# PROBABILISTIC MODELS TO ESTIMATE FIRE-INDUCED CABLE DAMAGE AT NUCLEAR POWER PLANTS

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# OUTLINE

- BACKGROUND.
- OBJECTIVE.
- PROPOSED MODELS.
    - HEAT TRANSFER MODEL.
    - “K FACTOR” MODEL.
- DATA GATHERING AND ANALYSIS.
- DAMAGE-ENDURANCE MODEL DEVELOPMENT.
- RESULTS ANALYSIS.
- CONCLUSIONS AND RECOMMENDATIONS.

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## BACKGROUND

- FIRE-INDUCED ELECTRICAL CABLES/CIRCUITS FAILURE MODES
- CONDUCTOR TO CONDUCTOR SHORTING FAILURE MODE.
- FIRE TESTING PROGRAMS (EPRI, NRC, …)

⇓

- ✓ BETTER UNDERSTANDING OF FIRE-INDUCED CABLE FAILURE MODES.
- ✓ KNOWLEDGE OF CABLE FAILURE BEHAVIOR UNDER EXTERNAL THERMAL INSULT.
- ✓ IDENTIFICATION OF INFLUENCE FACTORS TO KEY CIRCUIT FAILURES MODES.
- ✓ QUALITATIVE APPROCHES TO ESTIMATE THE PROBABILITY OF CABLE DAMAGE.

**THE OBJECTIVE OF THIS RESEARCH IS TO DEVELOP PROBABILISTIC MODELS TO ESTIMATE LIKELIHOOD OF FIRE-INDUCED CABLE DAMAGE GIVEN A SPECIFIED FIRE PROFILE.**

**The results of this research will:**

- **Help to develop a consistent framework to estimate fire-induced cable failure modes likelihood**
- **Develop guidance to evaluate and/or reduce the risk associated with these failure modes in existing and new power plants**

