Thermal Image Analysis of How Accelerated Aging Temperature Affects the Flame Retardancy of Class 1E Cables

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1. Introduction

In nuclear power plants (NPPs), cables play a role in power supply and signal transmission for the control and communication of safe shutdown equipment, systems, and instruments. Such cables, installed throughout NPPs, can be major combustibles in the case of fire. In addition, cables installed in the containment building are continuously exposed to an environment affected by radiological materials in high temperature and high pressure. Therefore, Class 1E cables used in the NPPs should be proven to have flame-retardant capabilities over their lifetime, as per flame test standards like IEEE-383 [1] and IEEE-1202 [2].

Many experimental studies [3-7] have been conducted on the flame retardancy of cables used in NPPs. In those experiments, the flame-retardant properties of aged cables were different from those of unaged cables. Also, the change in the accelerated thermal aging condition affected the flame-retardant properties of the aged cables. However, previous studies did not quantitatively analyze time-dependent average temperature and average flame height that can characterize the cable flame retardancy.

This study conducted vertical tray flame tests (VTFTs) of two Class 1E cables according to the IEEE-383 standard. The cables were thermally accelerated to 40-year aging. In addition, a thermal image analysis was conducted to investigate how changing the accelerated aging temperature affects the flame retardancy of the cables. To this end, a new image-processing method was developed. The thermal images of the cable fire tests were analyzed in terms of the time-dependent average temperature and average flame height. This method will be useful for quantitatively analyzing thermal images of cable fire tests to characterize the cable flame retardant properties.

Table I: Specifications of Class 1E cables A and B

Specifications		Cable-A	Cable-B
Application		Power/Control	
Voltage (V)		600	
Outer Diameter (mm)		14.5	28.7
Material Properties	Sheath	Chlorosulfonated polyethylene Rubber (CSPE)	
	Insulation	Ethylene propylene Rubber (EPR)	
	Core	Copper	

2. Methodology

2.1 Flame Retardancy Test

In this study, flame retardancies of two Class 1E cables (cable-A and cable-B) used in NPPs were tested. Table I lists the specifications of cable-A and cable-B. Both consisted of a sheath composed of chlorosulfonated polyethylene (CSPE), an insulation composed of ethylene propylene (EPR), and copper conductors. The outer diameters of cables A and B were 14.5 mm and 28.7 mm, respectively. Fig. 1 shows their cross-sectional areas.

The flame retardancy of the cables was tested using a VTFT configuration according to the IEEE-383 standard. Fig. 2 shows a typical example of fire experiments on cables A and B. Owing to different outer diameters of the cables, eight cable-A samples and four cable-B samples were tested.

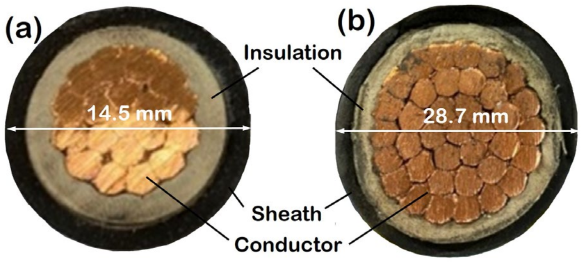

Fig. 1 Cross-sectional view of two Class 1E cables (a) cable-A and (b) cable-B.

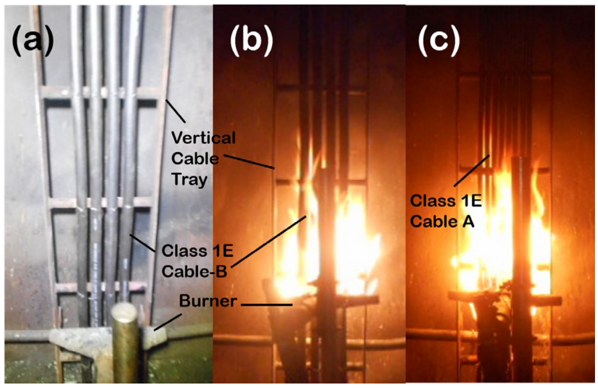

Fig. 2 Vertical tray flame test (VTFT) of Class 1E cables, A and B, according to the requirements of IEEE-383: (a) the installation configuration of cable-B before the flame test, (b) fire test of cable-B, and (c) fire test of cable-A.

