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Evaluation of the Cables Types during the Fire Conditions in Nuclear Power Plants

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Abstract: The relatively high dangerous thermal effects of electric cable in the Nuclear Power Plants (NPPs) is the concern to study the cable insulation behavior during a fire accident. This paper provides a comprehensive evaluation for the thermal failure in different cables types of the standard main control room (MCR) in nuclear power plants. Evaluation of the effective parameters is carried out using (CFAST) zone fire modeling. The fire growth in a MCR, is modeled and simulated to determine the effect of thermal failure temperatures corresponding to cable functional failures. This is to develop realistic single point thermal failure thresholds and probability distributions for specific cable insulation types.The output data are assessed for the different cable insulation materials according to the specific thermal failure thresholds, as well as to develop the electrical cable thermal fragility distributions. The present results show the cable functionality interdependence on the external firing.

Keywords: Main control room, Fire modeling, CFAST, Cable insulation heat flux.

1. INTRODUCTION

Extending the lifetime of a nuclear power plants (NPPs) to 60+ years is one of the most important concerns in the global nuclear industry. For instance, in case of the electric cables that are one of the long life items that have not been considered for replacement during the design life of NPPs (typically 40 years), assessing their degradation state and predicting their remaining lifetime are very critical issues. [1]

The nuclear energy standards coordination collaborative (NESCC) is a joint initiative established under the sponsorship of the U.S. department of energy (DOE) and the U.S. nuclear regulatory commission (NRC) in coordination with the national institute of standards and technology (NIST) and the American national standard institute (ANSI) [2]. NESCC discussions revealed electrical cable aging and condition monitoring to be two common concerns with nuclear power plant cables as plants age.

Electrical cables, especially their insulation and jacket materials, are susceptible to aging degradation under service conditions in nuclear power plants. Historically, cables for this application have been subjected to accelerated thermal and radiation aging and testing to demonstrate a qualified life of 40 years. Installed cables have subsequently been qualified for an extended qualified life of 60 years or more. Improved methods for monitoring and assessing the in-service performance and condition of cables are needed.

In Nuclear Power Plants the cables ‘fire causes many dangerous events in electrical or mechanical operations that may lead to nuclear reactor melt down; thus main control room (MCR) in NPPs have special concern in fire protection system.

There is different models of fire that divide the building into different numbers of control volume [3]. The most common model is the zone model that uses two control volumes, upper layer and lower layer to describe a compartment. This approach is based on simulation of real-scale fire scenario and are taken from real experiments. Hot gases are collected up the ceiling and fill the compartment layer at the top. While the experiments show some variation in conditions within the layer, those may be small compared to the differences between both layers. Thus, the zone model can produce a fairly realistic simulation. On the other hand, field model divides the compartment into thousands of volumes. Accordingly, field models are able to predict the variation in conditions within the layers, but require much longer run times than zone models. Thus, it is used when highly detailed calculations are essential where the compartment is highly

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irregular. In zone models, it takes less time to simulate a fire and it is easily applicable on relatively small rectangular areas like cable spreading or pump rooms and main control room (MCR). The validation and verification of zone models are presented early [4].

In this present work, CFAST as a type of zone fire modeling simulation tool is applied in the main control room [5]. The simulation is being done considering that, there is fire inside cabinets of control cables in the a standard main control room using the target of many types of cables used inside at different interior temperature (13, 20 and 25^{0}C) and source of fire with heat of combustion (10,300 kJ / kg) during simulation time 2700s. The simulation results producethe temperature and heat flux of cables. The data resultsare being used to evaluate the cables types,to determine the best of these covers of insulating cable material according to the fire-resistant.

2. FIRE MODELING OF THE MAIN CONTROL ROOM

A. General Description of the Room

The MCR contains a Cabinet which is accommodating different electrical cable types. One wall of the compartment is made of 0.9 m -thick concrete with no additional lining material. The other bounding walls are constructed of 1.6 cm gypsum board supported by steel studs. The floor is a slab of concrete covered with low-pile carpet that is nominally 1.25 cm thick. The ceiling is concrete with the same thickness as the floor (0.5 m), but with no lining material[6]. Thermal conductivity (kW/ (m. ^{o}c) for gypsum wall, concrete ceiling and concrete floor respectively are (0.00017, 0.0016 and 0.0016), density (kg/m^3) are (960, 2400 and2400), specific heat (kj/ (kg^{o}c) are consequently (1.1, 0.75 and 0.75) and thickness (m) are (0.015875, 0.9 and 0.5).

