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Aging of Power Cables in Nuclear Power Plant due to Influence of Local Temperature Conditions

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ABSTRACT

A significant number of operating nuclear power plants (NPP) is approaching the end of the initially estimated design life. Considering that plants are stable and competitive, it may be possible to extend design lives to 60 years (perhaps even longer).

Before expending life time, ageing in NPPs must be effectively managed to ensure the availability of design functions throughout the plant service life. From the safety perspective, this means controlling ageing degradation and wear-out within acceptable safety limits so that adequate safety margins remain, i.e. integrity and functional capability in excess of normal operating requirements.

Even though cables are not active component, they are vital components in NPPs since they link the system components with instruments and control equipment used to monitor and control the plant. Consequently, the functionality of the cable necessary for nuclear safety is necessity for ensuring the functionality of equipment relevant to nuclear safety.

Since the cable ageing have been recognized as potential threat to safe operation of NPP, this paper deals with cable ageing aimed at identifying effects of aging and to determine whether the degradation caused by aging is within the stipulated tolerance limits. Also, it analyses the impact of ambient temperature changes on the cable ageing comparing to a qualified life. For an illustration, Arrhenius's model was used to calculate cable ageing in hot spot with the increased local temperature.

1 INTRODUCTION

Currently, there are 436 nuclear reactors in the world with a total of 370.5 MW of installed capacity in operation. The largest number of reactors started in 1970 and most of those had designed life expectancy of 30-40 years. These plants are approaching the end of the initial estimated life span, while working well and competitive. Therefore, there is interest in extending their time of exploitation. The reasons are primarily economic since the costs to extend the lifetime are minor compared with the capital costs of any replacement plants.

However, it is necessary to determine whether aging of the exposed components, structures and systems nuclear power plant can meet its intended design function in the case extending the life of exploitation. Aging equipment can be defined as a continuous, time-dependent degradation of the material. For nuclear power plant, operating conditions are difficult security requirements of the

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accident situations. Equipment important to nuclear safety must be functional both in normal and anticipated transient operating conditions and in accident conditions that are caused by the events defined by the project (for example, loss of coolant, LOCA). Generally, the cables themselves are not active safety equipment; cables transmit signals for indication, control and management commands or energy to the equipment that performs a security function. Consequently, the functionality of the cables necessary for nuclear safety is to ensure functionality of the equipment relevant to nuclear safety. Functionality of cable is defined by continuous cable operations to maintain proper operation of equipment important to nuclear safety. This means that the cable must remain operational and accidental conditions of the end of its qualified life.

One of the major causes of cable aging is temperature; therefore, by monitoring the ambient temperature and understanding of the aging mechanisms, cable aging can be assessed and preventive action is possible.

This paper analyses the aging effect due to elevated ambient temperature and its influence on cable qualified life. For an illustration, Arrhenius's model was used to evaluate changes in the cable qualified life in relation to environmental conditions.

2 AGING OF CABLES

Cables inside the containment building of NPP are exposed to various environmental conditions of which the most important factors are temperature and ionizing radiation. The electrical cables in NPPs are also used over very long periods of time, which can typically reach 40 to 50 years. The three basic factors for ageing are therefore present and will cause ageing of the polymeric materials of the cables. The consequences of this ageing on the required functional capability of cables need to be considered.

Aging is defined as the gradual degradation of the physical characteristics that occur due to passage of time or work in conditions that may reduce the reliability or functionality. It turned out that the aging of the cable depends on the aging of electrical insulation, therefore the main object of interest electrical insulation. External jacket is not considered subject to aging assessment, since it is considered that the physical protection on primary isolation, although our situation is actually sheathed cables can be used as an indicator of primary isolation. Even more so, because the cable sheath is usually made of a material that is slightly lower than the basic properties of insulation, so they are visible on it before the negative environmental impacts (if any).

The external jacket and the insulating materials are formulated organic compounds. They are made of a basic polymer (a macromolecular chain obtained by multiple replications of a unitary monomer) or co-polymer and of additives which provide the material with specific properties. These additives are mainly protective agents (anti-oxidants, thermal stabilizers and fire retardants), mineral fillers, plasticizers, oil (used to aid manufacture of the material), pigments etc. Some complex compounds may contain up to ten or fifteen different constituents. Variations in formulation can affect both the activation energy and rate of thermal ageing and the maximum dose for radiation ageing.

3 CABLE SPECIFICATION AND ANALYSIS DOMAIN

One of the common reasons for decreasing the cable lifetime in nuclear power plants is the possibility of exposure to elevated temperature due to a fracture of fluid transfer system. Such event, analysed here, is the fracture of blow-down system (BDS) pipe which is above 6.3 kV power cable.

