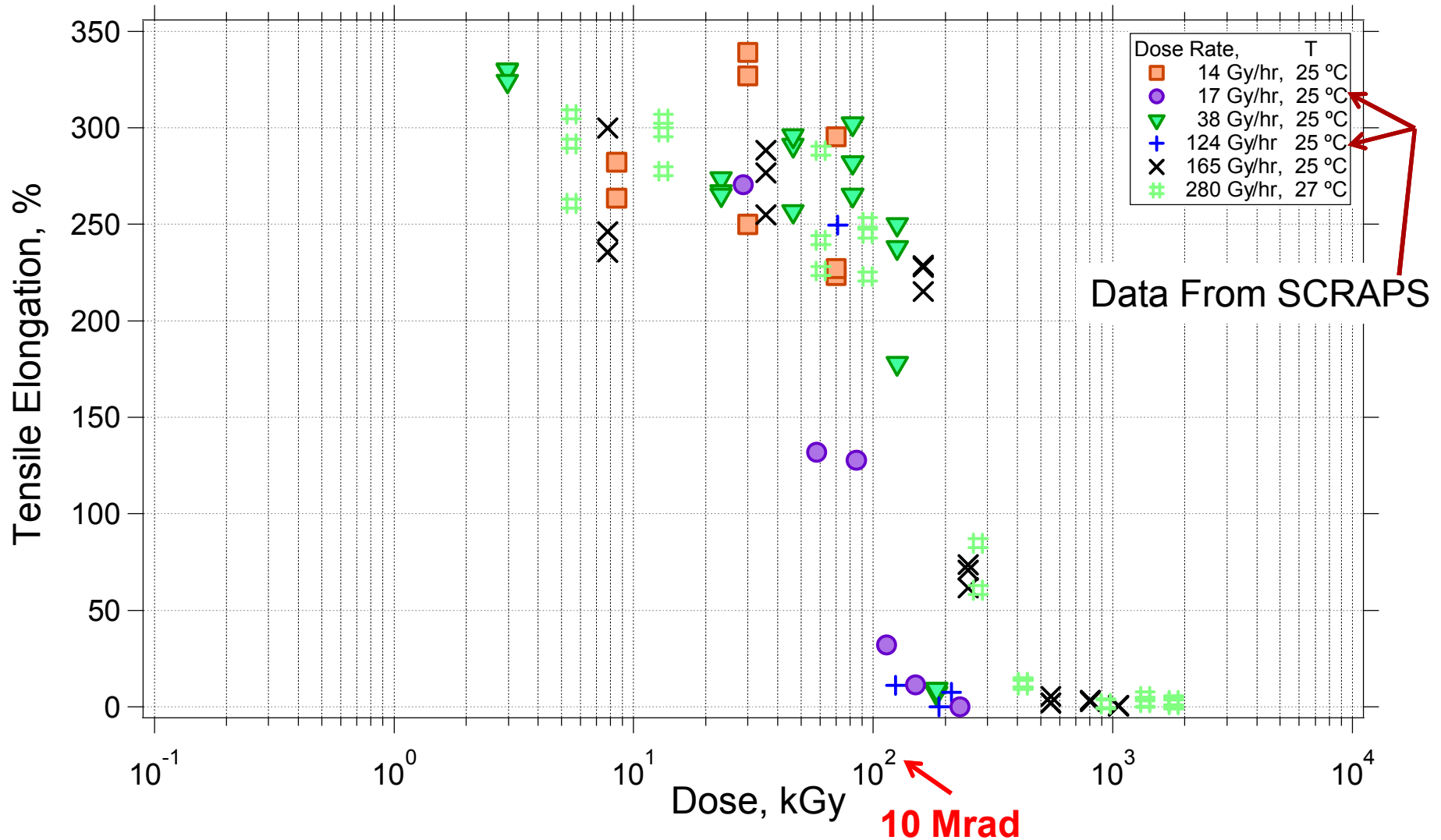


**Sandia
National
Laboratories**

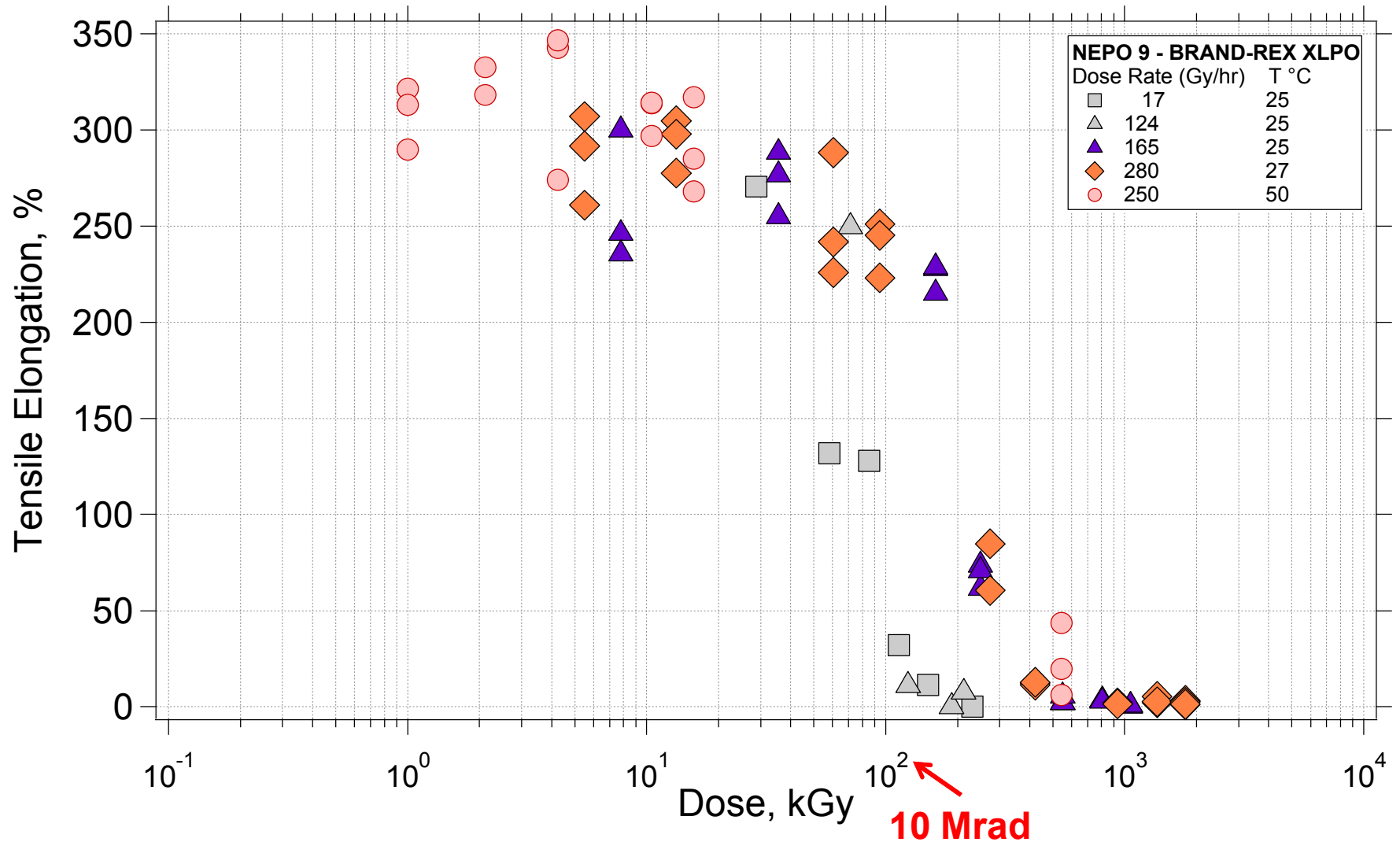


NEPO 9 – BRAND-REX XLPO

(with SCRAPS Data)

