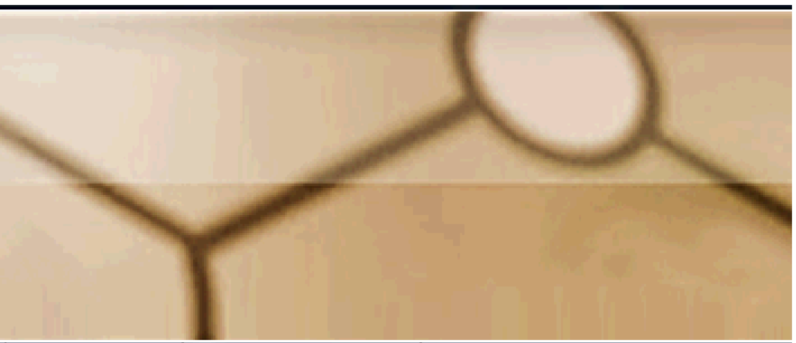
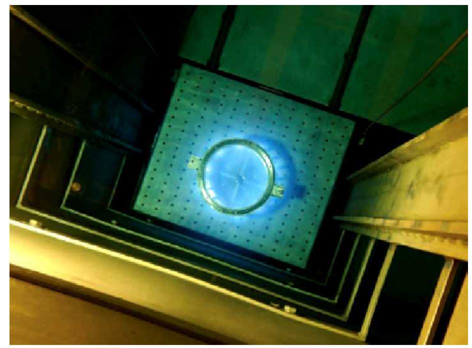
SAND2012-9845C

Exceptional service in the national interest

Sandia National Laboratories





Current and Ongoing Cable Aging to Support Life Extension Decisions

Gregory Von White II,* Derek J. Wichhart, Robert Bernstein, and Kenneth T. Gillen

Sandia National Laboratories

U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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SNL in Round Numbers

Sandia National Laboratories

More than 8,600 full-time employees

~7,800 in New Mexico

~800 in California

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

apd1

Slide 2

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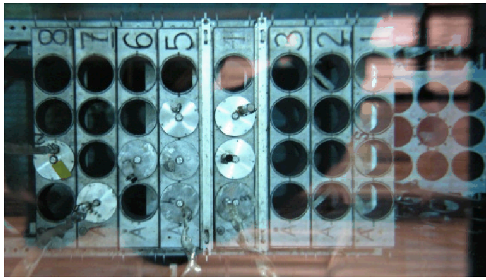
apd1 Nothing more current?
Alton P. Donnell, Jr., 12/7/2010

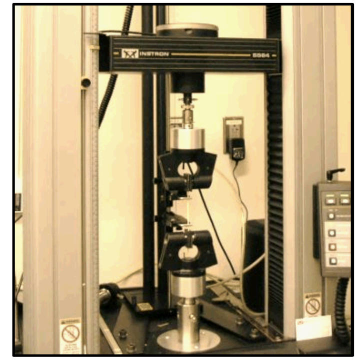
Outline

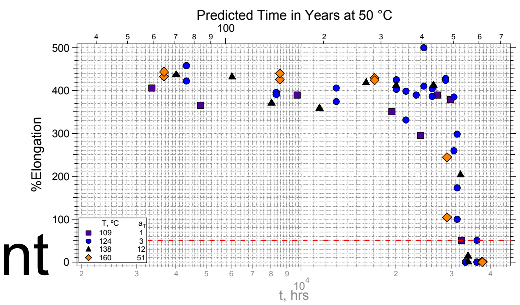


Background

Accelerated Aging

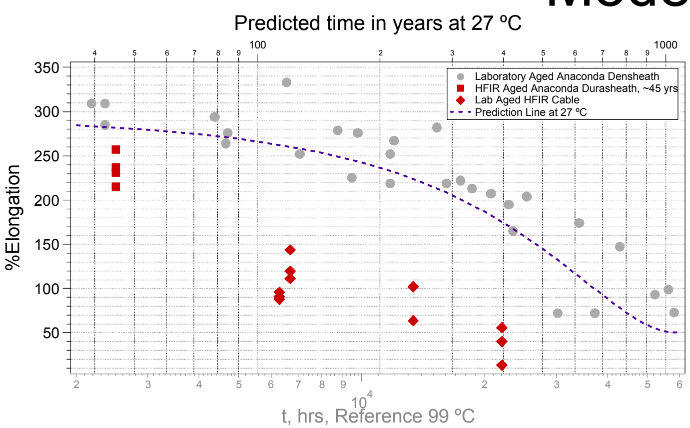
Approach





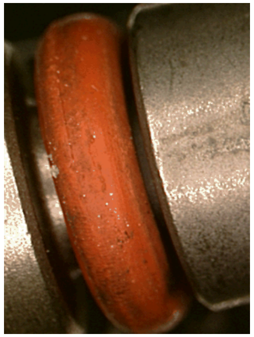
Model Development

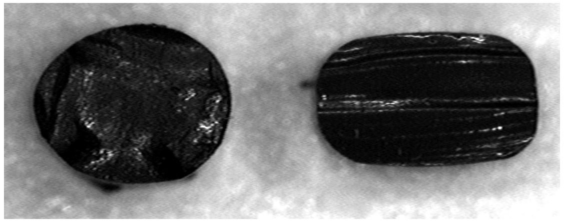
Model Validation



Future Directions

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





UNAGED   15 yr in field

O-rings

Nuclear Power Plant Cable Insulation

Textiles/Fibers

Protective Clothing

Polymer Aging - Approaches/Goals

Sandia National Laboratories

Macroscopic level

Physical Properties

Tensile Property

Permeation

Elongation

Dimensional changes

Molecular Level

Chemical Properties

UV-VIS Spectroscopy

Infra-red Spectroscopy

Surface Analysis

Differential Scanning Calorimetry

Molecular Weight Analysis

X-Ray Analysis

Density

Additives

Nuclear Magnetic Resonance

GPC

Mass Spectrometry

Goals

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

Polymer Aging - Approaches/Goals

Macroscopic level

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Goals

- **Prediction of physical properties vs. time**
    - **Predict remaining physical properties of field materials**
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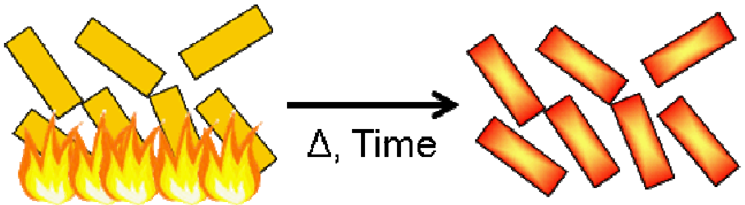
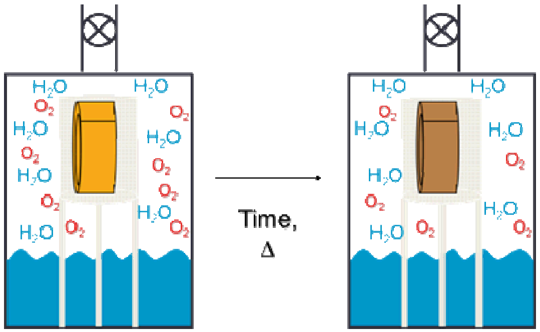
Methodologies

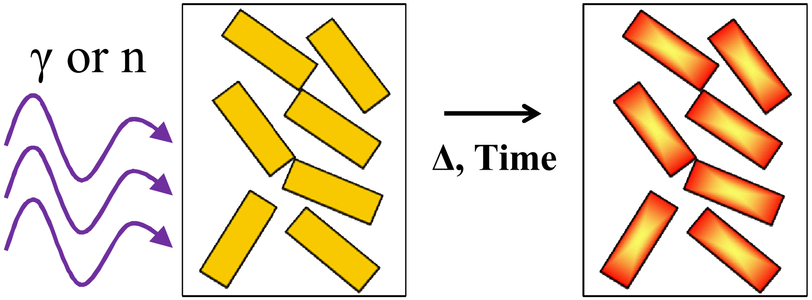
Sandia National Laboratories



Thermal-Oxidative Aging

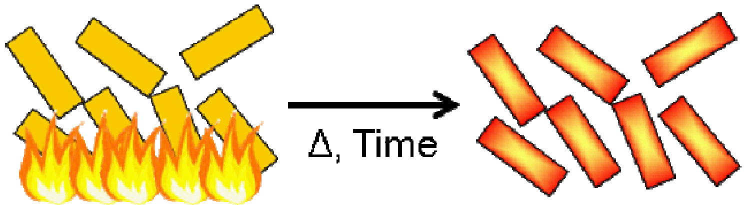


Humidity Aging



Radiation Aging

Methodologies



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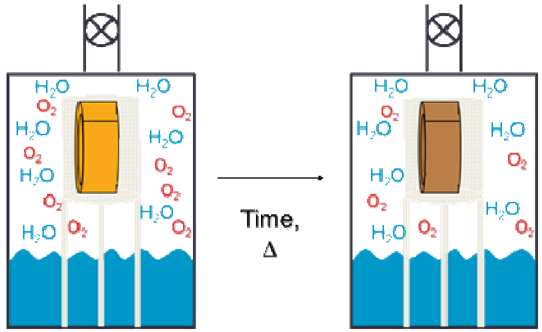

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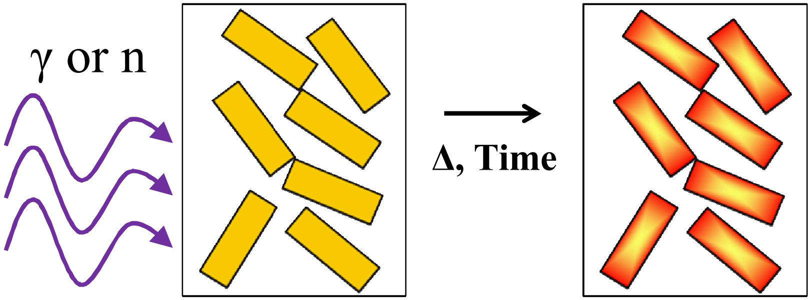

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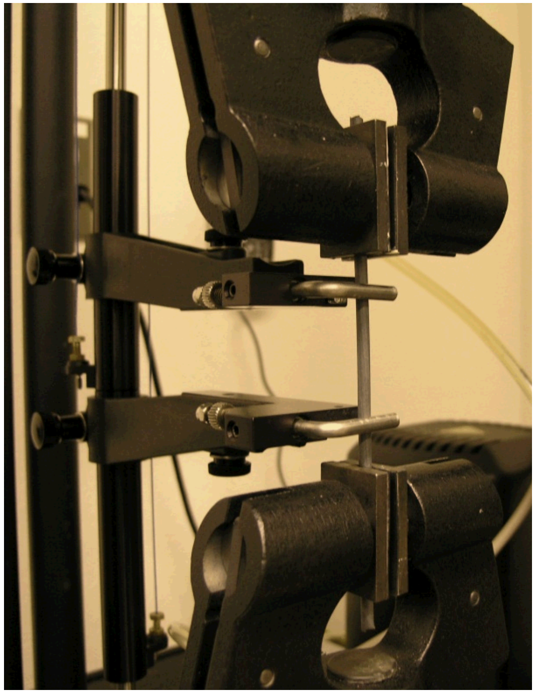
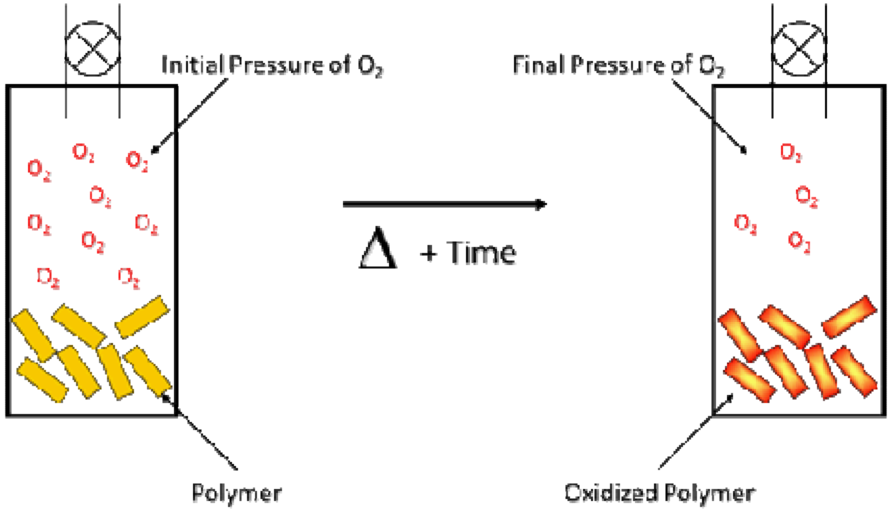


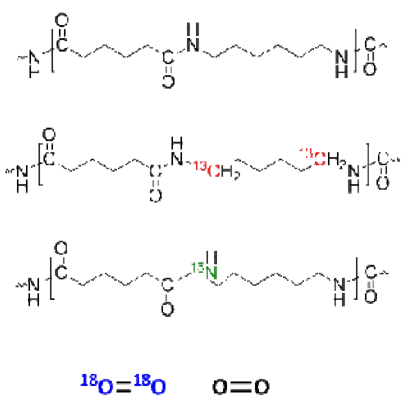
Tensile Testing

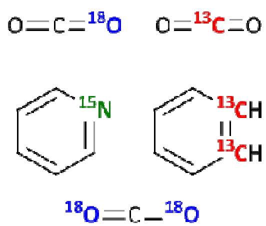
Methodologies

Sandia National Laboratories



Oxygen Consumption





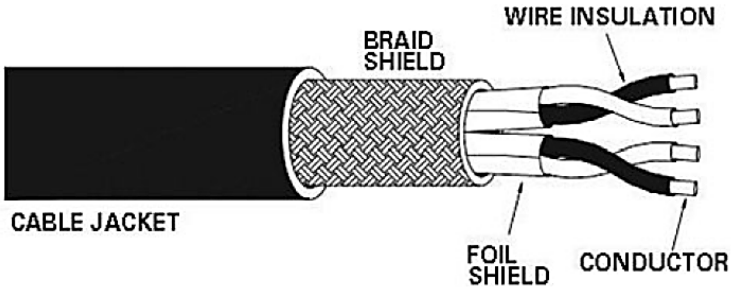
Proposal of Underlying Degradation Mechanisms

Power Plant Cables

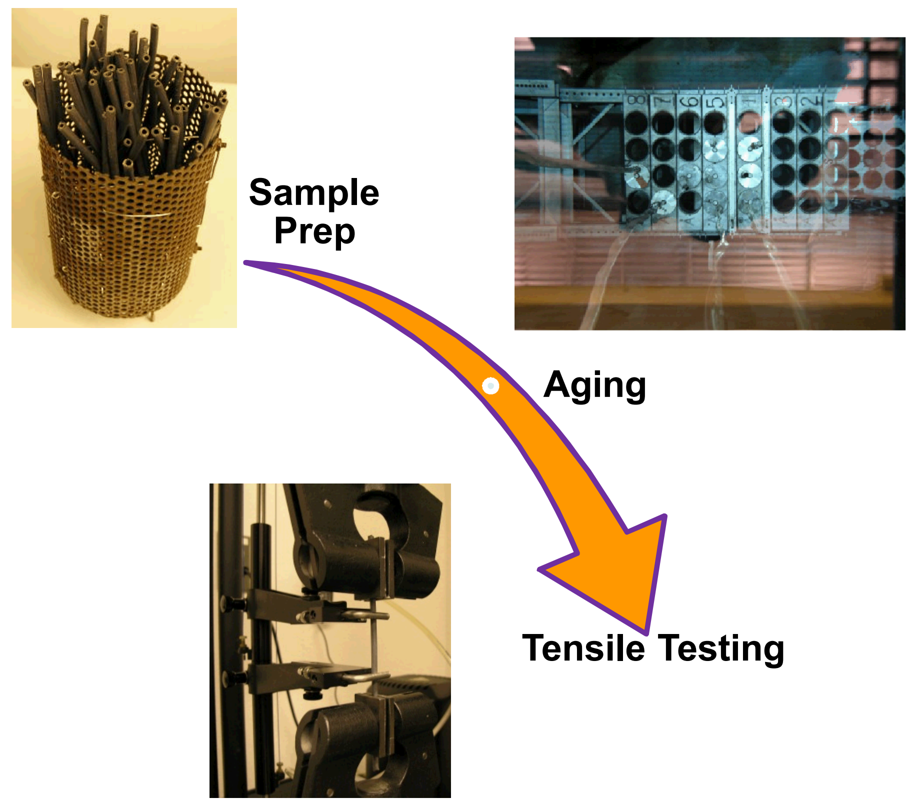
Nuclear Power Plant Cable Insulation

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

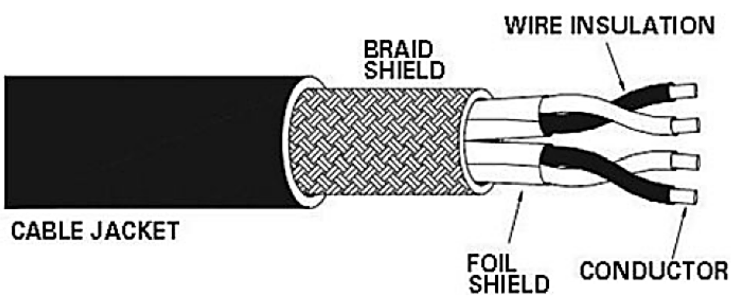
IEEE 383-1974: ~50 Mrad (500 kGy) in 40 years at 50 °C



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



Power Plant Cables



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

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%)*

Nuclear Power Plant Cable Insulation

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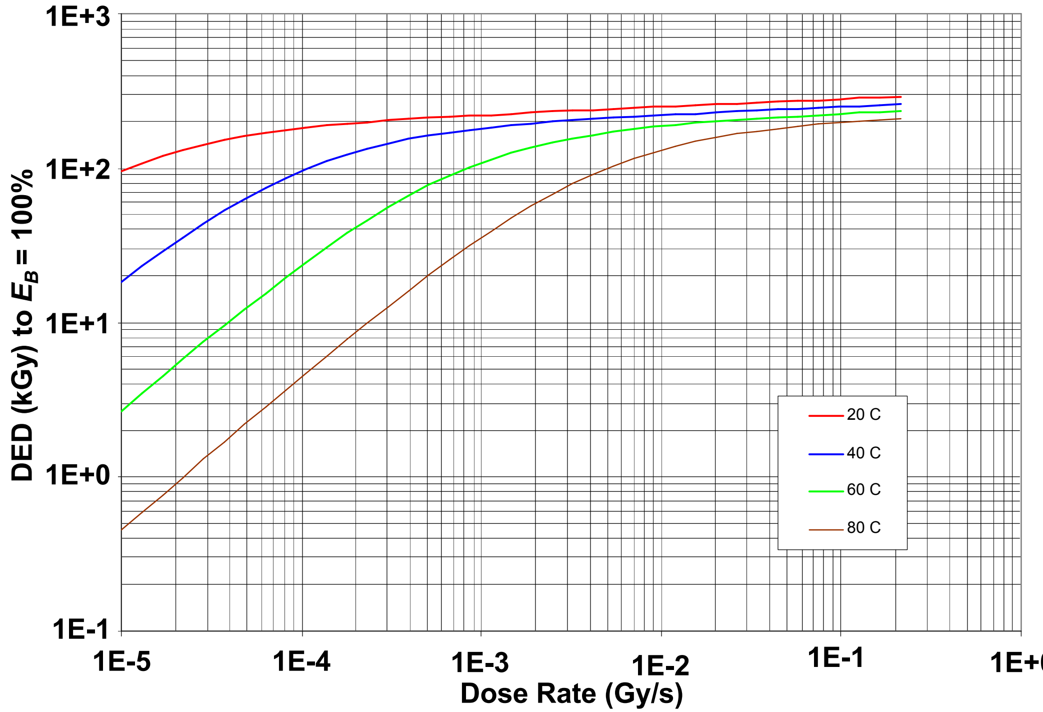
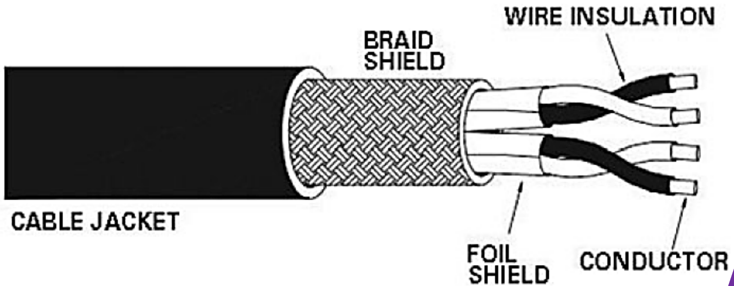