The detectors are UL-listed with a nominal sensitivity of 4.9 %/m as listed in [7]. **U**pon smoke detector activation, the mechanical ventilation fans start with suitable air flow rate. Mechanical ventilation is provided through six supply diffusers and two return vents of nominally the same size. The room has one door on the left wall that is normally closed.

B. Cables in electrical cabinets (target)

Geometry of cabinet inside MCR are cabinet width =0.5 m, length = 1 m, height =1.2 m and absolute width = 1.5 m, absolute length =3 m, absolute height =2.1 m. it contains various types of cables with deferent insulating materials. Those cables can be separated into two major categories, thermosetting (TS) and thermoplastics (TP). Thermoplastic materials are polyethylene (PE) polyvinylchloride (PVC). And PE-insulated, and PVC-Jacketed (PE/PVC) cable. Thermoset materials are ethylene-propylene rubber (EPR), cross-linked polyethylene (XLPE). Thermal properties of various cable insulation materials in the compartment are listed in Table.

Table I Thermal properties for various cable insulation materials

Insulation material	Conductivity (kw/mk)	Density (kg/m^3)	Specific Heat (kJ/kg/K)	Emissivity	REF
PVC	0.092	1710	1.040	0.9	Ref.[8]
PE	0.490	764	2.25	0.9	Ref.[9]
PE/PVC	0.192	1380	1.289	0.9	Ref[10]
EPR	0.622	393	1.35	0.8	Ref. [11]
XLPE	0.177	918	1.849	0.9	Ref.[12]

C. Fire scenario

A fire is described as a source of heat placed at a specific point, within cabinets inside MCR, that generates combustion products according to specified combustion chemistry. Consistent with typical practice for the use of zone fire models for electrical cabinet fires, the fire is positioned at the top of the air vent, 0.3 m below the top of the cabinet, at the center of the cabinet. The air vent dimensions are 0.6 m wide and 0.2 m height. The effective diameter of the fire is approximately 0.4 m. The fire's heat release rate (HRR) has "t-squared" curve to a maximum value of 702 kW in 12 min and remains steady for eight additional minutes. After 20 min, the fire's (HRR) decays linearly to zero in 19 min.

For the scenario with no ventilation, the classic definition of the Equivalence Ratio does not apply because there is no supply of oxygen in the room. However, it can be shown that there is sufficient oxygen in the room to sustain the specified fire. The total mass of oxygen in the room is the product of the density of air,ρ, the volume of the room, ***V***, and the mass fraction of oxygen in the air,

$\boldsymbol{Y_{02}}$: $mo_{2,tot} = \rho V Yo2$ (1)

$= 1.2\ kg/m^3 \times 1945\ m^3 \times 0.23 = 537\ kg$

Where:

$Mo_{2,tot}$ is total mass of oxygen in the room.

ρ isdensity of air.

V is volume of the room.

Yo_2 is mass fraction of oxygen in the air.

The mass of oxygen required to sustain the fire is equal to the total energy produced by the fire divided by the energy released per unit mass oxygen consumed:

$$m_{o_{2,req}} = \frac{Q}{\Delta H_{o_2}} \quad (2)$$

$$\cong \frac{702KW \times \frac{60s}{min} \times \left(\frac{12}{3} + 8 + \frac{19}{2}\right) min}{13.100 kJ/kg} \cong 69\ kg$$

Where:

$m_{o_{2,req}}$ is mass of oxygen required to sustain the fire.

Q is total energy produced by the fire.

ΔH_{o_2} is the energy released per unit mass

oxygen consumed.

These calculations show that, the quantity of oxygen in the room would be able to sustain the specified cabinet fire.

3. Parameters and conditions of simulated models

The main control room is implementing using the CFAST (fire simulation model). The simulation is being done supposing that, there is fire inside control cabinet, cables (target) in the standard MCR, and fire started at different inside temperature of (13^0C, 20^0C, 25^0C). The source of fire with heat of combustion (10,300 kJ / kg) for scenario time of (2700s).

In each of the simulations, the followings were calculated temperatures of the upper and lower layers, heat flux, the concentrations of oxygen, carbon dioxide, carbon monoxide, hydrogen chloride and target(cable) interior temperature.

