UPRAVLJANJE ŽIVOTNIM VIJEKOM KABELA KAO DIO PROGRAMA PRODULJENJA ŽIVOTNOG VIJEKA NUKLEARNE ELEKTRANE

CABLE AGING MANAGEMENT AS PART OF THE EXTENDED NUCLEAR POWER PLANT LIFESPAN PROGRAMME

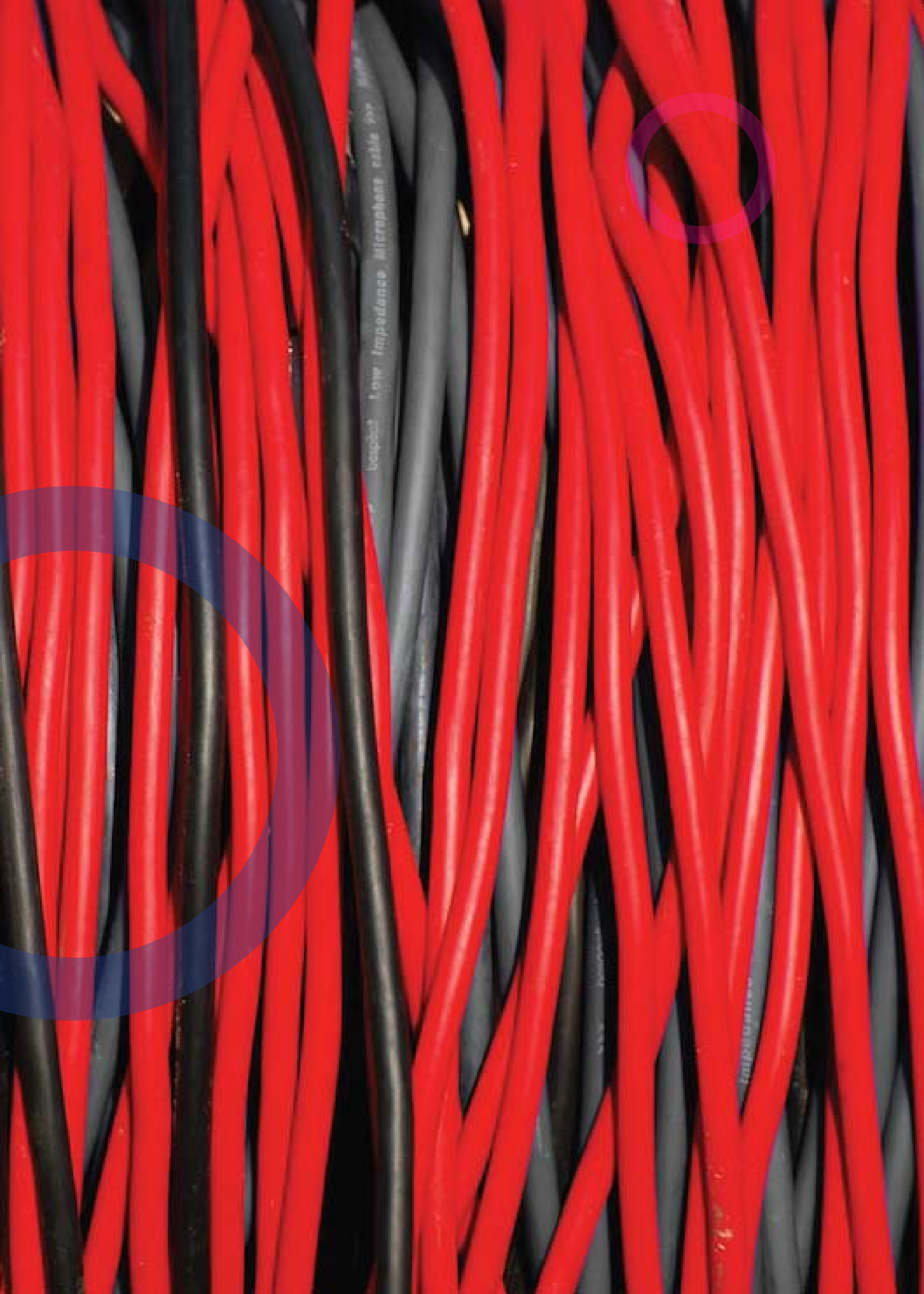
Nikola Čavlina – Irena Jakić – Renato Barbarić, Zagreb, Hrvatska
Bruno Glaser, Krško, Slovenija

Članak daje sveobuhvatan pregled procesa starenja kabela, od identifikacije mehanizama i procjene starenja te učinka na sigurnost nuklearnih elektrana do upravljanja samim procesom. Cilj je zaokružiti temu iz različitih perspektiva i dati informacije i zaključke utemeljene na iskustvu i pouzdanim rezultatima mjerenja.