Figure taken from a collaborative (NRC/DOE/EPRI) document ***in progress*** to be published later in 2012 – NUREG 6923, "Expert Panel Report on Proactive Materials Degradation Assessment"

Power Plant Cables



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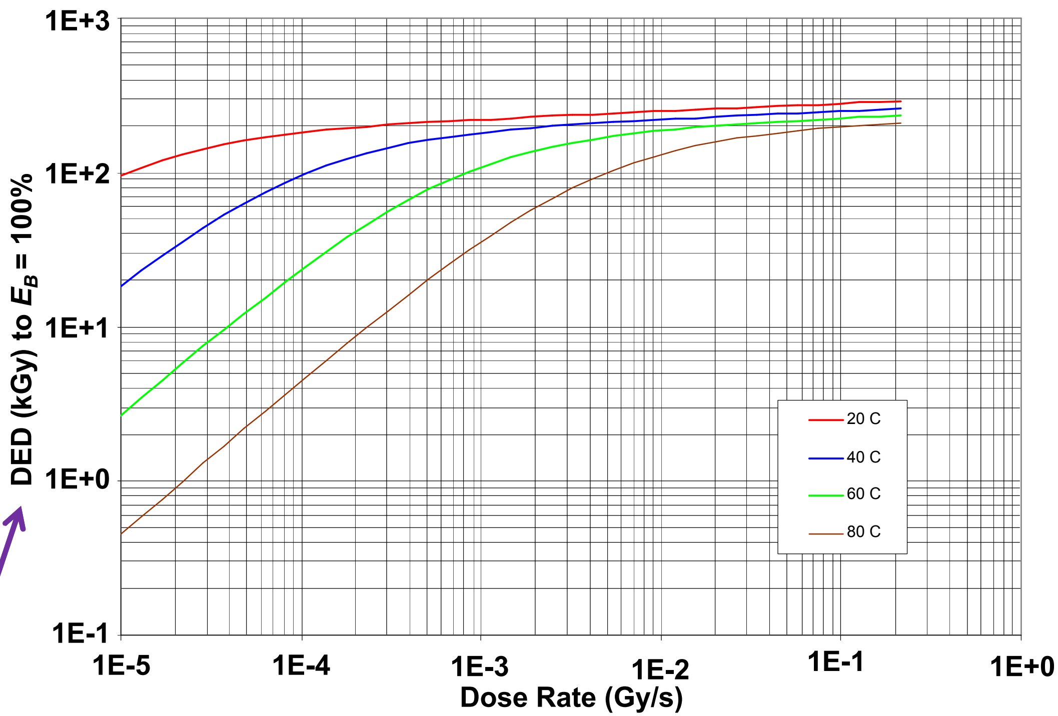

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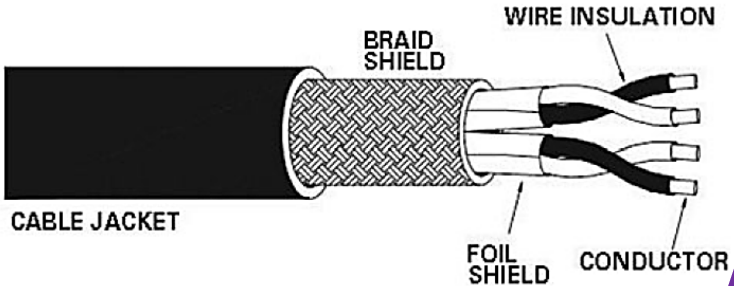

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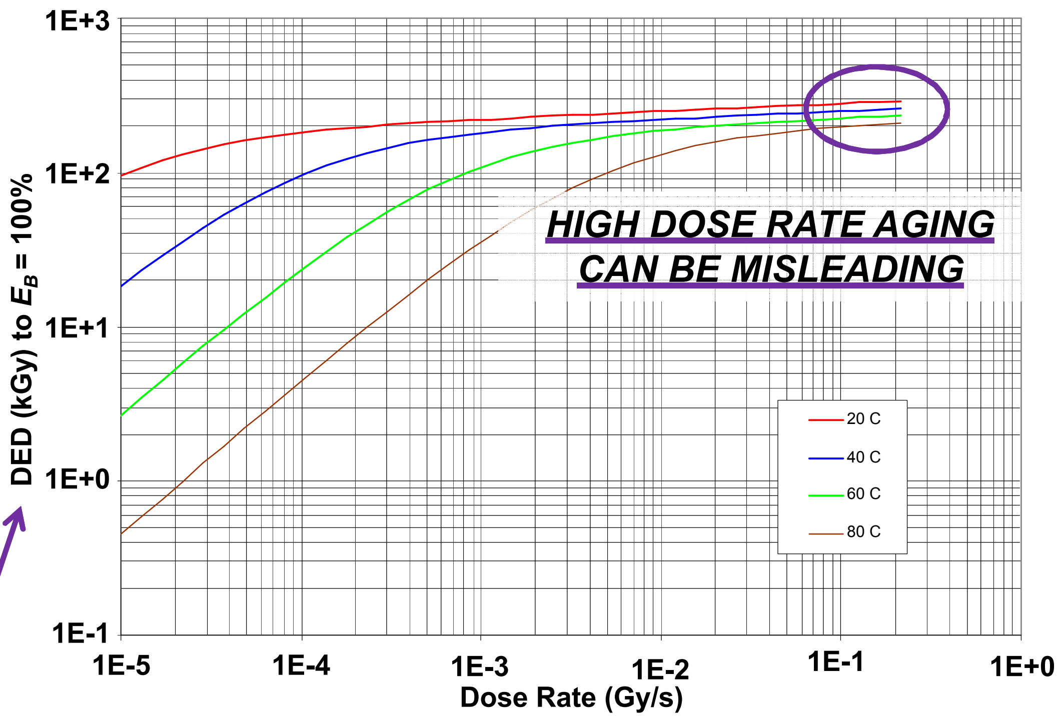

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Cables Insulation Types of Interest

Sandia National Laboratories

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	

EPRI TR-103841 (1994)

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

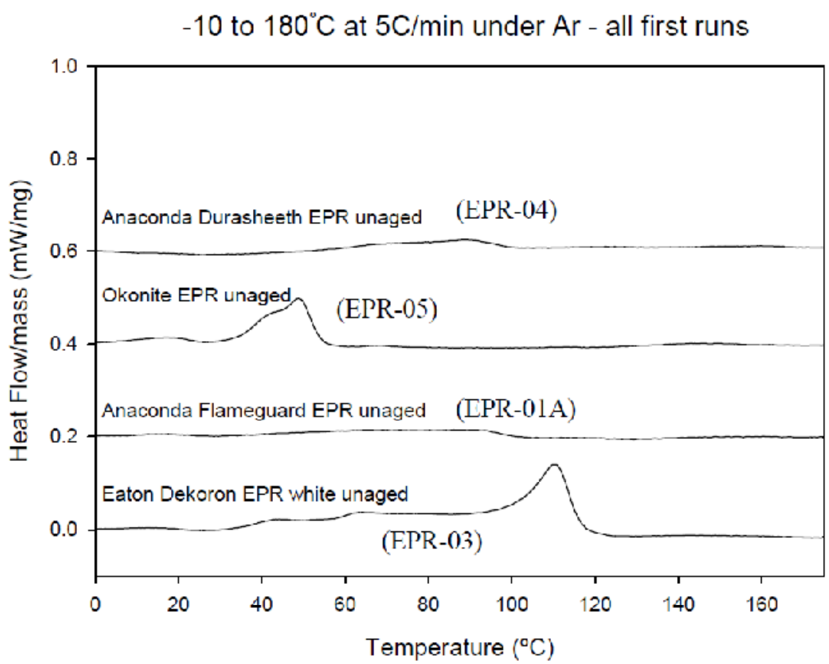
EPRI TR-103841 (1994)

Ethylene Propylene Rubber (EPR)

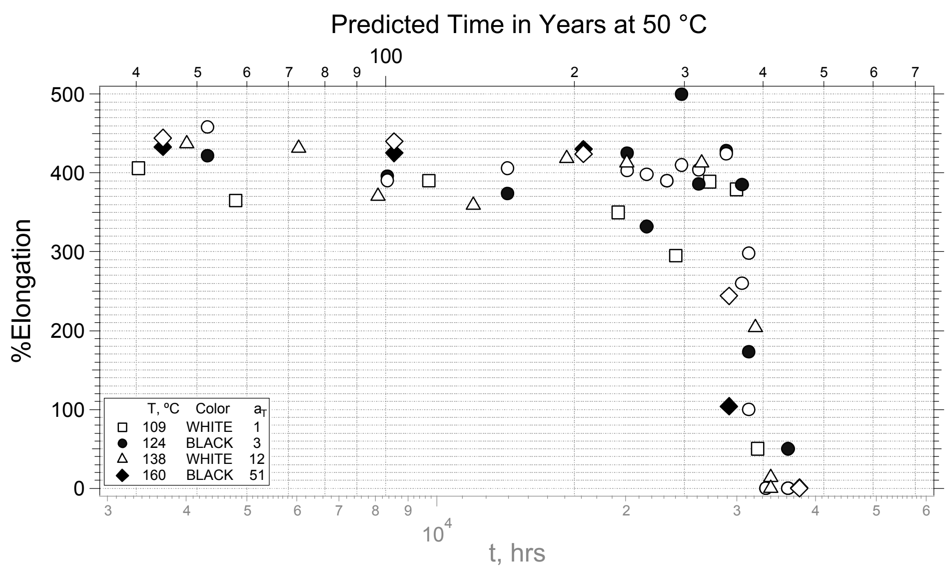
Sandia National Laboratories

Eaton Dekoron Elastoset EPR Cable Insulation

Highly crystalline polymer

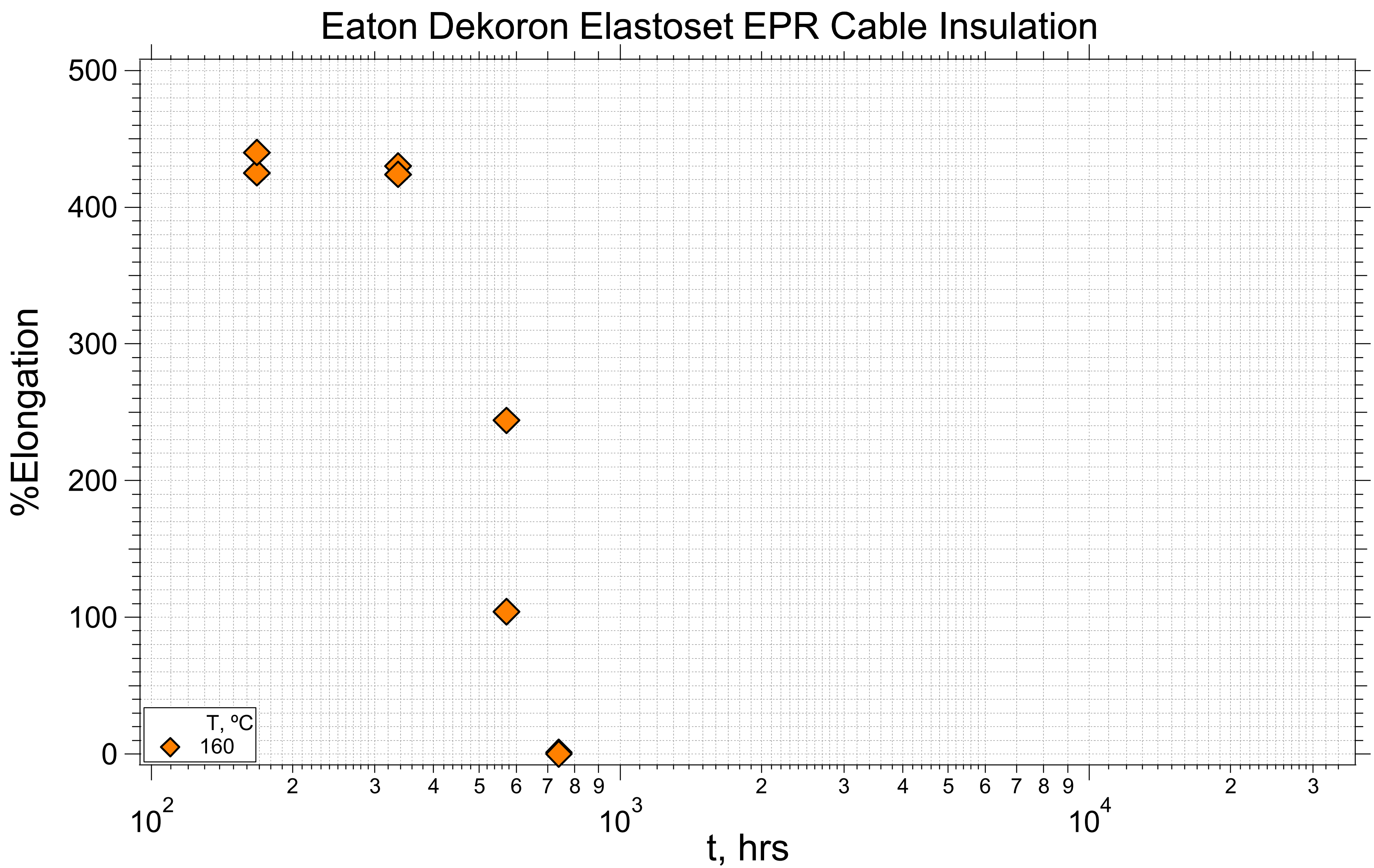


Exhibits Large "Induction Time"



SAND2005-7331 K. T. Gillen, R. A. Assink, and R. Bernstein

Tensile Properties – Thermal Aging



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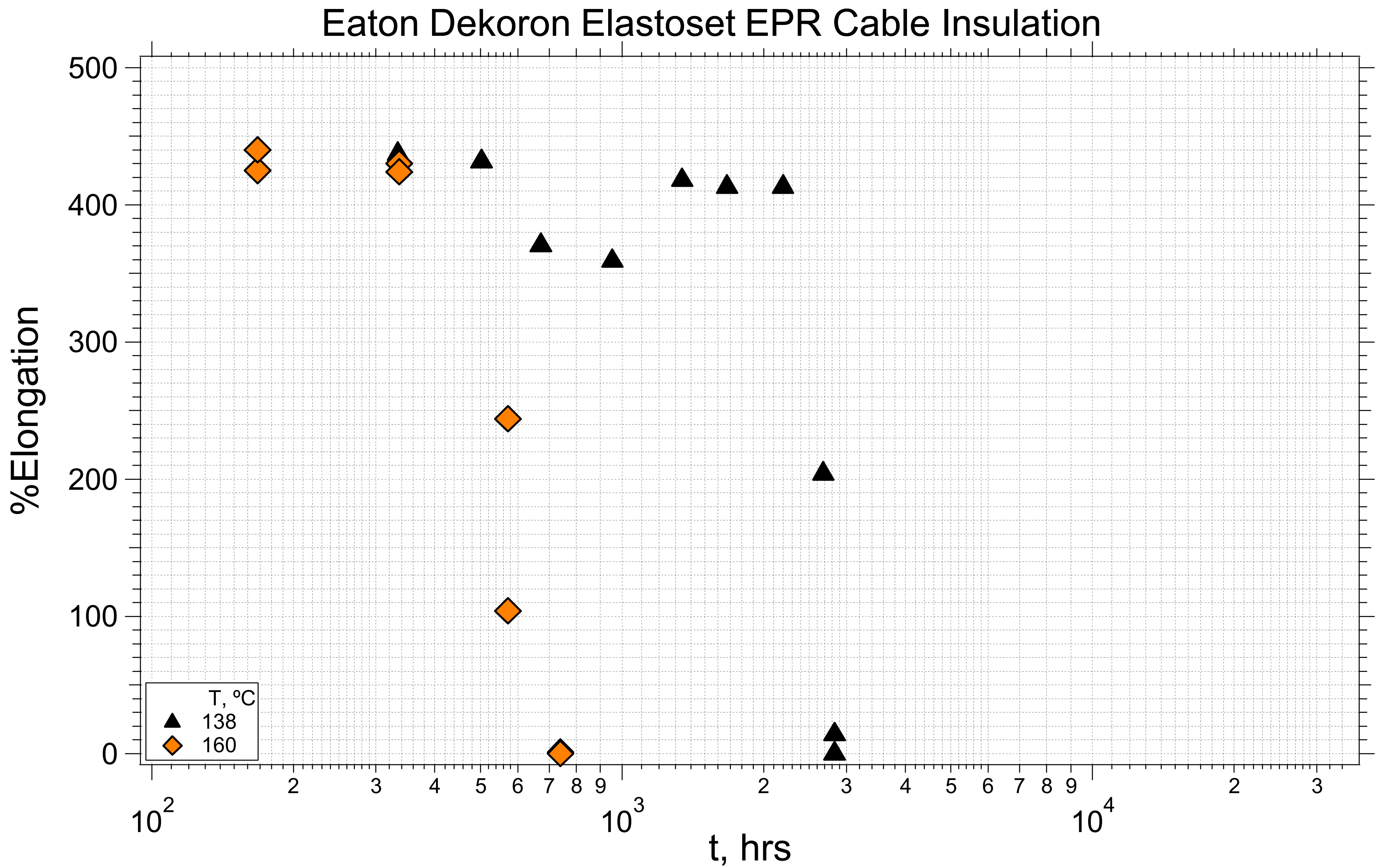

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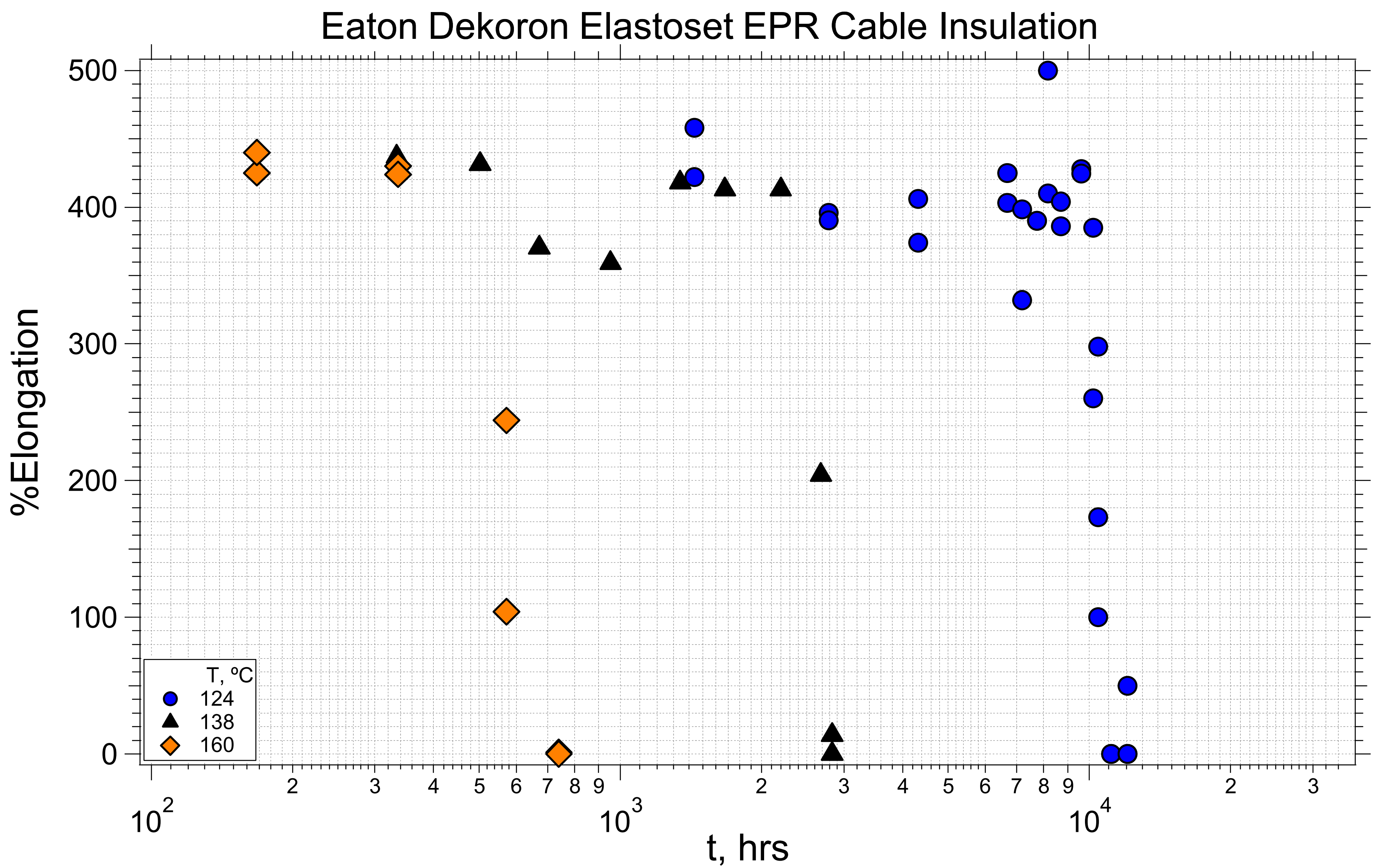