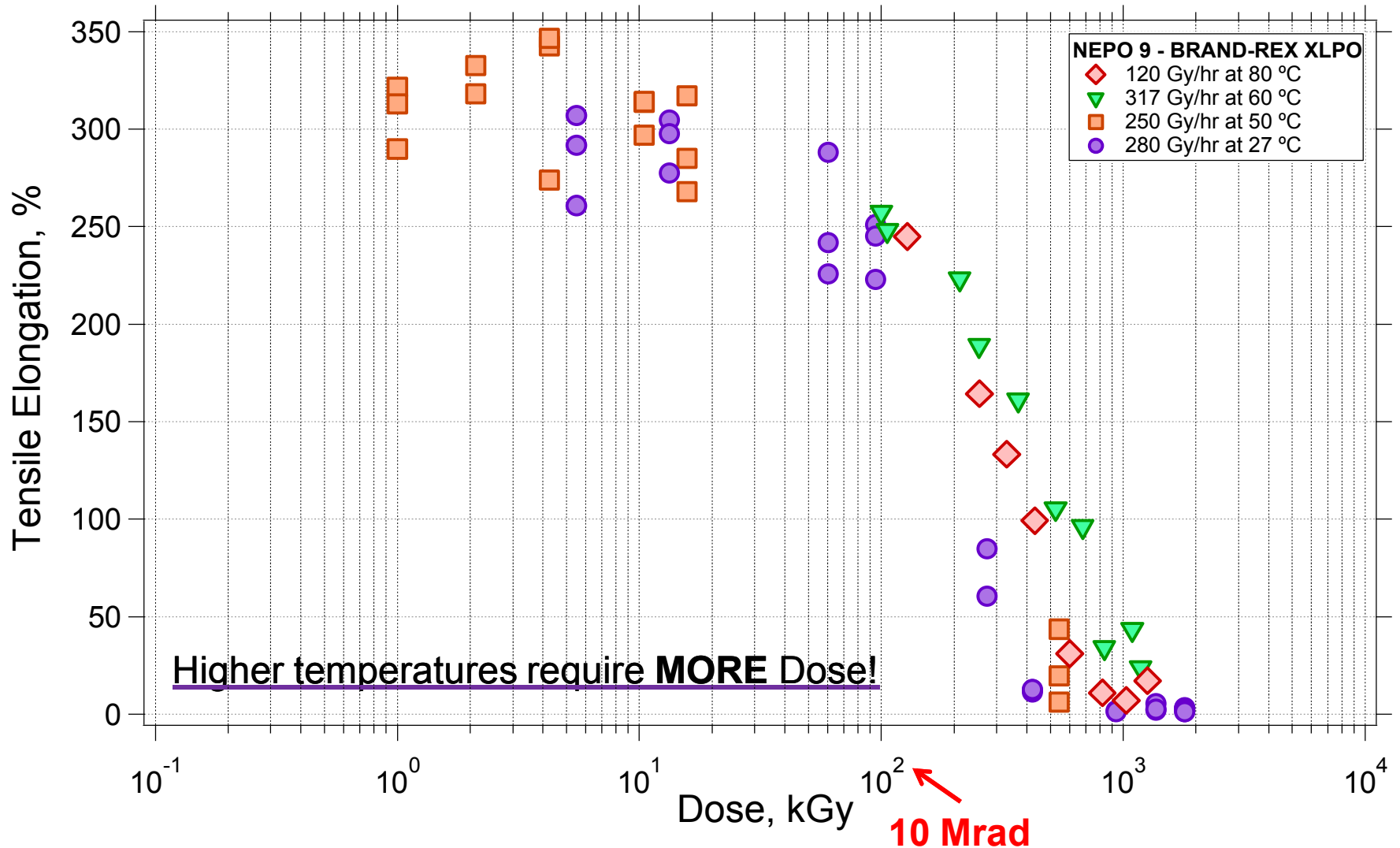


NEPO 9 – BRAND-REX XLPO



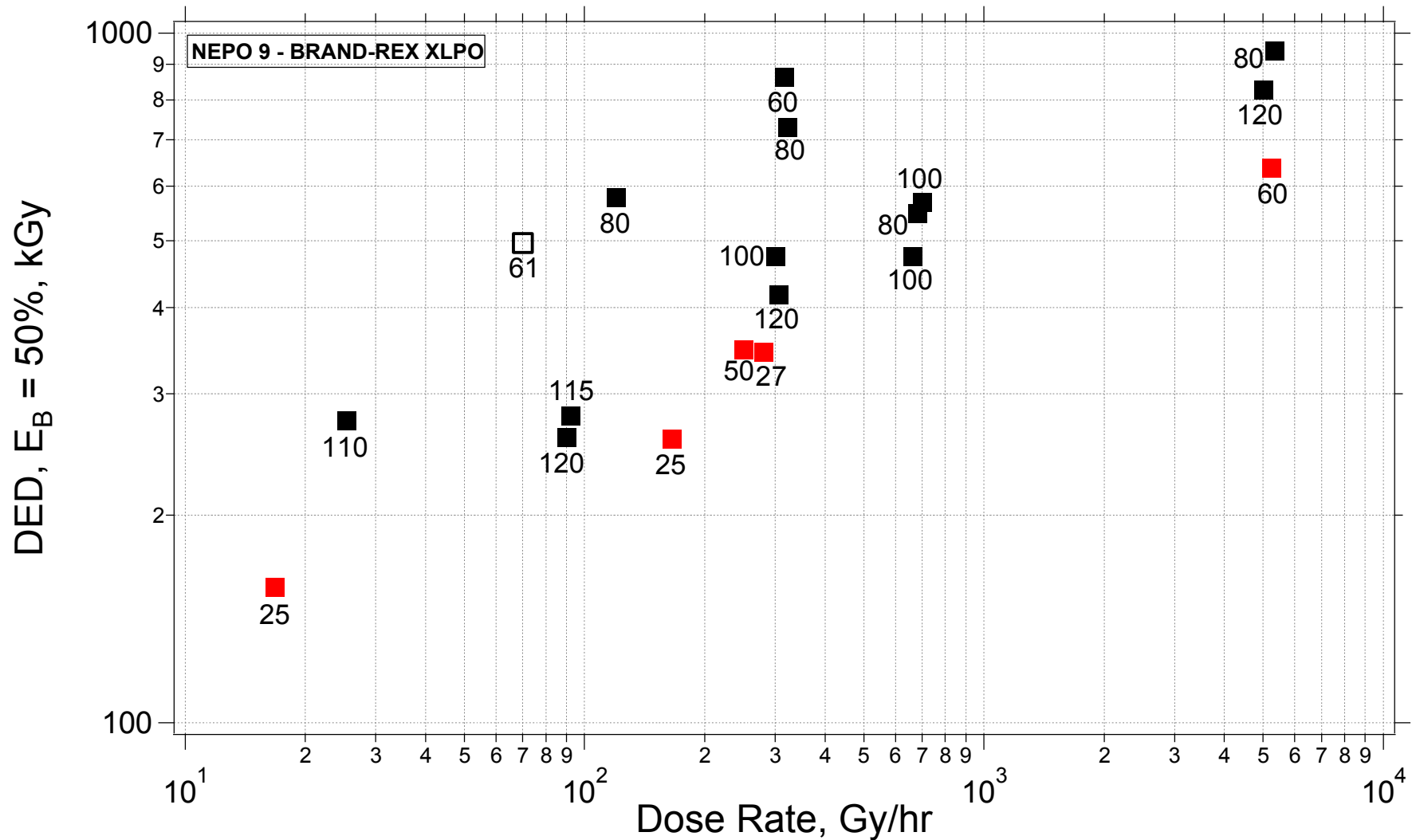
NEPO 9 – BRAND-REX XLPO

Thermal/Radiation Synergy



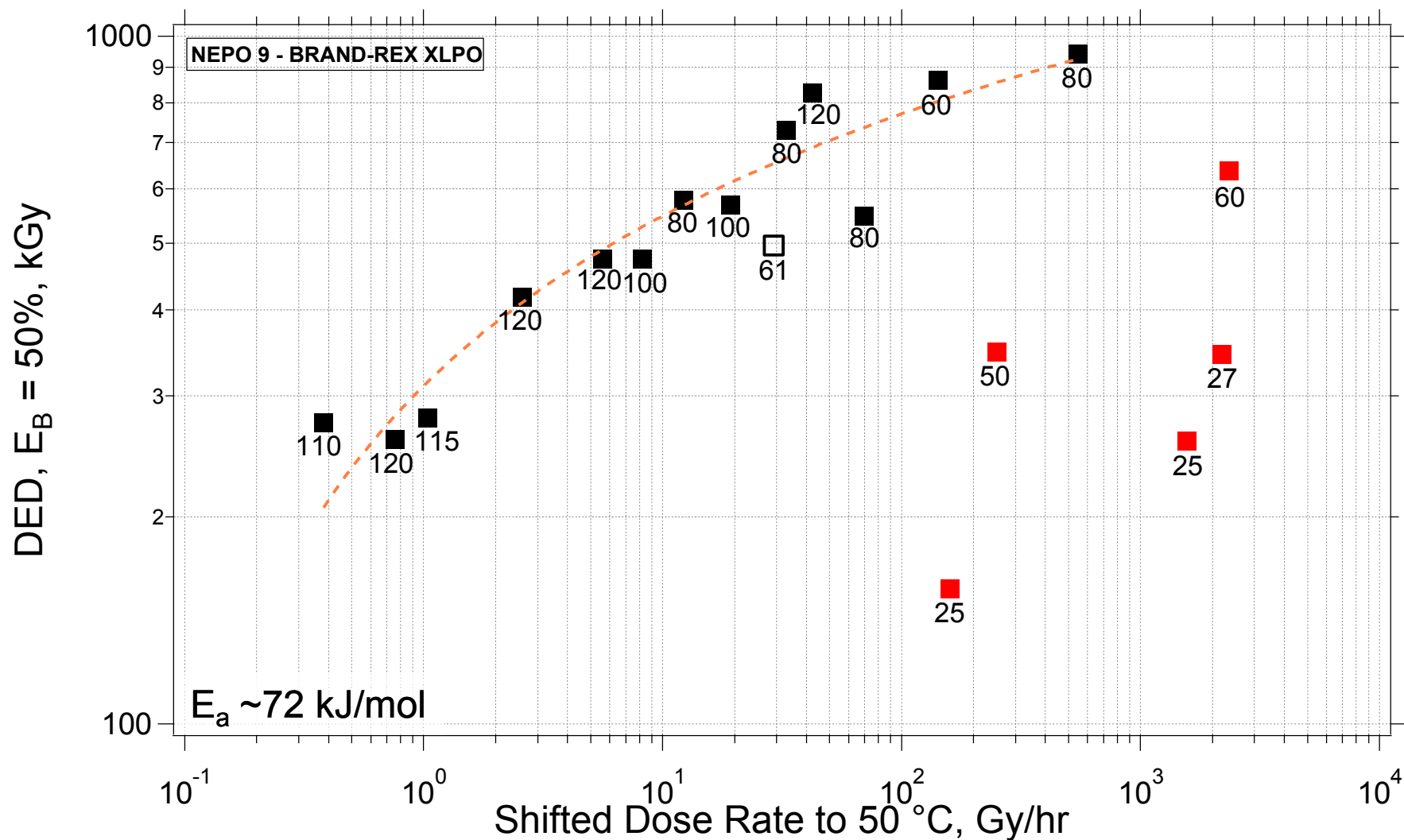
NEPO 9 – BRAND-REX XLPO

Thermal/Radiation Synergy



NEPO 9 – BRAND-REX XLPO

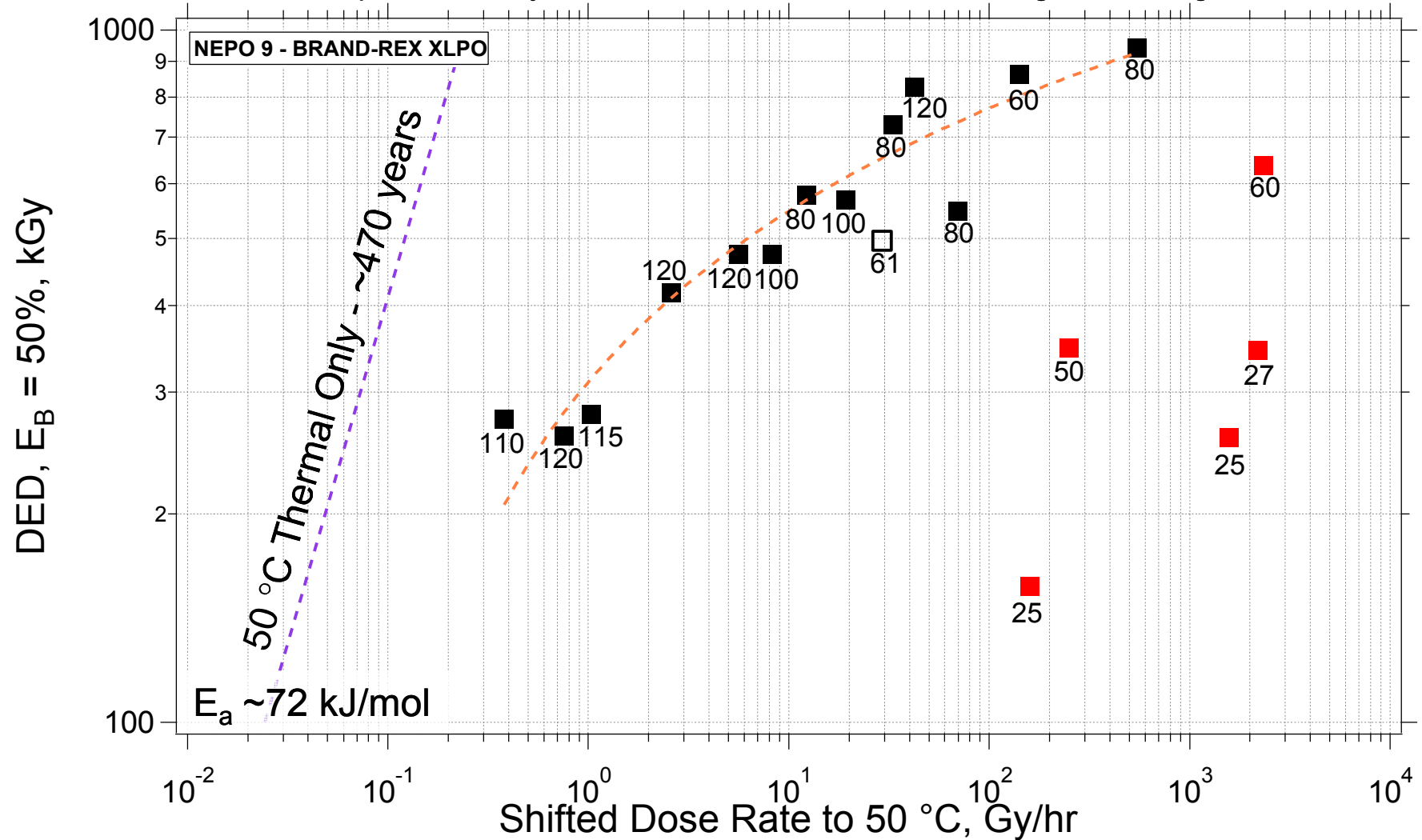
Thermal/Radiation Synergy



NEPO 9 – BRAND-REX XLPO

Per PWR Environmental Data:

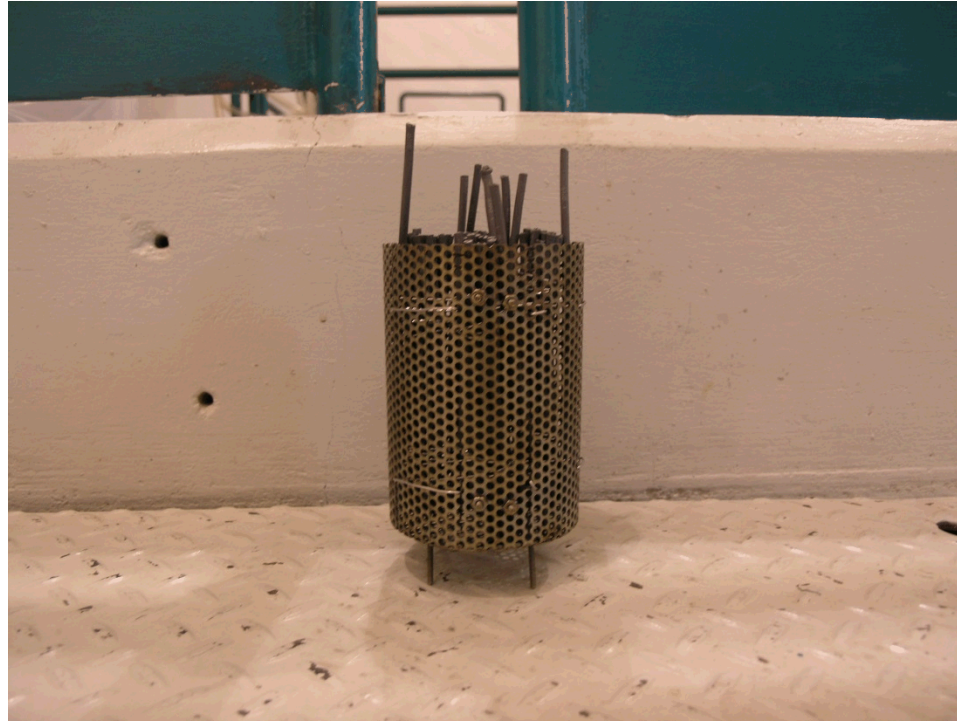
Brandrex XLPE cables are predominantly in the thermal-oxidative dominant degradation regime



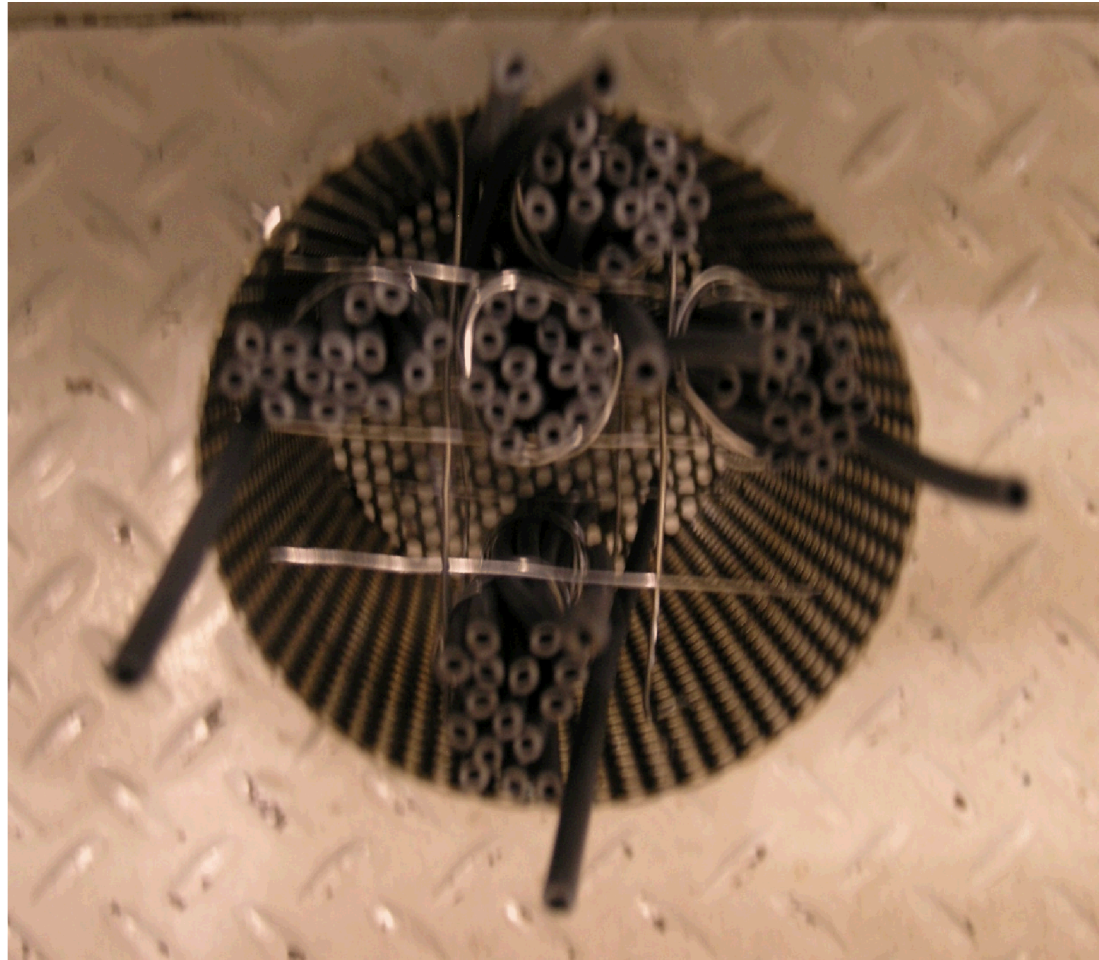
Specimen Location within same aging can

DOSE RATE EFFECTS?

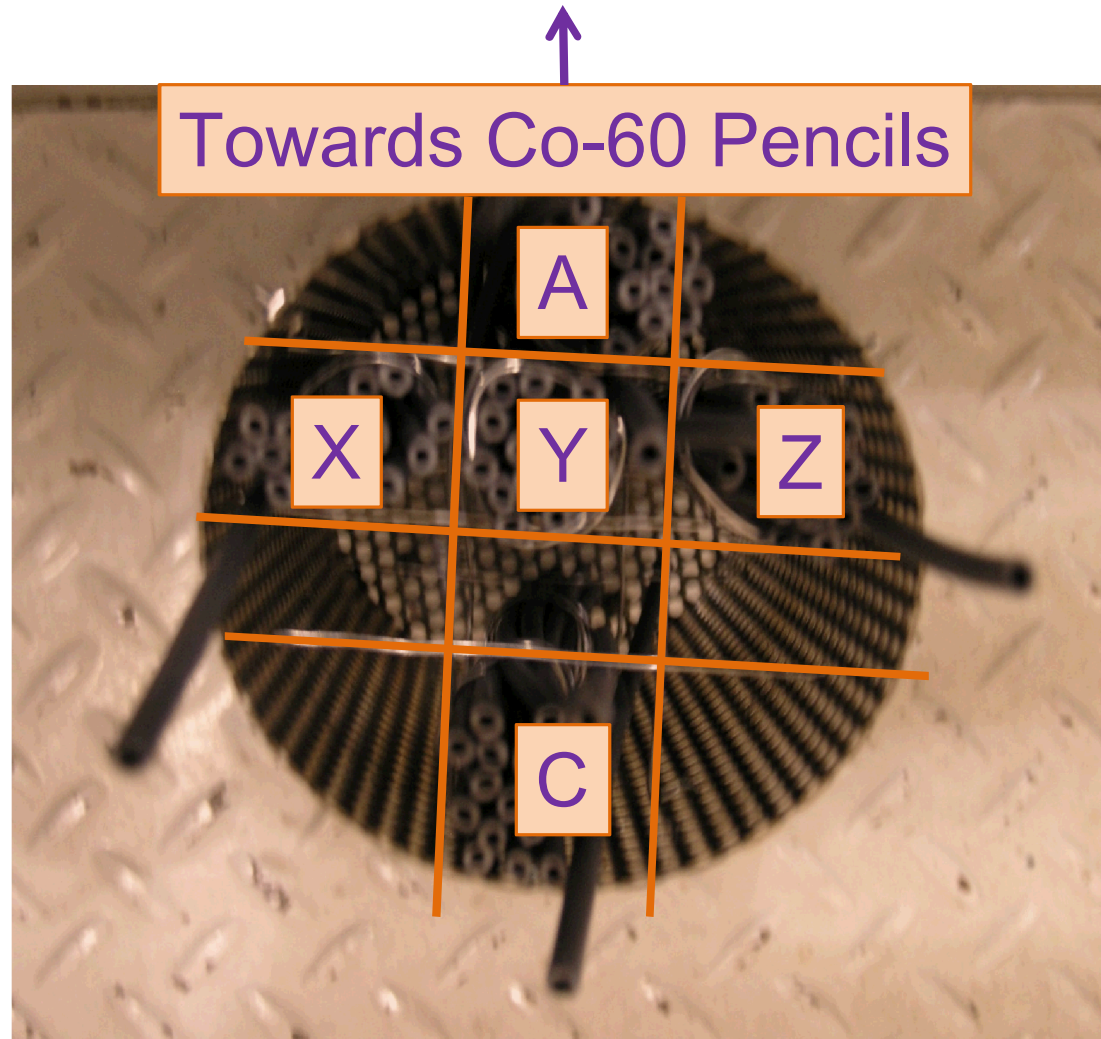
NEPO 9 – BRAND-REX XLPO



NEPO 9 – BRAND-REX XLPO

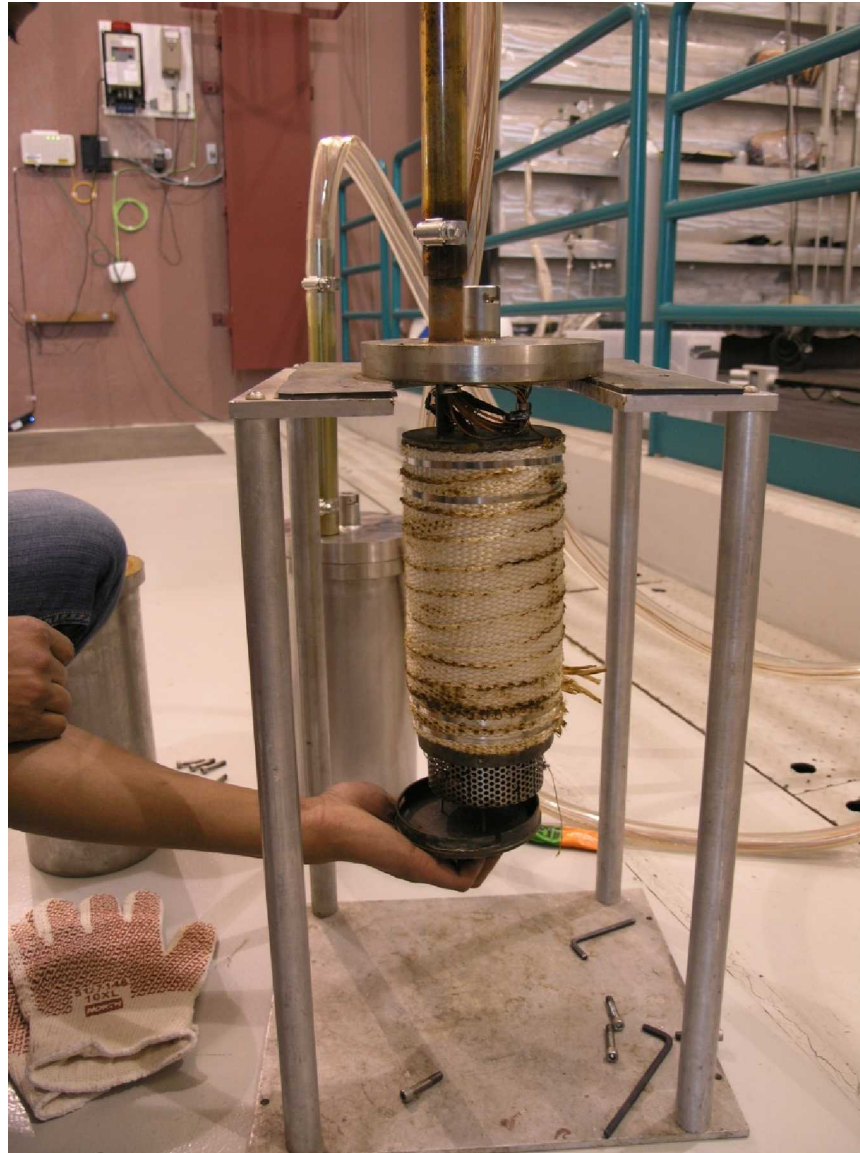


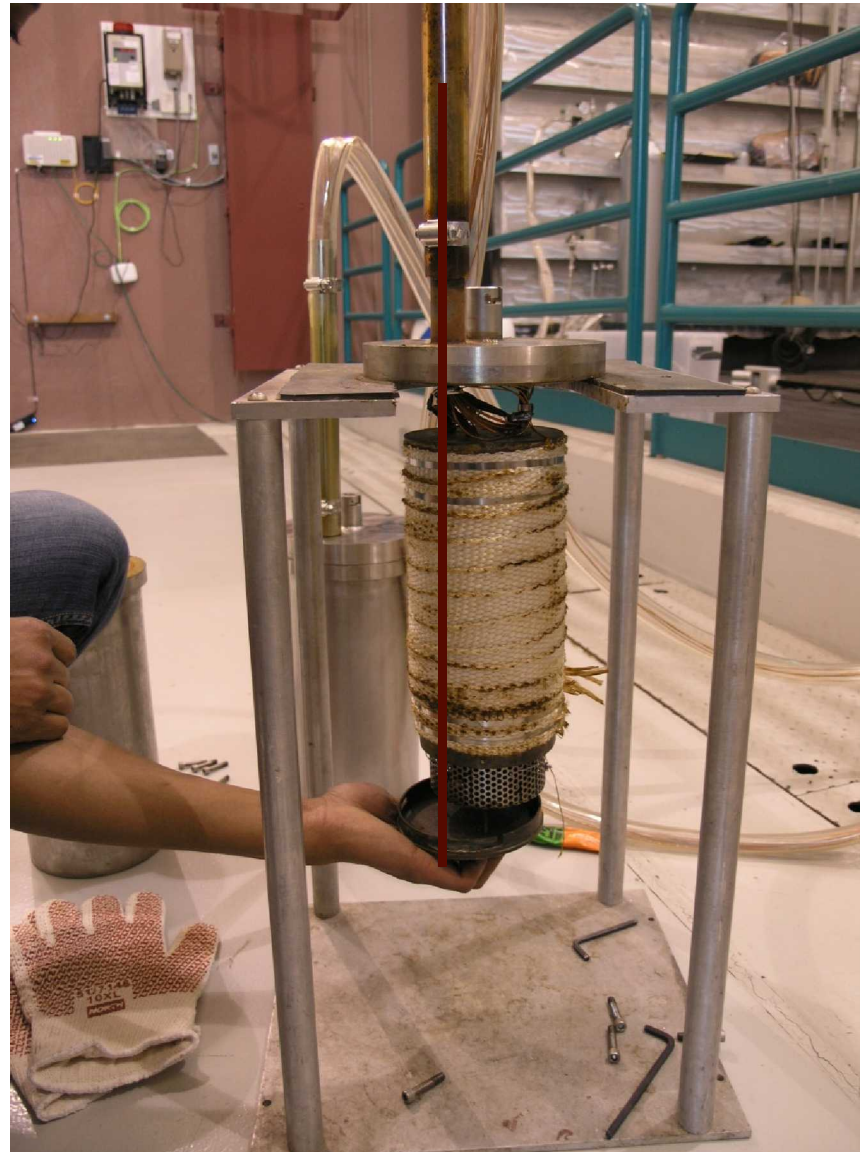
NEPO 9 – BRAND-REX XLPO



15 tensile specimens in A,X,Y, Z and C.
2 long gel-sol specimens in A,Y, and C.
1 long gel-sol specimen in X and Z.