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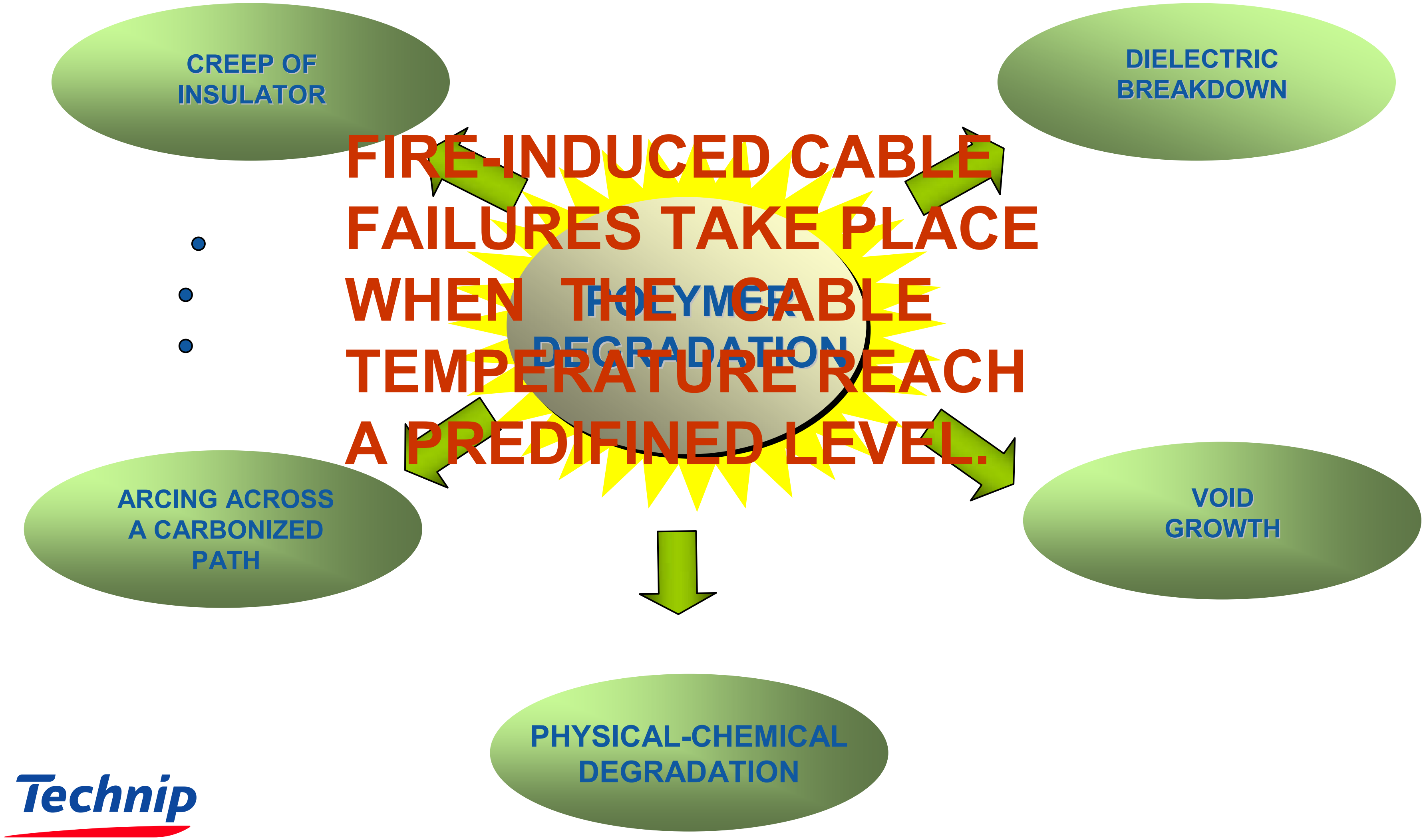
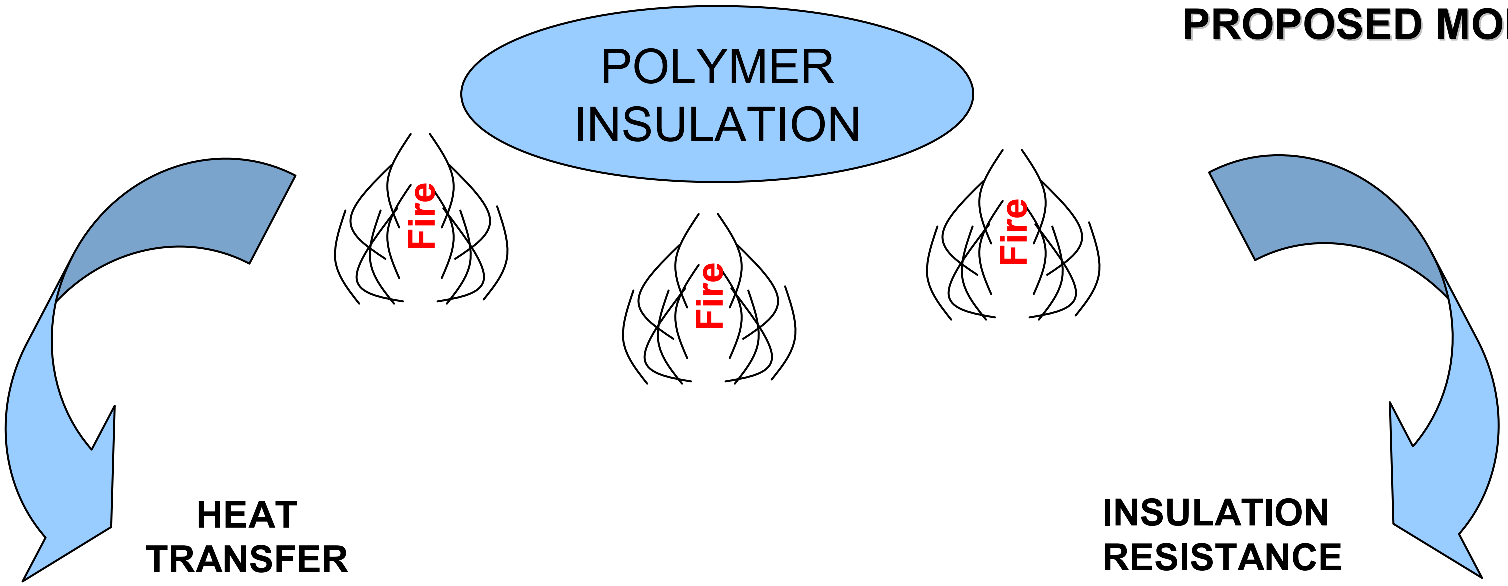
## PHYSICS - BASED MODEL



# PROPOSED MODELS




### HEAT TRANSFER

$$\frac{T - T_0}{T_u - T_0} = 1 - C_1 . e^{-\left[\left(\zeta_1^2 F_o\right) J_o(\zeta_1 r)\right]}$$

T: inner temperature of the cable at time t.
To: initial temperature of the cable (t = 0).
Tu: temperature in the surrounding area at time t.

- Homogeneous and infinite cylinder
- Constant thermo-physical properties
- No internal heat generation
- No heat losses through the conductors