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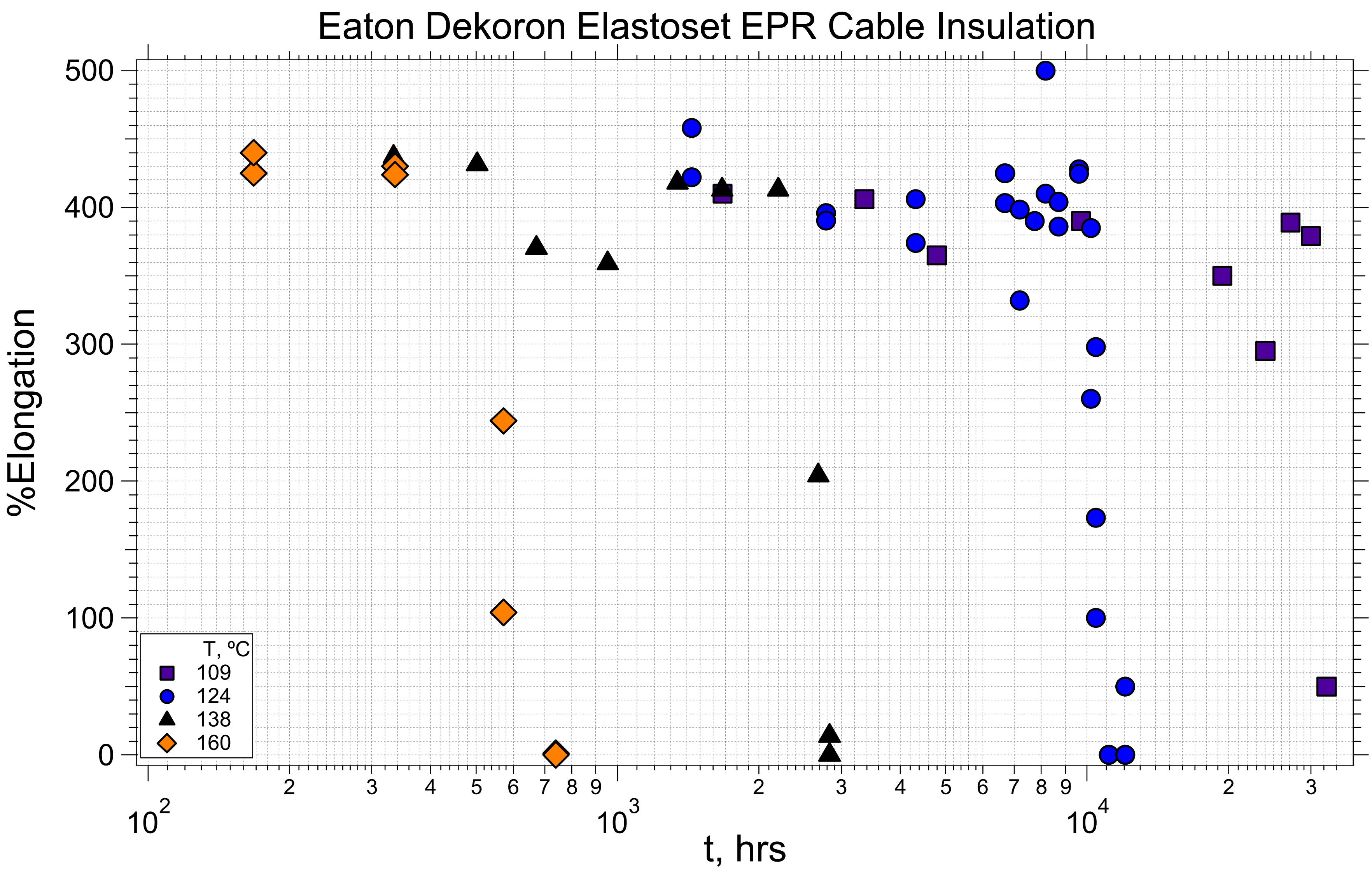


SAND2005-7331 K. T. Gillen, R. A. Assink, and R. Bernstein

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.

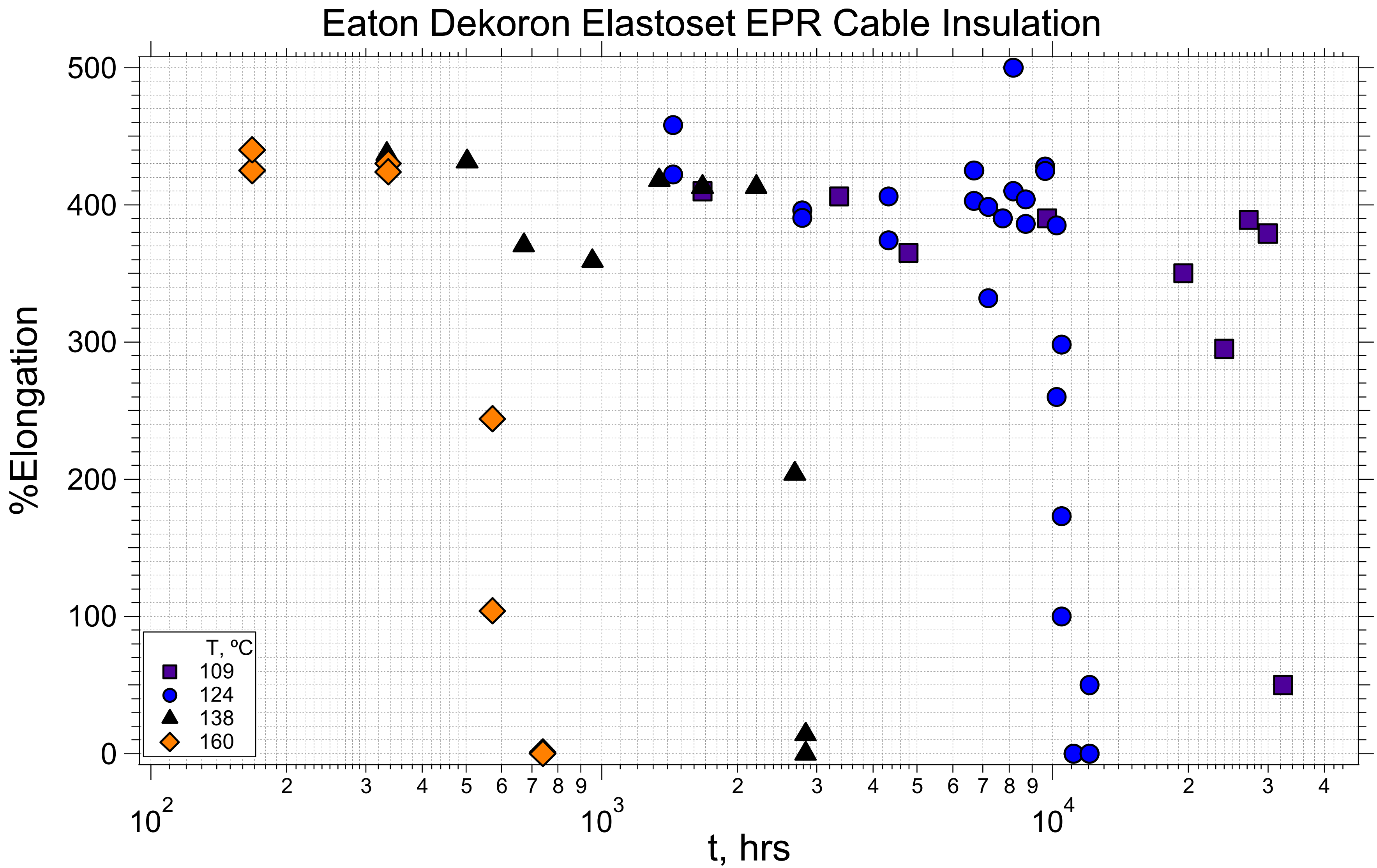
Arrhenius equation:

Empirical equation

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

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

Time-Temperature Superposition



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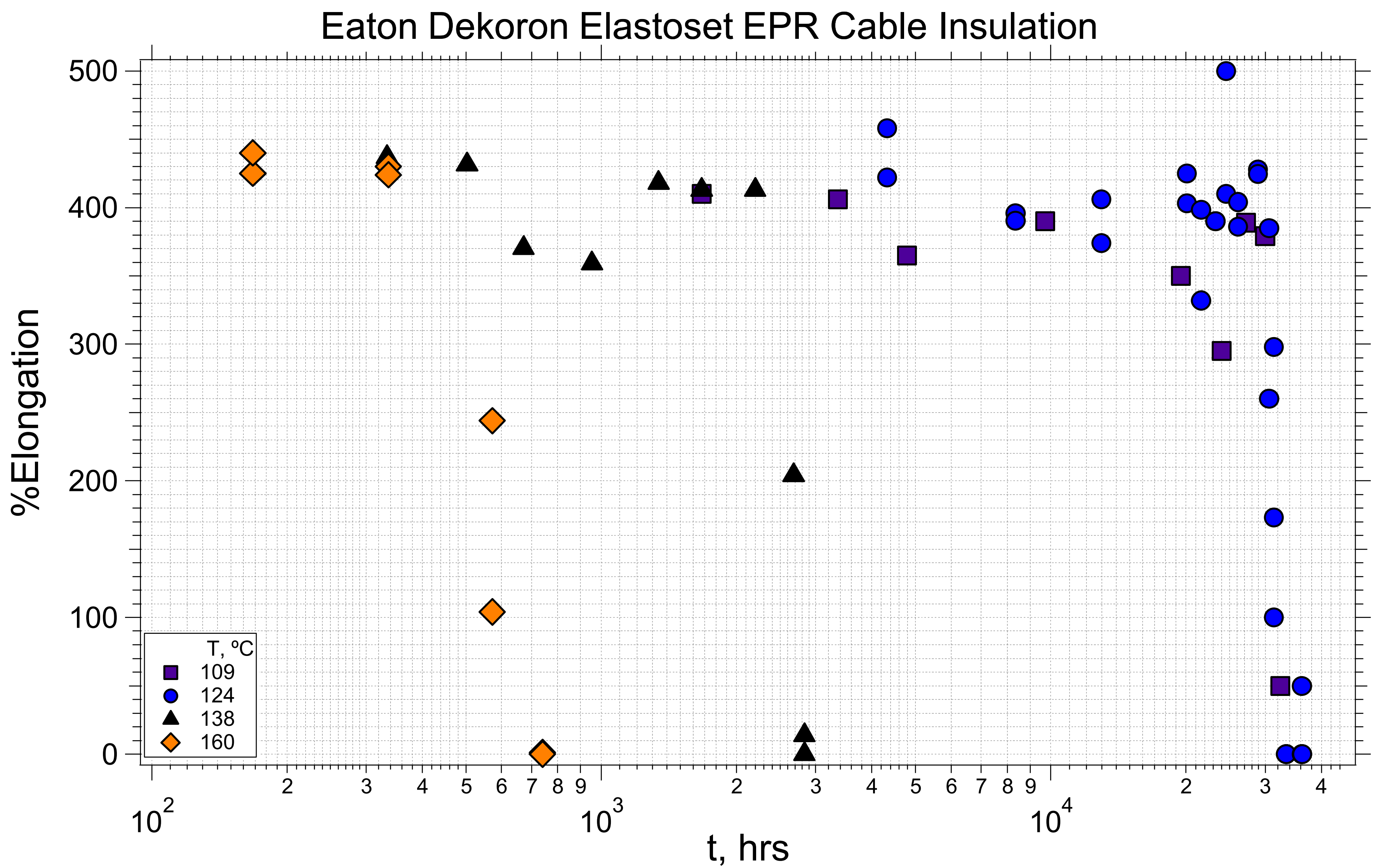

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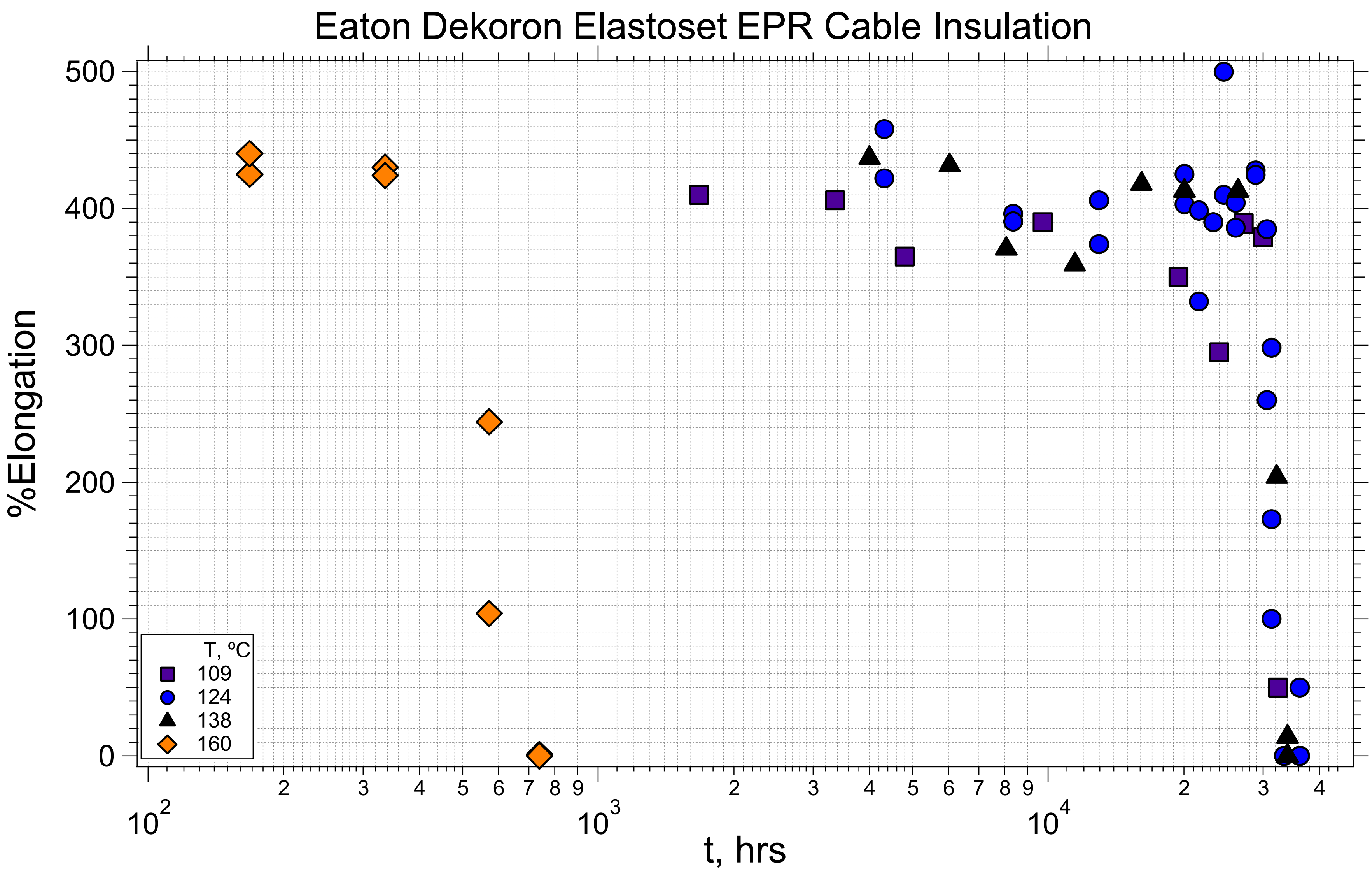

