ABSTRACT

Title of Document: PROBABILISTIC MODELS TO ESTIMATE FIRE-INDUCED CABLE DAMAGE AT NUCLEAR POWER PLANTS

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Even though numerous PRAs have shown that fire can be a major contributor to nuclear power plant risk, there are some specific areas of knowledge related to this issue, such as the prediction of fire-induced damage to electrical cables and circuits, and their potential effects in the safety of the nuclear power plant, that still constitute a practical enigma, particularly for the lack of approaches/models to perform consistent and objective assessments.

This report contains a discussion of three different models to estimate fire-induced cable damage likelihood given a specified fire profile: the kinetic, the heat transfer and the IR “K Factor” model. These models not only are based on statistical analysis of data available in the open literature, but to the greatest extent possible they use physics based principles to describe the underlying mechanism of failures that take place among the electrical cables upon heating due to external fires.

The characterization of cable damage, and consequently the loss of functionality of electrical cables in fire is a complex phenomenon that depends on a variety of

intrinsic factors such as cable materials and dimensions, and extrinsic factors such as electrical and mechanical loads on the cables, heat flux severity, and exposure time. Some of these factors are difficult to estimate even in a well-characterized fire, not only for the variability related to the unknown material composition and physical arrangements, but also for the lack of objective frameworks and theoretical models to study the behavior of polymeric wire cable insulation under dynamic external thermal insults.

The results of this research will 1) help to develop a consistent framework to predict fire-induced cable failure modes likelihood, and 2) develop some guidance to evaluate and/or reduce the risk associated with these failure modes in existing and new power plant facilities.

Among the models evaluated, the physics-based heat transfer model takes into account the properties and characteristics of the cables and cable materials, and the characteristics of the thermal insult. This model can be used to estimate the probability of cable damage under different thermal conditions.

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

By

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Dedication

To my wife Xiomara, and my daughters Génesis and Gineth.

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I would like to express my deepest appreciation to Dr. Mohammad Modarres for his encouragement, guidance and advice in the development of this work, as well as the valuable comments of Dr. Richard Baratta and Dr. Francisco Joglar.

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I am especially thankful to God, for giving me strength and wisdom.

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List of Acronyms

AWG:	American Wire Gauge.
Carolfire:	Cable Response to Live Fire.
CDF:	Core Damage Frequency.
CPT:	Control Power Transformer.
EPR:	Ethylene-Propylene Rubber
EPRI:	Electrical Power Research Institute.
HF:	Heat Flux.
HRR:	Heat Release Rate.
IR:	Insulation Resistance.
IRMS:	Insulation Resistance Measurement System.
NEA:	Nuclear Energy Agency.
NEI:	Nuclear Energy Institute.
NIST:	National Institute of Standard and Technology.
NPP:	Nuclear Power Plant.
PE:	Polyethylene.
PET:	Poly(ethylene terephthalate).
PRA:	Probabilistic Risk Assessment.
PS:	Polystyrene.
PTFE:	PolyTetraFluoroEthylene.
PVC:	Poly-vinyl Chloride.
SNL:	Sandia National Laboratories.
TP:	Thermoplastic.
TS:	Thermosets.
UMd:	University of Maryland.
USNRC:	United States Nuclear Regulatory Commission.
XLPE:	Cross-linked Polyethylene.
XLPO:	Cross-linked Polyolefin.

1. Introduction

In the last two decades the commercial nuclear power industry and regulatory organizations have been conducting research to gain better understanding of the types and relative likelihood of certain fire-induced failure modes of electrical circuits, particularly those leading to spurious operation of equipment. However, the characterization of the fire-induced failure process on cables and electrical circuits has not been solved due primarily to the lack of approaches/models to perform consistent and objective assessments, definitive test data, solid technical information and documented circuit behavior during real large fires (La Chance, Nowlen and Wyant, 1999; NEA, 2000; EPRI, 2002; Wyant and Nowlen, 2002).

To overcome some of these issues, industry and regulatory organizations undertook a fire test program (as part of their Fire-Induced Circuit Failure initiative) to obtain quantifiable data regarding circuit behavior during a fire, including the key factors related to certain specific failure modes (Wyant and Nowlen, 2002). During the last ten years, different experimental tests have been carried out, and some of them have provided valuable insights into the issues of concern (EPRI, 2002; Wyant and Nowlen, 2002; Nowlen and Wyant, 2007).

From all possible fire-induced electrical cable failure modes, the ones of greatest interest are those that produce conductor to conductor shorting such that certain equipment may be spuriously energized (or de-energized) through erroneous conduction paths.

Up to now, industry and regulatory organizations have expended significant effort to develop and perform fire tests. Analyses of these tests have improved our understanding of fire-induced cable failure modes. Some test data analyses performed have contributed to increase our knowledge of cable failure behavior upon fire, and particularly to identify primary influence factors to key circuit failure modes.

As part of the progress achieved, a comprehensive program undertaken by EPRI led to the formulation of probabilities of fire-induced cable damage. These probabilities were addressed through an expert elicitation process and defined in terms of the surrounding temperature (EPRI, 2002). However, in real fire scenarios the probability of cable damage (P_{CD}) is not a function solely of the peak temperature reached by the cable.

In the modeling arena, the effort has been devoted to develop data-based models to estimate the likelihood of fired-induced cable/circuit failure modes without characterizing the underlying causalities and mechanisms of failures that take place among the electrical cables exposed to external fires.

The purpose of this work is to develop probabilistic models to estimate fire-induced cable damage likelihood given a specified fire profile. The proposed models not only are based on statistical analysis of the existing data in the open literature, but to the greatest extent possible they use physics-based principles to describe the underlying mechanisms of failures that take place within or among the electrical cables upon heating due to external fires.

The role of fire-induced cable damage on fire probabilistic risk assessment (PRA) and a description of how the fire-induced cable damage likelihood can ultimately affect the safety performance of a nuclear power plant are presented in chapter 2. Chapter 3 describes the scope and the different steps of the research. Chapter 4 explains the physics-based models selected, while Chapter 5 explains the data gathering process. The estimation of damage-endurance threshold levels (endurance limits) for thermoplastic and thermosets insulated cables is presented in Chapter 6. Chapter 7 explains the damage-endurance models. Chapter 8 discusses important results based on numerical examples and possible extensions of the models developed and used. Finally, Chapter 9 presents concluding remarks and offers recommendations for further research and development.

2. Overview of Fire PRA and the Role of Fire-Induced Cable Damage

Even though numerous fire probabilistic risk assessments (PRAs) have shown that fire can be a major contributor to nuclear power plant risk, there are some specific areas of knowledge related to this issue that still constitute a practical enigma, particularly due to the lack of accepted approaches/models to perform consistent and objective assessments. Among these areas, one that, for more than a decade, has attracted the attention of specialists and regulators is the prediction of fire-induced damage to electrical cables and circuits, and their potential effects on the safety of the nuclear power plant (NEA, 2000; Siu, 2000; Bertrand, 2002).

In this research, the issue related to the prediction of fire-induced damage to electrical cable is addressed.

In general terms, the framework of fire PRAs for nuclear power plants relies on the estimation of the core damage frequency (CDF). Traditionally the CDF has been estimated as:

$$CDF = \sum_{i} \lambda_i \sum p_{ed,j|i} \sum_{k} p_{CD,k|i,j} \tag{1}$$

Where λ_i is the frequency of fire scenario i, $p_{ed,j|i}$ is the conditional probability of damage to critical equipment set j given the occurrence of fire scenario i, and $p_{CD,k|i,j}$ is the conditional probability of core damage due to plant response scenario k given fire scenario i and damage to critical equipment set j (NEA, 2000). As inferred from the above expression, when an initiating event such as a fire takes place it will not necessarily lead to core damage. The initiating event will lead to core damage if some combination of equipment failure and human error occurs.

Given a fire scenario in a nuclear power plant, the conditional probability of damage to key equipment ($p_{ed,j|i}$), and in our particular case, to key electrical cables needs to be determined. In this estimate a variety of elements are considered, among them the cable response to the thermal stress, the characteristics and pattern of the fire, and the response time to detect, mitigate and/or suppress the fire before reaching the minimum target damage time. (NEA, 2000; Bertrand, 2002).

In most of the current PRAs, it is assumed that electrical cables get damaged when they are exposed to a threshold temperature and/or heat flux for at least a minimum period of time (damage time). Once this threshold thermal insult is reached in any of the potential scenarios evaluated as part of a PRA, the probability of such scenarios need to be determined.

In the case of interest, the target damage time is compared to the duration of a specific fire scenario. The conditional probability of damage to the "critical cable" is equal to the probability of that fire scenario if the damage time is less than the duration of the fire scenario (see Figure 1).

If all conditions required to produce cable damage have been met and cables reach certain level of damage (e.g. capable of developing a particular failure mode such as a maintained conductor-to-conductor shorting), a characterization of potential cable behaviors should be addressed, and all the possible modes of cable conductor failure should be identified. A further step would be to evaluate the effects of these identified failure modes in the performance of the safety shutdown systems and equipment, and how these effects can ultimately lead or contribute to core damage probability ($p_{CD,k|I,j}$) (La Chance, 2003).

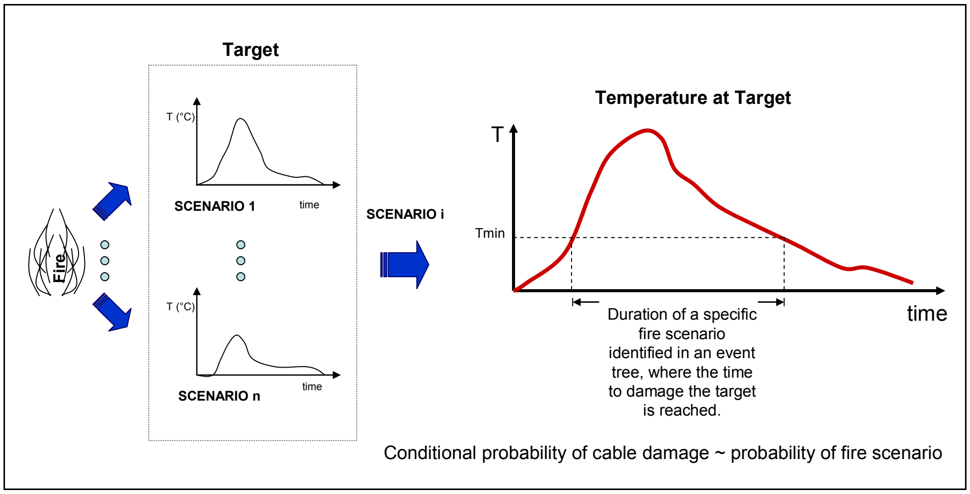


Figure 1. Target Damage Time

The critical issue associated with fire-induced cable damage in nuclear power plants, and generally speaking in high risk process industries is based on the fact that it could cause spurious actuation of equipment whose operation could affect safe shutdown (NEI, 2002).

According to EPRI (2002), the change in the CDF originated by the spurious actuation of an electrical circuit can be estimated through the following expression:

$$\Delta CDF = \lambda_i \,.\, P_E \,.\, P_{AS} \,.\, P_{DM} \,.\, P_{SA} \,.\, P_{CCD} \tag{2}$$

where:

- λ_i: frequency of fires (per reactor year).
- P_E: fire size parameter; fraction of fires in the area capable of reaching damaging exposures.
- P_{AS}: probability of failure on demand of automatic suppression.
- P_{DM}: probability of failure on demand of the detection and manual suppression systems.
- P_{SA}: probability of spurious operation of one or more circuit components for a specific fire exposure.
- P_{CCD}: conditional core damage probability given fire-induced failures (including spurious actuations) of one or more components.

In this research we are developing models to estimate P_{SA} in equation (2).

The Guidance for Post-Fire Safe Shutdown Circuit Analysis (NEI, 2002) defines the probability of spurious actuation "P_{sa}" as the following product:

$$P_{SA} = P_{CD} * P_{SACD} \tag{3}$$

where:

P_{CD}: probability of cable damage given a specified fire profile.

P_{SACD}: probability of spurious operation given cable damage.

As such, the problem of estimating the probability of spurious actuation was broken down into two factors. The first factor defines the probability of cable damage to electrical cables given a specific fire profile exposure (specified set of time-temperature and fire severity condition); and the second is the conditional probability of spurious actuation given certain level of cable damage.

Few approaches have been proposed to estimate P_{CD} and $P_{SACD.}$ One of these is the procedure discussed by NEI (2002) and EPRI (2002). This procedure describes the use of fragility curves to estimate cable damage versus temperature for thermosets, thermoplastic and armored cables. The second factor of equation (3) (P_{SACD}), can be estimated using tables provided for different insulation materials and configurations. In addition, the probability of spurious actuation given the cable jacket/insulation has been damaged can be statistically estimated based on the number of combinations of actuating erroneous signals (NEA, 2000).

These approaches used the temperature around the target electrical cable as a key input parameter. This parameter can be estimated for a characterized fire with a given level of confidence using existing analytical methods (EPRI, 2002).

In this research, the probability of cable damage given a specified time-temperature profile due to external fire is determined using not only an statistical analysis of the data available in the open literature (probabilistically driven), but also to the extent possible, attempting to use physics-based models to describe the underlying mechanism of failures that take place within or among the electrical cables during the fire accident.

In this context, the level of cable damage of interest, defined in terms of polymeric insulation degradation, is a level capable of developing a maintained conductor-to-conductor shorting.

The characterization of cable damage, and consequently the loss of functional integrity of electrical cables in fire is a complex phenomenon that depends on a variety of intrinsic factors such as cable materials and dimensions, and extrinsic factors such as electrical and mechanical loads on the cables, heat flux severity, and exposure time (La Chance, Nowlen and Wyant, 1999; NEA, 2000; Bertrand, 2002). Some of these factors are difficult to estimate even in a well-characterized fire, not only for the variability related to the unknown material composition and physical arrangements, but also for the lack of objective frameworks and theoretical models to study the behavior of polymeric wire cable insulation under dynamic external thermal insults. This is pointed out in the results of an expert elicitation program undertaken by EPRI (2002):

> "*What actually happens in practice when a given fire damages a given cable or group of cables is not only highly dependent on the detailed layout and cable configuration, but also somewhat stochastic*".

Questions such as what temperature a polymeric cable insulation will fail at, which conductor shorts to other conductor, or shorts to ground, or goes to an open circuit state are dependent on the fire phenomenon itself, external factors such as physical cable configuration and arrangement, cable material composition, etc. (EPRI, 2002).

Some of these factors have been analyzed in the past. For instance, according to EPRI (2002), the differences observed in experiments with cable under plume and hot layer fire conditions are not significant. According to the results obtained, the only important parameter useful for the fire behavior standpoint is the actual temperature reached by the target cables.

Similarly, according to these results, cable tray fill and cable location within the tray are believed to be of secondary importance compared to the dominant role played by the temperature profile at the target cable (EPRI, 2002).

Once the cable reaches a given level of damage, the effect of the fire-induced cable failure on the operation and performance of an electrical circuit depends on the cable failure mode, circuit's specific design, operating parameters, cable geometry, etc. (EPRI, 2002); therefore, a characterization of potential circuit behaviors should be addressed, and the effects of these behaviors in the performance of the safety shutdown systems and equipments, and how they can lead to or contribute to core damage should be evaluated.

3. Objectives, Scope and Methodology

3.1. Objective

> *The objective of the 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 1) help to develop a consistent framework to estimate fire-induced cable failure modes likelihood, and 2) develop some guidance to evaluate and/or reduce the risk associated with these failure modes in existing and new power plant facilities.

The proposed models will help the nuclear industry and in general the process industry to address the following issues:

- Increase the knowledge and understanding of fire-induced circuit failure modes for typical nuclear power plant circuits and arrangements.
- Develop conditional probabilities for spurious actuation of devices in electrical circuits due to fire-induced damage to electrical cables.
- Estimate the probability that a fire-initiated transient could lead to catastrophic outcomes, such as core damage in a nuclear power plant.
- Identify and prioritize actions to be taken in order to achieve and maintain safe and stable shutdown operation under fire conditions.

3.2. Scope

This research addresses the following aspects:

- Develop probabilistic models to estimate fire-induced cable damage likelihood given a specified fire profile.

  The research is expected to lead to refined probabilistic models for estimating likelihood of fire-induced cable damage. The new models not only are based on probabilistic analysis of the data available, but also to the extent possible, on physics-based principles to describe the underlying mechanism of failures that take place within or among the electrical cables during the fire accident.

- Identify key factors related to cable damage given a specific fire profile.

  The key influencing factors related to fire-induced damage of electrical cables, and particularly with a level of damage capable of producing conductor to conductor shorting is addressed.

The general models to predict the fire-induced cable damage are customized for particular scenarios (given materials, thermal exposures, etc) in order to develop particular models depending on the nature of the cables involved.

In general this research encompasses the analysis of the behavior of electrical cable upon heating, particularly those designated as "Control Cables" (usually # 12 AWG and # 14 AWG). Electrical cables designated as "Instrument Cables" (14 AWG and smaller) or "Power Cables" (12 AWG or larger) are out of the scope of this research. However, the models proposed can be extended to evaluate these cables as well.

3.3. Methodology

The research involves the following steps:

- ✓ Selection of physics-based models.
- ✓ Data gathering.
- ✓ Degradation estimation: time-temperature profile.
- ✓ Damage-Endurance model development.
- ✓ Result analysis and validation.

The specific tasks associated with each step are:

3.3.1. Selection of Physics-Based Models

- ☐ Review the open literature to identify the different mechanisms of failures that take place during the degradation process of the polymeric covers of electrical cables under fire conditions.
- ☐ Prioritize and select the main mechanisms of failure that take place during the degradation process of the polymeric covers.
- ☐ Characterize the dynamic behavior of the degradation process.

3.3.2. Data Gathering

- ☐ Develop databases for assessing the statistical behavior of the parameters associated with the physics-based models selected to describe the dynamic degradation process under study.
- ☐ Characterize each parameter of the degradation models selected through the development of appropriate probabilistic distributions, taking in consideration the nature and physics meaning of the parameter and the context-based dependencies.

3.3.3. Degradation Estimation: Time-Temperature Profile

- ☐ Estimate the degradation level of polymeric covers of typical electrical cables traditionally used in nuclear power plants at failure instances as a function of a given time-temperature profile.
- ☐ Develop databases for assessing the degradation level of polymeric covers of electrical cables involved in the different scenarios/applications to be analyzed.

3.3.4. Damage-Endurance Model Development

- ☐ Develop damage-endurance models for each scenario/application to be analyzed, through which the probability of cable damage capable of producing conductor to conductor shorting can be addressed.

- Estimate the probability of fire-induced cable damage, given a particular time-temperature profile, for electrical cables traditionally used in nuclear power plants.

3.3.5. Results Analysis and Validation

- Use the probabilistic models developed to simulate particular scenarios, and compare the results with the experimental data derived from the fire tests programs conducted by industry and regulatory agencies.
- Identify key factors in the fire-induced cable damage process.

4. Selection of Physics-Based Models

The first and probably simplest model used to predict fire-induced cable damage and consequently cable failure modes is a probabilistic model driven by the data available. The intention of this data-base model is to develop empirical relationships to determine the time to failure (*e.g.* time to short circuit) using the results of the numerous experimental tests performed by industry and regulators.

For every particular application (cable configuration, type of polymer insulation, some predefined fire characterizations, etc) the time to failure obtained experimentally can be collected, and a particular probability density function can be fitted to it.

For example, if we consider the scenario of two cables, one with a PVC polymeric insulation and the other with XLPE insulation, we can collect the time to failure obtained in each one of the experimental tests carried out and reported in the open literature.

Experiment No. 1:	time to failure: t_{11}, t_{12}, … t_{1m}
Experiment No. 2:	time to failure: t_{21}, t_{22}, … t_{2m}
	o
	o
	o
Experiment No. n:	time to failure: t_{n1}, t_{n2}, … t_{nm}

Based on the time to failure data set, a probability distribution can be assigned to each pair of cables involved in the scenario considered.

This model however has significant limitations. Specifically, it does not consider factors that have been identified as important in a thermal response of polymeric cable insulation, such as the characteristics of the external fire, its intensity, or its distance to the target cables, cable geometry, among others factors.

An alternative way to reduce the effect of this lack of context-dependent interrelation will be the characterization of the different plausible scenarios using some kind of qualitative framework where a reduced number of scenarios may be specified with a level of generality capable of describing any practical real fire in a nuclear power plant. However, given the diversity of potential scenarios, in addition to the variability of the thermal degradation process itself, it would be difficult to identify this reduced number of scenarios.

In order to develop a model that is not only statistically driven by data available, but also takes into consideration the mechanism of failures taking place within or among electrical cables upon heating, it is necessary to start analyzing what occurs when a given fire affects a bundle of electrical cables (see Figure 2).

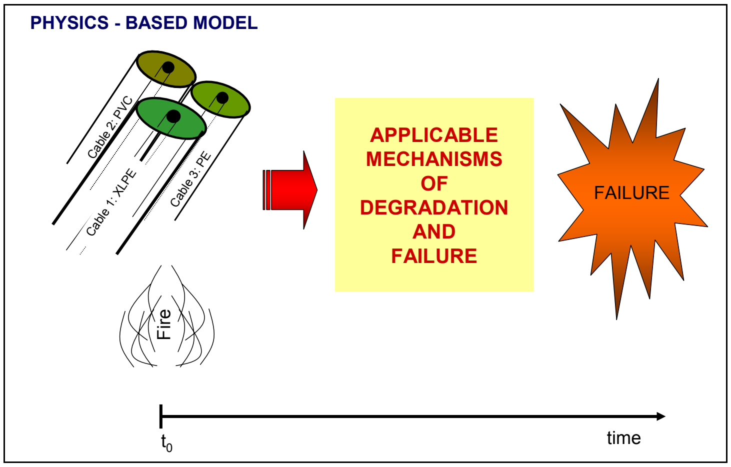


Figure 2. Physic-Based Model

As shown in Figure 2, when a cable is exposed to an external thermal insult, certain mechanisms of failure are activated and progressively the polymeric cable insulation degrades. Eventually the cable can reach a degradation level where a failure is imminent.

Figure 3 shows some of the mechanisms of failures that might take place when polymeric wire/cable insulation is exposed to external heating (*e.g.* fire). Among them are dielectric breakdown, arcing across a carbonized path, void growth, progressive deformation (creep of insulation), and physical-chemical degradation (Babrauskas, 2005).

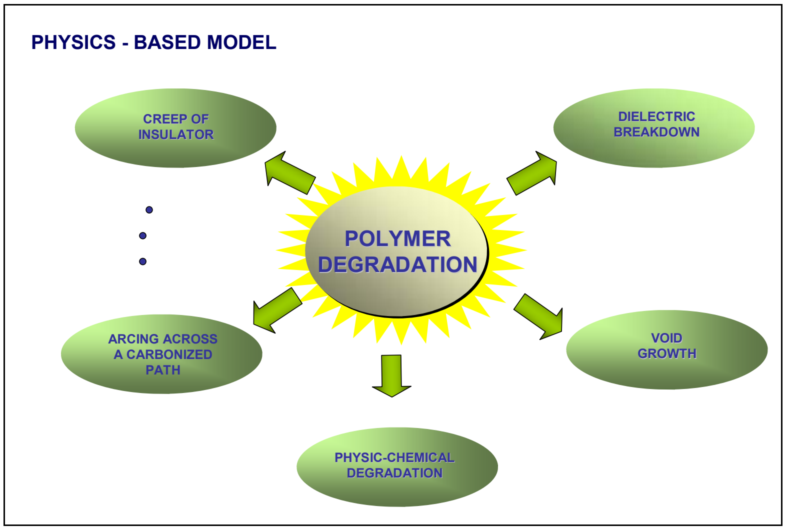


Figure 3. Polymeric Mechanisms of Failure upon Heating

Upon the absorption of thermal energy, the polymeric insulation suffers changes in two interrelated categories (see Figure 4), microscopic changes such as tree growth, void formation, crack, and molecular degradation that change the chemical nature of the polymer molecules (*e.g.* dehydrochlorination) (Wolter, Johnson and Tanaka, 1983).

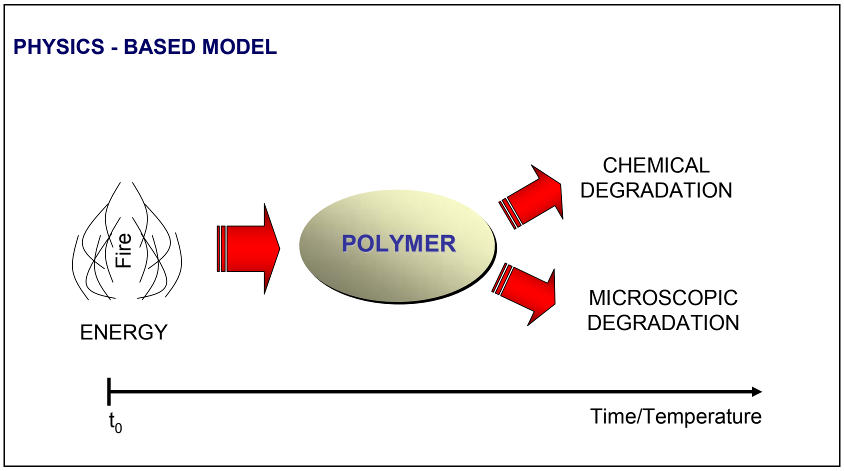


Figure 4. Polymeric Degradation

4.1. Microscopic Changes

Dielectric breakdown is defined as the voltage required for an insulator to break down. It is a function of the insulator's thickness. Values reported for wire-insulation PVC formulations are typically 600 – 900 V/mil (24 – 36 MV/m) (Babrauskas, 2005).

The breakdown phenomenon for different polymeric material has been investigated, and some mathematical models have been proposed to characterize the breakdown voltage in terms of the thickness and other properties of the insulation materials (Masayuki, 1980; Abed, 1982).

Even though thickness effects have not been extensively explored for solid insulators, preliminary results have shown that dielectric breakdown values depend on the voltage waveform applied. For instance, breakdown strength of PVC under *dc* conditions tends to be twice than at 60 Hz (Babrauskas, 2005).

Evidence found in open literature reveals that plastics show a relation where the breakdown voltage scales with the square root of thickness. Polyethylene follows a linear law for *dc*, but a square root law for *ac*. In the case of PVC, some experiments have revealed a linear behavior; other studies have shown a square root behavior. However, breakdown behavior at very small thicknesses (≤ 0.1 mm) has not been reported (Babrauskas, 2005).

For the majority of the conventional polymeric materials used in the commercial cable industry, the electrical breakdown strength is on the order of tens of KV/mm, which leads to a very low likelihood of having this particular phenomenon in a conventional nuclear power plant application. However, during a fire, the cable polymeric material is exposed to a thermal insult that among other effects changes the properties of the polymeric material, promoting in some cases the breakdown phenomenon. An important aspect highlighted for the majority of the studies conducted on breakdown theories suggest that the dielectric breakdown of solids normally occurs when changes in the molecular structure take place that ultimately change its conductivity properties.

On the other hand, a relatively high voltage is required to break PVC cable insulation, but the presence of manufacturing defect sites and the reduction of breakdown stress due to elevated temperatures can create the appropriate conditions for breakdown at very low voltage conditions. Additionally, when polymeric cable insulation is heated, the residual products of the thermal degradation can create a carbonized path through which the probability of voltage breakdown can increase (Babrauskas, 2005).

Eventually an arc discharge may occur along a carbonized path between two electrical conductors. The voltage required to create an electrical arc via this pathway is much lower than the voltage required for simple breakdown in air between two electrodes. In fact, some studies have shown that voltage around 600 VAC is sufficient to cause an arc discharge across electrical conductors. Some other experiments have shown that under specific conditions, much less than 24 V is sufficient to cause arc tracking (Babrauskas, 2003).

These carbonized paths become conductive pathways for arcs and electrical leakage discharges. During the arc generating process, temperatures up to 1000 °C can be generated, which promote the process of polymer carbonization. Due to these high temperatures, portion of the conductors may melt since the temperature of an electric arc could exceed the melting temperature of copper (1085 °C) or aluminum (660 °C). Under this arc tracking process a metal to metal contact (short circuits) can occur (Babrauskas, 2003).

The temperature at which the carbonization of polymer takes place varies according to the polymer being considered, but it could be surprisingly low; for instance, Japanese studies showed that for PVC, a short term exposure at about 160 °C is sufficient (Babrauskas, 2005).

The arcing propensity, and consequently the dynamics of the electrical mechanism of failure depend on factors including the molecular structure of the polymer among others. As pointed out by Babrauskas et al. (2005), in general the arc tracking phenomenon is more likely in those polymer that char (aliphatic polymers: PE, PTFE, etc). If the degradation product is gaseous rather than a char, a conductive track cannot be established (PS, PET, etc).

Regarding the void growth phenomenon, some studies have estimated the remaining life of electrical cables in power plant applications based on this mechanism of failure. The theory behind these studies assumes that voids will grow and the void density will increase as a function of absorbed energy.

As was noted previously, when a polymer is exposed to an external thermal insult, various gases are produced that can create new void sites and/or accumulate in nearby voids contributing to a progressive increment of void size and density. Eventually a threshold level can be reached at which partial discharge and/or voltage breakdown between nearby conductors can take place. This mechanism is also promoted by the capacitive effects created by the ionization of the gases trapped in the voids, which ultimately reduce the effective thickness of the polymeric insulation.

Some of the studies concerning void growth assume that the gaseous production rate will increase linearly as a function of temperature (Horvath, Wood and Wylie, 2000**.** This approach of void growth in combination with acoustic microscopy analysis has been proposed to determine electrical insulation life, but bibliographic references in this area are scarce in the open literature.

Other plausible causes of cable failure is the continuous deformation (creep) of the polymeric cable insulation imposed by significant mechanical load, which under the presence of pinch sites, can ultimately reduce the polymeric thickness to a point of imminent failure, particularly under the effect of an external thermal insult. However, studies in this matter and the characterization of major creep degradation in commercial wire cable insulation have not been found (Babrauskas, 2003).

4.2. Chemical Degradation

When a polymer is exposed to an external source of heat, it decomposes, releasing among other components, combustible gases, non-combustible gases and eventually solid charred residue.

It is important to clarify that the term thermal/chemical degradation of polymer refers to the process of thermal degradation in service as opposed to thermal degradation during polymer processing.

Studies have shown that the dynamic behavior of polymer thermal degradation depends not only on the chemical composition of polymers involved, but also on the heating rate, as well as the atmosphere in which the degradation process takes place (Shlensky, Akseno and Shashkov, 1991). In the presence of oxygen (thermo oxidative degradation), the polymer degradation process is more complex than a simple pyrolysis; because not only must the thermal degradation be considered, but also the oxidation of polyenes (Budrugeac, 2001).

The thermal behaviors of different polymers have been studied, and most particularly the polyvinyl chloride (PVC). Even though some studies have revealed that PVC pyrolysis involves a three stage process (Miranda, 1999), most have concluded that thermal degradation of PVC and some others solid polymeric involves a two stage decomposition process. The first stage is mainly a dehydrochlorination process resulting in the formation of hydrogen chloride (molecules of HCl are released), and the second step is a further cracking process of the residues that involves subsequent thermal degradation reactions, which largely depend on the chemical structure of the polymer (Heiberger and Nass, 1985; Shibai, Jun Lu and Jinseng, 2004).

Thermal degradation of PVC takes place when the temperature reaches a point at which its chemical structure breaks down, releasing hydrogen chloride. According to Babrauskas et al. (2005), the dehydrochlorination starts in the range of 90 °C - 180 °C; however, some other investigators suggest temperatures as higher as 240 °C, even 360 °C. The second stage takes place over a temperature range of about 350 °C - 500 °C. At temperatures above 350 °C, structural degradation of the backbone occurs, ultimately leading to a residual char. At the end of the degradation process, a cross linked, charred residue remains (Heiberger and Nass, 1985; Miranda, 1999; Babrauskas, 2005).

The first stage accounts for approximately 60% of the weight loss of the polymeric resin. The weight loss corresponds to the evolution of HCl and small amounts of benzene (Shibai, Jun Lu and Jinsheng, 2004). About 90% of chloride contained in PVC becomes gaseous HCl. As outline by Shibai, Jun Lu, and Jinsheng (2004) the C-Cl bond in the PVC structure has lower bond energy than other bonds in its structure; therefore, upon heating it will break first.

It is important to mention that the dehydrochlorination that takes place during the thermal degradation of polymer is an autocatalytic mechanism. For that reason in the PVC formulation for wire/cable insulation C_aCO_3 or similar filler is used to break the autocatalytic process.

During the polymer pyrolysis, a variety of decomposition products are generated (gas, tar, etc). Whether the decomposition steps occur sequentially, simultaneously or in some particular pattern is still a point of controversy. However, in general terms a simple model that shows reasonable agreement with thermal analysis data, numerical models of fire behavior, and experimental data is:

Polymer Solid "P" ↔ *Reactive Intermediate* ↔ *Fuel Gases, Char*

An understanding of polymeric wire/cable insulation degradation will lead to a more refined model to estimate the likelihood of fire-induced cable damage, and cable failure modes, and ultimately help to develop guidance to evaluate and/or reduce the risk associated with these failure modes in existing and new facilities.

In the following sections two different models are proposed to estimate the likelihood of fire-induced cable damage; the first one based on kinetic equations in which the rate of thermal decomposition is addressed, and the second model based on a heat transfer model. In addition to these physics-based oriented models, an empirical model refers to as IR "K factor" model is also described.

4.3. Kinetic Model

Studies on polymer pyrolysis have been performed by some researchers to investigate the structural changes during their thermal decomposition, and also to identify the reactions involved during the thermal degradation process. As the result of these studies the rate of weight loss during each reaction have been determined (Miranda, 1999), and some kinetic relationships have been proposed to characterize the heat-induced decomposition process as shown in Figure 5 (Wu, 1994).

Theoretical analyses of kinetic data obtained under increasing temperature conditions reveal that the kinetic behavior of the polymer thermal degradation process is governed by equations that follow the following relation:

$$rate\ of\ reaction = \frac{d\alpha}{dt} = Af(\alpha)\,e^{-\frac{E}{RT}} \tag{4}$$

where:

$\alpha(t)$: fraction of reaction completed by time "t".

$f(\alpha)$: function of the particular mechanism involved in the reaction (ex. thermal-oxidative degradation).

A: frequency factor or pre-exponential factor of the Arrhenius model (s^{-1} or m^{-1}).

E: activation energy of the Arrhenius model (KJ/mol).

R: universal gas constant (8314 KJ/mol-°K).

T: absolute temperature in °K.

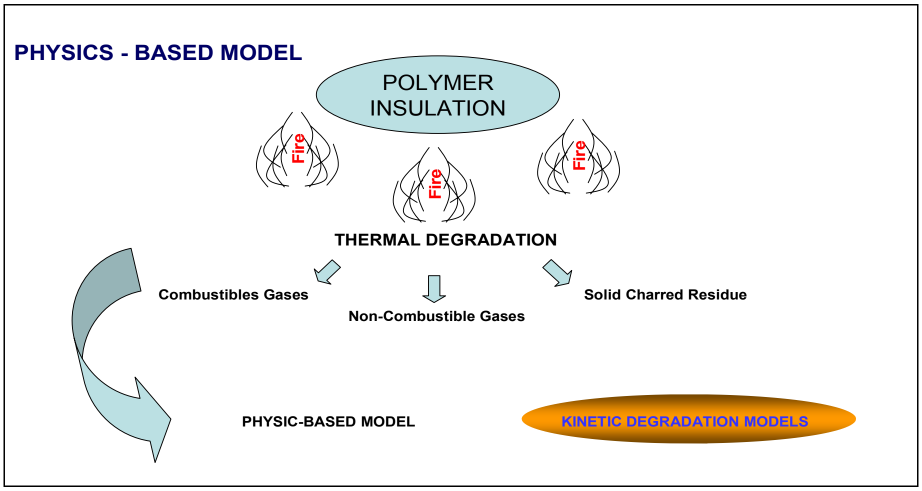


Figure 5. Polymeric Decomposition – Kinetic Model

The selection of $f(\alpha)$ depends on the specific reaction mechanisms on place. In some instances the existence of an autocatalytic mechanism, in which a product of the reaction catalyzes the reaction, can play an important role where a simple nth order reaction is not valid. In some other cases different autocatalytic reactions coexist, and consequently different activation energies and pre-exponential factors should be considered (Cheng, 2003). Alternatively, some studies have shown that the two main kinetic parameters, the activation energy "E" and the pre-exponential factor "A", vary as a function of temperature and extent of conversion (Shlensky and Shashkov, 1991; Ding, 2001; Chenyang, 2003); other studies have shown that these parameters are not independent, which imposes another level of complexity in the characterization of the thermal degradation process (Babrauskas, 2003).

Even though there is not a universal kinetic equation that consistently describes the dynamic behavior of polymer thermal degradation, some models traditionally used as $f(\alpha)$ to describe thermal degradation are (Montserrat, Malek, 1998):

$f(\alpha) = (1-\alpha)^n$ ………………………. (5a)

$f(\alpha) = m(1-\alpha)[-\ln(1-\alpha)]^{1-\frac{1}{m}}$ ……..… (5b)

$f(\alpha) = (1-\alpha)^n \alpha^m [-\ln(1-\alpha)]^p$ ………. (5c) It is often referred to as the Sestak-Berggren equation (Brown, 1997).

where: n, m and p are constants.

The parameter "n" defines the order kinetics. In most of the experimental studies carried out, polymer degradation process has been traditionally represented as first-order kinetics, which is generally true for most of the polymers (Gupta, 2002).

Using equation (5c):

$$\frac{d\alpha}{d\tau} = A e^{-\frac{E}{RT}} \{(1-\alpha)^n \alpha^m [-\ln(1-\alpha)]^p\} \qquad (6)$$

For non-isothermal conditions, T is a function of time; therefore: T = g(t). If a linear heating profile of the form: $T = T_0 + \beta t$ is assumed, equation (6) becomes:

$$\frac{d\alpha}{dt} = A e^{-\frac{E}{R(T_0+\beta t)}} \{(1-\alpha)^n \alpha^m [-\ln(1-\alpha)]^p\} \qquad (7)$$

When m = n = 1 and p = 0, the general equation becomes the Prout-Tompkins equation:

$$\frac{d\alpha}{dt} = A e^{-\frac{E}{RT}}[\alpha(1-\alpha)] \tag{8}$$

When n = 1 and m = p = 0, the general equation becomes:

$$\frac{d\alpha}{dt} = A e^{-\frac{E}{RT}}(1-\alpha) \tag{9}$$

It is important to mention that there is not a universally accepted model that can describe the dynamics of the thermal degradation process consistently. Most of these models are only valid under certain controlled conditions that differ from the conditions existing when a bundle of electrical cables are exposed to thermal insults.

Many solids decompose on heating to give a sigmoidal α-time curve. This is the case of polyvinyl chloride, which is evidence of the autocatalytic nature of the reaction. For instance, the experimental kinetic curves given by Heiberger and Nass et al. (1985) show that the degradation rate has maximum value at the beginning and then decreases during the early stage and becomes steady.

The α-time curve is sensitive to the medium where the reaction takes place. Most of the experiments have been carried out in an inert atmosphere (nitrogen, argon or vacuum), and only few of them in air. In the latter, the presence of oxygen caused faster degradation compared to the inert environment (Gupta, 2002).

According to Andricic, Kovacic and Ivka et al. (2002), thermo degradation of PVC in presence of oxygen (thermo-oxidative degradation) is about three times faster than the thermal degradation in an atmosphere of nitrogen. Additionally, according to some specialists, thermo oxidative degradation of polymer is more complex than simple pyrolysis (Andricic, Kovacic and Ivka, 2002).

As was noted previously, the selection of one of these kinetic models depends on the reaction mechanisms in place (thermal degradation, thermal oxidative degradation, autocatalytic mechanism, etc). In some other cases different autocatalytic reactions coexist, and consequently different activation energies and pre-exponential factors should be considered (Cheng, 2003). In many studies it is difficult to determine which of the above mentioned kinetic equations best describes the thermal decomposition process; however, generally the polymer thermal decomposition is described parametrically by an increasing exponential behavior (Brown, 1997).

> *"It cannot be expected that the kinetic equations described above, with only a few parameters can adequately characterized the complex and numerous processes that take place during the thermal degradation of polymers. However, experimental tests have shown that the dynamic behavior of this degradation process is in general well described by these set of equations"* (Polyakov and Shlenskii, 1985).

As was mentioned, the thermal decomposition of electrical cables in fire is a complex process that depends on different factors, among them, cable material and dimensions, cable arrangement, electrical and mechanical loads on the cables, heat release rate and pattern, and time-temperature profile (Shlensky, Akseno and Shashkov, 1991; Budrugeac, 2001). According to NEA (2000), for a slow heating process, the insulation material softens in the course of time and disperses away from around the conductors, depending on the mechanical tension acting on the cable. On the other hand, if heated rapidly, cables may remain functional even beyond the moment when their jackets already have been ignited.

Other difficulty of applying the kinetic model is the complexity displayed by the degradation behavior of polymeric materials. In some cases a particular kinetic equation applies at a given degree of transformation, while other models describe the remaining thermal degradation process (Zaikov, 1998). In some other cases, thermal exposure conditions influence the process in such a way that the behavior of the mechanism of failure change and consequently the degradation process behaves in a different way.

On the other hand, values of activation energies and to a lesser degree of pre-exponential factors for some polymeric materials have been reported in the open literature, but given the high variability reported, the reliability and/or significance of these values remains in doubt (Galwey and Brown, 1987) (see Table 1).

In some cases the dependence of these parameters on the temperature range used as the thermal insult is significant, which hinders the formulation of a kinetic model that leads to consistent results without the explicit incorporation of these dependence effects**.** Some analysts have attributed these differences in kinetic parameters to experimental conditions, characteristics of the samples, and some other factors such as the autocatalytic effect of HCl in case of PVC (Miranda, 1999).

These data suggest that polymeric thermo degradation is a complex process not unequivocally defined for a particular kinetic equation, which in addition to the lack of data, and the variety of the influencing factors not explicitly defined in the previous kinetic equations (see Appendix I), increase the difficulty to set-up an analytical framework approach leading to estimate the likelihood of fire induced cable damage.

Based on the previous statements, the kinetic model is only developed on a theoretical basis. The detailed development of a thermal degradation model based on the use of kinetic equations, its practical feasibility and its further validation can be done when more consistent and reliable characterization data for the kinetic properties of interest is available. At this stage, this research considers the use of the first equation described in Appendix I to describe in general terms the development of this model.

Table 1. Kinetic Parameters

Source (Reference)	Material Designation	Temperature °C	Parameter "A_1" (s^{-1})	Parameter "Ea_1" (KJ/mol)	Comments
Chenyang (2003) (1)	High-density polyethylene	N/A	7.37E+03	101	Reaction order n ~ 1 (0.77). Medium: N_2. B: 2 C/min
Chenyang (2003) (1)	High-density polyethylene	N/A	3.17E+20	320	Reaction order n ~ 1 (0.77). Medium: N_2. B: 2 C/min
Budrugeac (2001)	Low-density polyethylene	20-500	2.53E+10	143	Medium: Air.
Ding (2001)	Low-density polyethylene	200	2.50E+02		Medium: Air.
Gupta (2002) (2)	PolyEtherTher Ketone	N/A	3.10E+03	111.4	Medium: Air. Conversion rate: 5/10/15/20 /25 %
Gupta (2002) (2)	PolyEtherTher Ketone	N/A	2.30E+08	178.3	Medium: Air. Conversion rate: 5/10/15/20 /25 %
Chien (1978)	Polypropylene (amorphous)	240	2.27E-03	71.15	Reaction order n: 1. Medium: Air. B: 40 C/min
Chien (1978)	Polypropylene (amorphous)	289	1.02E-02	71.15	Reaction order n: 1. Medium: Air. B: 40 C/min
Wu (1994)	Polyvinyl Chloride	N/A	4.80E+16	267	Reaction order n: 1.5. Medium: N_2.
Wu (1994)	Polyvinyl Chloride	N/A	5.60E+12	218	Reaction order n: 1.5. Medium: N_2.
Miranda (1999)	Polyvinyl Chloride	150-1000	7.50E+07	135	Reaction order n: 1. Medium: N_2.

(1) Values reported for different types of reactions during the thermal degradation process.

(2) Values reported for different conversion level.

An alternative way to characterize the cable thermal degradation behavior is the analysis of this phenomenon using a heat transfer model. Up to date, most of the studies carried out and documented in the open literature have concluded that fire-induced cable failures take place when the external thermal insult is enough to increase the temperature in the surrounding area of the cable above a threshold level (EPRI, 2002; NEI, 2002).

Based on this experimental evidence, one plausible option to develop a probabilistic model to estimate fire-induced cable damage likelihood is through the development of a heat transfer model to estimate the inner cable temperature as a function of the outer temperature of the cable, and the correlation of these temperatures with the functional integrity of the cable.

4.4. Heat Transfer Model

The estimation of the inner cable temperature of an electrical cable induced by an external fire involves not only the characterization of the fire generated conditions near the cable, but also the characterization of the thermal behavior of the cable polymeric insulation.

Thermal behavior characterization of cable polymeric insulation is a complex assessment problem due to multidimensional and heat generation effects. Basically, it represents a transient heat transfer problem, where not only the temperature gradient generated for the external thermal insult should be considered, but also the contribution of the heat arising for the normal operation of the cable (Joule effect).

Regarding the characterization of the fire generated exposure, presently analytical methods exist to estimate the heat flux of a hypothetical fire and determine the time-temperature profile at a target component, such as an electrical cable (EPRI, 2002). Based on the estimation of the temperature in the surrounding area of the target cable, it is possible to develop analytical models to estimate the temperature in the inner section of the cable. In a recent research reported by Andersson and Van Hees et al. (2005), a simple heat conduction model was developed and the predicted temperatures were compared to experimental data.