3.1 Cable specification

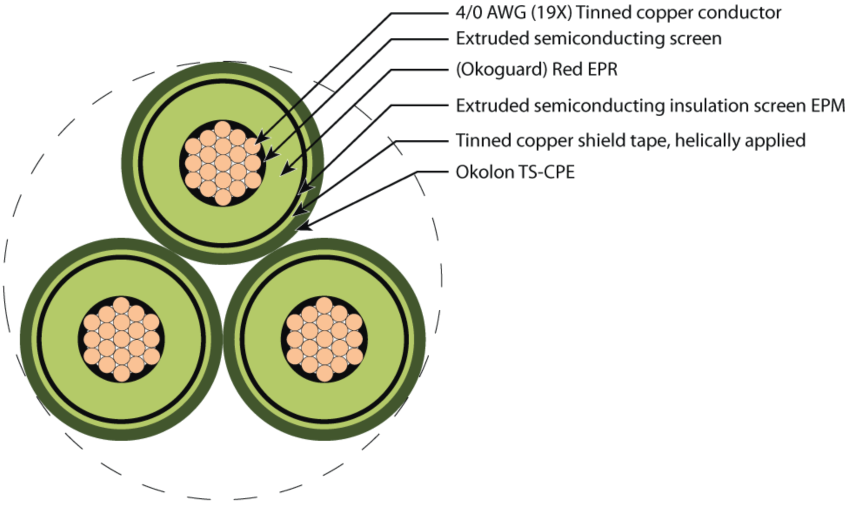

Figure 1 Cable configuration

Table 1Cable specification

Manufacturer	The Okonite Company
Voltage level	10 kV (6,3 kV)
Conductor	4/0 AWG (19X) Tinned copper conductor
Conductor screen	Extruded semiconducting screen
Insulation	Red EPR
Separator	Extruded semiconducting insulation screen EPM
Insulation screen	Tinned copper shield tape, helically applied
Separator	Tape
Jacket	TS-CPE

3.2 Analysis domain

The choice of the spot (IB-21) was based on the result from previous analysis (*Gothic* model developed to determine the environmental parameters) which showed the greatest impact on the ambient temperature increase.

Inside the room, two volumes were identified in the immediate vicinity of pipeline. Additionally, the subvolume (IB-21) includes a power cable. (Such a discretization was made to get better determination of the local conditions.)

For the purpose of analysis, dominant influence of mass transfer after opening the door to turbine building was examined. (The influence of heat transfer to the environment is limited.) All relevant concrete structures (walls, floor and ceiling) were part of the model. The equipment inside the premises was excluded. Thermal coefficient is defined assuming heat transfer by natural convection, depending on the orientation and type of surface and condensation on the surface. Thermal structure representing cable was added to the model. It was used pipe-type structure where the pipe wall is composite, consisting of an inner layer and the copper equivalent thickness of the outer insulation material. The copper is possible to have or not a source of heat due to ohmic heating. Additionally, surface of the cable can radiate heat, in exchange with the surface of BDS pipe. That impact is small on the total heating of the cable. Also, it can be significant for the local conditions (and for the formation of the overall temperature in the area of IB-21) in steady state.

First step in this analysis is calculation of the mass and energy content of the released fluid. For this purpose, simplified BDS model is added to the existing *RELAP5* model. It is assumed that total cut of the BDS pipeline (pipeline is 10m long and its outer diameter is 3in. (76.2mm)) which is isolated manually after 1800s. Insulation of the pipeline is neglected in the calculation to gain a greater temperature rise. Figure 2 shows the mass flow of water and steam after the cut.