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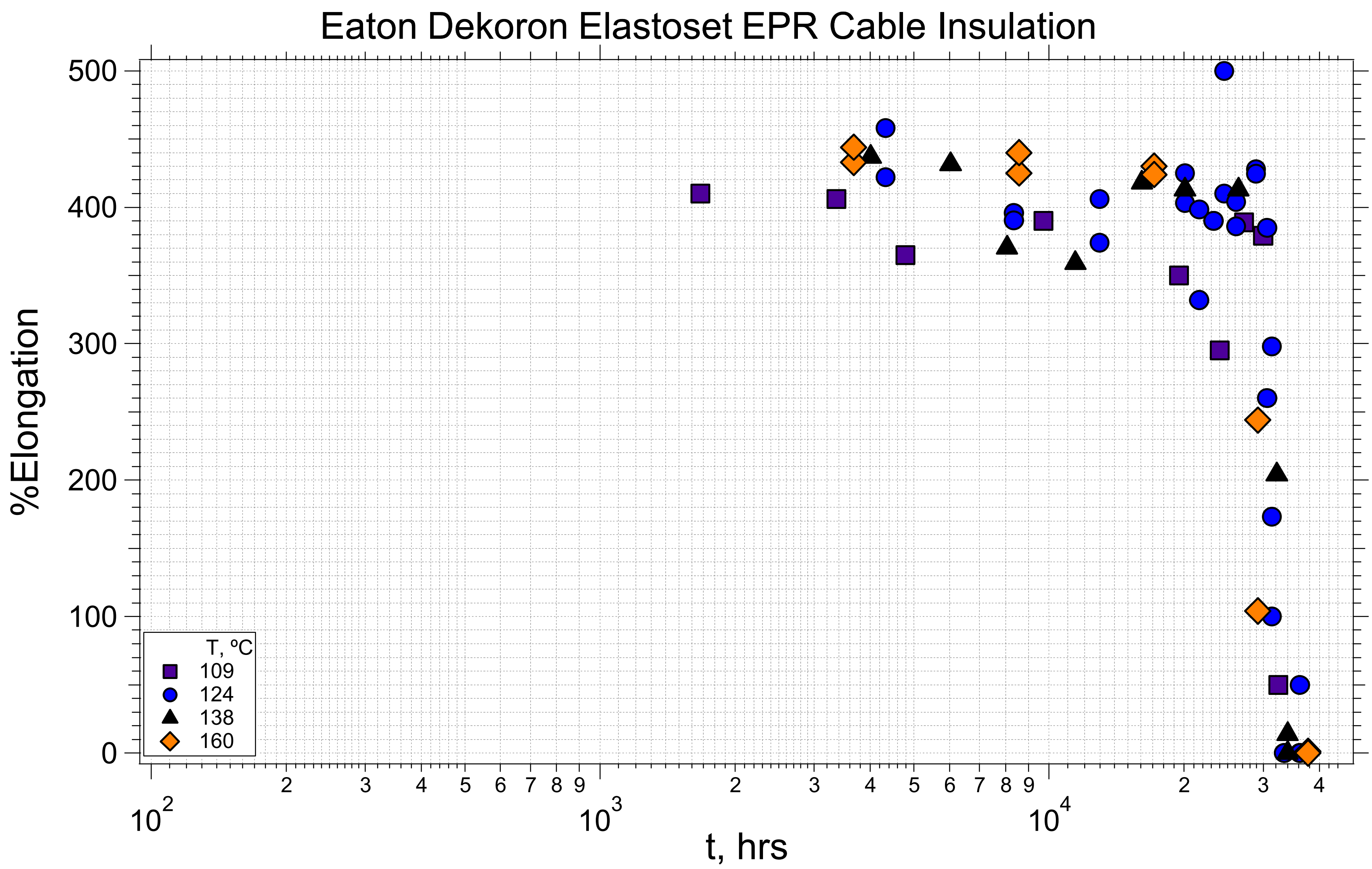
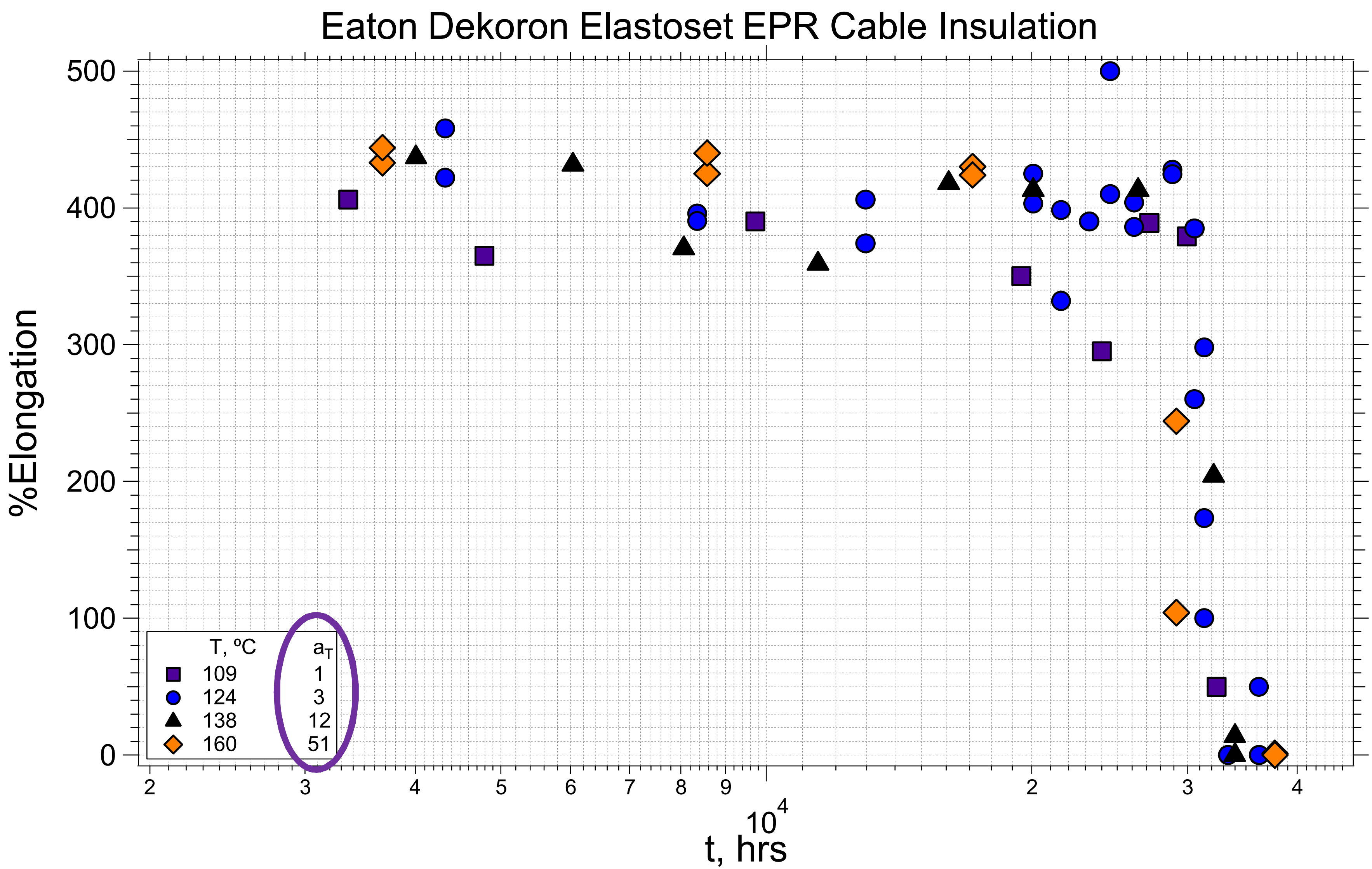


SAND2005-7331 K. T. Gillen, R. A. Assink, and R. Bernstein

Arrhenius Plot



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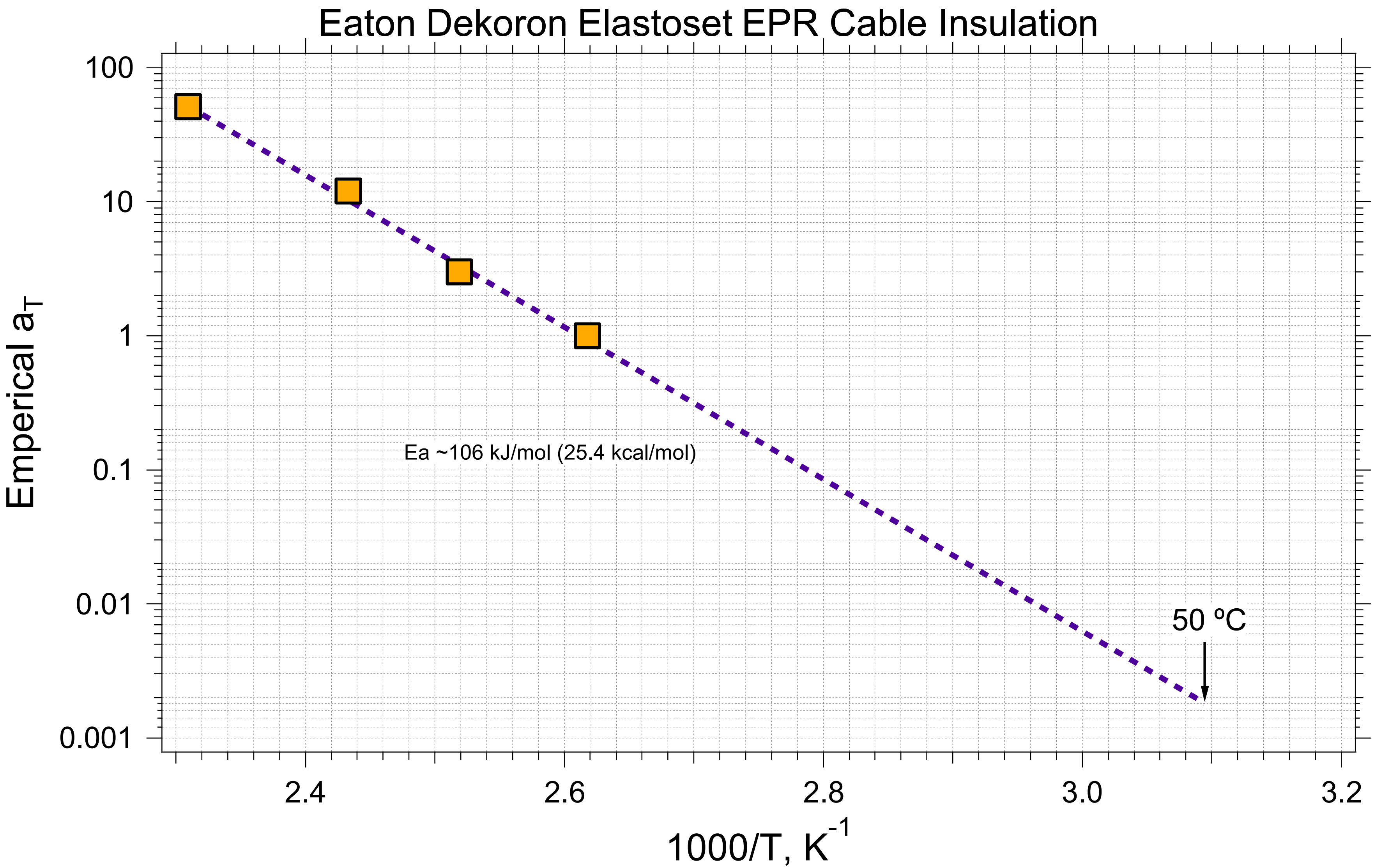

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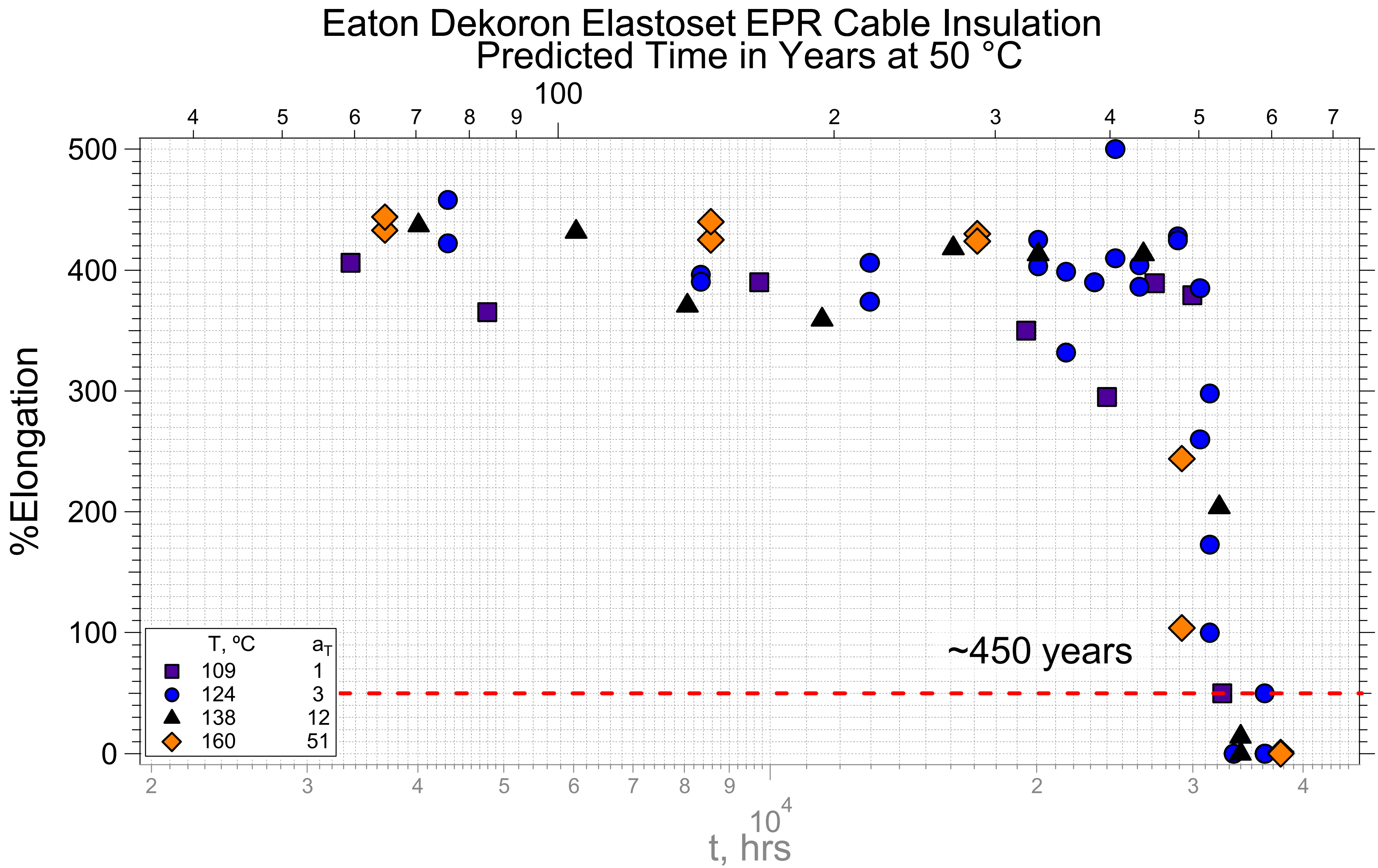
Thermal-Oxidative Prediction



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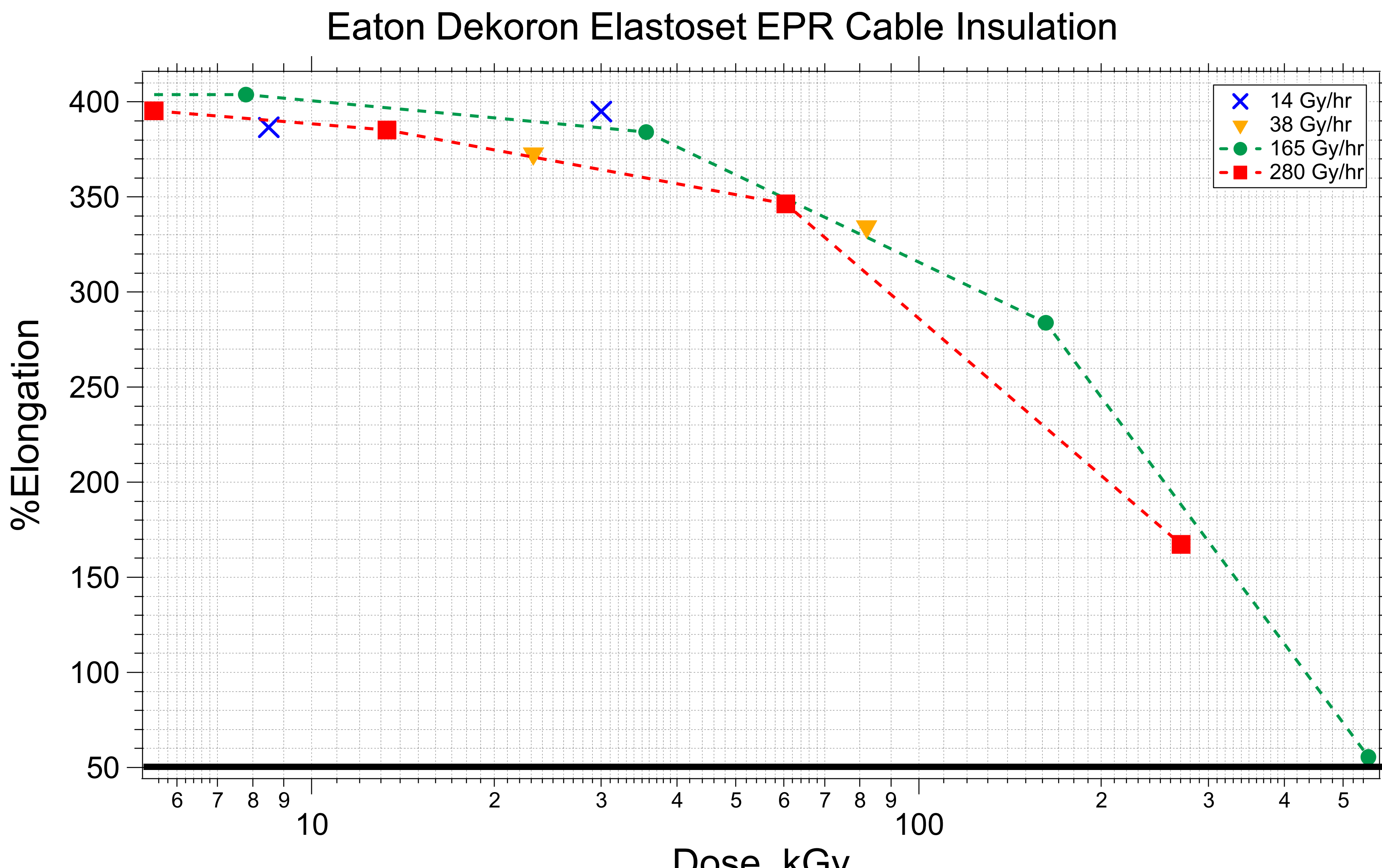
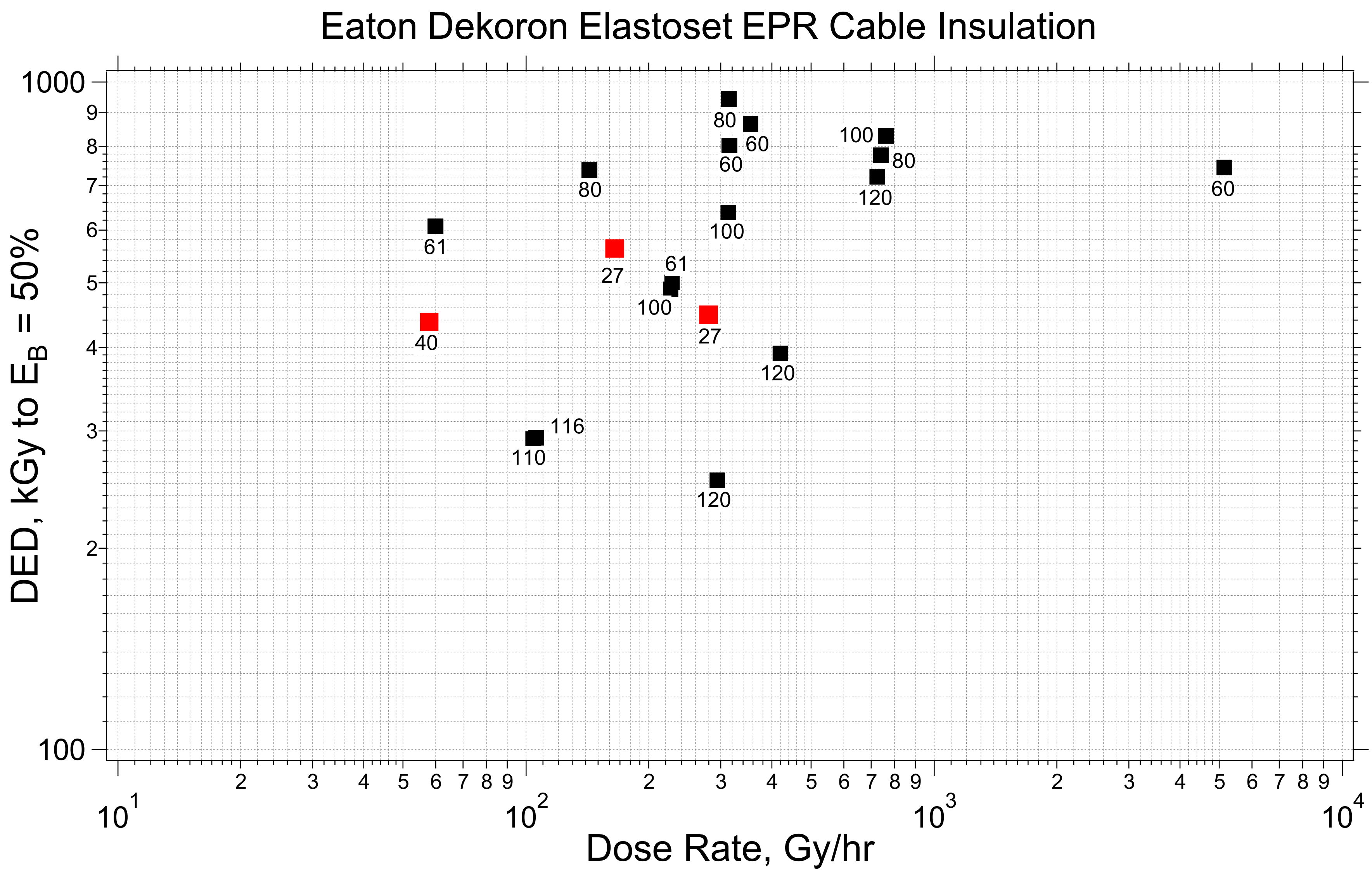
Gamma Irradiation + Thermal Effects