Andersson and Van Hees et al. (2005) discussed an analytical model to predict the thermal transient behavior of an electrical cable assuming an infinite homogeneous cylinder. Even though they worked with a particular insulation material (PVC), they were able to show the similarity between the thermal response given by the analytical solution and the one given by numerical estimation. In their research they concluded that in spite of the assumptions adopted, the simple analytical solution looks promising.

The heat transfer model described by Andersson and Van Hees et al. (2005) used as inputs the basic physical and electrical characteristics of the cables/conductors considered and the time-temperature profile in the surrounding area induced by the external fire, which can be estimated through existing fire codes.

The heat transfer model to be developed as part of this research is a simple heat transfer response model based on the following assumptions:

- The temperature surrounding the cable can be predicted by the existing analytical methods and fire codes as the thermal driving force.
- The cable is modeled as a homogeneous and infinite cylinder. This particular assumption limits the analysis of heat conduction in the radial direction (heat conduction in cylindrical geometries). It is a reasonable assumption for cylinders having ratio length to radius higher than 10 (Incropera, 1996).
- No internal heat generation is considered.
- Heat losses through the conductors are not considered.
- Uniform initial temperature across the radial section and throughout the length of the cable.
- Constant thermo-physical properties of the polymeric material (ex. constant thermal conductivity, thermal diffusivity, etc.).

The most common methods to analyze the heat conduction in cylindrical geometries are the *Lumped Capacitance* and the *Exact method* (Incropera, 1996).

4.4.1.The Lumped Capacitance Method

This method is applicable where temperature gradients within the solid (polymeric insulation) are small, so the temperature is spatially uniform.

In practical applications, if the *Biot* (*Bi*) number is much smaller than 1 (*Bi* << 1), the lumped capacitance method is an attractive alternative to solve heat transfer problems.

Assuming a long cylinder to represent a typical electrical cable, the *Biot* number can be approximated to:

$$B_i = \frac{h}{k} r_0 \tag{10}$$

where:

r_0 = radius of cable (m)

h = heat transfer coefficient (kw/m^2)

k = thermal conductivity (w/k.m)

Considering the thermal properties and dimensions of the electrical cables traditionally used in nuclear power plants (thermal conductivities around 0.15 to 0.40 W/K.m), the condition *Bi* << 1 is not normally satisfied; therefore, the lumped capacitance method is not applicable in most of the cases. For particular scenarios the applicability of this method should be evaluated considering its contribution to the overall uncertainty in the thermal assessment process.

4.4.2.Exact Solution

Modeling an electrical cable as a homogeneous and infinite cylinder, the core temperature of the cable can be estimated from (Incropera, 1996):

$$\theta^* = \frac{T - T_0}{T_u - T_0} = 1 - \sum_{n=1}^{\infty} C_n e^{-\left[\left(\zeta_n^2 F_o\right) J_o(\zeta_n r)\right]} \tag{11}$$

where:

T: inner temperature of the cable (polymeric cylinder) at time t.

T_o: initial temperature of the cable (t = 0).

T_u: temperature in the surrounding area of the cable at time t.

$$C_n = \frac{2}{\zeta_n} \frac{J_1(\zeta_n)}{J_o^2(\zeta_n) + J_1^2(\zeta_n)} \tag{12}$$

ζ_n are positive roots of the transcendental equation:

$$\zeta_n \frac{J_1(\zeta_n)}{J_o^2(\zeta_n)} = B_i \tag{13}$$

J_1 is Bessel function of type 1 of order 1, and J_0 is Bessel function of type 1 of order 0.

$$F_o = \frac{\alpha t}{r_o^2} \qquad \text{(Fourier number)} \tag{14}$$

where:

α: thermal diffusivity (m^2/s)

t: time (s).

It has been shown that for values of Fourier number higher than 0.2 ($F_o > 0.2$) the infinite series solution can be approximated by the first term of the series (Incropera, 1996). Even though values of thermal diffusivity for the complete set of materials of interest have not been found or represent a large range, preliminary results support the statement of values of F_o higher than the 0.2 threshold, particularly after several minutes of fire exposure.

Using the one term approximation:

$$\theta^* = \frac{T - T_0}{T_u - T_0} = 1 - C_1 . e^{-\left[\left(\zeta_1^2 F_o\right) J_o(\zeta_1 r)\right]} \tag{15}$$

where:

$$C_1 = \frac{2}{\zeta_1} \frac{J_1(\zeta_1)}{J_o^2(\zeta_1) + J_1^2(\zeta_1)} \tag{16}$$

ζ_1 is the positive root of the transcendental equation:

$$\zeta_1 \frac{J_1(\zeta_1)}{J_o^2(\zeta_1)} = B_i \tag{17}$$

Values of the coefficients C_1 and ζ_1 have been determined and are available from open literature.

$$\frac{T - T_0}{T_u - T_0} = 1 \quad - \quad \frac{2}{\zeta_1} \frac{J_1(\zeta_1)}{J_o^2(\zeta_1) + J_1^2(\zeta_1)} . e^{-\left[\left(\zeta_1^2 F_o\right) J_o(\zeta_1 r)\right]} \tag{18}$$

$$T \quad = \quad T_U + (T_O - T_U).C_1.e^{-\varphi t} \tag{19}$$

where:

$$\varphi = \left(\zeta_1^2 \frac{\alpha}{r_o^2} \right) J_o(\zeta_1 r) \tag{20}$$

It is important to mention that the above equation is valid for a constant surrounding temperature; however, in a real fire scenario it is expected to have a temperature profile where the temperature varies, sometimes significantly, with time. For that reason, the above equation was solved numerically using a finite-difference method.

$$T_{(K+1)} = T_{(K)} + \left(T_{U(K+1)} - T_{U(K)}\right) - C_1.e^{-\varphi t_K}\left(T_{U(K+1)} - T_{U(K)}\right) + C_1.\Delta t.\varphi.e^{-\varphi t_K}\left(T_{U(K)} - T_O\right) \tag{21}$$

where:

$T_{(k+1)}$: inner temperature of the cable (polymeric cylinder) at time $t_{(k+1)}$

$T_{(k)}$: inner temperature of the cable (polymeric cylinder) at time $t_{(k)}$

T_o: initial temperature of the cable (t = 0)

$T_{u(k+1)}$: temperature in the surrounding area of the cable at time $t_{(k+1)}$

$T_{u(k)}$: temperature in the surrounding area of the cable at time $t_{(k)}$

k: step parameter

The transient thermal response and the failure behavior are characterized probabilistically, so the uncertainties involved in the heat transfer phenomenon is considered.

4.5. Insulation Resistance (IR) Model

An alternative way to characterize the cable thermal degradation phenomenon leading to fire-induced cable damage is the analysis of the dynamic behavior of the cable insulation resistance (IR) in the presence of an external thermal insult. The insulation resistance is one of the parameter proposed to measure the functional integrity of an electrical cable.

Nowlen et al. (2000) defines the term *cable functionality* as the ability of a cable to perform its intended function and/or the methods of demonstrating that ability. In other words, it implies that the cable should be able to maintain its electrical functional integrity. In this context the term functional integrity refers to:

- Transmission of power, control or instrument signals.
- Insulation resistance.

- Protection against adverse ambient conditions.

A fire can damage a cable polymeric cover in such a way that its functional integrity is jeopardized. However, the definition of *loss of functional integrity*, to a certain extent, is difficult to apply in practical scenarios (EPRI, 2002).

Readers should note that if the intended function of a specific cable is to transmit a signal with certain characteristics in terms of voltage, current intensity and time behavior from point A to point B, any operational condition (*e.g.* cause by a fire) capable of affecting these parameters and moving them out of a specified range represent a loss of functional integrity. This interpretation of functional failure or simply cable damage is easy to understand and digest; however, it is impractical and difficult to correlate with the dynamic functional behavior of electrical circuits.

As pointed out in NEA (2000), loss of functionality of electrical cables, particularly under fire conditions is a complex phenomenon that depends on a variety of intrinsic (cable materials and dimensions) and extrinsic factors (electric and mechanical loads on the cables, heat flux severity, exposure time, etc) (Bertrand, 2002). From here the necessity of defining the term "cable damage" through an indirect measurement of cable functional integrity such as its insulation resistance in case of the so called "K Factor" model, or alternatively, the inner cable temperature in case of the heat transfer model, or in terms of the fraction of reaction in case of the thermal degradation model (using the kinetic equations).

The idea of estimating the functional integrity of an electrical cable using the insulation resistance (IR) is not new. Nowlen et al. (2000) proposed it as a direct measurement technique to assess cable functionality. Generally speaking the level of insulation resistance assures the ability of a cable to transmit the electrical signal under given conditions from a source point to a target point. If the insulation resistance decreases significantly, the electrical signal eventually is not able to get to the target point at the level required to perform its intended function.

Past testing in fire and equipment qualification indicates that polymers have a progressive breakdown in their electrical insulating strength with increasing temperature. It represents one of the main causal processes expected to induce shorting in a cable exposed to tougher thermal environment (Nowlen, 2006).

In the last 40 years, different experimental tests have been conducted to evaluate how the insulation resistance of certain polymeric cover insulations behaves at high temperatures. The results from these experimental tests have suggested, for example, the insulation resistance of vinyl cord covering through heating follows a decreasing exponential behavior, and decreases from values closed to $10^8\ \Omega$ to values lower than $10^3\ \Omega$ for temperatures closed to 500°C (Soma, 1965). Other experiments have shown that the electrical resistance of the PVC covering can reach values below $10^2\ \Omega$ with temperature rise of about 300°C, suggesting that the PVC covering change from electrical insulator to organic semiconductor (Nagata and Yokoi, 1983).

Some investigations carried out by The Fire Prevention Society of Japan (Soma, 1965) have shown how the electric resistance of a vinyl chloride cord decreases through heating. The results reveal that the electric resistance decreases up to 10^8 Ω at 200°C in approximately 30 minutes, reaching 10^3 Ω at 500°C in the same time frame. In general, when cables are exposed to extreme ambient temperatures such as those created by a fire, their IR typically drop several orders of magnitude, following an exponential behavior.

When the IR starts decreasing, the signal to be transmitted is dissipated through the different leakage paths created and eventually can drop below a minimum acceptable level. On the other hand, the signal to be transmitted may also become contaminated from other signals in other cables exposed to the same condition and the same breakdown.

The acceptable IR level depends on the application; therefore, it is different for a cable used in a control circuit, than for a cable used in a supply power circuit. In fact if the evaluation is limited to control circuits, the level of acceptable IR will even depend on a variety of factors among them the circuit design features, voltage level, the power level, cable physical features, and the functional characteristics of the final elements under control.

Based on the insulation resistance approach, the USNRC has established a minimum acceptance criterion of 10^6 Ω over a 1000 foot length of conductor or cable (Nowlen, 2000) for applications using less than 1000 volts. For a typical 120 volts circuit it represents a leakage current of approximately 0.12 mA for this length of cable. The idea of defining a damage criteria based on IR has been challenged because experimental evidence has shown that IR decreases continuously during a thermal insult, so the problem of defining a damage criteria in form of an IR level remained unsolved (Andersson, Van Hees, 2000). This behavior has been particularly observed in thermosets.

Measuring the insulation resistance is quite complicated, particularly if the application involves a large number of conductors. Some specific measurement configurations have been implemented to address this limitation. Particularly, Sandia National Laboratories (SNL) has proposed and used in most of its recent experimental tests the measurement system shown in Figure 6. This measurement system allows measuring the IR of different multiconductors in a sequential base.

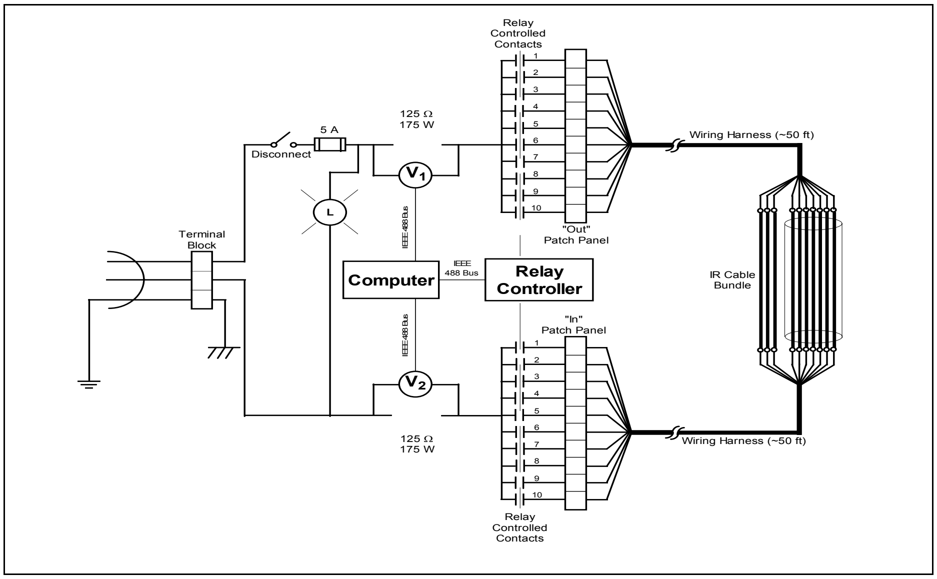


Figure 6. SNL IRMS (NUREG/CR-6776)

Even though the direct measurement of IR constitutes a mechanism to determine the functional integrity of electrical cable, it is quite impractical and difficult to associate with the typical variables involve in a fire scenario. Based on this, an alternative model called IR "*K Factor*" was proposed to measure the electrical functional integrity of a cable expose to external fire.

This model is based on the assumption that for most modern cable insulations (XLPE, PVC, EPR, etc) the IR drops exponentially as temperature increases. As is shown in Figure 7 (Nowlen, 2000), most of the cable insulation materials commonly used in nuclear power plants behave in similar manner; so the IR drops by order of magnitude at the temperature surrounding the cable increases.

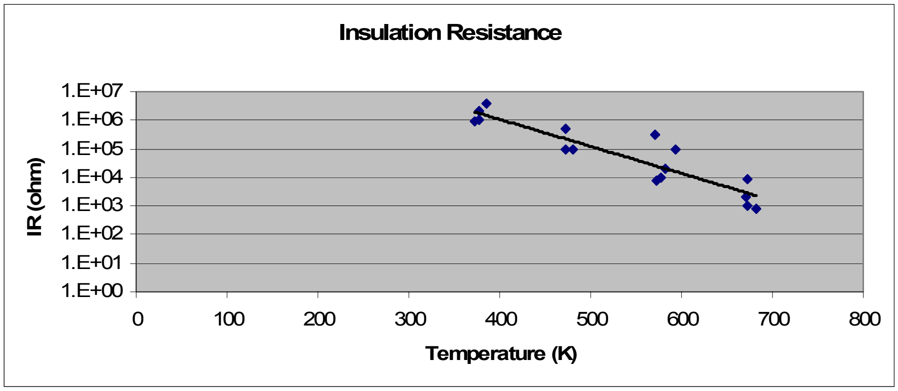


Figure 7. IR-Temperature Profile

It is important to mention that the variation in IR can be caused not only by external temperatures changes (*e.g.* fires), but also due to the heat generated inside the cable due to its resistance. For example, if a cable is used to transmit power to a specific device, characterized for a specific voltage and current intensity, the conductor in the cable (typically cupper) will increase its temperature due to Joule effect. It is one of the factors considered in a cable sizing and selection.

As noted previously, for simplicity purposes our model does not consider the internal thermal effect. At this point is important to mention that cables are selected and sized such that resistive heating is relative minor; therefore, thermal effects of a fire would render Joule heating negligible.

4.5.1.IR "K Factor" Model

For most modern cable insulation materials, insulation resistance drops exponentially with increasing temperature. One of the models proposed to evaluate cable functionality upon external thermal insult is the IR "*K factor"* model (Nowlen, 2000). The "*K Factor*" model assumes IR as function of temperature varies as follow:

$$IR = K(T_k).\ln\left(\frac{D_{out}}{D_{in}}\right) \tag{22}$$

$$K(T_K) = C_1 .e^{-(C_2 T_k)} \tag{23}$$

where:

D_{out} = outer diameter of the insulation (m)

D_{in} = inside diameter of the insulation (m)

C_1 and C_2 constant for a given insulation material.

T = temperature on the cable outer surface (°K).

or,

$$IR = C_1 . e^{-(C_2 T_k)} . \ln\left(\frac{D_{out}}{D_{in}} \right) \tag{24}$$

One of the limitations of this model is that the only dependent variable explicitly used to define the behavior of a cable under external thermal insult is the surrounding temperature, and as it was pointed out in previous sections, there is a variety of factors that eventually can increase or decrease the thermal cable susceptibility.

In this approach it is important to define the IR endurance limit below which cable damage is imminent. As mentioned, this endurance limit is context dependent; particularly it depends on the nature and features of the electrical circuits under consideration. Some studies have suggested 1000 Ω as representative of this endurance limit (EPRI, 2002); other researchers have used a more conservative criterion (Nowlen, 2000).

CAROLFIRE (Nowlen and Wyant, 2007) testing program establishes preliminary cable failure endurance limit of 1,000 Ω for control cables and 10,000 Ω for instrument cables (Nowlen and Wyant, 2007). However the IR value at which a given cable will cause a spurious operation is application dependent; for motor control devices the maximum IR capable of inducing spurious operation could be lower than hundreds of ohms; on the other hand, for low power consumption devices, the IR endurance limit could be substantially higher than 1,000 Ω. These IR endurance limits were selected as initial trigger values that indicate the differences in cable application. It is important to point out that past testing has shown that once the cable IR degradation begins; the values will decay abruptly in a way such that regardless of the IR endurance limit (1,000 Ω to 5,000 Ω) the time to failure behavior will be almost the same. This behavior is particularly evident in thermoplastics.

If the analysis is limited to conventional control circuits, normally operated in 120 VAC or 125 VDC, a representative endurance limit might be 1,000 Ω. It represents a conservative initial threshold level. This criteria is based on the assumption that most of the final control elements in conventional control circuits (solenoids valves, relays, etc) fed with 125 VDC require an intensity current about 100 -150 mA to operate appropriately, so any leakage current at or above this level is able to eventually energize these devices. A 125 VDC circuit is able to drain a current of 125 mA if the resistance of the leakage path is about 1,000 Ω.

It is important to mention that this endurance limit is used just as an initial threshold value because the final value is derived experimentally based on the electrical responses of cable/circuits upon external thermal insult.

Regardless of the models used to evaluate the fire-induced cable failure phenomenon, it is important to know what actually occurs in practice when a given cable or group of cables are exposed to an external thermal insult. The damage level is not only highly dependent on aspects related to cable configuration, material composition, and physical arrangement, but also the outcome is stochastic (EPRI, 2002). There are several sources of uncertainty involved in the characterization of the thermal degradation process of polymer.

These sources of variability and uncertainties include, but are not limited to:

- Variability in material characterization: most of the materials used in commercial cables present a variable composition not found in the open literature. Basically manufacturers add specific additives and fillers to improve the performance of their cables, keeping this information confidential.

  For example, when PVC is used as cable jacket and/or insulation, it is not used as a pure polymer. In fact, PVC cable insulation typically contains no more than 65% of PVC resin, and the remainder is composed of a variety of other components added to improve the performance of the polymeric insulation (Babrauskas, 2005).

  A typical PVC wire cable insulation composition would be as follows (Babrauskas, 2005):

PVC resin	……………………..	52 – 63%
Plasticizer	……………………..	25 – 29%
Filler	……………………..	16% (sometimes ≤ 5 %)
Stabilizer	……………………..	2 – 4%
Wax	……………………..	0.2 – 0.3%

Due to the variability imposed by commercials PVC cable insulation composition, random structural abnormalities and other external factors, the characterization of the PVC degradation onset temperature (defined as the temperature at which significant HCl evolution commences) is difficult (Babrauskas, 2005), and consequently the characterization of the degradation process under external thermal insult does not necessarily obey a consistent behavior.

The variability associated with the material composition is equally applicable to the majority of the polymer composite used for commercial applications.

- Most of the available data come from experiments carried out under different conditions (different heating rates, different commercial polymer wire/cable insulations, different sample configurations, different sample sizes of specimens, air flow velocity, oxygen concentration, etc) (Kashiwagi, Omori, 1988); consequently, the databases developed represent the aggregation of a variety of scenarios (non-homogeneous in nature) from which is difficult to infer consistent conclusions.

  In addition to this non homogeneity, the thermal decomposition of electrical cable under fire is a complex process that depends on a variety of factors not explicitly defined in the models considered. For example, according to NEA (2000), if the cable is heated slowly, the insulation material softens in the course of time and disperses away from around the conductors, depending on the mechanical loads acting on the cable. On the other hand, if heated rapidly, cables may remain functional even beyond the moment when their jackets already have been ignited (NEA, 2000).

- There is no universal standardized testing methodology to evaluate the behavior of polymeric material upon heating (Salley, 2000).

- There is no a clear criterion that establishes the damage/failure condition. In some of the experiments carried out, the short circuit condition is evident; however, there are certain cases where this is not so clear due to the dynamic behavior of the failure, limitations of the measurement systems used, or simply due to ambiguities in the description of the experiments and final results (Salley, 2000).

- The temperature used to determine the degradation process is measured at different locations and at different instances among the experimental tests. Some researchers measure the temperature of the cable surface (*e.g.* jacket), others measured the temperature at the surrounding air, and others measured the temperature at the closest cable (Salley, 2000). As outlined by Salley et al. (2000), in some cases reported in the open literature the reference temperature for the data obtained is that of the furnace space rather than the insulation temperature.

Among all these source of uncertainties, one of the most critical factors involved in the thermal degradation assessment process, is the actual temperature distribution of the polymeric wire/cable insulation across its radial section during the thermal degradation process.

- The voltage used to feed the electrical circuits varies from a few volts to hundreds of volts. Some tests are run using DC electrical power, some others using AC, which offer a greater resistance to a flow of current (Landinger, 2003). In some cases circuits are equipped with control power transformers (CPT), which appears to be an important factor affecting the probability of short circuits (Nowlen, Wyant, 2006).

- Only few of the experimental tests carried out to assess the damageability of polymeric wire/cable insulation have been developed under normal operating load current (NEA, 2000).

- The thermal decomposition not only depends on factors such as temperature, pressure, reactant concentration, presence of catalysts, activators or inhibitors (Perez, Silva, 1988) but also is influenced by geometrical, structural, diffusional and mechanical factors that may play an important role under certain conditions (Shlensky, Akseno and Shashkov, 1991).

Besides the logical differences obtained in the degradation process among different cables, due to the nature and composition of wire/cable insulation, cable's function and construction, the results in a real fire can also vary from the one given by the model developed, due to other factors such as:

- Cable tray fill percentage: large amount of cables, and consequently greater mass, act as thermal heat sink delaying the effective degradation process (Salley, 2000).

- Age of cable. Even though the experimental results about this issue are conflicting, in general terms an aged cable will lose its functionality faster than a new cable (Salley, 2000).

- Cable operating load current. Depending on the load current handled by the cables, their temperature could exceed the ambient temperature significantly. In the case of power cables, their temperature may exceed the surrounding temperature by up to 50 °C due to the operating current intensity. Therefore, the results derived from tests where cables have not been loaded may be optimistic (NEA, 2000).

- Cable physical properties/configuration factors:
    - Number of conductors.
    - Cable size.
    - Armoring.
    - Shielding of conductor pairs.

- Routing factors:
    - Cable tray type.
    - Overall raceway fill.
    - Raceway orientation.
    - Bundling of cables.
    - Location of cable within bundle.

- Electrical function factors:
    - Circuit voltage.
    - Cable ampacity.

- Fire exposure condition factors:
    - Exposure mode.
    - Exposure intensity and duration.

All the mechanisms of failure highlighted in Figure 8 might take place when cable degradation (in terms of fraction of reaction, inner cable temperature or insulation resistance) reaches a predefined endurance limit. As can be seen in Figure 8, the mechanisms of failure involved in a thermal polymeric cable degradation process are diverse and have not been deeply studied. On the other hand, given the variability associated with cable behavior upon fire, which are dependent not only in external factors such as fire exposure, but also to cable material composition, arrangement and sizing, it is assumed that there is a high level of synergy among these mechanisms, and the results of a cable exposed to an external thermal insult could be defined for the dynamic interaction among these not well characterized mechanisms.

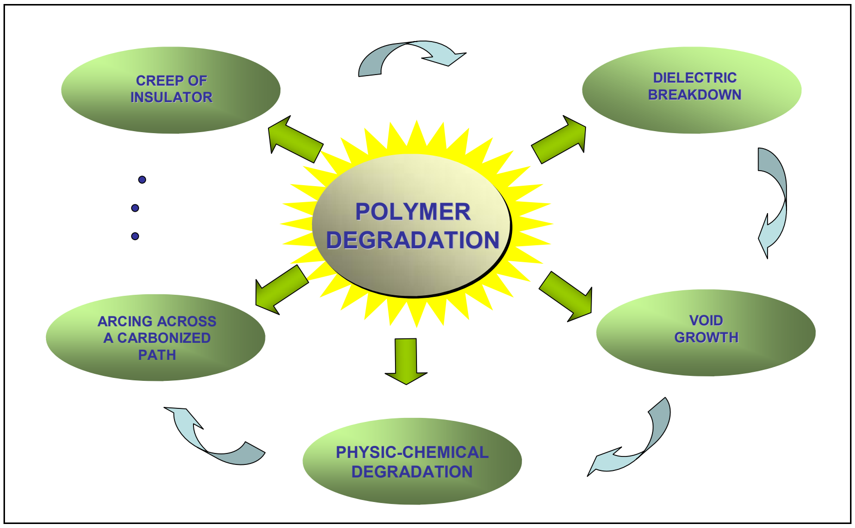


Figure 8. Synergy among Mechanisms of Failure

Due to the variety of mechanisms of failure involved, and the lack of plausible physics-base models to characterize them and their synergistic interrelations, the three different models proposed in this research (kinetic equations, heat transfer, and IR “K Factor”) are complemented with experimental data on cable behavior in extreme external thermal insults. The objective is to combine the limited analytical knowledge on thermal degradation with experimental evidence of failure upon fire, which looks promising from an engineering perspective for risk analysis applications.

It is expected that these new models, which combines the results of the experimental tests with the characterization of some of the mechanisms of failure involved in thermal degradation processes provides a consistent framework to estimate the likelihood of fire-induced cable damage (see Figure 9).

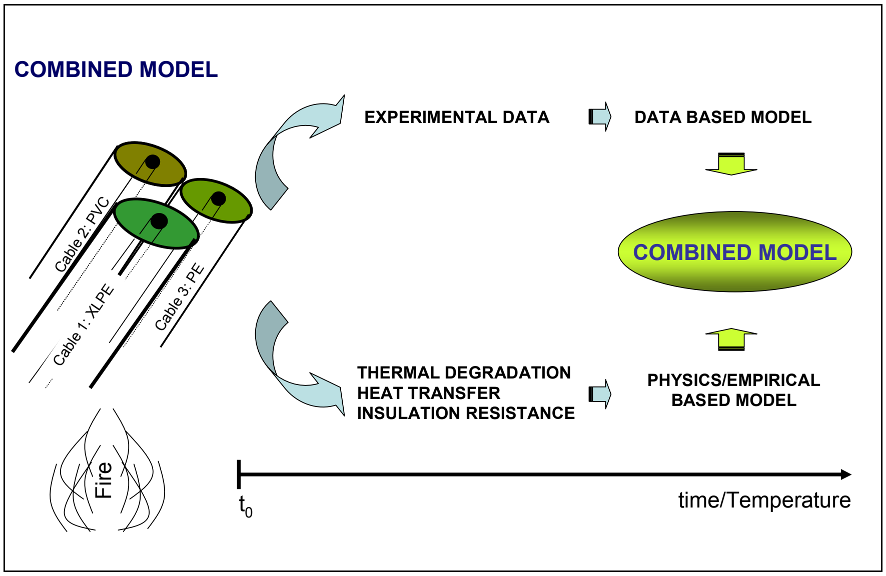


Figure 9. Combined Model

The experimental data obtained from the fire testing programs performed during the last two decades is used to define the time-temperature conditions at which the cable failure occurred for each one of the tests. On the other hand, the physic-based or empirical models (thermal degradation, heat transfer and IR models) are used to determine the thermal degradation, inner cable temperature and insulation resistance (depending on the model selected) as a function of time/temperature associated with each cable polymeric material for a particular time-temperature profile.

The combination of these two results lead to the estimation of the endurance limit in terms of thermal degradation (fraction of reaction), inner cable temperature and insulation resistance (depending on the model selected) associated with each cable polymeric material considered.

The failure behavior is characterized probabilistically, so the uncertainties involved in the estimation of the thermal degradation, inner cable temperature and insulation resistance is considered. This type of probabilistic approach will allow for a direct method of incorporating failure time uncertainty into a risk analysis estimate (e.g. core damage frequency). The model's output is a probability of damage versus time and/or temperature for a given time-temperature profile.

It is important to mention that the different models developed (kinetic equations, heat transfer, and IR "K Factor") are applicable to fire scenarios where single conductor cables, with polymeric insulation made of homogeneous materials, are exposed to an external thermal insult (external fire). These models are not directly applicable to complex cable arrangements and configurations (multi-conductors with different insulation and jacket materials, armored cables, etc). On the other hand, conditions associated with particular scenarios such as physical load imposed for the weight of other cables located in the same cable tray, aging, bend radius, or geometrical, structural and diffusional defects in the cable manufacturing process are not considered. The existence of these factors in particular fire scenarios may affect the fire-induced cable damage likelihood.

5. Data Gathering

During the last 10 years, industry and regulatory organizations have expended significant effort to develop and perform fire tests in order to improve our understanding of fire-induced cable and circuit failures. Some test data analyses have been performed, particularly to identify primary influence factors to key circuit failure modes.

The diversity of fire tests performed encompasses a large number of experiments involving varied arrays of cables, cable raceways, and fire exposures. Some of the tests performed follow a progression of increasingly more complex test conditions and configurations. The first series of tests consisted on small-scale radiant heating tests, most often utilizing a controlled radiant heating chamber, and the latest tests correspond to large-scale room fire tests in which conditions better representative of those found in nuclear power plants tend to be replicated.

During the different tests, cables are run in either a vertical or horizontal configuration, either with or without a supporting raceway (tray or conduit), from a single cable in open air, through a single cable in a cable raceway, up through small bundles of cables.

Particularly in large-scale tests, cables are exposed to extreme thermal insults from exposure sources such as pool fire or gas burner. Sometimes, cables in one or more electrical raceways are exposed to a direct effect of fire (e.g., flames impingement) with the intent that one (or more) of them will ignite. In general, cable targets are placed in various exposure conditions (e.g., plume, hot gas layer, radiant) and intensity of thermal insults (different heat release rates and heat fluxes).

During the development of these diverse tests, cables are monitored for thermal and electrical response. The overall goal is to measure the variables related to the thermal and electrical behavior of cable upon heating and the more significant surrounding variables, such that the cable functionality issue can be conveniently addressed. Among the variables typically monitored are the cable's surface temperature and the cable’s insulation resistance level.

From a survey of the available and most relevant fire test programs conducted by industry and regulatory organizations, different databases were developed with the intent to collect the necessary data on electrical cable response upon heating, required to complete this research. Among these data sources, the following can be mentioned:

- NUREG/CR 6776, SAND 2002 - 0447P

  Cable insulation resistance measurements made during cable fire tests.

  The report derived from this fire testing program provides information about how the insulation resistance among conductors exposed to external thermal insults varies as a function of time of exposure.

  During these tests, the conductor insulation integrity of each conductor of interest was monitored in real time through the Sandia National

Laboratories Insulation Resistance Measurement System SNL IRMS (Wyant and Nowlen, 2002).

Using this particular data acquisition system was possible to determine and log the conductor-to-conductor IR for individual conductor pairs, as well as the equivalent conductor-to-ground IR for each conductor independently (see Figure 6). A complete description of this apparatus and examples of its application can be found in Wyant and Nowlen et al. (2002).

A total of 18 tests were carried out during this fire testing program. All these tests were conducted in a steel chamber measuring 3 m wide, 3 m deep and 2.4 m high. The fire intensity was varied from 70 to 350 KW by controlling the propane gas flow through a diffusion burner.

A ladder-back type cable tray was used in most of the tests. Depending on the type of exposure desired (plume or hot gas layer); the cable tray was positioned at different height above the floor. Appendix II shows a summary of the different tests performed and the more relevant fire exposure conditions.

Although this report does not provide complete information about the specific cables used during the different tests and their particular thermal properties (thermal conductivity, thermal diffusivity, heat transfer coefficient, etc), it represents a valuable source of data, particularly to develop the “K Factor” model.

- NUREG/CR-5546, SAND 90-0696

  An investigation of the effects of thermal aging on the fire damageability of electric cables.

  Two different electric cables were evaluated during this testing program, the first one (Rockbestos) represented by a 3 conductor, neoprene jacketed, cross-linked polyethylene (XLPE) insulated cable (12 AWG); and the second (BIW) represented by a 2 conductor twisted shield pair, chlorosulfonated polyethylene (CSPE or Hypalon) jacketed, ethylene-propylene rubber (EPR) insulated cable (16 AWG).

  These two qualified electric cables, both unaged and thermally aged samples were exposed to steady-state elevated temperature conditions until conductor to conductor electrical shorting was observed.

  In this report the cable internal temperature responses for different fire test scenarios are highlighted. Figure 3.1 and Figure 4.1 in this report show a typical cable internal temperature for an unaged sample of Rockbestos and BIW cables respectively.

  It also provides information about leakage current vs. time, and contains figures showing how the leakage current behaves under a thermal insult as a function of time of exposure and when a short circuit state is reached. Based on the circuit configuration used in these tests, it is not possible to determine whether the short circuit took place between intracables or intercables (conductor to cable tray).

- EPRI 1003326

  Characterization of fire-induced circuit faults: Results of cable fire testing.

  The EPRI 1003326 fire testing program comprises a series of different cable bundle configurations (single and multiple conductors), raceway types and orientation, fire exposures and a combination of thermosets and thermoplastics cables. This testing program focused on the factors affecting fire-induced spurious actuation of equipment.

  The test carried out as part of this testing program were conducted in parallel to the tests carried out by SNL, reported in NUREG/CR 6776, SAND 2002 - 0447P; therefore, the same fire exposure scenarios apply here.

  Appendix II shows a summary of the different tests performed and the more relevant fire exposure conditions.

  The corresponding report provides information about the time-temperature profile in the target cables for a given thermal insult, in addition to the behavior of the leakage current between conductor-to-conductor and conductor-to-ground.

  Even tough it does not provide information about the thermal properties of the cable materials evaluated; it represents a valuable source of data, particularly to develop the “heat transfer model”.

- *Cable Response to Live Fire (CAROLFIRE)*

  A combined test effort involving representatives of NRC, SNL, NIST, and UMd (in progress).

  This combined testing program encompasses numerous fire test scenarios, intended to address two specific areas: (1) those items identified as “Bin 2” circuit configurations in RIS 2004-03, Rev. 1, 12/29/04, and (2) ongoing needs related to the verification and validation (V&V) of fire modeling tools.

  CAROLFIRE testing included a series of 78 small-scale radiant heating tests in a cylindrical exposure chamber called Penlight, and a second series of 16 intermediate scale open burn tests, in which cables are exposed to open fires created by a propane (propylene) gas diffusion burner. Cables were tested in cable trays, in conduits, and in air drop configurations. The intermediate scale tests included exposure of cables both in the fire plume and under hot gas layer exposure conditions.

  During these tests the inner and outer cable temperature, as well as the surrounding temperature were measured to characterize the cable thermal response. Similarly, the polymeric insulation integrity of each conductor of interest was monitored in real time through the SNL IRMS.

  In the selection of the variables to be measured, particular care was taken to warrant, to the extent possible, an effective scan rate of the more significant variables, such as those related to the thermal degradation of the polymeric insulation and the magnitude and characterization of the thermal insult. Surrogate variables, such as the ceiling temperature, wall temperature, etc, were also measured in the room scale tests.

The preliminary data arising from these ongoing tests have provided valuables insights to understand the thermal degradation process of commercial cables exposed to external thermal insults. It also has provided information about the predominant failures modes and how the dynamic of these failures affect the normal behavior of electrical circuits.

Even tough it does not provide information about the thermal properties of the cable materials evaluated; it represents a valuable source of data to develop the "heat transfer model" and the IR "K Factor" model.

More information about the different scenarios evaluated in this fire testing program can be found in Appendix II.

Table 2 below shows the main features and exposure conditions encountered in the testing programs described above. It can be noted, that the different experiments were carried out at different conditions (different heating rate, different commercial polymer wire/cable insulation, different sample sizes of specimens, etc), which lead to a significant level of variability in the results.

As part of the information collected in this phase, in addition to the results of the experimental tests performed, it was also necessary to collect information regarding the characteristic and dimensions of the different cables utilized in the tests (radius of cable insulation and jacket, thermal conductivity, thermal diffusivity, etc).

Table 2. Summary of Conditions of Testing Programs

Source (Reference)	Cable Material	AWG	Cable Bundle Configuration	Raceway Type	Fire Exposure	Thermal Exposure	Comments
NUREG/ CR 6776, SAND 2002 - 0447P	XLPE, Neoprene, EPR, Hypalon, Tefzel, EP, PE, PVC, EPDM.	12, 14, 16	8/c armored, 1/c, 2/c, 3/c, 5/c, 6/c, 7/c, 9/c	tray, conduit, air drop (horizontal and vertical orientation)	plume, hot gas layer, radiant.	HRR (KW): 70, 145, 200, 250, 350, 450	Include large scale tests
NUREG/ CR-5546, SAND 90-0696	XLPE, Neoprene, EPR, Hypalon.	12, 16	2/c, 3/c	horizontal (?)	hot gas layer, radiant.	Not reported	Do not include large scale tests
EPRI 1003326	XLPE, PVC, Neoprene, EPR, Hypalon, Tefzel, PE.	10, 12, 14	8/c armored, 1/c, 7/c, 9/c	tray, conduit, air drop (horizontal and vertical orientation)	plume, hot gas layer, radiant.	HRR (KW): 70, 145, 200, 250, 350, 450	Include large scale tests
Carolfire NUREG/ CR Report (Draft)	XLPE, EPR, Silicone, Hypalon, XLPO, Vita Link, Tefzel, PE, PVC.	8, 12, 14, 16, 18	2/c, 3/c, 7/c, 12/c	tray, conduit, air drop (horizontal and vertical orientation)	plume, hot gas layer, radiant.	HF (KW/m^2) : 6.1, 7.2, 15.5, 17.3, 20, 23, 30 (small scale tests)	Include intermediate scale tests

Thermal property data was obtained as available from the open literature and manufacturers. When unavailable, a generic material property for the general class of each material was used.

6. Degradation Estimation: Time-Temperature Profile

Based on the analysis of the data obtained through the experimental fire tests performed during the last two decades and available in the open literature, the endurance limit associated with each one of the proposed models was assessed.

The following sections describe how these endurance limits in terms of level of degradation of the polymeric material, inner cable temperature and insulation resistance were estimated for the kinetic, heat transfer and IR "K Factor" models respectively.

6.1. Kinetic Model

The concept is to develop a damage-endurance model in which the level of degradation of the polymeric cable insulation, induced by the external thermal insult and determined through one of the kinetic equations described in Appendix I, can be compared to the endurance limit of the cable material under study.

Based on the experimental tests described in Appendix II, the time-temperature profile and the time to failure for each polymeric material were determined and recorded. Using these times to failure and their corresponding temperatures as independent variables of one of the kinetic equations described in Appendix I, it is possible to estimate endurance limit (expressed as % of fraction of reaction) for each polymeric insulation material of interest (PVC, XPLE, EPR, Tefzel, etc). Basically, as depicted in Figure 10, a level of degradation "α_i" can be determined for each failure identified during the running of the different tests, and the set of individual "α_i" associated with each particular cable material can be aggregated to characterize an endurance limit. This endurance limit represents the level of degradation at which the corresponding cable polymeric material has lost its insulation integrity. In other words, the cable has lost its functional integrity, and in consequence a short circuit might take place.

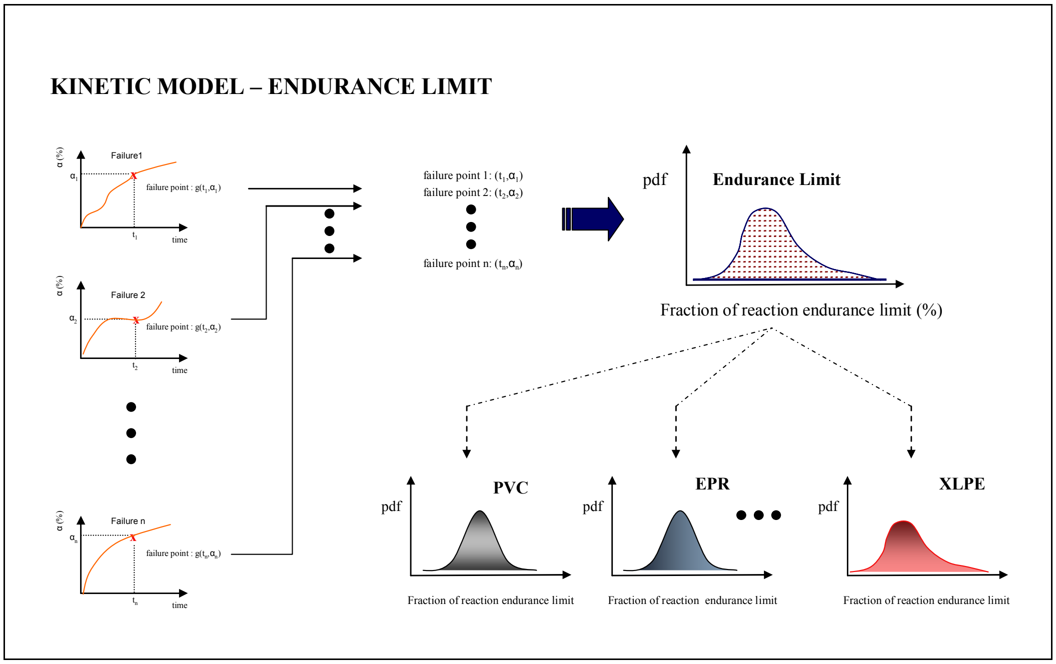


Figure 10. Kinetic Model – Endurance Limit

Given the scarcity of data and the lack of consistency in the characterization of the kinetic parameters, it is not possible to assess the endurance limits for this model at this time.

6.2. Heat Transfer Model

In this case, the concept is to develop a damage-endurance model in which the inner cable temperature induced by the external thermal insult can be compared to the endurance temperature level of the cable material under study.

As described in Figure 11, for each one of the experimental tests described in Appendix II, the time-temperature profile and the time to failure were determined and recorded. Furthermore, the inner cable temperature associated with each time to failure previously identified was estimated for each polymeric insulation material of interest (PVC, XPLE, EPR, PE, etc).

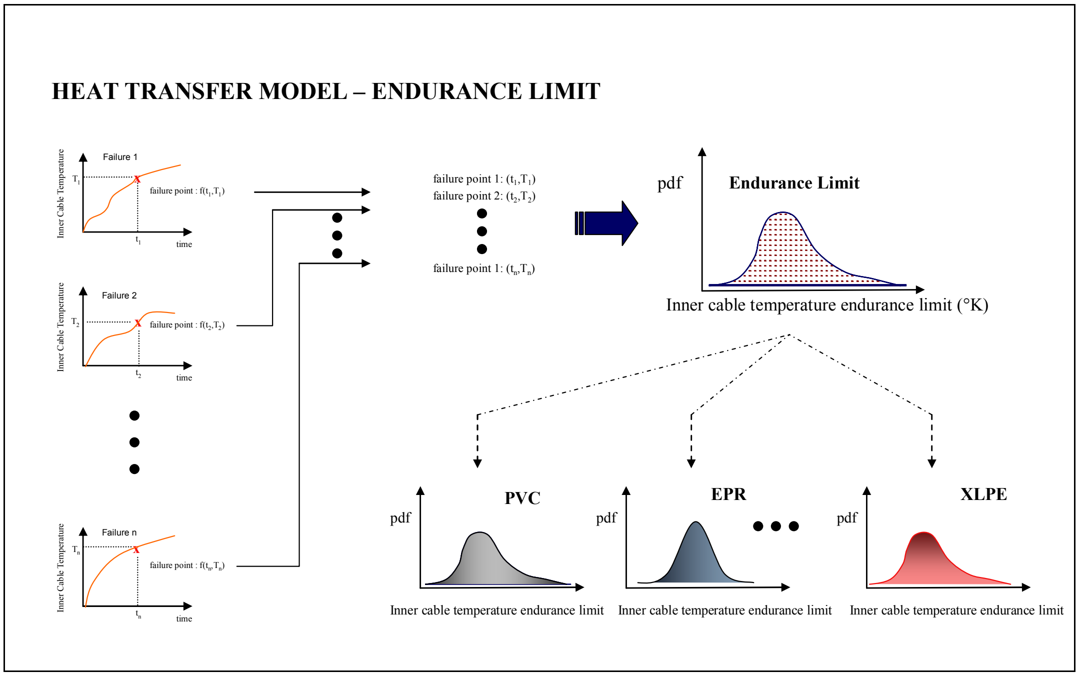


Figure 11. Heat Transfer Model – Endurance Limit

The set of individual inner cable temperature endurance limit "T_i" associated with each particular cable material was aggregated to characterize a temperature endurance limit as a probability density function. This endurance limit distribution represents the inner cable temperature at which the corresponding cable polymeric material has lost its insulation integrity, so a short circuit might take place.