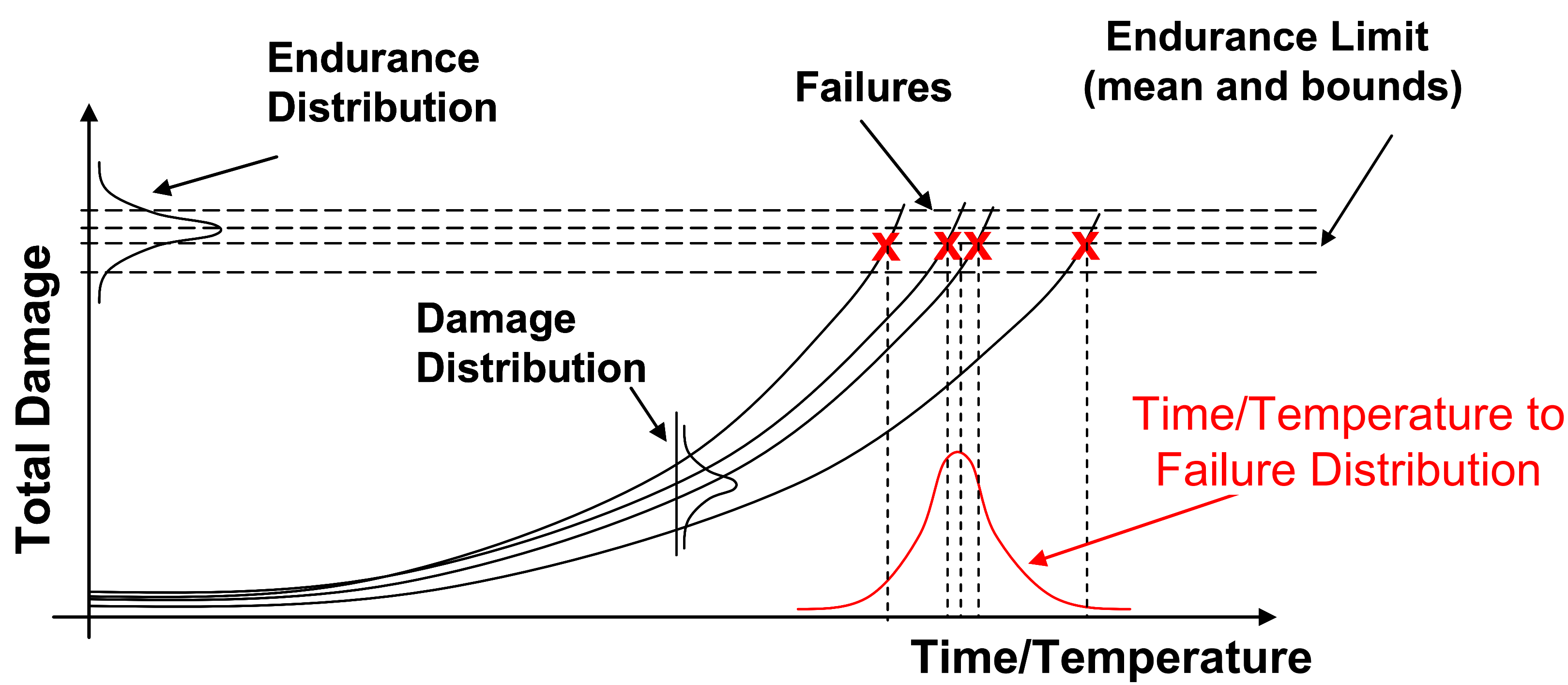
### INSULATION RESISTANCE

$$IR = C_1 . e^{-(C_2 T_k)} . \log\left(\frac{D_{out}}{D_{in}}\right)$$

$D_{0ut}$ = outer diameter of the insulation (m)
$D_{in}$ = inside diameter of the insulation (m)
$C_1$ and $C_2$ constant for a given material.

For most modern cable insulation materials, insulation resistance drops exponentially with increasing temperature

PROPOSED MODELS



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## DATA SOURCES

*NUREG/CR-5546, SAND 90-0696.*
*Investigation of the Effects of Thermal Aging on the fire Damageability of Electric Cables.*

NUREG/CR 6776, SAND 2002 - 0447P.
*Cable Insulation Resistance Measurements made during Cable Fire Tests.*

*EPRI 1003326.*
*Characterization of Fire-Induced Circuit Faults: Results of Cable Fire Testing .*

*Cable Response to Live Fire (CAROLFIRE).*
*A combined test effort involving representatives of RES, SNL, NIST, and UMD.*

# HEAT TRANSFER MODEL: ENDURANCE LIMIT

| CAROLFIRE | PVC | XLPE | EPR | PE | TEFZEL (1) | EP (1) |
|---|---|---|---|---|---|---|
| Mean (°k) | 4.93E+02 | 6.66E+02 | 6.92E+02 | 5.23E+02 | NA | NA |
| Standard Deviation | 1.97E+01 | 3.33E+01 | 1.44E+01 | 1.05E+01 | NA | NA |

| NUREG | PVC (1) | XLPE | EPR | PE (1) | TEFZEL | EP (2) |
|---|---|---|---|---|---|---|
| Mean (°k) | NA | 6.58E+02 | 7.23E+02 | NA | 4.59E+02 | 6.51E+02 |
| Standard Deviation | NA | 3.02E+01 | 3.84E+01 | NA | 2.48E+01 | 3.45E+00 |

| EPRI | PVC | XLPE | EPR | PE | TEFZEL | EP (1) |
|---|---|---|---|---|---|---|
| Mean (°k) | 4.56E+02 | 6.72E+02 | 7.04E+02 | 4.52E+02 | 5.00E+02 | NA |
| Standard Deviation | 3.18E+01 | 4.26E+01 | 5.50E+01 | 4.08E+01 | 4.61E+01 | NA |