Data Actively Being Collected

Gamma Irradiation + Thermal Effects



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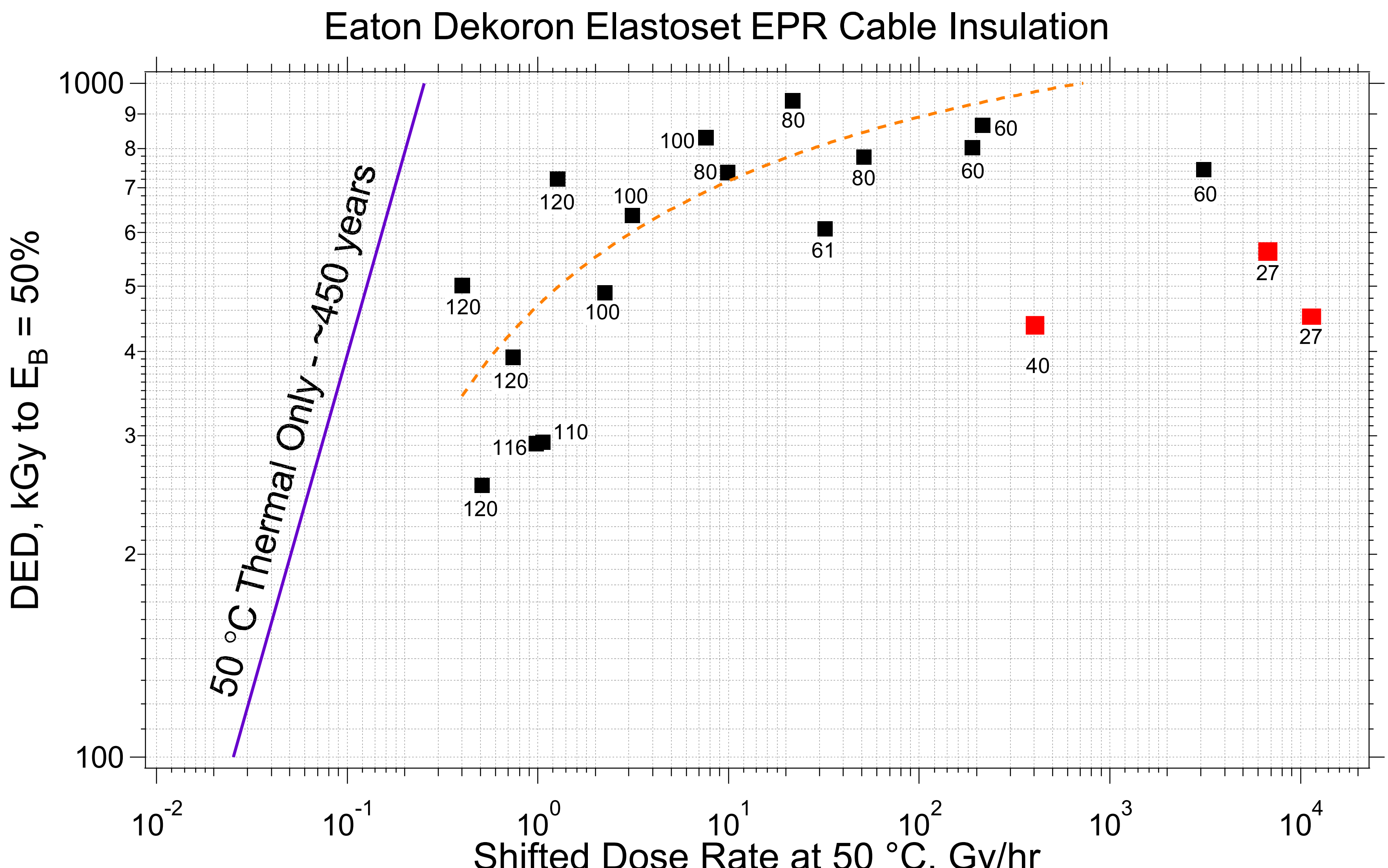
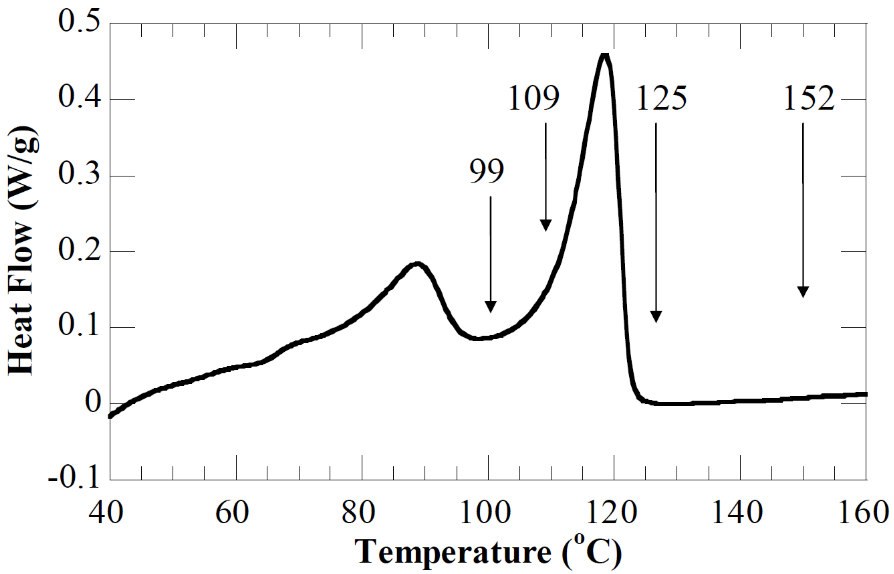


Inverse Temperature Effects

Brandrex 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



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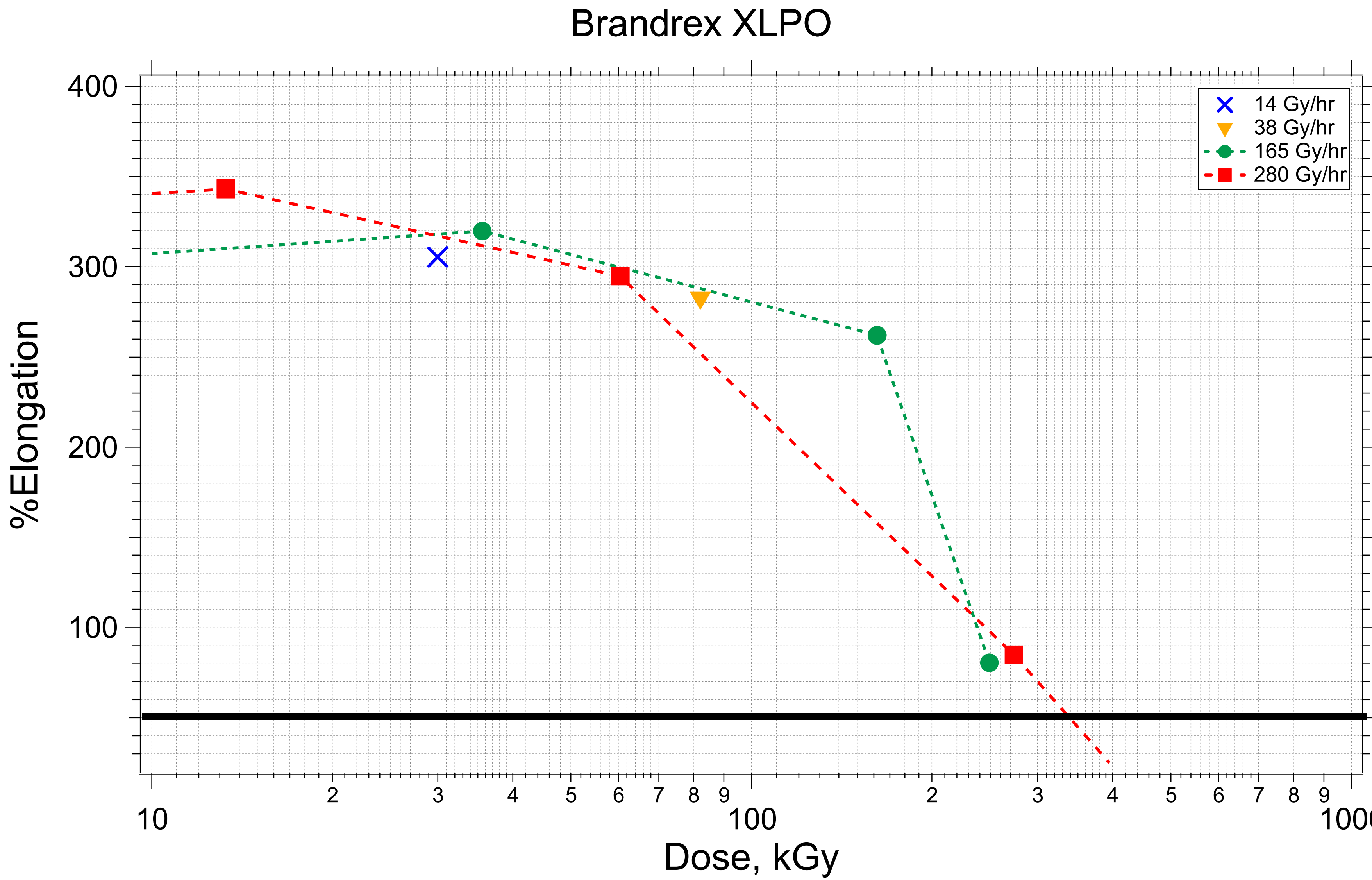

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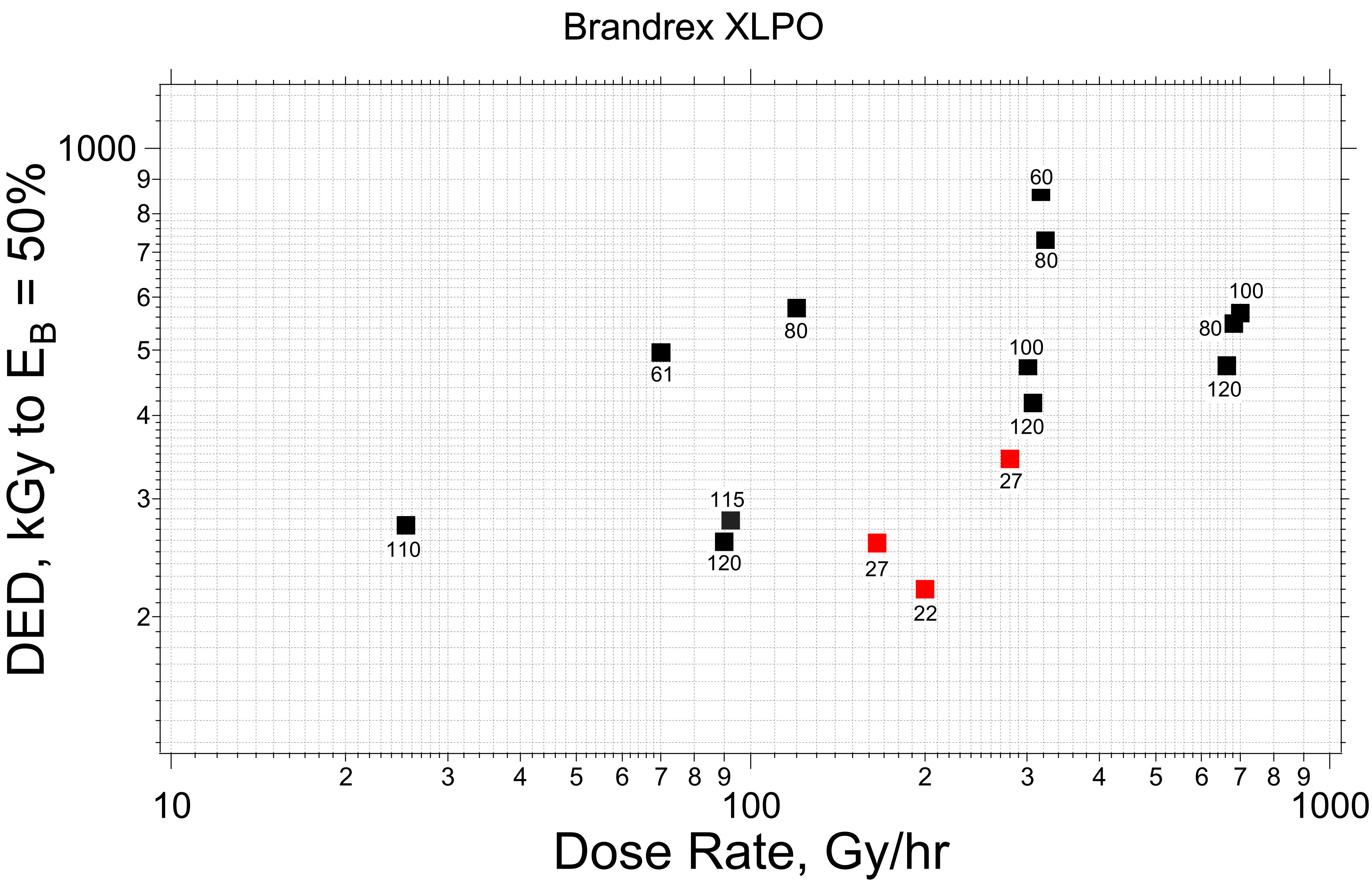

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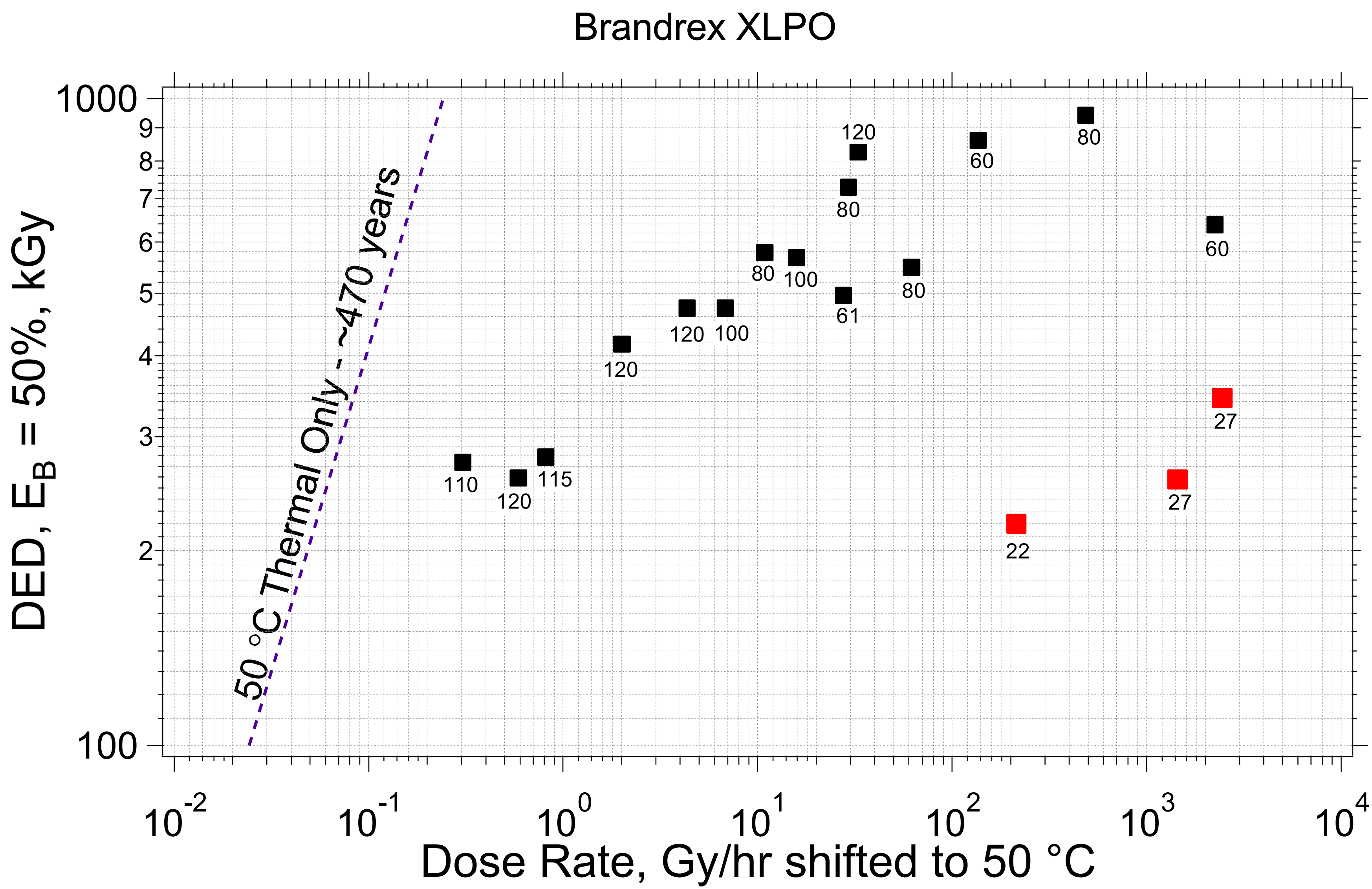
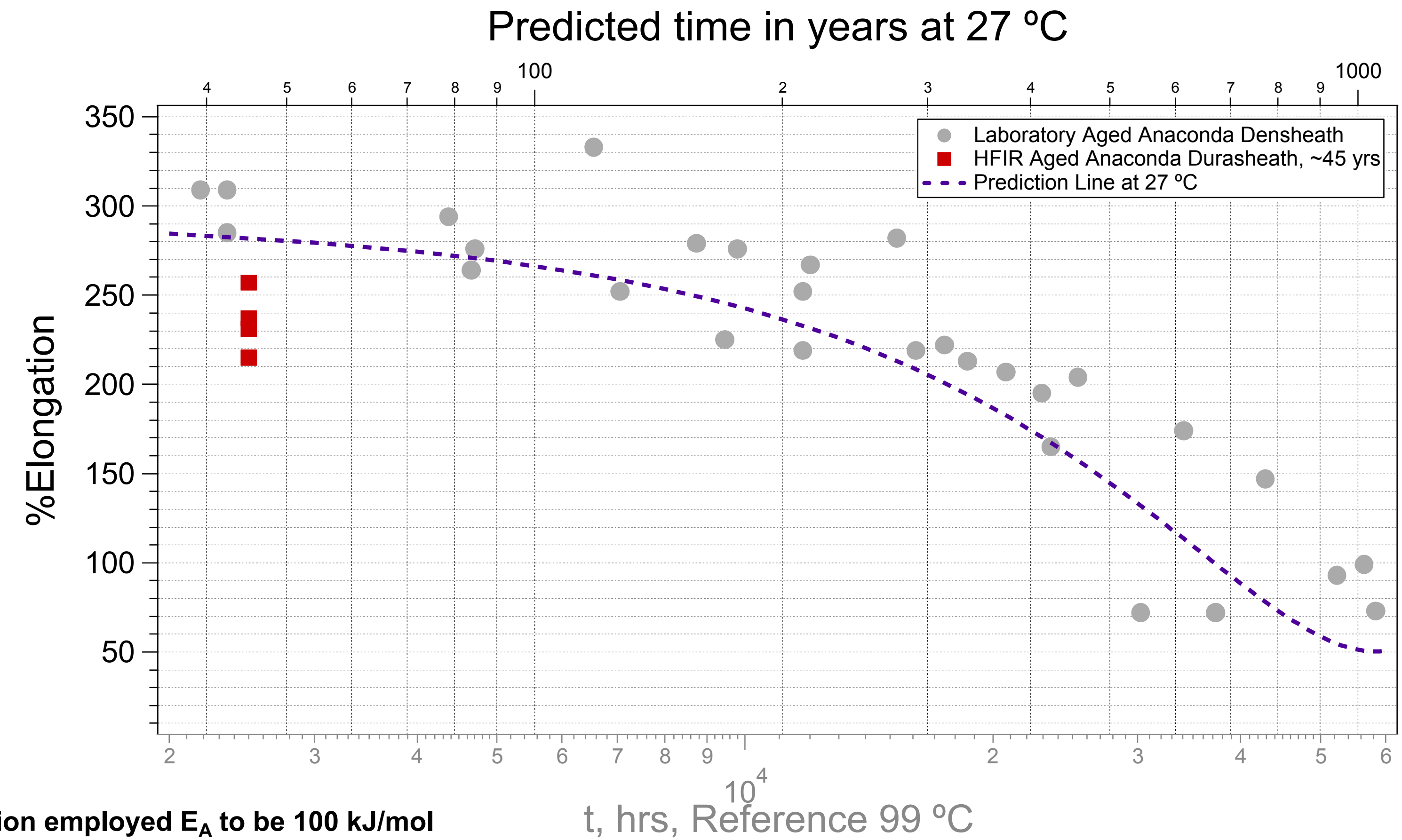


Field Returned Materials

VALIDATION OF PREDICTIVE MODELS

Validation of Field Aged Materials

Making Predictions is easy… Validating predictions provides confidence in both the predictions and the methodologies employed in our aging programs.



Prediction employed E_A to be 100 kJ/mol

Ultimate tensile elongation data for Anaconda *Densheath* EPR cables returned from HFIR at ORNL (~45 yrs of age, T_{avg} ~ 27 °C, RH ~70%, shown in red, plotted with previously obtained accelerated aging data for Anaconda *Durasheeth* EPR cable data (shown in grey).