2.2 Accelerated Aging Temperature Conditions

The design life of pressurized light-water reactor NPPs is approximately 40 ~ 60 years, depending on the reactor type. Thus, aged cables should be used in cable flame retardancy tests. However, finding cables already used for 40 ~ 60 years is difficult. Therefore, thermally accelerated aging cables are used.

In this study, the time required for accelerated thermal aging was determined using the Arrhenius equation [3,4]:

$$k(T_{Aging}) = \frac{k(T)}{exp\left[\frac{E_a}{K_B}\left(\frac{1}{T_{Aging}} - \frac{1}{T}\right)\right]} \quad (1)$$

where $k(T_{Aging})$ is the reaction rate at the accelerated aging temperature T_{Aging}, $k(T)$ is the reaction rate at the operating temperature T, E_a is the activation energy of the cable, and K_B is Boltzmann constant (8.617 x 10^{-5} eV/K). To fabricate a 40-year-old cable using Equation (1), accelerated aging durations of 16 h at 150 °C, 99 h at 130 °C, and 754 h at 110 °C were used.

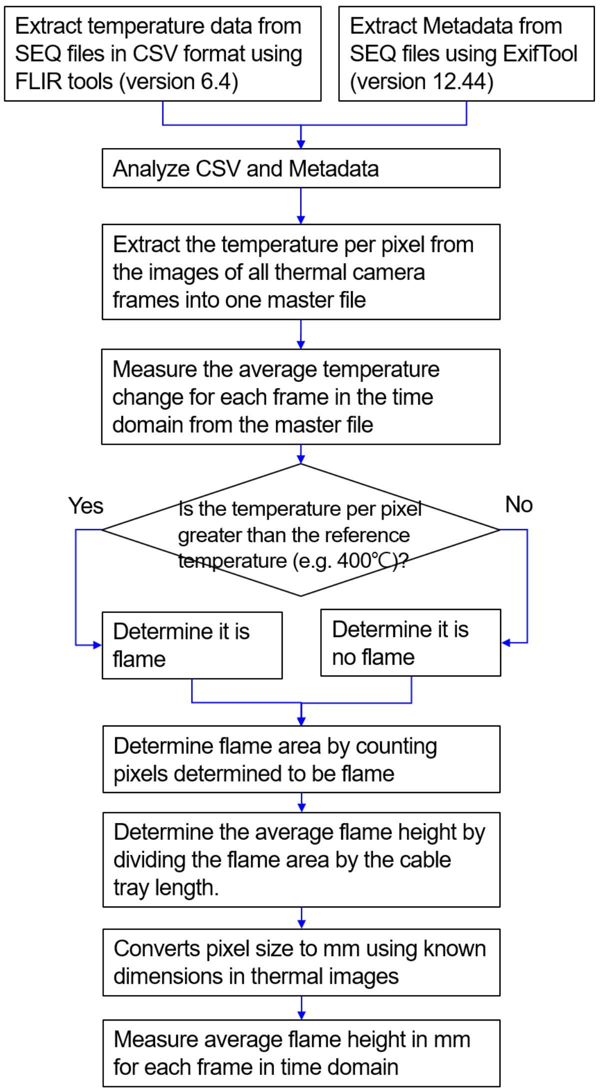

Fig. 3 Schematic illustration of image-processing method for thermal image analysis

2.3 Thermal Imaging Process

Fig. 3 shows the procedure for analyzing the thermal images of the cable flame tests newly developed in this study. Thermal images of the cable flame retardancy tests were originally recorded in an SEQ file format using a thermal imaging camera. The recorded SEQ files were extracted as CSV files and metadata. All extracted information was stored in a master file. The average temperature per camera frame was determined by averaging the temperatures of all pixels in the field of view. The test time corresponding to each camera frame was determined, and the mean temperature curve of the time-dependent cable flame was developed.