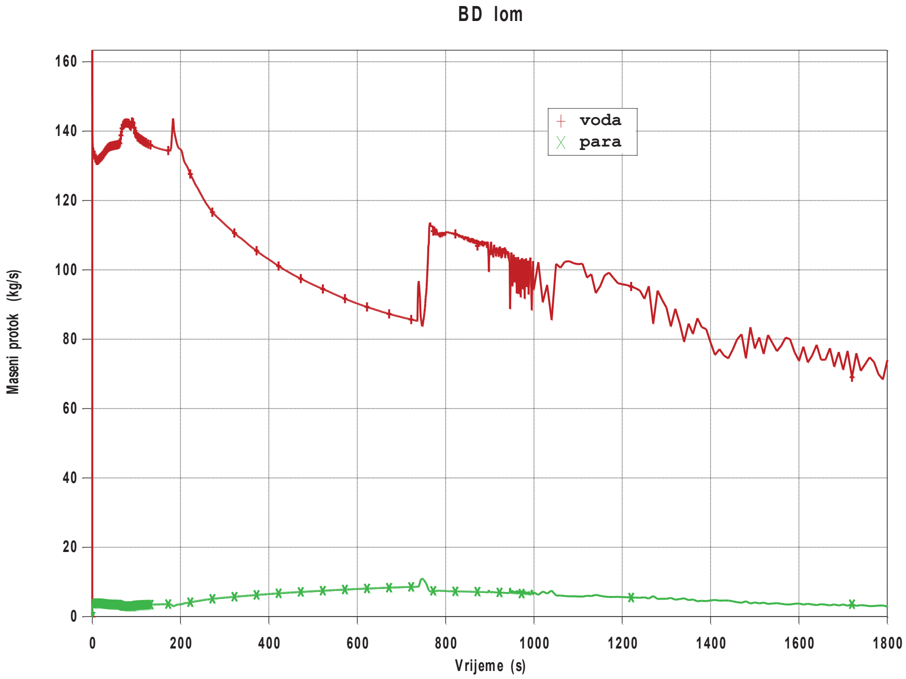

Figure 2 Mass flow (water and steam)

These data are used as boundary conditions to define disorder in the *Gothic* model. Assumed initial parameters of the premises are 40˚C and 60% relative humidity, at atmospheric pressure. The maximum design temperature in these areas was used as the ambient temperature when selecting equipment for installation in the room (hence the scaling and qualification of electrical cables).

Two scenarios were analysed, operating and non-operating cable. The calculation was carried out for over two days which is approximately the time during which environmental conditions should return to normal without any additionally treatment related to ventilation.

Short-term increase of the air temperature (Figure 3) has no effect on cable heating and insulation aging, but can lead to immediate failure of the cable if the temperature is too high and continues long time. The maximum ambient temperature is about 150˚C (Figure 4). The design temperature used to determine the maximum power load cable is 40˚C.

Visible is the difference in the cable temperature depending on whether there is an internal heat source (operating cable) or the cable is only heated due to pipeline fracture (non-operating cable).

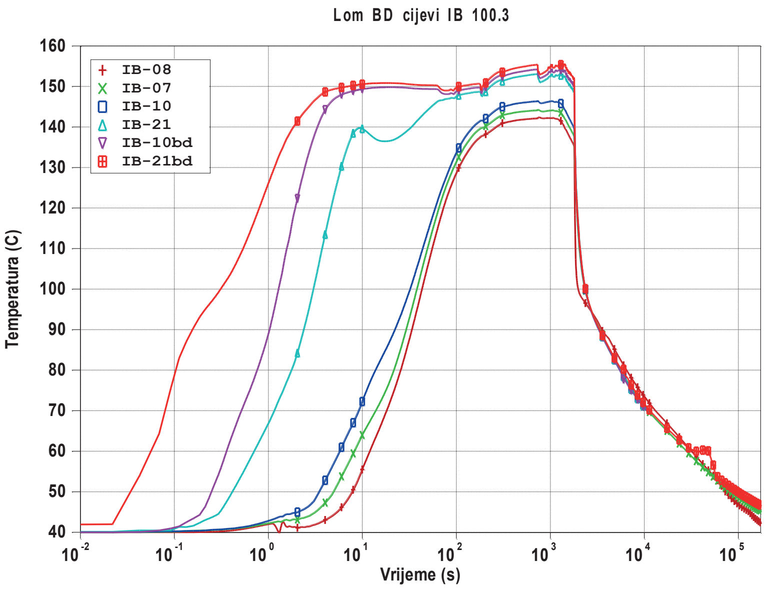

Figure 3 Distribution of the air temperature during BDS pipeline fracture

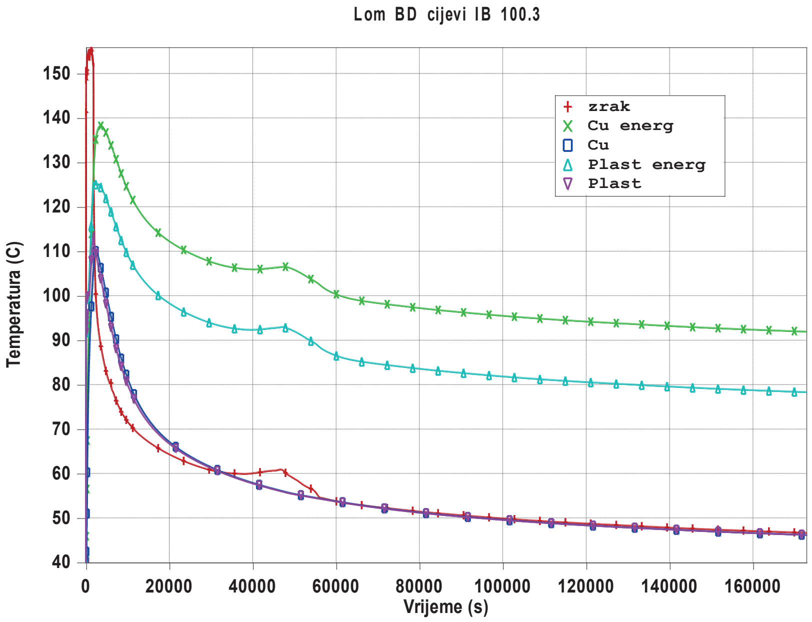

Figure 4 Distribution of the cable temperature (conductor and insulation)

4 CALCULATION OF CABLE HEATING

First step was the analysis of the steady-state conditions for which *ALGOR* (program for Finite element method, FEM) was used. In this model, cable is divided in four sectors to facilitate the assignment of boundary conditions which take into account the different convective heat transfer and spatially dependent radiate heat transfer from the pipeline.