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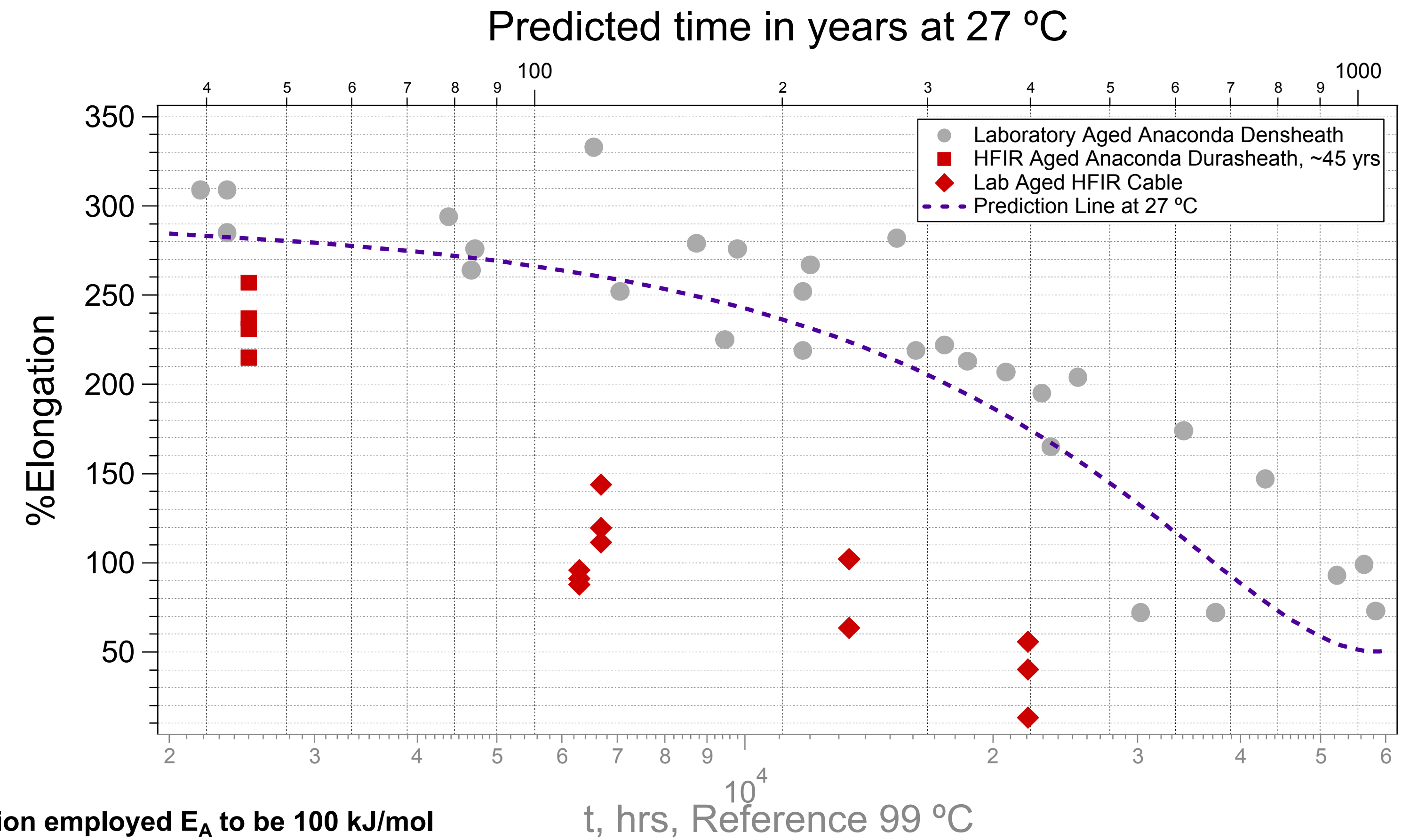

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Future Directions

- Work towards understanding relevant/abnormal NPP cable conditions (temperature, dose rates/total expected dose) to increase the veracity of the current predictive models
  - Collaborate with EPRI and Industry to identify these conditions
- Investigate inverse temperature and dose rate effects at low dose-rates and low temperatures for EPR and XLPO materials
- Validate predictive models

Acknowledgements

- Sandia National Laboratories
- Jeremy Busby (ORNL)
- Sherry Bernhoft (EPRI)
- Bo Clark (EPRI)
- Andrew Mantey (EPRI)
- Sheila Ray (NRC)
- Darrell Murdock (NRC)
- Kevin Simmons (PNNL)
- Raymond Boucher (SNL)
- Maryla Wasiolek (SNL)
- Don Hanson (SNL)

Thank you for your attention!

QUESTIONS?

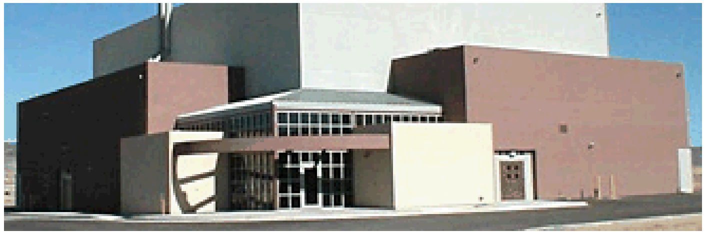
BACKUP SLIDES

Recent Modernization

LICA AND THE CURRENT CAPABILITIES?

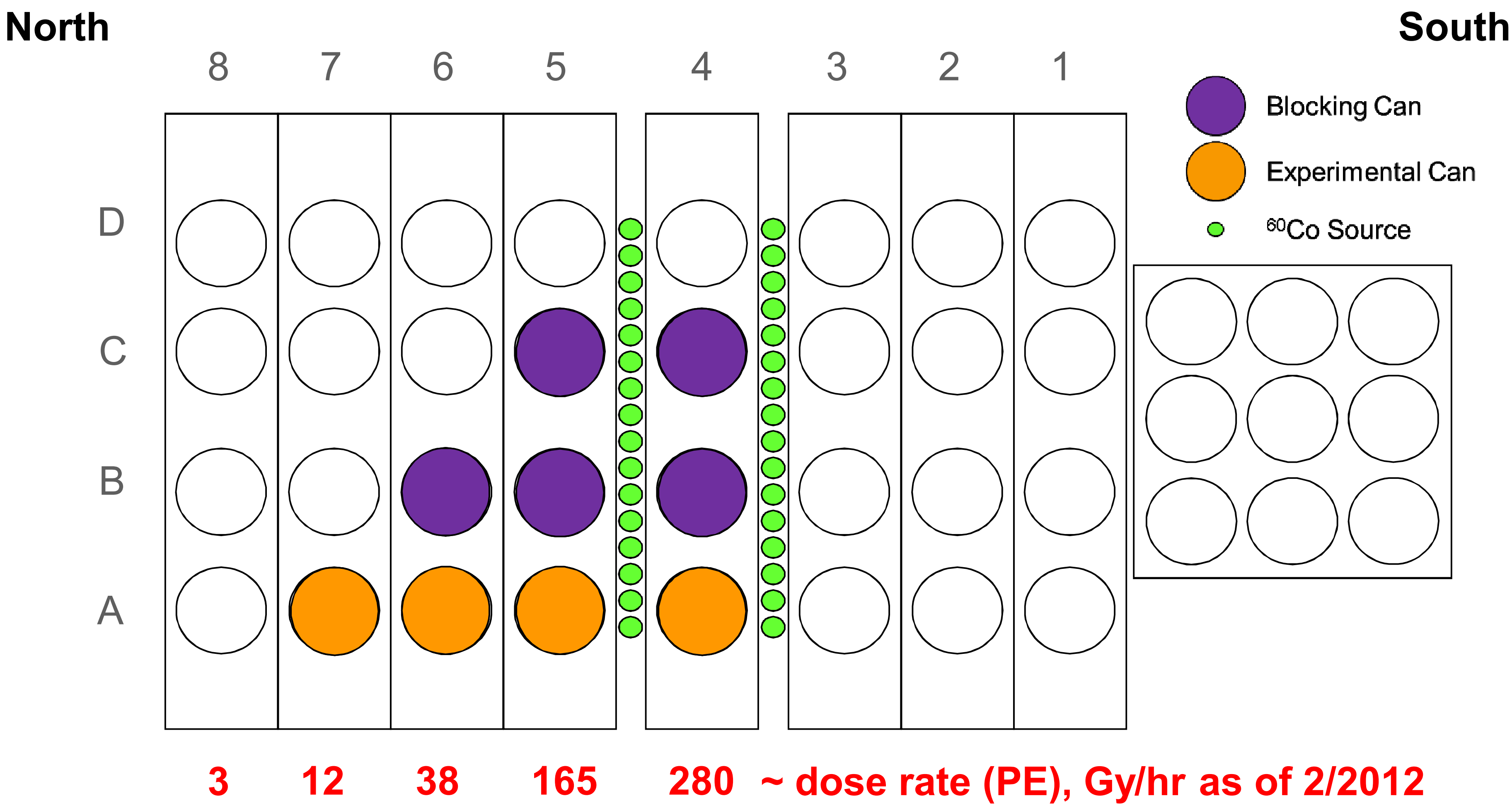
Low Intensity Cobalt Array

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.

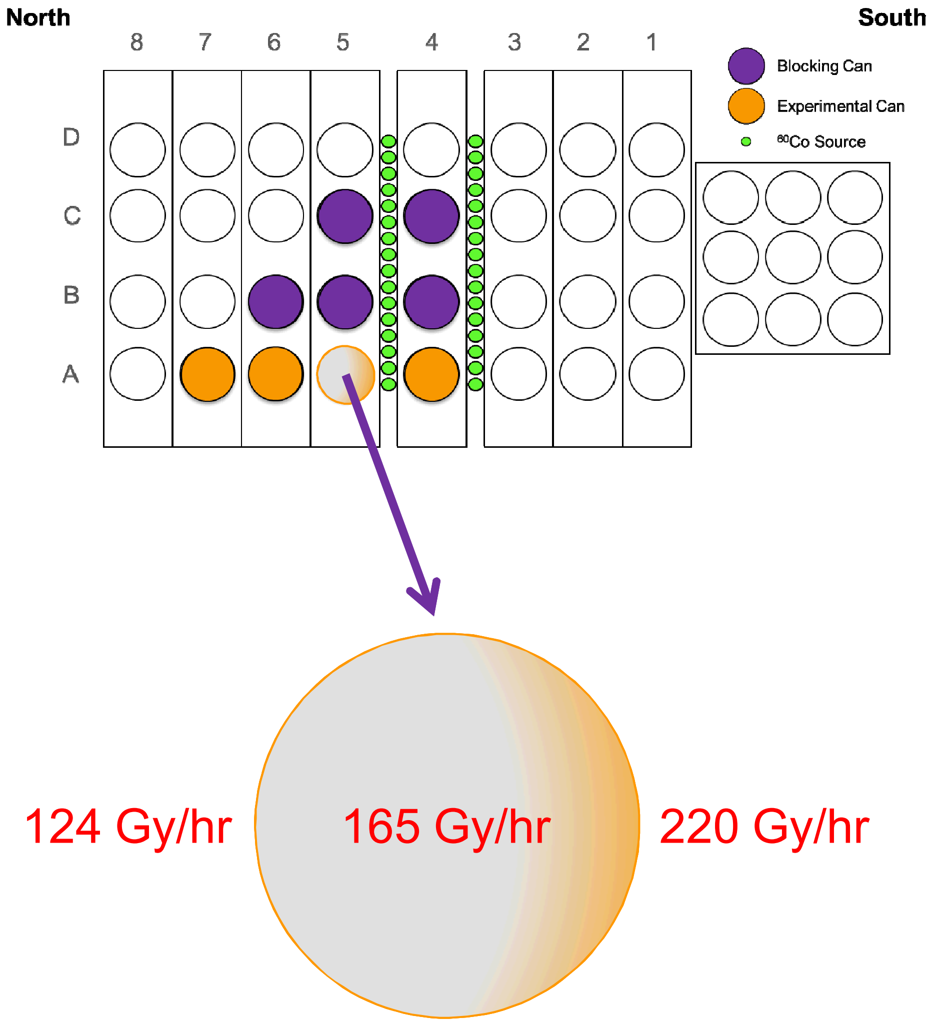
Irradiation Dose Rates

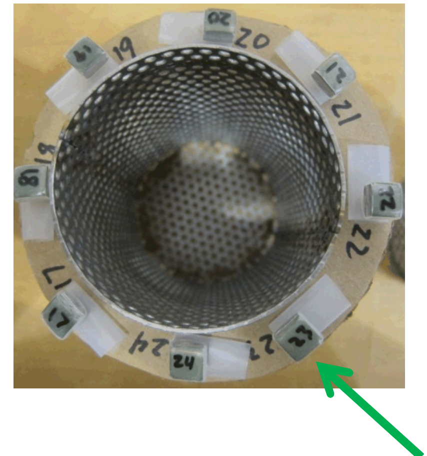


- Headspace gas control (flowing system)
- Thermal control

Irradiation Dose Rates

Sandia National Laboratories





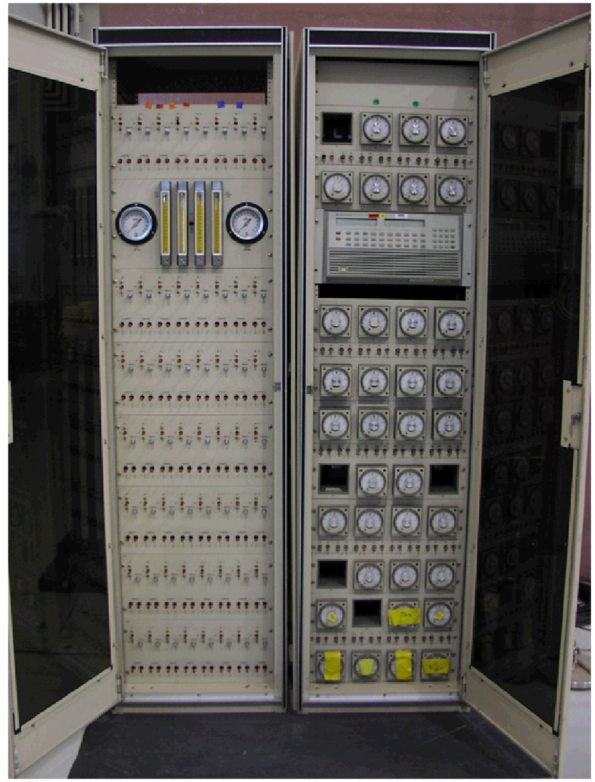
Dosimetry is measured with CaF_2 TLDs as a function of position within the cans. The dose rates are corrected for material of interest, e.g. polyethylene.

