Module III – Fire Analysis

Appendix H: Damage Criteria and Damage Time

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A Collaboration of the Electric Power Research Institute (EPRI) & U.S. NRC Office of Nuclear Regulatory Research (RES)

Damage Criteria
Characterizing targets

- A target is something <u>other</u> than the fire ignition source that may become involved in the fire
  - Defined as a part of the fire scenario
- Generally there are two target types:
  - Damage target: A component (or cable) that is important to plant operations that may be damaged by an exposing fire
  - Secondary ignition target: Any object that is combustible and that may be ignited by an exposing fire thereby spreading the fire
- One object can actually be both
  - e.g., the first cable tray above a fire ignition source…
- This presentation is mainly about *damage targets*, but the same general approach applies to ignition targets as well

Damage Criteria
Damage Thresholds

- Damage (or Failure) Threshold: the minimum value of an exposure environment parameter that *can* lead to the failure of the damage target of interest within the time scale of the fire
  - Can be a temperature – exposure to high temperatures such as in a hot gas layer or fire plume
  - Can be a radiant heat flux – generally due to direct radiant heating from the luminous flame zone of a fire
  - In theory, it could be a minimum smoke density, but we aren't that smart (more on smoke shortly)
- Corresponding PRA Standard SRs: FSS-C5, C6 and D9

Damage Criteria
Damage Thresholds

- Damage thresholds are of primary interest to Task 8 – Scoping Fire Modeling, but also play a role in Task 11 – Detailed Fire Modeling
- Zone-of-Influence (ZOI) – The area around a fire where radiative and convective heat transfer is sufficiently strong to damage equipment or cables and/or heat other materials to the point of ignition.
  - Damage thresholds are most useful when screening out specific fire ignition sources in Task 8:
    - If the closest target is outside the ZOI (no damage) <u>and</u> fire cannot ignite any secondary combustibles, then we screen that source out of the analysis as non-threatening (more later)
  - When we get to Task 11, we'll need damage time (more later)
- *Also Note:* If an electrical cable is damaged, we assume that it will also be ignited. FAQ 16-0011 offers a clarification on cable tray ignition, damage and fire propagation through cable trays
    - Based on testing experience – arcing causes piloted ignition. FAQ 16-0011 clarifies the conditions for fire propagation after ignition.

Damage Criteria
Damage Thresholds

- The *damage threshold* is specific to the damage target based on target type and target characteristics
  - What type of component?
  - What are it's vulnerabilities (e.g., heat, smoke, water…)?
  - What is the weak link relative to damage and the fire scenario?

- Most fire scenarios focus on:
  - Electrical cables (power, control, and instrumentation)
  - Electronics and integrated circuit devices

Cables
Classification of cables by insulation type

Cable insulations fall into one of two major categories:

- Thermoplastic (TP): capable of softening or fusing when heated and of hardening again when cooled (Merriam-Webster)
  - TP materials melt when heated and solidify when cooled
- Thermoset (TS): capable of becoming permanently rigid when heated or cured (Marriam-Webster)
  - On heating TS materials may soften, swell, blister, crack, smolder and/or burn but they won't melt

- Both types are used in U.S. NPPs
  - Thermoplastic is more common in older plants, also used in non-vital applications such as lighting and communications
  - Thermoset is more common in newer plants
  - Practices also vary based on utility preference at the time of construction

Damage Criteria
Cable damage thresholds

- The following are defined as generic damage thresholds for the most common damage targets – cables:

Cable Type	Radiant Heating Criteria	Temperature Criteria
Thermoplastic	6 kW/m² (0.5 BTU/ft2s)	205°C (400°F)
Thermoset	11 kW/m² (1.0 BTU/ft2s)	330°C (625°F)

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	Cable Damage/Ignition Criteria		Bulk Cable/Tray Ignition Criteria*	
Cable Type	Radiant Heating	Temperature	Radiant Heating	Temperature
Thermoplastic	6 kW/m²	205°C	25 kW/m²	500°C
Thermoset	11 kW/m²	330°C		

FAQ 16-0011

*if you have case specific information, you may use alternate values if you can establish a technical basis – many specific cable types will have much higher damage thresholds if you can establish a more specific insulation type for target cables