To measure the flame size in a camera frame, the evaluation criteria must determine the part of the image that can be considered as the flame. In this study, a new method was devised for measuring the flame's height.

When the temperature at each pixel position was greater than the reference temperature, the pixel was considered a flame. In this study, the reference temperature is assumed to be 400 °C. The pixel size was converted to millimeters by calibrating the dimensions of an object already known in the thermal image. The average flame height for each camera frame was determined by dividing the area considered as the flame by the cable-tray length.

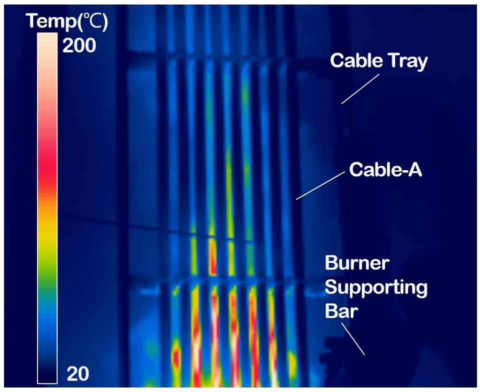

Fig. 4 Typical thermal image of vertical tray flame test of Class 1E cable-A with temperature range of 20 (dark blue) ~ 200 °C (white).

3. Results and Discussions

3.1 Average Temperature

Fig. 4 shows a typical thermal image of the vertical tray flame test of cable-A. Lack of space in the test chamber made it difficult to determine the camera position with an appropriate field of view. Therefore, the field of view of the camera frame is small. Even worse, the supporting structure for the burner was located on the right side of the thermal image. With the burner support covering the cable tray in the field of view of the thermal camera frame, the high-temperature area of the cable tray could not be measured. This was considered as an incorrect image analysis. In this study, the image processing analysis was performed only on the images in which the burner support did not cover the cable tray.

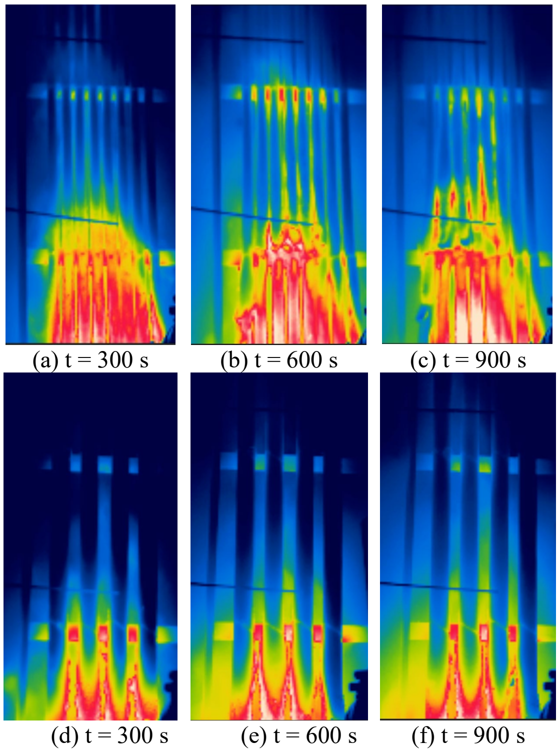

Fig. 5 Cropped thermal images of (a) ~ (c) non-aged cable-A and (d) ~ (f) non-aged cable-B with temperature range of 100 (dark blue) ~ 700 °C (white).