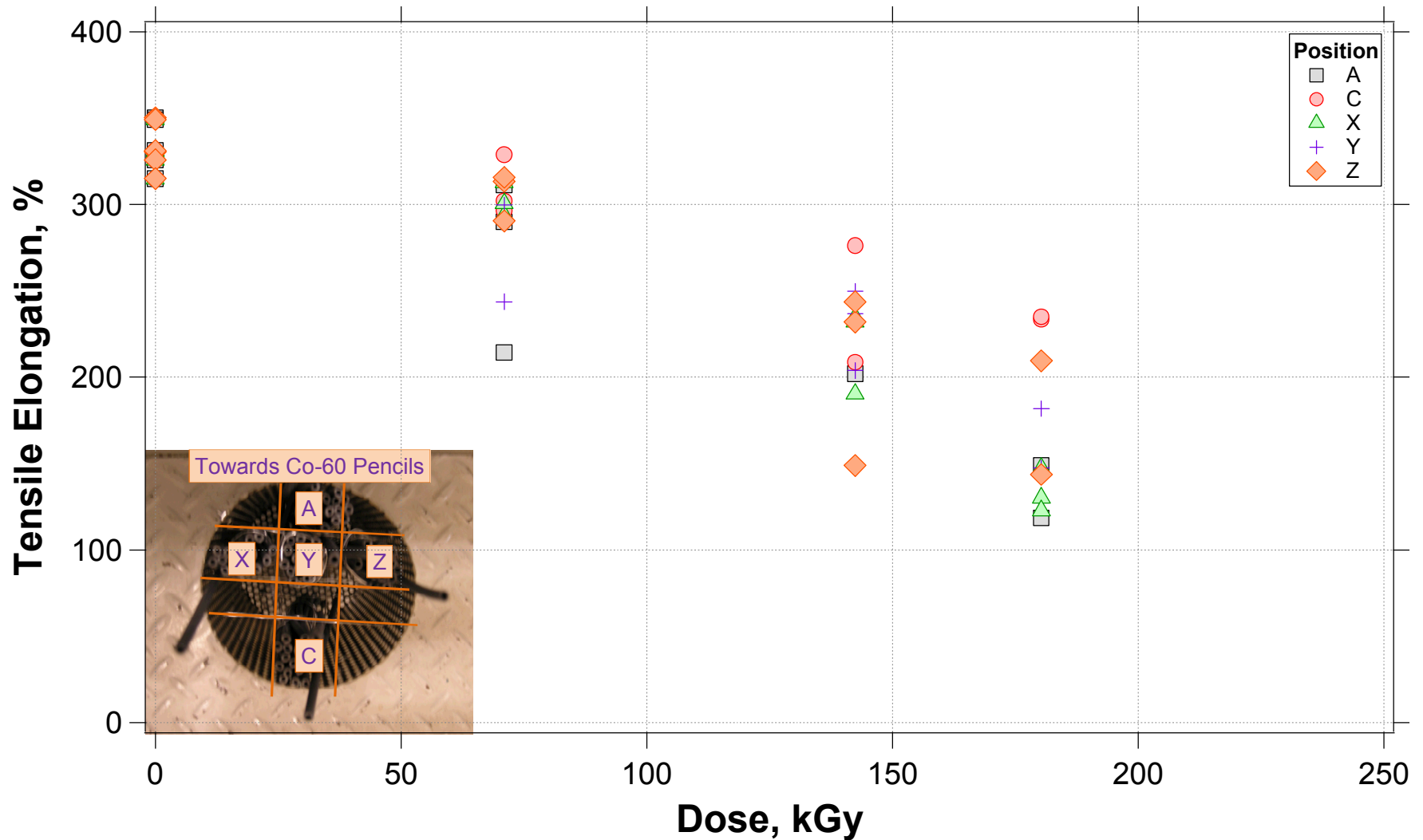
NEPO 9 – BRAND-REX XLPO





2x Screws at back align with metal line

NEPO 9 – BRAND-REX XLPO

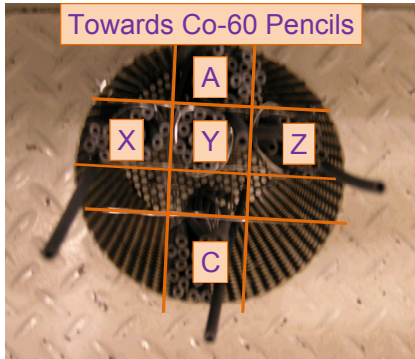


NEPO 9 – BRAND-REX XLPO

Raw Data!

A_142 kGy	A 142 Elongation	C_142 kGy	C 142 Elongation	X_142 kGy	X 142 Elongation	Y_142 kGy	Y 142 Elongation	Z_142 kGy	Z 142 Elongation
0.0	350.2	0.0	350.2	0.0	350.2	0.0	350.2	0.0	350.2
0.0	349.1	0.0	349.1	0.0	349.1	0.0	349.1	0.0	349.1
0.0	330.4	0.0	330.4	0.0	330.4	0.0	330.4	0.0	330.4
0.0	331.2	0.0	331.2	0.0	331.2	0.0	331.2	0.0	331.2
0.0	325.8	0.0	325.8	0.0	325.8	0.0	325.8	0.0	325.8
0.0	315.0	0.0	315.0	0.0	315.0	0.0	315.0	0.0	315.0
71.0	290.0	71.0	302.2	71.0	293.7	71.0	317.3	71.0	313.5
71.0	214.2	71.0	296.4	71.0	300.6	71.0	243.7	71.0	290.5
71.0	311.5	71.0	328.8	71.0	312.7	71.0	299.7	71.0	315.7
142.4	202.1	142.4	276.2	142.4	232.1	142.4	203.9	142.4	232.0
180.3	118.6	142.4	208.8	142.4	190.3	142.4	249.8	142.4	243.8
180.3	149.1	180.3	233.5	142.4	234.7	142.4	237.0	142.4	148.9
		180.3	235.1	180.3	130.4	180.3	147.5	180.3	143.7
				180.3	122.9	180.3	181.9	180.3	209.6
				180.3	147.4				

