# Lifetime prediction methods and accelerated testing

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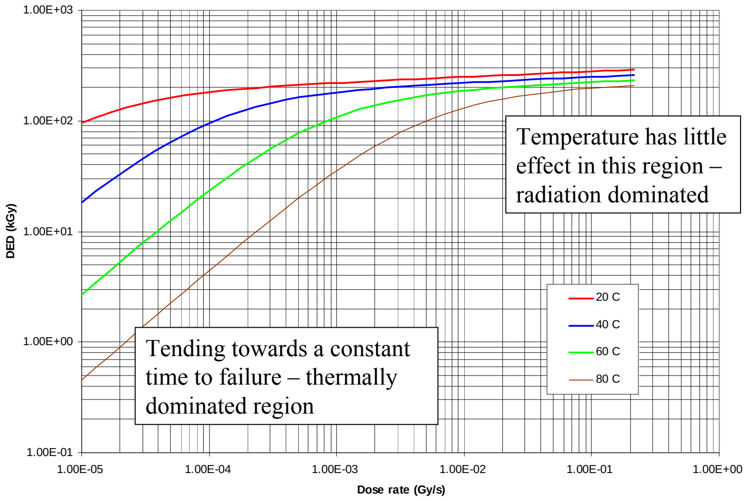
## Why do we need predictive modelling?

- Qualification of components aims to demonstrate that they can continue to fulfil their safety function for their qualified life
- Requirement to simulate the ageing that would occur in the plant, using worst case environmental conditions
- Thermal and radiation ageing needs to be simulated in an accelerated time frame but is this accelerated ageing an accurate simulation?
- Predictive modelling can be used to optimise replacement schedules for components e.g. seals, using actual environmental conditions

# What are the issues for lifetime prediction of polymers in NPPs?



Temperature has little effect in this region – radiation dominated

Tending towards a constant time to failure – thermally dominated region

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# Lifetime prediction methods

- Thermal ageing – Arrhenius and its limitations
- Radiation ageing – power law extrapolation
- Combined thermal & radiation ageing – two approaches to modelling
  - Superposition of time dependent data
  - Superposition of dose to equivalent damage (DED) data
- Limitations of prediction methods

# Accelerated thermal ageing

- Usually based on Arrhenius relationship, using following equation

  $$t_1 = t_2 \exp [E_a/R\ (1/T_1 - 1/T_2)]$$

  - Where $t_1$ is ageing time required at a temperature $T_1$ to simulate a service life of $t_2$ at a temperature $T_2$. $E_a$ is the activation energy for thermal ageing and R is the gas constant
- Assumes that
  - A single degradation mechanism is in operation
  - Degradation mechanisms are the same at the higher temperature used for accelerated ageing
  - Activation energy $E_a$ is constant and value is known for specific cable formulation

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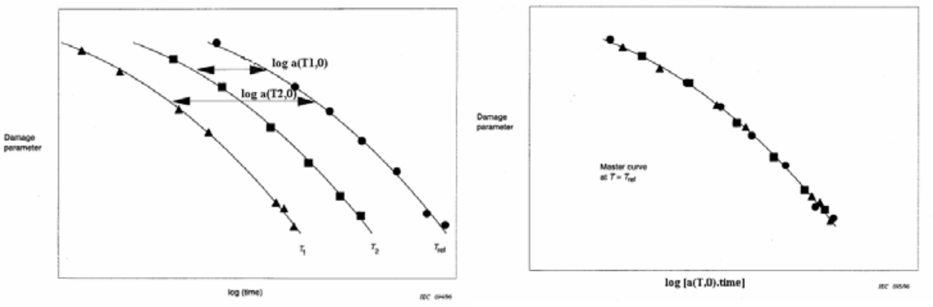
# What to look for

- Are the curve shapes the same for each temperature?
  - Can check by determining time to reach different levels of degradation and comparing slope of 1/T plots
  - If not, degradation mechanisms are not the same at different temperatures
- Is it possible to interpolate to the required end-point?
  - If not, use superposition to maximise use of data and use shift factors plotted against 1/T to determine $E_a$
- $E_a$ determined from slope since
  - $E_a = R \log_e (t_1/t_2) / (1/T_1 - 1/T_2)$