Since the thickness of the copper shield, about 0.13 mm, the average length of the final element is set on 0.1 mm. The area is covered with a homogeneous quadrilateral mesh of linear elements using an automatic mesh generator. The total number of nodes is 84.934, and the total number of finite elements is 84.362.

Steady-state linear analysis was performed (ambient temperature was set on default value, 40°C and convective heat transfer coefficient from the surface was 6W/m^{2}K; only resistive losses of the conductor were taken into account). Results are shown Figure 5

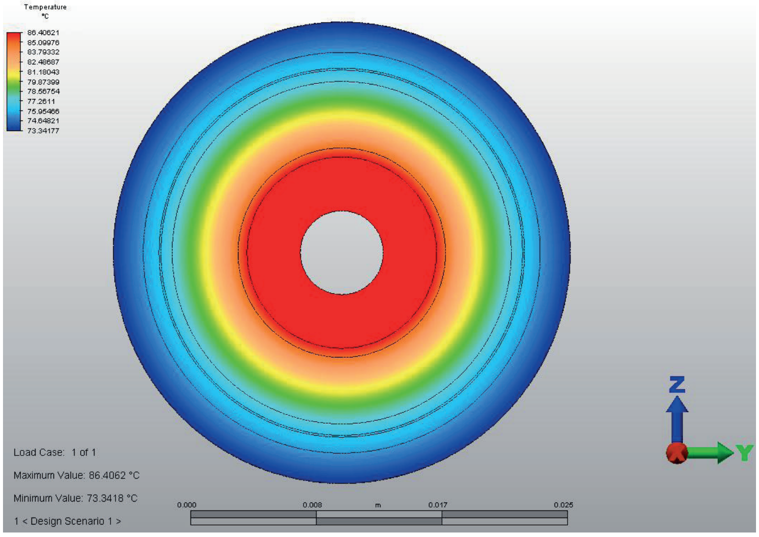

Figure 5 Distribution of operating cable temperature, nominal current

Obtained temperature distribution is completely symmetric and can be obtained by 1D calculation. In reality, the three cables in specific configuration do not have the same cooling conditions, nor individual conductor do not have equal convective heat transfer from the upper and lower surfaces. As an illustration, Figure 6 shows the temperature distribution in the cable where the heat transfer coefficient convection in the upper half of the 6W/m^{2}K, and the one with the lower half is 3W/m^{2}K (this situation corresponds to the cable laid on the poorly conducting surface).

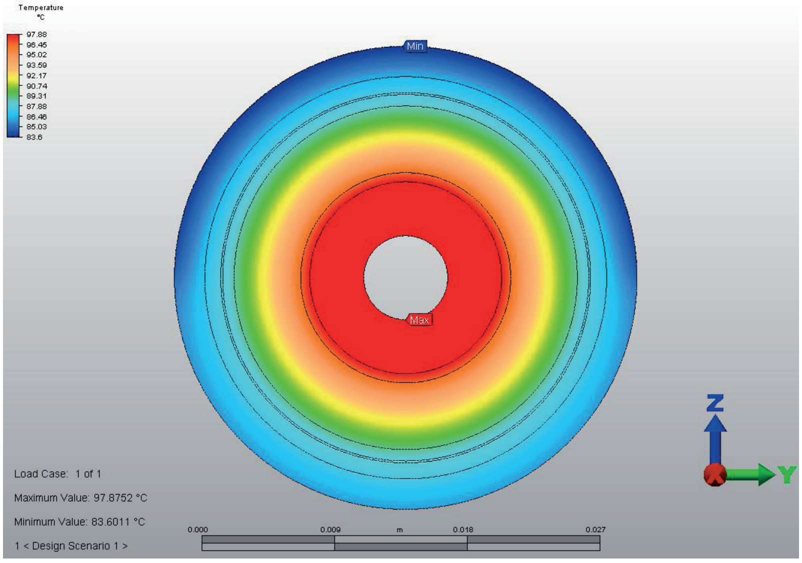

Figure 6 Distribution of operating cable temperature, nominal current where lower part of the cable has lower heat transfer coefficient

In order to conservatively estimate the possible radiate cable heating due to BDS tube above it, it was assumed that the tube has no insulation and outside diameter temperature is constant 260°C. The problem is due to transfer heat very nonlinear. The formula gives the heat transferred from the pipe, and the visible surface.