Damage Criteria
Sensitive Electronics

- Electronic devices refers mainly to control components that are based on integrated circuit type devices
  - Circuit cards, amplifiers, D/A and A/D converters, signal conditioning devices, communications equipment, computers, instrument transmitters, etc.
- Does not include electro-mechanical devices that lack integrated circuit elements
  - Relays, switches, indicating lights, breakers, etc.
- Typical damage thresholds for electronics are much lower than cables:
  - 3 kW/m^2 (0.25 BTU/ft^2) and 65°C (150°F)
  - FAQ 13-004 Treatment of Sensitive Electronics

Damage Criteria
Sensitive Electronics

- FAQ 13-004 discusses an approach for treating "sensitive electronics" targets in fire scenarios
  - Points out that there is no clear definition of what constitute "sensitive electronics" in NUREG/CR-6850
  - Proposed treatment assumes that equipment that is sensitive to increased temperatures will be located inside electrical enclosures
  - Guidance is based on FDS fire simulations
    - 317kW transient fire located 1 m from a cabinet
    - Radiometer located inside the cabinet to measure internal heat fluxes
  - In order to reach damaging heat fluxes inside the cabinet, conditions outside the cabinet are consistent with the damage criteria for Themoset cables

Damage Criteria
Some other specific cases

- Some items are considered invulnerable to fire-induced damage:
  - Ferrous metal pipes and tanks
  - Passive components such as flow check valves
  - Concrete structural or partitioning elements except when considering random failure likelihood in multi-compartment scenarios
    - i.e., we *do not* consider fire-induced structural failure of concrete
- Things you still need to watch for:
  - Soldered piping (e.g., air/gas lines that are soldered copper)
  - Flexible boots/joints/sleeves on piping (e.g., the Vandellos scenario)
  - Exposed structural steel given a very large fire source (e.g., catastrophic loss of the main TG set – more later)

Damage Criteria
Everything else…

- For other devices (e.g., motors, switchgear, etc.) we typically look to either the supporting cables or controls
  - A electric motor driven pump is fed by power cables, and those cables are generally more vulnerable to fire damage than the pump itself
  - A switchgear is supported by both power and control cables – typically loss of the control cables means loss of functionality (no control power means breaker will not auto-cycle and cannot be remotely cycled)
  - A battery charger usually contains some integrated circuit cards that control charging rate and monitor battery status
  - A motor operated valve… again, look at the cables

Damage Criteria
Damage Thresholds

- For additional rules related to damage criteria, see H.1.1; e.g.:
  - Cables in conduit: potential damage targets, but will not contribute to fire growth and spread – no credit to conduit for delaying the onset of thermal damage.
  - Cables coated by a fire-retardant coating: treat as exposed cables for damage purposes – coating may slow the subsequent spread of fire, but we are NOT specific here.

Damage Criteria
Damage Thresholds

- Plant-specific or product-specific damage thresholds *may be used* if appropriate basis is established
  - NUREG/CR-6850 provides some references for information specific to many popular types and brands of cables
  - Example:

Table H-4
Failure Temperatures for Specific Cable Products as Reported in Table 5 of Reference H.2

Cable Manufacturer	Description of Cable Tested	Failure Threshold (°C)
Brand Rex	Cross-linked polyethylene (XLPE) Insulation, Chlorosulfonated Polyethylene (CSPE) Jacket, 12 AWG, 3-Conductor (3/C), 600 Volt (V)	385
Rockbestos	Firewall III, Irradiation XLPE Insulation, Neoprene Jacket, 12 AWG, 3/C, 600 V	320-322
Raychem	Flamtrol, XLPE Insulation, 12 AWG, I/C, 600 V	385-388
Samuel Moore	Dekoron Polyset , Cross-Linked Polyolefin (XLPO) Insulation, CSPE Jacket, 12 AWG, 3/C and Drain	299-307
Anaconda	Single Conductors Removed From: Anaconda Y Flame- Guard Flame Retardant (FR) Ethylene Propylene (EP), Ethylene Propylene Rubber (EPR) Insulation, Chlorinated Polyethylene (CPE) Jacket, 12 AWG, 3/C, 600 V	381
Anaconda	Anaconda Flame-Guard EP, EPR Insulation, Individual CSPE Jacket, Overall CSPE Jacket, 12 AWG, 3/C, I000 V	394
Okonite	Okonite Okolon, EPR Insulation, CSPE Jacket, 12 AWG, I/C, 600 V	387