# Superposition principle



- Often used in thermal ageing to determine activation energy
- Data obtained at different temperatures are superposed by applying a multiplying factor – shift factors a(T)
- Generates a ‘master curve’ at a reference temperature $T_{ref}$

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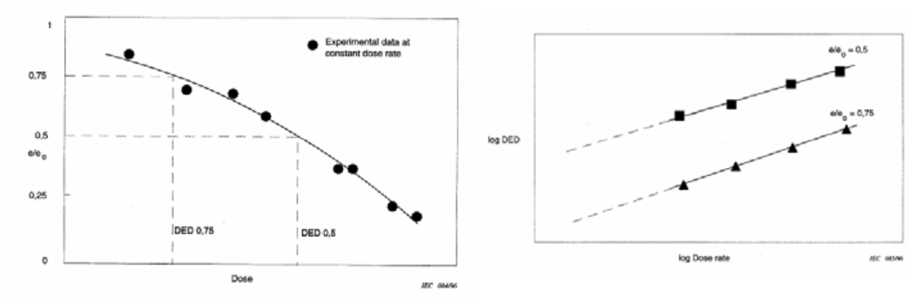
# Predicting radiation ageing – power law extrapolation method

- Dose to equivalent damage (DED) given by

  **DED = C. $D^x$**

  where D is the dose rate, exponent x <1, C is a constant for the material
- Simple model, applicable particularly to polyolefin materials at near ambient temperature
  - Described in detail in IEC1244-2
- Currently the only model available for polymers with a reverse temperature effect

# Power law – generating data required



- Ageing at constant temperature, several dose rates
- Test data (e.g. EAB, set) plotted against radiation dose
- DED values extracted for different dose rates
- Log/log plot of DED versus dose rate is linear

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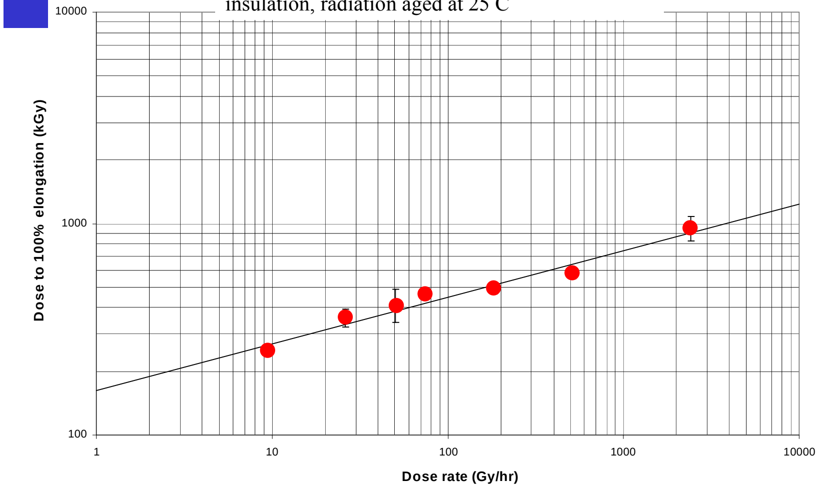
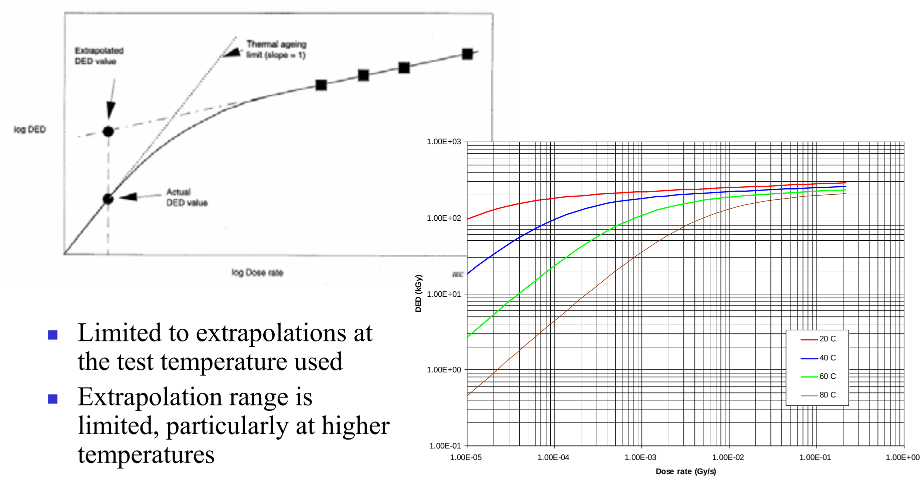
# Example of power law method applied to a cable insulation material (XLPE)