Table 3, Table 4 and Table 5 contain the endurance limits, in terms of inner cable temperature in Kelvin, for the polymeric materials evaluated based on the Carolfire (Nowlen and Wyant, 2007), NUREG/CR 6776 and EPRI 1003326 databases respectively. It is important to mention that at the moment Carolfire testing program is in progress; therefore, only few of the tests developed under this program were considered in this analysis (see Appendix II).

Table 3. Endurance Limit – Heat Transfer Model (Carolfire)

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

(1) No available

Table 4. Endurance Limit – Heat Transfer Model (NUREG)

NUREG/CR 6776	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

(1) No available
(2) Estimation based on one test.

Table 5. Endurance Limit – Heat Transfer Model (EPRI)

EPRI 1003326	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

(1) No available

As inferred from these tables, thermoplastic materials as PVC, PE and Tefzel have an average endurance limit in the range from 452 °K (179 °C) to 523°K (250 °C), while thermosets materials such as XLPE and EPR has a higher endurance limit 658°K to 723 °K (385°C to 450 °C) as expected.

The endurance limits are modeled as lognormal probability density functions for several reasons. First, the lognormal distribution fits very well with the experimental data available. Second, the temperatures at which the failures take place is a positive value than can extend to infinity, depending on the particular thermal insult and cables properties. Third, the inherent nature of this parameter let infer that it is positively skewed. In addition, there have been cases where cables have withstand high temperatures, even after the polymeric insulation have reached the ignition point, without experienced electrical failures. Therefore, the lognormal distribution is an appropriate choice.

Appendix III contains the inner temperature endurance limit probability density function for the polymeric materials evaluated under this research.

6.3. IR “K Factor” Model

Similar to the previous models, in case of the IR “K factor” model, the concept is to develop a damage-endurance model in which the remaining/diminished cable insulation resistance (IR) induced by the external thermal insult can be compared to the endurance insulation resistance of the cable material under study.

Based on the experimental tests described in Appendix II, where the time-temperature-insulation resistance profile and the time to failure were determined and recorded, a set of insulation resistances to failure (Ω) was estimated for each polymeric insulation material of interest (PVC, XPLE, EPR, Tefzel, etc).

As depicted in Figure 12, the set of individual “IR_i“ associated with each particular cable material can be aggregated to characterize an IR endurance limit as a probability density function.

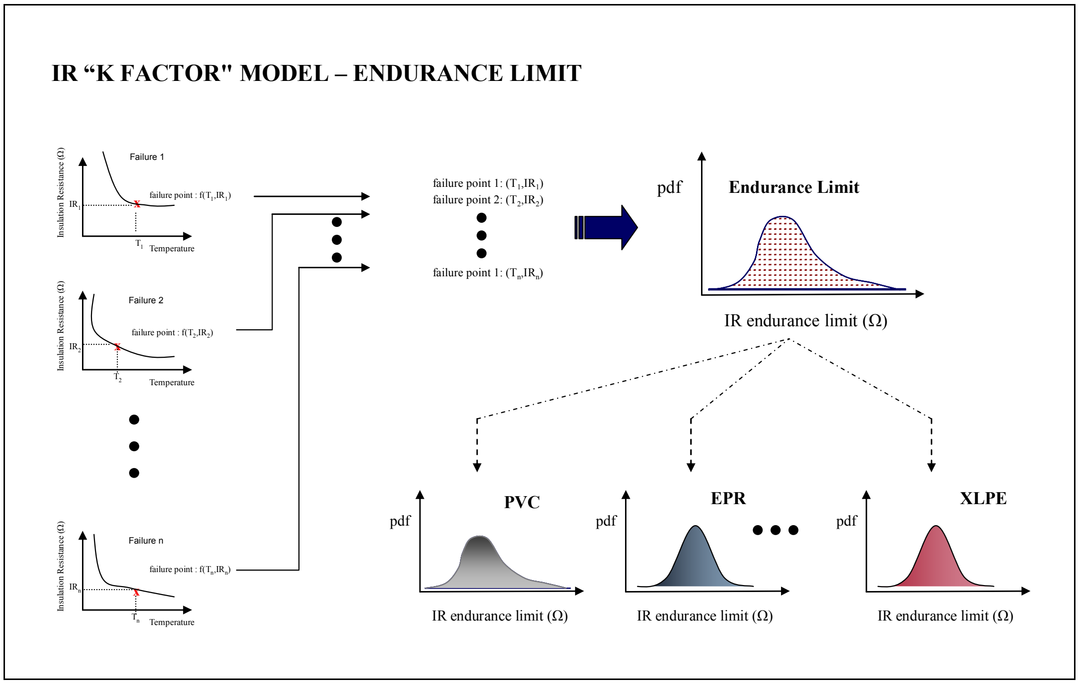


Figure 12. IR “K Factor” Model – Endurance Limit

The IR endurance limit represents the IR threshold level at which the corresponding cable polymeric material has lost its insulation integrity. In other words, the cable has lost its functional integrity, and in consequence a short circuit might take place.

In case of IR "K factor" model, the parameters of the equation (23), that is C_1 and C_2, which are supposed to be constant for a given insulation material were determined based on the failure data available as illustrated in Figure 13.

The analysis of the data provided by these studies reveals that for most modern cable insulation materials, IR will drop exponentially with increasing temperature. This behavior is more evident in thermosets materials; however, thermoplastic materials tend to have an abrupt break point. In general, thermosets cables had degraded signal outputs prior to failing.

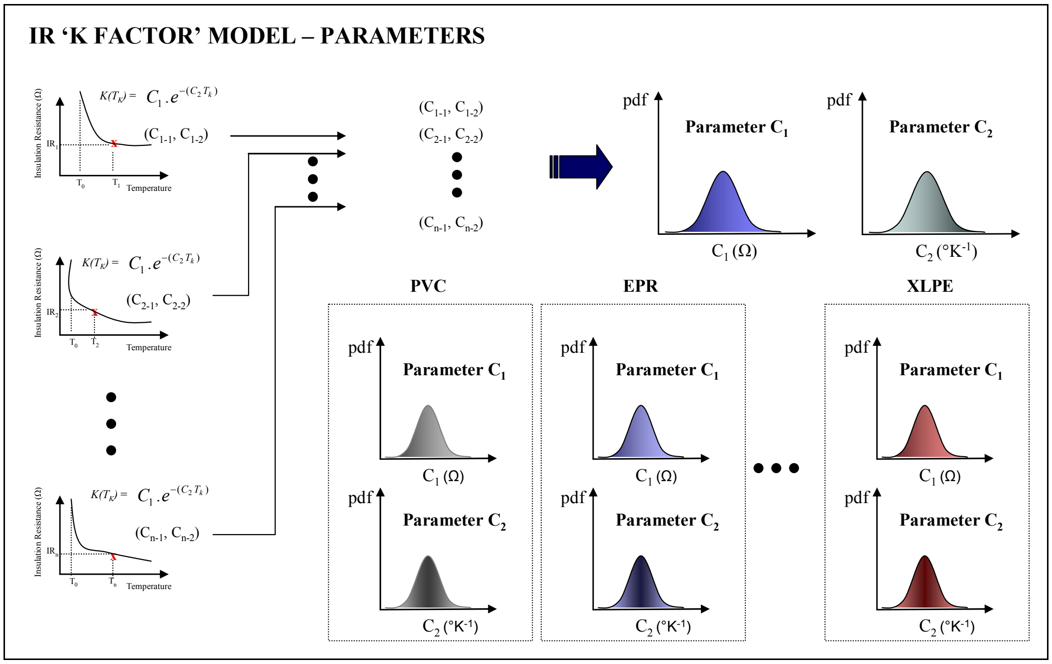


Figure 13. IR "K Factor" Model – Parameters

Contrary to the statement pointed out in EPRI (2002), the parameters C_1 and C_2 determined for a specific polymeric material using different databases are different, which can be explained given the different thermal exposure conditions in each one of these testing programs.

Table 6 and Table 7 contain the endurance limit (in terms of the IR levels) and the estimated parameters C_1 (in Ω) and C_2 (in $°K^{-1}$) for the polymeric materials evaluated based on the databases developed for NUREG/CR 6776 and Carolfire testing programs respectively.

Table 6. Damage-Endurance Parameters – IR "K Factor" Model (NUREG)

NUREG/CR 6776		PVC (1)	XLPE	EPR (2)	TEFZEL
IR Endurance limit (Ω)	Mean	3.29E+04	6.11E+03	1.06E+04	1.34E+04
	Standard Deviation	1.70E+04	2.43E+03	1.82E+04	6.75E+03
IR - C_1 (Ω)	Mean	5.53E+12	5.15E+11	7.61E+18	7.17E+10
	Standard Deviation	3.60E+14	3.99E+12	2.29E+20	2.50E+12
IR - C_2 ($°K^{-1}$)	Mean	2.75E-02	2.08E-02	4.07E-02	2.19E-02
	Standard Deviation	6.58E-03	1.52E-03	4.68E-03	5.70E-03

(1) Estimation based on one test.

(2) There was a significant variability in the assessment of the initial IR.

It is important to mention that at the time of this analysis, the Carolfire testing program is in progress; therefore, only few of the tests developed under this program were considered (see Appendix II).

The endurance limits are modeled as lognormal probability density functions for several reasons. First, the lognormal distribution fits very well with the experimental data available. Second, the IR at which the failures take place is a positive value than can be from 0 to thousand of ohms, depending on the particular thermal insult and cables properties. Third, the IR endurance limit can vary by order of magnitude, and intuitively it is assumed to be positively skewed. Therefore, the lognormal distribution is an appropriate choice.

Table 7. Damage-Endurance Parameters – IR “K Factor” Model (Carolfire)

CAROLFIRE		PVC	XLPE	EPR	TEFZEL(1)
IR Endurance limit (Ω)	Mean	2.19E+04	1.05E+04	7.82E+03	NA
	Standard Deviation	2.55E+04	8.66E+03	4.79E+03	NA
IR - C_1 (Ω)	Mean	1.00E+16	1.14E+15	3.03E+13	NA
	Standard Deviation	4.74E+18	9.02E+16	1.61E+14	NA
IR - C_2 (°K^{-1})	Mean	4.20E-02	2.83E-02	2.63E-02	NA
	Standard Deviation	1.01E-02	5.48E-03	3.97E-03	NA

(1) No Available.

Based on the empirical nature of this model, the IR endurance limits should be considered in association with the corresponding parameters C_1 and C_2. Therefore, it is not possible to infer consistent trends and behavior based on the comparison of the IR endurance limits from the different databases considered (NUREG/CR 6776 and Carolfire).

For example, comparing the IR endurance limits for EPR can be noted that the values coming from the NUREG/CR 6776 database are few orders of magnitude higher than the values derived from the Carolfire data base; however, in the latter, the corresponding values for the parameter C_1 are lower.

The high variability encountered in the characterization of C_1 is due to the diversity of electrical circuit arrangements and voltages (DC, AC, etc) and presumably cable's lengths and the configuration and calibration of the instrumentation and data acquisition systems used to measure the insulation resistance. Unfortunately, with the information available in the open literature was not possible to validate these statements.

Appendix IV contains the IR endurance limits probability density function of the polymeric materials evaluated under this research.

It is important to mention that the electrical response of electrical cables upon external thermal insults reveals that the precise selection of the IR endurance limit is irrelevant. Basically when the IR reached values below 5,000 ohms, the decrease of the IR drops so abruptly that for practical purposes select 5,000 ohms or 1,000 ohms lead to the same results for most of the cases (EPRI, 2002).

7. Damage-Endurance Model Development

As noted previously, when a cable is exposed to high temperatures different processes take place, among them creep, void growth, chemical decomposition, etc. In general, these failure mechanisms or physical/chemical processes whose occurrence either leads to or is caused by stress, can eventually deteriorate the cable strength or endurance.

As described by Modarres et al. (2005), different approaches have been successfully applied to asses the reliability of systems from a physic of failure perspective, among them the following can be mentioned (Modarres, 2006):

- **Stress-Induced Mechanisms**, which cause or are the result of localized stress (permanent or temporary). Example: elastic deformation, which disappears when the applied force is removed.
- **Strength-Reduced Mechanisms**, which lead to a reduction of the strength or damage endurance of the item. For example, radiation may cause material embrittlement, thus reducing the materials capacity to withstand cracks or other damages.
- **Stress-Increased Mechanisms**, their direct effect is an increase in the applied stress. For example, fatigue could cause permanent stress in an item.

In the particular case we are studying, the stress imposed by the high temperature caused by the external thermal insult can deteriorate the strength of the polymeric cable insulation to a point at which an imminent failure occurs; therefore, we are in the presence of a strength-reduced mechanisms which lead to a reduction of the strength or damage endurance of the cable (see Figure 14)

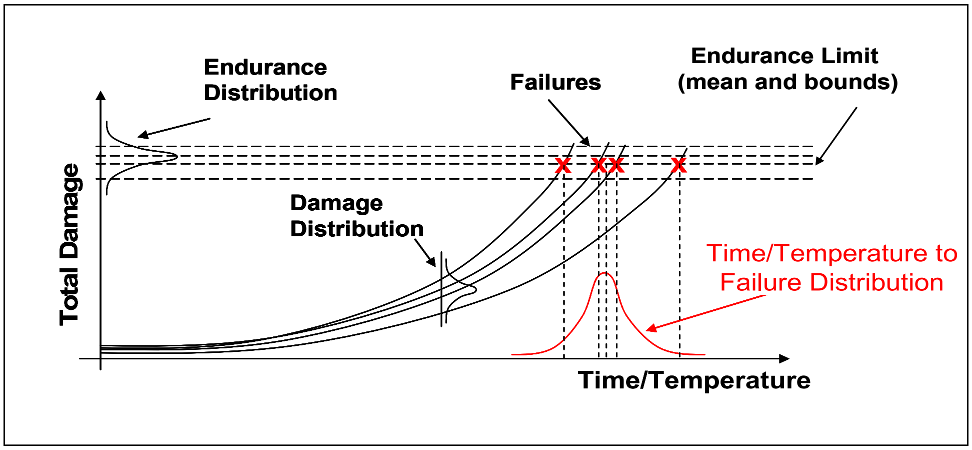


Figure 14. Damage Endurance Approach

As shown in Figure 14, the failure occurs when applied "thermal stress" causes permanent and irreversible damage in the polymeric cable insulation as a function of exposure time/temperature. When the damage reaches a threshold level that the item is unable to endure (endurance limit), the polymeric cable insulation looses its functional integrity (fails).

As mentioned before, the damage and endurance are not single values. Damage depends on a variety of factors particularly related to thermal exposure conditions, while endurance limit depends on polymeric material, but also is influenced by geometrical, structural, diffusional and mechanical factors (Shlensky, Akseno and Shashkov, 1991). Therefore, the damage and the endurance limit are characterized as distributions. Figure 14 shows how the interference of damage and endurance makes a statistical distribution of time/temperature to failure.

Under fire conditions, a temperature rise causes an irreversible degradation of the cable polymeric cover, and consequently a decrease of its mechanical properties that endures past the end of the thermal insult (Biron, 2004); however, it is important to mention that some experimental tests have shown some recovery/restoration process of the insulation capacity of the polymeric cover (Siu, 2000; La Chance, Nowlen and Wyant, 2003).

The general approach illustrated in Figure 14, was customized to each one of the engineering-based models of damage accumulation described in section 6, namely:

1. Kinetic model
2. Heat transfer model, and
3. IR "K Factor" model

Figure 15 shows a schematic of the damage endurance approach developed using the "Kinetic model" as the engineering-based model of damage accumulation.

A temperature rise causes a thermal degradation of the cable polymeric cover, denoted as $\alpha(t)$, which is compared to the corresponding thermal degradation endurance limit (see section 6.1). The interference of damage and endurance, in terms of percentage of thermal degradation (fraction of reaction), makes a statistical distribution of time/temperature to failure.

As shown in Figure 15, the parameters of the kinetic model used to assess the degradation process, the pre-exponential factor “A” and the activation energy “Ea” are characterized as probability distributions (see section 6).

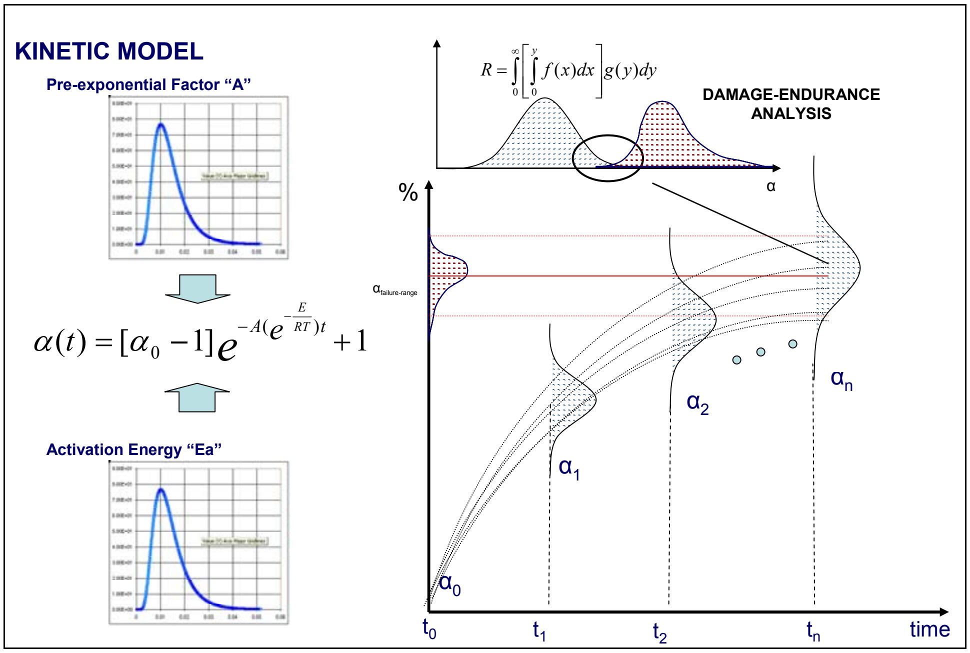


Figure 15. Damage-Endurance Approach- Kinetic Model

Due to scarcity of data and the lack of consistency in the characterization of the kinetic parameters, the kinetic model could not be developed to the same level as the heat transfer and IR “K Factor” models; however, its theoretical frame work has been described as a reference.

Figure 16 shows in schematic form the damage endurance approach developed using the heat transfer model as the engineering-based model of damage accumulation.

In this particular case, the external thermal insult increases the inner cable temperature (damage), estimated through equation (21), which is compared to the corresponding inner cable temperature endurance limit (see section 6.2). The interference of damage and endurance, in terms of inner cable temperature, makes a statistical distribution of time/temperature to failure.

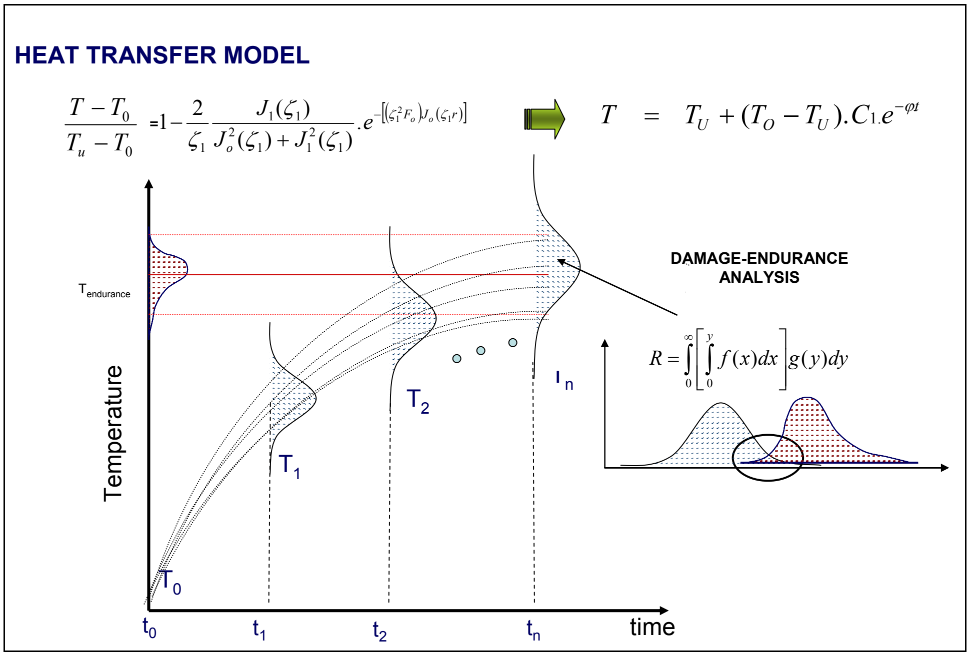


Figure 16. Damage-Endurance Approach- Heat Transfer Model

Figure 17 shows in schematic form the damage endurance approach developed using the IR “K Factor” model as the engineering-based model of damage accumulation.

In this particular case, the insulation resistance of the polymeric cover drops exponentially with increasing surrounding temperature. When the IR, estimated through equation (24) reaches values defined by the endurance limit (see section 6.3), the polymeric cable insulation looses its functional integrity and a failure occurs.

As shown in Figure 17, the parameters of the IR "K Factor model" (C_1 and C_2) are characterized as probability distributions (see section 6).

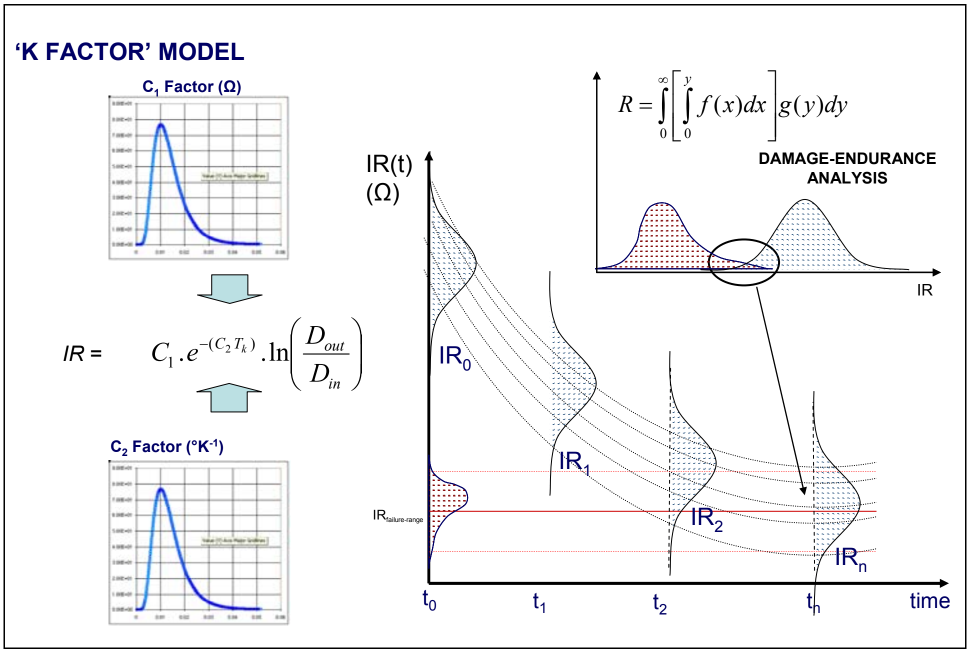


Figure 17. Damage-Endurance Approach- "K Factor" Model

The damage-endurance approach proposed is based on the comparison of the degradation level of the polymeric cable insulation in terms of fraction of reaction, inner cable temperature and IR, when it is exposed to an external thermal insult, to the corresponding endurance limit. Based on this comparison the probability of fire-induced cable damage is estimated.

As described in section 6, an endurance limit was estimated for each one of the polymeric materials considered for the kinetic, heat transfer and IR models. On the other hand, the parameters of these models for each one of the material considered were determined based on the fundamental physics principles and the experimental data collected.

Once the endurance limits and the parameters of the models are defined, the current level of degradation, in terms of thermal decomposition, inner cable temperature or insulation resistance (depending on the selected model) is compared to the respective endurance limit. The level of degradation is computed in a time base scale and depends on the dynamic behavior of the fire and the characteristic of the polymeric material under evaluation.

As noted, the application of the heat transfer model or IR "K factor" model to estimate the probability of fire-induced cable damage, given a specified fire, requires the following steps:

- Determine the time-temperature profile in the surrounding area of the target cable.
- Estimate the inner cable temperature in case of heat transfer model, or the insulation resistance in case of IR "K Factor" model.
- Apply the heat transfer or insulation resistance damage endurance model using the endurance limits estimated experimentally.

For a given fire, characterized for a particular time-temperature profile, the probability of cable damage is estimated in a time base scale. This probability of cable damage represents the expected probability of cable damage (to a degree at which a short circuit can take place) for a specific exposure time given a characterized fire.

It is important to mention that the failure behavior and the transient thermal response in the models proposed are characterized probabilistically, so the model's output is not a single cable damage time, but rather, a probability distribution of the likelihood of damage versus time. This type of probabilistic approach will allow for a direct method of incorporating failure time uncertainty into a risk analysis estimate (e.g. core damage frequency).

8. Result Analysis and Validation

8.1. Kinetic Model

As indicated before, due to the scarcity of data, the uncertainty about the specific kinetic equation describing the thermal decomposition process, and the lack of consistency in the characterization of the kinetic parameters, the kinetic model could not be developed to the same level as the heat transfer and IR “K Factor” models; however, its theoretical framework has been described as a reference.

As discussed in previous sections, the following aspects should be considered for the further development of this model:

- Not in all cases, thermal degradation is accompanied by the release of volatiles, leading to a decrease in mass of the polymer under consideration. In fact, the introduction of fillers and additives incorporated in the manufacturing process try to modify this expected behavior, in terms of their physicochemical and mechanical properties.
- Most of the kinetic models described in section 4.3, in the simplest case suggest sigmoid kinetic weight-loss curve vs. temperature. However, this sigmoid curve behavior is valid for well characterized material, which properties and kinetic parameters (the order of reaction, the pre-exponential factor and the activation energy) remain almost constant through the entire thermal degradation process (Budrugeac, 2001); or as it is indicated by Bryk et al. (1991), in spite of the multistage process, the reaction orders and

activation energies of individual stages are close enough to create a clean "average" sigmoid kinetic weight-loss curve.

- The addition of additives and fillers in the manufacturing process of commercial cables has the objective to change particular properties of a polymeric composite, and probably the kinetic parameters of individual stages of the thermal degradation process are considerably different from each other, leading to a very unpredicted combination of two or more sigmoidal behavior (Bryk, 1991). In some cases the rate of degradation changes, depending of the nature of polymer added, on the degree of miscibility of the polymer pair or on the interaction of degradation products (Andricic, Kovacic, Ivka, 2002). Some studies have suggested alternatives methods to deal with the kinetic analysis of the degradation of polymer composites (Bryk, 1991).
- The thermal responses derived from the use of kinetic equation described in Section 4.3, assume a constant heating rate to predict the thermal degradation of a polymer. According to Shlensky, Akseno and Shashkov et al. (1991), kinetic equations described in section 4.3, are not appropriate to describe the kinetics of non-isothermal decomposition of polymers. In this reference, it is pointed out that thermal decomposition of solids is influenced by geometrical, structural, diffusional and mechanical factors that under certain conditions may play a dominant role. Additionally, Montserrat and Malek et al. (1998) concluded that kinetic parameters obtained by kinetic analysis of isothermal and non-isothermal data are different, which reveals that the time-temperature profile can affect the dynamic of the thermal degradation process.

- The dehydrochlorination that takes place during the thermal degradation of polymer is an autocatalytic mechanism, for that reason in the PVC formulation for wire/cable insulation C_aCO_3 or similar filler is used to break the autocatalytic process. On the other hand, considering that initiation sites for dehydrochlorination depend on different factors, particular structural abnormalities, it can't be modeled and predicted from a representation of an ideal polymer (Babrauskas, 2005).

In the future, with the development of further kinetic analyses, a better understanding of the kinetic interrelation in the thermal degradation process of polymeric materials, and a more accurate characterization of the kinetic parameters of thermoplastic and thermosets materials will be possible to evaluate the feasibility of this particular model.

8.2. Heat Transfer Model

The inner cable temperature endurance limit of electrical cables with different polymeric materials was estimated using equations (19) to (21) and the results of the experimental tests described in Appendix II (see section 4).

Table 8 and Table 9 summarize the resulting inner cable temperature endurance limits for thermoplastic (PVC and PE) and thermosets (XLPE and EPR) commercial cable polymeric materials, respectively.

Table 8. Inner Cable Temperature Endurance Limits – Heat Transfer Model (Thermoplastic)

Material/ Data Base	**PVC**			**PE**		
	CAROLFIRE	NUREG 6776	EPRI 1003326	CAROLFIRE	NUREG 6776	EPRI 1003326
Mean (°K)	4.93E+02	NA	4.56E+02	5.23E+02	NA	4.52E+02
Standard Deviation	1.97E+01	NA	3.18E+01	1.05E+01	NA	4.08E+01

Table 9. Inner Cable Temperature Endurance Limits – Heat Transfer Model (Thermosets)

Material/ Data Base	**XLPE**			**EPR**		
	CAROLFIRE	NUREG 6776	EPRI 1003326	CAROLFIRE	NUREG 6776	EPRI 1003326
Mean (°K)	6.66E+02	6.58E+02	6.72E+02	6.92E+02	7.23E+02	7.04E+02
Standard Deviation	3.33E+01	3.02E+01	4.26E+01	1.44E+01	3.84E+01	5.50E+01

As can be observed in Table 8, considering only the mean values, the inner temperature endurance limit for thermoplastic insulated cables is about 452 °K to 523 °K (179 °C to 250 °C). This range is closed to the cable temperature endurance limit reported in NEA (2000) for conventional cables, which goes from 423 °K to 523 °K (150 °C to 250 °C).

From Table 9, considering only the mean values, the inner cable temperature endurance limit for thermosets insulated cables is about 658 °K to 723 °K (385 °C to 450 °C). The lower temperature to cable damage for thermosets cables reported by Miranda et al. (1999) varies from 572 °K (299 °C) to 633 °K (360 °C), which are slightly lower than the endurance limits pointed out in Table 9.

8.2.1.Heat Transfer Model: Constant Inner Cable Temperature

Given a characterized fire, the probability of cable damage can be estimated comparing the inner cable temperature, estimated through the equation (21) or any other plausible heat transfer model, to the particular endurance limit of the material considered.

As an example, a cable with a commercial XLPE insulation is considered in the next analysis. Figure 18 shows the inner cable temperature endurance limit, represented by the distribution g(y), according to Carolfire database for this particular polymeric material.

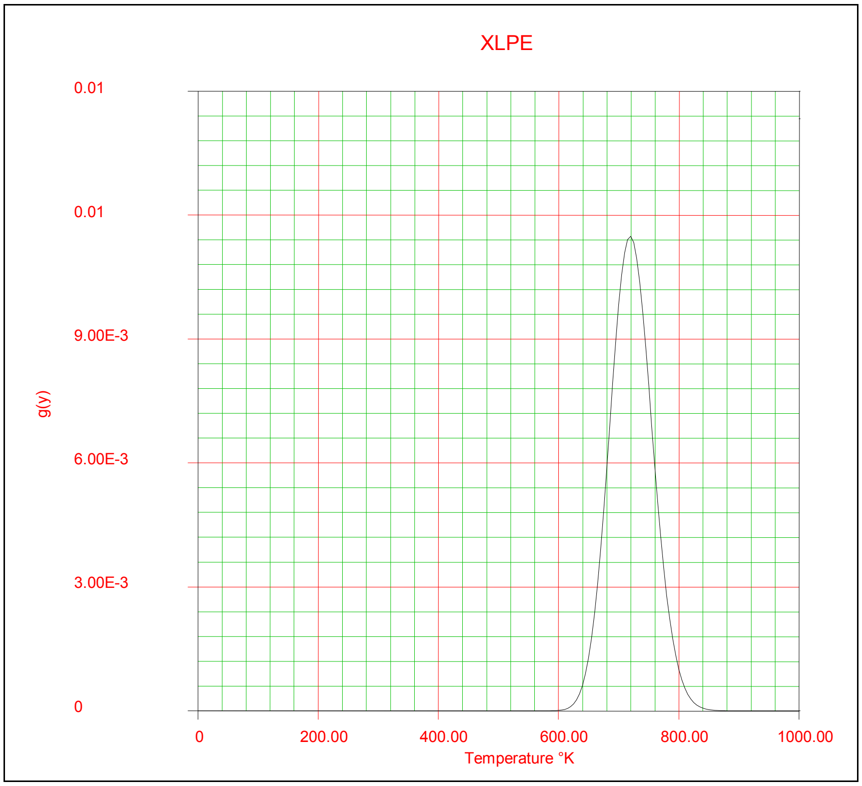


Figure 18. XLPE Endurance Limit – Heat Transfer Model (Carolfire)

Given a hypothetical fire scenario, where a temperature T_a in the surrounding area is reached, and a corresponding temperature $T_{a'}$ is estimated in the inner section of the cable, the probability of cable damage capable of creating a short circuit condition can be estimated as (Ebeling, 1997):

$$Pfalla = P(Endurance \leq Damage) = \int_{-\infty}^{T_{a'}} g(y) d_y \qquad (25)$$

where:

$T_{a'}$: inner cable temperature (°K)

$g(y)$: endurance limit probability density function

y: random variable representing the endurance (°K)

Figure 19 shows a typical scenario, where the damage "d" is represented by a constant temperature $T_{a'}$ and the endurance limit is a random variable having a probability density function g(y).

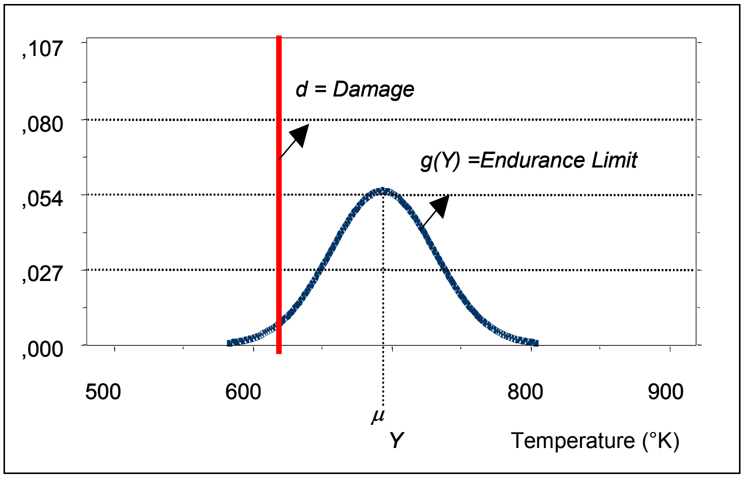


Figure 19. Damage-Endurance Model (XLPE) – Heat Transfer Model

Solving equation (25) numerically for values of T_a, from 573°K to 783°K (300°C to 510°C) and the endurance limit given by a log-normal probability density function whose means and standard deviations are given in Table 9 for the three databases considered, the probability of cable damage shown in Table 10 is obtained.

Table 10. Probability of Cable Damage (Constant Inner Cable Temperature) – Heat Transfer Model (XLPE)

Temperature °C	Temperature °K	**XLPE**		
		CAROLFIRE	NUREG 6776	EPRI 1003326
300	573	0.00	0.00	0.01
305	578	0.00	0.00	0.01
310	583	0.01	0.01	0.01
315	588	0.01	0.01	0.02
320	593	0.01	0.02	0.03
325	598	0.01	0.02	0.04
330	603	0.02	0.03	0.05
335	608	0.04	0.05	0.06
340	613	0.05	0.06	0.08
345	618	0.07	0.09	0.10
350	623	0.09	0.12	0.13
355	628	0.13	0.16	0.15
360	633	0.17	0.21	0.18
365	638	0.21	0.26	0.22
370	643	0.26	0.31	0.25
375	648	0.31	0.37	0.29
380	653	0.35	0.44	0.34
385	658	0.41	0.51	0.38
390	663	0.47	0.57	0.42
395	668	0.53	0.64	0.47
400	673	0.59	0.70	0.51
405	678	0.65	0.76	0.55
410	683	0.70	0.80	0.60
415	688	0.74	0.84	0.64
420	693	0.79	0.87	0.68
425	698	0.82	0.91	0.72
430	703	0.86	0.93	0.76
435	708	0.89	0.95	0.79
440	713	0.92	0.96	0.83
445	718	0.94	0.98	0.86
450	723	0.95	0.98	0.88

Table 10 (Continuation)

Temperature °C	Temperature °K	XLPE		
		CAROLFIRE	NUREG 6776	EPRI 1003326
455	728	0.96	0.99	0.90
460	733	0.97	0.99	0.92
465	738	0.98	~1.00	0.93
470	743	0.98	~1.00	0.95
475	748	0.99	~1.00	0.96
480	753	0.99	~1.00	0.97
485	758	0.99	~1.00	0.97
490	763	~1.00	~1.00	0.98
495	768	~1.00	~1.00	0.98
500	773	~1.00	~1.00	0.99
505	778	~1.00	~1.00	0.99
510	783	~1.00	~1.00	~1.00

As can be observed in the table above, the minimum inner cable temperature capable of initiating certain level of damage to the XLPE cable insulation is about 603°K (330°C), 598°K (325°C), and 588°K (315°C) for the Carolfire, NUREG/CR 6776 and EPRI 1003326 databases, respectively. For temperatures higher than 753°K (480°C) the probability of cable damage for this particular polymeric material is close to 1 for all databases considered. The EPRI 1003326 database represents the maximum dispersion in the inner temperature endurance limit; however, the probability of damage at a specific temperature follows the same pattern for all databases.

Appendix V contains the probability of cable damage at different inner temperatures for the remaining materials evaluated in this research.

Figure 20 and Figure 21 show the results of probability of cable damage estimated using the previous procedure for thermoplastics (PVC and PE) and thermosets (XLPE and EPR) respectively.

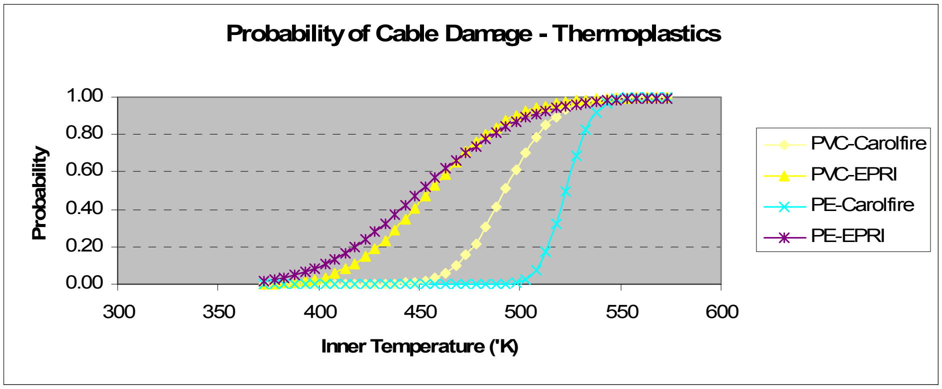


Figure 20. Probability of Cable Damage (Constant Inner Cable Temperature) – Heat Transfer Model (Thermoplastic)

For thermoplastics, as can be noted from the graph above, the probability of cable damage for inner temperature lower than 373 °K (100 °C) is negligible. Basically the minimum trigger temperature estimated is about 400 °K (127 °C), above which the probability increases significantly. For temperature higher than 548 °K (275 °C), the probability of cable damage tend to 1 for all of the cable analyzed.

The curves corresponding to PE for both databases considered (Carolfire and EPRI 1003326) differs significantly. In the Carolfire testing program, most of the tests carried out using PE insulation cable experienced failures consistently in the range from 500 °K (227 °C) to 548 °K (275 °C). However, during the EPRI testing program the variability observed in the thermal behavior of PE was significantly higher. It is important to mention that only few tests from the

Carolfire testing program were considered as part of this evaluation, mainly small scale tests, while the EPRI testing program involved large scale tests (see Table 2).

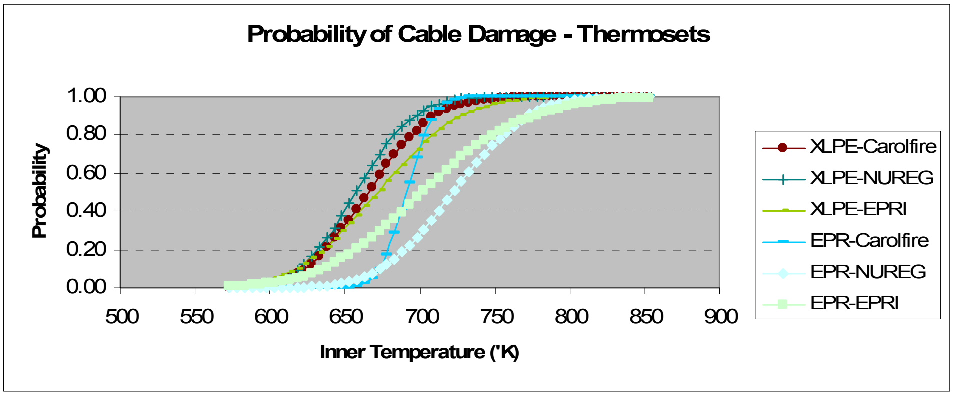


Figure 21. Probability of Cable Damage (Constant Inner Cable Temperature) – Heat Transfer Model (Thermosets)

For thermosets, as can be noted, the probability of cable damage for inner temperature lower than 600 °K (327 °C) is negligible. Basically the trigger temperature is about 625 °K (352 °C), above which the probability increases significantly. In general, for temperatures higher than 753°K (480°C) the probability tends to 1.

The curves corresponding to both thermosets materials evaluated (XLPE and EPR) for both databases (Carolfire and EPRI 1003326) are similar, revealing a consistent thermal behavior.

Figure 22 summarizes in the same chart the results of probability of cable damage estimated for thermoplastics (PVC and PE) and thermosets (XLPE and EPR). In this figure the differences in the inner temperature endurance limit for thermoplastic and thermosets materials can be observed.

As can be noted in Figure 22, for the same inner temperature the probability of damage is higher in thermoplastics cables compared to thermosets cables as expected.

Figure 22 also reveals that the variability in the estimation of probability of cable damage for thermoplastic materials (PVC and PE) is greater than for thermosets. The comparison of the thermal behavior of the two thermosets materials evaluated (XLPE and EPR) shows more consistency. In general, the analysis of the data provided for the fire testing programs considered reveals a higher level of consistency in the thermal behavior of thermosets in comparison to thermoplastics.

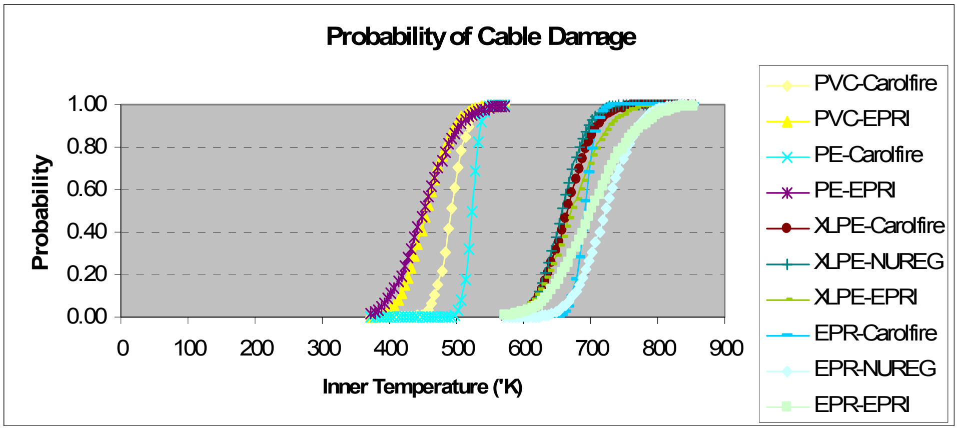


Figure 22. Probability of Cable Damage (Constant Inner Cable Temperature) – Heat Transfer Model

8.2.2.Heat Transfer Model: Random Inner Cable Temperature

Similar to the constant damage case, given a characterized fire the probability of cable damage can be estimated by comparing the inner cable temperature to the specific endurance limit of the material considered. However, given the uncertainties of thermal properties, exposure conditions and physical dimension and arrangement of cables it is expected to have a degree of uncertainty in the estimation of the inner cable temperature. This uncertainty should be considered if a more realistic estimation is required.

As an example, a commercial cable with PVC insulation is considered in the next analysis, in which the uncertainty in the estimation of the inner cable temperature is considered.

Figure 23 shows the inner cable temperature endurance limit, according to Carolfire database, for PVC cable polymeric material.

Given a hypothetical fire scenario with a temperature T_a in the surrounding cable area and an estimated temperature $T_{a'}$ in the inner section of the cable defined by a probability density function f(x), the probability of cable damage can be estimated as (Ebeling, 1997):

$$Pfalla = P(Endurance \leq Damage) = 1 - \int_0^\infty \left[\int_0^y f(x) d_x \right] g(y) d_y \qquad (26)$$

where:

f(x): damage probability density function (inner cable temperature °K).

g(y): endurance limit probability density function.

y: random variable representing the endurance (°K).

x: random variable representing the damage (°K).