Towards Co-60 Pencils

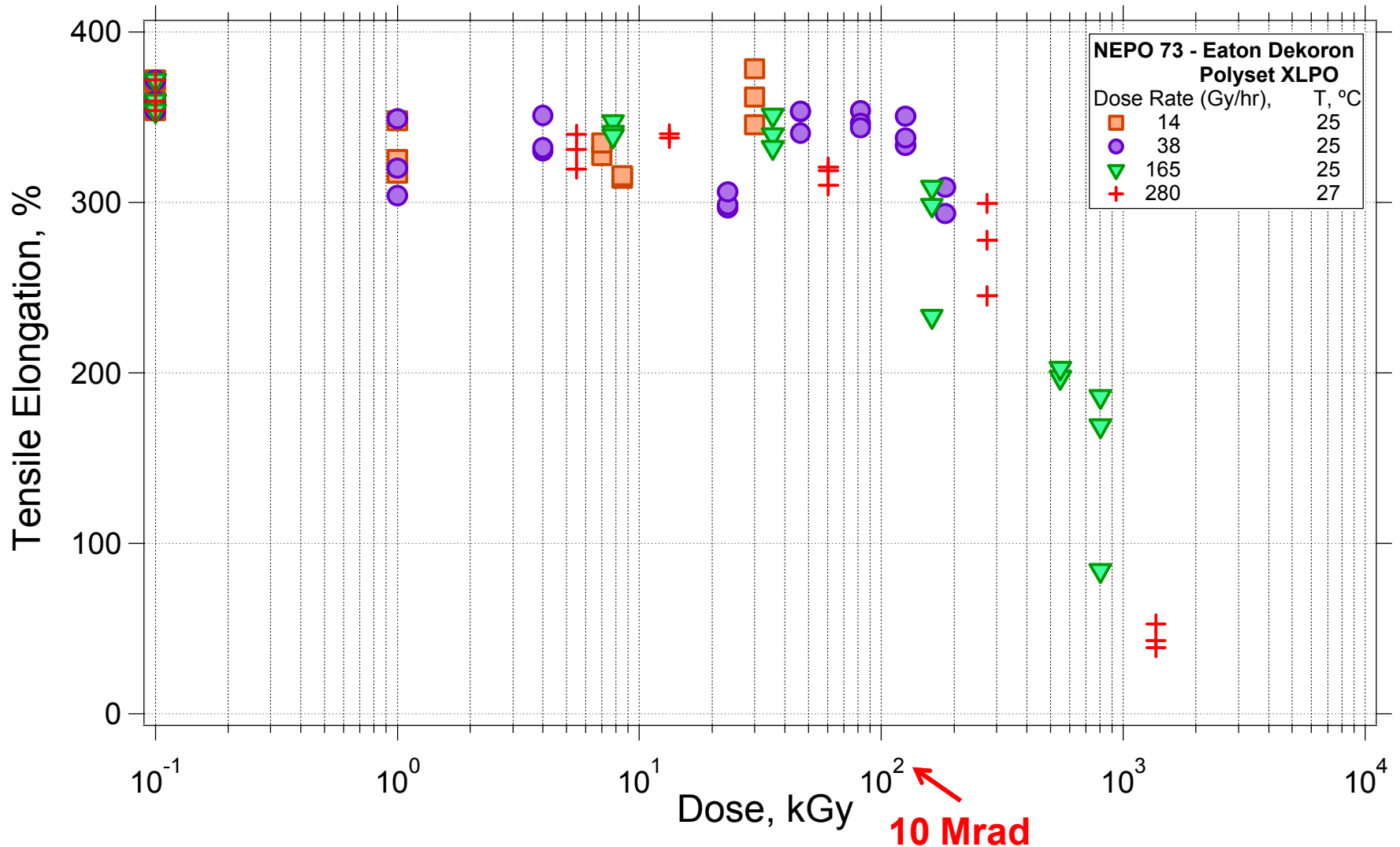


NEPO 73

EATON DEKORON POLYSET XLPO

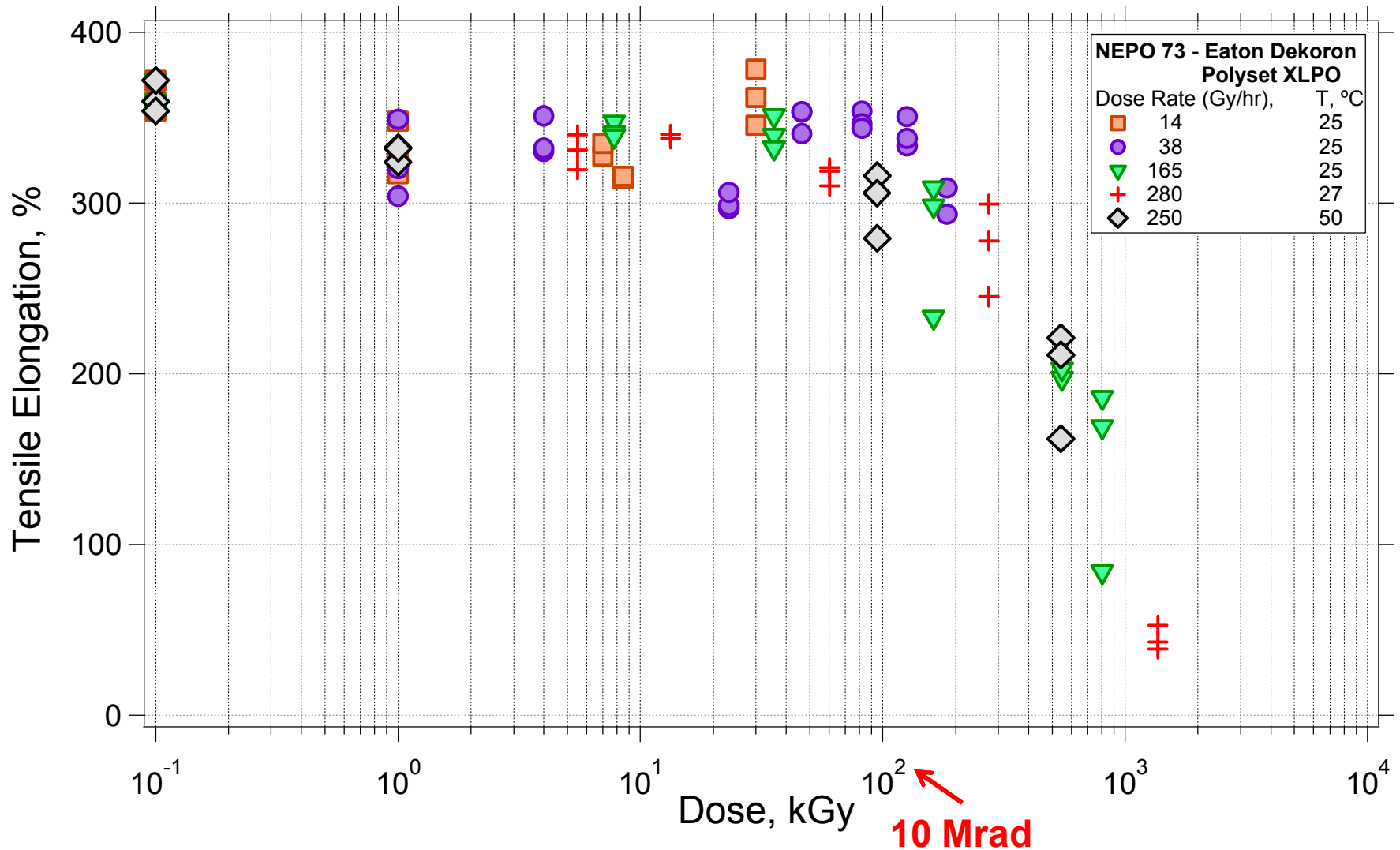
NEPO 73 – Eaton Dekoron Polyset XLPO

Thermal/Radiation Synergy

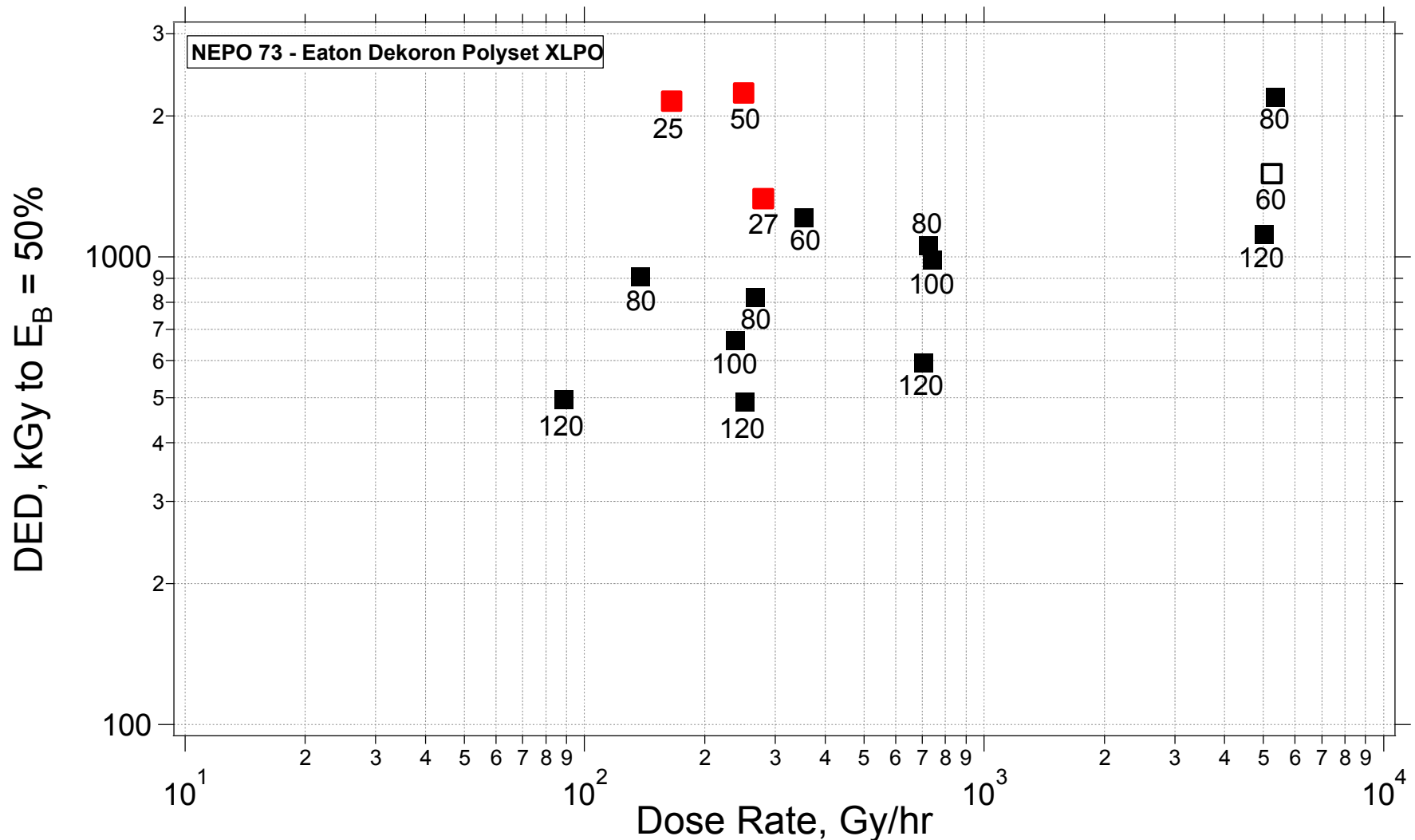


NEPO 73 – Eaton Dekoron Polyset XLPO

Thermal/Radiation Synergy

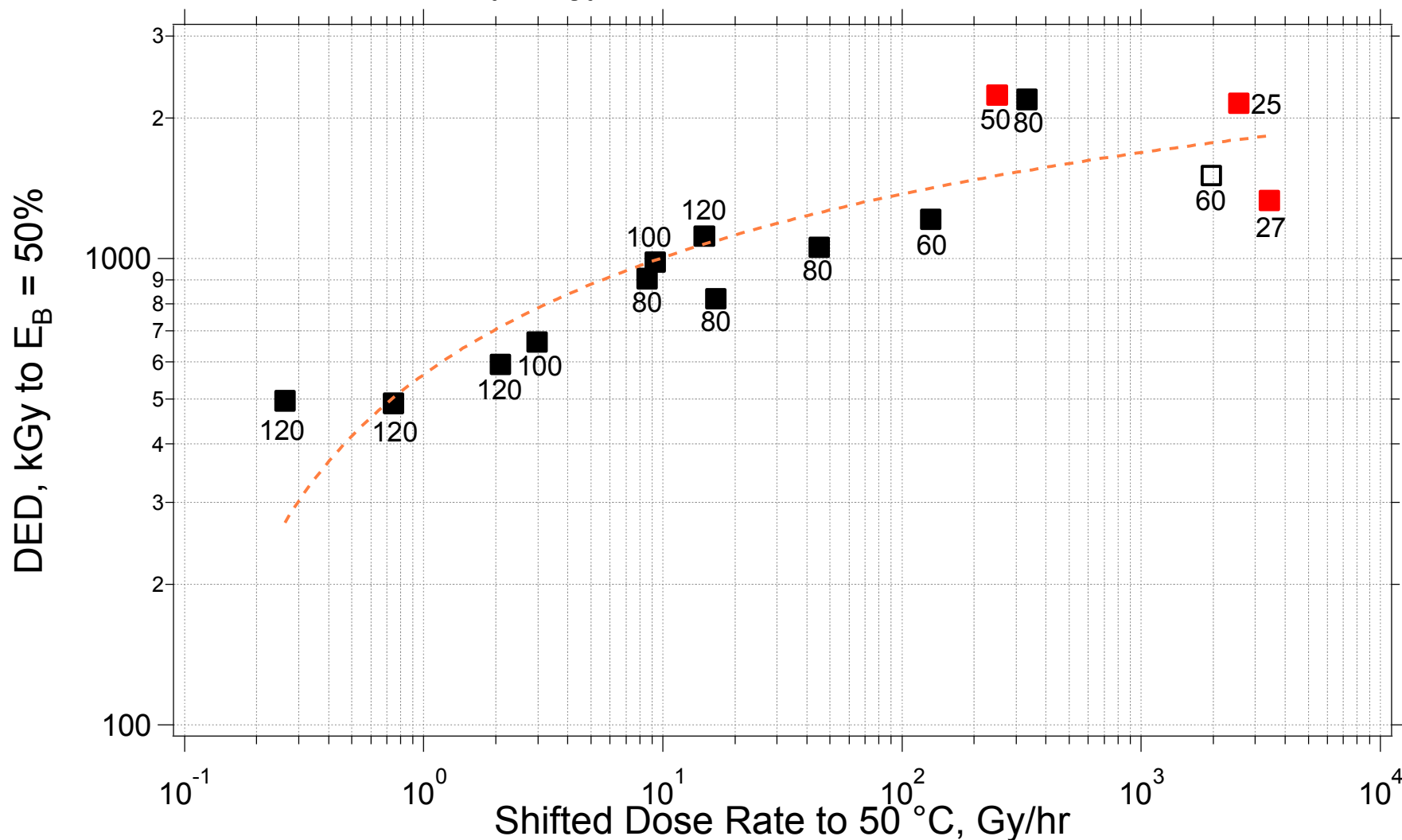


NEPO 73 - Eaton Dekoron Polyset XLPO



NEPO 73 – Eaton Dekoron Polyset XLPO

Thermal/Radiation Synergy



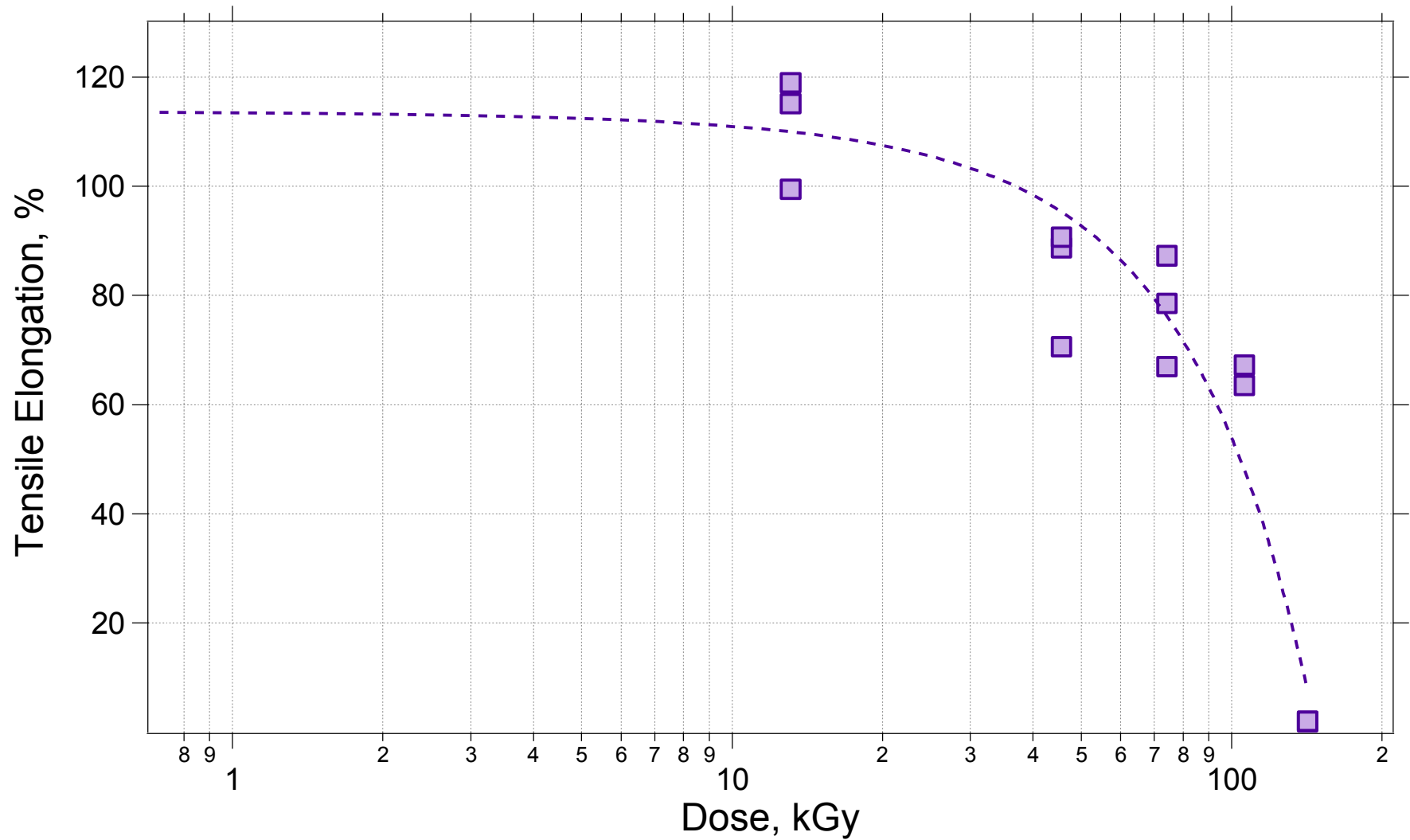
FO-GG-001 r 1				Gerencia de coordinación de proyectos CNEA NA-SA		IN-CPCN/GE-72 Rev.: 0	
				Page: 1 of 6			
TITLE: Report on previous experience on silicone rubber cable.							
1. OBJECTIVE The objective of this report is to summarize the previous experience in silicone rubber cables installed in NPP in Argentina.							
2. SCOPE This procedure is applicable to silicone rubber cables studies under agreement between CNEA and NA-SA within the scope of CP AI 02-10 contract. This report is issue under the cooperation agreement between Argentinean Secretary of Energy and United State department of Energy.							
Preparó		Revisó			Intervino calidad	Aprobó	
Jorge Zorrilla		Elvio Antonaccio			Jorge Zorrilla	Juan Manuel Ranalli	
REVISIONES							
Rev.	Fecha	Modificaciones					
FECHA DE VIGENCIA:							

US-Argentine BEWG

SILICONE RUBBER

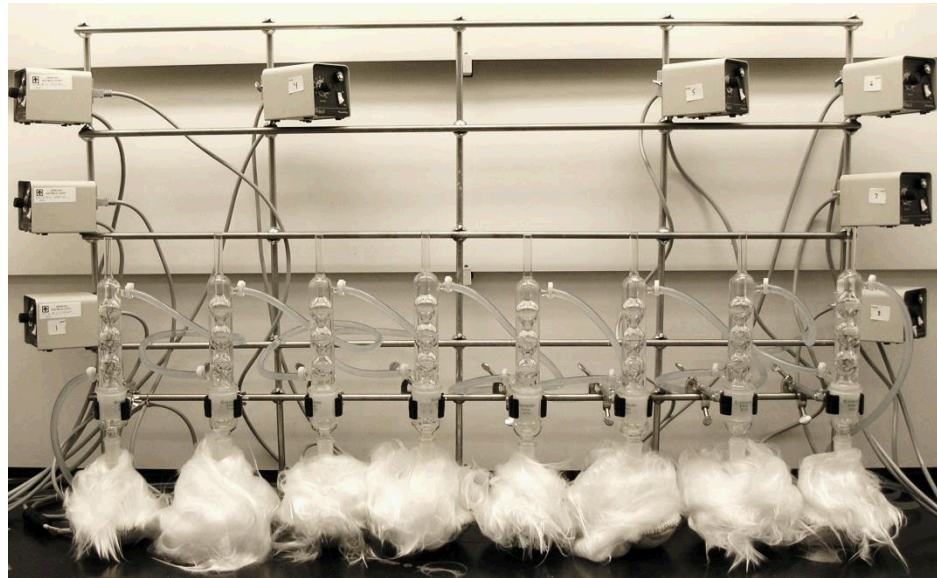


Tensile Data



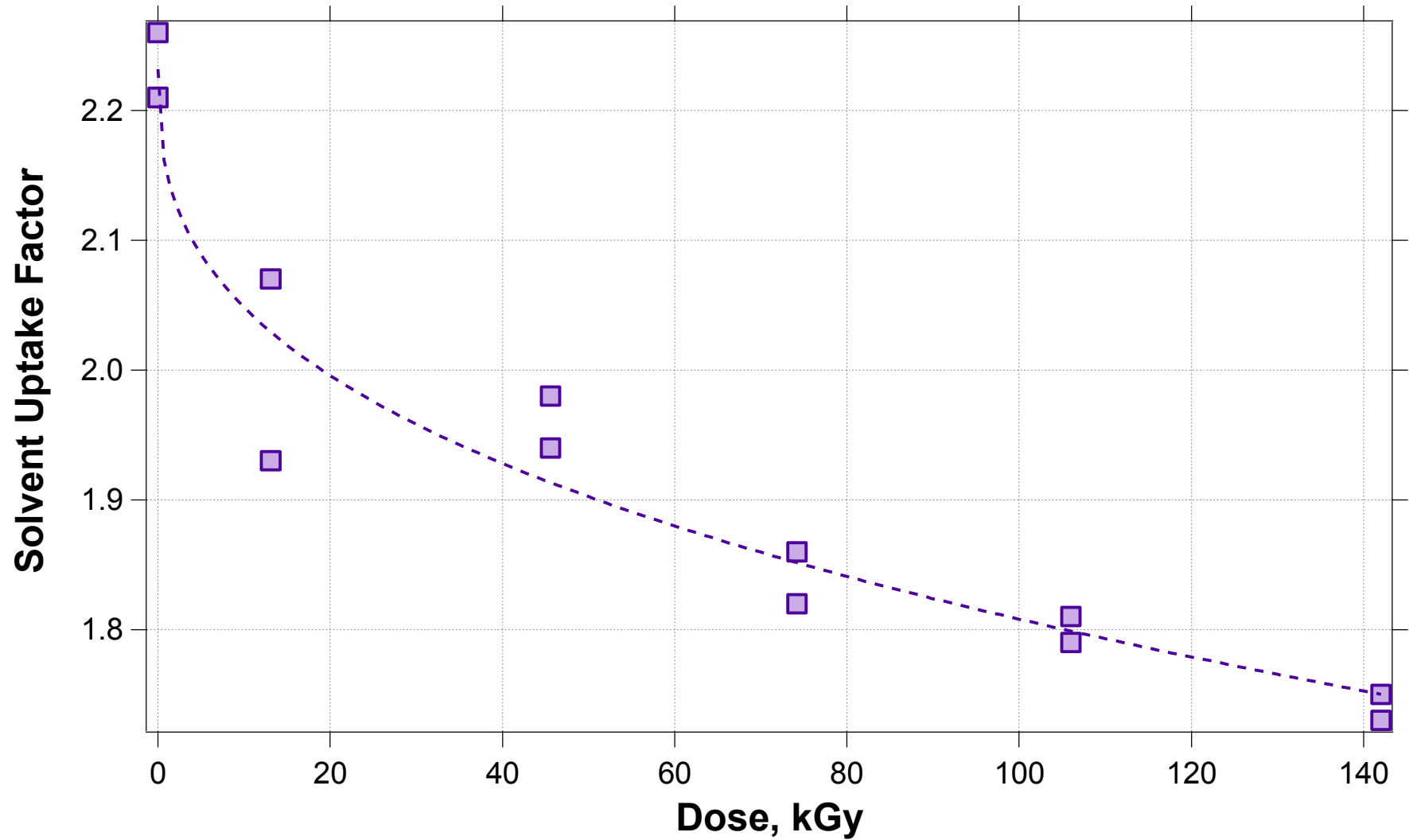
Physical Property Testing

- Is there correlation between mechanical properties and gel content and/or solvent uptake factors?

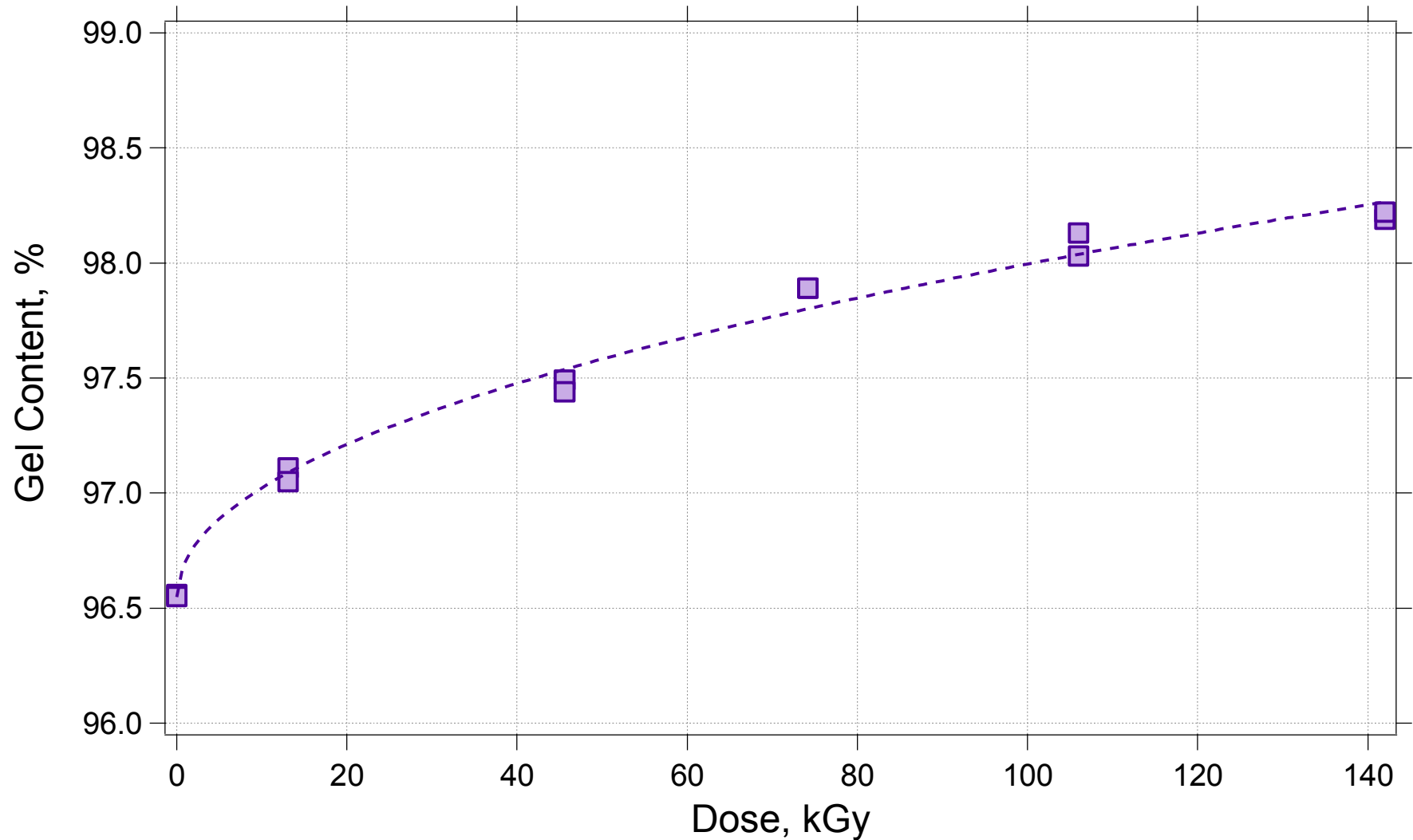


If so, these techniques could be employed as future condition monitoring techniques.