Dose to reach 100% elongation for XLPE cable insulation, radiation aged at 25 C



# Limitations of power law predictive model

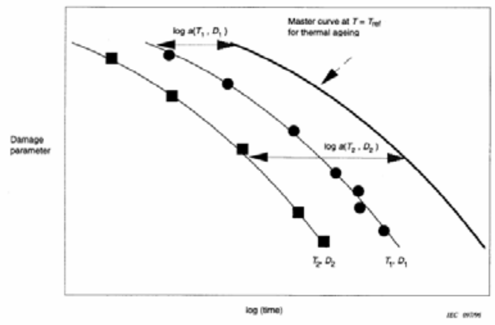


- Limited to extrapolations at the test temperature used
- Extrapolation range is limited, particularly at higher temperatures

# Predicting combined thermal/radiation ageing – superposition of time-dependent data

- Requires matrix of test data at different dose rates and temperatures
- Time-dependent data are superposed to give master curve using shift factors a(T,D)
- Semi-empirical model links a(T,D) values to temperature and dose rate
  - Described in detail in IEC1244-2

# Superposition of combined radiation/thermal ageing data



- Same principle of superposition is used to generate a ‘master curve’ for all of the data
- Shift factors a(T,D) are a function of both temperature and dose rate

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# Typical master curve generated by superposition

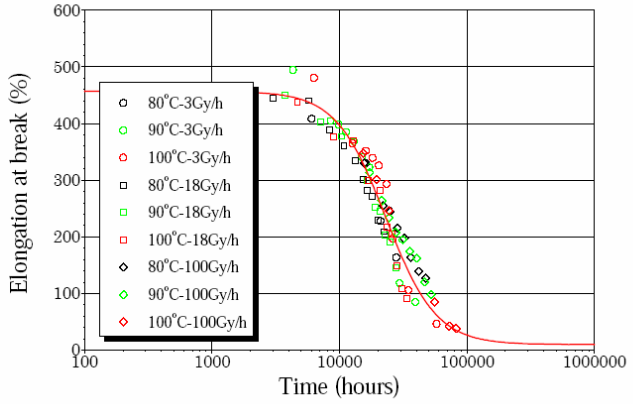

**Fig. 3.2-17 Superposition of time dependent data of the FR-EPR insulator (red core) made by Company C E=15kcal/mol, k=191.1, x=0.8439**

# Modelling the shift factors a(T,D)

- Semi-empirical equation

$$a(T,D) = \exp\{-E/R\,(1/T - 1/T\mathrm{ref})\}\ [1 + k\,.\,D^{x}.\exp\{Ex/R\,(1/T - 1/T\mathrm{ref})\}]$$