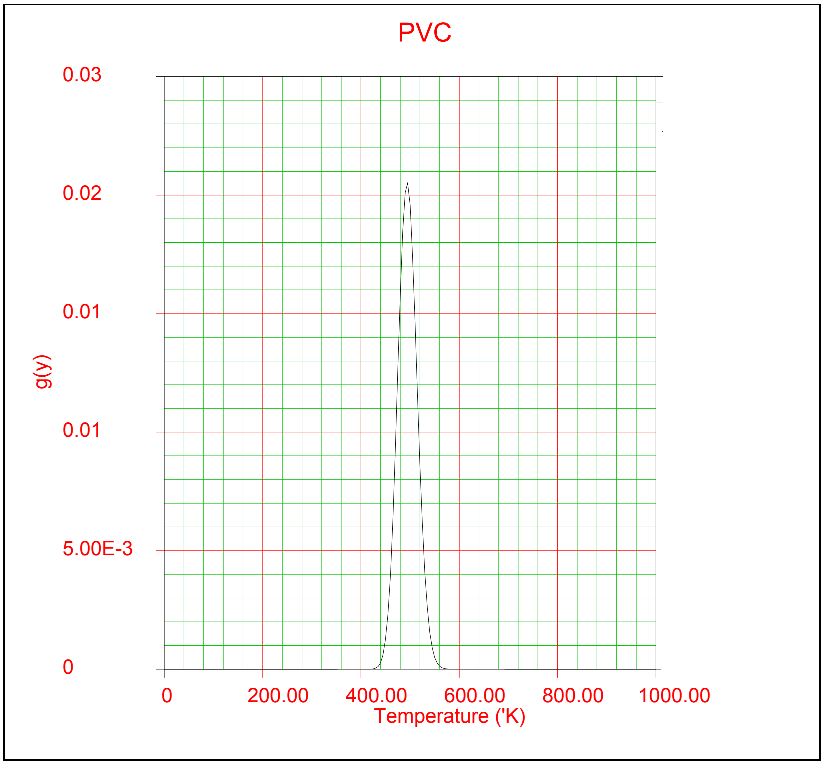


Figure 23. PVC Endurance Limit – Heat Transfer Model (Carolfire)

Figure 24 shows this typical scenario, where the damage represented by a temperature $T_{a'}$ is defined by a probability density function f(x) and the endurance limit is a random variable having a probability density function g(y).

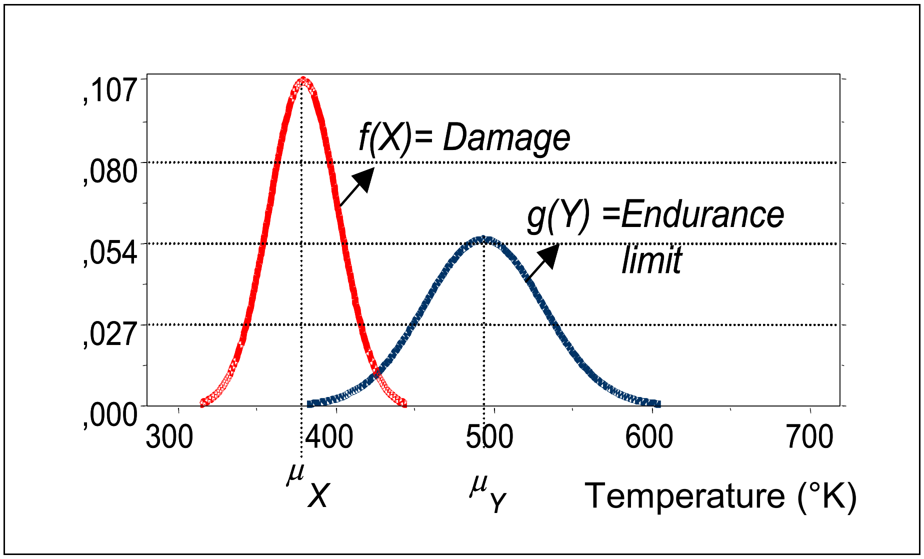


Figure 24. Damage-Endurance Model (PVC) – Heat Transfer Model

Solving equation (26) numerically for a damage f(x) and an endurance level g(y) given by log-normal probability density functions whose means and standard deviations are given in Table 8, the probability of cable damage shown in Table 11 is obtained.

Appendix VI contains the probability of cable damage at different inner temperatures (characterized probabilistically) for the remaining materials evaluated in this research.

Table 11. PVC Probability of Cable Damage – Heat Transfer Model

Temperature °K (mean, std. dev.)	PVC		
	CAROLFIRE	NUREG 6776	EPRI 1003326
(373, 37.3)	0.00	NA	0.05
(378, 37.8)	0.01	NA	0.05
(383, 38.3)	0.01	NA	0.07
(388, 38.8)	0.01	NA	0.08
(393, 39.3)	0.02	NA	0.11
(398, 39.8)	0.02	NA	0.13
(403, 40.3)	0.03	NA	0.14
(408, 40.8)	0.04	NA	0.17
(413, 41.3)	0.04	NA	0.19
(418, 41.8)	0.06	NA	0.23
(423, 42.3)	0.07	NA	0.25
(428, 42.8)	0.08	NA	0.28
(433, 43.3)	0.11	NA	0.31
(438, 43.8)	0.12	NA	0.35
(443, 44.3)	0.16	NA	0.39
(448, 44.8)	0.18	NA	0.42
(453, 45.3)	0.21	NA	0.47
(458, 45.8)	0.25	NA	0.50
(463, 46.3)	0.27	NA	0.53
(468, 46.8)	0.29	NA	0.57
(473, 47.3)	0.33	NA	0.60
(478, 47.8)	0.37	NA	0.63
(483, 48.3)	0.42	NA	0.68
(488, 48.8)	0.46	NA	0.70
(493, 49.3)	0.49	NA	0.71
(498, 49.8)	0.54	NA	0.77
(503, 50.3)	0.57	NA	0.78
(508, 50.8)	0.60	NA	0.81
(513, 51.3)	0.64	NA	0.83
(518, 51.8)	0.65	NA	0.84
(523, 52.3)	0.69	NA	0.86
(528, 52.8)	0.74	NA	0.88
(533, 53.3)	0.76	NA	0.89
(538, 53.8)	0.79	NA	0.91
(543, 54.3)	0.82	NA	0.92
(548, 54.8)	0.83	NA	0.93
(553, 55.3)	0.84	NA	0.94
(558, 55.8)	0.86	NA	0.94
(563, 56.3)	0.89	NA	0.96
(568, 56.8)	0.90	NA	0.96
(573, 57.3)	0.91	NA	0.97
(578, 57.8)	0.92	NA	0.97
(583, 58.3)	0.93	NA	0.98
(588, 58.8)	0.94	NA	0.98

Table 11 (Continuation)

Temperature °K (mean, std. dev.)	PVC		
	CAROLFIRE	NUREG 6776	EPRI 1003326
(593, 59.3)	0.95	NA	0.98
(598, 59.8)	0.96	NA	0.99
(603, 60.3)	0.97	NA	0.99
(608, 60.8)	0.97	NA	0.99
(613, 61.3)	0.98	NA	0.99
(618, 61.8)	0.98	NA	0.99
(623, 62.3)	0.99	NA	~1.00
(628, 62.8)	0.99	NA	~1.00
(633, 63.3)	0.99	NA	~1.00
(638, 63.8)	0.99	NA	~1.00
(643, 64.3)	0.99	NA	~1.00
(648, 64.8)	0.99	NA	~1.00
(653, 65.3)	~1.00	NA	~1.00
(658, 65.8)	~1.00	NA	~1.00
(663, 66.3)	~1.00	NA	~1.00
(668, 66.8)	~1.00	NA	~1.00
(673, 67.3)	~1.00	NA	~1.00

Figure 25 and Figure 26 show the probability of cable damage estimated using the previous procedure for thermoplastics (PVC and PE) and thermosets (XLPE and EPR) respectively.

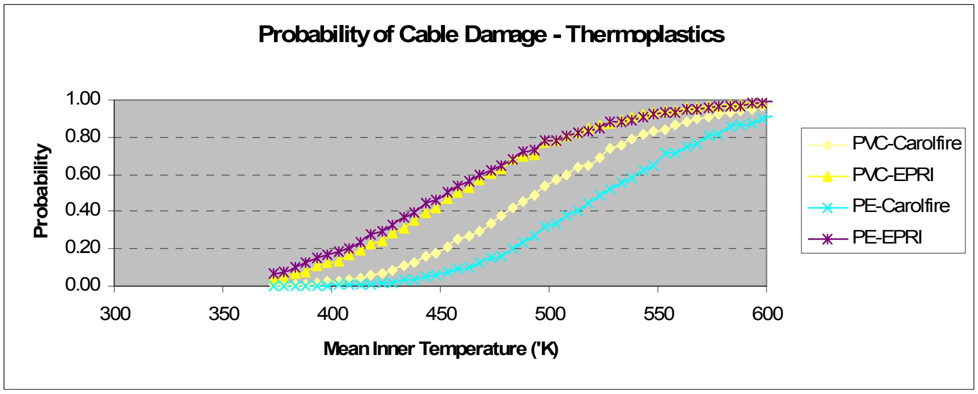


Figure 25. Probability of Cable Damage (Random Inner Cable Temperature) – Heat Transfer Model (Thermoplastic)

For thermoplastics, the behavior in terms of probability of cable damage is similar to the one encountered for constant damage (Figure 20), with the peculiarity that the spam of temperatures is wider as expected considering the distributed damage. The same conclusion can be inferred from Figure 26 and Figure 21 for thermosets.

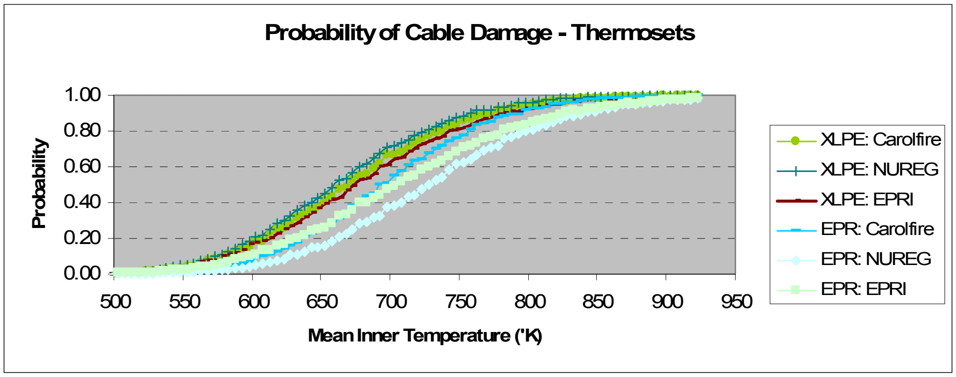


Figure 26. Probability of Cable Damage (Random Inner Cable Temperature) – Heat Transfer Model (Thermosets)

Figure 27 summarizes in the same chart the probability of cable damage estimated for thermoplastics (PVC and PE) and thermosets (XLPE and EPR). In this Figure, the difference in the inner temperature endurance limit for thermoplastics and thermosets materials can be observed. However, there is certain level of overlapping in the range of temperatures for thermoplastic and thermosets, which is due to the distributed nature of the damage considered.

It is important to mention that Figure 25, Figure 26 and Figure 27 represent only the mean of the damage (inner cable temperature), but as indicated in Table 11, each damage level is defined as a lognormal distribution whose standard deviation is 10% of the corresponding mean.

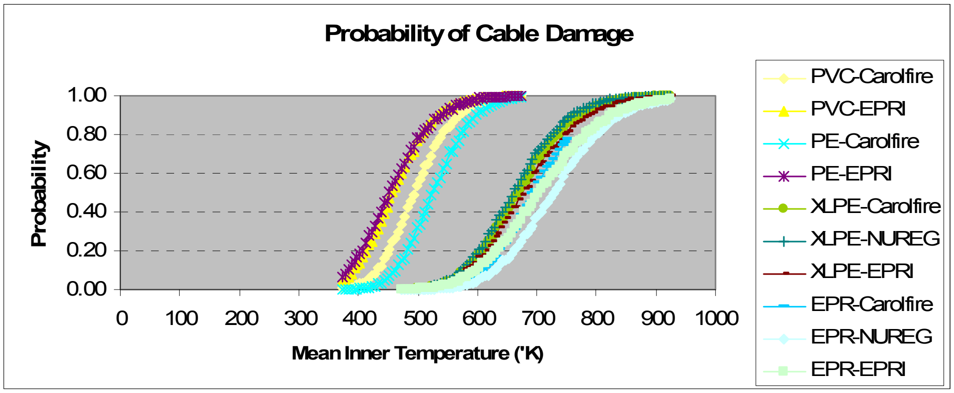


Figure 27. Probability of Cable Damage (Random Inner Cable Temperature) – Heat Transfer Model

8.2.3.Heat Transfer Model: Time-Temperature Profile

In the previous sections the prediction of cable damage was based on scenarios where a specific surrounding temperature was assumed, and the corresponding inner temperature was also assumed either as a point estimate or as a parametric distribution. However, in real fire scenarios the surrounding temperature varies as a function of time, depending on, factors such as exposure type, environmental context, the existence of mitigating systems, among others.

Consequently, in real fire scenarios the temperature around the target cables is characterized by a time-temperature profile P(t,T). Therefore, the probability of cable damage should be determined based on this time-temperature profile.

The first step is to estimate the corresponding inner cable temperature given the time-temperature profile P(t,T). Once the inner time-temperature profile has been estimated (dynamic damage level), the damage-endurance model described in section 7 can be applied.

Appendix VII shows some test scenarios taken from the Carolfire testing program, in which the inner cable temperature for a given time temperature profile has been estimated using equation (24). As observed in these examples, the estimated inner cable temperature follows the real temperature measured with thermocouples installed in the cables during the tests.

To better understand this model, a practical example considering thermoplastics (PVC, PE) and thermosets (XLPE, EPR) is developed. All assumptions pointed out in section 4.4 are considered; namely:

- Cables are modeled as homogeneous and infinite cylinders.
- No internal heat generation is considered.
- Heat losses through the conductors are not considered.
- Constant thermal parameters.
- Uniform initial temperature.

All four cables considered (PVC, PE, XLPE and EPR) represent single conductor cables with an internal radius of 0.0041 m and an insulation thickness of 1.91 mm.

Table 12 shows the values of thermal conductivity and diffusivity used in this practical application for each one of the polymeric materials considered (DuPont, 2006).

First of all, the inner time-temperature profile for a given surrounding time-temperature profile should be estimated. As an example, assume the surrounding time-temperature profile depicted in Figure 28.

Table 12. Thermal Properties – Heat Transfer Model

Thermal Properties		PVC	XLPE	EPR	PE	TEFZEL	EP
Thermal Conductivity (W/K.m)	5th percentile	0.15	0.17	0.30	0.30	0.20	0.25
	95th percentile	0.22	0.24	0.40	0.37	0.28	0.35
Thermal Diffusivity (m^2/s)	5th percentile	8.00E-08	8.70E-08	8.50E-08	6.33E-07	3.50E-08	8.50E-08
	95th percentile	3.50E-06	1.33E-07	1.20E-07	3.50E-06	8.00E-07	1.25E-07

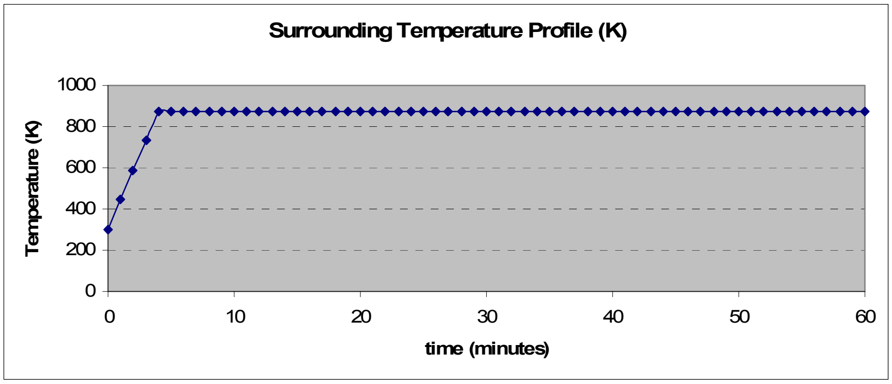


Figure 28. Surrounding Time-Temperature Profile – Heat Transfer Model

Figure 29 and Table 13 show the 10th percentile, mean and 90th percentile of the inner cable temperature estimated for EPR using equation (21) and the assumptions described above. As can be observed, initially the inner cable temperature is lower than the surrounding temperature, but the former starts increasing exponentially. Step by step the inner temperature tends to equate the surrounding temperature.

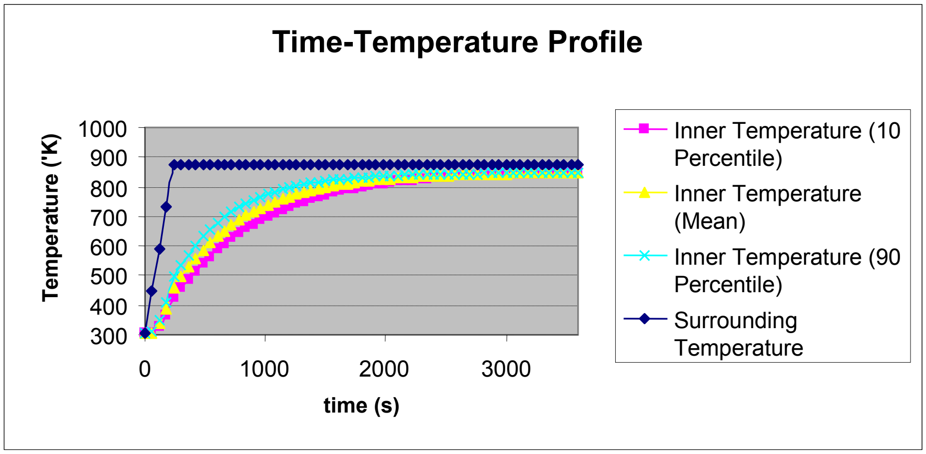


Figure 29. EPR Inner Cable Temperature – Heat Transfer Model (Carolfire)

The uncertainty observed in the inner cable temperature estimated, is due primarily to the probabilistic characterization of the thermal properties (see Table 12).

As shown in Figure 30, given the higher thermal diffusivity assigned to thermoplastics, the inner cable temperatures estimated for PVC and PE follow in a faster way the patter of the surrounding temperature. Therefore, according to the thermal properties selected, for the same surrounding temperature the inner temperature in a thermoplastic insulated cable is higher than a thermosets insulated cable.

Table 13. EPR Inner Cable Temperature – Heat Transfer Model (Carolfire)

time (s)	time (m)	Surrounding temperature (°C)	Surrounding temperature (°K)	Inner Cable Temperature (°K)		
				10 Percentile	Mean	90 Percentile
0	0	30	303	303	303	303
60	1	173	446	303	307	310
120	2	315	588	325	336	348
180	3	458	731	366	388	411
240	4	600	873	424	458	494
300	5	600	873	457	495	535
360	6	600	873	487	528	571
420	7	600	873	515	558	603
480	8	600	873	541	586	631
540	9	600	873	565	610	656
600	10	600	873	587	632	678
660	11	600	873	608	653	697
720	12	600	873	626	671	715
780	13	600	873	644	687	730
840	14	600	873	660	702	743
900	15	600	873	674	716	755
960	16	600	873	688	728	766
1020	17	600	873	701	739	775
1080	18	600	873	713	749	783
1140	19	600	873	723	758	790
1200	20	600	873	733	766	797
1260	21	600	873	742	774	803
1320	22	600	873	751	781	808
1380	23	600	873	759	787	812
1440	24	600	873	766	792	816
1500	25	600	873	773	798	819
1560	26	600	873	779	802	822
1620	27	600	873	785	806	825
1680	28	600	873	790	810	827
1740	29	600	873	795	814	829
1800	30	600	873	799	817	831
1860	31	600	873	803	820	833
1920	32	600	873	807	822	834
1980	33	600	873	811	825	836
2040	34	600	873	814	827	837
2100	35	600	873	817	829	838
2160	36	600	873	820	831	839
2220	37	600	873	822	832	839
2280	38	600	873	825	834	840
2340	39	600	873	827	835	841
2400	40	600	873	829	836	841

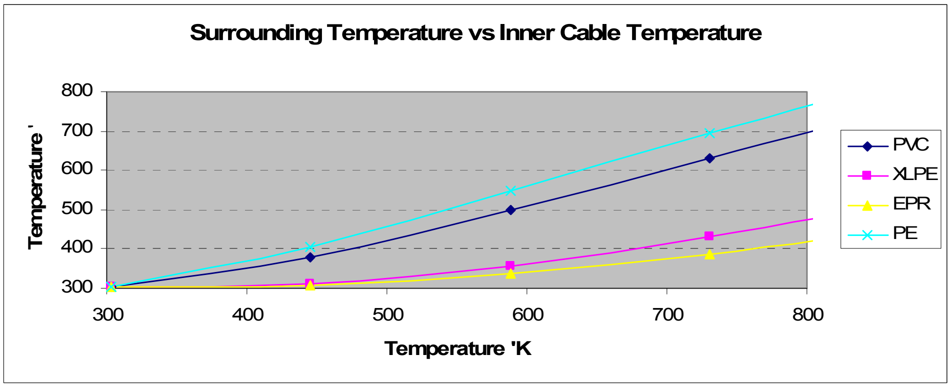


Figure 30. Surrounding Temperature vs. Inner Cable Temperature – Heat Transfer Model

Once the inner cable temperature has been determined (damage level), the probability of cable damage can be estimated comparing the inner temperature of the cable to the specific damage endurance limit of the material considered (see Table 9). This calculation can be performed at each instant of time during the fire exposure.

Table 14 shows the probability of cable damage (P_{CD}) for EPR using the endurance limit defined for the three databases considered (Carolfire, NUREG and EPRI).

Values in Table 14 represent the probability of cable damage at a time "t_i" given the time-temperature profile P(t,T) depicted in Figure 28 (Table 13). As expected, the longer the exposure to the thermal insults, the higher the probability of cable damage. This model takes into account the temperature and the time of exposure.

Table 14. EPR Probability of Cable Damage – Heat Transfer Model

time (m)	**Temperature °C:**	**Temperature °K:**	**Probability of Cable Damage: EPR**		
			Carolfire	NUREG 6776	EPRI 1003326
0	30	303	0.00	0.00	0.00
1	173	446	0.00	0.00	0.00
2	315	588	0.00	0.00	0.00
3	458	731	0.00	0.00	0.00
4	600	873	0.00	0.00	0.00
5	600	873	0.00	0.01	0.02
6	600	873	0.00	0.03	0.06
7	600	873	0.00	0.05	0.13
8	600	873	0.00	0.12	0.21
9	600	873	0.01	0.20	0.31
10	600	873	0.06	0.30	0.41
11	600	873	0.15	0.38	0.50
12	600	873	0.30	0.48	0.59
13	600	873	0.46	0.57	0.66
14	600	873	0.64	0.65	0.73
15	600	873	0.77	0.72	0.78
16	600	873	0.87	0.79	0.81
17	600	873	0.93	0.83	0.85
18	600	873	0.96	0.87	0.88
19	600	873	0.98	0.90	0.90
20	600	873	0.99	0.92	0.92
21	600	873	~1.00	0.94	0.94
22	600	873	~1.00	0.96	0.94
23	600	873	~1.00	0.97	0.95
24	600	873	~1.00	0.97	0.96
25	600	873	~1.00	0.98	0.96
26	600	873	~1.00	0.98	0.97
27	600	873	~1.00	0.99	0.98
28	600	873	~1.00	0.99	0.98
29	600	873	~1.00	0.99	0.98
30	600	873	~1.00	0.99	0.98
31	600	873	~1.00	0.99	0.99
32	600	873	~1.00	0.99	0.99
33	600	873	~1.00	0.99	0.99
34	600	873	~1.00	0.99	0.99
35	600	873	~1.00	0.99	0.99
36	600	873	~1.00	~1.00	0.99
37	600	873	~1.00	~1.00	0.99

In the next paragraphs the results of applying the previous model to different polymeric materials under different time-temperature profiles are discussed. Basically the same assumptions considered in the previous application case are assumed. Regarding the time-temperature profile, it is assumed that the initial temperature in the surrounding area is 303 °K (30 °C), and it takes 4 minutes to reach the steady state temperature, so when a scenario is defined by a nominal temperature of 673 °K (400 °C), the time-temperature profile is given by:

- An initial surrounding temperature of 303 °K (30 °C).
- A linear ramp-up of 4 minutes to reach the nominal temperature (673 °K / 400 °C).
- After 4 minutes, a constant temperature (nominal temperature: 673 °K / 400 °C).

All the scenarios have been evaluated for an exposure time of 15 minutes; therefore, the reported probability corresponds to the probability of cable damage (P_{CD}) at 15 minutes given the time-temperature profile depicted in Figure 28.

Table 15 shows the probability of cable damage for 16 different time-temperature profiles, starting from a nominal temperature of 373 °K (100 °C), to a maximum nominal temperature of 1073 °K (800 °C). The P_{CD} was estimated according to the endurance limit defined using the Carolfire database.

Table 15. Probability of Cable Damage (%) – Heat Transfer Model (Carolfire)

Temperature °C:	**Temperature °K:**	**CAROLFIRE Database**			
		PVC	XLPE	EPR	PE
100	373	0%	0%	0%	0%
200	473	6%	0%	0%	0%
250	523	74%	0%	0%	20%
300	573	97%	0%	0%	~100%
350	623	98%	0%	0%	~100%
400	673	99%	7%	0%	~100%
450	723	99%	39%	0%	~100%
500	773	99%	81%	5%	~100%
550	823	~100%	97%	37%	~100%
575	848	~100%	99%	60%	~100%
600	873	~100%	~100%	77%	~100%
625	898	~100%	~100%	88%	~100%
650	923	~100%	~100%	95%	~100%
700	973	~100%	~100%	99%	~100%
750	1023	~100%	~100%	~100%	~100%
800	1073	~100%	~100%	~100%	~100%

Table 16 shows the P_{CD} for the same time-temperature profiles described above, but using the endurance limit defined using the NUREG/CR 6776 database.

Table 16. Probability of Cable Damage (%) – Heat Transfer Model (NUREG)

Temperature °C:	**Temperature °K:**	**NUREG 6776 Database**			
		PVC(1)	XLPE	EPR	PE(1)
100	373	NA	0%	0%	NA
200	473	NA	0%	0%	NA
250	523	NA	0%	0%	NA
300	573	NA	0%	0%	NA
350	623	NA	0%	0%	NA
400	673	NA	8%	0%	NA
450	723	NA	49%	3%	NA
500	773	NA	86%	19%	NA
550	823	NA	99%	46%	NA
575	848	NA	~100%	60%	NA
600	873	NA	~100%	72%	NA
625	898	NA	~100%	80%	NA
650	923	NA	~100%	86%	NA
700	973	NA	~100%	94%	NA
750	1023	NA	~100%	98%	NA
800	1073	NA	~100%	99%	NA

(1) No available

Similar to Table 15 and Table 16, Table 17 shows the P_{CD} for the same 16 time-temperature profiles described above, but using the endurance limit defined using the EPRI 1003326 database.

Table 17. Probability of Cable Damage (%) – Heat Transfer Model (EPRI)

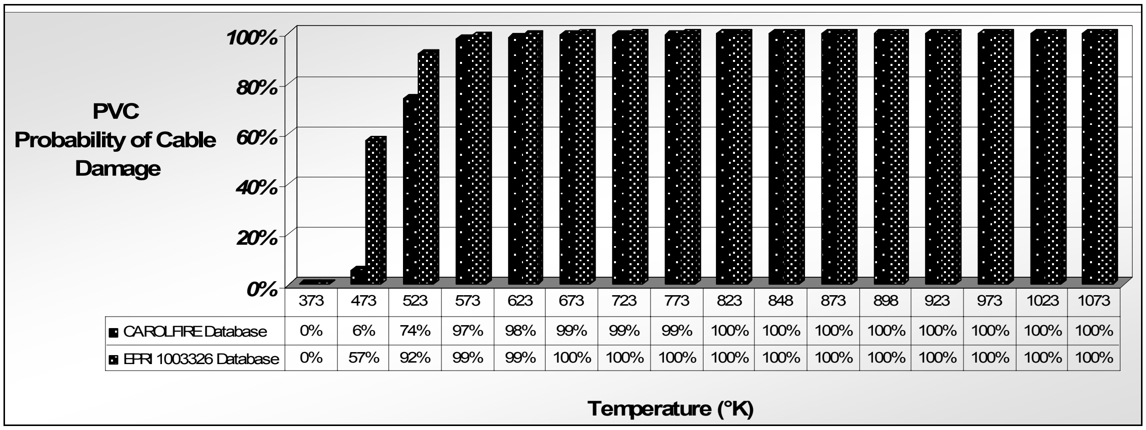
Temperature °C:	**Temperature °K:**	**EPRI 1003326 Database**			
		PVC	XLPE	EPR	PE
100	373	0%	0%	0%	1%
200	473	57%	0%	0%	66%
250	523	92%	0%	0%	93%
300	573	99%	0%	0%	99%
350	623	99%	1%	0%	~100%
400	673	~100%	15%	3%	~100%
450	723	~100%	47%	12%	~100%
500	773	~100%	81%	34%	~100%
550	823	~100%	95%	58%	~100%
575	848	~100%	97%	68%	~100%
600	873	~100%	99%	78%	~100%
625	898	~100%	~100%	84%	~100%
650	923	~100%	~100%	90%	~100%
700	973	~100%	~100%	95%	~100%
750	1023	~100%	~100%	98%	~100%
800	1073	~100%	~100%	99%	~100%

Based on the P_{CD} estimated for the above different time-temperature profiles, and summarized in Table 15, Table 16 and Table 17, the P_{CD} of each polymeric material under evaluation (PVC, XLPE, EPR, PE) for the 3 different databases developed can be compared in order to identify similarities and differences.

Figure 31 to Figure 34 shows the P_{CD} for PVC, XLPE, EPR and PE respectively.

As shown in Figure 31 for both databases (Carolfire and EPRI 1003326), with the exception of the 473°K (the 200°C) profile, the estimated probability of cable damage P_{CD} for the different time-temperature profiles are consistent. The P_{CD} derived from the Carolfire database is significant lower (6%) compared to the P_{CD}

derived from the EPRI 1003326 database (57%). This difference may be the result of external factors (exposure type, cable arrangement, cable tray fill, etc) and internal factors (cable material composition, thermal properties, etc). As it was mentioned, Carolfire database only includes some tests of the Carolfire testing program (see Appendix II).



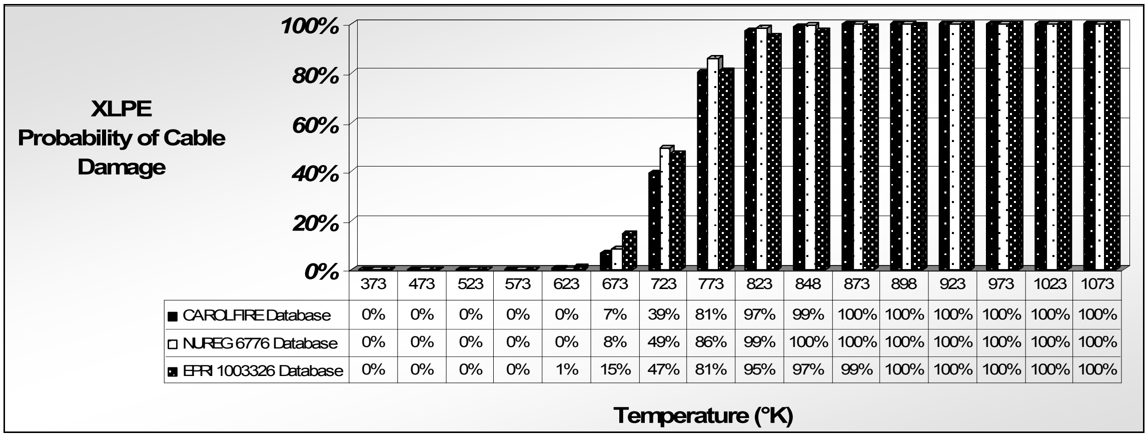
	373	473	523	573	623	673	723	773	823	848	873	898	923	973	1023	1073
■ CAROLFIRE Database	0%	6%	74%	97%	98%	99%	99%	99%	100%	100%	100%	100%	100%	100%	100%	100%
▨ EPRI 1003326 Database	0%	57%	92%	99%	99%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%

Figure 31. PVC Probability of Cable Damage (%) – Heat Transfer Model

Temperature to cable damage for instruments cables with PVC insulation has been reported as 469°K (196°C) (Salley, 2000), which is in the temperature interval defined in Figure 31. However, it is expected that instruments cables be more sensitive to thermal effects than control cables.

Regardless of the differences in the results for the 473°K (200°C) and 523°K (the 250°C) profiles, which are due to the uncertainties associated with the characterization of the thermal process and the randomness associated with the short circuit process, the results reveal that PVC does not withstand temperatures above 523°K (250°C) for period of time equaling or exceeding 15 minutes (Bertrand, 2002).

Regarding XLPE cables, as shown in Figure 32 for all databases (Carolfire, NUREG/CR 6776 and EPRI 1003326), the estimated probability of cable damage P_{CD} for the 16 different time-temperature profiles are consistent. As can be observed, for the 623°K (350°C) profile the estimated P_{CD} from the Carolfire, NUREG/CR 6776 and EPRI 1003326 databases is ~0%, ~0% and 1% respectively. The probability of cable damage for the remaining time-temperature profiles follows approximately the same consistent pattern



	373	473	523	573	623	673	723	773	823	848	873	898	923	973	1023	1073
■ CAROLFIRE Database	0%	0%	0%	0%	0%	7%	39%	81%	97%	99%	100%	100%	100%	100%	100%	100%
□ NUREG 6776 Database	0%	0%	0%	0%	0%	8%	49%	86%	99%	100%	100%	100%	100%	100%	100%	100%
▩ EPRI 1003326 Database	0%	0%	0%	0%	1%	15%	47%	81%	95%	97%	99%	100%	100%	100%	100%	100%

Figure 32. XLPE Probability of Cable Damage (%) – Heat Transfer Model

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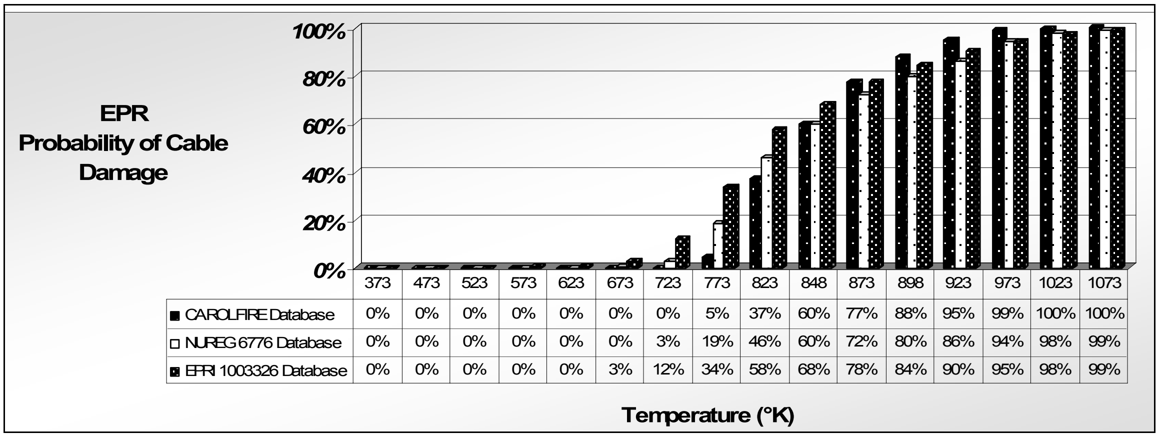
According to Figure 32, under the time-temperature profile evaluated, the minimum temperature capable of inducing thermal damage to XLPE insulation cables is above 623°K (350°C). This finding is in agreement with the results described in USNRC (2005), in which is stated that during high temperature exposure tests conducted on XLPE insulated cables, electrical failures were observed at temperature of 623°K (350°C) in a range of time of exposure between 7 to 28 minutes (an average of 13 minutes). In this reference two samples of XLPE insulated cables were exposed to a temperature of 325°C and no failures were observed during exposure times of approximately 80 minutes. However, this reference also pointed out that during high temperature exposure tests conducted on XLPE insulated cables, electrical failures were observed at temperature as low as 270°C for exposures times ranging from 30 to 82 minutes, and averaging 56 minutes.

The cable temperature endurance limit for a XLPE cable was estimated at about 593°K (320°C) (USNRC, 2005); while Salley et al. (2000) outlined an endurance limit in the range of 598°K - 603°K (325°C - 330°C) for control cables with XLPE insulation.

Regarding EPR cables, as shown in Figure 33 for all databases (Carolfire, NUREG/CR 6776 and EPRI 1003326), the estimated probability of cable damage P_{CD} for the different time-temperature profiles are consistent with the exception of the 723°K (450°C), 773°K (500°C) and 823°K (550°C) profiles. The highest difference is found for the 773°K (500°C) profile, where the estimated P_{CD} from the Carolfire, NUREG/CR 6776 and EPRI 1003326 databases is 5%, 19% and 34% respectively, which appears to be acceptable when the heterogeneity of the tests in each testing program is considered.

According to Figure 33, under the time-temperature profile evaluated the minimum temperature capable of inducing thermal damage to EPR insulation cables is above 673°K (400°C) for exposure time around 15 minutes. For exposure time higher than 15 minutes this threshold temperature will be lower. This finding is in agreement with the results described by Nowlen et al. (2000), in which the thermal endurance limit for unaged EPR insulated cable is estimated at 638°K to 643°K (365°C - 370°C). In this reference two samples of EPR insulated cables were exposed to a temperature of 618°K (345°C) and no failures were observed during exposure times no less than 80 minutes.

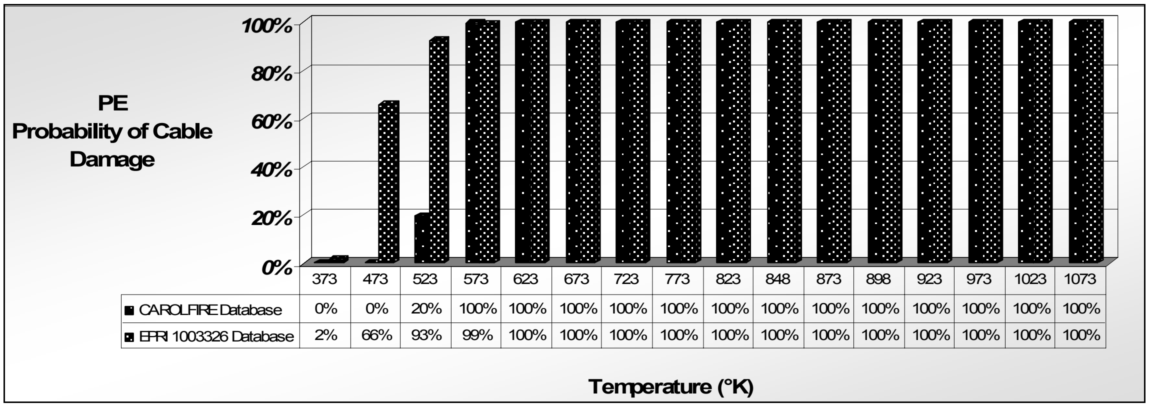


	373	473	523	573	623	673	723	773	823	848	873	898	923	973	1023	1073
■ CAROLFIRE Database	0%	0%	0%	0%	0%	0%	0%	5%	37%	60%	77%	88%	95%	99%	100%	100%
□ NUREG 6776 Database	0%	0%	0%	0%	0%	0%	3%	19%	46%	60%	72%	80%	86%	94%	98%	99%
▨ EPRI 1003326 Database	0%	0%	0%	0%	0%	3%	12%	34%	58%	68%	78%	84%	90%	95%	98%	99%

Figure 33. EPR Probability of Cable Damage (%) – Heat Transfer Model

In case of PE insulation cables, as shown in Figure 34 for both databases (Carolfire and EPRI 1003326), the estimated probability of cable damage P_{CD} for the different time-temperature profiles are consistent with the exception of the 473°K (200°C) and 523°K (250°C) profiles.

The P_{CD} derived from the Carolfire database for the 473°K (200°C) and 523°K (250°C) profiles are significantly lower (0% and 20%) compared to the P_{CD} derived from the EPRI 1003326 database (66% and 93%). This difference may be the result of external factors (exposure type, cable arrangement, cable tray fill, etc) and internal factors (cable material composition, thermal properties, etc). In particular, the EPRI 1003326 database consisted of large scale tests with heat release rates higher than 70 KW, while the Carolfire database was developed mostly with the results of small scale tests (see Table 2). On the other hand, the existence of short circuits among cables is not only determined by the melting of the thermoplastic material, but also by the stresses and mechanical proximity between the conductors (Babrauskas, 2003).



	373	473	523	573	623	673	723	773	823	848	873	898	923	973	1023	1073
■ CAROLFIRE Database	0%	0%	20%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
▨ EPRI 1003326 Database	2%	66%	93%	99%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%

Figure 34. PE Probability of Cable Damage (%) – Heat Transfer Model

Regardless of the differences in the results for the 473°K (200°C) and 523°K (250°C) profiles, the results reveal that PE does not withstand temperatures above 523°K (250°C) for periods of time exceeding 15 minutes. Electrical failures on experimental tests conducted in PE insulated cables at temperature as low as 250°C for exposures times ranging from 1.5 to 23.5 minutes (average 9 minutes) have been reported (USNRC, 2005).

8.3. IR “K Factor” Model

The IR endurance limit of different polymeric materials was estimated using equation (24) and the results of the experimental tests described in Appendix II (see section 6.3). Tables 6 and 7 contain the endurance limits, in terms of the IR and the estimated parameters C_1 and C_2, for the thermoplastic (PVC and TEFZEL) and thermosets (XLPE and EPR) commercial cable polymeric materials evaluated.

The dimensions of the cables used in this section are similar to the ones used in section 8.2.3 to describe the heat transfer model.

8.3.1. IR “K Factor” Model: Constant Surrounding Temperature

Given a characterized fire, the probability of cable damage can be estimated by comparing the remaining/diminished cable insulation resistance (IR) induced by the external thermal insult to the endurance insulation resistance of the cable material under study.

As an example, a cable with commercial PVC insulation similar to the one used in section 8.2.2 is considered in the next analysis. Figure 35 shows the IR endurance limit, according to Carolfire database, for this particular polymeric material.

Given a hypothetical fire scenario, with a constant temperature T_a in the surrounding area, the probability of cable damage capable of creating a short circuit condition can be estimated using equation (25) as:

$$Pfalla = P(Endurance \leq Damage) = \int_{-\infty}^{R_i} g(y)d_y \tag{25}$$

where:

R_i: Instantaneous IR at temperature T_a (Ω)

g(y): endurance limit probability density function

y: random variable representing the endurance (Ω)

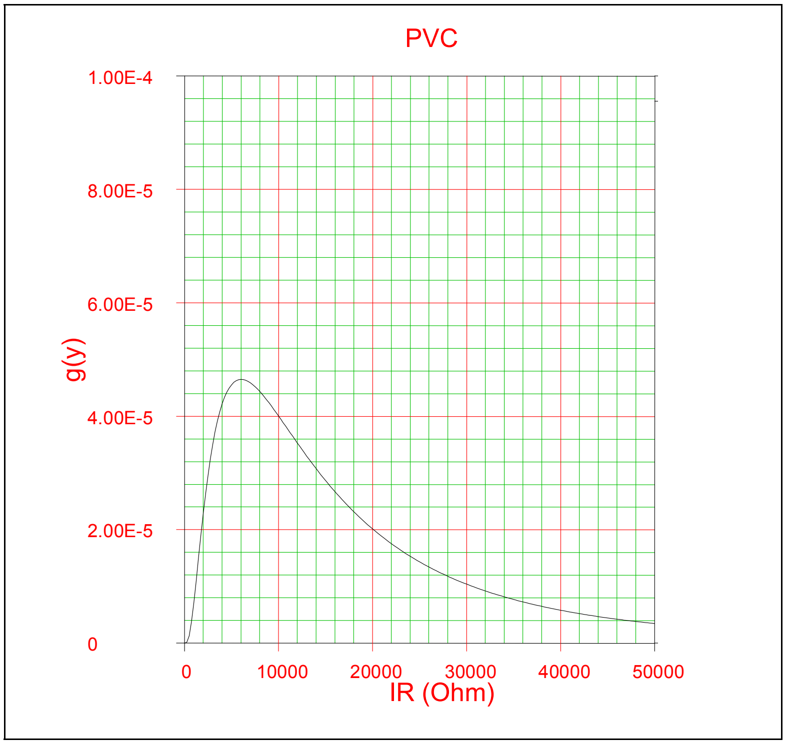


Figure 35: PVC Endurance Limit– IR “K Factor” Model (Carolfire)

The instantaneous IR at temperature T_a is estimated using equation (24) as:

$$IR = C_1 . e^{-(C_2 T_a)} . \ln\left(\frac{D_{out}}{D_{in}}\right) \qquad (24)$$

where:

D_{out} = outer diameter of the insulation (m)

D_{in} = inside diameter of the insulation (m)

C_1 and C_2 constant for a given insulation material.

Therefore, once the values of IR as a function of the surrounding temperature T_a are obtained through equation (24), the probability of cable damage can be estimated through equation (25).

Assuming a range of values of T_a from 373°K to 673°K (100°C to 400°C) and the constant C_1 and C_2 given by a lognormal probability density function whose mean and standard deviation are given in Table 7, the IR from PVC varies as shown in Figure 36.