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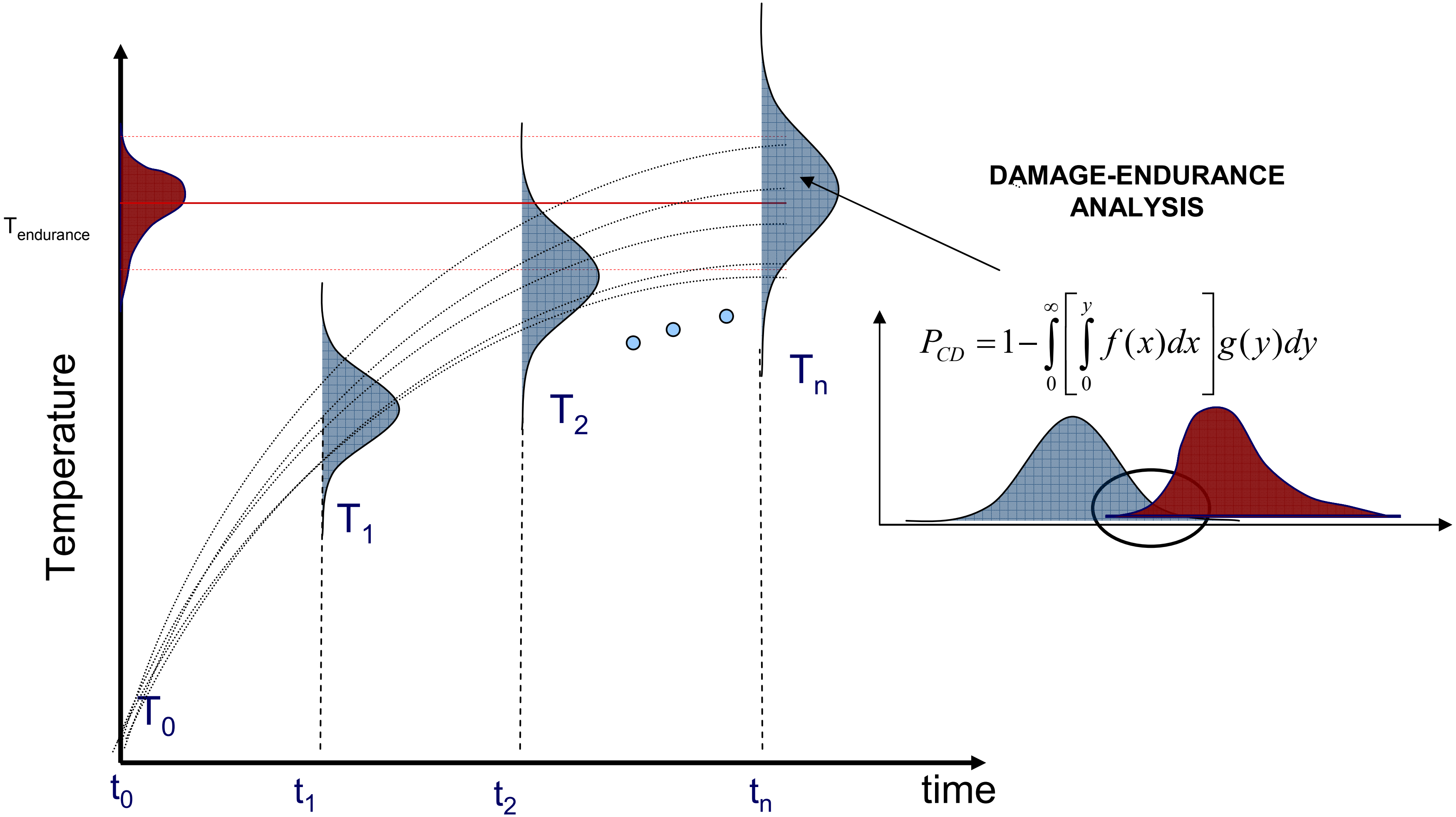
## DAMAGE ENDURANCE MODEL

**HEAT TRANSFER MODEL** $$\frac{T - T_0}{T_u - T_0} = 1 - C_1 . e^{-\left[\left(\zeta_1^2 F_o\right) J_o\left(\zeta_1 r\right)\right]}$$