Damage Criteria
Damage Time

- It is both appropriate and desirable to consider, not just the possibility of damage, but also the time before damage occurs
  – This is part of Task 11 – Detailed Fire Modeling
- It takes time to heat a target to its damage temperature
  – If the air temperature (or heat flux) equals the damage threshold, damage times may be prolonged (e.g., 30-60 minutes or more)
  – As exposure conditions become more severe, time to damage decreases (e.g., if immersed in flames, may be a few seconds)
- A damage time gives us a "hook" to credit fire intervention:
  – It tells you how long you have to put the fire and prevent damage
  – We can then ask "what is the probability that given the fire, it will be put out before damage occurs?"
  – More details on that process later in the week, but for now we'll talk a little about estimating damage time

Damage Criteria
Damage time – three common approaches

- Predict when a fire grows large enough to create damaging environment at the target location (generally most conservative)
- Empirical approach (intermediate approach, e.g., SDP*)
  - Predict the peak exposure condition (temperature or heat flux)
  - Use a look-up table to estimate time to damage
  - Catch: look-up tables currently only available for generic thermoset and thermoplastic cables
- Direct modeling of target thermal response based on fire environment (generally most realistic)
  - Use a fire model to predict the temperature response of the target
  - When the predicted temperature of the target reaches the damage threshold, assume target failure
  - Catch: need fire model that does target response calculation
  - Simplest example: THIEF model for cables (more later)

* Significance Determination Process

Damage Criteria
Damage time – time to threshold

- One simple approach is to assume damage occurs when the conditions at the target location first reach the damage threshold
  - Generally gives the most conservative answer of the three approaches
- If you can characterize fire growth versus time, then you can use that to predict the fire environment over time even using simple correlations that are based on fire heat release rate
  - Plume temperature correlation
  - Radiant heating correlation
  - Steady state hot gas layer temperature correlation
- If you are in a hot gas layer situation, you can predict transient temperature profile using a fire model like CFAST or MAGIC
  - Won't help much unless you have a transient fire growth profile because HGL develops to steady state very quickly in these models

Damage Criteria
Damage time – the look-up tables

- The empirical time to damage tables are an intermediate approach
  - Still very simple but somewhat conservative
- Given exposure temperature, look-up tables give estimated time to damage