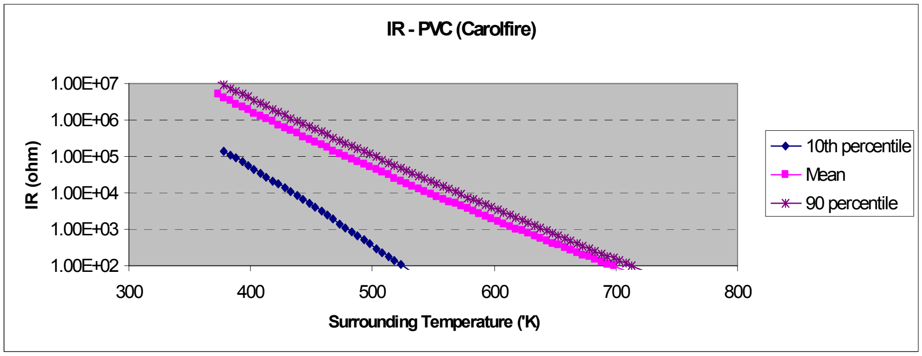


Figure 36. IR PVC vs. Surrounding Temperature (Carolfire)

As shown in Figure 36, the insulation resistance decreases exponentially with increasing temperature. Specifically for PVC the IR drops below hundreds of ohms for temperatures higher than 700°K (427°C). The gap between the 10th and 90th percentile observed in this Figure shows the uncertainty in the estimation of the IR. This uncertainty is particularly attributed to the parameter C_1, which differs significantly from test to test (see standard deviation in Table 7).

Using the IR estimated above, and the endurance level given by a log-normal probability density function whose mean and standard deviation are given in Table 7, the probability of cable damage shown in Table 18 is obtained.

Table 18. PVC Probability of Cable Damage (Constant T_a) – IR "K Factor" Model

Temperature °C	**Temperature °K**	**Probability of Cable Damage**
		PVC-Carolfire
100	373	0.01
105	378	0.02
110	383	0.02
115	388	0.03
120	393	0.04
125	398	0.05
130	403	0.06
135	408	0.07
140	413	0.09
145	418	0.11
150	423	0.13
155	428	0.15
160	433	0.17
165	438	0.20
170	443	0.23
175	448	0.25
180	453	0.29
185	458	0.31
190	463	0.35

Table 18 Continuation

Temperature °C	**Temperature °K**	**Probability of Cable Damage**
		PVC-Carolfire
195	468	0.38
200	473	0.41
205	478	0.45
210	483	0.48
215	488	0.51
220	493	0.54
225	498	0.58
230	503	0.61
235	508	0.64
240	513	0.67
245	518	0.70
250	523	0.73
255	528	0.75
260	533	0.78
265	538	0.80
270	543	0.82
275	548	0.84
280	553	0.86
285	558	0.87
290	563	0.88
295	568	0.90
300	573	0.91
305	578	0.92
310	583	0.93
315	588	0.94
320	593	0.95
325	598	0.96
330	603	0.96
335	608	0.97
340	613	0.97
345	618	0.97
350	623	0.98
355	628	0.98
360	633	0.99
365	638	0.99
370	643	0.99
375	648	0.99
380	653	0.99
385	658	0.99
390	663	0.99
395	668	~1.00
400	673	~1.00

As can be observed the minimum surrounding temperature capable of initiating certain level of damage to the PVC cable insulation is about 398°K (125°C) for the Carolfire database. For temperatures higher than 658°K (385°C) the probability of cable damage for this particular polymeric material tends to 1.

Appendix VIII includes the probability of cable damage at different surrounding temperatures for the remaining materials and databases evaluated in this research. As shown in Appendix VIII the minimum surrounding temperature capable of initiating certain level of damage to PVC insulated cable is about 423°K (150°C) according to the NUREG/CR 6776 database. Similar to the results from the Carolfire database, for temperatures higher than 658°K (385°C) the probability of cable damage for this particular polymeric material is close to 1. The probability of damage at a specific temperature is consistent for all databases considered.

Figure 37 shows the results of probability of cable damage estimated using the previous procedure for thermoplastics (PVC and Tefzel) and thermosets (XLPE and EPR). This figure also reveals the differences in the surrounding temperature endurance limits for thermoplastics and thermosets.

For thermoplastics, the probability of cable damage for surrounding temperatures lower than 393 °K (120 °C) is negligible. The minimum trigger temperature above which the probability increases significantly is approximately 400 °K (127 °C). For temperature higher than 658 °K (385 °C), the probability approaches 1.

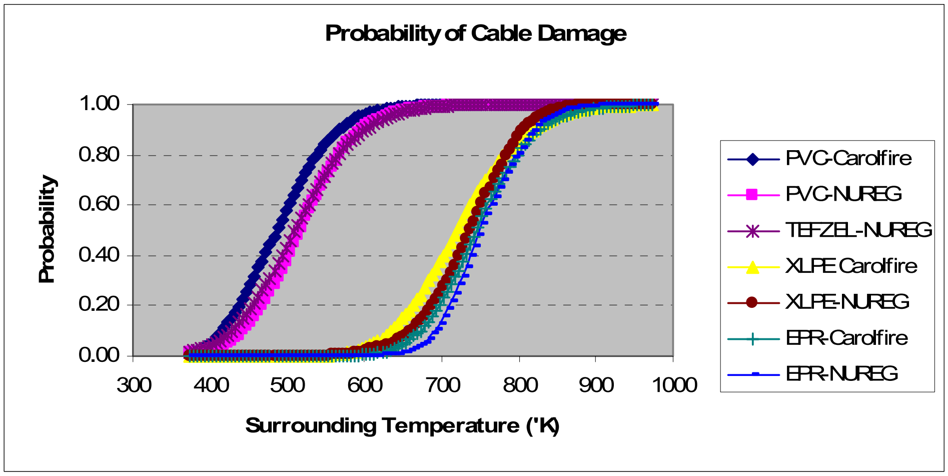


Figure 37. Probability of Cable Damage (Constant T_a) – IR "K Factor" Model

On the other hand, for thermosets the probability of cable damage for surrounding temperatures lower than 600 °K (327 °C) is negligible. The trigger temperature above which the probability increases significantly is about 615 °K (342 °C), and approaches 1 for temperatures higher than 830°K (557°C).

As noted in Figure 37, for the same inner temperature the probability of damage is higher in thermoplastics cables compared to thermosets cables as expected.

Figure 38 and Figure 39 show the mean of the IR estimated for thermoplastics and thermosets for the range of temperatures T_a from 373°K to 673°K (100°C to 400°C) and the constant C_1 and C_2 given by a lognormal probability density function whose means and standard deviations are given in Table 6 and Table 7.

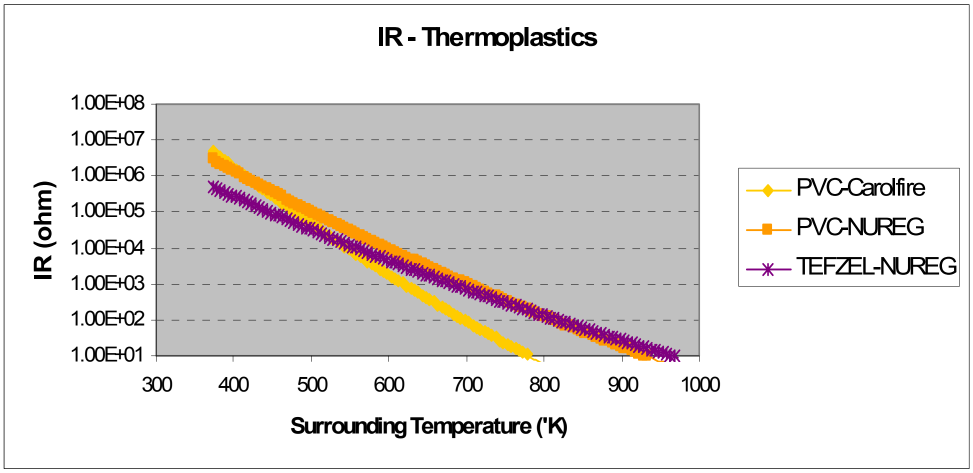


Figure 38. IR vs. Surrounding Temperature (Thermoplastics)

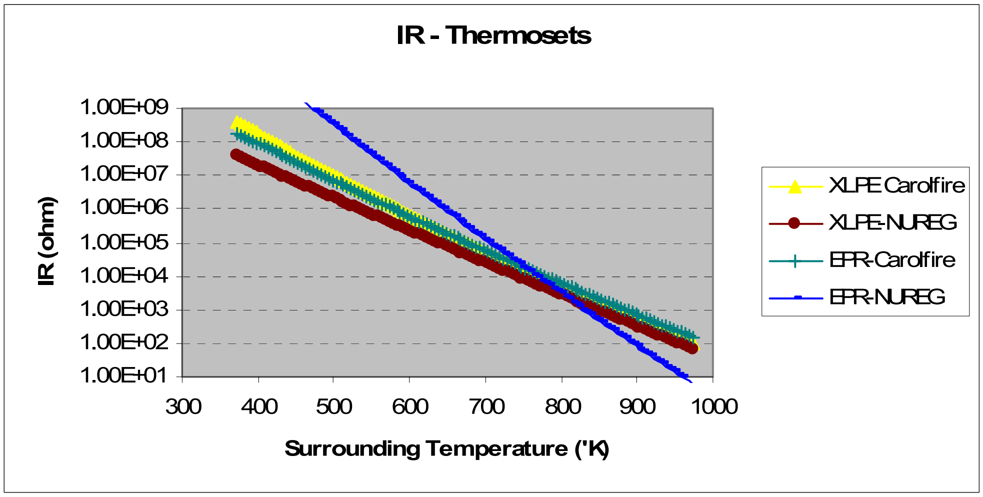


Figure 39. IR vs. Surrounding Temperature (Thermosets)

8.3.2.IR “K Factor” Model: Random Surrounding Temperature

As in the constant damage case, given a characterized fire, the probability of cable damage can be estimated comparing the remaining/diminished cable insulation resistance (IR) induced by the external thermal insult to the IR endurance limit of the cable material under study. However, in this particular section the uncertainty about the estimated surrounding temperatures T_a is considered.

This section is developed using as an example a commercial EPR cable polymeric material. Figure 40 shows the IR endurance limit according to Carolfire database for this particular polymeric material.

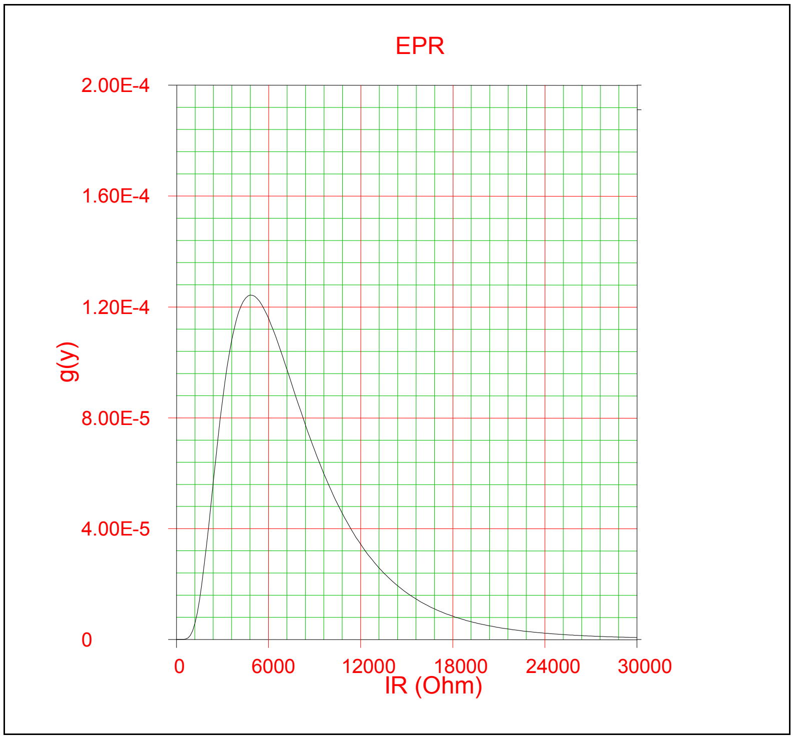


Figure 40. EPR Endurance Limit– IR “K Factor” Model (Carolfire)

Given a hypothetical fire scenario, the probability of cable damage capable of creating a short circuit condition can be estimated using equation (26) as:

$$Pfalla = P(Endurance \leq Damage) = 1 - \int_0^\infty \left[\int_0^y f(x) d_x \right] g(y) d_y \qquad (26)$$

where:

f(x): damage probability density function (IR at temperature T_a in Ω)

g(y): endurance limit probability density function

y: random variable representing the endurance (Ω)

x: random variable representing the damage (Ω)

The IR at temperature T_a is estimated using equation (24) as:

$$IR = C_1 . e^{-(C_2 T_a)} . \ln\left(\frac{D_{out}}{D_{in}}\right) \tag{24}$$

Therefore, once the values of IR as function of the surrounding temperature T_a are obtained through equation (24), the probability of cable damage can be estimated through equation (26). In this particular case T_a is characterized by a lognormal probability density function whose standard deviation is 10% of the corresponding mean.

Assuming a surrounding temperature T_a, given by a lognormal distribution whose mean varies from 373°K to 673°K (100°C to 400°C) and the constant C_1 and C_2 given by a lognormal probability density function whose mean and standard deviation are given in Table 6 and Table 7, the probability of cable damage shown in Table 19 is obtained.

As can be observed the minimum surrounding temperature capable of initiating certain level of damage to the EPR cable insulation is about 613°K (340°C) for both databases. For temperatures higher than 958°K (685°C) the probability of cable damage for this particular polymeric material tends to 1.

Table 19. EPR Probability of Cable Damage (Random T_a) – IR “K Factor” Model

Temperature °K (mean, std. dev.)	**Probability of Cable Damage-EPR**	
	Carolfire	NUREG 6776
(573, 57.3)	0.02	0.01
(578, 57.8)	0.02	0.01
(583, 58.3)	0.02	0.02
(588, 58.8)	0.03	0.02
(593, 59.3)	0.03	0.02
(598, 59.8)	0.04	0.03
(603, 60.3)	0.04	0.03
(608, 60.8)	0.05	0.04
(613, 61.3)	0.05	0.04
(618, 61.8)	0.06	0.05
(623, 62.3)	0.07	0.05
(628, 62.8)	0.08	0.06
(633, 63.3)	0.09	0.07
(638, 63.8)	0.10	0.08
(643, 64.3)	0.11	0.09
(648, 64.8)	0.12	0.10
(653, 65.3)	0.13	0.12
(658, 65.8)	0.15	0.13
(663, 66.3)	0.16	0.14
(668, 66.8)	0.17	0.16
(673, 67.3)	0.19	0.17
(678, 67.8)	0.20	0.19
(683, 68.3)	0.22	0.20
(688, 68.8)	0.24	0.22
(693, 69.3)	0.25	0.24
(698, 69.8)	0.27	0.26
(703, 70.3)	0.29	0.28
(708, 70.8)	0.31	0.30
(713, 71.3)	0.33	0.32
(718, 71.8)	0.35	0.34
(723, 72.3)	0.37	0.36
(728, 72.8)	0.39	0.38
(733, 73.3)	0.41	0.40
(738, 73.8)	0.43	0.43
(743, 74.3)	0.45	0.45
(748, 74.8)	0.47	0.47
(753, 75.3)	0.49	0.49
(758, 75.8)	0.51	0.51
(763, 76.3)	0.53	0.54
(768, 76.8)	0.55	0.56
(773, 77.3)	0.57	0.58
(778, 77.8)	0.59	0.60

Table 19. Continuation

Temperature °K (mean, std. dev.)	**Probability of Cable Damage-EPR**	
	Carolfire	NUREG 6776
(783, 78.3)	0.61	0.62
(788, 78.8)	0.63	0.64
(793, 79.3)	0.64	0.66
(798, 79.8)	0.67	0.68
(803, 80.3)	0.68	0.70
(808, 80.8)	0.70	0.72
(813, 81.3)	0.71	0.73
(818, 81.8)	0.72	0.74
(823, 82.3)	0.74	0.76
(828, 82.8)	0.76	0.77
(833, 83.3)	0.78	0.79
(838, 83.8)	0.79	0.81
(843, 84.3)	0.80	0.82
(848, 84.8)	0.81	0.84
(853, 85.3)	0.83	0.85
(858, 85.8)	0.84	0.86
(863, 86.3)	0.85	0.87
(868, 86.8)	0.86	0.87
(873, 87.3)	0.87	0.89
(878, 87.8)	0.88	0.89
(883, 88.3)	0.88	0.90
(888, 88.8)	0.89	0.91
(893, 89.3)	0.90	0.92
(898, 89.8)	0.91	0.93
(903, 90.3)	0.91	0.93
(908, 90.8)	0.92	0.94
(913, 91.3)	0.93	0.94
(918, 91.8)	0.93	0.95
(923, 92.3)	0.94	0.96
(928, 92.8)	0.94	0.96
(933, 93.3)	0.95	0.96
(938, 93.8)	0.95	0.96
(943, 94.3)	0.95	0.97
(948, 94.8)	0.96	0.97
(953, 95.3)	0.96	0.97
(958, 95.8)	0.97	0.98
(963, 96.3)	0.97	0.98
(968, 96.8)	0.97	0.98
(973, 97.3)	0.97	0.98

Appendix IX contains the probability of cable damage at different surrounding temperatures for the remaining materials and databases evaluated in this research. In this Appendix can be observed that the probability of damage for thermoplastics and thermosets at a specific temperature is consistent.

Figure 41 shows the results of probability of cable damage estimated using the previous procedure for thermoplastics (PVC and Tefzel) and thermosets (XLPE and EPR). In this Figure the differences in the surrounding temperature endurance limits for thermoplastic and thermosets materials can be observed.

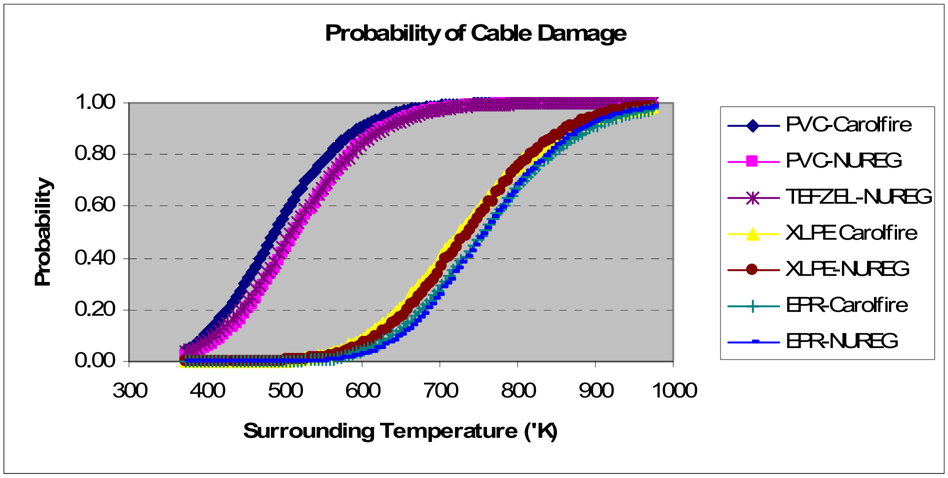


Figure 41. Probability of Cable Damage (Random T_a) – IR “K Factor” Model

For thermoplastics and thermosets, the behavior in terms of probability of cable damage is similar to that encountered for constant temperature T_a (Figure 37), with the peculiarity that the span of temperatures is wider than expected considering the distributed damage. As observed in Figure 41, there is certain level of overlapping in the range of temperatures for thermoplastic and thermosets, which is due to the distributed nature of the damage considered.

8.3.3.`IR “K Factor” Model: Time-Temperature Profile

Up to this stage, the prediction of cable damage has been based on scenarios where a specific surrounding temperature is assumed either as a point estimate or as a parametric distribution, and the corresponding IR is estimated at a specific instant of the thermal insult. However, in real fire scenarios the temperature surrounding the target cables is characterized for a time-temperature profile P(t,T); therefore, the probability of cable damage should be determined based on this time-temperature profile.

This model is described through a practical example considering thermoplastics (PVC, Tefzel) and thermosets (XLPE, EPR). The cables considered in this section have the same physical characteristics of the ones used in the previous section; therefore, all four cables considered (PVC, Tefzel, XLPE and EPR) represent single conductor cables with an internal radius of 0.0041 m and an insulation thickness of 1.91 mm. On the other hand, the time-temperature profiles assumed for the surrounding temperatures are the same used in section 8.2.3.

Table 20 and Figure 42 show the 10th percentile, mean and 90th percentile of the IR estimated for XLPE given the P(t,T) depicted in Figure 28. As can be observed, the IR decreases exponentially with increasing temperature.

The uncertainty observed in the IR estimated is primarily due to the characterization of the parameters C_1 and C_2 (see Table 6).

Table 20. Insulation Resistance - XLPE – IR “K Factor” Model (NUREG)

time (m)	**Surrounding temperature (°C)**	**Surrounding temperature (°K)**	**Insulation Resistance XLPE (Ω)**		
			10 Percentile	Mean	90 Percentile
0	30	303	2.73E+06	6.56E+07	1.50E+08
1	173	446	1.84E+05	2.50E+06	5.93E+06
2	315	588	1.23E+04	9.98E+04	2.29E+05
3	458	731	8.14E+02	4.17E+03	8.93E+03
4	600	873	5.48E+01	1.83E+02	3.51E+02
5	600	873	5.48E+01	1.83E+02	3.51E+02
6	600	873	5.48E+01	1.83E+02	3.51E+02
7	600	873	5.48E+01	1.83E+02	3.51E+02
8	600	873	5.48E+01	1.83E+02	3.51E+02
9	600	873	5.48E+01	1.83E+02	3.51E+02
10	600	873	5.48E+01	1.83E+02	3.51E+02
11	600	873	5.48E+01	1.83E+02	3.51E+02
12	600	873	5.48E+01	1.83E+02	3.51E+02
13	600	873	5.48E+01	1.83E+02	3.51E+02
14	600	873	5.48E+01	1.83E+02	3.51E+02
15	600	873	5.48E+01	1.83E+02	3.51E+02
16	600	873	5.48E+01	1.83E+02	3.51E+02
17	600	873	5.48E+01	1.83E+02	3.51E+02
18	600	873	5.48E+01	1.83E+02	3.51E+02
19	600	873	5.48E+01	1.83E+02	3.51E+02
20	600	873	5.48E+01	1.83E+02	3.51E+02
21	600	873	5.48E+01	1.83E+02	3.51E+02
22	600	873	5.48E+01	1.83E+02	3.51E+02
23	600	873	5.48E+01	1.83E+02	3.51E+02
24	600	873	5.48E+01	1.83E+02	3.51E+02
25	600	873	5.48E+01	1.83E+02	3.51E+02
26	600	873	5.48E+01	1.83E+02	3.51E+02
27	600	873	5.48E+01	1.83E+02	3.51E+02
28	600	873	5.48E+01	1.83E+02	3.51E+02
29	600	873	5.48E+01	1.83E+02	3.51E+02
30	600	873	5.48E+01	1.83E+02	3.51E+02

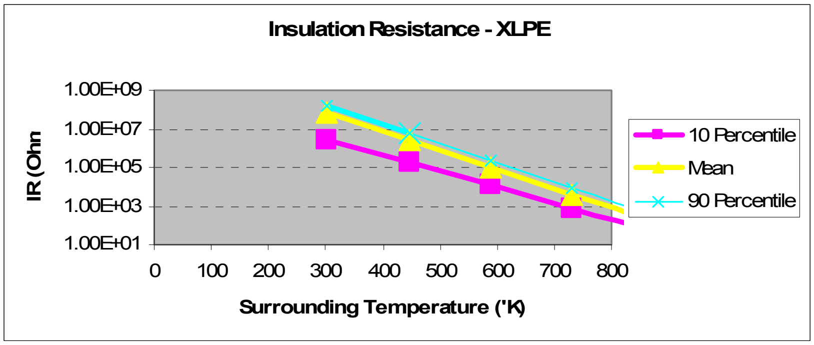


Figure 42: Insulation Resistance - XLPE – IR “K Factor” Model (NUREG)

Once the IR has been estimated at each instant of time during the fire exposure (dynamic damage level) the damage-endurance model described in section 8.3.2 can be applied. Table 21 shows the probability of cable damage for XLPE using the endurance limits defined for the two databases considered.

Table 21. XLPE Probability of Cable Damage – IR "K Factor" Model

time (m)	**Temperature °C:**	**Temperature °K:**	**Probability of Cable Damage: XLPE**	
			Carolfire	NUREG 6776
0	30	303	0.00	0.00
1	173	446	0.00	0.00
2	315	588	0.00	0.01
3	458	731	0.55	0.42
4	600	873	~1.00	~1.00
5	600	873	~1.00	~1.00
6	600	873	~1.00	~1.00
7	600	873	~1.00	~1.00
8	600	873	~1.00	~1.00
9	600	873	~1.00	~1.00
10	600	873	~1.00	~1.00
11	600	873	~1.00	~1.00
12	600	873	~1.00	~1.00
13	600	873	~1.00	~1.00
14	600	873	~1.00	~1.00
15	600	873	~1.00	~1.00
16	600	873	~1.00	~1.00
17	600	873	~1.00	~1.00
18	600	873	~1.00	~1.00
19	600	873	~1.00	~1.00
20	600	873	~1.00	~1.00
21	600	873	~1.00	~1.00
22	600	873	~1.00	~1.00
23	600	873	~1.00	~1.00
24	600	873	~1.00	~1.00
25	600	873	~1.00	~1.00
26	600	873	~1.00	~1.00
27	600	873	~1.00	~1.00
28	600	873	~1.00	~1.00
29	600	873	~1.00	~1.00
30	600	873	~1.00	~1.00

Values in Table 21 represent the probability of cable damage (P_{CD}) at a time "t_i" given the time-temperature profile P(t,T) depicted in Figure 28. In contrast to the heat transfer model, a longer exposure to the thermal insult does not represent a higher probability of cable damage (this model does not take into account the time of exposure).

8.4. Heat Transfer Model vs. IR "K Factor" Model

Clearly, the fundaments of the heat transfer model and the IR "K factor" model are different. The former uses the heat transfer principles to estimate the inner cable temperature, while the latter uses an empirical relation to estimate the insulation resistance as a function of the surrounding temperature.

The physics-based heat transfer model, takes into account the properties and characteristics of the cables and cable materials (thermal properties, density, insulation thickness, etc.) and the characteristics of the thermal insult (surrounding temperature, time of exposure, heat transfer coefficient, etc). However, the IR "K factor" model just takes in consideration the surrounding temperature and the insulation-conductor radius rate of the cables, without considering the dynamics of the thermal insult.

To illustrate the limitation of the IR "K factor" model, a particular scenario considering EPR insulated cable is assumed in which the thermal insult follows the time-temperature profile P(t,T) depicted in Figure 43.

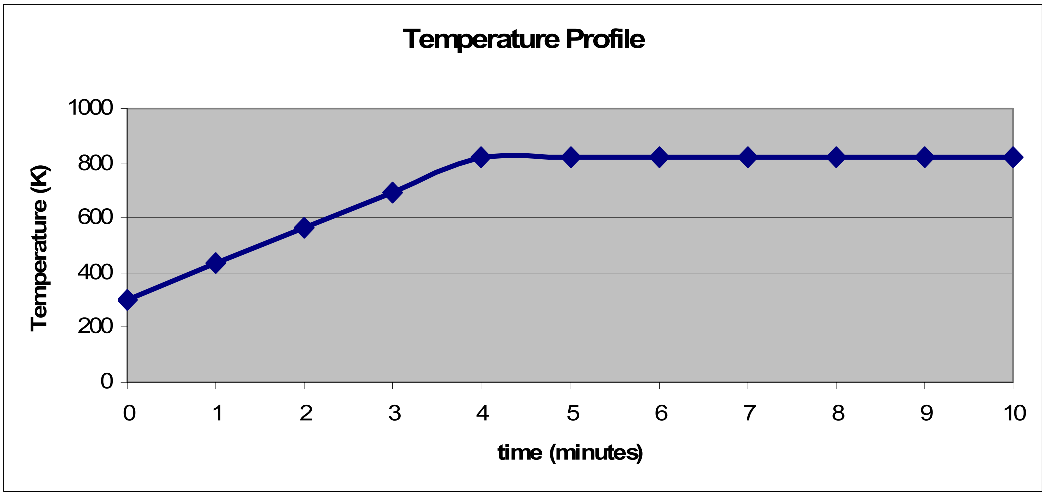


Figure 43: Time-Temperature Profile

Assuming and exposure time of 15 minutes and using the heat transfer model a P_{CD} of 37% and 46% is estimated using the Carolfire and NUREG/CR 6776 databases, respectively. However the P_{CD} estimated using the IR "K factor" model is 81% and 86% for the same databases. The significant difference in the estimated $P_{CD,}$ in addition to the differences in the fundamental principles of each model (heat vs. electrical resistance), is due mainly to the following reason:

> The heat transfer model considers the dynamic of the thermal insult and the thermal behavior of the cable material; therefore, even though a temperature of 823 °K (550 °C) is reached, it only lasts for few minutes, which is not enough to increase the inner cable temperature beyond the endurance limit. In consequence the probability of cable damage estimated is lower.

On the other hand, the IR “K factor” model does not consider the “*time*”, it just considers the “*temperature*”; therefore, even though the highest temperature of 823 °K (550 °C) was just reached for few minutes, the model predicts a high P_{CD}.

As noted, the heat transfer model as a physic-based model is much robust and leads to more representative results than the IR “K factor” model, because it considers the dynamic of the thermal insult evaluated to a greater extent. However, for more complex cables configurations and arrangements (multi-conductors, armored cables, etc), specific heat transfer models should be developed in order to estimate the inner cable temperature and be able to apply the proposed damage-endurance model.

8.5. Time to Cable Damage

In some cases it is important to determine the time to cable damage given a fire scenario. The time to cable damage, sometime refers to as *minimum target damage time* (NEA, 2000), depends on a variety of aspects, among them the cable response to the thermal stress and the characteristics and pattern of the fire. There are cases where the response time to detect, mitigate and/or suppress the fire is lower than the minimum target damage time and not electrical failure occurs.

Given the probabilistic nature of the models proposed to determine the fire-induced cable damage likelihood, there is not a deterministic value for the target damage time but a time to failure distribution. Different target damage times can be estimated for different probability of cable damage. Therefore, given a fire scenario characterized for a time-temperature profile P(t,T), there will be a target damage time for 25%, 50%, 75% or any other percentile of the probability of cable damage. Of course, a statistical figure of merit such as the mean, mode or median can be selected to represent the minimum target damage time.

Table 22 shows the target damage time for XLPE and EPR insulation cables under the scenario described in section 8.2.3. It shows the target damage time for the 5th, 50th and 95th percentile of the probability of cable damage. It is important to mention that the resolution used in the numerical simulation of this scenario is 1 minute; therefore, it is not possible to quantified time intervals lower than 1 minute.

Figure 44 shows the target damage time for the specific case of EPR insulation cables using the Carolfire database. As expected the target damage time decreases progressively as exposure temperature increases.

Figure 45 and Figure 46 show the target damage time for thermoplastic and thermosets cables. These figures reveal the high variability in the results, particularly for thermoplastics. As pointed out previously, the different results obtained through the different databases are mainly due to the diversity of thermal insults exposures and cable to cable differences.

Table 22. XLPE/EPR Time to Cable Damage – Heat Transfer Model

Temperature °K:	Probability %	Time To Cable Damage XLPE (m)			Time To Cable Damage EPR (m)		
		Carolfire	NUREG	EPRI	Carolfire	NUREG	EPRI
473	5%	> 60	> 60	> 60	> 60	> 60	> 60
473	50%	> 60	> 60	> 60	> 60	> 60	> 60
473	95%	> 60	> 60	> 60	> 60	> 60	> 60
523	5%	> 60	> 60	> 60	> 60	> 60	> 60
523	50%	> 60	> 60	> 60	> 60	> 60	> 60
523	95%	> 60	> 60	> 60	> 60	> 60	> 60
573	5%	> 60	> 60	> 60	> 60	> 60	> 60
573	50%	> 60	> 60	> 60	> 60	> 60	> 60
573	95%	> 60	> 60	> 60	> 60	> 60	> 60
623	5%	> 60	> 60	> 60	> 60	> 60	> 60
623	50%	> 60	> 60	> 60	> 60	> 60	> 60
623	95%	> 60	> 60	> 60	> 60	> 60	> 60
673	5%	13	13	10	> 60	> 60	17
673	50%	> 60	> 60	60	> 60	> 60	> 60
673	95%	> 60	> 60	60	> 60	> 60	> 60
723	5%	9	9	7	22	16	11
723	50%	16	15	15	34	60	> 60
723	95%	> 60	> 60	> 60	> 60	> 60	> 60
773	5%	7	7	5	15	10	8
773	50%	11	10	10	20	24	18
773	95%	20	18	> 60	29	> 60	> 60
823	5%	6	6	4	11	8	7
823	50%	9	8	7	15	15	13
823	95%	14	12	15	21	36	60
848	5%	5	5	3	10	7	6
848	50%	8	8	7	14	13	12
848	95%	12	11	13	19	26	29
873	5%	5	5	3	9	6	5
873	50%	7	7	6	13	12	11
873	95%	11	10	11	17	21	22
898	5%	5	4	3	9	6	5
898	50%	7	6	5	12	11	9
898	95%	10	9	10	16	20	20
923	5%	4	4	3	8	6	5
923	50%	6	6	5	11	10	9
923	95%	9	9	9	15	18	17
973	5%	4	4	3	7	5	4
973	50%	6	5	5	9	8	8
973	95%	8	8	8	13	15	15
1023	5%	3	3	3	6	4	4
1023	50%	5	5	4	8	7	7
1023	95%	7	7	7	11	13	13
1073	5%	3	3	3	6	4	3
1073	50%	4	4	4	8	7	6
1073	95%	6	6	6	10	11	11

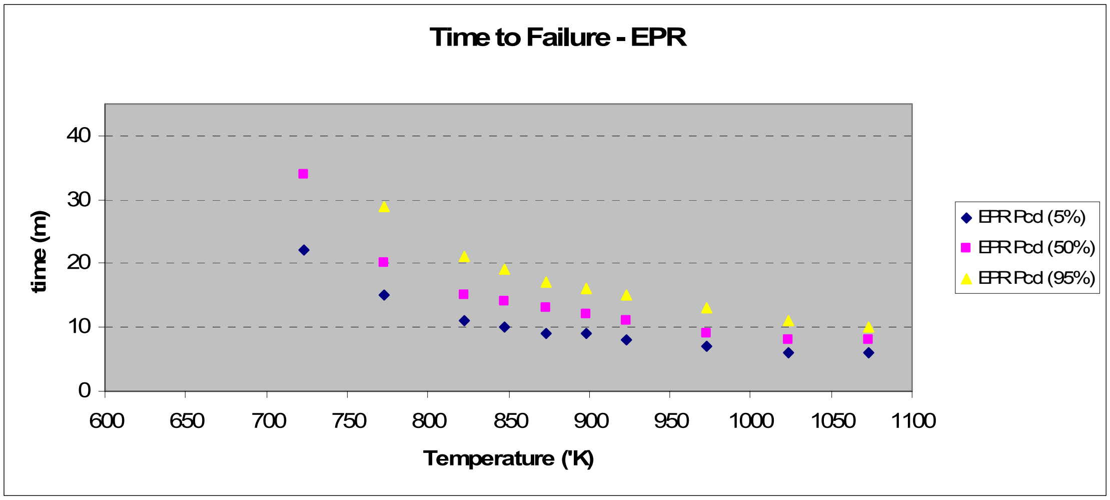


Figure 44. EPR Time to Cable Damage– Heat Transfer Model (Carolfire)

Times to cable damage for electrical cables exposed to external thermal insults have been also reported in USNRC (2005). In this reference information about the particular thermal exposure conditions and cables characteristics used during the experimental tests are not reported; therefore, it was not possible to perform an objective comparison between the reported times to cable damage and the times to cable damage represented in Figure 45 and Figure 46. As mentioned before, the time to cable damage represented in these figures are particular results for thermal insult scenarios and cables characteristics described in section 8.2.3.

Alternatively, the time to cable damage for particular scenarios of interest can be characterized probabilistically, either using a parametric or a non-parametric distribution. There are some cases reported in the open literature where particular distributions have been assigned to this variable for specific thermal insult scenarios (Mangs and Keski-Rahkonen, 2003; Babrauskas, 2005).

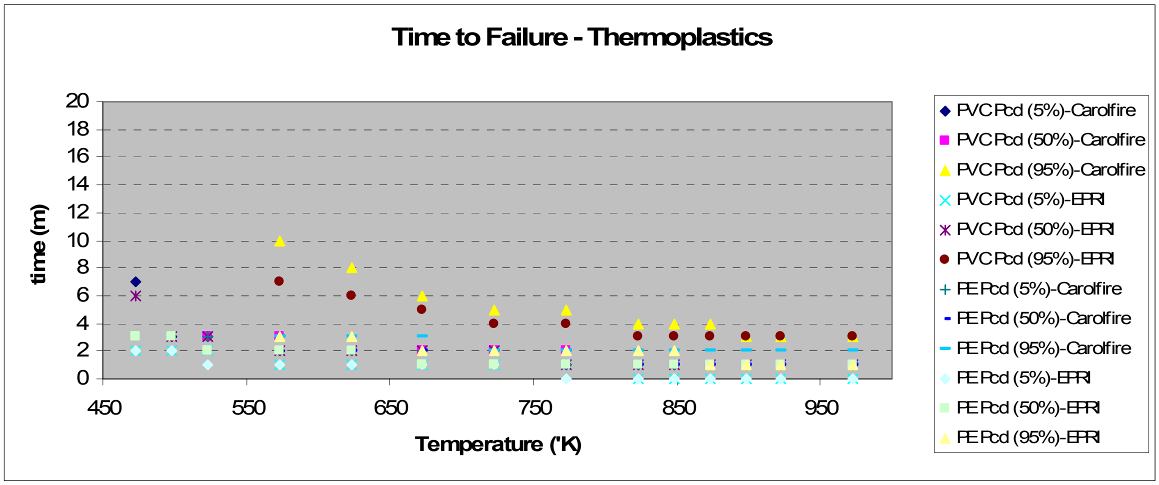


Figure 45. Time to Cable Damage, Thermoplastics – Heat Transfer Model

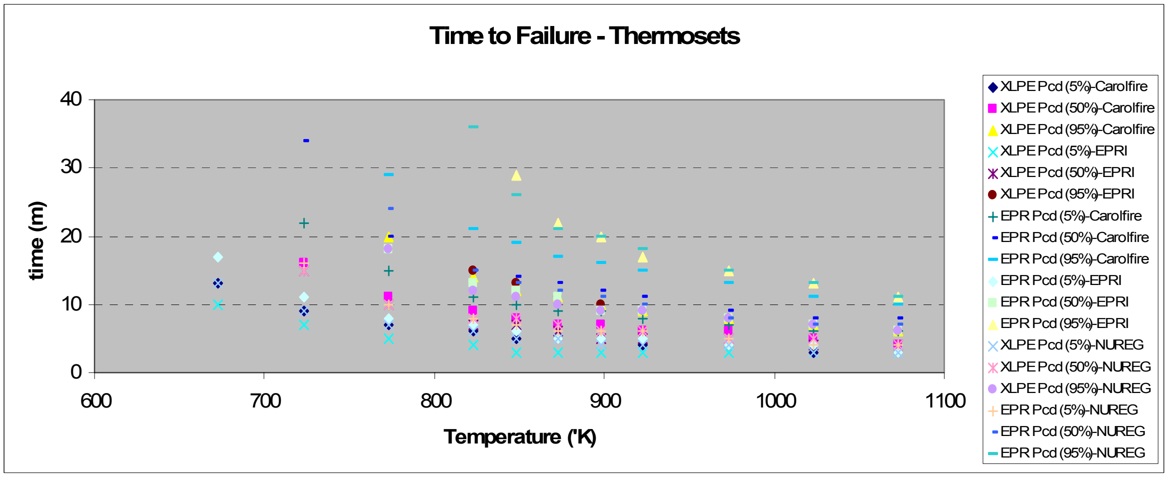


Figure 46. Time to Cable Damage, Thermosets – Heat Transfer Model

8.6. Fragility Curves

In this section the results from the models proposed are compared to the results described in NEI (2002) and EPRI (2002).

In these references the fire-induced cable damage phenomenon is analyzed in an effort to attempt to determine the likelihood of spurious actuation of electrical circuits exposed to fire. The probability of cable damage is addressed through an expert elicitation approach and defined in terms of the surrounding temperature. The following estimates are provided in these references:

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)

These estimates are assumed as the temperature where the probability of cable damage P_{CD} is 0.05, 0.5 and 0.95 respectively. As pointed out in these references, the wide range in these estimates, representing “uncertainty” is due to differences in test conditions and cable-to-cable differences. The authors suggest interpreting this uncertainty as “aleatory” uncertainty; therefore, the estimated P_{CD} can be used directly in equation (2).

Based on these estimates, NEI (2002) and EPRI (2002) define the so-called "*fragility curves*" to estimate the probability of cable damage P_{CD} in terms of temperature of exposure. Figure 47 shows the "*fragility curves*" defined in these references for thermoplastic and thermosets electrical cables.

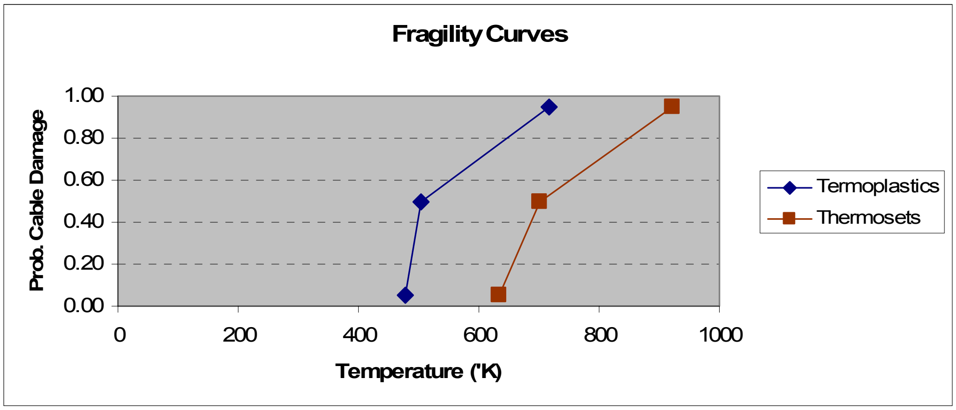


Figure 47. Fragility Curves

Even though in NEI (2002) and EPRI (2002) is recognized that P_{CD} is not a function solely of the peak temperature reached by the cable, it is assumed that under gradual heat-up conditions the damage breakdown can be usefully characterized by a temperature.

In the next paragraphs the fragility curves depicted in Figure 47 are compared to the results obtained in the previous sections for the IR "K factor" and the heat transfer models. It is important to mention that the models proposed in this research consider a series of factors not addressed in the definition of the "fragility curves". For instance, the heat transfer model takes in consideration the cable insulation thickness, the thermal properties of the materials and the dynamic of the thermal insult; so if any of these parameters change the results from the heat transfer model will also change.

First at all, the P_{CD} results from the IR "K factor" model considering constant and distributed damage (see Figure 37 and Figure 41) are compared to the 5th, 50th and 95th percentile defined in the fragility curves. Figure 48 and Figure 49 show the probability of cable damage using the IR "K factor" model assuming a constant surrounding temperature and the corresponding values defined in the fragility curves for thermoplastic and thermosets respectively.

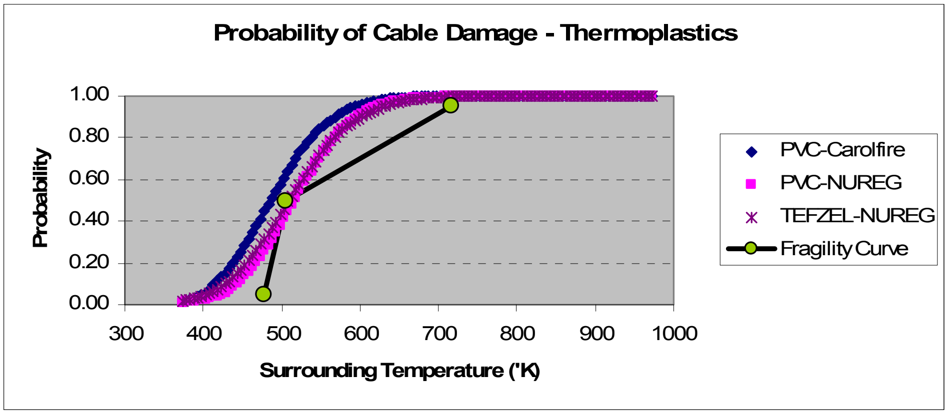


Figure 48. P_{CD} (Constant T_a) – IR "K factor" Model vs. Fragility Curve (Thermoplastics)

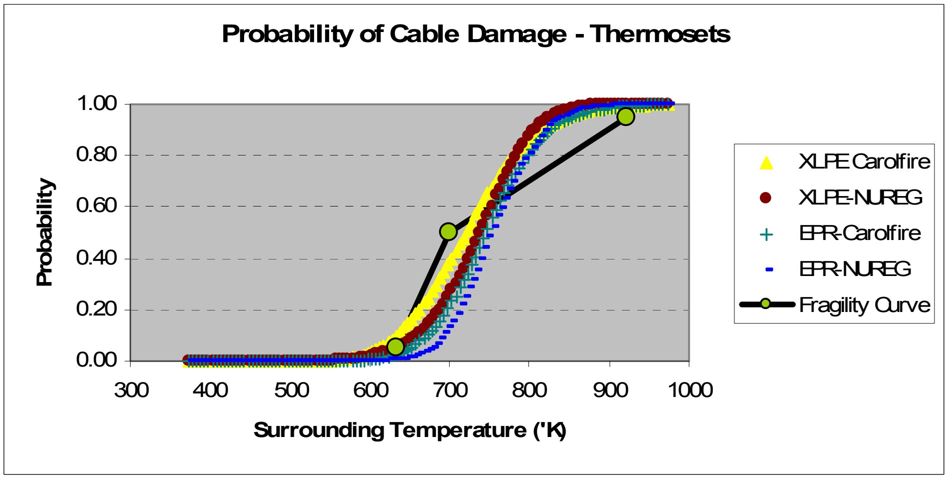


Figure 49. P_{CD} (Constant T_a) – IR "K factor" Model vs. Fragility Curve (Thermosets)

As shown in Figure 48 and Figure 49, the 5th, 50th and 95th percentile defined in the fragility curves are different to the corresponding percentiles of P_{CD} using the IR "K factor" model assuming constant surrounding temperature. The major difference can be seen in the 5th percentile for thermoplastic, while the fragility curve estimates 477 °K (204 °C), the IR "K factor" model predict a temperature about 410 °K (137 °C); therefore, this model predicts a lower trigger temperature capable of affecting the functional integrity of a thermoplastic insulated cable. This statement is also valid for the 95th percentile.