The value of flux and cables interior temperature is very important for determine the failure of cables. The rate of increase or decrease oxygen gas due to external factors such as ventilation vents and room doors ….etc, indicates the risk as to be considerable or negligible respectively. One can contribute the possible change in the oxygen gas ratio as the most important factor contributes to the probability of re-ignition. The rate of carbon dioxide is important on one hand because it could cause suffocation to whoever is inside, on other hand might step in to extinguish the fire. Furthermore, carbon monoxide and hydrogen chloride are seen as the toxic gases.

4. Simulation results

The results obtained from CFAST simulator are to be presented as follows.

Part I

In spite of the reaction against the firing in the NPP_S will take place in apart of a second or may be less, one can select the long CFAST simulation time for more details of the cable parameters.

Fire Simulation of MCR at 20 ℃ interior temperature is done during 2700s CFAST simulation time.

The cables (thermoplastic materials) are (PE), (PVC)and (PE/PVC) cables and thermoset materials are (EPR), (XLPE) have almost the same behavior during all simulation time. A good logic agreement between the obtained and the standard results (typical compartment fire curve). [13]

Figures 1 shows that upper layer temperature of the room is forward proportional with the time in range from (0 to 650s) while it is very slow increasing in rang (650 to 1800s). The last part of the curve shows the room temperature decaying. Results show that the upper layer temperature of MCR has no distinguish influence between cable types. The temperature of upper layer in MCR is started at 20℃ (ignition) and gradually increases up to 52°C at 320s. The temperature continued to increase till 60°C (fully development of fire condition), then remains constant until 1900s. On the meanwhile the fire decaying will start and continue up to around 2700s (burnout).

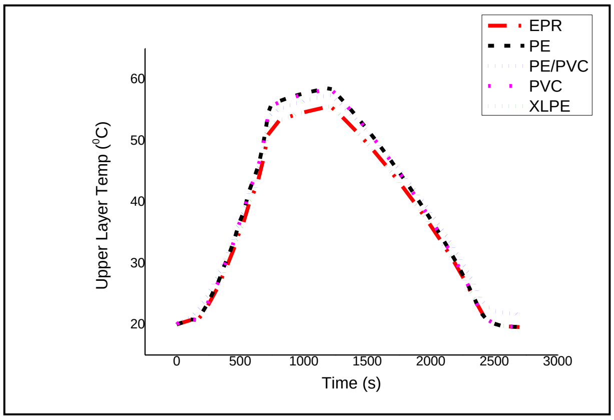

Figure 1. Upper layer temperature in MCR at 20℃

Figure 2 shows that, the temperature of lower layer in MCR is changed for combustion of the two-group cables. Temperature started at 20℃ and then decreased due to mechanical ventilation and flow rate of O2; and then, re-ignition will be happened. The figure clearly depicts that PE/PVC sustain a high temperature than PE and PVC where it withstands the heat of 26.6 ^{0}C at 1360s. The resulting room temperature of thermoset cable during the burning is identical.

The resulting gases due to the burning of the cable are graphically presented in figure (3, 4, and 5).Although the gases HCL, CO2 and CO have different values during the cable burning. The graphs are similar as well as are in a satisfying agreement with the (compartment fire carve). HCL, CO2 and CO gases are released from PE and PVC cable, but with lower rates in comparison with the rate of PE/PVC cable. Results of this figures show the released gases from the two types of thermoset cable materials have the same releasing rate. One can see the different values of the HCL, CO2 and CO where the highest percentage of: CO2 is 0.0092mol.frac, CO is 794.9 ppm and HCL is 2293.7 ppm. The figure shows the difference of the thermoplastic behavior in correspondence with thermoset.