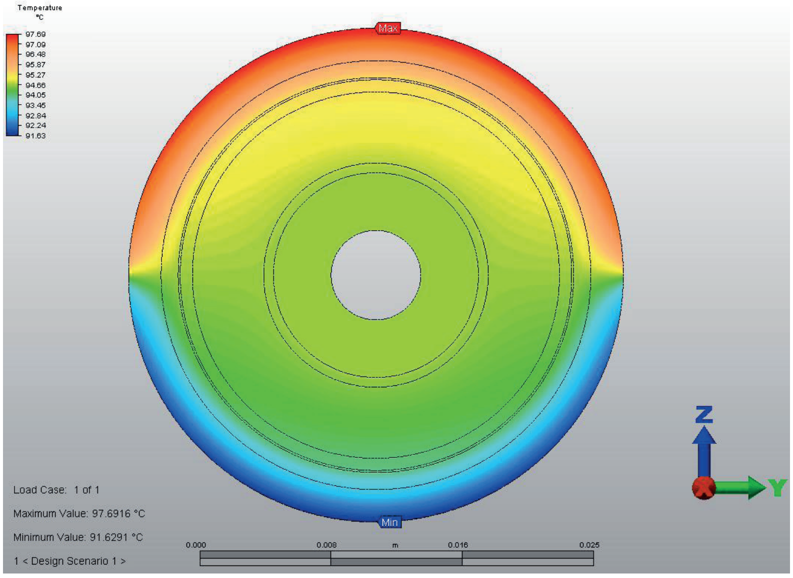

Figure 7 Distribution of non-operating, upper-placed cable temperature

5 ARRHENIUS'S MODEL

Once the actual temperature conditions and possible deviations from design conditions are established, we analyse impact it has on the design life of the cable.

Arrhenius's law (Eq. 1) is often used as a physical model for lifetime prediction during thermal ageing. It assumes that the rate of the thermal ageing mechanism decreases with the inverse of the temperature, such that the rate constant k can be described by the following equation:

$$R = Ce^{-E_a/kT} \tag{1}$$

C – Constant,
k – Boltzmann constant [8,617343·10^{-5} eV/K],
E_a – Activation energy [eV],
T – Absolute temperature [K].

Based on probability theory, middle time to failure is defined as shown in Eq.

$$MTTF = \int_0^\infty t \cdot f_\tau(t)\,dt \tag{1}$$

and if using Arrhenius's law, middle time to failure is

$$MTTF = \tau = \left[A \cdot \exp\left(-\Phi/kT\right)\right]^{-1} \tag{2}$$

The Equations (2) is usually used for correlation of two different lifetime, depending on different temperatures

$$\frac{MTTF_1}{MTTF_2} = \frac{t_1}{t_2} = e^{\left[\frac{\Phi}{k}\left(\frac{1}{T_1}-\frac{1}{T_2}\right)\right]} \tag{3}$$

If we understand relations that exposure of the material with an activation energy Φ temperature T_2 during the time t_2 has degrading effect equivalent to the exposure to the temperature T_1 over time t_1, we can estimate the impact of a history of exposure to the temperature to changes of the lifetime of a designed temperature. It should be noted that the Arrhenius law can be applied only to the slow and long-term degradation processes that do not involve exposure to extreme conditions that can cause immediate failure. Nevertheless, form of the above equation can be used to split continuous time interval t_2 down to smaller intervals and in this way can be approximately taken into account exposure to fluctuating temperatures. The relation enables the reduction of each individual impact on the reference temperature. Incorporating a simple application in the programming language Fortran 90, can load an arbitrary time dependence of temperature or can be manually entered to simulate an operational history. Program, by seeking file name with the time dependence of temperature, read a free format and automatically determine the size of the required fields. In addition, it is necessary to enter the temperature for which the initially designated lifetime is and the whole calculation will be reduced to the calculation of equivalent effect. The activation energy needs to be entered and measuring temperature unit must be set (C, K or F). The program converts temperature into absolute temperature [K]. It is important that the time dependence temperature and design temperature are the same units since they are transformed in the same way the absolute temperature.

Program find the average temperature for every two consecutive time points and calculate the cable lifetime as if the cable is exposed to constant high temperature within that time step. Arrhenius's relation is used to determine the equivalent time that would cause the same degradation temperature at the designed temperature for the actual time interval t_2 and temperature T_2.