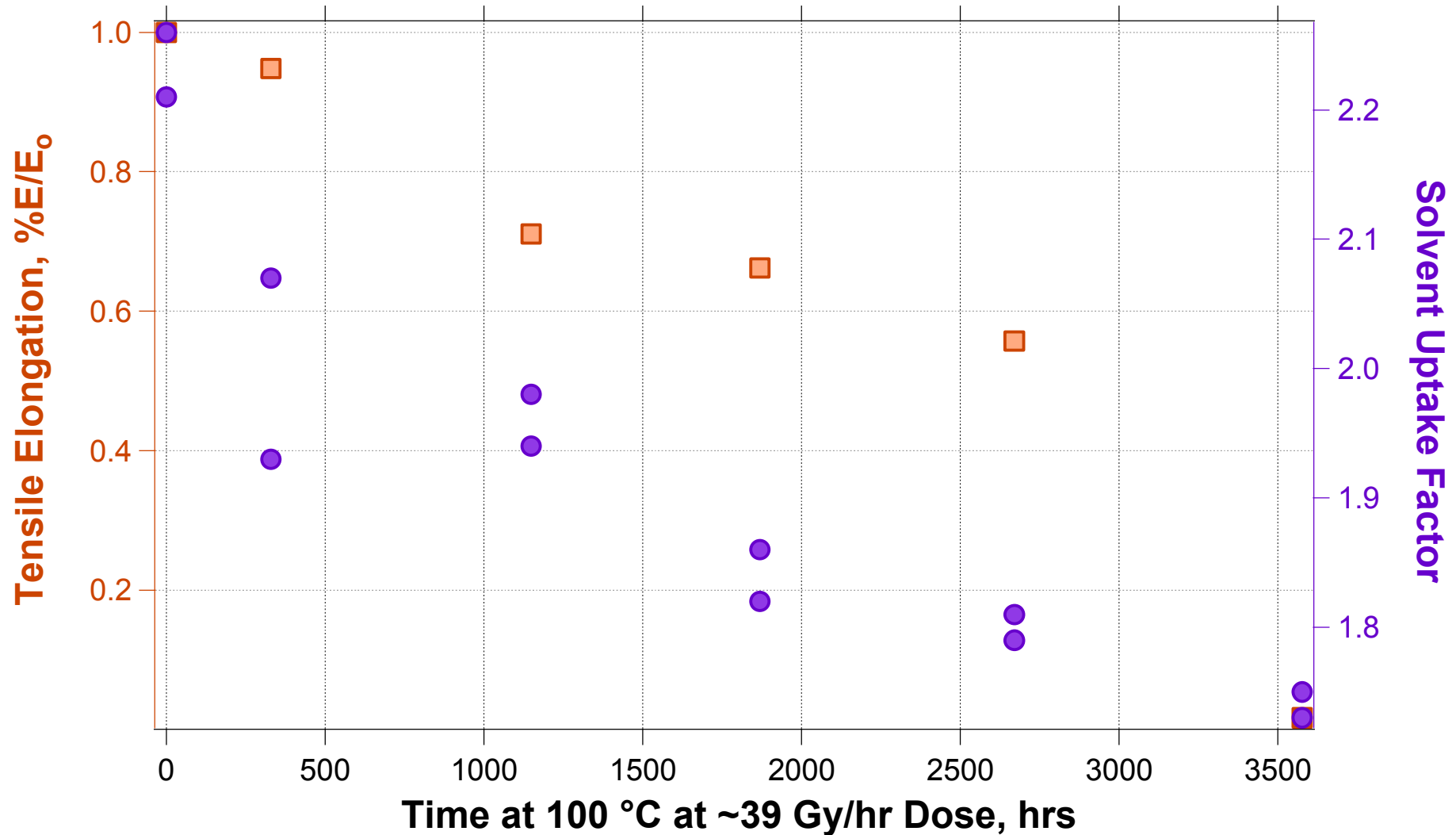
Solvent Uptake Factor



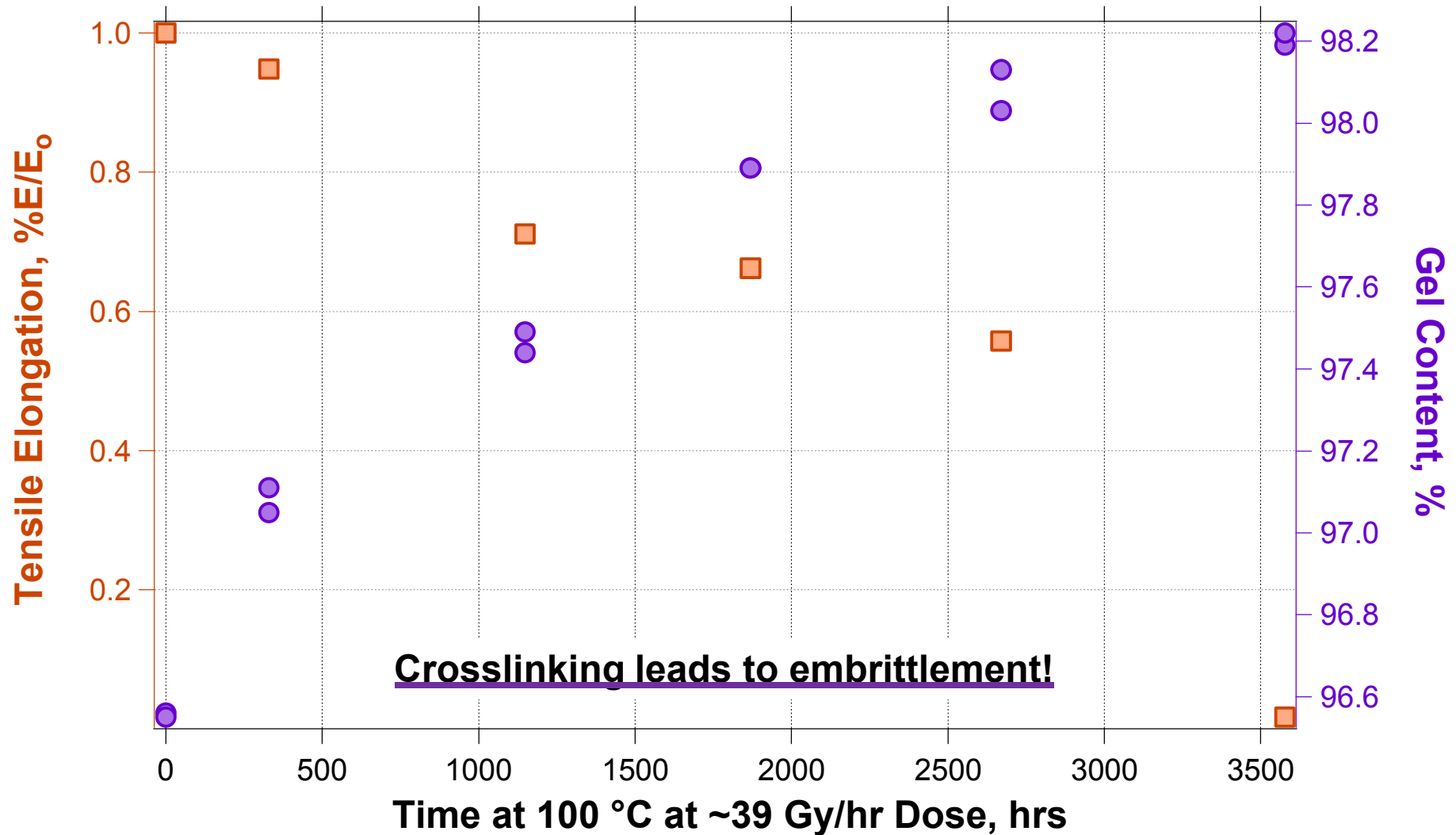
Gel Content Analysis



Correlation to Performance?



Correlation to Performance?



Future Directions

- Work towards understanding relevant NPP cable conditions (temperature, dose rates) to better tailor current predictive models
 - EPRI and Industry are leading these efforts to identify their conditions
- Validate predictive models with service cables (e.g., cables from the Zion Nuclear Power Station)
- Investigate radiation effects at low dose-rates and plant relevant temperatures for EPR, XLPO, and SiR materials

Acknowledgements

- Jeremy T. Busby (ORNL)
- Kathryn A. McCarthy (INL)
- Andrew Mantey (EPRI)
- Gary Toman (EPRI)
- Sherry Bernhoft (EPRI)
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- Sheila Ray (NRC)
- Darrell Murdock (NRC)
- Kevin Simmons (PNNL)
- Jorge Zorrilla (CNEA)
- Maryla Wasiolek (SNL)
- Don Hanson (SNL)



BACKUP SLIDES

Recent Modernization

LICA AND THE CURRENT CAPABILITIES?

Low Intensity Cobalt Array

LICA is a unique low intensity gamma irradiation facility located in TA-V at SNL NM.

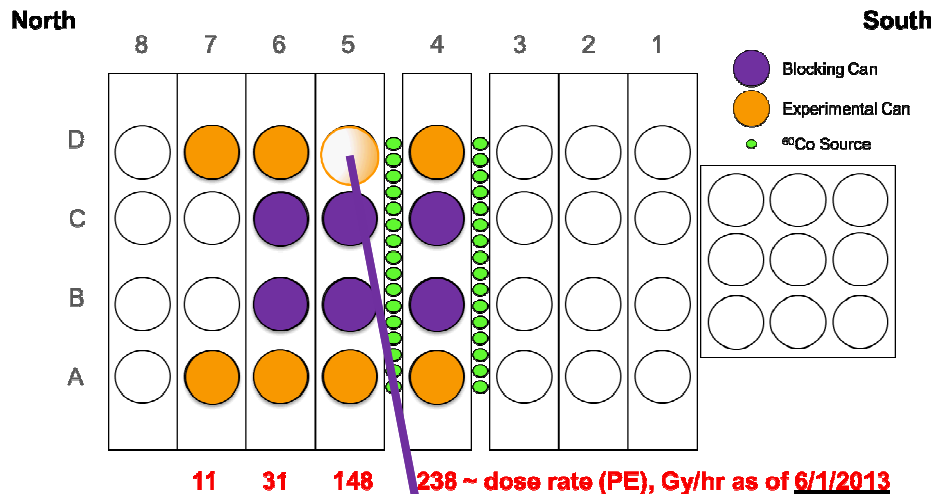


Studies conducted here can be tailored to help elucidate gamma irradiation effects on materials and components.

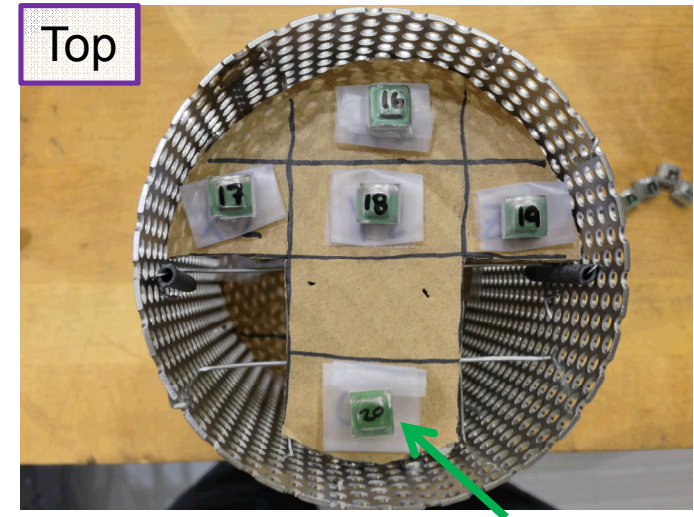
**Sandia
National
Laboratories**



Irradiation Dose Rates



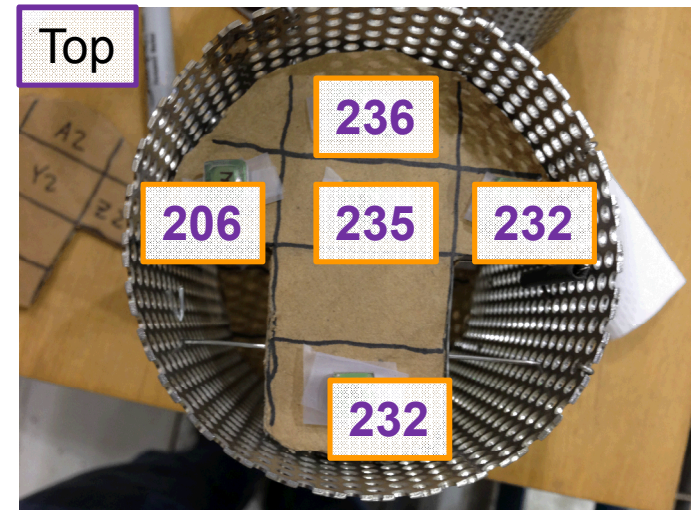
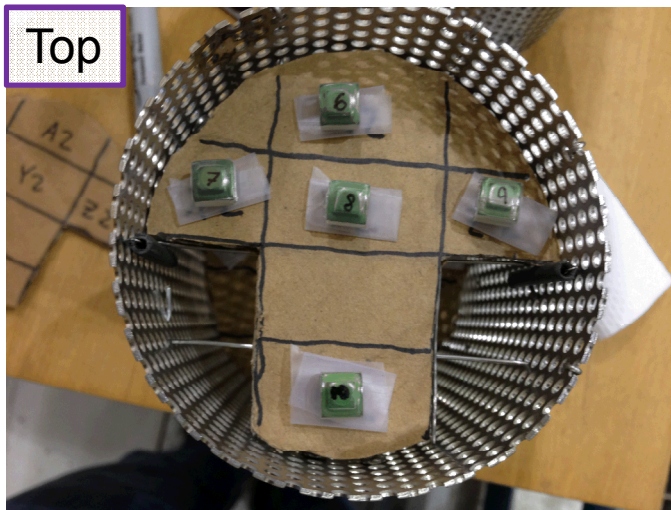
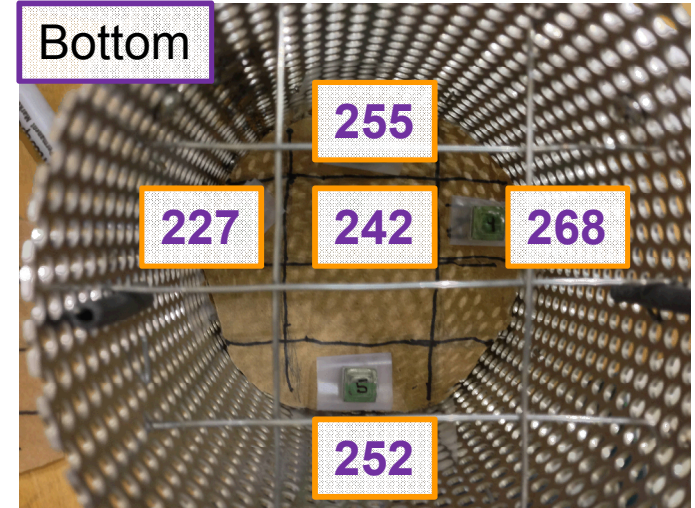
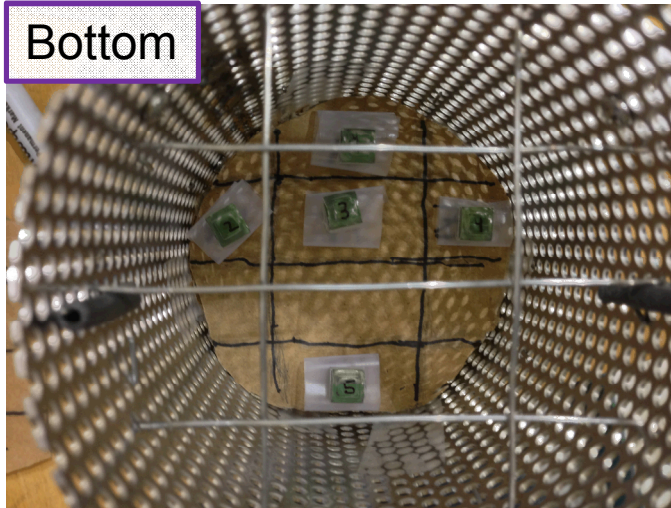
Dose rates are corrected for PE



Dosimetry is measured with CaF_2 TLDs as a function of position within the cans (in all 3 axial directions). The dose rates are corrected for material of interest, e.g. polyethylene.

Can 7, Position D4 (5/29/2013)

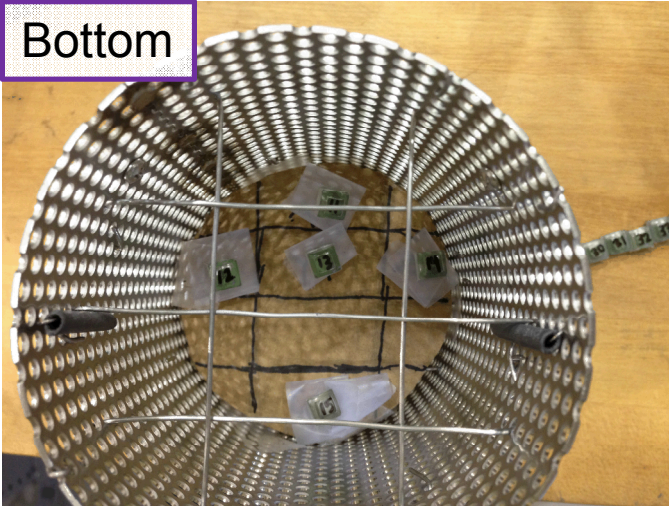
Dose Rates in Gy/hr corrected for PE



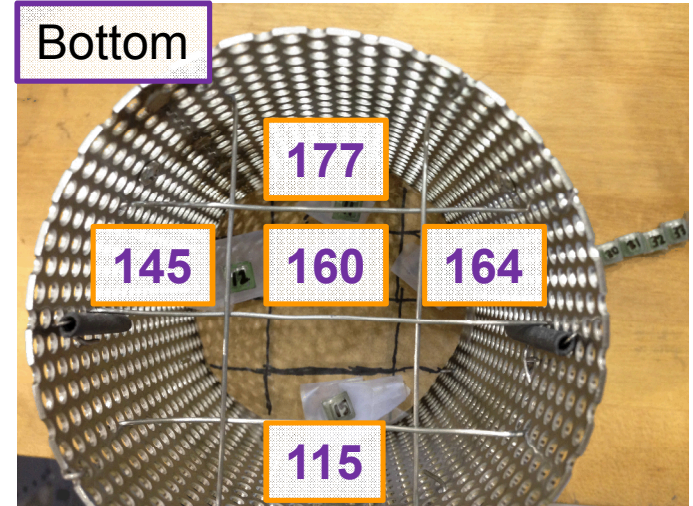
Can 8, Position D5 (5/29/2013)