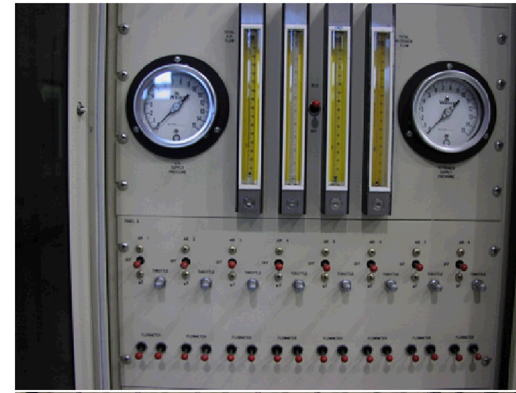
LICA Control System, ~2011

Tunable

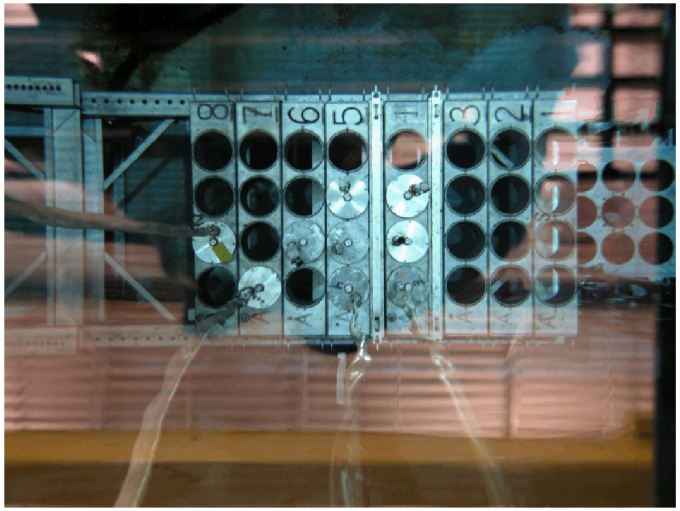
- Temperature
- Gas Environment

"Ancient" Technology



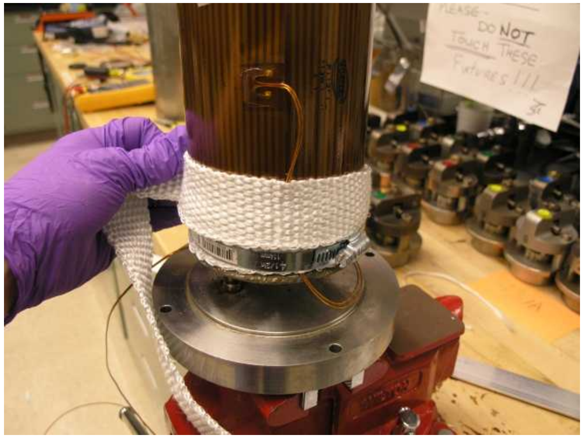


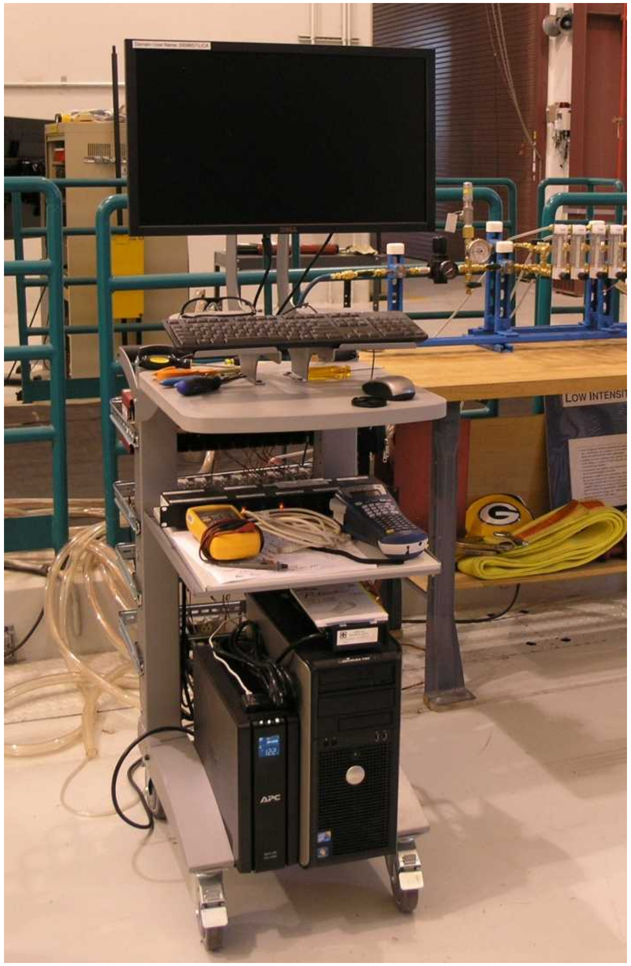
Gas Environments



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

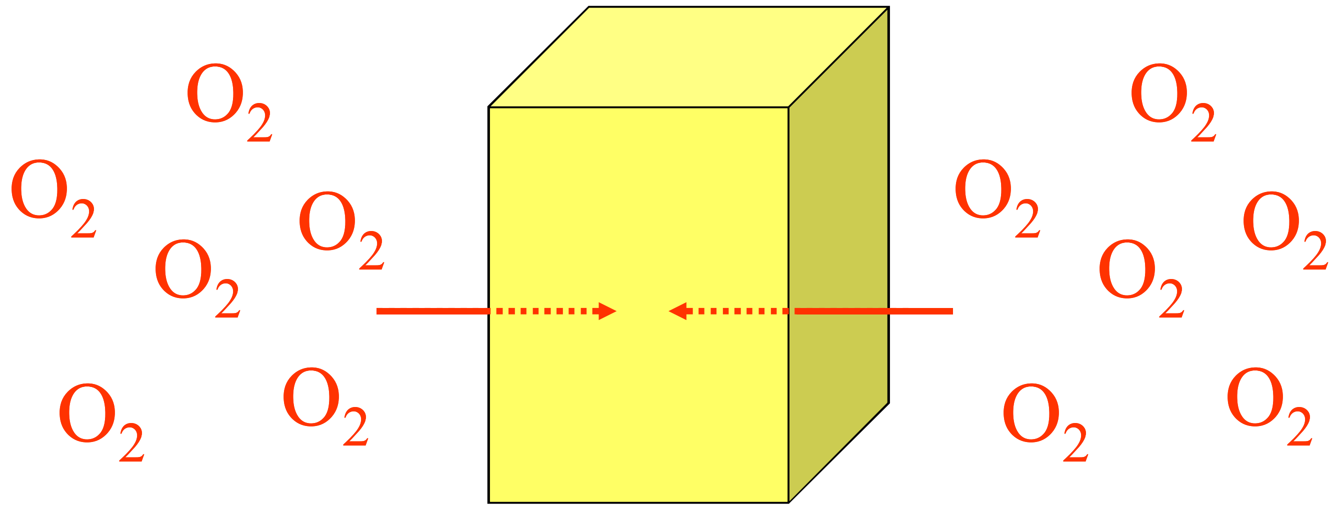
Thermal Environments





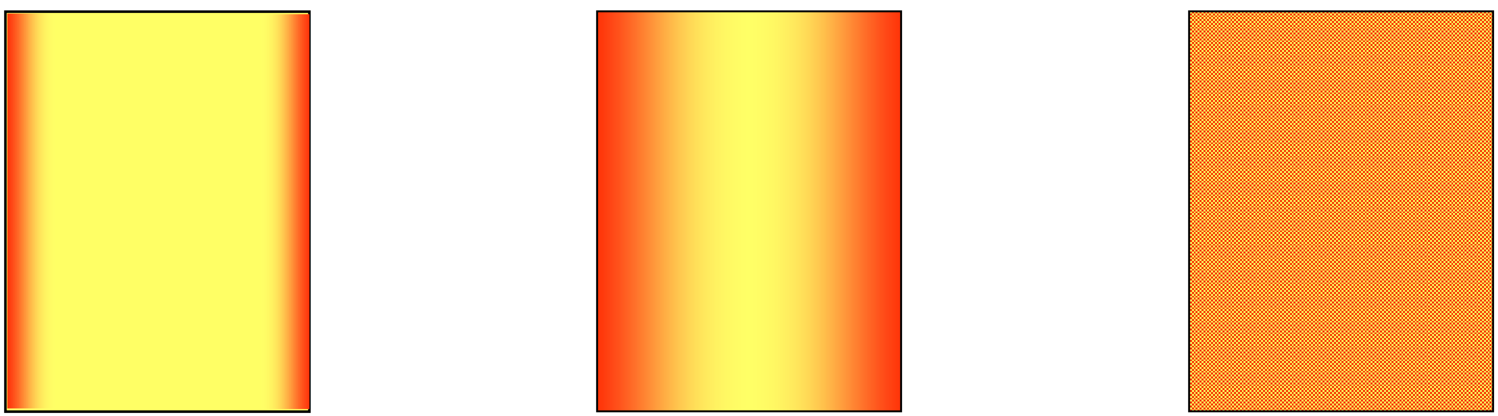
- Experiments can be performed at varying temperatures
  - 27 °C to 150 °C (± 0.2 °C)
- Remote access for thermal control and monitoring on the SRN
- Email alerts for extreme temperature variation
- Backup power supply for data logging in case power loss
- 4 elevated temperature cans and up to 7 ambient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

Diffusion Limited Oxidation



rxn rate > diffusion rate

rxn rate < diffusion rate



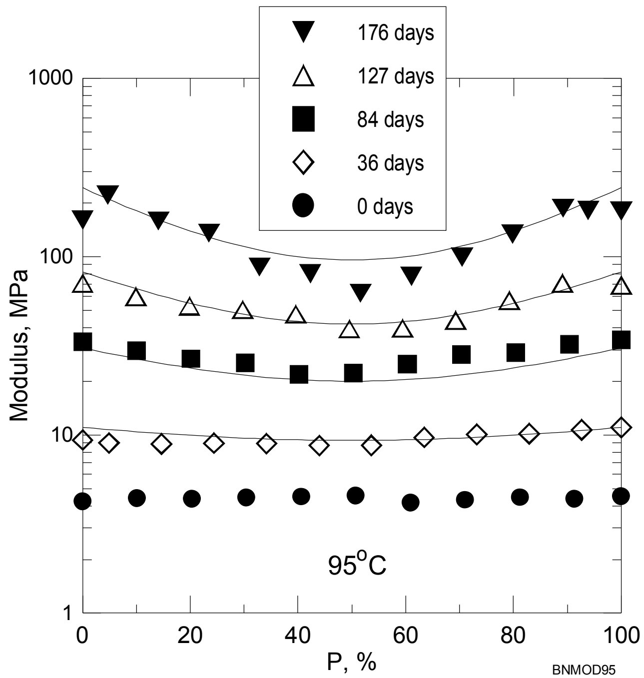
Heterogeneous

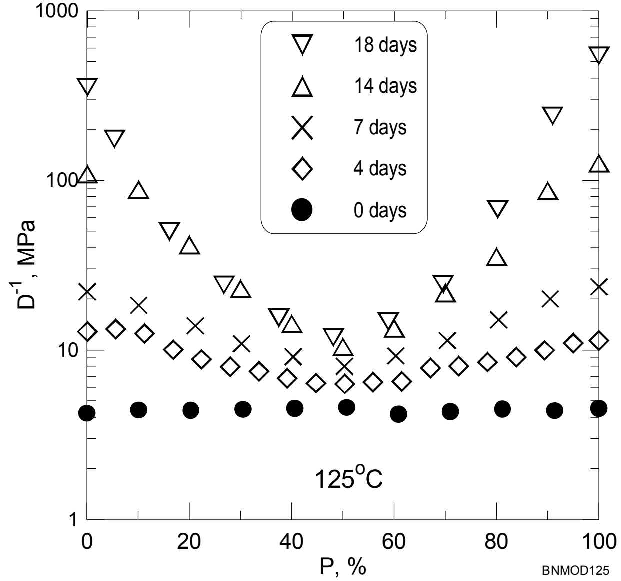
Homogeneous

DLO Effects with Temperature

Sandia National Laboratories

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

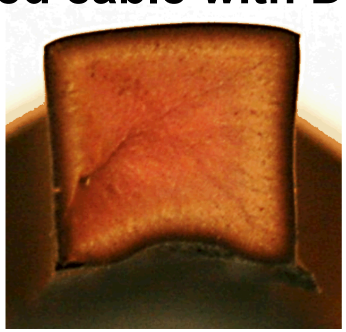




Wise, J.; Gillen, K. T.; Clough, R. L. Polymer Degradation and Stability, 1995, 49, 403-418.

Images shown below courtesy from our collaborator Kevin Simmons at PNNL

Aged cable with DLO

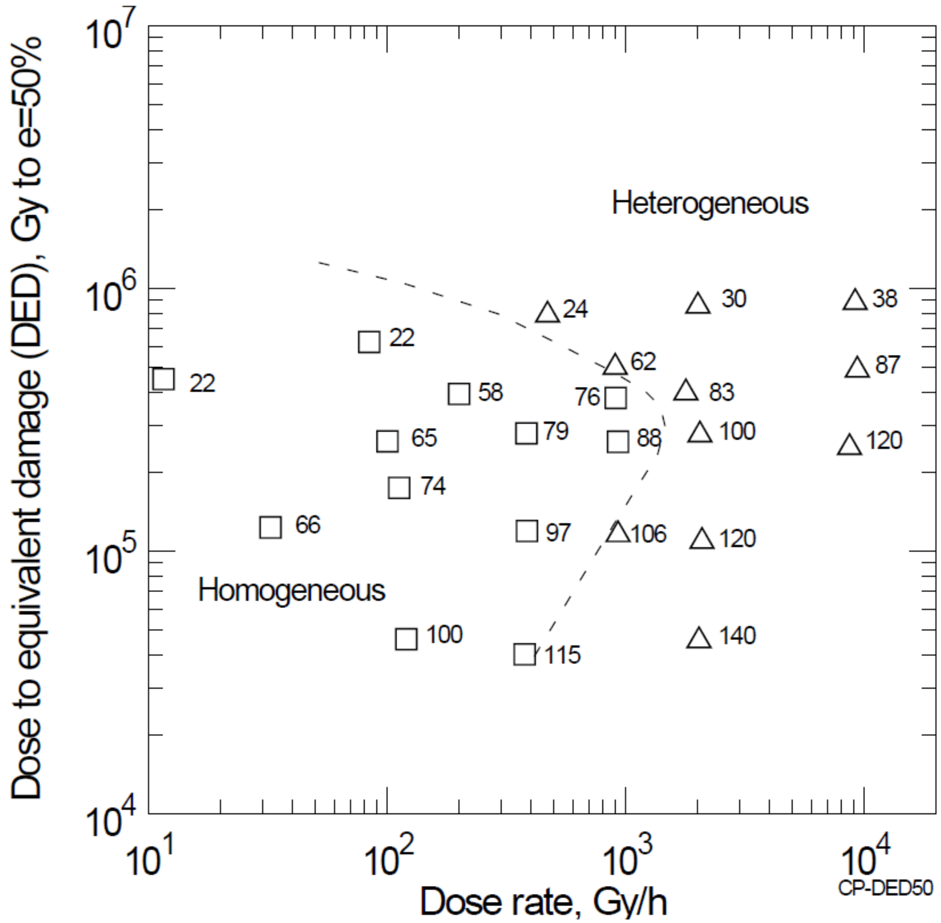


Virgin vs Aged

DLO Effects in Combined Environments

Sandia National Laboratories

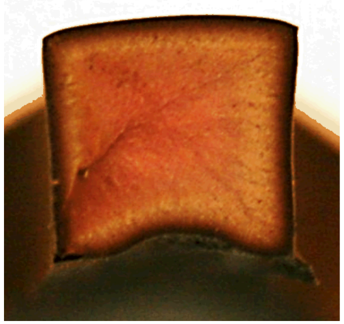
Combined environment tensile aging data for Okonite neoprene material with DED = 50% E_B



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

Images shown below courtesy from our collaborator Kevin Simmons at PNNL

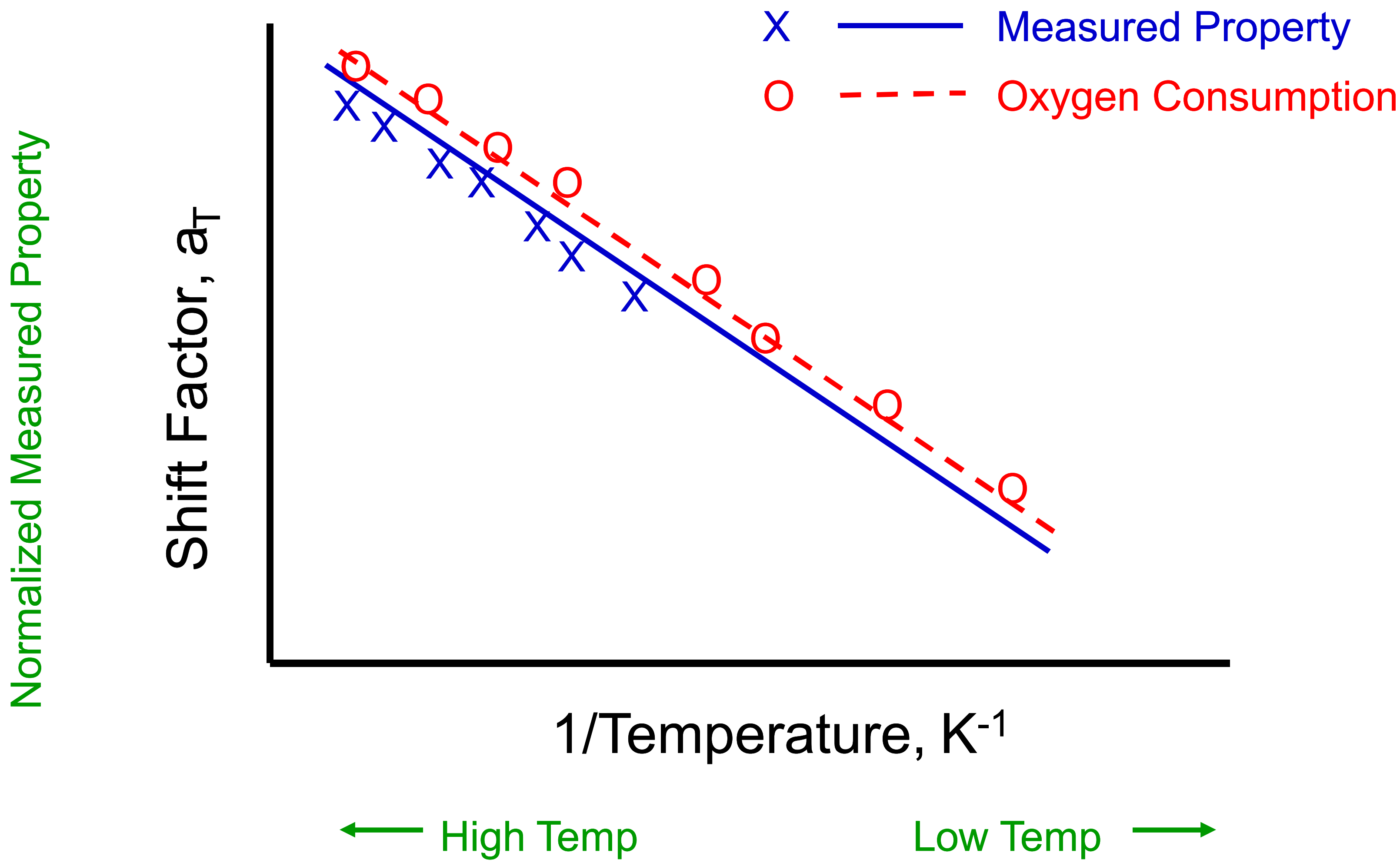
Aged cable with DLO



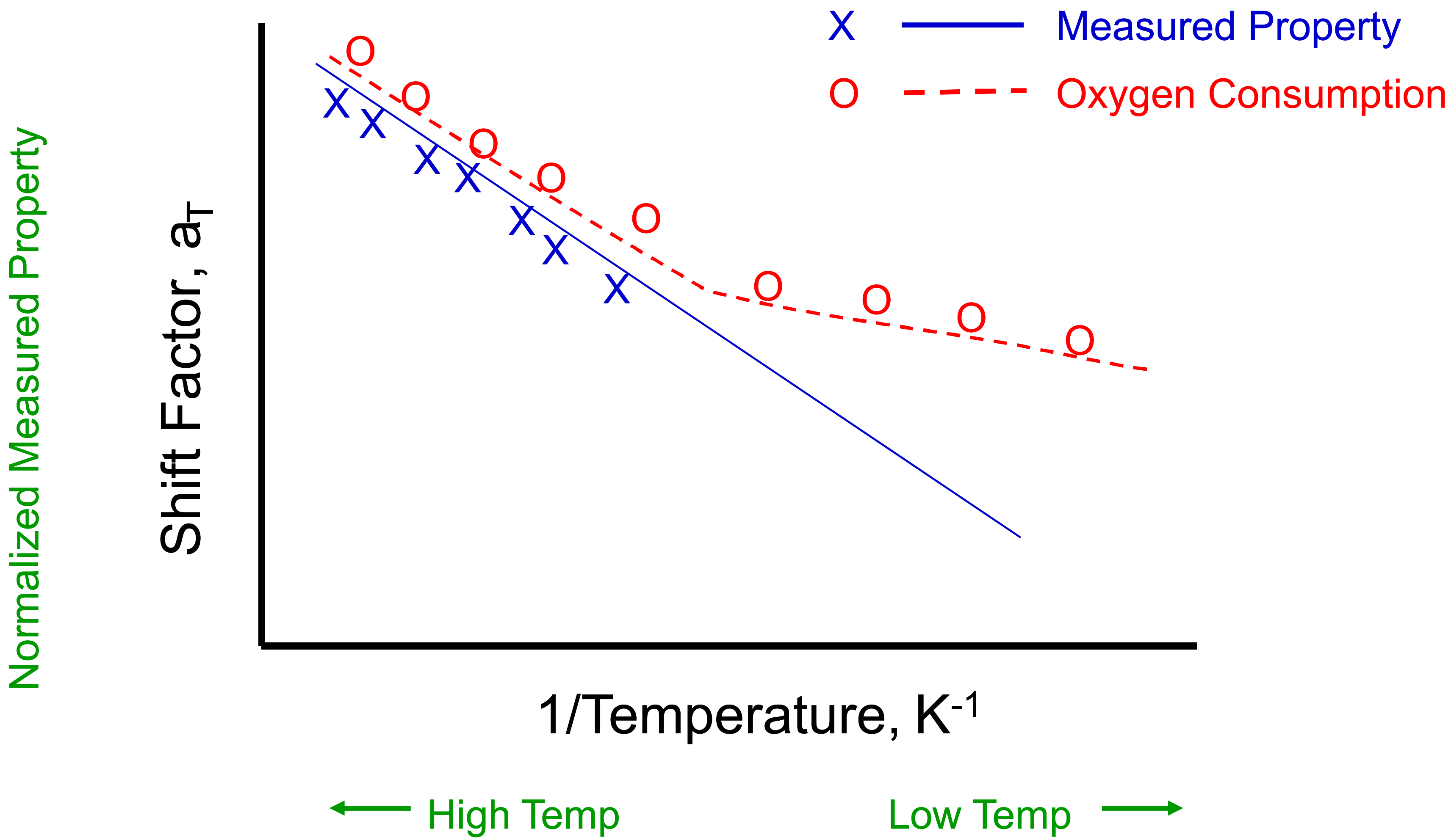
Virgin vs Aged

This same phenomena has been noted for irradiation dose rates…

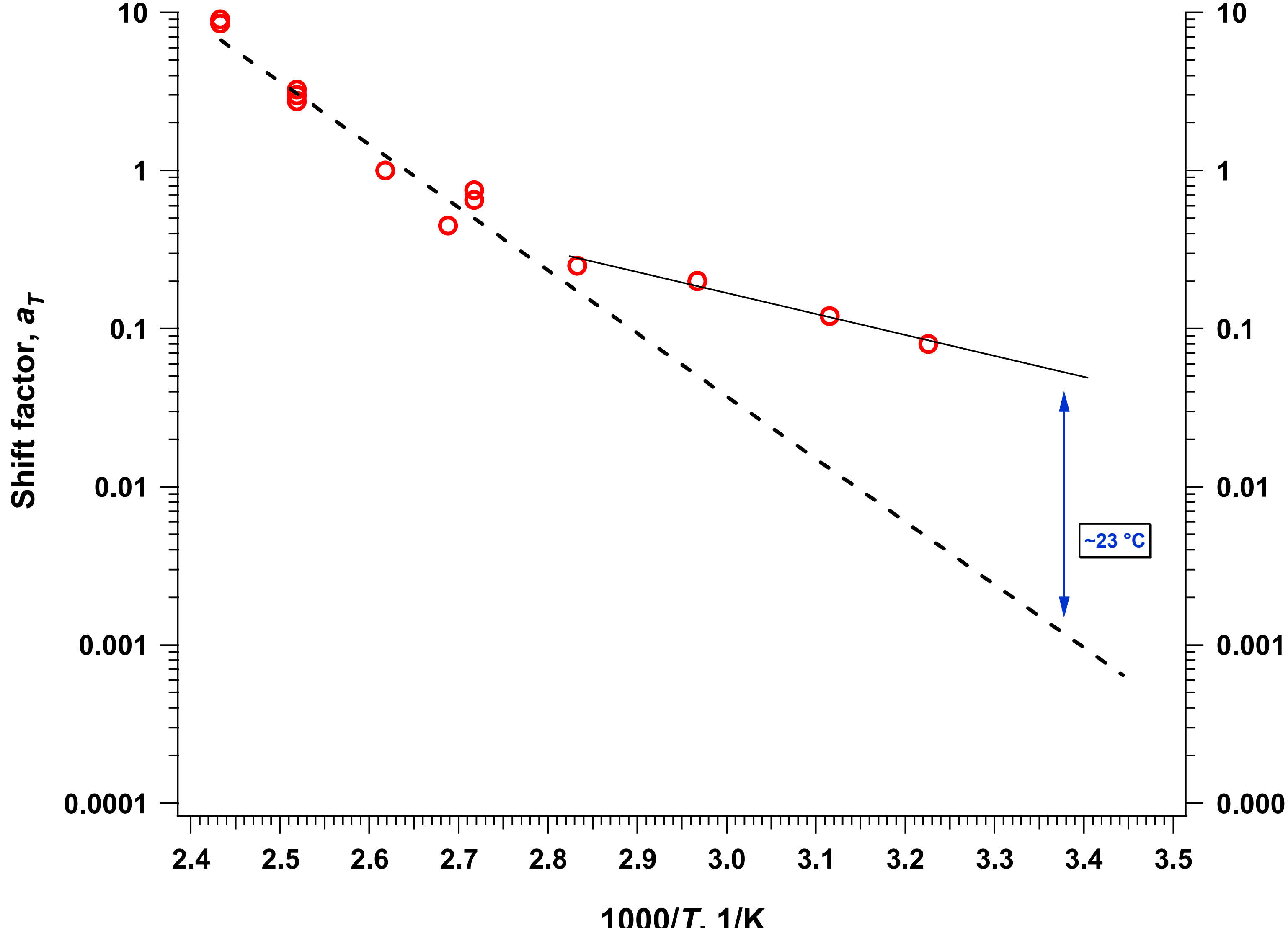
Enhanced Extrapolation 'Good'