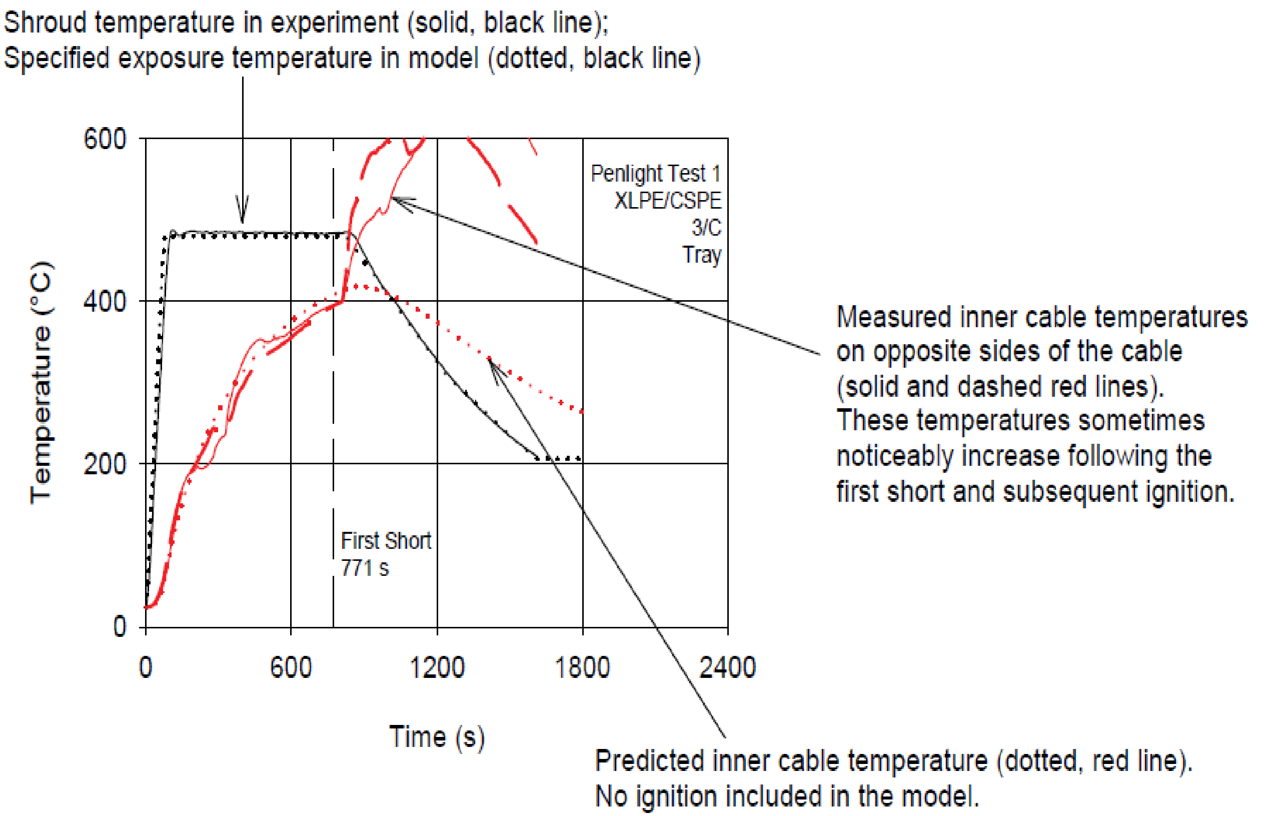
Table H-5: Failure Time-Temperature Relationship for Thermoset cables (Table A.7.1 from reference H.6).

Exposure Temperature		Time to Failure (minutes)
°C	°F	
330	625	28
350	660	13
370	700	9
390	735	7
410	770	5
430	805	4
450	840	3
470	880	2
490 (or greater)	915 (or greater)	1

Damage Criteria
Damage time – direct response modeling (e.g., THIEF)

- See: NUREG/CR-6931 V3
- Simple one-dimensional homogeneous heat transfer model

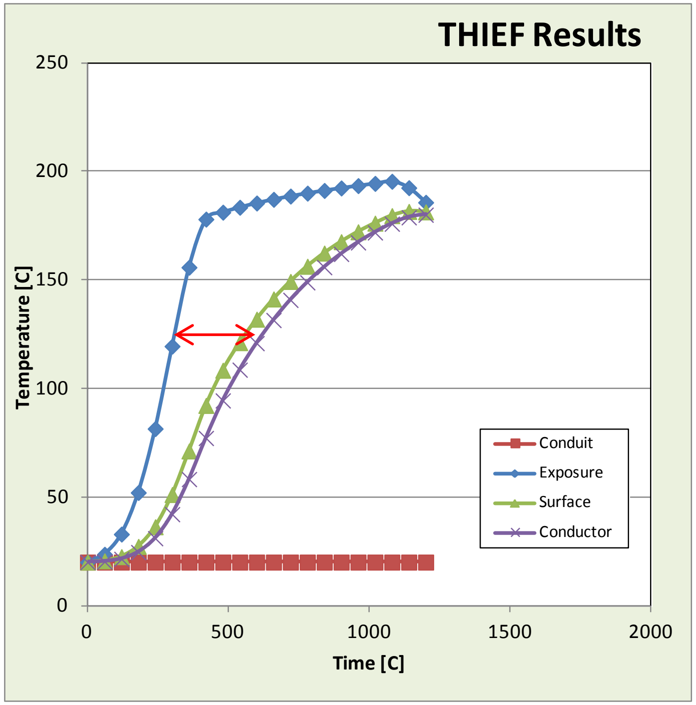
- Assumes a single cable in air (or in a conduit in air)
- Input is an air temperature profile
- Output is cable temperature vs time
- Assume damage when cable temperature exceeds threshold
- Now part of CFAST and FDS; FDTs