Dose Rates in Gy/hr corrected for PE

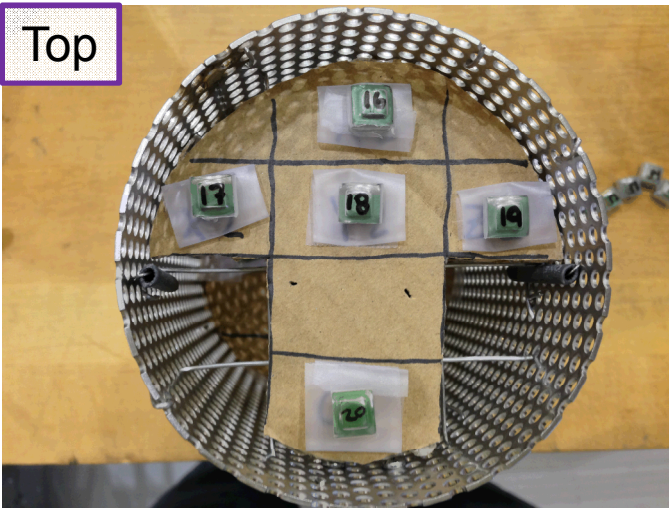
Bottom



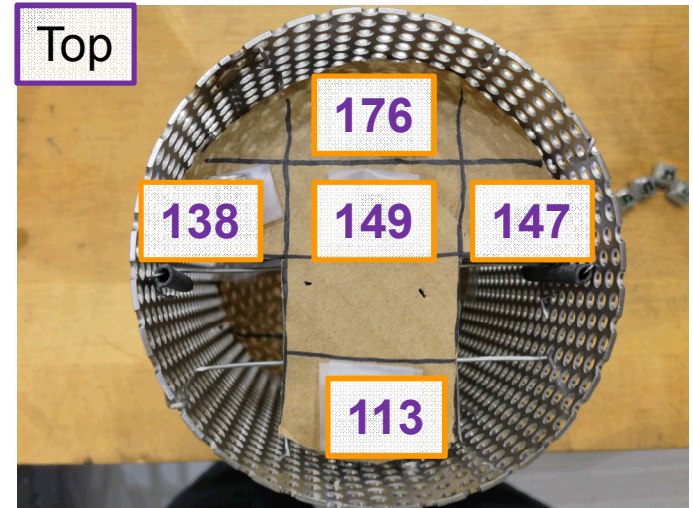
Bottom



Top

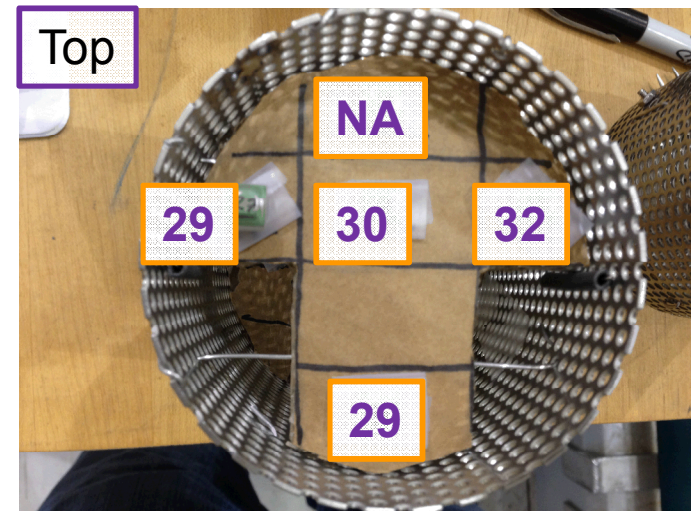
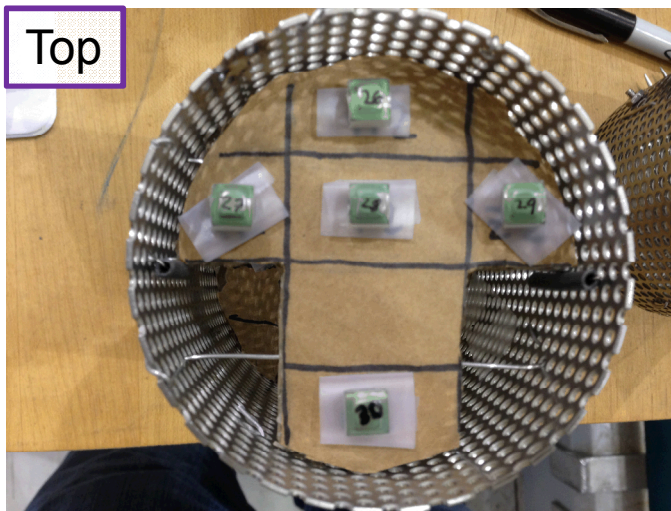
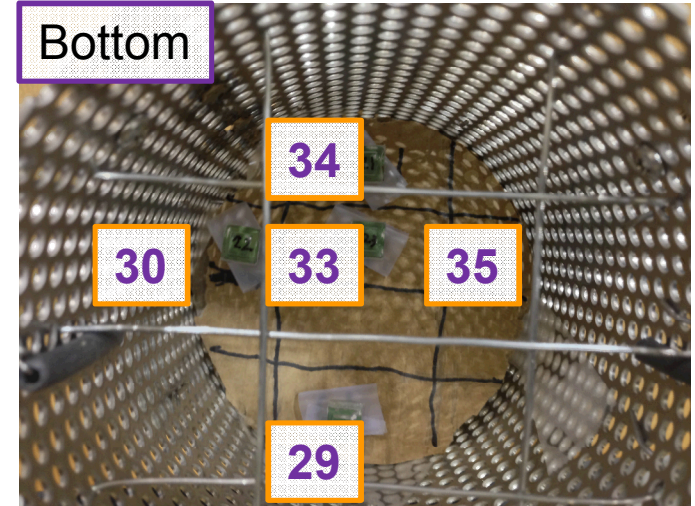


Top



Can 9, Position D6 (5/31/2013)

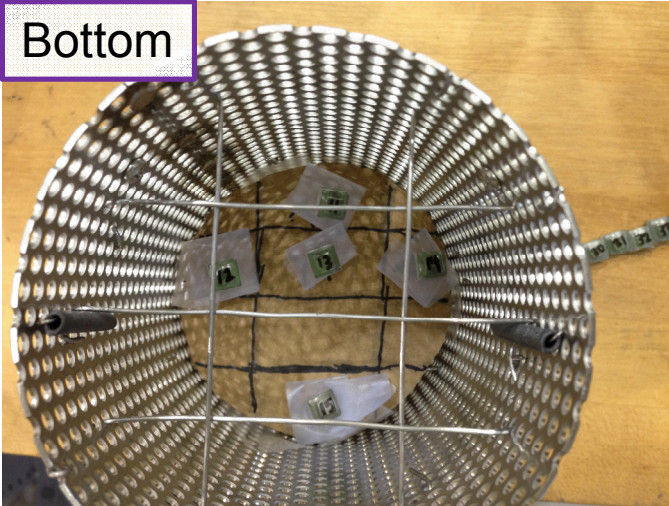
Dose Rates in Gy/hr corrected for PE



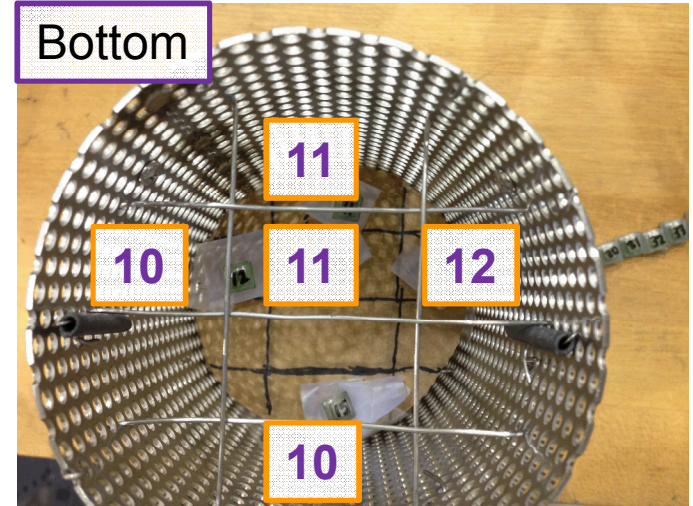
Can 10, Position D7 (5/31/2013)

Dose Rates in Gy/hr corrected for PE

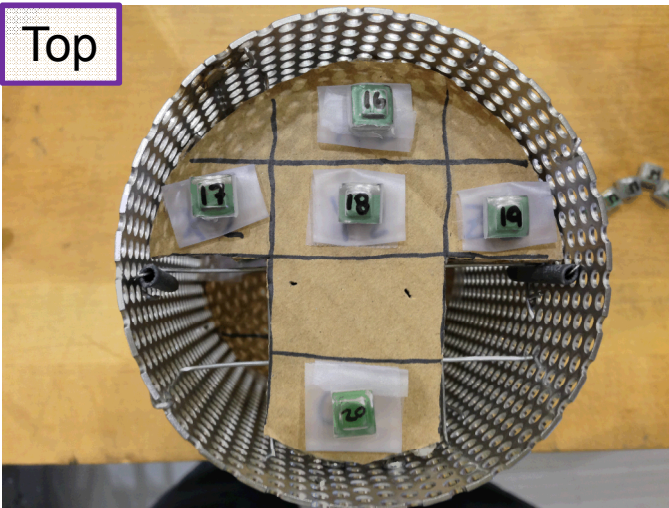
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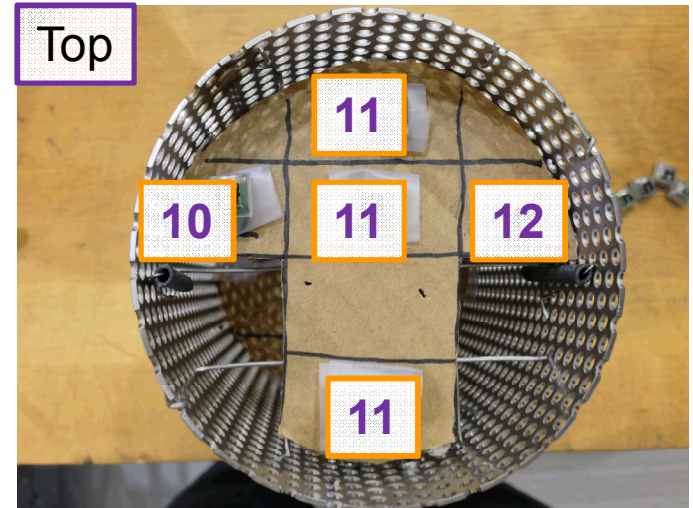
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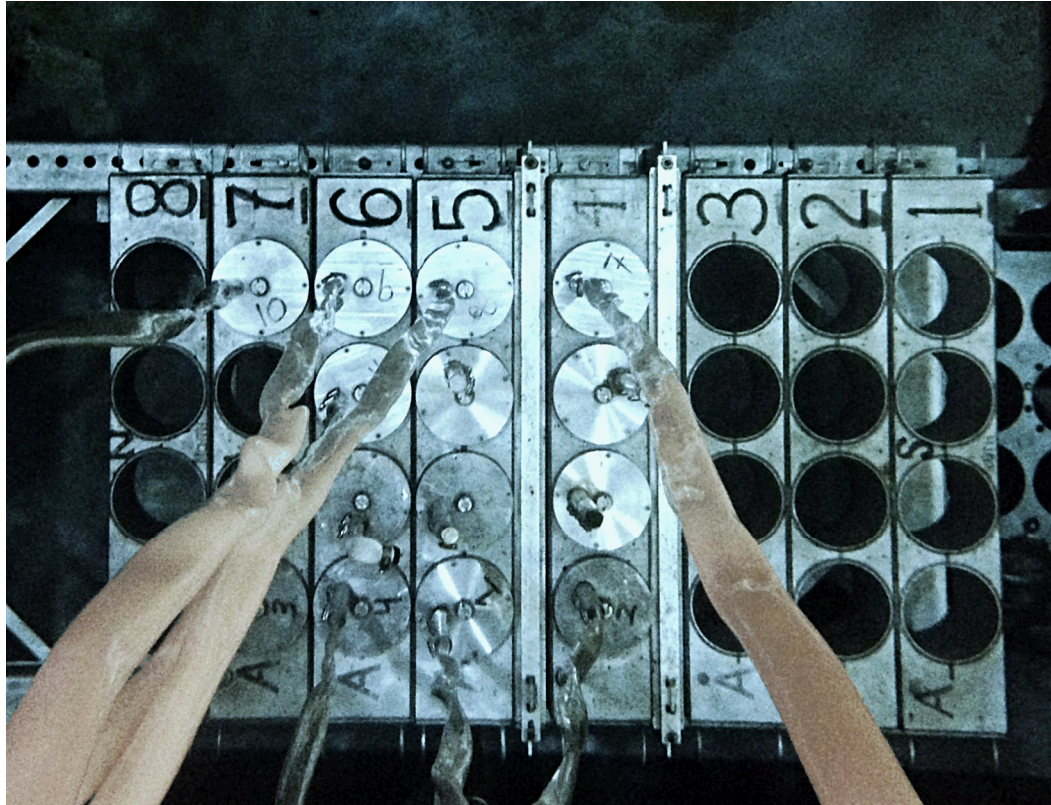
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Top



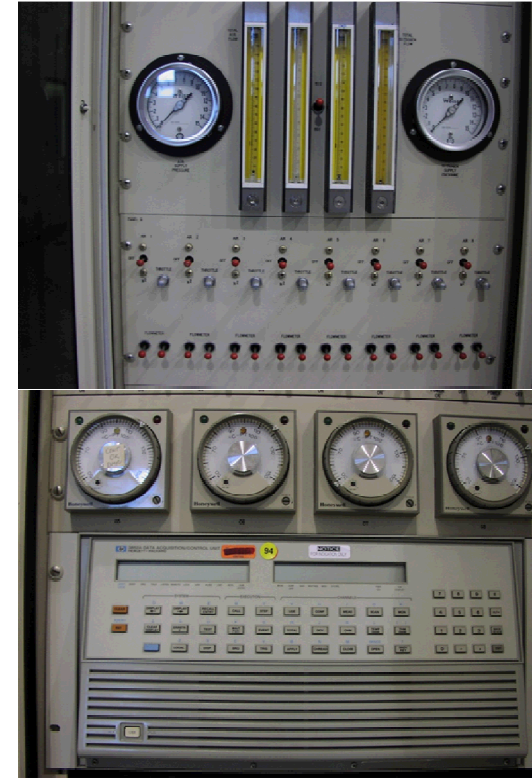
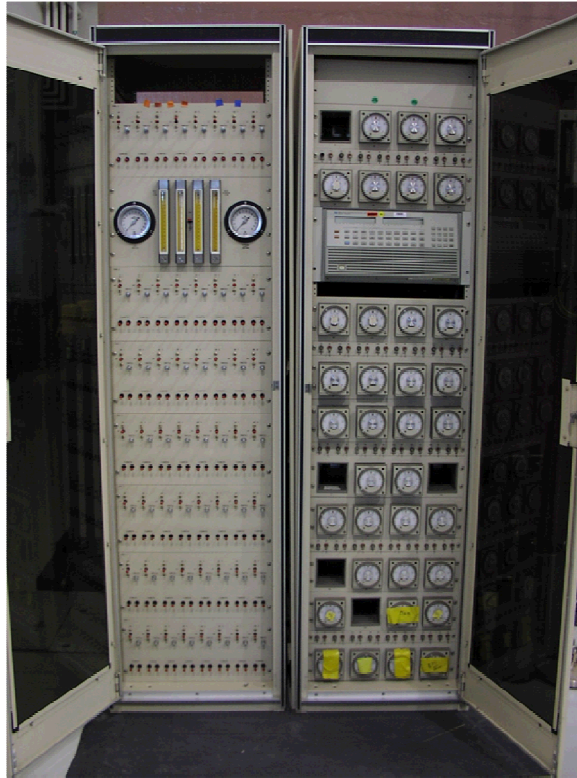
Dosimetry, May 2013



LICA Control System, ~2011

Tunable

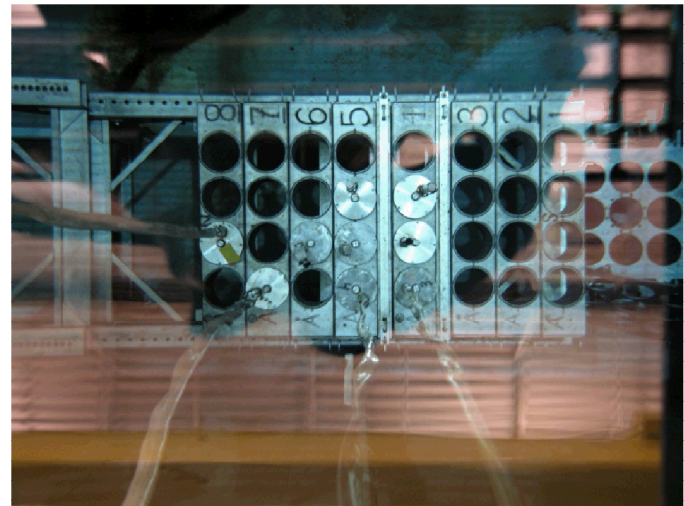
- Temperature
 - Gas Environment
- “Ancient” Technology



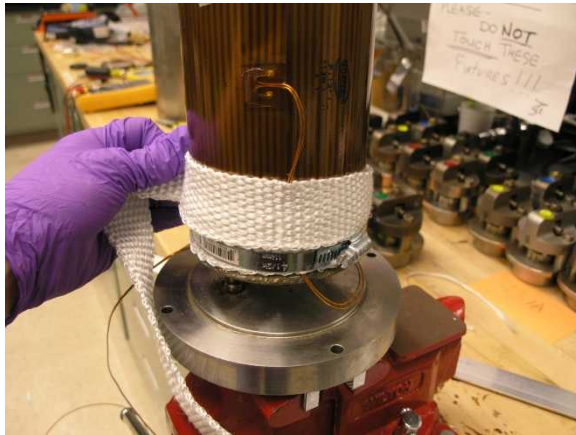
Gas Environments



- Capability to perform experiments in an air or inert atmosphere
 - Current experiments are run with an air flow rate of $5 \text{ cm}^3/\text{min}$



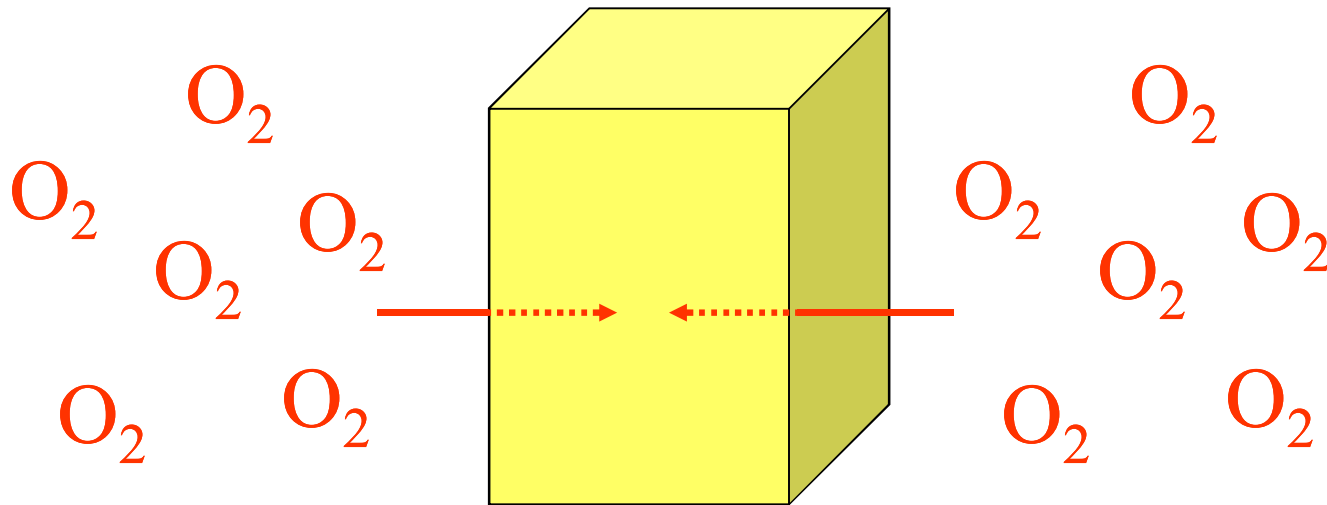
Thermal Environments



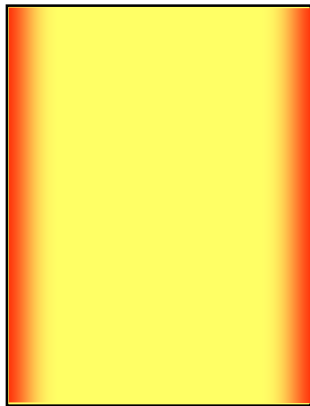
- Experiments can be performed at varying temperatures
 - 27 °C to 150 °C (± 0.2 °C)
- Remote access for thermal control and monitoring on the SRN
- Email alerts for extreme temperature variation
- Backup power supply for data logging in case power loss
- 4 elevated temperature cans and up to 7 ambient temperature cans