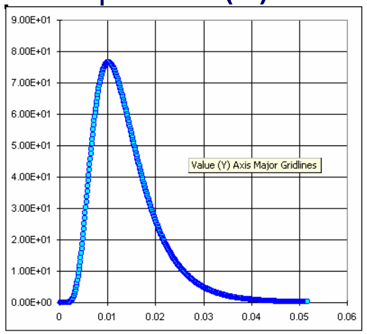



$$P_{CD} = 1 - \int_0^{\infty} \left[ \int_0^{y} f(x)dx \right] g(y)dy$$

## DAMAGE ENDURANCE MODEL

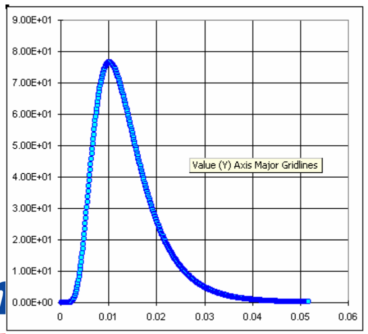
## ‘K FACTOR’ MODEL

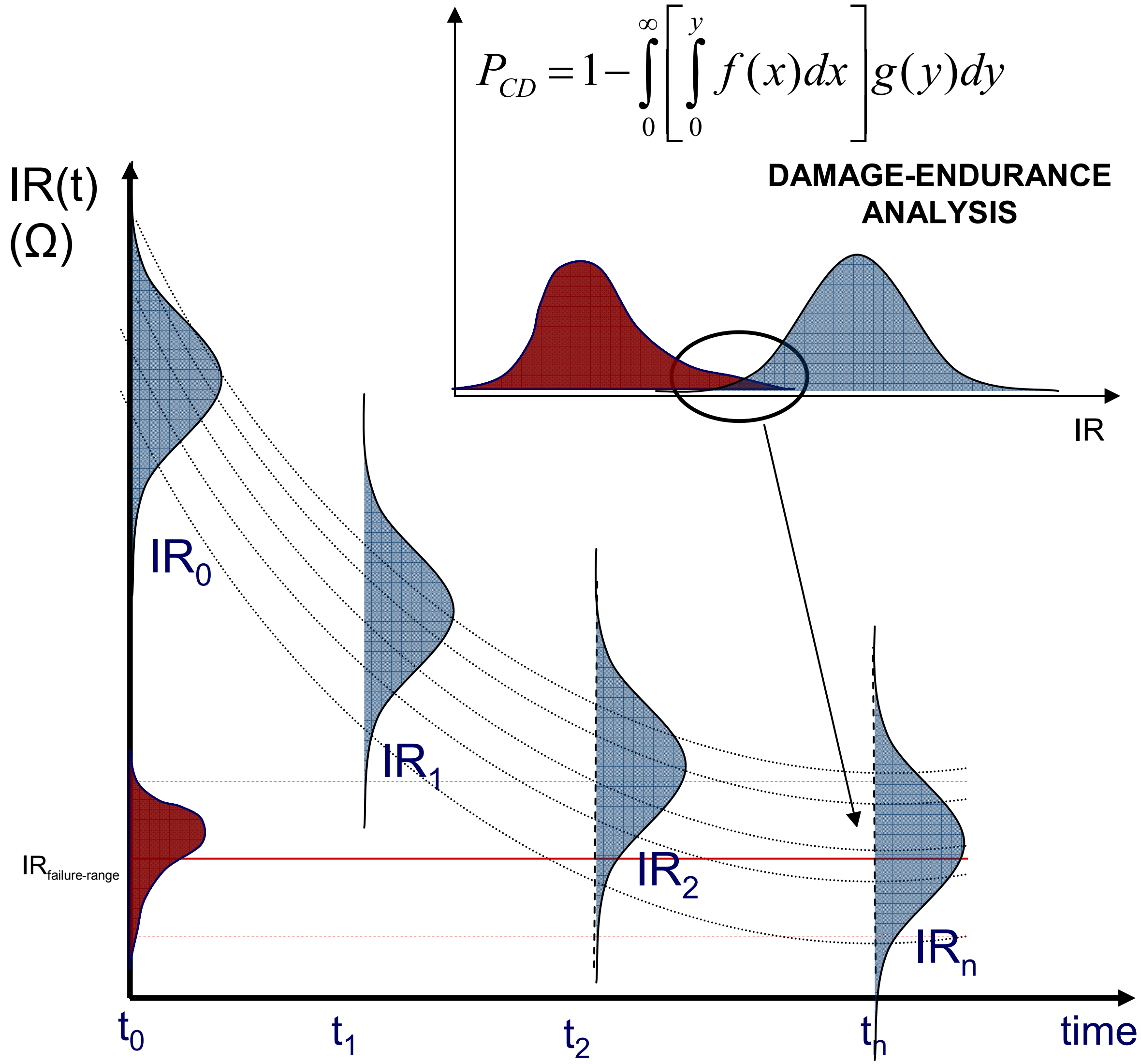
**$C_1$ Factor (Ω)**




$$IR = C_1 \cdot e^{-(C_2 T_k)} \cdot \ln\left(\frac{D_{out}}{D_{in}}\right)$$

**$C_2$ Factor (°K$^{-1}$)**