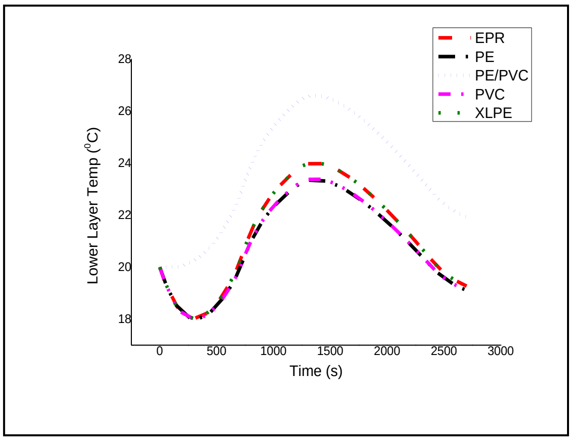

Figure 2. Lower layer temperature in MCR at 20°C

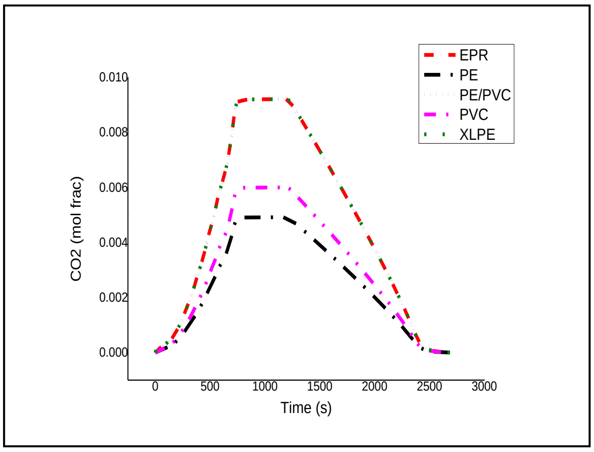

Figure 3. Concentration of carbon dioxide in MCR at 20°C

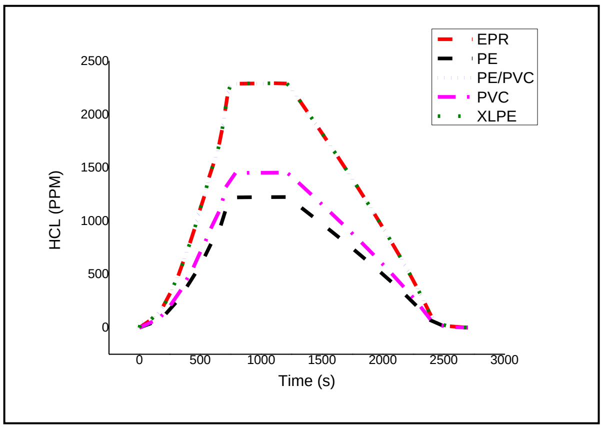

Figure 4. Concentration of hydrogen chloride in MCR at 20°C

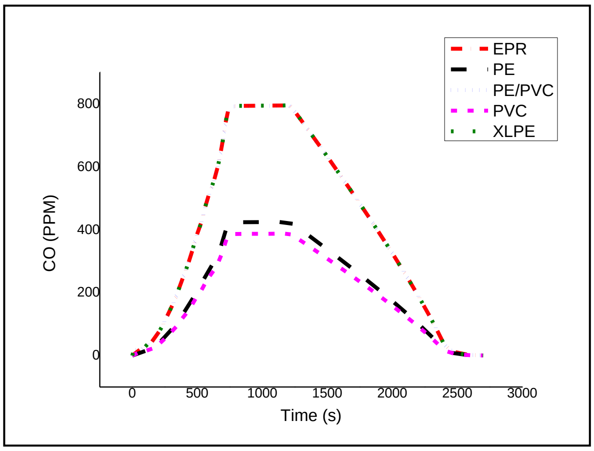

Figure 5. Concentration of carbon monoxide in MCR at 20°C.

Figure6 shows the concentration of the oxygen decreases from 20.5 at 0.0s until reaches to 18.9 at time 690s. This is due to flow rate of O2 flow from mechanical ventilation then re-ignition will be happened, then will be increased to 18.8 at the end of simulation. The figure shows the rate of consumed oxygen in the fire. The results illustrates that more oxygen was consumed by PE cable in comparison with the other two types of thermoplastic cable materials.

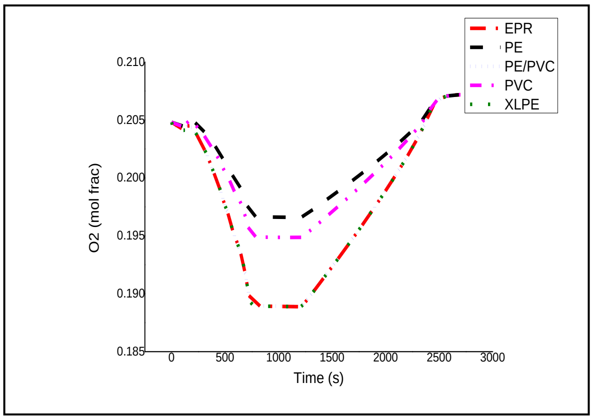

Figure 6. Concentration of oxygen in MCR at 20°C

Figures 7 show that the fire flux in target (cables) will be started at 0.0s (ignition) and fire flux growth until reaches 25 w/m^2 at 470s and then increased to reach 45 w/m^2 at time 1190s (fully developed fire). This occurs when rapid fire growth stops because of limited oxygen, as well as fuel geometry limitations, or chemical kinetic restrictions. Then it happens to them decay to the end of the simulation time (burnout) when the cables are exhausted.