- Simplifies to the Arrhenius equation for D=0

$$a(T,0) = \exp\{-E/R\,(1/T - 1/T\mathrm{ref})\}$$

- At the reference temperature T=Tref, simplifies to

$$a(T\mathrm{ref}, D) = 1 + k\,.D^{x}$$

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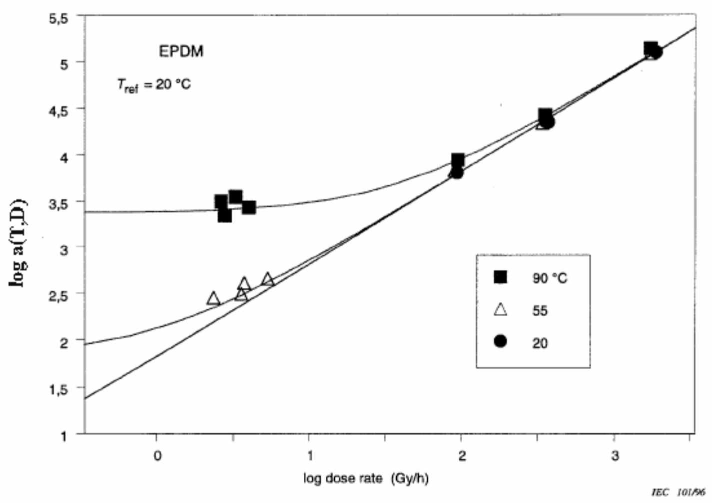
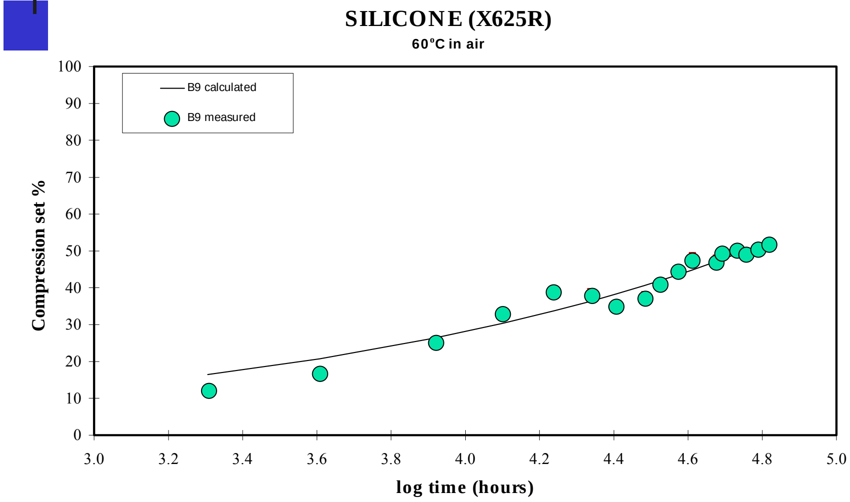
# Fitting experimental values of a(T,D) to the equation - example



IEC 101/96

# Example of superposition model used for radiation/thermal ageing of a seal – long term validation test at 60 C, 6 Gy/hr



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# Limitations and use of model based on superposition of time dependent data

- Requires a large matrix of data
- Superposition only possible if single degradation mechanism is dominant, so that curve shape remains same
- Demonstrated for wide range of polymers (particularly seal materials)
- Works best for amorphous materials, not usually good for polyolefins or semi-crystalline EPRs

## Curve shape must be same at different dose rates and temperatures to use superposition – model should not be used for this material

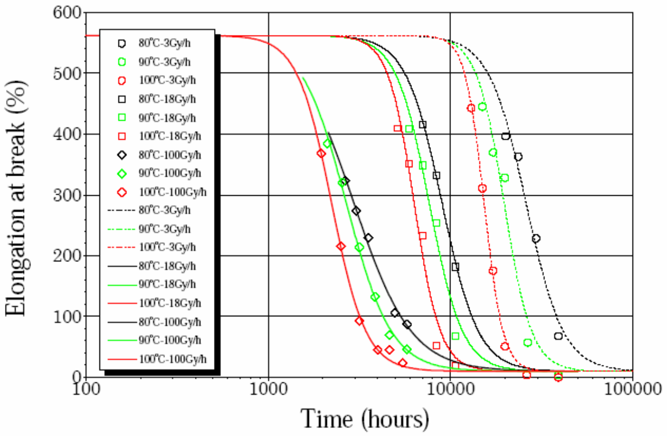

**Fig. 1.2-7 Simultaneous aging characteristics I of the FR-XLPE insulator (black core) made by Company B**

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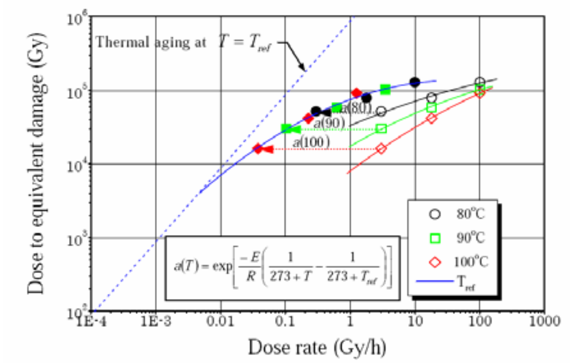
## Predicting radiation ageing – superposition of DED data