Equivalent time is saved in the first output file as a function of real time. Then total exposure time equivalent to the transient and the time that would produce the same effect on the design temperature. Remaining lifetime is designed lifetime for given temperature reduced for the equivalent time for designed temperature in that time interval. Shortening life expectancy is given as the difference of the equivalent time and real time spent the time-dependent temperature. The program actually calculates equivalent exposure time on designed temperature for each real time of exposure to specific temperature.

If the equivalent time is greater than the real-time it means that the actual temperature conditions are worse than the design and that we need a longer exposure to the design temperature to achieve the same adverse effect. Usually, we know the qualified lifetime of the designed temperature and determine the appropriate period of time at a different temperature. Here, we know the actual time spent on an actual historical temperature and calculate the equivalent of time spent on the design temperature.

6 RESULTS

The program was tested for three simple constant temperature profiles. In the first case, the cable worked 40 years at 90˚C and it is also the projected lifespan of the cable insulation and the design temperature. In the second case, the cable was exposed to a temperature of 100˚C for 40 years and the third case, the cable was exposed to a temperature of 80˚C for 40 years. The first history of the project corresponds to the situation, and the equivalent time is no different from the actual exposure time and the curve is inclined at 45˚. In the second case when the cable is exposed to temperatures greater than designed and equivalent time grows faster (steeper than 45˚). For the cable operating for 40 years at 100˚C, calculated equivalent time is 111 years of design temperatures. (Figure 8, Figure 9 and Figure 10)