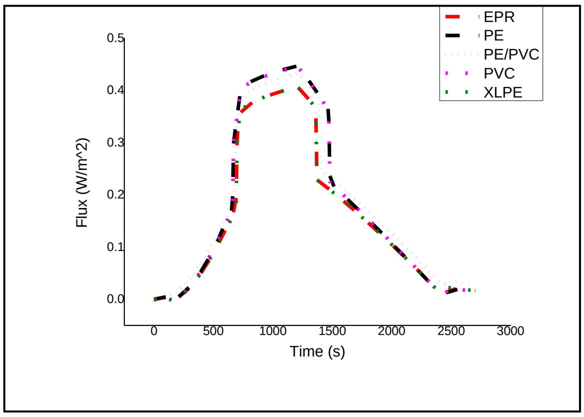

Figure 7. Fire sizes of targets (cables) in MCR at 20℃

Figure 8 shows thatinternal cable temperature of PE/PVC reach to 27 °C while EPR with stand to 30 °C at 2700s. Two types of cables tolerant to high temperatures and thus seen as the best of their kind.

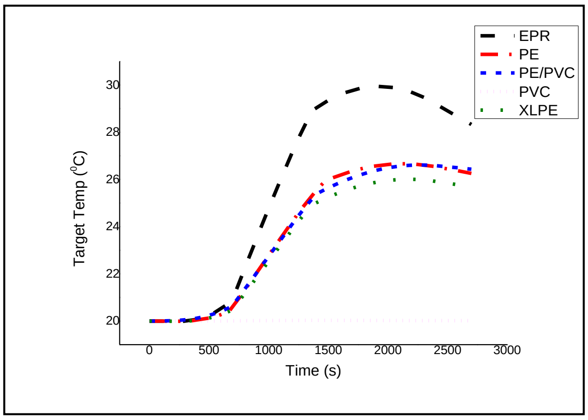

Figure 8. Internal target temperature in MCR at 20°C.

Part II

When the interior temperature of MCR variesto13^{0}Cand 25^{0}C it can beconcluded that the heat flux for the two groups of cables whether thermoplastic orthermoset will decrease when increasing interior temperature of MCR. It could be found that there is an inverse relationship with temperature. Where internal cable temperature isdirectly proportional with the increase of the MCRtemperature.

Figure 9 shows, heat flux of EPR cable as an example of the used ones in the simulation for evaluating the effect of changing interior temperature on cable heat flux in MCR. Indeed, the figure shows that there is an inverse relationship between the heat flux and the room temperature. This is due to the inverse relationship between the increase in the internal temperature of the room and the proportion of oxygen.

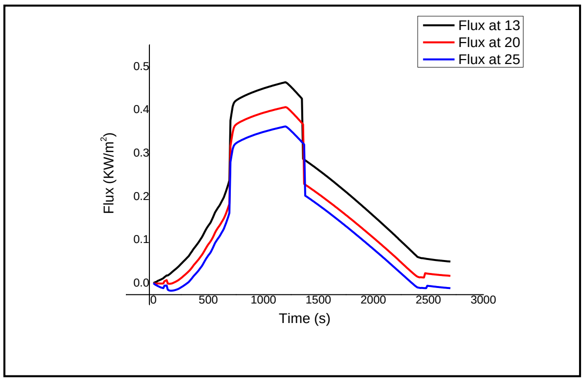

Figure 9.Heat flux of EPR.

5. CONCLUSION

The integrity of the cables located in NPPsespecially in the main control room is very important for the fire protection system. For this reason, the fire has been modeled and simulated in this work. Predicting and evaluating the most dominant NPPs cable to select the best of them for achieving a safe-shutdown.

The simulation results at different simulation time 2700s at 20 ℃ interior temperature show that, the thermoplastic cable material PE/PVC type produce lower heat flux than PVC and PE. The cables insulated with ethylene propylene rubber (EPR) have the same average failure time compared to XLPE. Thermoset cable materials would decrease the time to failure than thermoplastic cable materials. On another side, PE/PVC thermoplastic cable material can survive high temperatures than the other types that means the cables make fire resistance and keep its circuit function at the best time. The EPR thermoset cable material withstands a higher interior temperature than XLPE. Finally, the ethylene propylene (EPR) cable seems more robust than all other types according to CFAST simulator results.

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