Similarly, Figure 50 and Figure 51 show the probability of cable damage using the IR "K factor" model assuming a random surrounding temperature and the corresponding 5th, 50th and 95th percentile defined in the fragility curves. As observed, the values defined in the fragility curves are closed to the values predicted using the IR "K factor" model. However, the same statement pointed out above regarding to the 5th percentile applied.

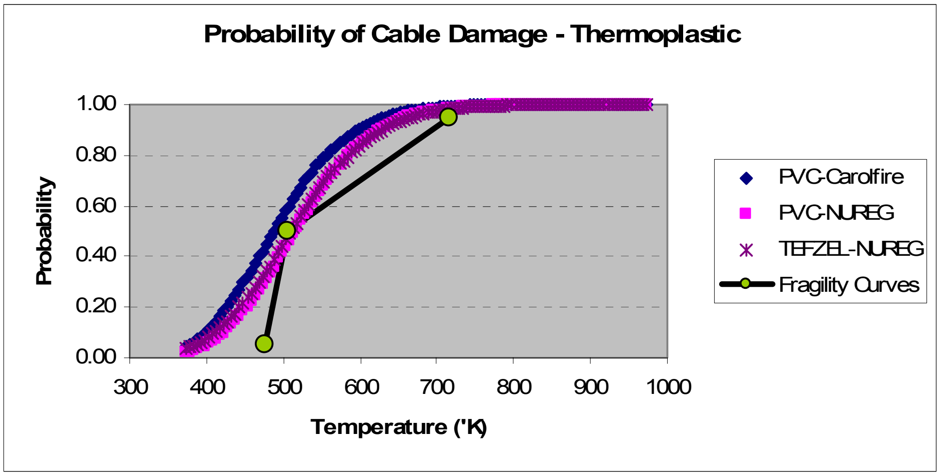


Figure 50. P_{CD} (Random T_a) – IR "K factor" Model vs. Fragility Curve (Thermoplastics)

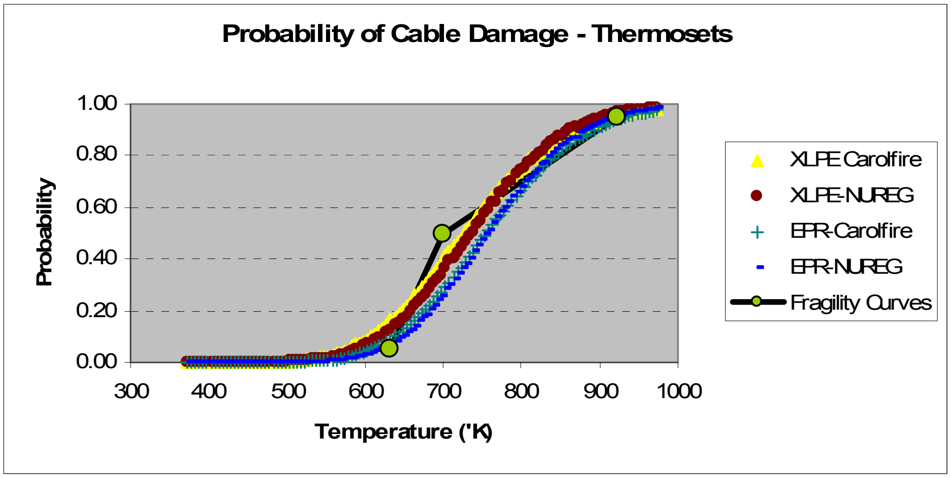


Figure 51. P_{CD} (Random T_a) – IR "K factor" Model vs. Fragility Curve (Thermosets)

The comparison of the fragility curves to the results provided by the heat transfer model is not direct because this model as a physics-based model considers a series of parameters specific for each scenario; therefore, for the same surrounding temperature the P_{CD} will vary depending on the characteristics of the thermal insult (*e.g.* exposure time) and the thermal properties of the specific insulation material under study. Just for comparison purposes the results obtained in section 8.2.3 (Table 15, Table 16 and Table 17) are used.

Figure 52 and Figure 53 show the P_{CD} of some of the polymeric material under evaluation (PVC, XLPE, EPR, PE) for the 3 different databases developed and the corresponding fragility curves for thermoplastic and thermosets respectively.

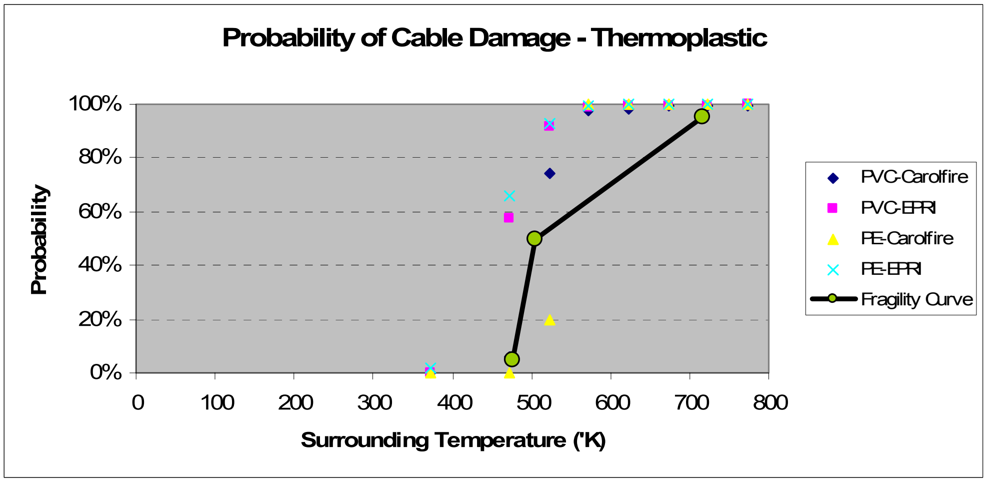


Figure 52. P_{CD} – Heat Transfer Model vs. Fragility Curve (Thermoplastics)

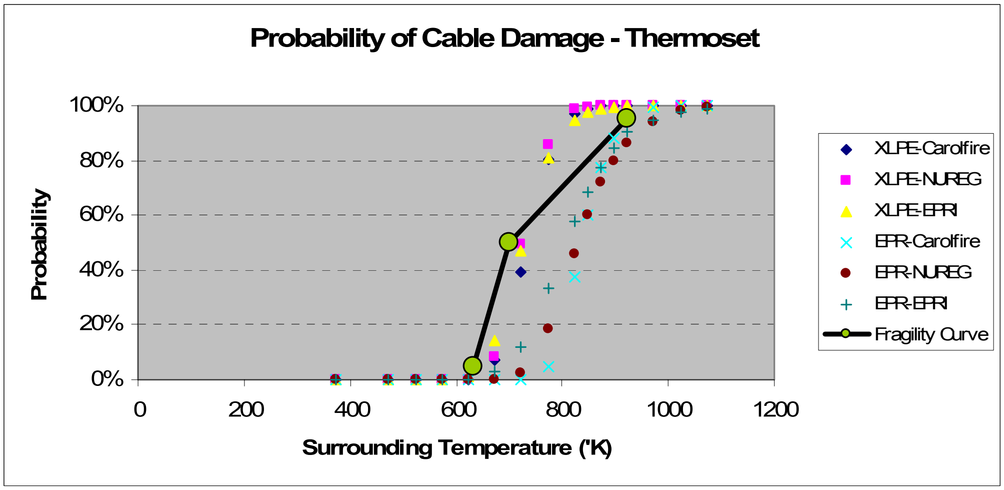


Figure 53. P_{CD} – Heat Transfer Model vs. Fragility Curve (Thermosets)

As shown in Figure 52 and Figure 53, the 5th, 50th and 95th percentile defined in the fragility curves differ slightly from the corresponding percentiles of P_{CD} using the heat transfer model. The major differences can be seen in thermoplastics, which in part is due to the significant variability among the thermal behavior of all the thermoplastic materials evaluated. Even though the P_{CD} estimated for thermoplastic using the Carolfire database follows closely the values described by the fragility curves, at least for probabilities lower than 50%, the remaining estimated values show less consistency.

The P_{CD} estimated for thermosets shows a more consistent behavior to the 5th, 50th and 95th percentile defined in the fragility curves.

In order to demonstrate the context-dependency characteristic of the heat transfer model, the previous comparison is performed again but considering two different scenarios:

- Different time-temperature profile P(t,T).
- Different thermal properties and thickness of the insulation.

As it was described in section 8.2.3 the time-temperature profile P(t,T) assumed above considers a linear ramp-up of 4 minutes, but a new ramp-up time of 20 minutes is considered (less severe thermal insult), so when a scenario is defined by a nominal surrounding temperature of 473 °K (200 °C), the time-temperature profile is given by:

- An initial surrounding temperature of 303 °K (30 °C).
- A linear ramp-up of 20 minutes to reach the nominal temperature (473 °K/200 °C).
- After 20 minutes, a constant temperature (nominal temperature: 473 °K/200 °C).

Figure 54 and Figure 55 show the probability of cable damage P_{CD} at 30 minutes of exposure time using the heat transfer model and assuming the new P(t,T). This figure also shows the corresponding 5^{th}, 50^{th} and 95^{th} percentile defined in the fragility curves for thermoplastic and thermosets respectively.

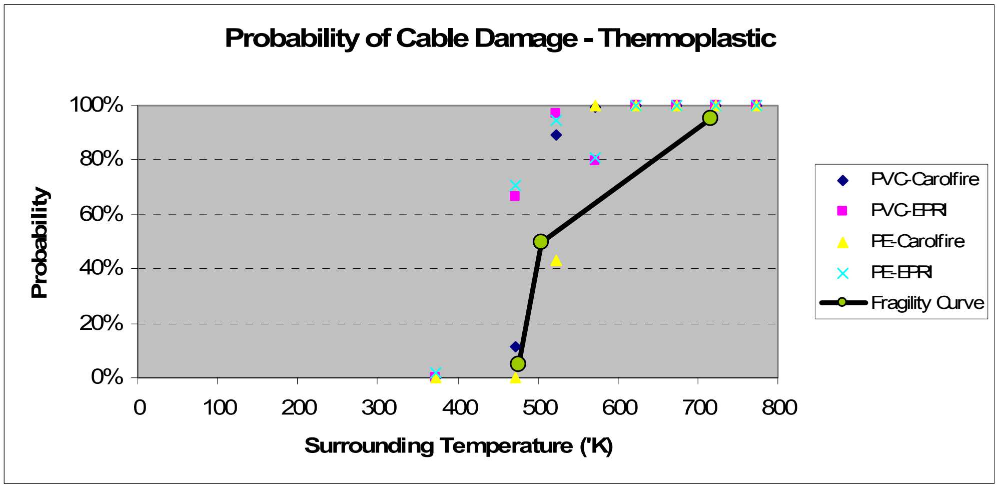


Figure 54. P_{CD} – Heat Transfer Model vs. Fragility Curve (Thermoplastics)

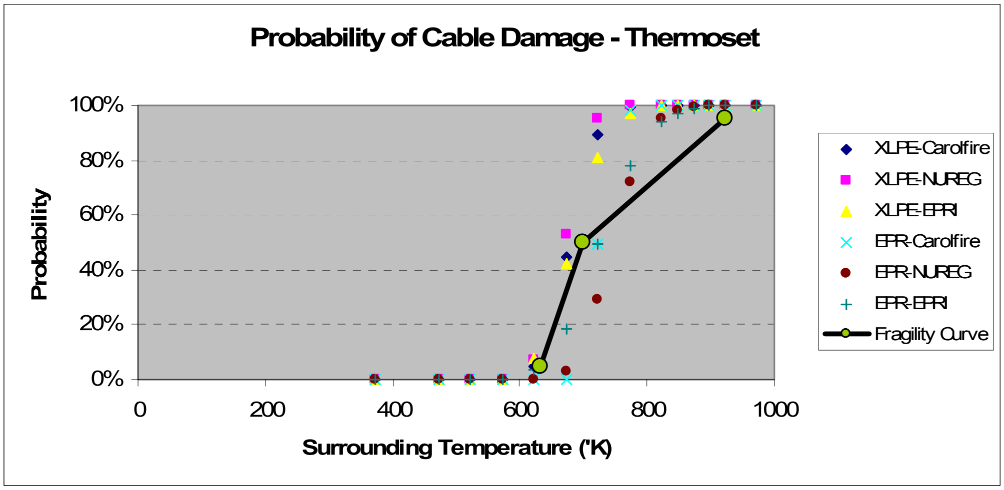


Figure 55. P_{CD} – Heat Transfer Model vs. Fragility Curve (Thermosets)

As shown in Figure 54, in case of thermoplastic cables, the 5th, 50th and 95th percentile defined in the fragility curves do not match the P_{CD} using the heat transfer model, but in general they follow the same pattern. In case of thermosets, the 5th, 50th and 95th percentile defined in the fragility curves are closed to the P_{CD} estimated using the heat transfer model.

Now the case with different thermal properties will be considered. For simplicity purposes just the thermal diffusivity is modified as indicated in Table 23. In these new scenarios an initial cable temperature of 348 °K (75 °C) is considered. Additionally, the thickness of the cable insulation is reduced to 1.31 mm.

Table 23: Thermal Properties – Heat Transfer Model

Thermal Properties		PVC	XLPE	EPR	PE	TEFZEL	EP
Thermal Diffusivity (m^2/s)	5th percentile	1.60E-07	1.74E-07	1.70E-07	1.27E-06	7.00E-08	1.70E-07
	95th percentile	7.00E-06	2.66E-07	2.40E-07	7.00E-06	1.60E-06	2.50E-07

Figure 56 and Figure 57 show the probability of cable damage P_{CD} using the heat transfer model and assuming the new thermal diffusivities and conditions.

As shown in Figure 56 and Figure 57, the fragility curves do not match the corresponding percentiles estimated using the heat transfer model, but in general they follow the same pattern, particularly the thermosets. As in the previous cases, the major differences can be seen in thermoplastics.

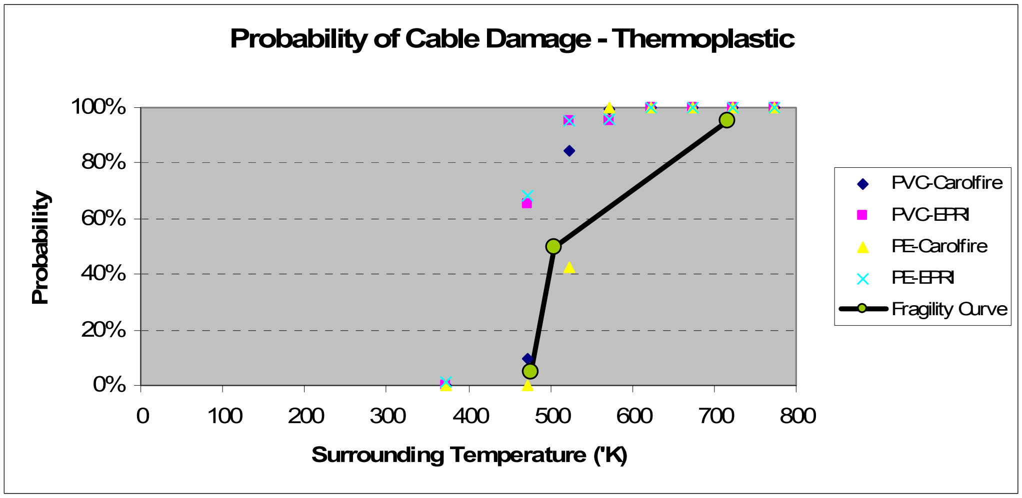


Figure 56. P_{CD} – Heat Transfer Model vs. Fragility Curve (Thermoplastics)

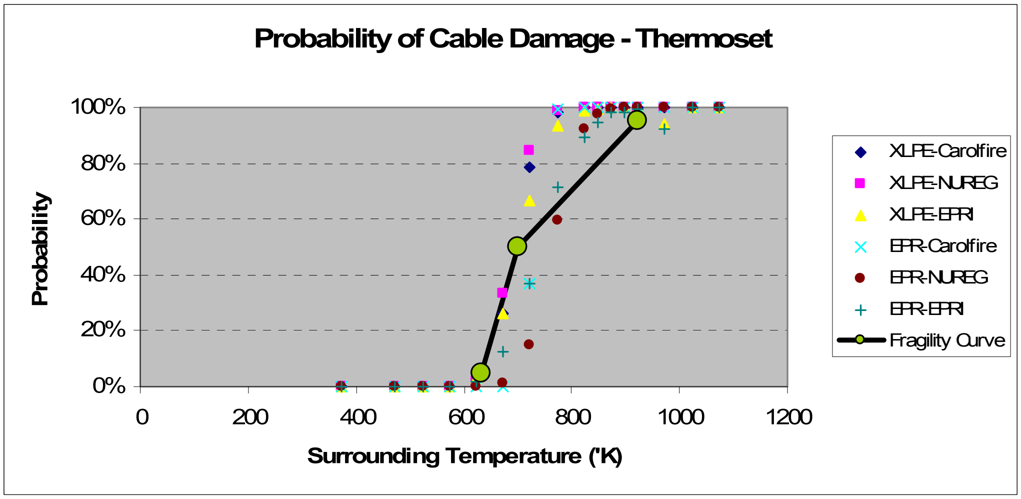


Figure 57. P_{CD} – Heat Transfer Model vs. Fragility Curve (Thermoplastics)

Figure 58 shows in the same chart the fragility curves for thermosets and thermoplastics and the probability of cable damage P_{CD} estimated for the three cases evaluated in this section using the heat transfer model.

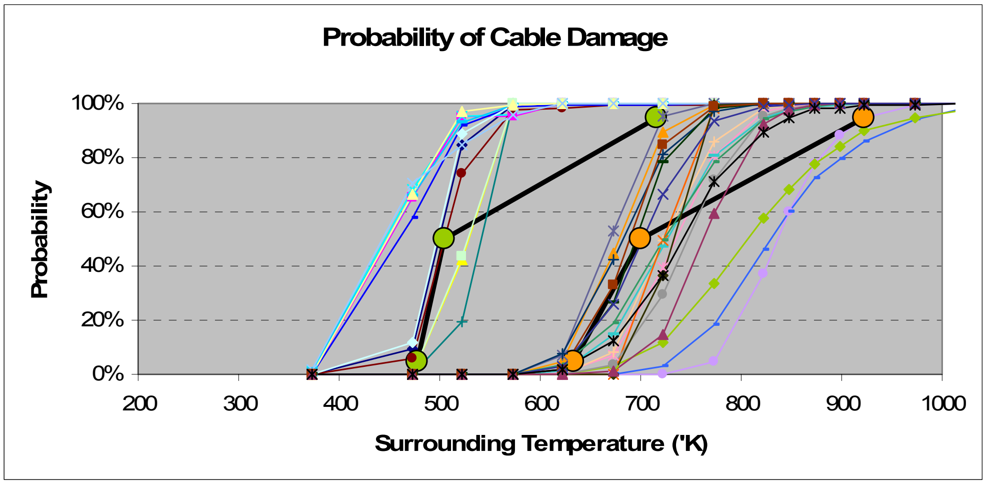


Figure 58. P_{CD} – Heat Transfer Model vs. Fragility Curve

From Figure 58 can be inferred that values given by the fragility curves constitute an acceptable representation of the probability of cable damage of thermosets and thermoplastics for the scenarios considered. Of course, if one of the parameters of the heat transfer model is modified in order to evaluate a specific fire scenario (e.g. exposure time) the results provided by the heat transfer model will be different, but in general they will follow the same patter illustrated in Figure 58.

Figure 58 is a clear proof of the applicability of the heat transfer model and the endurance-damage approach to estimate the probability of cable damage for a given fire. This model allows the estimation of the probability of cable damage for specific thermal insults considering its dynamic behavior. However, it is necessary to point out that the scenarios evaluated in this study corresponds to simple cable configurations, where the cable are single-conductor and the insulation and jacket are from the same material.

The estimation of probability of cable damage of more complex cable configurations, such as multi-conductors, with different insulation and cable materials requires the development of heat transfer models to estimate the inner temperature in the target cables. Once this parameter is estimated, the damage-endurance approach can be applied.

9. Conclusions and Recommendations

Currently, the available models to estimate the likelihood of fire-induced cable damage do not consider the underlying causalities and mechanisms of failures that take place within or among the electrical cables during the fire accident.

This research represents a step forward in the characterization of the thermal degradation process of electric cables expose to fire, and provides an alternative way to estimate the fire-induced cable damage likelihood based on models that consider the dynamic of the fire. This estimation can be performed for fire scenarios characterized for particular time-temperature profiles (scenario-based approach). Additionally, the uncertainty in the characterization of the thermal degradation process can be incorporated into the model.

The estimation of fire-induced cable damage likelihood has been addressed through three different models: the kinetic, the heat transfer and the IR “K Factor” model. All these models were developed using an endurance damage approach where the functional integrity of the polymeric cable insulation, in terms of thermal degradation, inner cable temperature and IR (depending on the selected model) is compared to the respective endurance limit. Based on this comparison the probability of fire-induced cable damage is estimated.

For a given fire, characterized for a specific time-temperature profile, the probability of cable damage was estimated on a time-base scale.

Several practical examples were developed under different thermal exposure conditions, and the results obtained were compared to studies reported in the open literature.

The more relevant conclusions and recommendations from this research are:

1. In light of the current knowledge and experimental evidence it is not possible to evaluate the feasibility of the kinetic model. Uncertainty associated with the characterization of kinetic parameters in addition to a lack of a universally accepted kinetic model capable of modeling the thermal degradation process in a wide range of conditions; prevent the development of this model at this time.

   It is recommended that a project be initiated to evaluate this model for a specific and well characterized polymeric material, preferably under controlled and well-characterized thermal insults. Depending of the results obtained, one could evaluate the feasibility of extending this physics-based model to real fire scenarios.

2. The physics-based heat transfer model takes into account the properties and characteristics of the cables and cable materials, and the characteristics of the thermal insult. It is a model capable of predicting the probability of cable damage under different thermal conditions. This model could be used to consider to a greater extent the dynamic of the thermal insult.

In order to improve the robustness of this model, it is recommended that work be done to:

- Enrich the existing databases for cables made of PVC, PE, XLPE, and EPR and develop new databases for other common polymeric cable materials encountered in nuclear power plants (Tefzel, Silicone, XLPO, etc). The update of the existing inner cable temperature endurance limit probability density function can be performed using a Bayesian approach, where the prior information is given by the endurance limits reported in this study and the evidence will be given by the results of the new testing programs.
- Develop heat transfer models through which the inner cable temperature of complex cable arrangements and configurations can be estimated. Once this parameter is estimated, the damage-endurance approach proposed can be applied.
- Develop a database for thermal properties of polymeric cable materials of interest. One of the weaknesses of this model is the scarcity of representative thermal properties for thermoplastic and thermosets materials typically used in the commercial cable industry. Manufacturers normally include additives and fillers that change the nominal or tabulated thermal properties of polymers. The possibility that manufacturers provide this information as part of cable specification should be evaluated.

3. The IR “K factor” model is an empirical model that is simple to apply, and it only requires the conductor-insulation radius rate once the characterization of the parameters C_1 and C_2 has been accomplished. However, given the simplicity of the model, it does not consider the dynamic of the thermal insult (exposure time), just the surrounding temperature.

   In order to improve the robustness of this model, it is recommended that work be done to:

   - Enrich the existing databases for cables made of PVC, Tefzel, XLPE, and EPR and develop new databases for other common polymeric cable materials encountered in nuclear power plants (PE, Silicone, XLPO, etc). It is presumed that the high variability observed in the characterization of C_1 and C_2, beside the expected differences for compositional variations (aleatory uncertainty), is due to thermal exposure differences and probably to differences associated with the configuration and arrangement of the data acquisition systems and cable’s lengths. The validation of these statements should be evaluated.
   - Evaluate the feasibility of this model for complex cable arrangements and configurations (multi-conductors with different insulation and jacket materials, armored cables, etc).

4. The models proposed were developed with experimental evidence from different fire testing programs (NUREG/CR-5546, NUREG/CR-6776, EPRI 1003326 and Carolfire). However, most of the experimental tests represent fire scenarios where the rate of temperature rise, the heat release rate and other thermal exposure conditions remain within given ranges that do not necessarily cover the expected spectrum of real fires scenarios in a NPP.

   Therefore, the validity of these models should be evaluated for scenarios out of the limits defined in these testing programs. For instance, for extreme high temperatures, the melting point of the conductors can be reached (aluminum 933 °K / 660 °C and copper 1085°K / 812°C) and different thermal behavior may be observed.

APPENDIX I: Kinetic Model

In the following sections some of the conventional models proposed to analyze the dynamic behavior of the thermal degradation process of polymers are described.

1st Case: $$\frac{d\alpha}{dt} = A(1-\alpha)e^{-\frac{E}{RT}}$$

Solution: $$\alpha(t) = [\alpha_0 - 1]e^{-A(e^{-\frac{E}{RT}})t} + 1$$

Assuming $\alpha_{(t=0)} = 0$, and considering that $\alpha_{(t)}$ is given by:

$$\alpha(t) = \frac{m_0 - m(t)}{m_0 - m_f}$$

The mass of the specimen in term of time is given by:

$$m(t) = [m_0 - m_f]e^{-A(e^{-\frac{E}{RT}})t} + m_f$$

where:

m_0 = initial mass

m_f = final mass

This equation is in agreement with the approach developed by Mieling and Pardue for calculation of first-order rate constant (Perez and Silva, 1988). It is also equivalent to the mathematical expression described by Harper et al. (2004):

$$\frac{m(t)}{m_0} = Yc_{(T)} + [1 - Yc_{(T)}]e^{-k_p t}$$

where:

$$k_p = A(e^{-\frac{E}{RT}})$$

$$Yc_{(T)} = \frac{m_f}{m_0}$$

2nd Case: $$\frac{d\alpha}{dt} = A_1(1-\alpha)e^{-\frac{E_1}{RT}} - A_2\alpha e^{-\frac{E_2}{RT}}$$

Solution:

$$\alpha(t) = [\alpha_0 - \frac{A_1 e^{-\frac{E_1}{RT}}}{A_1 e^{-\frac{E_1}{RT}} + A_2 e^{-\frac{E_2}{RT}}}]e^{-[A_1(e^{-\frac{E_1}{RT}})+A_2(e^{-\frac{E_2}{RT}})]t} + \frac{A_1 e^{-\frac{E_1}{RT}}}{A_1 e^{-\frac{E_1}{RT}} + A_2 e^{-\frac{E_2}{RT}}}$$

Assuming $\alpha_{(t=0)} = 0$, the mass of the specimen in term of time is given by:

$$m(t) = m_0 + \frac{A_1 e^{-\frac{E_1}{RT}}}{A_1 e^{-\frac{E_1}{RT}} + A_2 e^{-\frac{E_2}{RT}}}.m_0\left(e^{-[A_1(e^{-\frac{E_1}{RT}})+A_2(e^{-\frac{E_2}{RT}})]t} - 1\right) - \frac{A_1 e^{-\frac{E_1}{RT}}}{A_1 e^{-\frac{E_1}{RT}} + A_2 e^{-\frac{E_2}{RT}}}.m_f\left(e^{-[A_1(e^{-\frac{E_1}{RT}})+A_2(e^{-\frac{E_2}{RT}})]t} - 1\right)$$

3rd Case: $$\frac{d\alpha}{dt} = A_1(1-\alpha)e^{-\frac{E_1}{RT}} + A_2\alpha e^{-\frac{E_2}{RT}}$$

Solution:

$$\alpha(t) = [\alpha_0 - \frac{A_1 e^{-\frac{E_1}{RT}}}{A_1 e^{-\frac{E_1}{RT}} - A_2 e^{-\frac{E_2}{RT}}}]e^{-[A_1(e^{-\frac{E_1}{RT}})-A_2(e^{-\frac{E_2}{RT}})]t} + \frac{A_1 e^{-\frac{E_1}{RT}}}{A_1 e^{-\frac{E_1}{RT}} - A_2 e^{-\frac{E_2}{RT}}}$$

Assuming $\alpha_{(t=0)} = 0$, the mass of the specimen in term of time is given by:

$$m(t) = m_0 + \frac{A_1 e^{-\frac{E_1}{RT}}}{A_1 e^{-\frac{E_1}{RT}} - A_2 e^{-\frac{E_2}{RT}}} .m_0 \left(e^{-[A_1(e^{-\frac{E_1}{RT}}) - A_2(e^{-\frac{E_2}{RT}})]t} - 1 \right) - \frac{A_1 e^{-\frac{E_1}{RT}}}{A_1 e^{-\frac{E_1}{RT}} - A_2 e^{-\frac{E_2}{RT}}} .m_f \left(e^{-[A_1(e^{-\frac{E_1}{RT}}) - A_2(e^{-\frac{E_2}{RT}})]t} - 1 \right)$$

4th Case: $$\frac{d\alpha}{dt} = A_1(1-\alpha) e^{-\frac{E_1}{RT}} + A_2(1-\alpha) e^{-\frac{E_2}{RT}}$$

Solution:

$$\alpha(t) = 1 - e^{-[\beta_1 A_1(e^{-\frac{E_1}{RT}}) + \beta_2 A_2(e^{-\frac{E_2}{RT}})]t} + \alpha_0 e^{-[\beta_1 A_1(e^{-\frac{E_1}{RT}}) + \beta_2 A_2(e^{-\frac{E_2}{RT}})]t}$$

Assuming $\alpha_{(t=0)} = 0$, the mass of the specimen in term of time is given by:

$$m(t) = m_0 e^{-[\beta_1 A_1(e^{-\frac{E_1}{RT}}) + \beta_2 A_2(e^{-\frac{E_2}{RT}})]t} + m_f - m_f e^{-[\beta_1 A_1(e^{-\frac{E_1}{RT}}) + \beta_2 A_2(e^{-\frac{E_2}{RT}})]t}$$

5th Case: $$2A \xrightarrow{K_1} B \xrightarrow{K_2} C$$

Amount at time t = 0	$[A]_0$	0	0
Amount at time t = 0	[A]	[B]	[C]

The mathematical solution of the kinetics of this system requires the assumption that the following relationship holds true at any time:

$$[A]_0 \quad = \quad [A] \quad + \quad [B] \quad + \quad [C]$$

The change in concentration of the individual species is given by the following set of equations:

$$-\frac{d[A]}{dt} = 2k_1[A]^2$$

$$\frac{d[C]}{dt} = k_2[B]$$

The rate of change in the concentration of [B] is the difference between both above equations:

$$\frac{d[B]}{dt} \quad = \quad -\frac{d[A]}{dt} - \frac{d[C]}{dt} \quad = \quad 2k_1[A]^2 - k_2[B] \quad \Rightarrow \quad \frac{d[B]}{dt} + k_2[B] \quad = \quad 2k_1[A]^2$$

Solving this expression, following the procedure and assumption described by Capellos and Benon et al. (1972), we obtain:

$$[C] \quad = \quad [A]_0 - \frac{[A]_0}{w} - [A]_0 e^{aw} \left\{ e^a - \frac{e^{aw}}{w} + a\left[\log w + \frac{a}{1!}(w-1) + \frac{a^2}{2.2!}(w^2-1) + \frac{a^3}{3.3!}(w^3-1) + \ldots \right] \right\}$$

Where:

$$w = 1 + 2k_1[A]_0 t \qquad\qquad k_1 = A_1 e^{-\frac{E_1}{RT}}$$

$$a = \frac{k_2}{2k_1[A]_0} \qquad\qquad k_2 = A_2 e^{-\frac{E_2}{RT}}$$

It is important to mention that there is no a universally accepted model that broadly describes the dynamic of the thermal degradation process. Most of these models are only valid under certain controlled conditions that are not representative of the conditions existing when a bundle of electrical cables are exposed to thermal insults.

APPENDIX II: Summary of Tests (NUREG 6776, EPRI 1003326 and Carolfire).

Test No.	**Fire Exposure**	**Cable Material**		**Cable Bundle Configuration**	**Raceway Type**	**~ Maximum Temperature**	
		Jacket	Insulation			° C	° F
NUREG/CR 6776 Test 1	plume	PVC	XLPE	8/c armored	tray (horizontal orientation)	440	824
NUREG/CR 6776 Test 2	plume	Neoprene, Hypalon	XLPE, EPR	7/c, 1/c	tray (horizontal orientation)	400	752
NUREG/CR 6776 Test 3	plume	Neoprene, Hypalon	XLPE, EPR	7/c, 1/c	tray (horizontal orientation)	500	932
NUREG/CR 6776 Test 4	plume	Tefzel	Tefzel	7/c, 1/c	tray (horizontal orientation)	420	788
NUREG/CR 6776 Test 5	hot gas layer	Hypalon	EPR	7/c, 1/c	tray (horizontal orientation)	350	662
NUREG/CR 6776 Test 6	hot gas layer	Tefzel	Tefzel	7/c, 1/c	tray (horizontal orientation)	350	662
NUREG/CR 6776 Test 7	plume	Hypalon	EPR	7/c, 1/c	tray (horizontal orientation)	500	932
NUREG/CR 6776 Test 9	plume	Hypalon	EPR	7/c, 1/c	tray (horizontal orientation)	550	1022
NUREG/CR 6776 Test 10	hot gas layer, radiant	Hypalon	EPR	7/c, 1/c	tray (vertical orientation)	500	932
NUREG/CR 6776 Test 12	plume	Neoprene, Hypalon	XLPE, EPR	7/c, 1/c	tray (horizontal orientation)	575	1067
NUREG/CR 6776 Test 13	hot gas layer	PVC	XLPE	8/c armored	tray (horizontal orientation)	700	1292
NUREG/CR 6776 Test 15	hot gas layer	Neoprene, Hypalon	XLPE, EPR	7/c, 1/c	tray (horizontal orientation)	550	1022
NUREG/CR 6776 Test 16	plume	PVC	PE	9/c, 1/c	tray (horizontal orientation)	500	932
NUREG/CR 6776 Test 17	hot gas layer	PVC	PE	9/c, 1/c	tray (vertical orientation)	475	887

Test No.	Fire Exposure	Cable Material		Cable Bundle Configuration	Raceway Type	~ Maximum Temperature	
		Jacket	Insulation			° C	° F
EPRI Test 1 Cable DA # 1	hot gas layer	PVC	XLPE	8/c armored	tray (horizontal orientation)	371	700
EPRI Test 1 Cable DA # 2	hot gas layer	PVC	XLPE	8/c armored	tray (horizontal orientation)	427	800
EPRI Test 1 Cable DA # 3	hot gas layer	PVC	XLPE	8/c armored	tray (horizontal orientation)	385	725
EPRI Test 1 Cable DA # 4	hot gas layer	PVC	XLPE	8/c armored	tray (horizontal orientation)	343	650
EPRI Test 2 Cable DA # 1	plume	Neoprene, Hypalon	XLPE, EPR	7/c, 1/c	tray (horizontal orientation)	343	650
EPRI Test 2 Cable DA # 2	plume	Neoprene, Hypalon	XLPE, EPR	7/c, 1/c	tray (horizontal orientation)	343	650
EPRI Test 2 Cable DA # 3	plume	Neoprene, Hypalon	XLPE, EPR	7/c, 1/c	tray (horizontal orientation)	260	500
EPRI Test 2 Cable DA # 4	plume	Neoprene, Hypalon	XLPE, EPR	7/c, 1/c	tray (horizontal orientation)	232	450
EPRI Test 3 Cable DA # 1	plume	Neoprene, Hypalon	XLPE, EPR	7/c, 1/c	tray (vertical orientation)	427	800
EPRI Test 3 Cable DA # 2	plume	Neoprene, Hypalon	XLPE, EPR	7/c, 1/c	tray (horizontal orientation)	427	800
EPRI Test 3 Cable DA # 3	plume	Neoprene, Hypalon	XLPE, EPR	7/c, 1/c	tray (horizontal orientation)	468	875
EPRI Test 3 Cable DA # 4	plume	Neoprene, Hypalon	XLPE, EPR	7/c, 1/c	tray (horizontal orientation)	399	750
EPRI Test 4 Cable DA # 1	plume	PVC	Tefzel	7/c, 1/c	tray (horizontal orientation)	385	725
EPRI Test 4 Cable DA # 2	plume	PVC	Tefzel	7/c, 1/c	tray (horizontal orientation)	343	650
EPRI Test 4 Cable DA # 3	plume	PVC	Tefzel	7/c, 1/c	tray (horizontal orientation)	302	575
EPRI Test 4 Cable DA # 4	plume	PVC	Tefzel	7/c, 1/c	tray (horizontal orientation)	288	550
EPRI Test 5 Cable DA # 1	hot gas layer	Hypalon	EPR	7/c, 1/c	tray (horizontal orientation)	316	600
EPRI Test 5 Cable DA # 2	hot gas layer	Hypalon	EPR	7/c, 1/c	tray (horizontal orientation)	343	650
EPRI Test 5 Cable DA # 3	hot gas layer	Hypalon	EPR	7/c, 1/c	tray (horizontal orientation)	288	550
EPRI Test 5 Cable DA # 4	hot gas layer	Hypalon	EPR	7/c, 1/c	tray (horizontal orientation)	343	650
EPRI Test 6 Cable DA # 1	hot gas layer	PVC	Tefzel	7/c, 1/c	tray (horizontal orientation)	288	550
EPRI Test 6 Cable DA # 2	hot gas layer	PVC	Tefzel	7/c, 1/c	tray (horizontal orientation)	288	550
EPRI Test 6 Cable DA # 3	hot gas layer	PVC	Tefzel	7/c, 1/c	tray (horizontal orientation)	316	600
EPRI Test 7 Cable DA # 1	hot gas layer	Hypalon	EPR	7/c, 1/c	tray (horizontal orientation)	454	850
EPRI Test 7 Cable DA # 2	hot gas layer	Hypalon	EPR	7/c, 1/c	tray (horizontal orientation)	441	825
EPRI Test 7 Cable DA # 3	hot gas layer	Hypalon	EPR	7/c, 1/c	tray (horizontal orientation)	427	800
EPRI Test 7 Cable DA # 4	hot gas layer	Hypalon	EPR	7/c, 1/c	tray (horizontal orientation)	482	900
EPRI Test 8 Cable DA # 1	plume	Hypalon	EPR	7/c, 1/c	tray (horizontal orientation)	416	780

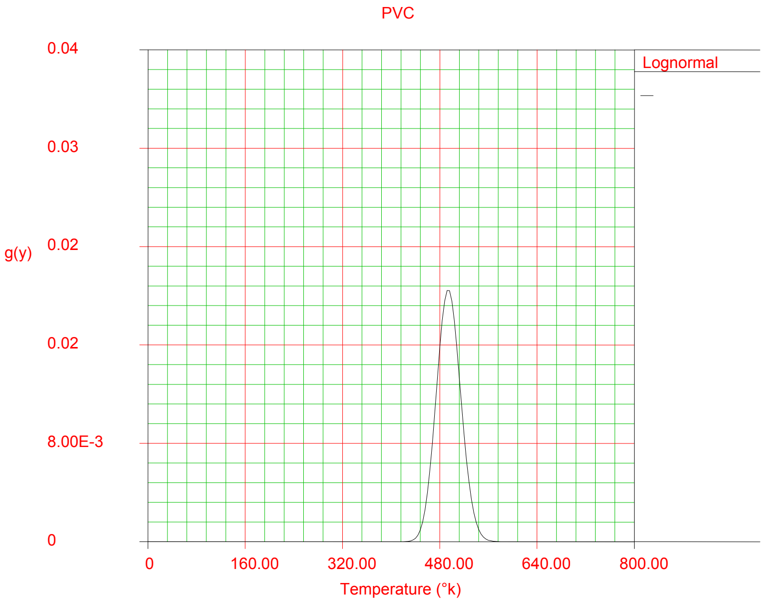
Test No.	Fire Exposure	Cable Material		Cable Bundle Configuration	Raceway Type	~ Maximum Temperature	
		Jacket	Insulation			° C	° F
EPRI Test 8 Cable DA # 2	plume	Hypalon	EPR	7/c, 1/c	tray (horizontal orientation)	399	750
EPRI Test 8 Cable DA # 3	plume	Hypalon	EPR	7/c, 1/c	tray (horizontal orientation)	399	750
EPRI Test 8 Cable DA # 4	plume	Hypalon	EPR	7/c, 1/c	tray (horizontal orientation)	316	600
EPRI Test 9 Cable DA # 1	plume	Hypalon	EPR	7/c, 1/c	tray (horizontal orientation)	454	850
EPRI Test 9 Cable DA # 2	plume	Hypalon	EPR	7/c, 1/c	tray (horizontal orientation)	510	950
EPRI Test 9 Cable DA # 3	plume	Hypalon	EPR	7/c, 1/c	tray (horizontal orientation)	538	1000
EPRI Test 9 Cable DA # 4	plume	Hypalon	EPR	7/c, 1/c	tray (horizontal orientation)	538	1000
EPRI Test 10 Cable DA # 1	Radiative, hot gas layer	Hypalon	EPR	7/c, 1/c	tray (vertical orientation)	538	1000
EPRI Test 10 Cable DA # 2	Radiative, hot gas layer	Hypalon	EPR	7/c, 1/c	tray (vertical orientation)	538	1000
EPRI Test 10 Cable DA # 3	Radiative, hot gas layer	Hypalon	EPR	7/c, 1/c	tray (vertical orientation)	538	1000
EPRI Test 10 Cable DA # 4	Radiative, hot gas layer	Hypalon	EPR	7/c, 1/c	tray (vertical orientation)	493	920
EPRI Test 11 Cable DA # 1	plume	Hypalon	EPR	7/c, 1/c	tray (horizontal orientation)	288	550
EPRI Test 11 Cable DA # 2	plume	Hypalon	EPR	7/c, 1/c	tray (horizontal orientation)	343	650
EPRI Test 11 Cable DA # 3	plume	Hypalon	EPR	7/c, 1/c	tray (horizontal orientation)	327	620
EPRI Test 11 Cable DA # 4	plume	Hypalon	EPR	7/c, 1/c	tray (horizontal orientation)	382	720
EPRI Test 12 Cable DA # 1	plume	Hypalon	EPR	7/c, 1/c	tray (horizontal orientation)	357	675
EPRI Test 12 Cable DA # 2	plume	Hypalon	EPR	7/c, 1/c	tray (horizontal orientation)	454	850
EPRI Test 12 Cable DA # 3	plume	Hypalon	EPR	7/c, 1/c	tray (horizontal orientation)	510	950
EPRI Test 12 Cable DA # 4	plume	Hypalon	EPR	7/c, 1/c	tray (horizontal orientation)	468	875
EPRI Test 13 Cable DA # 1	hot gas layer	PVC	XLPE	8/c	tray (horizontal orientation)	427	800
EPRI Test 13 Cable DA # 2	hot gas layer	PVC	XLPE	8/c	tray (horizontal orientation)	482	900
EPRI Test 13 Cable DA # 3	hot gas layer	PVC	XLPE	8/c	tray (horizontal orientation)	482	900
EPRI Test 13 Cable DA # 4	hot gas layer	PVC	XLPE	8/c	tray (horizontal orientation)	441	825
EPRI Test 14 Cable 1, 2, 3	plume	Hypalon	EPR	7/c, 1/c	tray (horizontal orientation)	468	875
EPRI Test 15 Cable DA # 1	hot gas layer	Hypalon	EPR	7/c, 1/c	tray (horizontal orientation)	>2500	>2500
EPRI Test 15 Cable DA # 2	hot gas layer	Hypalon	EPR	7/c, 1/c	tray (horizontal orientation)	538	1000
EPRI Test 15 Cable DA # 3	hot gas layer	Hypalon	EPR	7/c, 1/c	tray (horizontal orientation)	449	840
EPRI Test 15 Cable DA # 4	hot gas layer	Hypalon	EPR	7/c, 1/c	tray (horizontal orientation)	493	920
EPRI Test 16 Cable DA # 1	plume	PVC	PE, Tefzel	9/c, 1/c	tray (horizontal orientation)	538	1000
EPRI Test 16 Cable DA # 2	plume	PVC	PE, Tefzel	9/c, 1/c	tray (horizontal orientation)	427	800
EPRI Test 16 Cable DA # 3	plume	PVC	PE, Tefzel	9/c, 1/c	tray (horizontal orientation)	316	600
EPRI Test 16 Cable DA # 4	plume	PVC	PE, Tefzel	9/c, 1/c	tray (horizontal orientation)	260	500