Thermally-Induced Electrical Failure (THIEF) Example

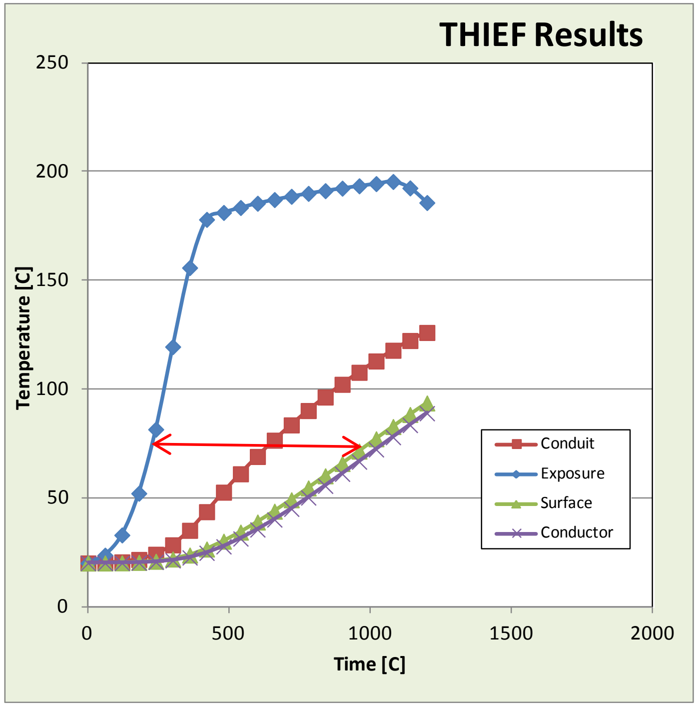
No Conduit

Cable diam	20	mm
Mass per length	0.3	kg/m
Jacket thickness	1.6	mm
Conduit diameter	14	mm
Conduit thickness	0	mm
Damage temp	205	C
Ambient temp	20	C



Cable Inside Conduit

Cable diam	20	mm
Mass per length	0.3	kg/m
Jacket thickness	1.6	mm
Conduit diameter	14	mm
Conduit thickness	5	mm
Damage temp	205	C
Ambient temp	20	C



Damage Criteria
Smoke Damage

- Appendix T provides an extended discussion of current knowledge regarding smoke damage
  - This is about smoke and the failure of equipment
  - It is not about the impact of smoke on people
- We are interested in short-term damage
  - Within the time scale of the fire scenario including plant shutdown
  - We do not consider longer term issues such as corrosion leading to failure some days or weeks after a fire
- Corresponding PRA Standard SR: FSS-D9

Damage Criteria
Smoke Damage

- Bottom Line: Some components are known to be vulnerable to smoke damage, but it takes a dense exposure to cause short term damage

- So what are the vulnerable components?
  - High voltage switching equipment (arcing)
  - High voltage transmission lines (arcing)
  - Devices such as strip chart recorders that are dependent on fine mechanical motion (binding)
  - Un-protected printed circuit cards (deposition and shorting)
    - e.g., exposed within a panel and not provided with a protective coating

Damage Criteria
Smoke Damage

- Smoke damage is assessed on an empirical basis:
  - We don't set quantitative thresholds
  - We don't try to use fire models
  - You should consider the potential failure of vulnerable components due to smoke as a part of your damage target set

Damage Criteria
Smoke Damage

- Assume that vulnerable components adjacent to or connected to the fire source will be damaged by smoke:
  - Within the same electrical cabinet or housing as a fire source
    - e.g. given a panel fire, the whole panel is lost due to smoke and/or heat
  - In an adjacent cabinet if the cabinet-to-cabinet partitions are not well-sealed
  - In a common *stack* of electrical cubicles
  - In a nearby cabinet with a direct connection to the fire source
    - e.g., a shared or common bus-duct

Questions?