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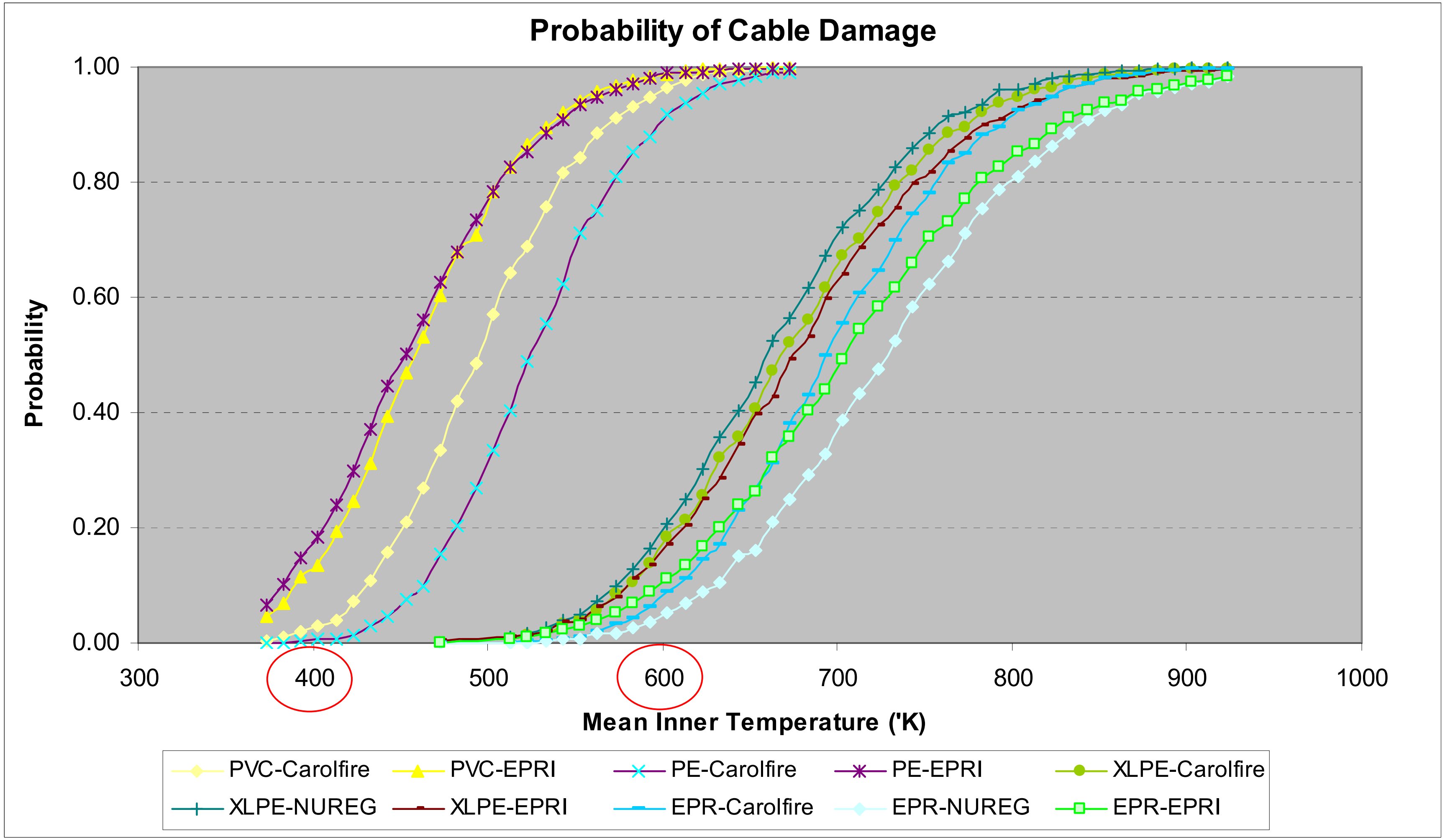
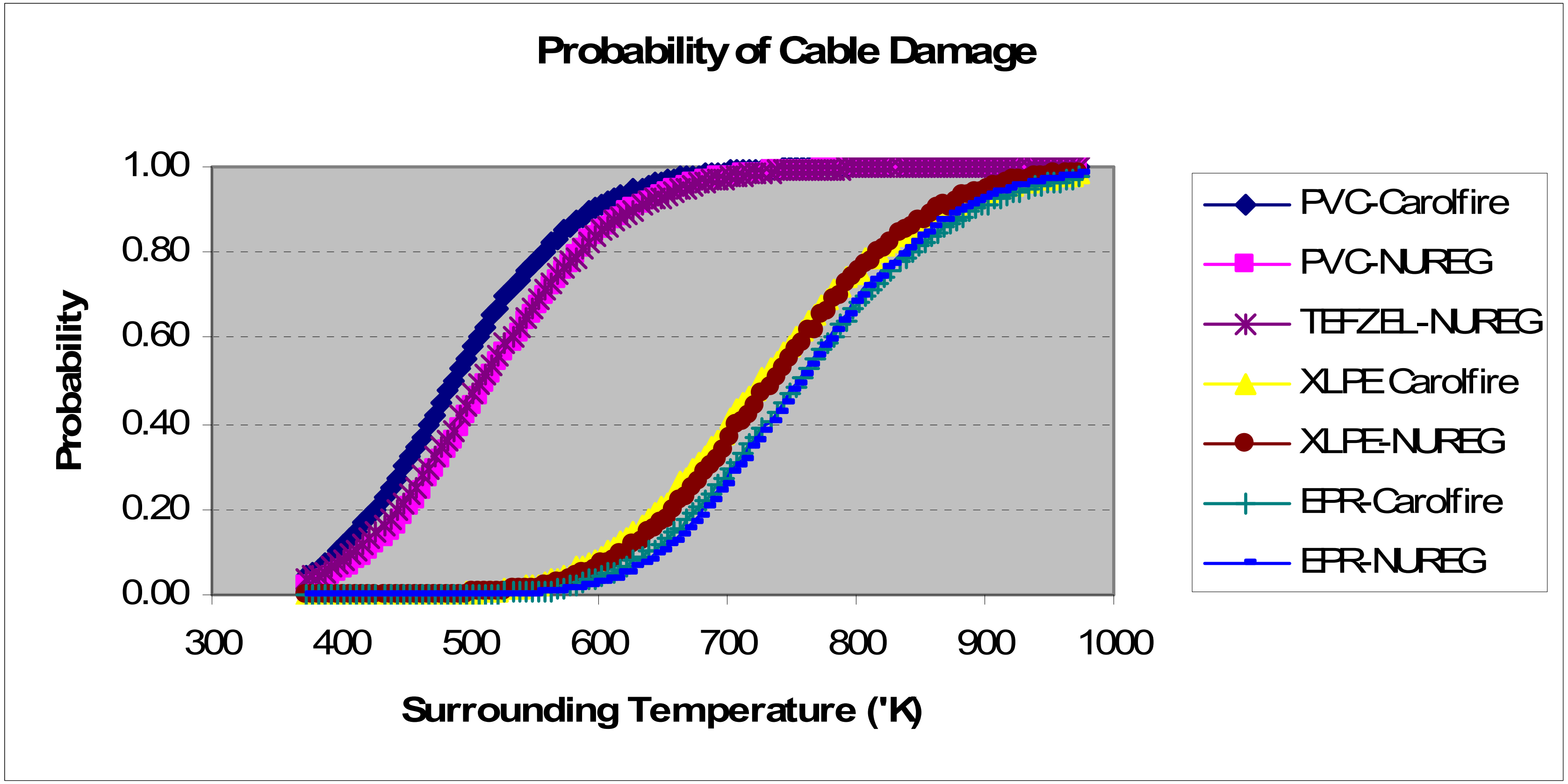
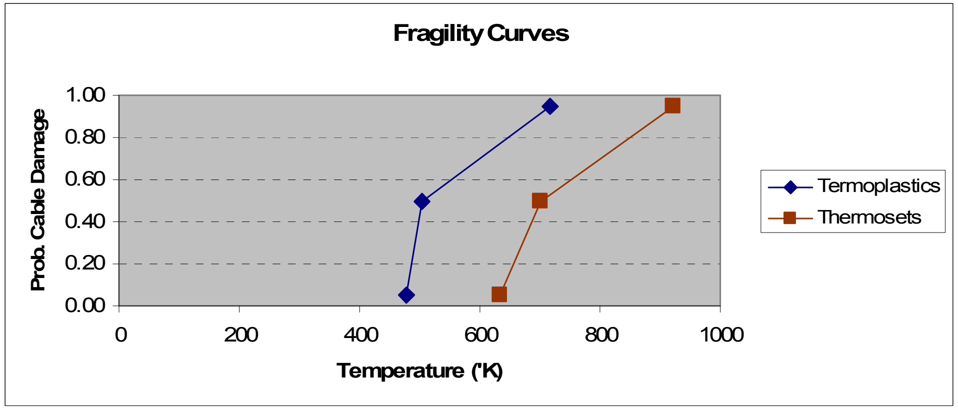
# HEAT TRANSFER MODEL:



## “K FACTOR” MODEL :



# FRAGILITY CURVES:




**Thermoplastics:**

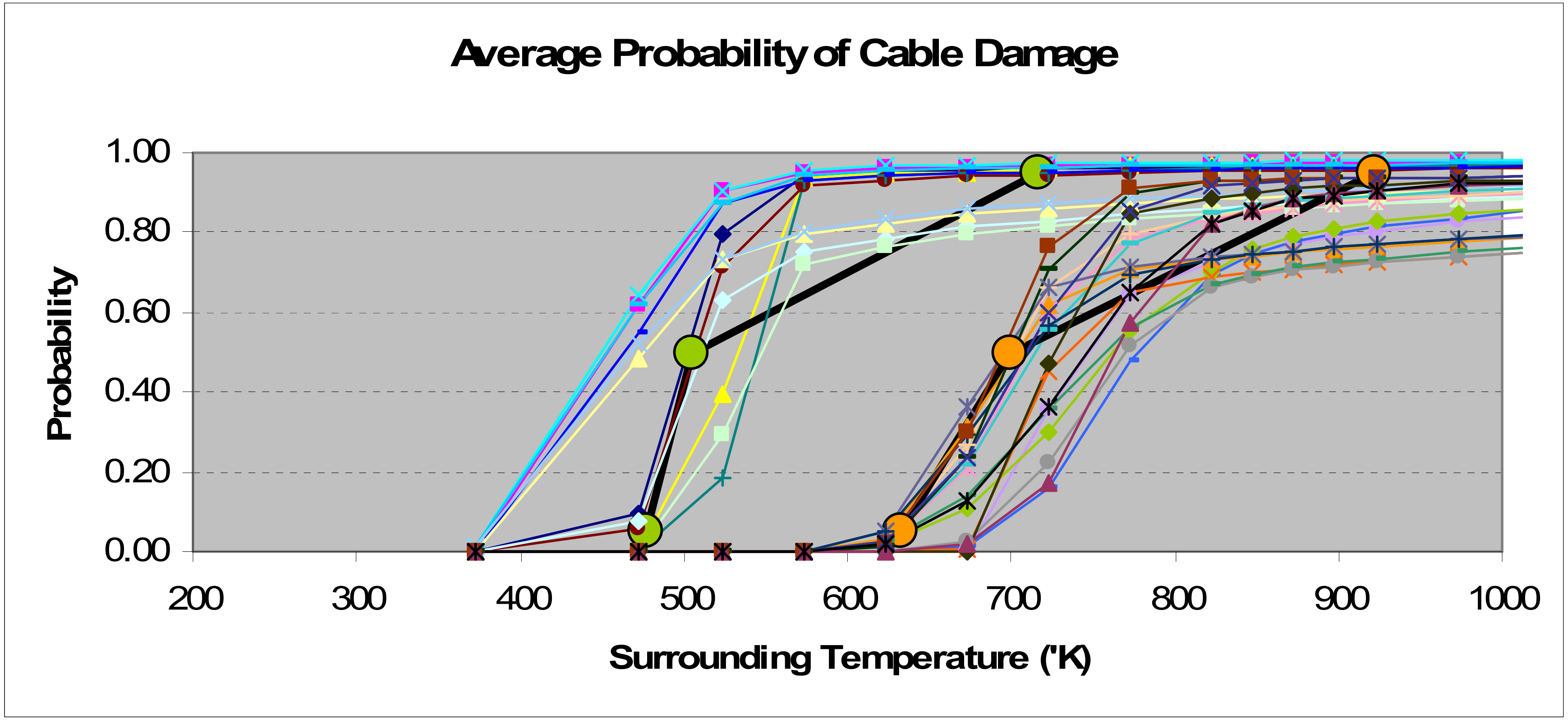
| | |
|---|---|
| Temperature below which essentially no failure occurs | 477 °K (204 °C) |
| Median or best estimate point | 505 °K (232 °C) |
| Temperature at which activity will almost surely occur | 700 °K (427 °C) |

**Thermosets:**

| | |
|---|---|
| Temperature below which essentially no failure occurs | 633 °K (360 °C) |
| Median or best estimate point | 700 °K (427 °C) |
| Temperature at which activity will almost surely occur | 922 °K (649 °C) |

Nuclear Energy Institute. (2002). Guidance for Post-fire Safe Shutdown Analysis. Washington DC. NEI 00-01 2002.
Electrical Power Research Institute (2002). Spurious Actuation of Electrical Circuits Due to Cable Fires: Results of an Expert Elicitation. California, EPRI 1006961.

# FRAGILITY CURVES vs. HEAT TRANSFER MODEL



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## CONCLUSIONS AND RECOMENDATIONS

- The estimation of fire-induced cable damage likelihood has been addressed through two different models: the heat transfer and the IR “K Factor” model.

  * Endurance damage approach
  * Comparison of inner cable temperature and IR to the endurance limit

- The physics-based HTM is a model capable of predicting the probability of cable damage under different thermal conditions.

  * Enrich existing databases
  * Develop HTM for complex cable arrangements
  * Develop thermal properties database

- The IR “K factor” model is an empirical model that is simple to apply, but does not consider the dynamic of the thermal insult.

- Validate the models proposed for fire conditions out of the scenarios described in the fire testing programs utilized in this research.

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# QUESTIONS?

# THANKS