- Requires matrix of test data at different dose rates and temperatures
- Also uses superposition but here DED data are superposed using shift factors a(T)
- Shift factors often related to temperature by Arrhenius equation
    - Described in detail in IEC1244-2

# Basic principle of method



- DED data at different dose rates are superposed using shift factors a(T) that only depend on temperature
- DED values will tend towards the thermal ageing limit at low dose rates

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# Superposition of DED data - example

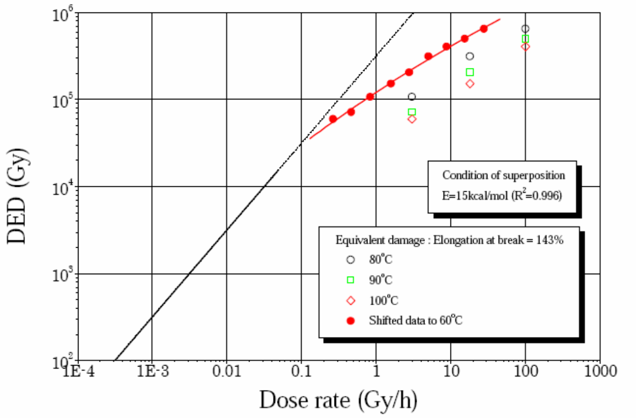

**Fig. 3.3-20 Superposition of DED data of the FR-EPR insulator (white core) made by Company C**
**Equivalent damage: EAB=143%, Temperature: 60°C**

## Limitations and use of model based on superposition of DED data

- Requires large matrix of data
- Cannot be applied to materials that show reverse temperature effects in the temperature range of interest
- Demonstrated on a range of polymers, particularly cable materials

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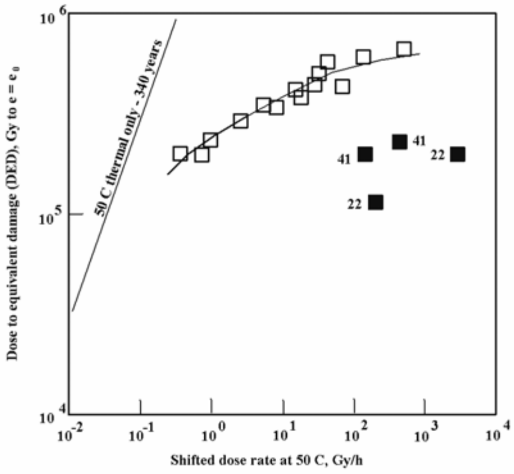
## Superposition of DED data – reverse temperature effects

- Superposition of DED data for a XLPO cable insulation material
- □ - radiation ageing data at ≥60°C
- 41■ and 22■ refer to data at 41°C and 22°C respectively
- Superposition would seriously underestimate degradation at low temperatures



## Superposition of DED data – example where ageing temperatures above crystalline melting point

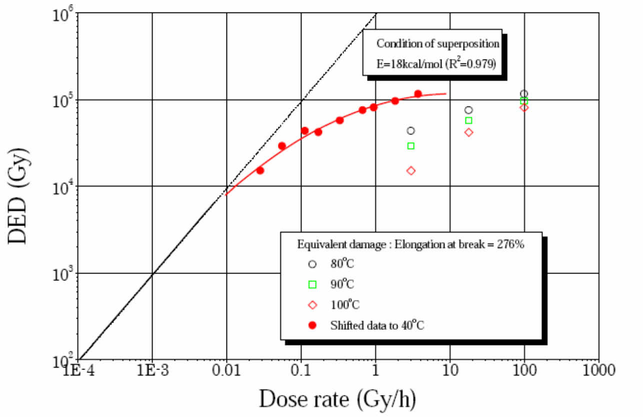


**Fig. 3.3-5 Superposition of DED data of the XLPE insulator made by Company A**

**Equivalent damage: EAB=276%, Temperature: 40°C**

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## Limitations of predictive models