Diffusion Limited Oxidation

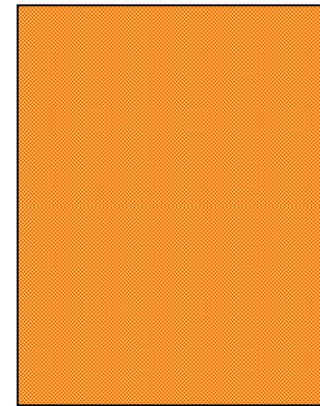


rxn rate > diffusion rate



Heterogeneous

rxn rate < diffusion rate



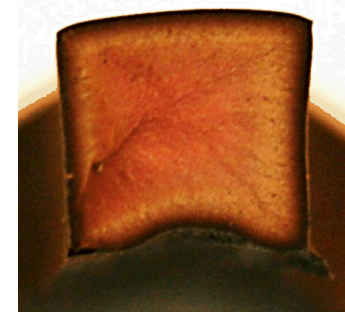
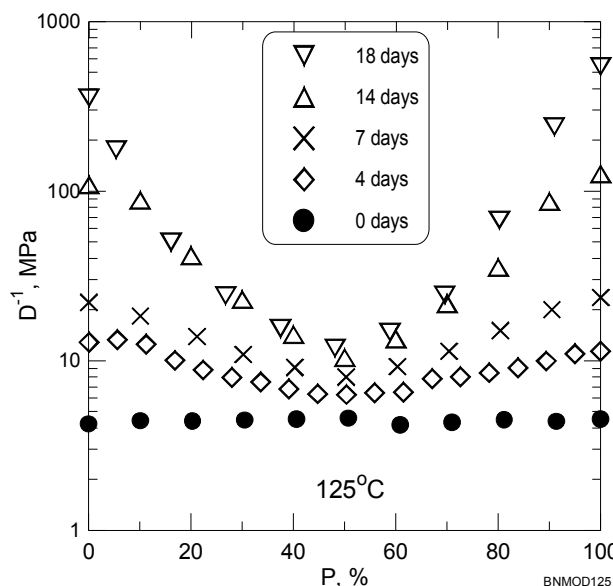
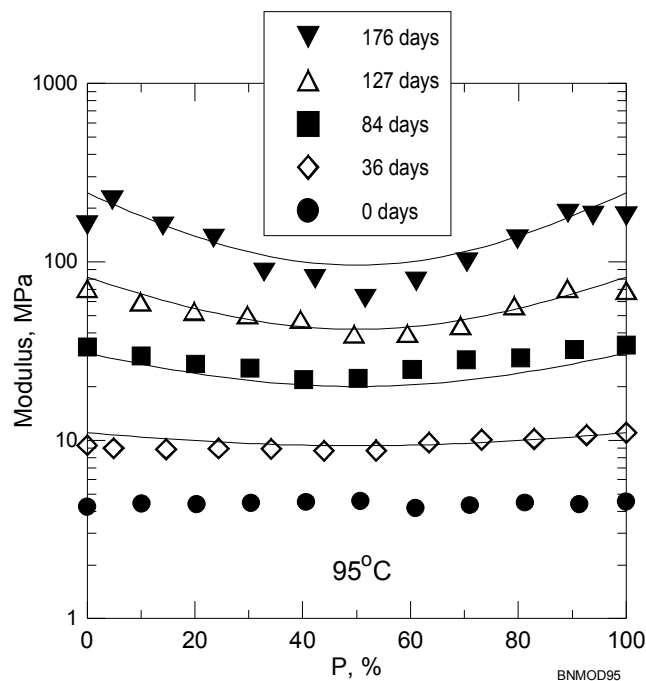
Homogeneous

DLO Effects with Temperature

Modulus profiles for samples aged at 95 °C show that diffusion-limited oxidation (DLO) is becoming important; at 125°C, DLO effects are very significant

Images shown below courtesy from our collaborator Kevin Simmons at PNNL

Aged cable with DLO



Wise, J.; Gillen, K. T.; Clough, R. L. Polymer Degradation and Stability, 1995, 49, 403-418.

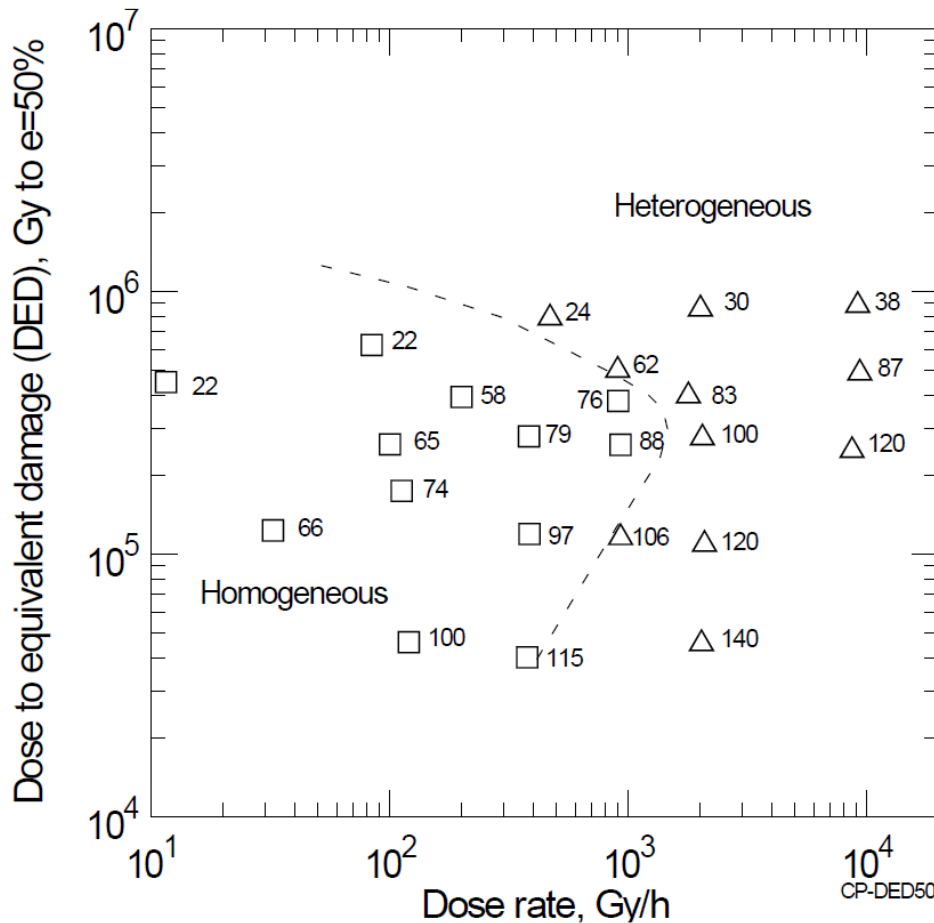
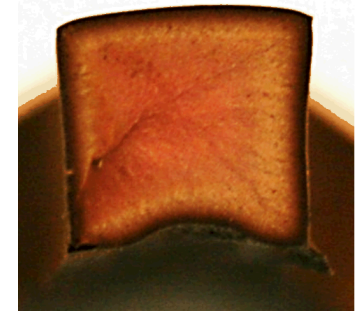
Virgin vs Aged

DLO Effects in Combined Environments

Combined environment tensile aging data for Okonite neoprene material with $DED = 50\% E_B$

Images shown below courtesy from our collaborator Kevin Simmons at PNNL

Aged cable with DLO

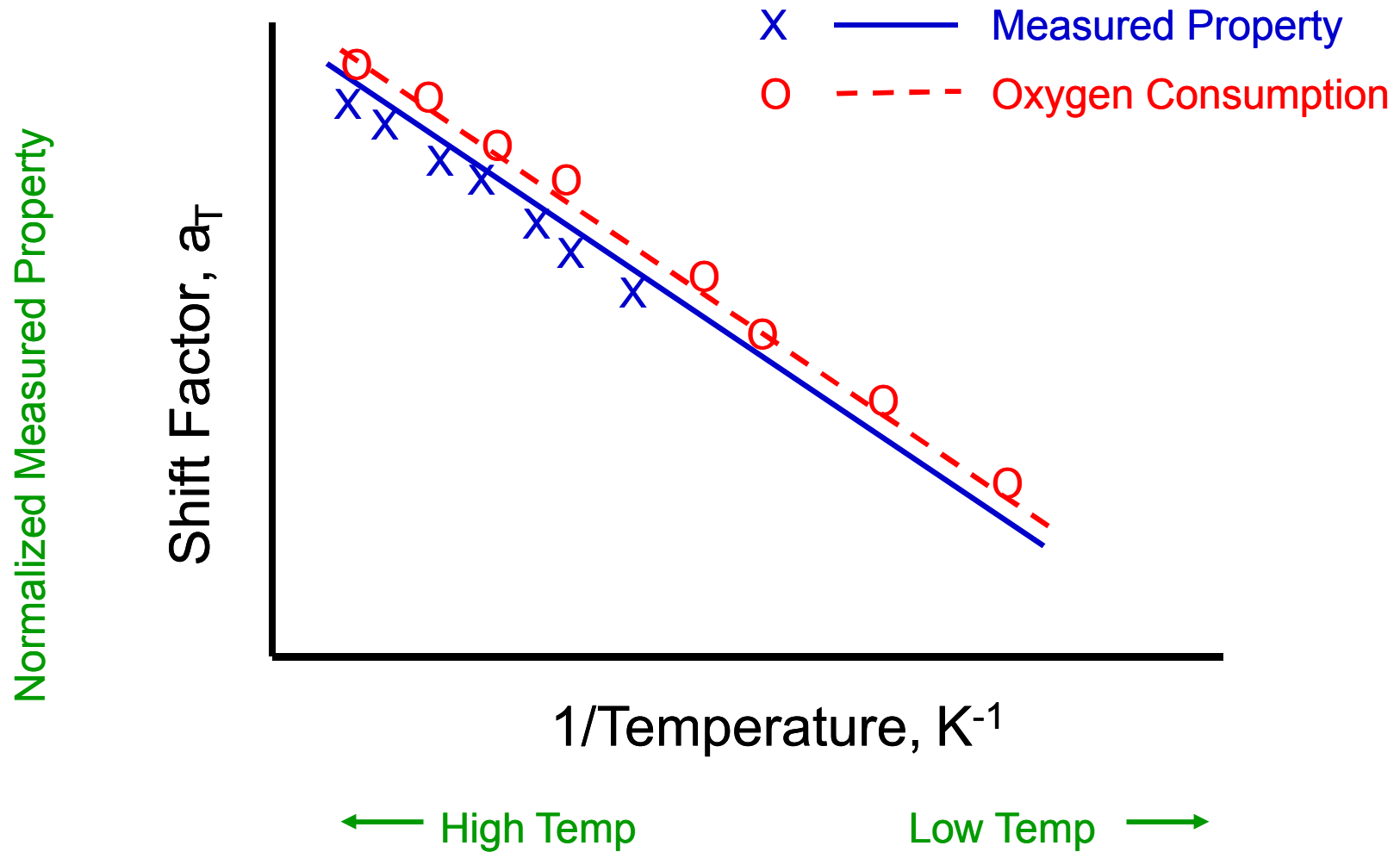


K. T. Gillen and R. Bernstein, SAND 2010-7266

This same phenomena has been noted for irradiation dose rates...

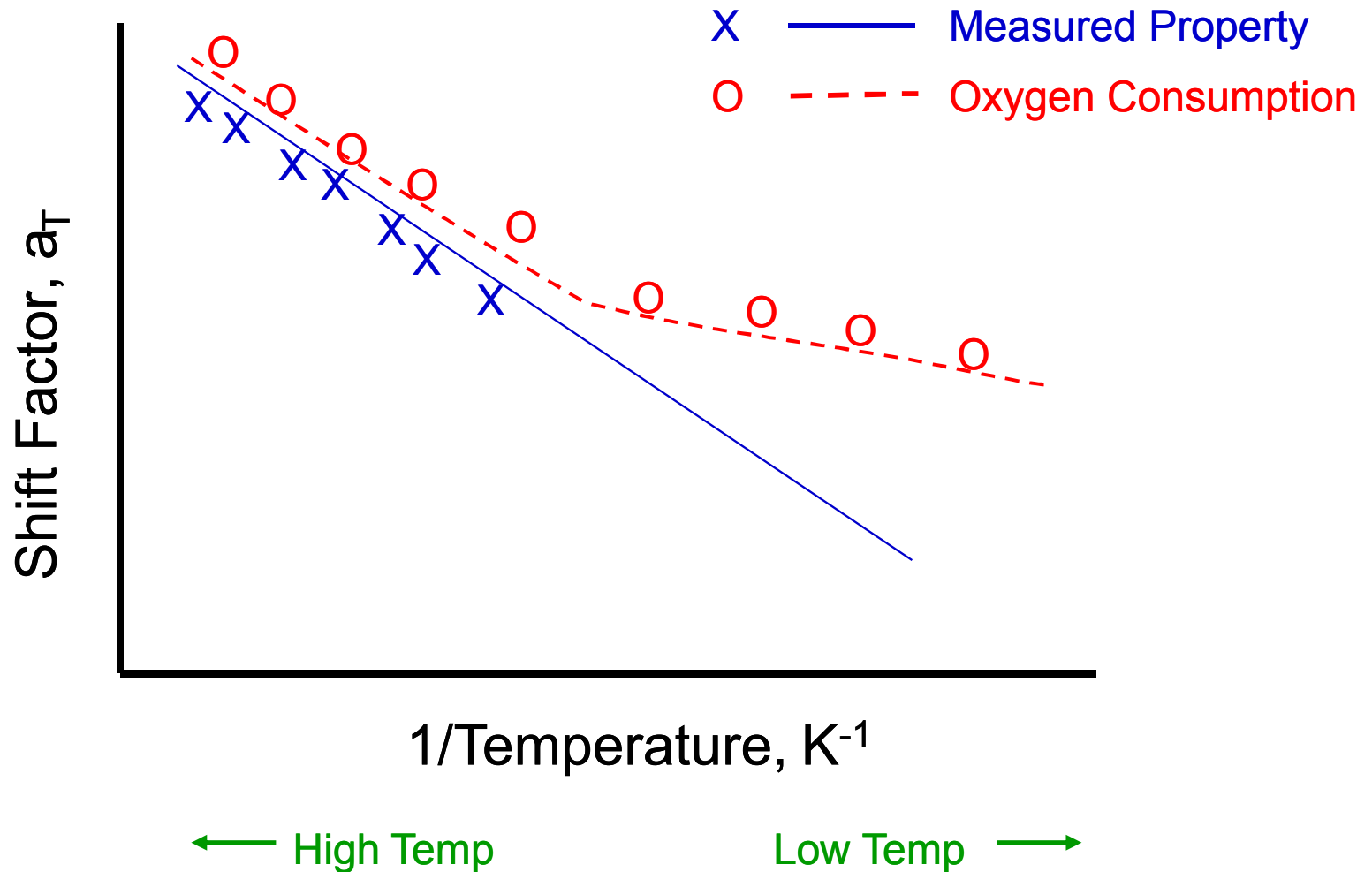
Virgin vs Aged

Enhanced Extrapolation 'Good'

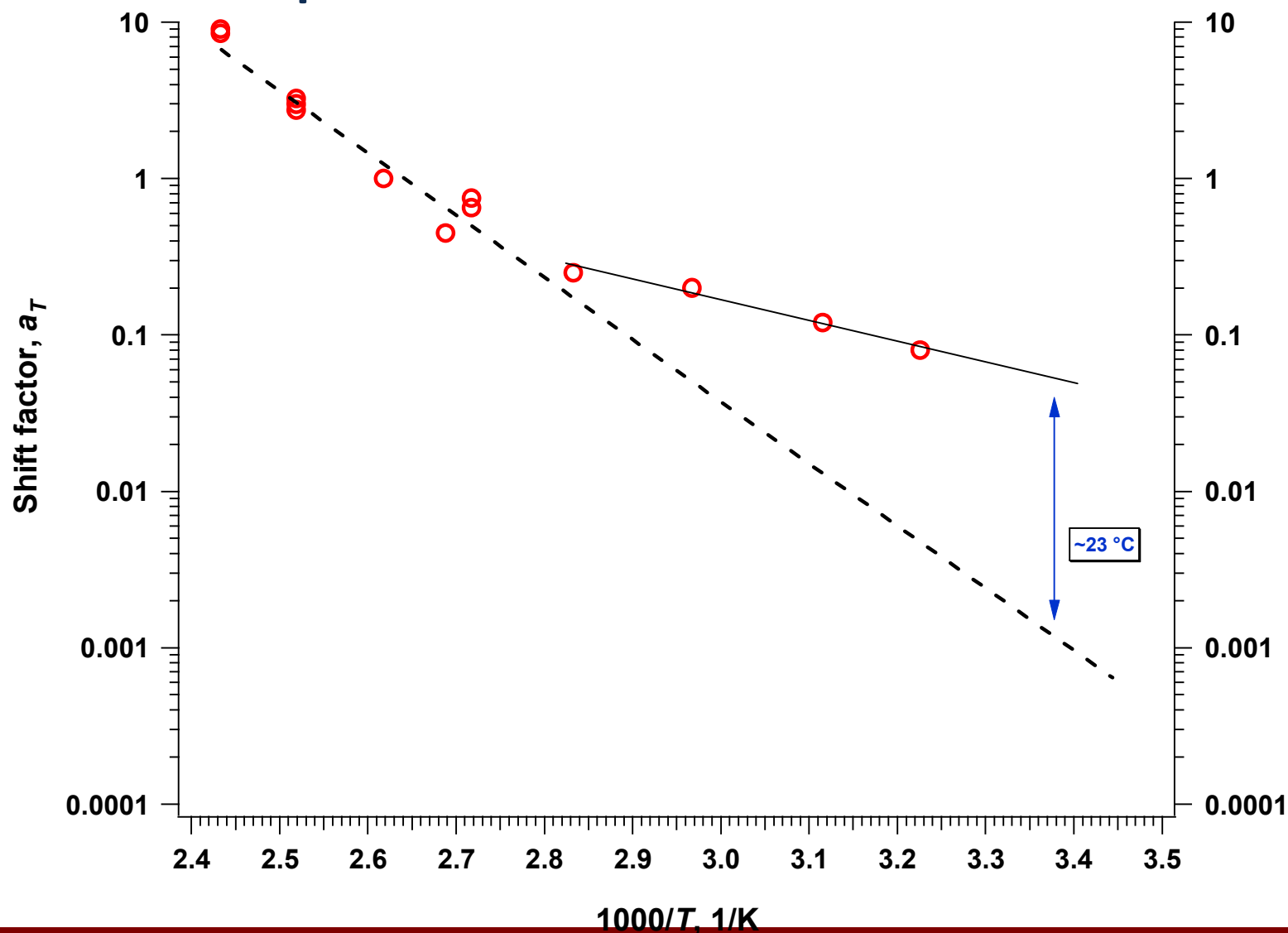


Enhanced Extrapolation: 'Bad'