Enhanced Extrapolation: 'Bad'



Thermal-oxidative Aging: Nylon Shift Factor Graph



Bernstein, R.; Gillen, K. T. *Polymer Degradation and Stability, Nylon 6.6 accelerating aging studies: II. Long-term thermal-oxidative and hydrolysis results 2010, 95, 1471-1479.*

Arrhenius Equation

Arrhenius equation:

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

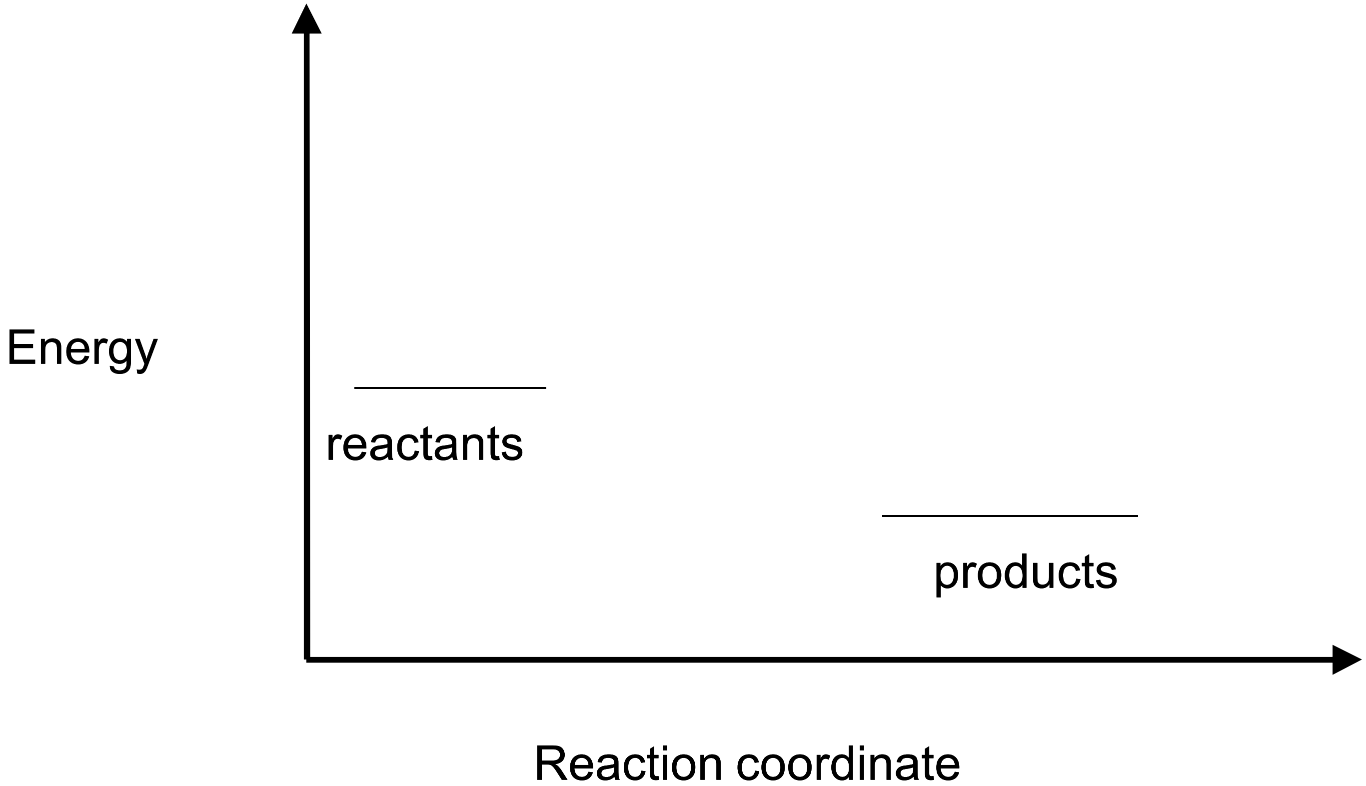
$\ln(k) = -(Ea/R)(1/T) + \ln(A)$

k = anything

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

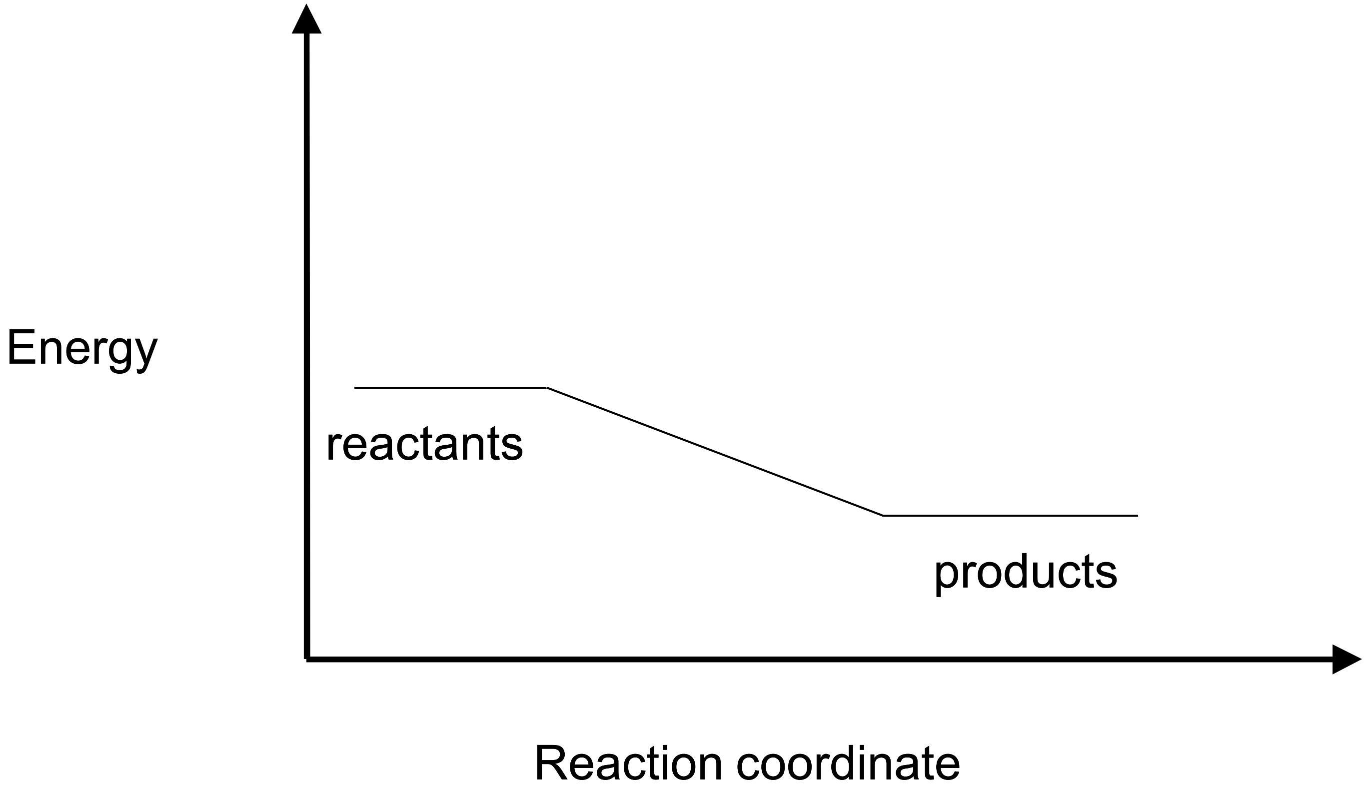
What is Ea?

E_a

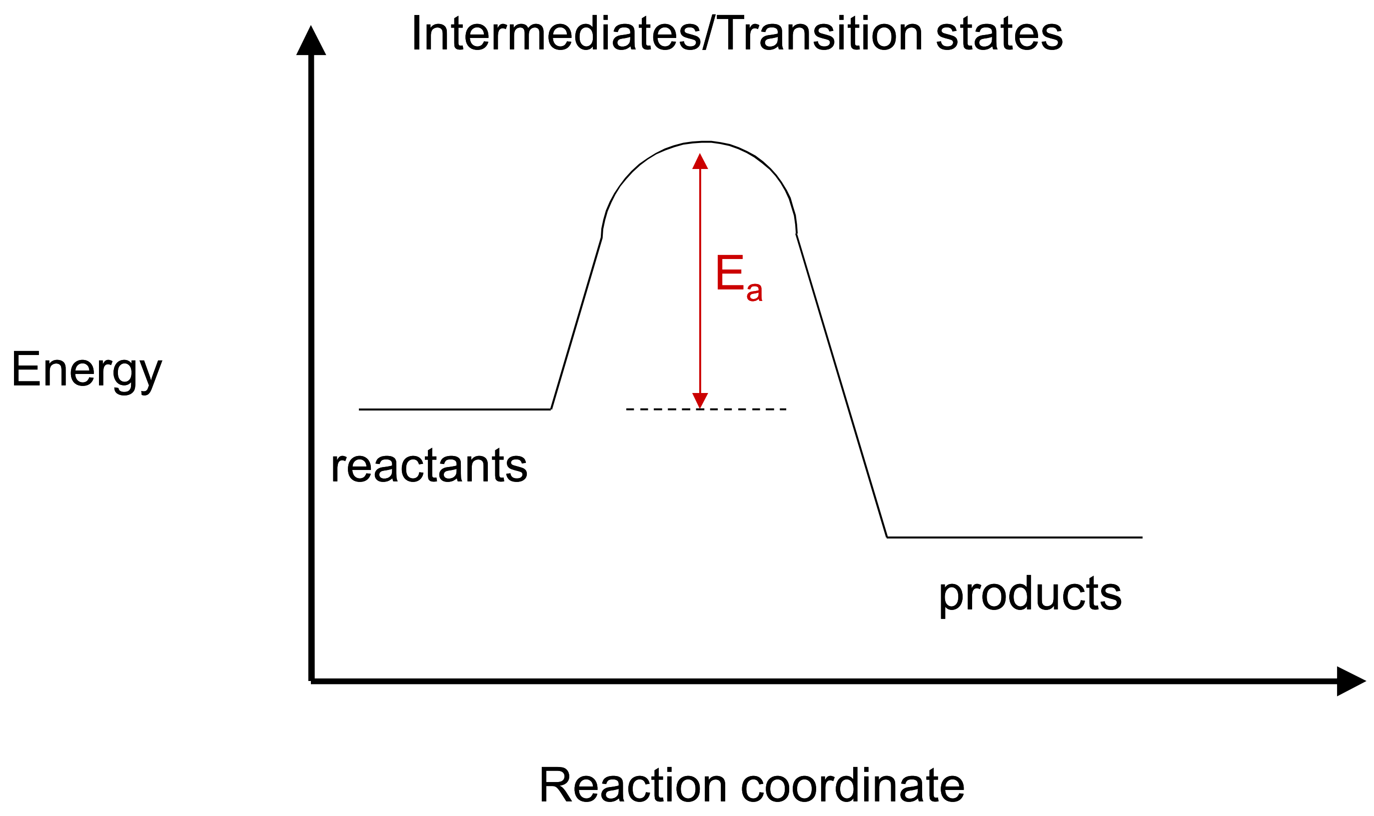


---Imagine a marble---

E_a

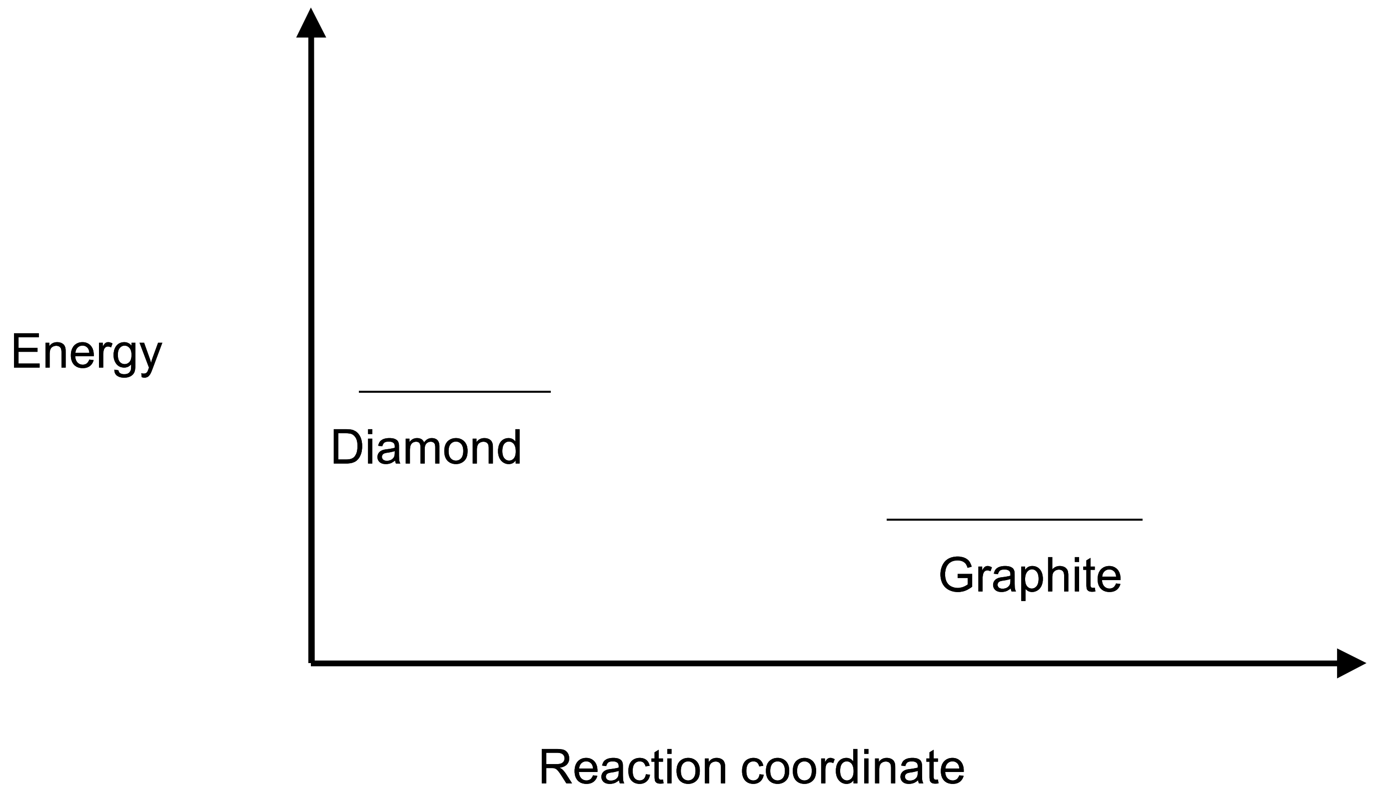


E_a

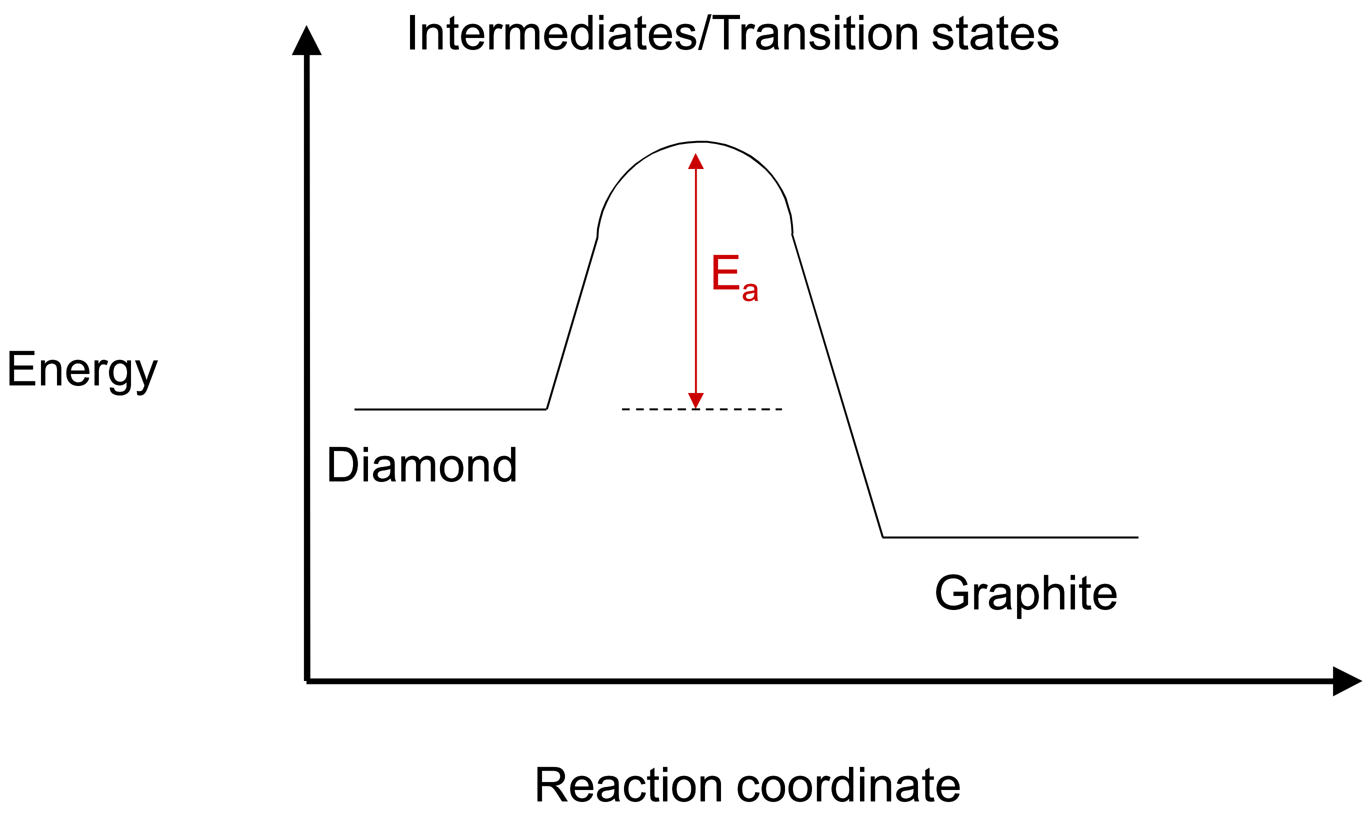


Intermediates/Transition states
Energy
Ea
reactants
products
Reaction coordinate

Kinetics vs. Thermodynamics (really the same thing)



E_a


Intermediates/Transition states
Energy
E_a
Diamond
Graphite
Reaction coordinate

Arrhenius Equation

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

Critical assumption is that E_a is CONSTANT