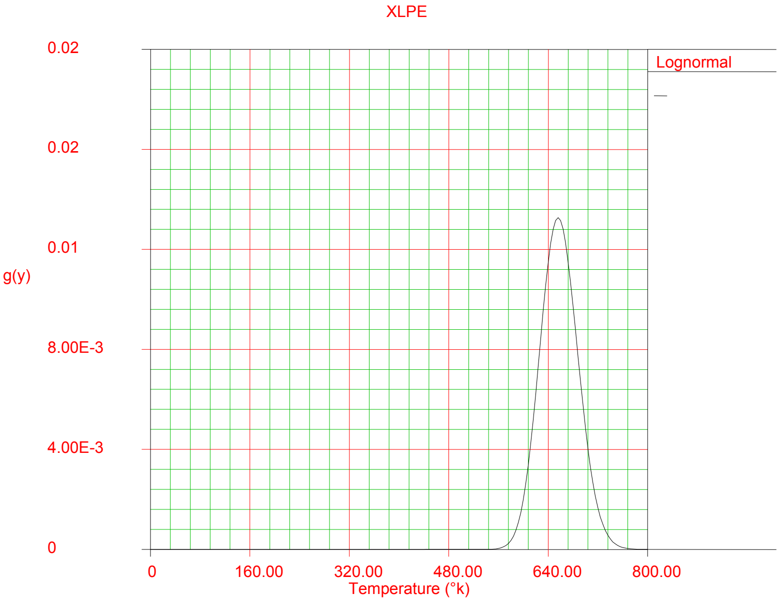
Test No.	Fire Exposure	Cable Material		Cable Bundle Configuration	Raceway Type	~ Maximum Temperature	
		Jacket	Insulation			° C	° F
EPRI Test 17 Cable DA # 1	Radiative, hot gas layer	Hypalon, PVC	EPR, PE, Tefzel	9/c, 7/c, 1/c	tray (vertical orientation)	441	825
EPRI Test 17 Cable DA # 2	Radiative, hot gas layer	Hypalon, PVC	EPR, PE, Tefzel	9/c, 7/c, 1/c	tray (vertical orientation)	413	775
EPRI Test 17 Cable DA # 3	Radiative, hot gas layer	Hypalon, PVC	EPR, PE, Tefzel	9/c, 7/c, 1/c	tray (vertical orientation)	329	625
EPRI Test 17 Cable DA # 4	Radiative, hot gas layer	Hypalon, PVC	EPR, PE, Tefzel	9/c, 7/c, 1/c	tray (vertical orientation)	385	725
EPRI Test 18 Cable 1, 2, 3	hot gas layer	Hypalon	EPR	7/c, 1/c	tray (horizontal orientation)	510	950

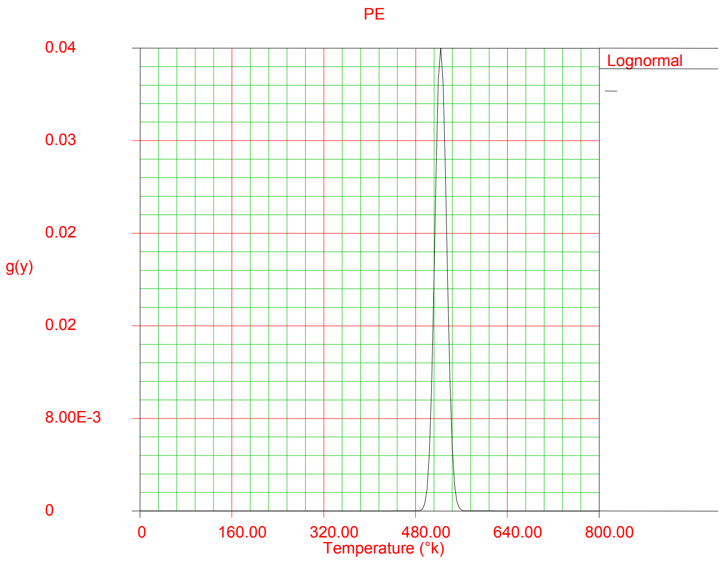
Test No.	Fire Exposure	Cable Material		Cable Bundle Configuration	Raceway Type	~ Maximum Temperature	
		Jacket	Insulation			° C	° F
Carolfire Test 1B	Radiative	Hypalon	XLPE	3/c plus drain wire	tray (horizontal orientation)	475	887
Carolfire Test 2B	Radiative	Hypalon	XLPE	3/c plus drain wire	tray (horizontal orientation)	470	878
Carolfire Test 3B	Radiative	Hypalon	XLPE	3/c plus drain wire	tray (horizontal orientation)	470	878
Carolfire Test 4B	Radiative	PVC	PVC	3/c plus drain wire	tray (horizontal orientation)	300	572
Carolfire Test 5B	Radiative	PVC	PVC	3/c plus drain wire	tray (horizontal orientation)	300	572
Carolfire Test 6B	Radiative	PVC	PVC	3/c plus drain wire	tray (horizontal orientation)	300	572
Carolfire Test 11B	Radiative	Hypalon	XLPE	7/c	tray (horizontal orientation)	470	878
Carolfire Test 12B	Radiative	Hypalon	XLPE	7/c	tray (horizontal orientation)	470	878
Carolfire Test 13B	Radiative	Hypalon	XLPE	7/c	tray (horizontal orientation)	470	878
Carolfire Test 14B	Radiative	PVC	PE	7/c	tray (horizontal orientation)	300	572
Carolfire Test 15B	Radiative	PVC	PE	7/c	tray (horizontal orientation)	325	617
Carolfire Test 16B	Radiative	PVC	PE	7/c	tray (horizontal orientation)	325	617
Carolfire Test 44B	Radiative	CSPE, CPE, PVC	XLPE, EPR, Silicone, XLPO, PE, Tefzel	7/c	tray (horizontal orientation)	525	977
Carolfire Test 45B	Radiative	CSPE, CPE, PVC	Silicone, XLPO, PE, Tefzel	7/c	tray (horizontal orientation)	525	977
Carolfire Test 46B	Radiative	CSPE, CPE, PVC	XLPE, EPR, TS/TP, PE, PVC, Tefzel	7/c	tray (horizontal orientation)	525	977
Carolfire Test 47B	Radiative	CSPE, CPE	XLPE, EPR	7/c	tray (horizontal orientation)	525	977
Carolfire Test PenPrelim_6_Item 10_XLPE_7C_665C_Rev0	Radiative	CSPE	XLPE	7/c	tray (horizontal orientation)	665	1229
Carolfire Test PenPrelim_7_Item 1_PVC_7C_300C_Rev0	Radiative	PVC	PVC	7/c	tray (horizontal orientation)	300	572
Carolfire Test PenPrelim_8_Item 1_PVC_7C_330C_Rev0	Radiative	PVC	PVC	7/c	tray (horizontal orientation)	330	626
Carolfire Test PenPrelim_9_Item 10_XLPE_7C_500C_Rev0	Radiative	CSPE	XLPE	7/c	tray (horizontal orientation)	500	932

APPENDIX III: Endurance Limits: Heat Transfer Model.

Carolfire Database:



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g(y)
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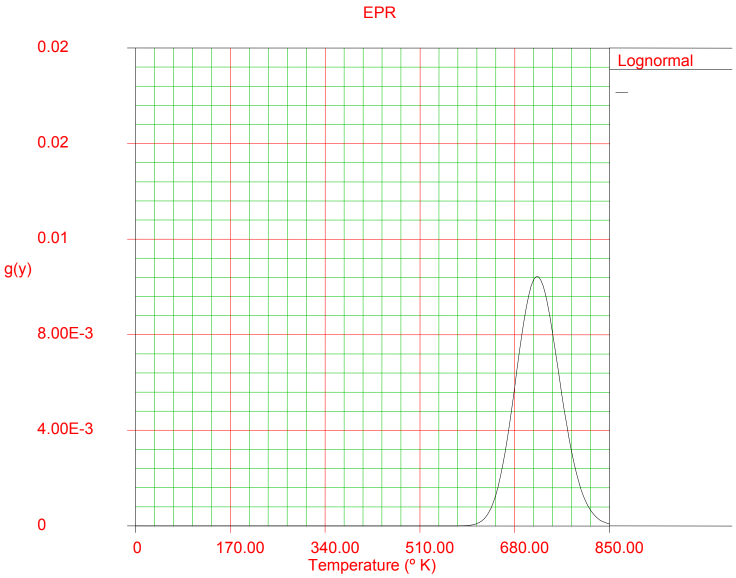
0
0
160.00
320.00
480.00
640.00
800.00
Temperature (°k)
Lognormal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g(y)
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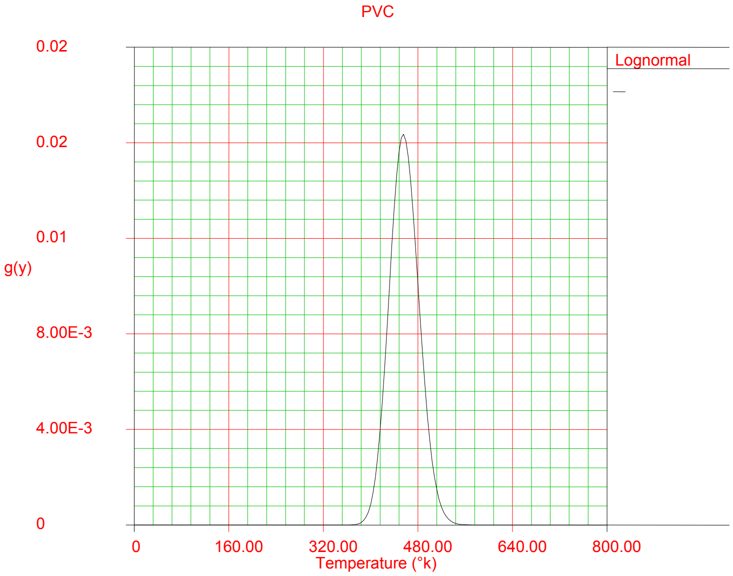
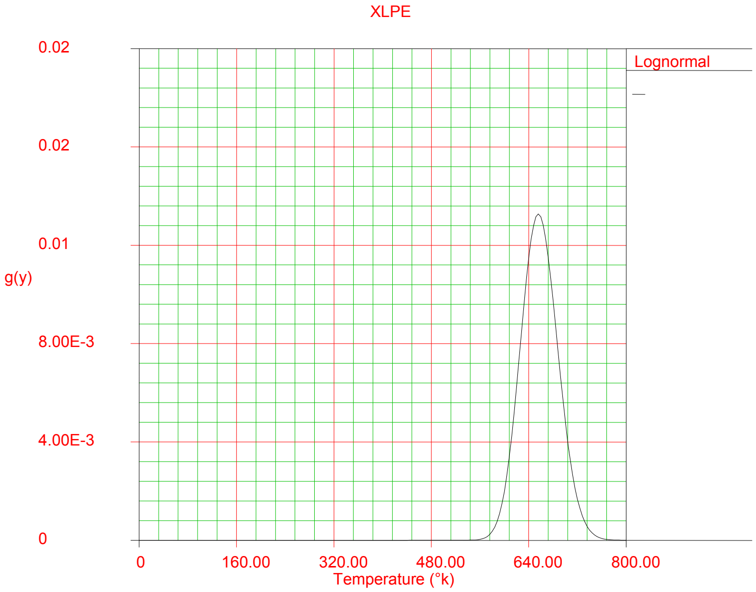
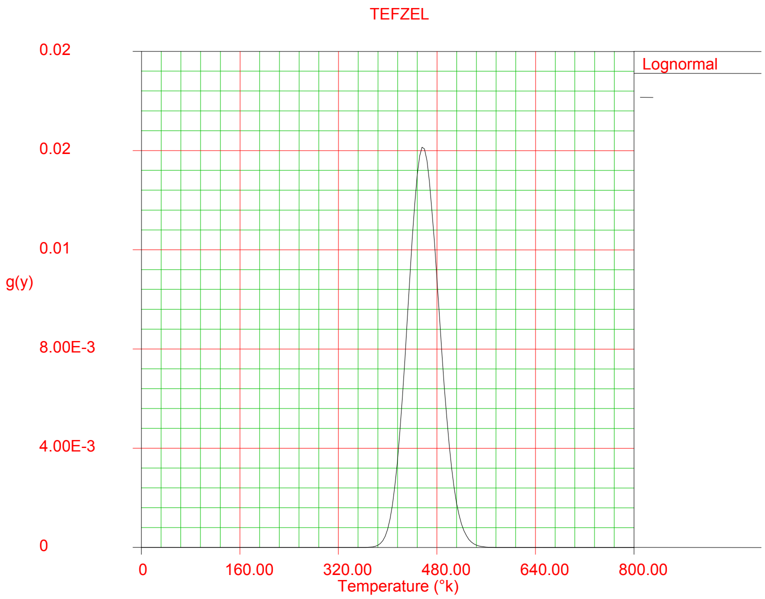
340.00
510.00
680.00
850.00
Temperature (° K)
Lognormal

NUREG/CR 6776 Database:



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Lognormal
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0.01
g(y)
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0
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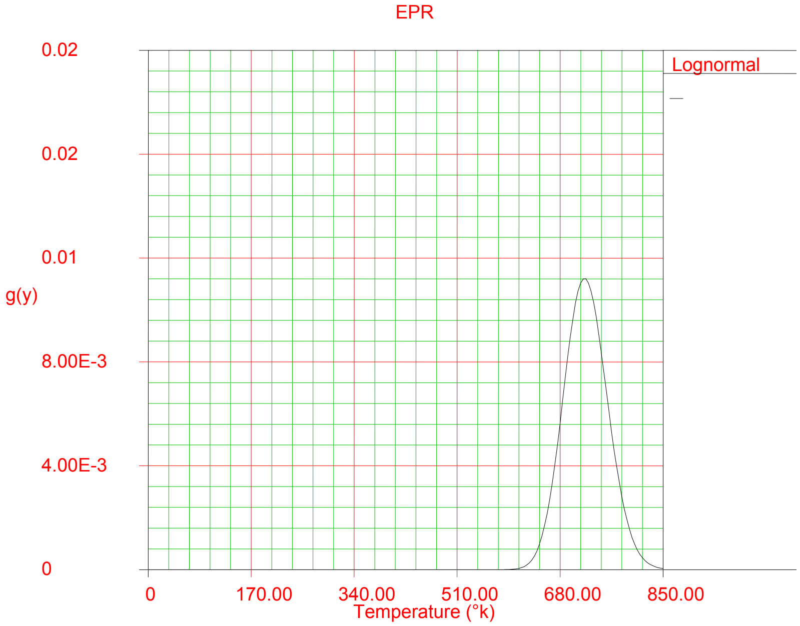
480.00
640.00
800.00
Temperature (°k)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g(y)
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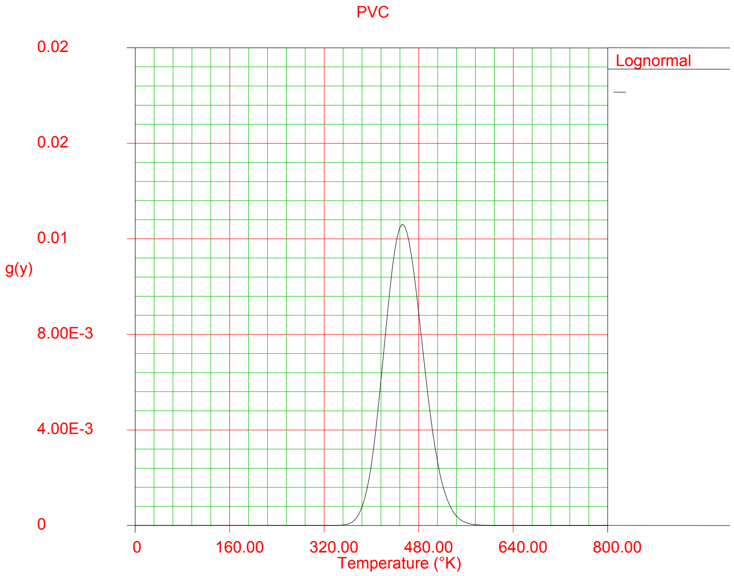
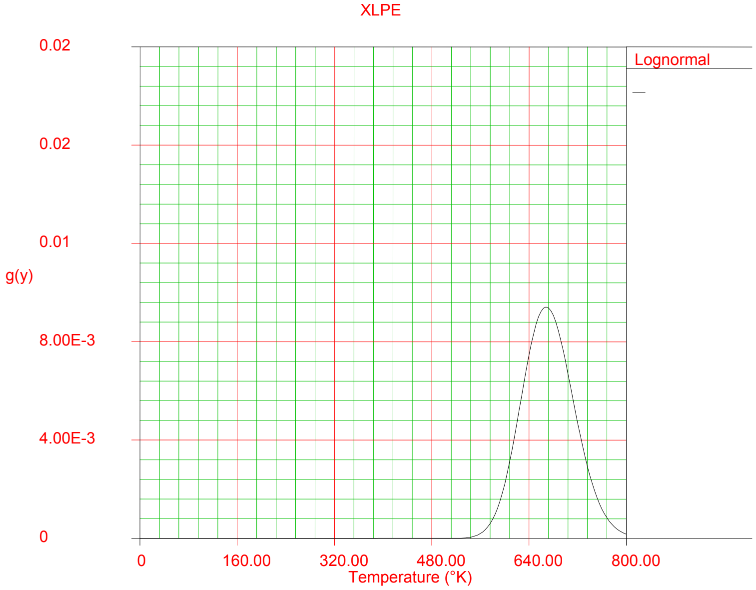
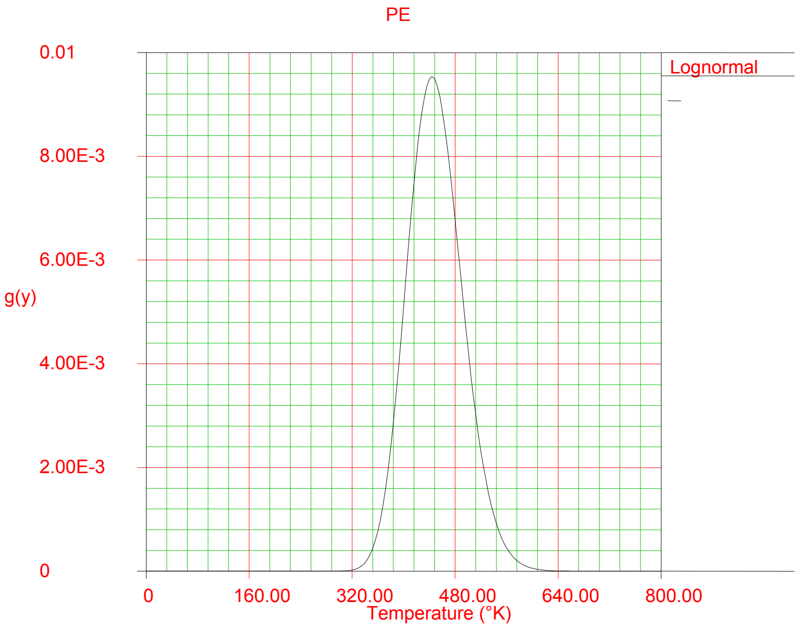
Temperature (°k)

EPRI 1003326 Database:



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g(y)
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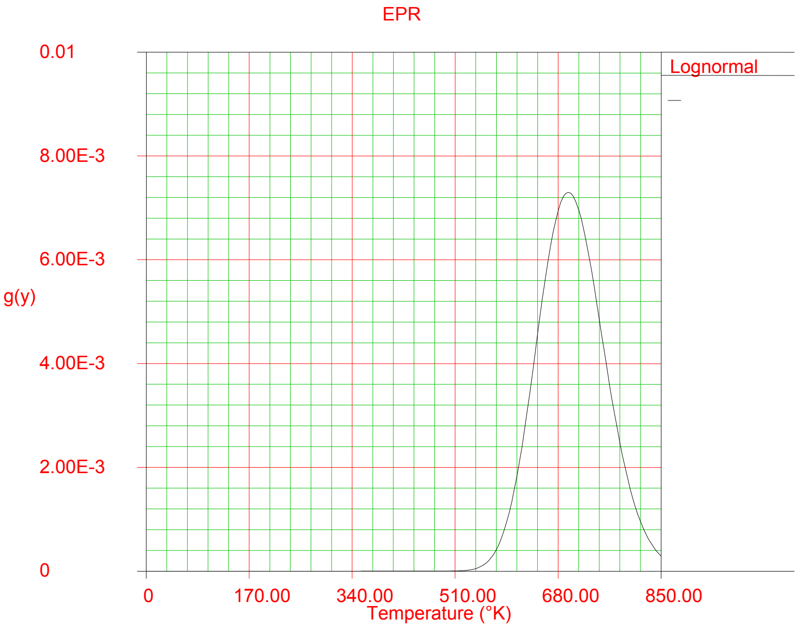
320.00
480.00
640.00
800.00
Temperature (°K)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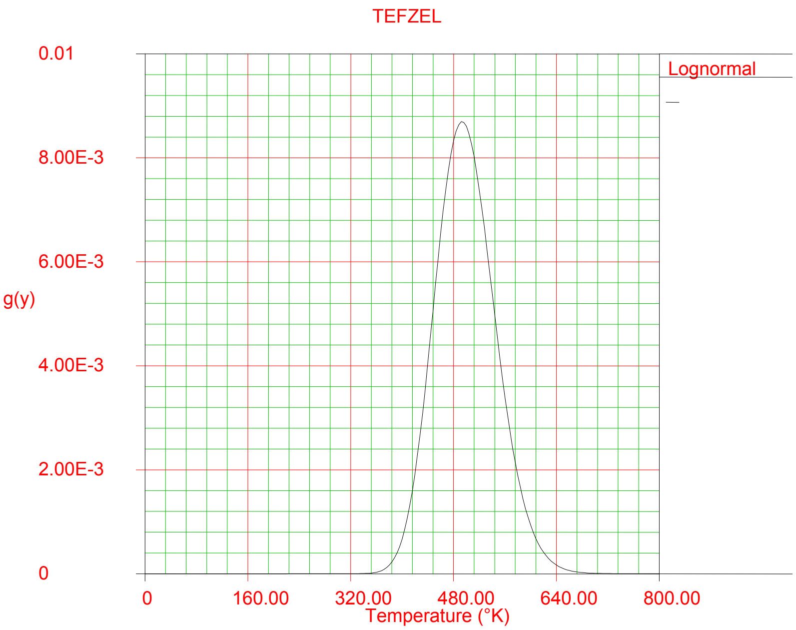
Temperature (°K)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g(y)
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2.00E-3
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640.00
800.00
Temperature (°K)
Lognormal

APPENDIX IV: Endurance Limits: IR “K Factor” Model.

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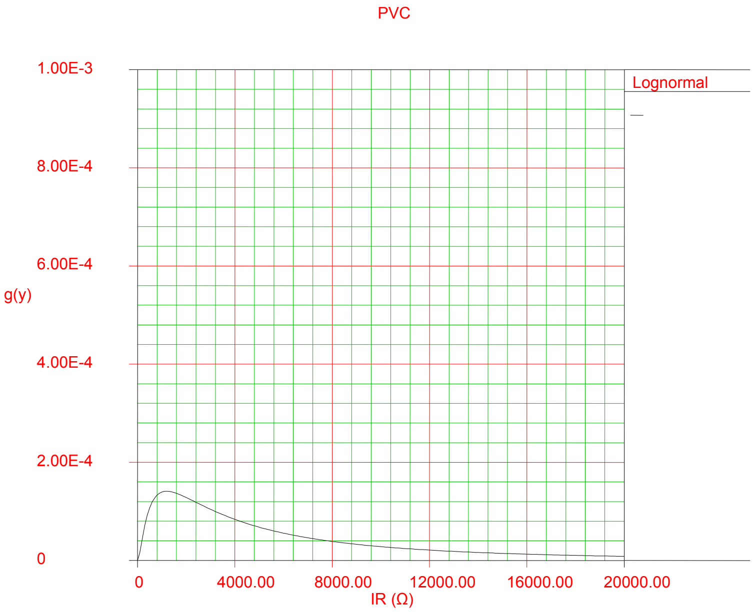

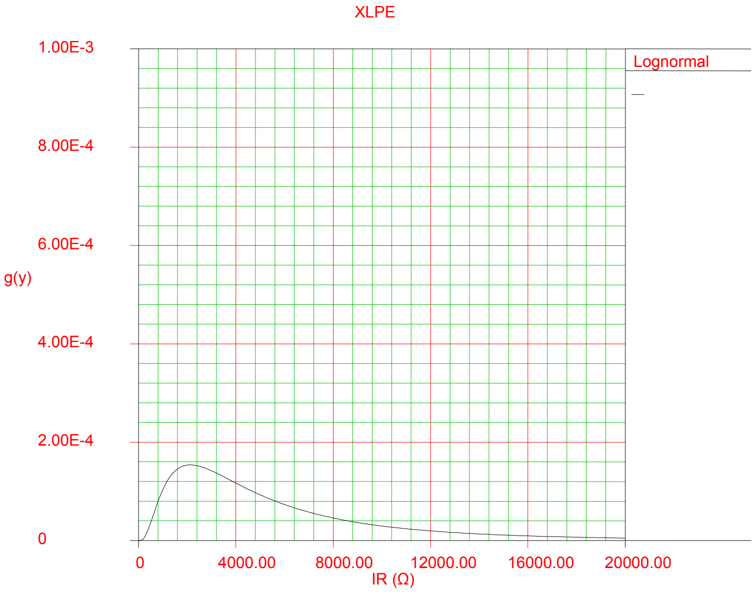

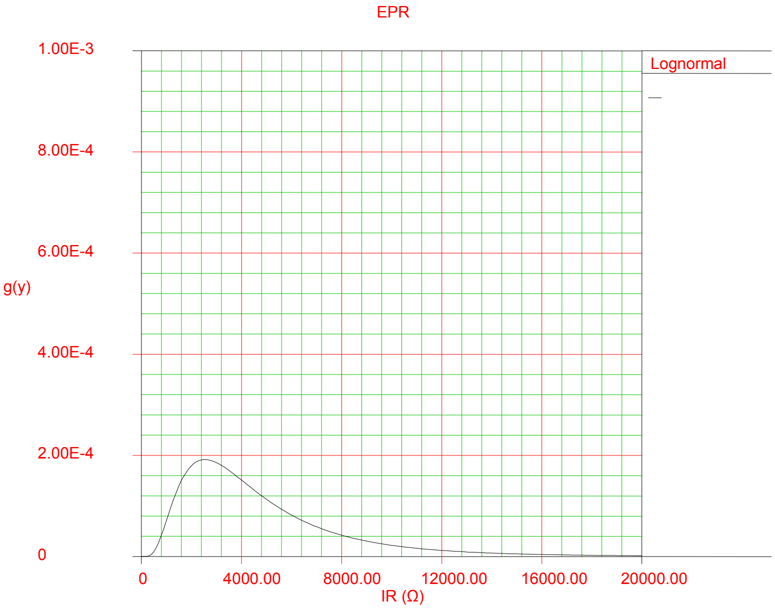
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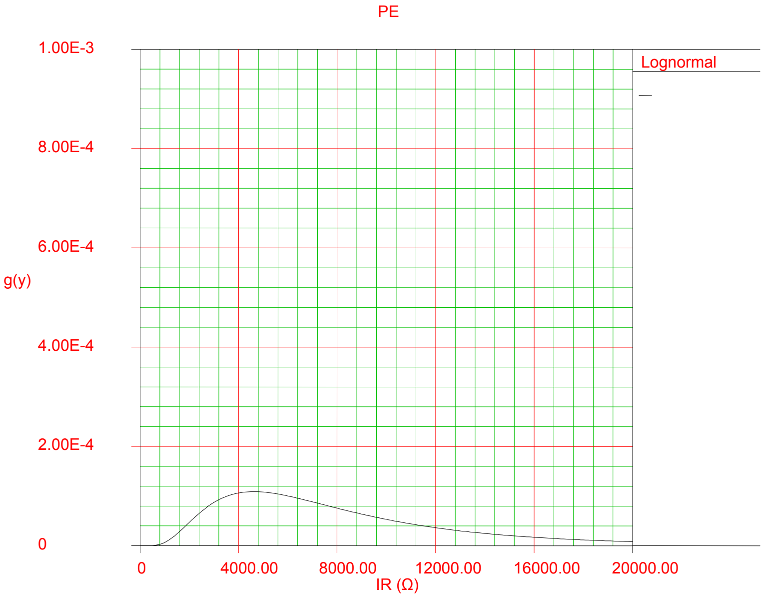
8000.00
12000.00
16000.00
20000.00
IR (Ω)
Lognormal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6.00E-4
g(y)
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2.00E-4
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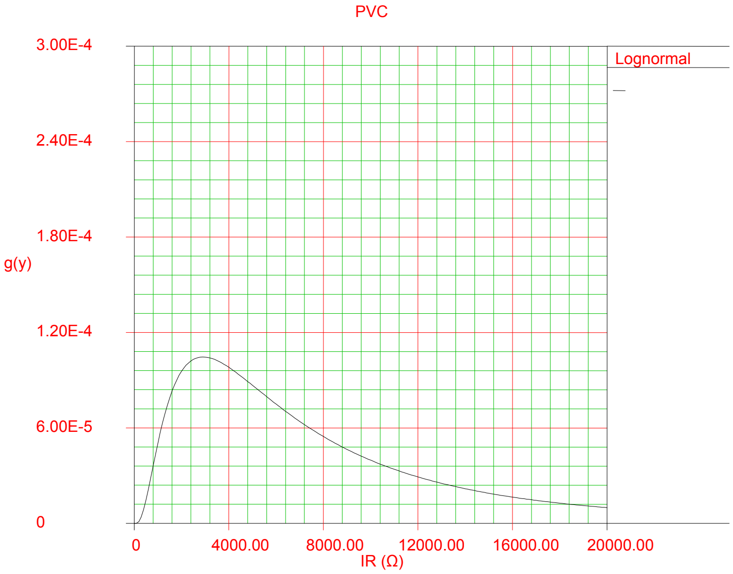
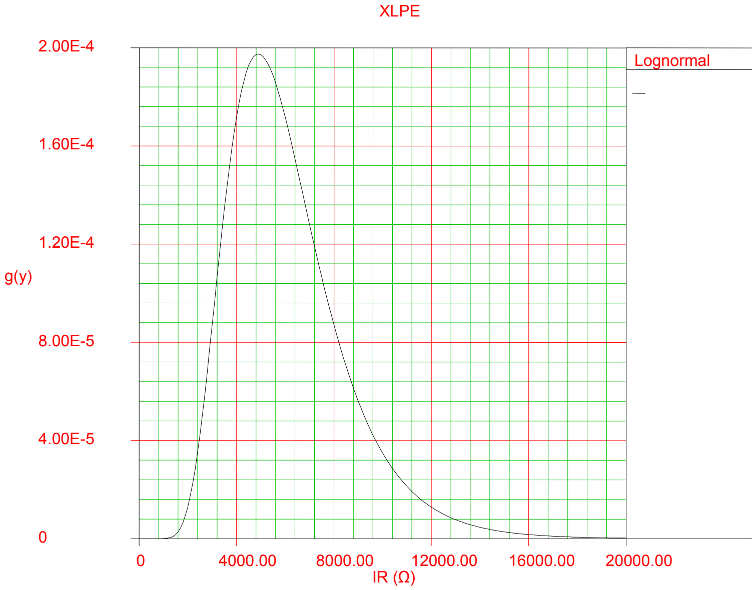
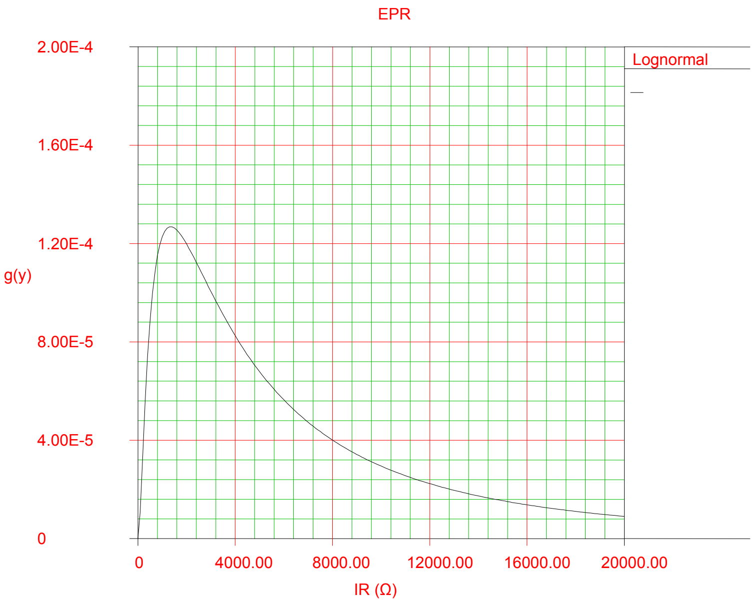
8000.00
12000.00
16000.00
20000.00
IR (Ω)
Lognormal

NUREG/CR 6776 Database:



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g(y)
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4.00E-5
0
0
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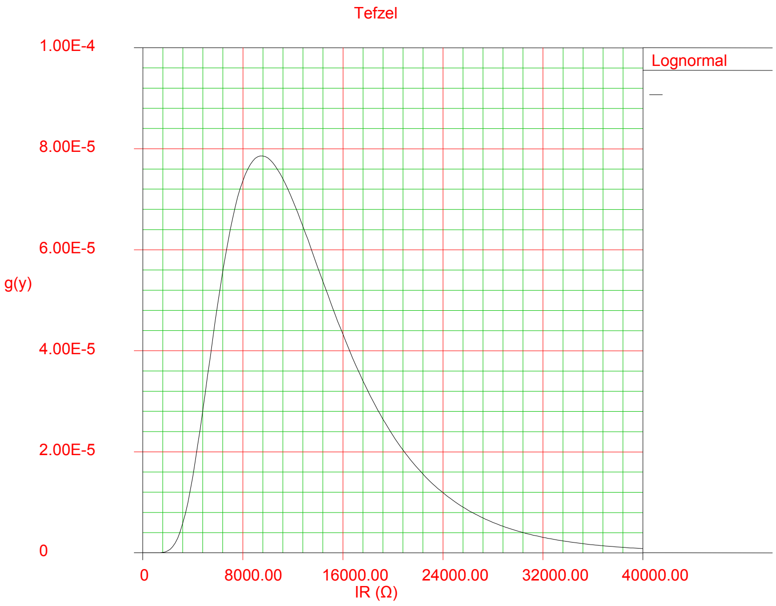
8000.00
12000.00
16000.00
20000.00
IR (Ω)
Lognormal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24000.00
32000.00
40000.00
IR (Ω)
Lognormal

APPENDIX V: Probability of Cable Damage – Heat Transfer Model (Constant Inner Cable Temperature)

Temperature °K	PVC			PE		
	CAROLFIRE	NUREG 6776	EPRI 1003326	CAROLFIRE	NUREG 6776	EPRI 1003326
373	0.00	NA	0.00	0.00	NA	0.02
378	0.00	NA	0.00	0.00	NA	0.02
383	0.00	NA	0.01	0.00	NA	0.03
388	0.00	NA	0.01	0.00	NA	0.05
393	0.00	NA	0.02	0.00	NA	0.07
398	0.00	NA	0.03	0.00	NA	0.09
403	0.00	NA	0.04	0.00	NA	0.11
408	0.00	NA	0.06	0.00	NA	0.14
413	0.00	NA	0.08	0.00	NA	0.17
418	0.00	NA	0.11	0.00	NA	0.20
423	0.00	NA	0.15	0.00	NA	0.24
428	0.00	NA	0.19	0.00	NA	0.28
433	0.00	NA	0.23	0.00	NA	0.32
438	0.00	NA	0.29	0.00	NA	0.38
443	0.00	NA	0.34	0.00	NA	0.42
448	0.01	NA	0.41	0.00	NA	0.47
453	0.02	NA	0.47	0.00	NA	0.52
458	0.04	NA	0.53	0.00	NA	0.57
463	0.06	NA	0.59	0.00	NA	0.62
468	0.10	NA	0.65	0.00	NA	0.66
473	0.15	NA	0.71	0.00	NA	0.70
478	0.22	NA	0.76	0.00	NA	0.74
483	0.31	NA	0.80	0.00	NA	0.78
488	0.41	NA	0.84	0.00	NA	0.81
493	0.51	NA	0.87	0.00	NA	0.84
498	0.61	NA	0.90	0.01	NA	0.87
503	0.70	NA	0.92	0.03	NA	0.89
508	0.78	NA	0.94	0.08	NA	0.91
513	0.85	NA	0.95	0.17	NA	0.93
518	0.90	NA	0.97	0.32	NA	0.94
523	0.93	NA	0.98	0.50	NA	0.95

Probability of Cable Damage – Heat Transfer Model (Constant Inner Cable Temperature). Continuation

Temperature °K	PVC			PE		
	CAROLFIRE	NUREG 6776	EPRI 1003326	CAROLFIRE	NUREG 6776	EPRI 1003326
528	0.96	NA	0.98	0.69	NA	0.96
533	0.97	NA	0.99	0.83	NA	0.97
538	0.99	NA	0.99	0.92	NA	0.98
543	0.99	NA	0.99	0.97	NA	0.98
548	1.00	NA	~1.00	0.99	NA	0.98
553	1.00	NA	~1.00	~1.00	NA	0.99
558	1.00	NA	~1.00	~1.00	NA	0.99
563	1.00	NA	~1.00	~1.00	NA	0.99
568	1.00	NA	~1.00	~1.00	NA	0.99
573	1.00	NA	~1.00	~1.00	NA	~1.00

Probability of Cable Damage – Heat Transfer Model (Constant Inner Cable Temperature)

Temperature °K	XLPE			EPR		
	CAROLFIRE	NUREG 6776	EPRI 1003326	CAROLFIRE	NUREG 6776	EPRI 1003326
573	0.00	0.00	0.01	0.00	0.00	0.01
578	0.00	0.00	0.01	0.00	0.00	0.01
583	0.01	0.01	0.01	0.00	0.00	0.01
588	0.01	0.01	0.02	0.00	0.00	0.01
593	0.01	0.02	0.03	0.00	0.00	0.02
598	0.01	0.02	0.04	0.00	0.00	0.02
603	0.02	0.03	0.05	0.00	0.00	0.03
608	0.04	0.05	0.06	0.00	0.00	0.03
613	0.05	0.06	0.08	0.00	0.00	0.04
618	0.07	0.09	0.10	0.00	0.00	0.05
623	0.09	0.12	0.13	0.00	0.00	0.06
628	0.13	0.16	0.15	0.00	0.00	0.07
633	0.17	0.21	0.18	0.00	0.01	0.09
638	0.21	0.26	0.22	0.00	0.01	0.11
643	0.26	0.31	0.25	0.00	0.02	0.13
648	0.31	0.37	0.29	0.00	0.02	0.15
653	0.35	0.44	0.34	0.00	0.03	0.17
658	0.41	0.51	0.38	0.01	0.04	0.20
663	0.47	0.57	0.42	0.02	0.06	0.23
668	0.53	0.64	0.47	0.05	0.07	0.26
673	0.59	0.70	0.51	0.10	0.10	0.29
678	0.65	0.76	0.55	0.17	0.12	0.32
683	0.70	0.80	0.60	0.28	0.15	0.36
688	0.74	0.84	0.64	0.41	0.19	0.39
693	0.79	0.87	0.68	0.55	0.22	0.43
698	0.82	0.91	0.72	0.68	0.26	0.47
703	0.86	0.93	0.76	0.79	0.31	0.51
708	0.89	0.95	0.79	0.88	0.35	0.54
713	0.92	0.96	0.83	0.93	0.40	0.58
718	0.94	0.98	0.86	0.97	0.46	0.62
723	0.95	0.98	0.88	0.98	0.51	0.65

Probability of Cable Damage – Heat Transfer Model (Constant Inner Cable Temperature). Continuation

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Temperature °K	XLPE			EPR		
	CAROLFIRE	NUREG 6776	EPRI 1003326	CAROLFIRE	NUREG 6776	EPRI 1003326
728	0.96	0.99	0.90	0.99	0.56	0.69
733	0.97	0.99	0.92	~1.00	0.61	0.72
738	0.98	1.00	0.93	~1.00	0.65	0.75
743	0.98	1.00	0.95	~1.00	0.70	0.77
748	0.99	1.00	0.96	~1.00	0.74	0.80
753	0.99	1.00	0.97	~1.00	0.78	0.82
758	0.99	1.00	0.97	~1.00	0.82	0.84
763	1.00	1.00	0.98	~1.00	0.85	0.86
768	1.00	1.00	0.98	~1.00	0.88	0.87
773	1.00	1.00	0.99	~1.00	0.91	0.89
778	1.00	1.00	0.99	~1.00	0.93	0.90
783	1.00	1.00	1.00	~1.00	0.94	0.92
788	1.00	1.00	1.00	~1.00	0.96	0.93
793	1.00	1.00	1.00	~1.00	0.97	0.94
798	1.00	1.00	1.00	~1.00	0.97	0.95
803	1.00	1.00	1.00	~1.00	0.98	0.96
808	1.00	1.00	1.00	~1.00	0.99	0.96
813	1.00	1.00	1.00	~1.00	0.99	0.97
818	1.00	1.00	1.00	~1.00	0.99	0.98
823	1.00	1.00	1.00	~1.00	0.99	0.98
828	1.00	1.00	1.00	~1.00	~1.00	0.98
833	1.00	1.00	1.00	~1.00	~1.00	0.99
838	1.00	1.00	1.00	~1.00	~1.00	0.99
843	1.00	1.00	1.00	~1.00	~1.00	0.99
848	1.00	1.00	1.00	~1.00	~1.00	0.99
853	1.00	1.00	1.00	~1.00	~1.00	~1.00

APPENDIX VI: Probability of Cable Damage – Heat Transfer Model (Random Inner Cable Temperature)

Temperature °K (mean, std. dev.)	PVC			PE		
	CAROLFIRE	NUREG 6776	EPRI 1003326	CAROLFIRE	NUREG 6776	EPRI 1003326
(373, 37.3)	0.00	NA	0.05	0.00	NA	0.07
(378, 37.8)	0.01	NA	0.05	0.00	NA	0.08
(383, 38.3)	0.01	NA	0.07	0.00	NA	0.10
(388, 38.8)	0.01	NA	0.08	0.00	NA	0.13
(393, 39.3)	0.02	NA	0.11	0.00	NA	0.15
(398, 39.8)	0.02	NA	0.13	0.00	NA	0.17
(403, 40.3)	0.03	NA	0.14	0.01	NA	0.18
(408, 40.8)	0.04	NA	0.17	0.01	NA	0.20
(413, 41.3)	0.04	NA	0.19	0.01	NA	0.24
(418, 41.8)	0.06	NA	0.23	0.01	NA	0.28
(423, 42.3)	0.07	NA	0.25	0.01	NA	0.30
(428, 42.8)	0.08	NA	0.28	0.02	NA	0.32
(433, 43.3)	0.11	NA	0.31	0.03	NA	0.37
(438, 43.8)	0.12	NA	0.35	0.04	NA	0.40
(443, 44.3)	0.16	NA	0.39	0.05	NA	0.45
(448, 44.8)	0.18	NA	0.42	0.06	NA	0.46
(453, 45.3)	0.21	NA	0.47	0.08	NA	0.50
(458, 45.8)	0.25	NA	0.50	0.09	NA	0.53
(463, 46.3)	0.27	NA	0.53	0.10	NA	0.56
(468, 46.8)	0.29	NA	0.57	0.13	NA	0.60
(473, 47.3)	0.33	NA	0.60	0.15	NA	0.63
(478, 47.8)	0.37	NA	0.63	0.16	NA	0.65
(483, 48.3)	0.42	NA	0.68	0.20	NA	0.68
(488, 48.8)	0.46	NA	0.70	0.24	NA	0.72
(493, 49.3)	0.49	NA	0.71	0.27	NA	0.73
(498, 49.8)	0.54	NA	0.77	0.32	NA	0.78
(503, 50.3)	0.57	NA	0.78	0.34	NA	0.78
(508, 50.8)	0.60	NA	0.81	0.38	NA	0.81
(513, 51.3)	0.64	NA	0.83	0.40	NA	0.83
(518, 51.8)	0.65	NA	0.84	0.44	NA	0.83
(523, 52.3)	0.69	NA	0.86	0.49	NA	0.85

Probability of Cable Damage – Heat Transfer Model (Random Inner Cable Temperature). Continuation