Fig. 5 shows the temperature distributions of non-aged cable-A and cable-B. Thermal image analysis made it possible to qualitatively evaluate the change in the flame temperature over time. In the case of cable-A, the high-temperature area in red expands in the vertical direction over time. However, in the case of cable-B, it was not significantly affected by time.

Fig. 6 shows the effect of the accelerated aging temperature on the time-dependent average temperature curve of cable tray fires. In the case of cable-A in Fig. 6(a), the temperature of the non-aged cable was the lowest after approximately 400 s. The time-dependent average temperature of the aged cable was the highest when the accelerated aging temperature was 110 °C. In Fig. 6(b), the temperature of the non-aged cable was observed to be below that of the aged cables. However, the temperatures of the aged cables were not affected by the accelerated aging temperature.

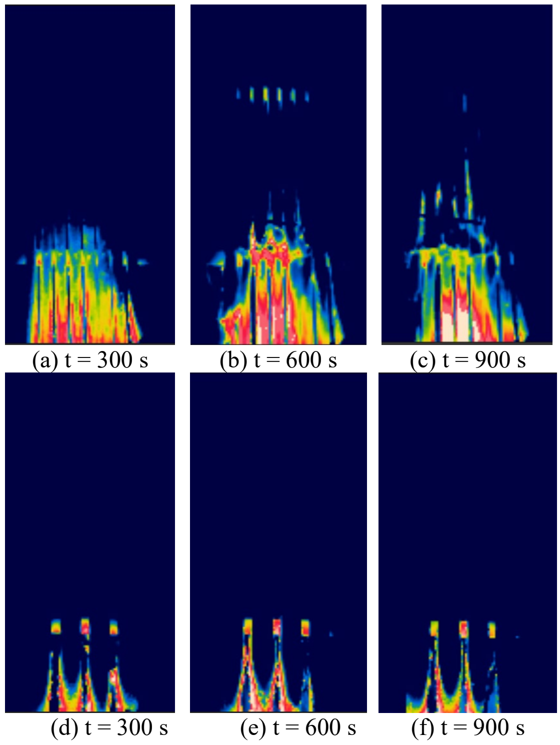

Fig. 7 Cropped thermal images of (a) ~ (c) non-aged cable-A and (d) ~ (f) non-aged cable-B with temperature range of 400 (dark blue) ~ 700 °C (white).

3.2 Average Flame Height

Fig. 7 shows typical examples of the thermal images of non-aged cables A and B in the temperature range of 400 ~ 700 °C. The temperature of the areas in dark blue is 400 °C or less, which is considered no flame. In the