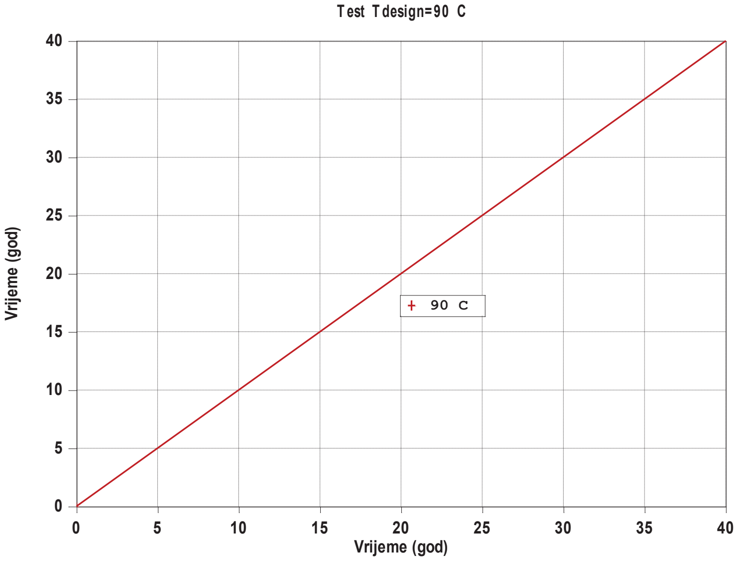

Figure 8 Equivalent time of exposure to designed temperature

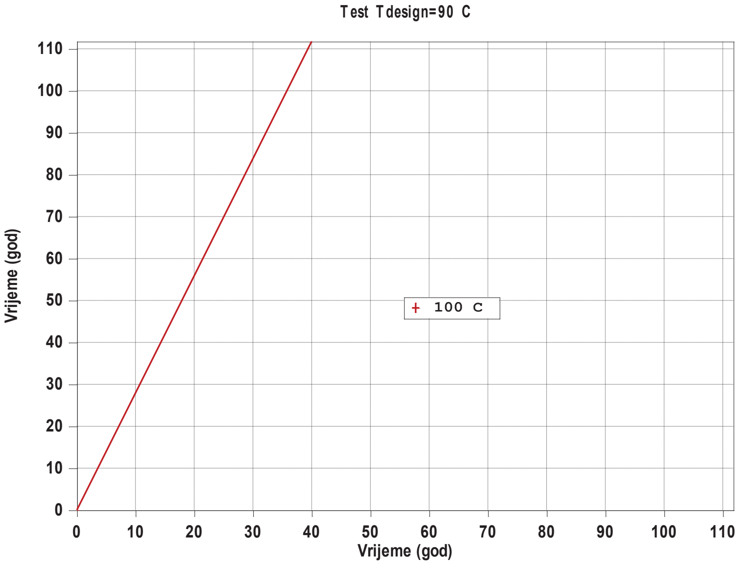

Figure 9 Equivalent time of exposure to temperature higher then designed

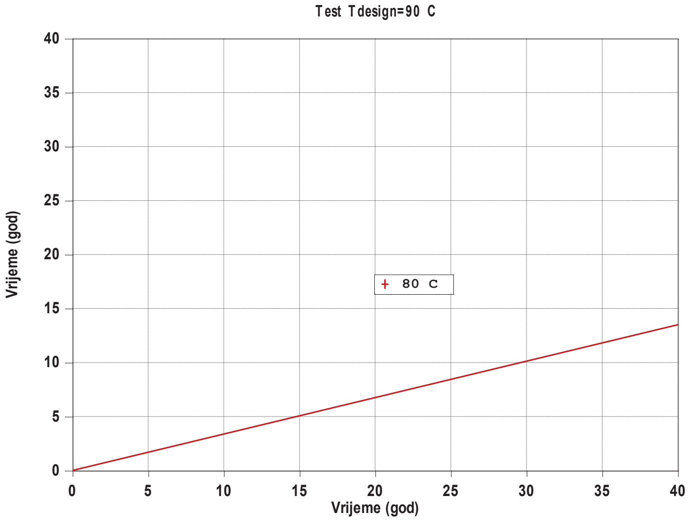

Figure 10 Equivalent time of exposure to temperature lower then designed

Arrhenius program was implemented to assess the effects of cable heating during the BDS pipeline fracture on qualified lifetime.

In Figure 11, the three historical profiles of temperature are shown (previously calculated by *Gothic*) that are used to assess the effects of aging. Profile marked with a temperature of Cu is scenario of cable in operation during BD fracture. The other two profiles are temperatures of the cable jacket in operating and non-operating state during the same transient. The reference temperature in all cases is 90˚C as the temperature of cable in continuous operation and as such is supposed to be used for defining the life span.

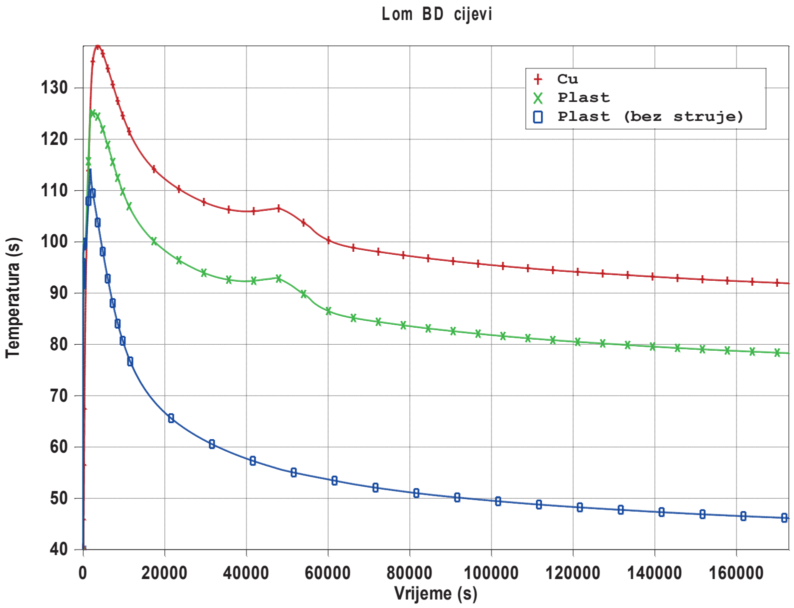

Figure 11 Cable temperatures for different scenarios

In Figure 12 shows the equivalent time of exposure to the designed temperature for the three considered profiles of temperature that can cause aging.

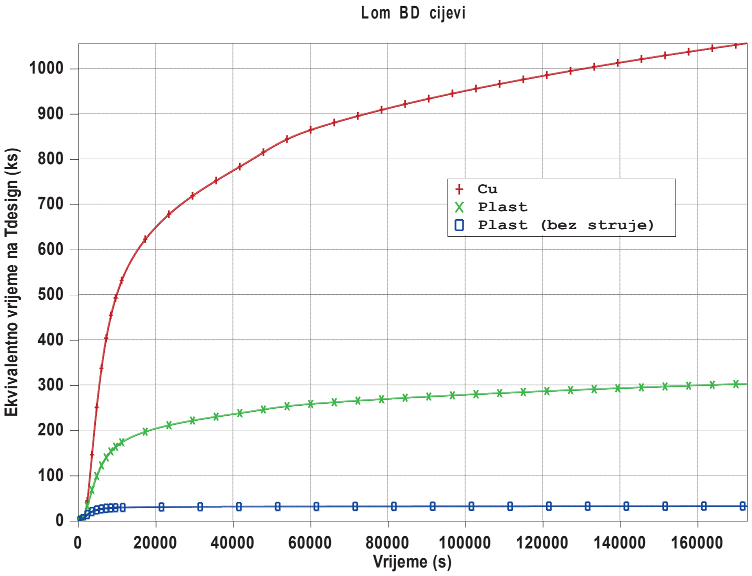

Figure 12 Equivalent time of exposure to cable temperature for different cases

Figure 13 shows shortening of cable lifetime compared to qualified life on designed temperature and Figure 14 presents data relatively, in percentage of qualified lifetime. Negative values correspond to extension of time and indications are that the cable is loaded less.