Normalized Measured Property



Thermal-oxidative Aging: Nylon Shift Factor Graph



Arrhenius Equation

Arrhenius equation:

$$k = Ae^{-E_a/RT}$$

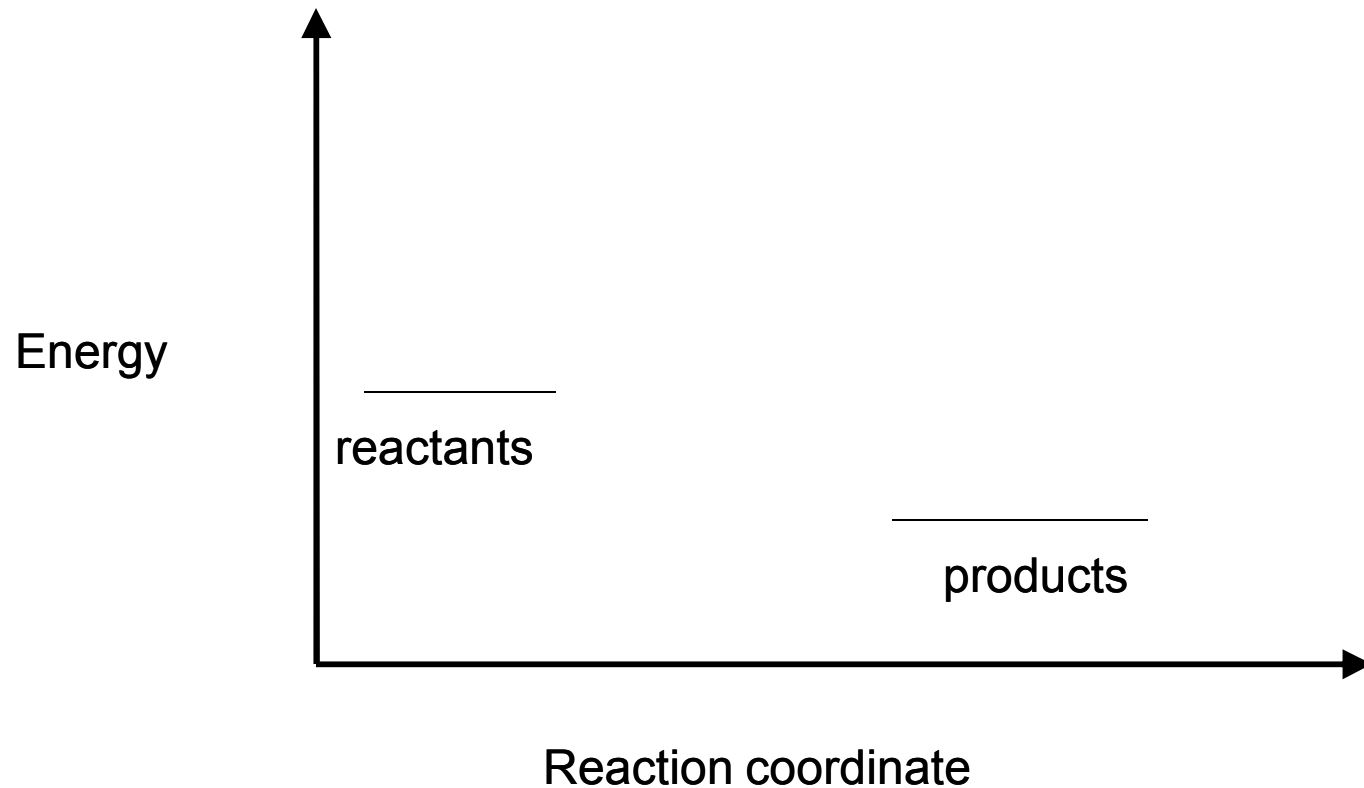
$$\ln(k) = -(E_a/R)(1/T) + \ln(A)$$

k = anything

Plot $\log(a_T)$ vs $1/T$ linear if Arrhenius

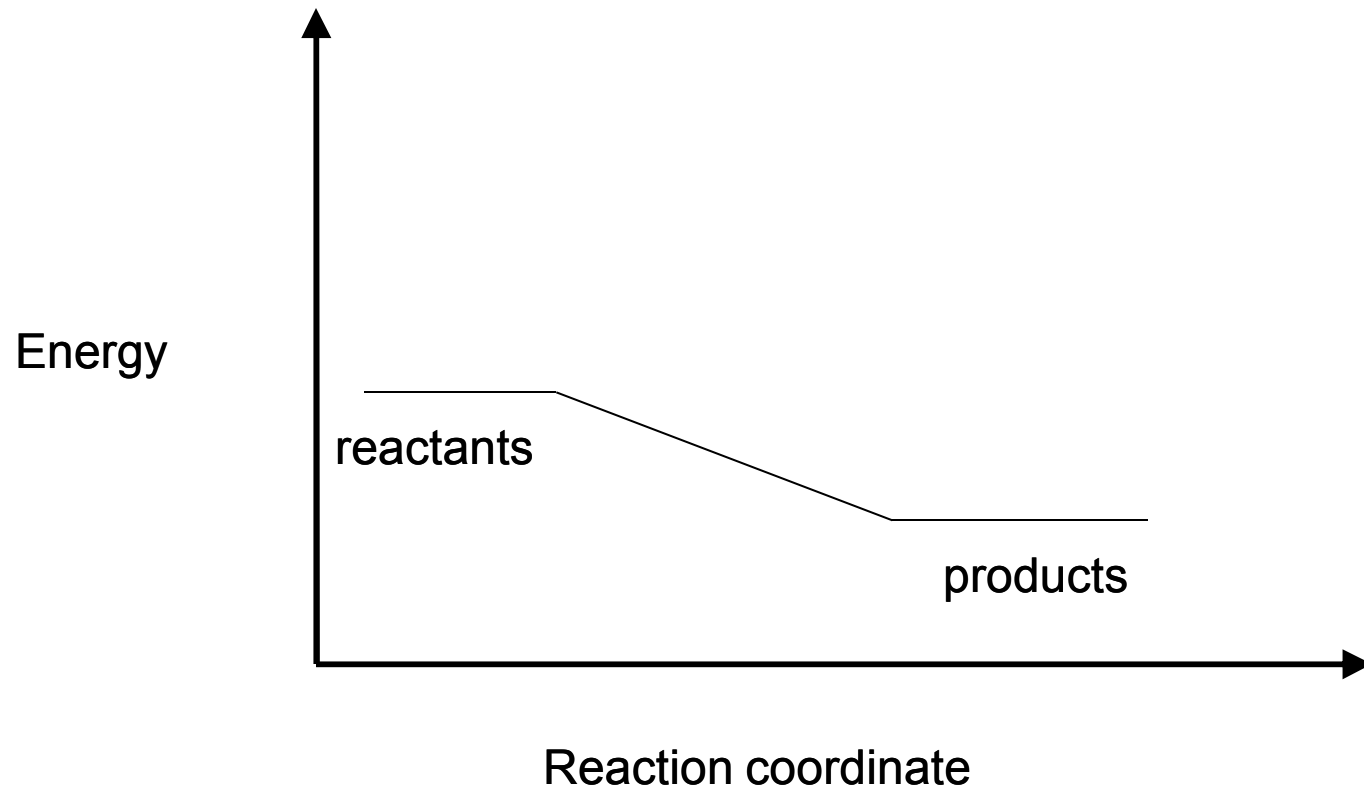
What is E_a ?

E_a

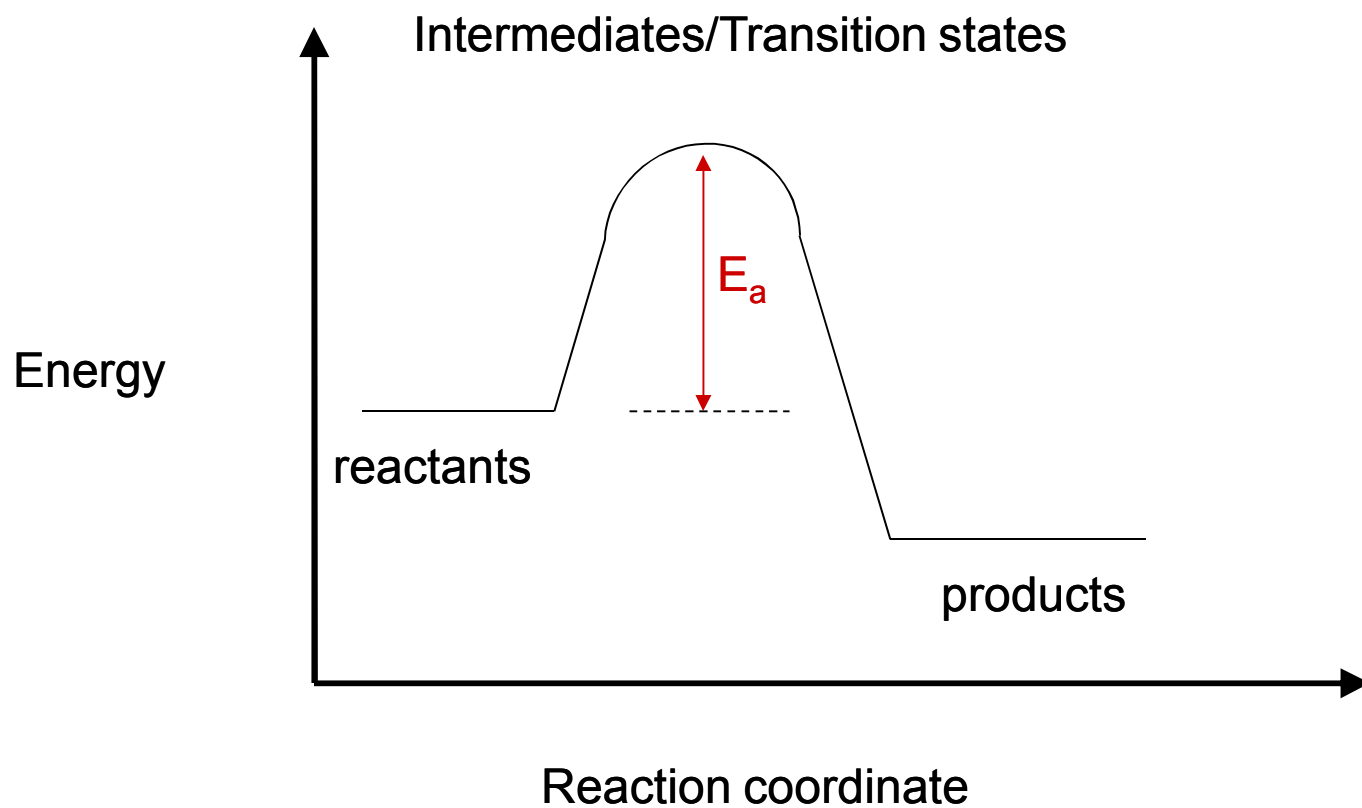


---Imagine a marble---

E_a

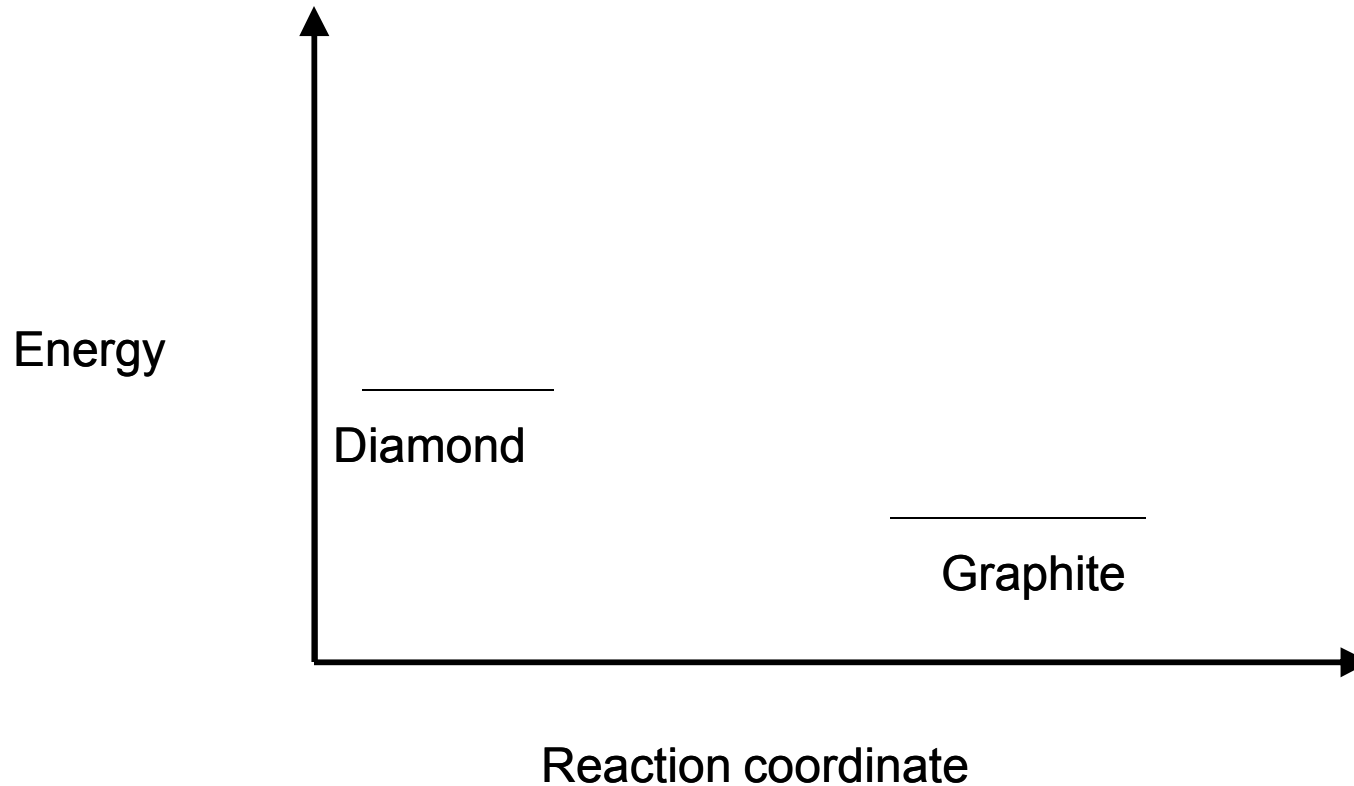


E_a

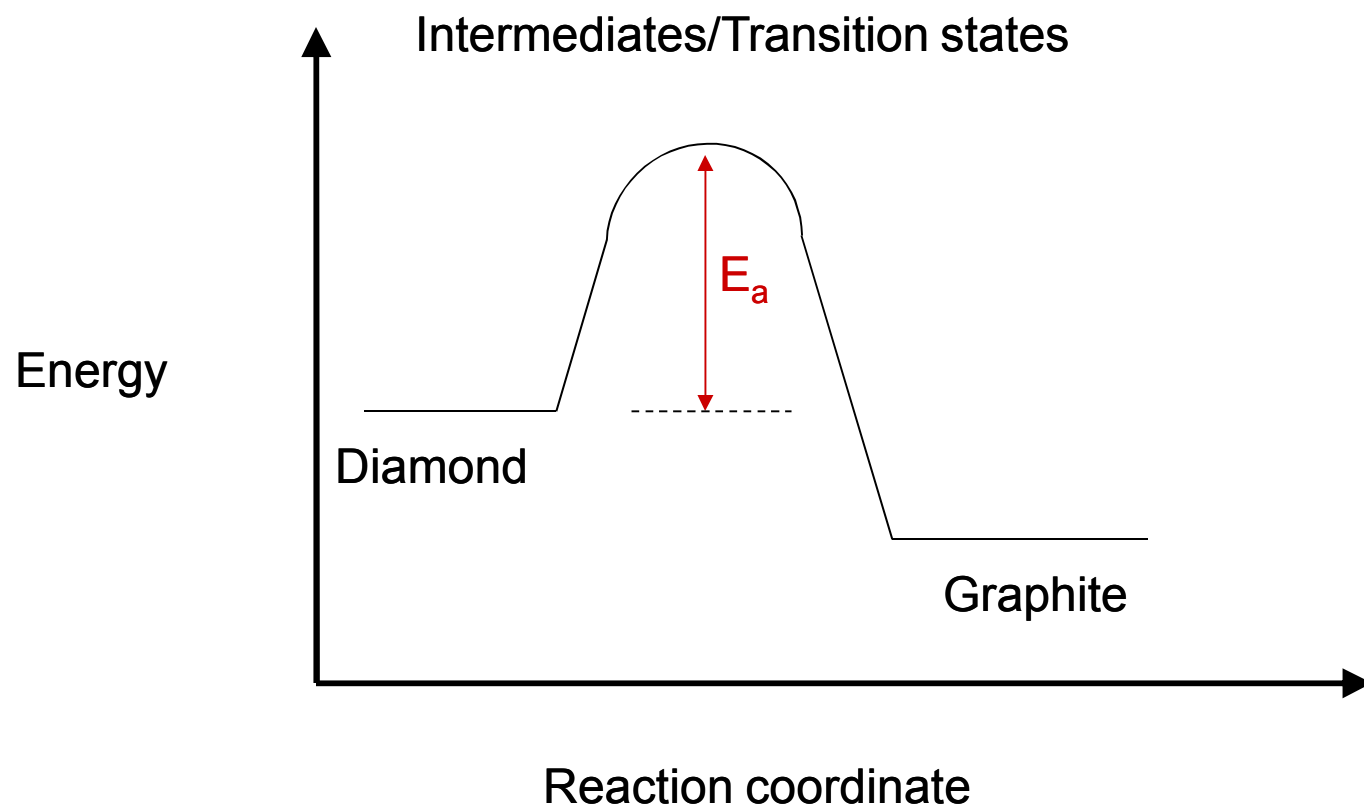


Kinetics vs. Thermodynamics

(really the same thing)



E_a



Arrhenius Equation

$$k = Ae^{-E_a/RT}$$

Critical assumption is that E_a is CONSTANT