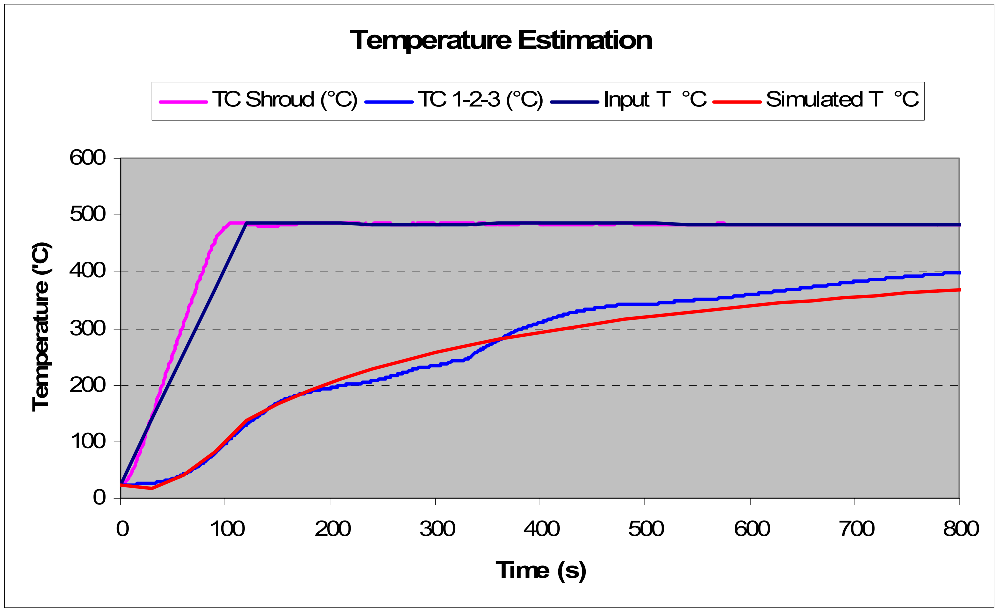
Temperature °K (mean, std. dev.)	PVC			PE		
	CAROLFIRE	NUREG 6776	EPRI 1003326	CAROLFIRE	NUREG 6776	EPRI 1003326
(528, 52.8)	0.74	NA	0.88	0.52	NA	0.88
(533, 53.3)	0.76	NA	0.89	0.56	NA	0.88
(538, 53.8)	0.79	NA	0.91	0.58	NA	0.89
(543, 54.3)	0.82	NA	0.92	0.62	NA	0.91
(548, 54.8)	0.83	NA	0.93	0.65	NA	0.92
(553, 55.3)	0.84	NA	0.94	0.71	NA	0.93
(558, 55.8)	0.86	NA	0.94	0.72	NA	0.93
(563, 56.3)	0.89	NA	0.96	0.75	NA	0.95
(568, 56.8)	0.90	NA	0.96	0.77	NA	0.95
(573, 57.3)	0.91	NA	0.97	0.81	NA	0.96
(578, 57.8)	0.92	NA	0.97	0.82	NA	0.96
(583, 58.3)	0.93	NA	0.98	0.85	NA	0.97
(588, 58.8)	0.94	NA	0.98	0.87	NA	0.97
(593, 59.3)	0.95	NA	0.98	0.88	NA	0.98
(598, 59.8)	0.96	NA	0.99	0.90	NA	0.98
(603, 60.3)	0.97	NA	0.99	0.92	NA	0.99
(608, 60.8)	0.97	NA	0.99	0.92	NA	0.99
(613, 61.3)	0.98	NA	0.99	0.94	NA	0.99
(618, 61.8)	0.98	NA	0.99	0.95	NA	0.99
(623, 62.3)	0.99	NA	~1.00	0.95	NA	0.99
(628, 62.8)	0.99	NA	~1.00	0.96	NA	0.99
(633, 63.3)	0.99	NA	~1.00	0.97	NA	0.99
(638, 63.8)	0.99	NA	~1.00	0.97	NA	~1.00
(643, 64.3)	0.99	NA	~1.00	0.98	NA	~1.00
(648, 64.8)	0.99	NA	~1.00	0.98	NA	~1.00
(653, 65.3)	1.00	NA	~1.00	0.98	NA	~1.00
(658, 65.8)	1.00	NA	~1.00	0.99	NA	~1.00
(663, 66.3)	1.00	NA	~1.00	0.99	NA	~1.00
(668, 66.8)	1.00	NA	~1.00	0.99	NA	~1.00
(673, 67.3)	1.00	NA	~1.00	0.99	NA	~1.00

Probability of Cable Damage – Heat Transfer Model (Random Inner Cable Temperature)

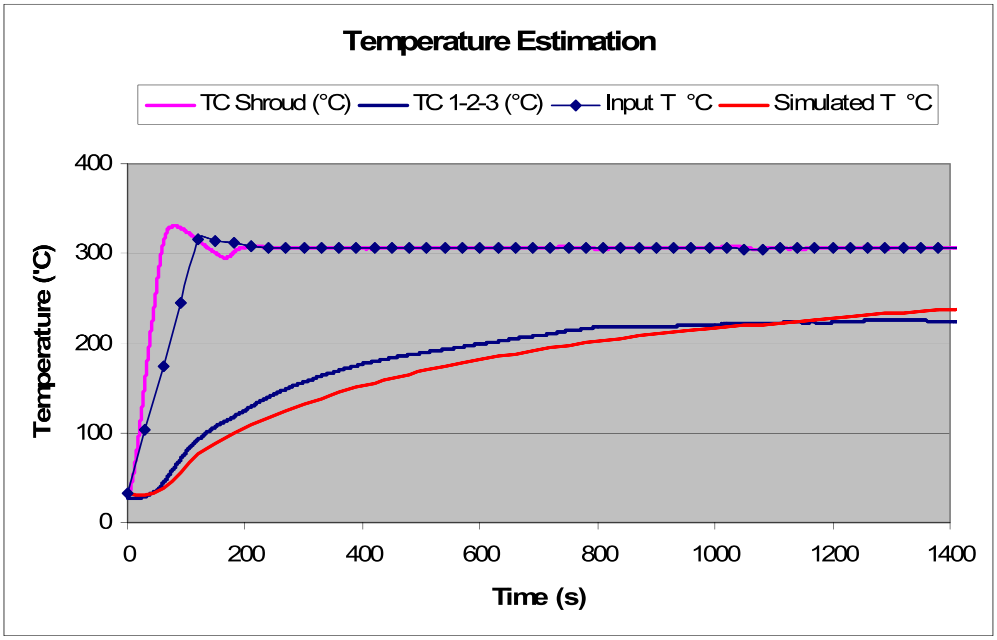
Temperature °K (mean, std. dev.)	XLPE			EPR		
	CAROLFIRE	NUREG 6776	EPRI 1003326	CAROLFIRE	NUREG 6776	EPRI 1003326
(473, 47.3)	0.00	0.00	0.00	0.00	0.00	0.00
(488, 48.8)	0.00	0.00	0.00	0.00	0.00	0.00
(493, 49.3)	0.00	0.00	0.00	0.00	0.00	0.00
(498, 49.8)	0.00	0.00	0.00	0.00	0.00	0.00
(503, 50.3)	0.00	0.01	0.01	0.00	0.00	0.00
(508, 50.8)	0.01	0.01	0.01	0.00	0.00	0.01
(513, 51.3)	0.01	0.01	0.01	0.00	0.00	0.01
(518, 51.8)	0.01	0.01	0.01	0.00	0.00	0.01
(523, 52.3)	0.01	0.02	0.01	0.00	0.00	0.01
(528, 52.8)	0.02	0.02	0.02	0.00	0.00	0.01
(533, 53.3)	0.02	0.03	0.02	0.00	0.00	0.02
(538, 53.8)	0.03	0.03	0.03	0.00	0.00	0.02
(543, 54.3)	0.03	0.04	0.03	0.01	0.01	0.02
(548, 54.8)	0.04	0.05	0.04	0.01	0.01	0.02
(553, 55.3)	0.04	0.05	0.04	0.01	0.01	0.03
(558, 55.8)	0.04	0.05	0.05	0.01	0.01	0.03
(563, 56.3)	0.06	0.07	0.06	0.02	0.02	0.04
(568, 56.8)	0.07	0.08	0.08	0.03	0.02	0.04
(573, 57.3)	0.09	0.10	0.08	0.03	0.02	0.05
(578, 57.8)	0.09	0.11	0.10	0.04	0.02	0.06
(583, 58.3)	0.11	0.13	0.11	0.04	0.02	0.07
(588, 58.8)	0.13	0.15	0.12	0.05	0.03	0.08
(593, 59.3)	0.14	0.17	0.13	0.06	0.04	0.09
(598, 59.8)	0.15	0.19	0.17	0.07	0.04	0.10
(603, 60.3)	0.18	0.21	0.17	0.09	0.05	0.11
(608, 60.8)	0.18	0.22	0.18	0.10	0.06	0.14
(613, 61.3)	0.21	0.25	0.20	0.11	0.07	0.13
(618, 61.8)	0.25	0.29	0.23	0.13	0.08	0.16
(623, 62.3)	0.25	0.30	0.25	0.14	0.09	0.17
(628, 62.8)	0.28	0.32	0.27	0.16	0.11	0.19
(633, 63.3)	0.32	0.36	0.29	0.17	0.11	0.20
(638, 63.8)	0.34	0.38	0.32	0.21	0.12	0.22
(643, 64.3)	0.36	0.40	0.35	0.23	0.15	0.24
(648, 64.8)	0.37	0.42	0.37	0.24	0.15	0.25
(653, 65.3)	0.41	0.45	0.40	0.27	0.16	0.26
(658, 65.8)	0.43	0.48	0.42	0.29	0.19	0.29
(663, 66.3)	0.47	0.52	0.43	0.31	0.21	0.32
(668, 66.8)	0.49	0.53	0.47	0.35	0.23	0.34
(673, 67.3)	0.52	0.56	0.49	0.38	0.25	0.36
(678, 67.8)	0.55	0.60	0.52	0.41	0.28	0.40
(683, 68.3)	0.56	0.62	0.53	0.43	0.29	0.40
(688, 68.8)	0.59	0.65	0.56	0.45	0.31	0.43
(693, 69.3)	0.62	0.67	0.60	0.50	0.33	0.44
(698, 69.8)	0.67	0.71	0.61	0.51	0.37	0.47

Temperature °K (mean, std. dev.)	XLPE			EPR		
	CAROLFIRE	NUREG 6776	EPRI 1003326	CAROLFIRE	NUREG 6776	EPRI 1003326
(703, 70.3)	0.67	0.72	0.64	0.55	0.39	0.49
(708, 70.8)	0.69	0.74	0.65	0.57	0.40	0.52
(713, 71.3)	0.70	0.75	0.68	0.61	0.43	0.54
(718, 71.8)	0.74	0.77	0.70	0.63	0.45	0.55
(723, 72.3)	0.75	0.79	0.73	0.65	0.47	0.58
(728, 72.8)	0.77	0.81	0.74	0.67	0.50	0.60
(733, 73.3)	0.79	0.83	0.75	0.70	0.52	0.62
(738, 73.8)	0.80	0.84	0.77	0.72	0.54	0.63
(743, 74.3)	0.82	0.86	0.80	0.74	0.58	0.66
(748, 74.8)	0.84	0.87	0.81	0.76	0.61	0.69
(753, 75.3)	0.86	0.88	0.82	0.78	0.62	0.71
(758, 75.8)	0.87	0.90	0.84	0.81	0.64	0.72
(763, 76.3)	0.88	0.92	0.85	0.83	0.66	0.73
(768, 76.8)	0.89	0.92	0.87	0.84	0.69	0.76
(773, 77.3)	0.90	0.92	0.88	0.85	0.71	0.77
(778, 77.8)	0.91	0.93	0.89	0.87	0.72	0.77
(783, 78.3)	0.92	0.93	0.90	0.88	0.76	0.81
(788, 78.8)	0.92	0.94	0.90	0.89	0.76	0.82
(793, 79.3)	0.94	0.96	0.91	0.89	0.79	0.83
(798, 79.8)	0.94	0.96	0.93	0.91	0.80	0.84
(803, 80.3)	0.95	0.96	0.93	0.92	0.81	0.85
(808, 80.8)	0.95	0.97	0.93	0.92	0.82	0.86
(813, 81.3)	0.96	0.97	0.94	0.94	0.83	0.87
(818, 81.8)	0.96	0.97	0.95	0.95	0.85	0.87
(823, 82.3)	0.97	0.98	0.95	0.95	0.86	0.89
(828, 82.8)	0.97	0.98	0.96	0.96	0.88	0.91
(833, 83.3)	0.98	0.98	0.96	0.96	0.89	0.91
(838, 83.8)	0.98	0.98	0.97	0.97	0.89	0.91
(843, 84.3)	0.98	0.99	0.97	0.97	0.91	0.92
(848, 84.8)	0.98	0.99	0.98	0.98	0.91	0.93
(853, 85.3)	0.99	0.99	0.98	0.98	0.92	0.94
(858, 85.8)	0.99	0.99	0.98	0.98	0.92	0.94
(863, 86.3)	0.99	0.99	0.98	0.98	0.94	0.94
(868, 86.8)	0.99	0.99	0.98	0.98	0.95	0.95
(873, 87.3)	0.99	0.99	0.98	0.99	0.95	0.96
(878, 87.8)	0.99	0.99	0.99	0.99	0.95	0.95
(883, 88.3)	0.99	1.00	0.99	0.99	0.96	0.96
(888, 88.8)	1.00	1.00	0.99	0.99	0.96	0.97
(893, 89.3)	1.00	1.00	0.99	0.99	0.96	0.97
(898, 89.8)	1.00	1.00	0.99	0.99	0.96	0.97
(903, 90.3)	1.00	1.00	0.99	~1.00	0.97	0.97
(908, 90.8)	1.00	1.00	0.99	~1.00	0.97	0.98
(913, 91.3)	1.00	1.00	0.99	~1.00	0.97	0.98
(918, 91.8)	1.00	1.00	~1.00	~1.00	0.98	0.98
(923, 92.3)	1.00	1.00	~1.00	~1.00	0.98	0.98

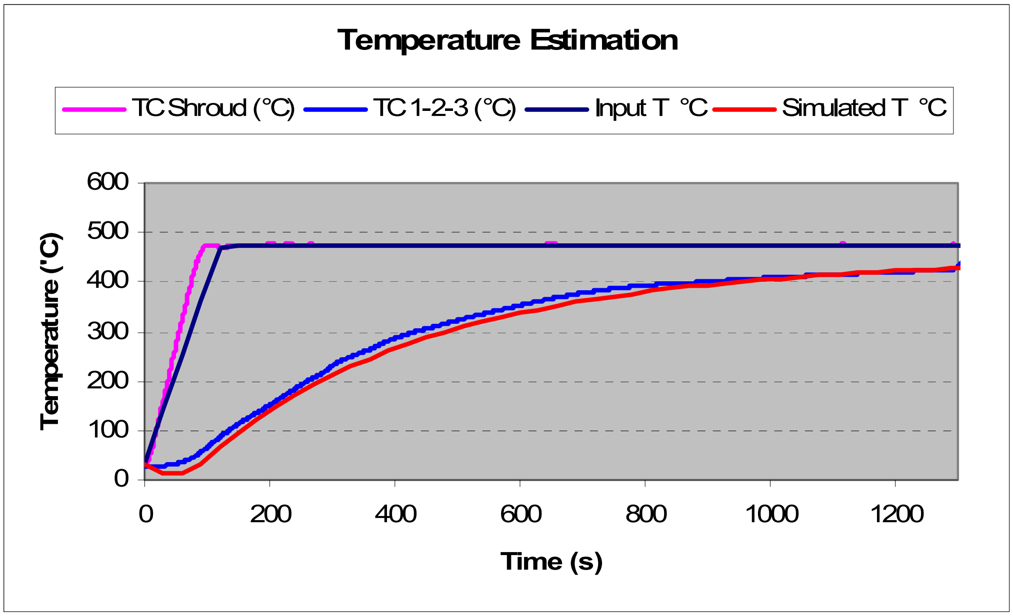
APPENDIX VII: Simulated Inner Cable Temperature



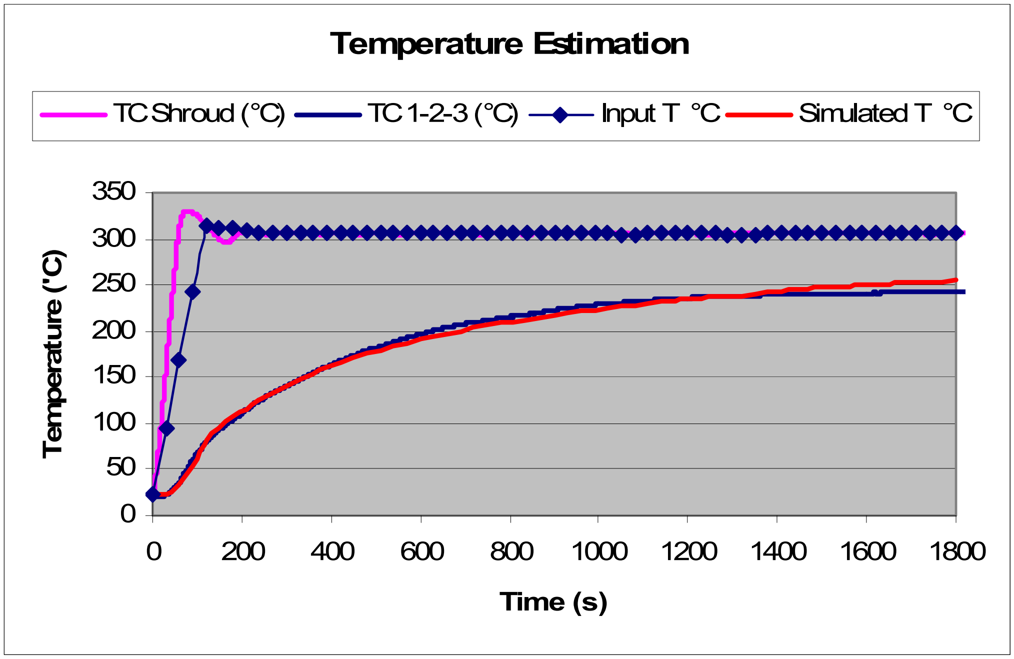
Penlight test 1B (Carolfire)



Penlight test 4B (Carolfire)



Penlight test 11B (Carolfire)



Penlight test 14B (Carolfire)

APPENDIX VIII: Probability of Cable Damage – IR "K Factor" Model (Constant Surrounding Temperature)

Temperature °C	Temperature °K	PVC		TEFZEL	
		CAROLFIRE	NUREG 6776	CAROLFIRE	NUREG 6776
100	373	0.01	0.01	NA	0.02
105	378	0.02	0.01	NA	0.02
110	383	0.02	0.01	NA	0.02
115	388	0.03	0.02	NA	0.03
120	393	0.04	0.02	NA	0.03
125	398	0.05	0.02	NA	0.04
130	403	0.06	0.03	NA	0.05
135	408	0.07	0.03	NA	0.05
140	413	0.09	0.04	NA	0.06
145	418	0.11	0.04	NA	0.07
150	423	0.13	0.05	NA	0.09
155	428	0.15	0.06	NA	0.10
160	433	0.17	0.07	NA	0.11
165	438	0.20	0.08	NA	0.13
170	443	0.23	0.10	NA	0.15
175	448	0.25	0.12	NA	0.17
180	453	0.29	0.14	NA	0.19
185	458	0.31	0.16	NA	0.21
190	463	0.35	0.18	NA	0.24
195	468	0.38	0.20	NA	0.26
200	473	0.41	0.23	NA	0.29
205	478	0.45	0.26	NA	0.31
210	483	0.48	0.29	NA	0.34
215	488	0.51	0.32	NA	0.37
220	493	0.54	0.35	NA	0.40
225	498	0.58	0.38	NA	0.43
230	503	0.61	0.42	NA	0.46
235	508	0.64	0.45	NA	0.49
240	513	0.67	0.48	NA	0.52
245	518	0.70	0.51	NA	0.55
250	523	0.73	0.55	NA	0.58
255	528	0.75	0.59	NA	0.61
260	533	0.78	0.62	NA	0.64
265	538	0.80	0.64	NA	0.66
270	543	0.82	0.68	NA	0.69
275	548	0.84	0.70	NA	0.71
280	553	0.86	0.73	NA	0.74
285	558	0.87	0.75	NA	0.76
290	563	0.88	0.78	NA	0.78
295	568	0.90	0.81	NA	0.80

Probability of Cable Damage – IR “K Factor” Model (Constant Surrounding Temperature).Continuation

Temperature °C	Temperature °K	PVC		TEFZEL	
		CAROLFIRE	NUREG 6776	CAROLFIRE	NUREG 6776
300	573	0.91	0.83	NA	0.82
305	578	0.92	0.85	NA	0.84
310	583	0.93	0.86	NA	0.86
315	588	0.94	0.87	NA	0.87
320	593	0.95	0.89	NA	0.88
325	598	0.96	0.90	NA	0.89
330	603	0.96	0.92	NA	0.90
335	608	0.97	0.93	NA	0.91
340	613	0.97	0.94	NA	0.92
345	618	0.97	0.94	NA	0.93
350	623	0.98	0.95	NA	0.94
355	628	0.98	0.96	NA	0.95
360	633	0.99	0.96	NA	0.96
365	638	0.99	0.97	NA	0.96
370	643	0.99	0.97	NA	0.97
375	648	0.99	0.98	NA	0.97
380	653	0.99	0.98	NA	0.97
385	658	0.99	0.98	NA	0.98
390	663	0.99	0.99	NA	0.98
395	668	~1.00	0.99	NA	0.98
400	673	~1.00	0.99	NA	0.99
405	678	~1.00	0.99	NA	0.99
410	683	~1.00	0.99	NA	0.99
415	688	~1.00	0.99	NA	0.99
420	693	~1.00	0.99	NA	0.99
425	698	~1.00	~1.00	NA	0.99
430	703	~1.00	~1.00	NA	~1.00
435	708	~1.00	~1.00	NA	~1.00
440	713	~1.00	~1.00	NA	~1.00
445	718	~1.00	~1.00	NA	~1.00
450	723	~1.00	~1.00	NA	~1.00
455	728	~1.00	~1.00	NA	~1.00
460	733	~1.00	~1.00	NA	~1.00
465	738	~1.00	~1.00	NA	~1.00
470	743	~1.00	~1.00	NA	~1.00
475	748	~1.00	~1.00	NA	~1.00
480	753	~1.00	~1.00	NA	~1.00
485	758	~1.00	~1.00	NA	~1.00
490	763	~1.00	~1.00	NA	~1.00
495	768	~1.00	~1.00	NA	~1.00

Probability of Cable Damage – IR "K Factor" Model (Constant Surrounding Temperature)

Temperature °C	Temperature °K	XLPE		EPR	
		CAROLFIRE	NUREG 6776	CAROLFIRE	NUREG 6776
100	373	0.00	0.00	0.00	0.00
105	378	0.00	0.00	0.00	0.00
110	383	0.00	0.00	0.00	0.00
115	388	0.00	0.00	0.00	0.00
120	393	0.00	0.00	0.00	0.00
125	398	0.00	0.00	0.00	0.00
130	403	0.00	0.00	0.00	0.00
135	408	0.00	0.00	0.00	0.00
140	413	0.00	0.00	0.00	0.00
145	418	0.00	0.00	0.00	0.00
150	423	0.00	0.00	0.00	0.00
155	428	0.00	0.00	0.00	0.00
160	433	0.00	0.00	0.00	0.00
165	438	0.00	0.00	0.00	0.00
170	443	0.00	0.00	0.00	0.00
175	448	0.00	0.00	0.00	0.00
180	453	0.00	0.00	0.00	0.00
185	458	0.00	0.00	0.00	0.00
190	463	0.00	0.00	0.00	0.00
195	468	0.00	0.00	0.00	0.00
200	473	0.00	0.00	0.00	0.00
205	478	0.00	0.00	0.00	0.00
210	483	0.00	0.00	0.00	0.00
215	488	0.00	0.00	0.00	0.00
220	493	0.00	0.00	0.00	0.00
225	498	0.00	0.00	0.00	0.00
230	503	0.00	0.00	0.00	0.00
235	508	0.00	0.00	0.00	0.00
240	513	0.00	0.00	0.00	0.00
245	518	0.00	0.00	0.00	0.00
250	523	0.00	0.00	0.00	0.00
255	528	0.00	0.00	0.00	0.00
260	533	0.00	0.00	0.00	0.00
265	538	0.00	0.00	0.00	0.00
270	543	0.00	0.00	0.00	0.00
275	548	0.00	0.00	0.00	0.00
280	553	0.00	0.00	0.00	0.00
285	558	0.00	0.00	0.00	0.00
290	563	0.01	0.00	0.00	0.00
295	568	0.01	0.01	0.00	0.00

Probability of Cable Damage – IR “K Factor” Model (Constant Surrounding Temperature).Continuation

Temperature °C	Temperature °K	XLPE		EPR	
		CAROLFIRE	NUREG 6776	CAROLFIRE	NUREG 6776
300	573	0.01	0.01	0.00	0.00
305	578	0.01	0.01	0.00	0.00
310	583	0.02	0.01	0.00	0.00
315	588	0.02	0.01	0.00	0.00
320	593	0.02	0.02	0.00	0.00
325	598	0.03	0.02	0.00	0.00
330	603	0.04	0.02	0.01	0.00
335	608	0.04	0.03	0.01	0.00
340	613	0.05	0.03	0.01	0.00
345	618	0.06	0.03	0.01	0.00
350	623	0.07	0.04	0.02	0.00
355	628	0.08	0.04	0.02	0.00
360	633	0.10	0.05	0.02	0.01
365	638	0.11	0.06	0.03	0.01
370	643	0.13	0.06	0.04	0.01
375	648	0.15	0.07	0.05	0.01
380	653	0.16	0.09	0.05	0.02
385	658	0.18	0.09	0.07	0.02
390	663	0.20	0.11	0.08	0.03
395	668	0.22	0.13	0.09	0.04
400	673	0.24	0.14	0.10	0.05
405	678	0.27	0.16	0.12	0.06
410	683	0.30	0.18	0.13	0.07
415	688	0.33	0.20	0.16	0.09
420	693	0.35	0.22	0.18	0.11
425	698	0.37	0.25	0.21	0.13
430	703	0.40	0.28	0.23	0.16
435	708	0.42	0.30	0.25	0.19
440	713	0.45	0.33	0.28	0.22
445	718	0.48	0.36	0.31	0.25
450	723	0.51	0.40	0.34	0.29
455	728	0.54	0.43	0.38	0.32
460	733	0.57	0.47	0.41	0.36
465	738	0.60	0.50	0.44	0.40
470	743	0.63	0.53	0.48	0.44
475	748	0.65	0.57	0.51	0.48
480	753	0.68	0.61	0.56	0.53
485	758	0.70	0.64	0.59	0.56
490	763	0.73	0.67	0.63	0.60
495	768	0.75	0.70	0.66	0.64

Probability of Cable Damage – IR “K Factor” Model (Constant Surrounding Temperature).Continuation

Temperature °C	Temperature °K	XLPE		EPR	
		CAROLFIRE	NUREG 6776	CAROLFIRE	NUREG 6776
500	773	0.77	0.74	0.68	0.67
505	778	0.79	0.76	0.71	0.70
510	783	0.81	0.80	0.73	0.73
515	788	0.83	0.82	0.75	0.76
520	793	0.84	0.85	0.77	0.79
525	798	0.86	0.87	0.80	0.81
530	803	0.87	0.89	0.83	0.83
535	808	0.88	0.91	0.84	0.85
540	813	0.89	0.92	0.86	0.88
545	818	0.90	0.93	0.88	0.89
550	823	0.91	0.95	0.89	0.92
555	828	0.92	0.95	0.91	0.93
560	833	0.93	0.96	0.92	0.94
565	838	0.93	0.97	0.93	0.95
570	843	0.94	0.98	0.93	0.96
575	848	0.95	0.98	0.94	0.97
580	853	0.96	0.99	0.95	0.97
585	858	0.96	0.99	0.95	0.98
590	863	0.97	0.99	0.96	0.98
595	868	0.97	0.99	0.96	0.99
600	873	0.97	0.99	0.97	0.99
605	878	0.98	~1.00	0.97	0.99
610	883	0.98	~1.00	0.98	0.99
615	888	0.98	~1.00	0.98	0.99
620	893	0.98	~1.00	0.98	0.99
625	898	0.99	~1.00	0.98	~1.00
630	903	0.99	~1.00	0.99	~1.00
635	908	0.99	~1.00	0.99	~1.00
640	913	0.99	~1.00	0.99	~1.00
645	918	0.99	~1.00	0.99	~1.00
650	923	0.99	~1.00	0.99	~1.00
655	928	0.99	~1.00	0.99	~1.00
660	933	0.99	~1.00	~1.00	~1.00
665	938	~1.00	~1.00	~1.00	~1.00
670	943	~1.00	~1.00	~1.00	~1.00
675	948	~1.00	~1.00	~1.00	~1.00
680	953	~1.00	~1.00	~1.00	~1.00
685	958	~1.00	~1.00	~1.00	~1.00
690	963	~1.00	~1.00	~1.00	~1.00
695	968	~1.00	~1.00	~1.00	~1.00
700	973	~1.00	~1.00	~1.00	~1.00

APPENDIX IX: Probability of Cable Damage – IR "K Factor" Model (Random Surrounding Temperature)

Temperature °K (mean, std. dev.)	PVC		TEFZEL	
	CAROLFIRE	NUREG 6776	CAROLFIRE	NUREG 6776
(373, 37.3)	0.05	0.02	NA	0.03
(378, 37.8)	0.05	0.03	NA	0.04
(383, 38.3)	0.06	0.03	NA	0.05
(388, 38.8)	0.08	0.04	NA	0.05
(393, 39.3)	0.08	0.04	NA	0.06
(398, 39.8)	0.10	0.05	NA	0.07
(403, 40.3)	0.12	0.06	NA	0.08
(408, 40.8)	0.13	0.07	NA	0.09
(413, 41.3)	0.14	0.08	NA	0.10
(418, 41.8)	0.17	0.09	NA	0.12
(423, 42.3)	0.18	0.10	NA	0.13
(428, 42.8)	0.20	0.12	NA	0.14
(433, 43.3)	0.23	0.13	NA	0.16
(438, 43.8)	0.25	0.15	NA	0.18
(443, 44.3)	0.27	0.16	NA	0.20
(448, 44.8)	0.30	0.19	NA	0.21
(453, 45.3)	0.32	0.20	NA	0.24
(458, 45.8)	0.34	0.22	NA	0.25
(463, 46.3)	0.37	0.24	NA	0.28
(468, 46.8)	0.40	0.27	NA	0.30
(473, 47.3)	0.42	0.29	NA	0.32
(478, 47.8)	0.45	0.32	NA	0.35
(483, 48.3)	0.48	0.34	NA	0.36
(488, 48.8)	0.50	0.36	NA	0.39
(493, 49.3)	0.53	0.39	NA	0.42
(498, 49.8)	0.55	0.42	NA	0.44
(503, 50.3)	0.58	0.44	NA	0.47
(508, 50.8)	0.60	0.47	NA	0.49
(513, 51.3)	0.63	0.49	NA	0.51
(518, 51.8)	0.65	0.51	NA	0.53
(523, 52.3)	0.67	0.54	NA	0.56
(528, 52.8)	0.70	0.57	NA	0.58
(533, 53.3)	0.72	0.59	NA	0.60
(538, 53.8)	0.73	0.61	NA	0.62
(543, 54.3)	0.76	0.64	NA	0.65
(548, 54.8)	0.77	0.66	NA	0.67
(553, 55.3)	0.79	0.68	NA	0.69
(558, 55.8)	0.80	0.70	NA	0.72
(563, 56.3)	0.82	0.72	NA	0.73
(568, 56.8)	0.83	0.74	NA	0.75

Probability of Cable Damage – IR “K Factor” Model (Random Surrounding Temperature). Continuation

Temperature °K (mean, std. dev.)	PVC		TEFZEL	
	CAROLFIRE	NUREG 6776	CAROLFIRE	NUREG 6776
(573, 57.3)	0.85	0.76	NA	0.77
(578, 57.8)	0.86	0.77	NA	0.78
(583, 58.3)	0.87	0.80	NA	0.79
(588, 58.8)	0.88	0.81	NA	0.81
(593, 59.3)	0.90	0.83	NA	0.82
(598, 59.8)	0.90	0.84	NA	0.84
(603, 60.3)	0.91	0.85	NA	0.85
(608, 60.8)	0.92	0.86	NA	0.86
(613, 61.3)	0.92	0.87	NA	0.87
(618, 61.8)	0.93	0.88	NA	0.88
(623, 62.3)	0.94	0.90	NA	0.89
(628, 62.8)	0.95	0.90	NA	0.90
(633, 63.3)	0.95	0.91	NA	0.91
(638, 63.8)	0.95	0.92	NA	0.92
(643, 64.3)	0.96	0.93	NA	0.92
(648, 64.8)	0.96	0.93	NA	0.93
(653, 65.3)	0.97	0.94	NA	0.94
(658, 65.8)	0.97	0.95	NA	0.94
(663, 66.3)	0.98	0.95	NA	0.95
(668, 66.8)	0.98	0.95	NA	0.95
(673, 67.3)	0.98	0.96	NA	0.96
(678, 67.8)	0.98	0.96	NA	0.96
(683, 68.3)	0.98	0.97	NA	0.96
(688, 68.8)	0.99	0.97	NA	0.97
(693, 69.3)	0.99	0.98	NA	0.97
(698, 69.8)	0.99	0.98	NA	0.97
(703, 70.3)	0.99	0.98	NA	0.98
(708, 70.8)	0.99	0.98	NA	0.98
(713, 71.3)	0.99	0.98	NA	0.98
(718, 71.8)	0.99	0.99	NA	0.98
(723, 72.3)	0.99	0.99	NA	0.98
(728, 72.8)	0.99	0.99	NA	0.99
(733, 73.3)	~1.00	0.99	NA	0.99
(738, 73.8)	~1.00	0.99	NA	0.99
(743, 74.3)	~1.00	0.99	NA	0.99
(748, 74.8)	~1.00	0.99	NA	0.99
(753, 75.3)	~1.00	0.99	NA	0.99
(758, 75.8)	~1.00	~1.00	NA	0.99
(763, 76.3)	~1.00	~1.00	NA	0.99
(768, 76.8)	~1.00	~1.00	NA	0.99

Probability of Cable Damage – IR "K Factor" Model (Random Surrounding Temperature). Continuation

Temperature °K (mean, std. dev.)	PVC		TEFZEL	
	CAROLFIRE	NUREG 6776	CAROLFIRE	NUREG 6776
(773, 77.3)	~1.00	~1.00	NA	0.99
(778, 77.8)	~1.00	~1.00	NA	0.99
(783, 78.3)	~1.00	~1.00	NA	~1.00
(788, 78.8)	~1.00	~1.00	NA	~1.00
(793, 79.3)	~1.00	~1.00	NA	~1.00
(798, 79.8)	~1.00	~1.00	NA	~1.00
(803, 80.3)	~1.00	~1.00	NA	~1.00
(808, 80.8)	~1.00	~1.00	NA	~1.00
(813, 81.3)	~1.00	~1.00	NA	~1.00
(818, 81.8)	~1.00	~1.00	NA	~1.00
(823, 82.3)	~1.00	~1.00	NA	~1.00
(828, 82.8)	~1.00	~1.00	NA	~1.00
(833, 83.3)	~1.00	~1.00	NA	~1.00
(838, 83.8)	~1.00	~1.00	NA	~1.00
(843, 84.3)	~1.00	~1.00	NA	~1.00
(848, 84.8)	~1.00	~1.00	NA	~1.00
(853, 85.3)	~1.00	~1.00	NA	~1.00
(858, 85.8)	~1.00	~1.00	NA	~1.00
(863, 86.3)	~1.00	~1.00	NA	~1.00
(868, 86.8)	~1.00	~1.00	NA	~1.00
(873, 87.3)	~1.00	~1.00	NA	~1.00
(878, 87.8)	~1.00	~1.00	NA	~1.00
(883, 88.3)	~1.00	~1.00	NA	~1.00
(888, 88.8)	~1.00	~1.00	NA	~1.00
(893, 89.3)	~1.00	~1.00	NA	~1.00
(898, 89.8)	~1.00	~1.00	NA	~1.00
(903, 90.3)	~1.00	~1.00	NA	~1.00
(908, 90.8)	~1.00	~1.00	NA	~1.00
(913, 91.3)	~1.00	~1.00	NA	~1.00
(918, 91.8)	~1.00	~1.00	NA	~1.00
(923, 92.3)	~1.00	~1.00	NA	~1.00
(928, 92.8)	~1.00	~1.00	NA	~1.00
(933, 93.3)	~1.00	~1.00	NA	~1.00
(938, 93.8)	~1.00	~1.00	NA	~1.00
(943, 94.3)	~1.00	~1.00	NA	~1.00
(948, 94.8)	~1.00	~1.00	NA	~1.00
(953, 95.3)	~1.00	~1.00	NA	~1.00
(958, 95.8)	~1.00	~1.00	NA	~1.00
(963, 96.3)	~1.00	~1.00	NA	~1.00
(968, 96.8)	~1.00	~1.00	NA	~1.00
(973, 97.3)	~1.00	~1.00	NA	~1.00

Probability of Cable Damage – IR "K Factor" Model (Random Surrounding Temperature)

Temperature °K (mean, std. dev.)	XLPE		EPR	
	CAROLFIRE	NUREG 6776	CAROLFIRE	NUREG 6776
(373, 37.3)	0.00	0.00	0.00	0.00
(378, 37.8)	0.00	0.00	0.00	0.00
(383, 38.3)	0.00	0.00	0.00	0.00
(388, 38.8)	0.00	0.00	0.00	0.00
(393, 39.3)	0.00	0.00	0.00	0.00
(398, 39.8)	0.00	0.00	0.00	0.00
(403, 40.3)	0.00	0.00	0.00	0.00
(408, 40.8)	0.00	0.00	0.00	0.00
(413, 41.3)	0.00	0.00	0.00	0.00
(418, 41.8)	0.00	0.00	0.00	0.00
(423, 42.3)	0.00	0.00	0.00	0.00
(428, 42.8)	0.00	0.00	0.00	0.00
(433, 43.3)	0.00	0.00	0.00	0.00
(438, 43.8)	0.00	0.00	0.00	0.00
(443, 44.3)	0.00	0.00	0.00	0.00
(448, 44.8)	0.00	0.00	0.00	0.00
(453, 45.3)	0.00	0.00	0.00	0.00
(458, 45.8)	0.00	0.00	0.00	0.00
(463, 46.3)	0.00	0.00	0.00	0.00
(468, 46.8)	0.00	0.00	0.00	0.00
(473, 47.3)	0.00	0.00	0.00	0.00
(478, 47.8)	0.00	0.00	0.00	0.00
(483, 48.3)	0.00	0.00	0.00	0.00
(488, 48.8)	0.00	0.00	0.00	0.00
(493, 49.3)	0.00	0.00	0.00	0.00
(498, 49.8)	0.00	0.00	0.00	0.00
(503, 50.3)	0.00	0.00	0.00	0.00
(508, 50.8)	0.00	0.01	0.00	0.00
(513, 51.3)	0.01	0.01	0.00	0.00
(518, 51.8)	0.01	0.01	0.00	0.00
(523, 52.3)	0.01	0.01	0.00	0.00
(528, 52.8)	0.01	0.01	0.00	0.00
(533, 53.3)	0.01	0.01	0.00	0.00
(538, 53.8)	0.02	0.01	0.01	0.00
(543, 54.3)	0.02	0.02	0.01	0.00
(548, 54.8)	0.02	0.02	0.01	0.00
(553, 55.3)	0.02	0.02	0.01	0.00
(558, 55.8)	0.03	0.02	0.01	0.01
(563, 56.3)	0.04	0.02	0.01	0.01
(568, 56.8)	0.04	0.03	0.02	0.01

Probability of Cable Damage – IR "K Factor" Model (Random Surrounding Temperature). Continuation

Temperature °K (mean, std. dev.)	XLPE		EPR	
	CAROLFIRE	NUREG 6776	CAROLFIRE	NUREG 6776
(573, 57.3)	0.05	0.03	0.02	0.01
(578, 57.8)	0.05	0.04	0.02	0.01
(583, 58.3)	0.06	0.04	0.02	0.02
(588, 58.8)	0.07	0.05	0.03	0.02
(593, 59.3)	0.07	0.05	0.03	0.02
(598, 59.8)	0.08	0.06	0.04	0.03
(603, 60.3)	0.09	0.07	0.04	0.03
(608, 60.8)	0.10	0.08	0.05	0.04
(613, 61.3)	0.11	0.08	0.05	0.04
(618, 61.8)	0.12	0.10	0.06	0.05
(623, 62.3)	0.13	0.10	0.07	0.05
(628, 62.8)	0.15	0.11	0.08	0.06
(633, 63.3)	0.16	0.13	0.09	0.07
(638, 63.8)	0.18	0.14	0.10	0.08
(643, 64.3)	0.19	0.15	0.11	0.09
(648, 64.8)	0.21	0.17	0.12	0.10
(653, 65.3)	0.22	0.18	0.13	0.12
(658, 65.8)	0.24	0.19	0.15	0.13
(663, 66.3)	0.27	0.22	0.16	0.14
(668, 66.8)	0.27	0.23	0.17	0.16
(673, 67.3)	0.30	0.25	0.19	0.17
(678, 67.8)	0.31	0.26	0.20	0.19
(683, 68.3)	0.33	0.29	0.22	0.20
(688, 68.8)	0.34	0.30	0.24	0.22
(693, 69.3)	0.36	0.32	0.25	0.24
(698, 69.8)	0.37	0.34	0.27	0.26
(703, 70.3)	0.42	0.37	0.29	0.28
(708, 70.8)	0.43	0.40	0.31	0.30
(713, 71.3)	0.45	0.40	0.33	0.32
(718, 71.8)	0.46	0.42	0.35	0.34
(723, 72.3)	0.48	0.44	0.37	0.36
(728, 72.8)	0.51	0.47	0.39	0.38
(733, 73.3)	0.53	0.49	0.41	0.40
(738, 73.8)	0.54	0.51	0.43	0.43
(743, 74.3)	0.57	0.53	0.45	0.45
(748, 74.8)	0.58	0.55	0.47	0.47
(753, 75.3)	0.60	0.57	0.49	0.49
(758, 75.8)	0.62	0.59	0.51	0.51
(763, 76.3)	0.64	0.62	0.53	0.54
(768, 76.8)	0.65	0.62	0.55	0.56

Probability of Cable Damage – IR “K Factor” Model (Random Surrounding Temperature). Continuation

Temperature °K (mean, std. dev.)	XLPE		EPR	
	CAROLFIRE	NUREG 6776	CAROLFIRE	NUREG 6776
(773, 77.3)	0.68	0.66	0.57	0.58
(778, 77.8)	0.69	0.66	0.59	0.60
(783, 78.3)	0.71	0.69	0.61	0.62
(788, 78.8)	0.72	0.70	0.63	0.64
(793, 79.3)	0.74	0.73	0.64	0.66
(798, 79.8)	0.75	0.75	0.67	0.68
(803, 80.3)	0.76	0.75	0.68	0.70
(808, 80.8)	0.79	0.77	0.70	0.72
(813, 81.3)	0.79	0.78	0.71	0.73
(818, 81.8)	0.80	0.80	0.72	0.74
(823, 82.3)	0.81	0.81	0.74	0.76
(828, 82.8)	0.83	0.82	0.76	0.77
(833, 83.3)	0.84	0.84	0.78	0.79
(838, 83.8)	0.85	0.85	0.79	0.81
(843, 84.3)	0.86	0.86	0.80	0.82
(848, 84.8)	0.87	0.88	0.81	0.84
(853, 85.3)	0.88	0.88	0.83	0.85
(858, 85.8)	0.89	0.89	0.84	0.86
(863, 86.3)	0.89	0.90	0.85	0.87
(868, 86.8)	0.90	0.91	0.86	0.87
(873, 87.3)	0.90	0.91	0.87	0.89
(878, 87.8)	0.91	0.92	0.88	0.89
(883, 88.3)	0.92	0.93	0.88	0.90
(888, 88.8)	0.93	0.93	0.89	0.91
(893, 89.3)	0.93	0.94	0.90	0.92
(898, 89.8)	0.94	0.94	0.91	0.93
(903, 90.3)	0.94	0.95	0.91	0.93
(908, 90.8)	0.95	0.95	0.92	0.94
(913, 91.3)	0.95	0.96	0.93	0.94
(918, 91.8)	0.96	0.96	0.93	0.95
(923, 92.3)	0.96	0.97	0.94	0.96
(928, 92.8)	0.96	0.97	0.94	0.96
(933, 93.3)	0.96	0.97	0.95	0.96
(938, 93.8)	0.97	0.98	0.95	0.96
(943, 94.3)	0.97	0.98	0.95	0.97
(948, 94.8)	0.97	0.98	0.96	0.97
(953, 95.3)	0.98	0.98	0.96	0.97
(958, 95.8)	0.98	0.98	0.97	0.98
(963, 96.3)	0.98	0.98	0.97	0.98
(968, 96.8)	0.98	0.99	0.97	0.98
(973, 97.3)	0.98	0.99	0.97	0.98

Glossary

Arcing: a luminous discharge of electrical current across an insulating material. The electrical discharge of an arc can involve extremely high temperatures (on the order of several thousand degrees Celsius).

Char: is the carbonaceous solid that remain after flaming combustion of the polymer.

Creep: continuous deformation of the polymeric cable insulation imposed by significant mechanical load. In materials science, creep is the term used to describe the tendency of a material to move or to deform permanently to relieve stresses.

Dielectric: electrical insulator, which is highly resistant to electric current.

Dielectric Breakdown: process through which an insulator material breaks down and looses its electrical insulation capacity (collapse and conduct). It is also referred to as maximum voltage difference required for an insulator material to break down (collapse and conduct). It is a function of the insulation material and its thickness.

Insulator: material which contains no free electrons to permit the flow of electricity.

Insulation Resistance: the resistance to flow on a direct current through an insulating material (dielectric).

Short circuit: abnormal connection (including an arc) of relatively low impedance, whether made accidentally or intentionally, between two points of different potential.

Thermoplastics: linear or branched material that can be melted and re-melted repeatedly upon the application of heat.

Thermosets: network polymers that are heavily crosslinked in which chain motion is greatly restricted. They are intractable once formed and degrade and char rather than melt upon the application of heat.

Void: empty space, mainly containing air, in a piece of insulating material. These “bubble of air” or “gas-filled cavities” ultimately reduce the effective thickness of the insulator.

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