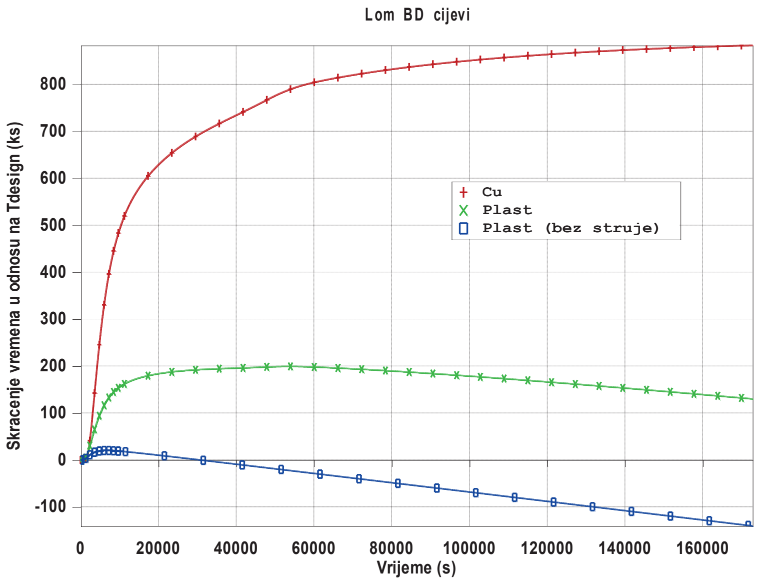

Figure 13 Lifespan changed due to increased cable temperature

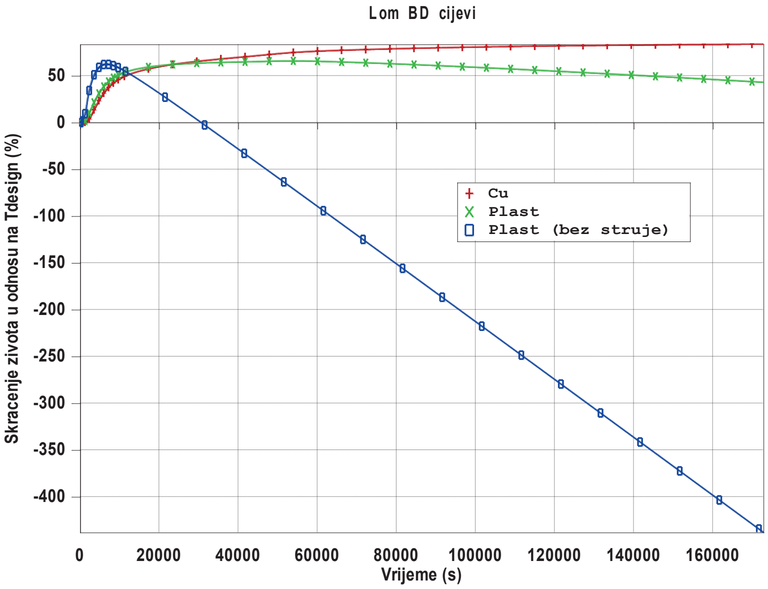

Figure 14 Lifespan changed due to increased cable temperature, relative

The meaning of the application is determination of the equivalent time of exposure to design temperature. The difference of the equivalent and real-time is the shortening of life span because the cable has spent more time on the design temperature than the actual length of exposure. In this case, cable was exposed to adverse environmental conditions for relatively short period of time.

If we were able to define the time dependence of the temperature of isolation from the moment of putting cable into operation until the present time, the described procedure could calculate the proper time spent on the design temperature. If obtained time subtract from qualified life, we would get the remaining time of the cable, on designed temperature.

7 CONCLUSION

Evaluation of cable aging is an important nuclear safety indicator and therefore, it is justified to analyse various potential events or situations that may reduce the lifespan of the energy cable.

Calculation described can be used to determine the local temperature in the steady state and the temperature rise during an unplanned event. Obtained results were input data for the estimation of effects on life expectancy using a simple model based on the Arrhenius equation. Scenarios for calculation were combination of events (normal operation and fracture of a BDS pipeline) for the different initial conditions of the cable (operating and non-operating cable).

The results show that the cable is functional for the entire projected life in all proposed combinations, except in the case of pipe fracture during operating cable. Given the role and function of the cable (cable supply safety pumps and is not expected to work in normal operation), respectively, cable load is very low, it can be concluded that it is not probable to lose the functionality of this cable. However, it should be checked if radiate heat exchange with BDS pipe can cause damage or reduce its effective life. Although the simplifications were introduced in the analysis and assumptions, it was not expected to have a significant impact on the final results.

From a security standpoint, it is useful to analyse possible hot spots and/or transient states with significant impact on worsening the environmental conditions.

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