- Semi-crystalline polymers
  - Tend to show reverse temperature effect, with degradation being greater at ambient temperature than elevated temperature
  - Arises from recrystallisation and recombination of radicals at higher temperatures
  - Power law method is currently only practical approach

# Lifetime prediction methods

Recommended for further reading

- IEC Technical Report IEC1244-2 (International Electrotechnical Commission, Geneva)
  - “Determination of long term radiation ageing in air. Part 2: Procedures for predicting ageing at low dose rates”
  - Details of practical methods for lifetime prediction and their limitations

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# Predictive modelling - summary

- For all predictive methods, essential to understand underlying assumptions and limitations
- Thermal ageing – Arrhenius equation of practical use
- Radiation ageing – power law method useful, particularly for materials (such as polyolefins) that show reverse temperature effect
- Combined thermal/radiation ageing – both superposition models have proved useful but do require large sets of test data

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# Developing a test matrix for accelerated ageing tests

- Identify aims of the test - for example
    - Simulation of service life
    - Simulation of accident conditions
    - Predictive modelling
    - Generation of CM correlation curves
- Identify timescales needed for the test
- Identify type of data needed and number of test conditions required

# Timescales of tests

- Factors to be considered:
  - Need to minimise acceleration factors
  - Limit extrapolation required (particularly for thermal ageing)
  - Limit maximum temperature used to avoid non-representative degradation mechanisms
  - Limit maximum dose rate to avoid heterogeneous oxidation

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# Types of data needed

- Proof tests and functional tests require limited number of test conditions
- Predictive modelling requires a large matrix of data with multiple temperature/dose rate conditions
- Generation of CM correlation curves require an intermediate no. of test conditions

# Test methods for specific materials

- Seal materials
  - Compression set used as basic indicator of degradation
  - Measurement of leakage rate or sealing force may be needed for functional tests
- Cable insulation and jacket materials
  - Elongation at break usually used as basic indicator of degradation
  - CM methods available for most materials
- Coatings
  - Adhesion tests

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# Thermal ageing tests

- Factors to be considered –
  - If activation energy E is not known, need a minimum of 3 test temperatures
  - Maximum temperature must be limited – changes in degradation mechanisms at high temperature
  - Test temperature should be near to service conditions (extrapolations should ideally be <25 C)
  - Heterogeneous oxidation likely at higher test temperatures and in large diameter seals or cables
  - Good oxygen access needed
  - For seals, ageing must be carried out in compressed state representative of seal housing

# Radiation ageing tests

- Factors to be considered –
  - If test matrix is for predictive modelling, need a minimum of 3 dose rates
  - Simulation of accident conditions can use high dose rates, but for service conditions use as low a dose rate as possible
  - Heterogeneous oxidation will occur at high dose rates or with thick samples (a major concern when testing seals or whole cables)
  - Good oxygen access needed
  - For seals, ageing must be carried out in compressed state representative of seal housing

# Functional tests on seals

- Factors to be considered –
  - High temperature tests
    - Can transient be simplified to isothermal steps?
    - Allow for outgassing at temperature in leakage measurements
  - Low temperature tests
    - Is there a glass transition near minimum temperature?
    - Use dry gas when measuring leakage rates

# Typical test matrices

| **Test type** | **Radiation dose rates** | **Temperature** |
|---|---|---|
| Predictive modelling | 25, 50, 100, 200 Gy/hr | 20 C |
| | 100 Gy/hr | 40, 60 C |
| | 0 Gy/hr | 80, 95, 110 C |
| CM correlation curves | 50, 200 Gy/hr | 20 C |
| | 100 Gy/hr | 40 C |
| | 0 Gy/hr | 100 C |
| Proof tests | 200 Gy/hr | 20 C |
| | plus 0 Gy/hr | 110 C |

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# Summary

- There are suitable predictive models for most types of polymers
- Modelling requires large matrix of data – may not be feasible for polymeric components in older plant
- Design of accelerated ageing tests must consider several factors to ensure that test is appropriate
- For new NPPs, recommend that data for predictive modelling is generated early in the build process