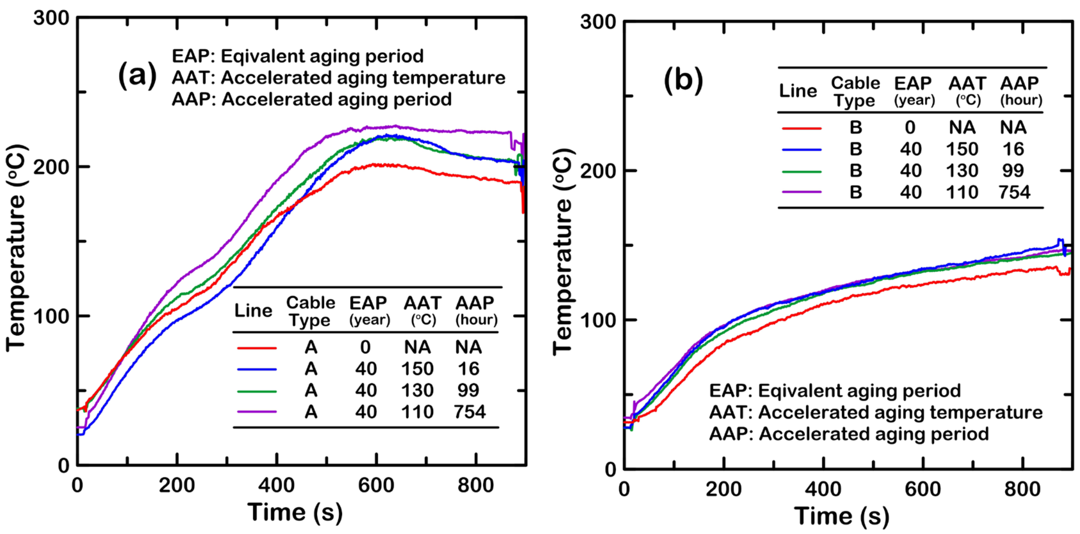

Fig. 6 Averaged temperature distribution of (a) cable-A and (b) cable-B with different accelerated aging conditions.

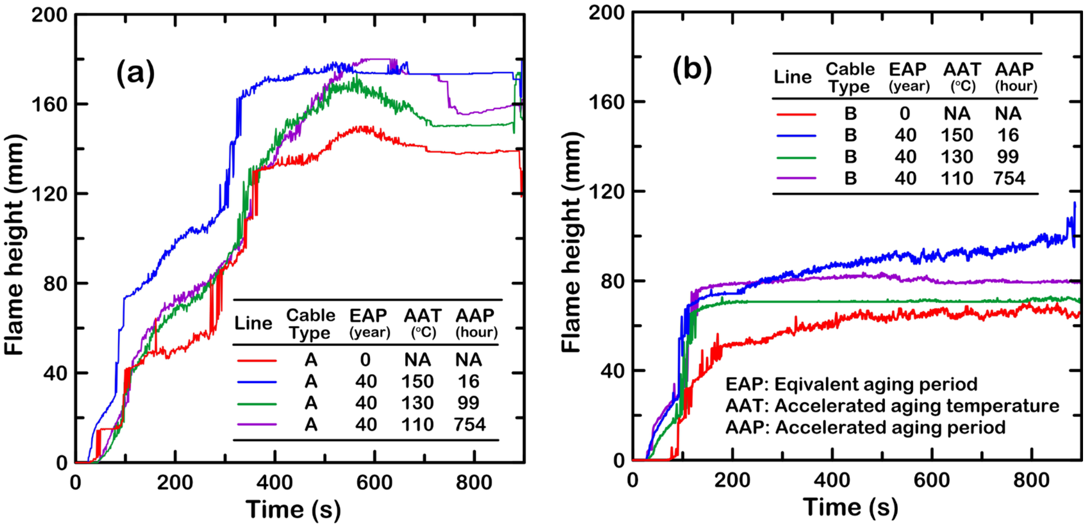

Fig. 8 Averaged flame height of (a) cable-A and (b) cable-B with different accelerated aging conditions.

case of cable-A, the area regarded as the flame increased over time. However, in the case of cable B, the area regarded as the flame was not significantly affected by time.

Fig. 8 shows the average flame heights of cables A and B. The average flame heights of cable-A were higher than those of cable-B. This is because twice as many cable-A types burned. The time-dependent average flame height curve of the aged cables was affected when the accelerated aging temperature conditions were changed. However, for both cable types, the average flame height of the aged cables was about 14 % greater than that of the non-aged cables.

3. Conclusions

In this study, thermal image analysis was performed on two Class 1E cable types to investigate the effect of accelerated aging temperature on their flame retardancy. Main conclusions are as follows:

- An image-processing method was developed for analyzing the average temperature and average flame height of a cable flame. This method could be used to quantitatively analyze thermal images to characterize the cable flame retardancy.
- The average temperature and flame height of cable-A were higher than those of cable-B. In the case of cable-A, the average temperature was affected by the accelerated aging temperature; however, in the case of cable-B, it was hardly affected.
- In terms of the average flame height, both cable-A and cable-B were affected by the accelerated aging temperature. The average flame height of the non-aged cables was smaller than that of the aged cables.

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