The article provides a comprehensive overview of the cable aging process, from mechanism identification and aging assessment and the effect on nuclear power plants' safety to the management of the process itself. The objective is to round up the subject from different perspectives and provide information and conclusions based on experience and reliable measurement results.

Ključne riječi: kabeli; nuklearna elektrana; produljenje životnog vijeka; sigurnost nuklearnih elektrana; starenje kabela
Key words: cables; cable aging; extended lifespan; nuclear power plant; nuclear power plants' safety

https://doi.org/10.37798/2009583299


Low Impedance Microphone cable for

1 UVOD

U svijetu je, prema podacima Međunarodne agencije za atomsku energiju, početkom 2009. godine bilo u pogonu ukupno 436 nuklearnih reaktora. Najveći je broj tih reaktora započeo s radom u 1970-tim godinama i većina je imala projektom predviđeni životni vijek od 30 do 40 godina.

Te se elektrane približavaju kraju početno predviđenog životnog vijeka, a istodobno rade dobro i konkurentne su. Stoga postoji veliki interes za produljenjem njihovog vijeka eksploatacije. Razlozi su prvenstveno ekonomski jer su kapitalni troškovi za produljenje životnog vijeka tih elektrana neusporedivo manji od troškova izgradnje bilo kojih drugih zamjenskih kapaciteta.

Međutim, potrebno je utvrditi da li starenju izložene komponente, strukture i sustavi nuklearne elektrane mogu ispuniti svoje projektom predviđene funkcije i u slučaju produljenja vijeka eksploatacije. Starenje opreme se može definirati kao kontinuirana, vremenski ovisna degradacija materijala zbog uvjeta rada, kako u normalnom pogonu, tako i u tranzijentnim uvjetima.

Redundancija i diverzifikacija su principi projektiranja sigurnosnih sustava nuklearne elektrane, kojima se osigurava da i pri pojavi slučajnog kvara barem jedan sigurnosni sustav ispunjava projektom predviđenu funkciju. Bojazan je da se zbog starenja opreme u slučaju dodatnih opterećenja na opremu ne desi simultani kvar u kritičnom vremenu. Takav bi kvar, u kombinaciji starenja i akcidentalnih ambijentalnih uvjeta, imao obilježja kvara sa zajedničkim uzrokom (engl. *Common cause failure*) i mogao bi učiniti neraspoloživim sve redundantne sustave, a kad su u pitanju električni kabeli, ni diverzitet u izvedbi sigurnosnog sustava ne bi puno pomogao.

Programom upravljanja životnim vijekom (engl. *Aging management programme* – AMP) na odgovarajući se način upravlja učincima starenja sustava, struktura i komponenti nuklearne elektrane. Posebna se pažnja posvećuje onim sustavima i komponentama koji nisu predmet redovnog održavanja. Cilj je identificiranje mehanizama i učinaka starenja, te utvrditi jesu li degradacije uzrokovane starenjem unutar dopuštenih granica, kako bi se osigurao siguran rad elektrane za budući period.

Program AMP uobičajeno se radi u dvije faze. U prvoj se identificiraju sustavi, strukture i komponente koje podliježu programu AMP. U drugoj fazi se radi evaluacija prema uvjetima okoliša, svojstvima materijala i učincima starenja.

1 INTRODUCTION

According to the data of the International Atomic Energy Agency, at the beginning of 2009, there was a total of 436 nuclear reactors operating throughout the world. The majority of those reactors started operating in the 1970s and most of them were engineered for the lifespan of 30 to 40 years.

Those power plants are nearing their initially prescribed lifespan but operating well and competitively at the same time. Therefore, extensive interest exists for the extension of their exploitation lifespan. The reasons are primarily economic because capital costs for the extension of the lifespan of those power plants are far lower than the costs of construction of any other alternative capacities.

However, it should be ascertained whether the components, structures and power plants systems exposed to aging can meet their engineered functions even in case of extended exploitation lifespan. Equipment aging can be defined as continued, time-dependant material degradation due to operating conditions, both during normal operation and in intermittent conditions.

Redundancy and diversification are principles of engineering nuclear power plants' safety systems which ensure that even if an accidental fault occurs, at least one safety system will meet its engineered function. It is feared that, in case of additional equipment loading and due to equipment aging, a simultaneous fault in critical time might happen. Such fault, in case aging was combined with accidental environmental conditions, would be characterized as a Common Cause Failure and it might make all redundant systems unavailable. When it comes to power cables, diversity in the performance of the safety system would not be very helpful either.

The Aging Management Programme (AMP) serves to adequately manage the effects of aging of the nuclear power plant's systems, structures and components. Special attention is given to those systems and components which are not subject to regular maintenance. The aim is to identify the mechanisms and aging effects, and determine whether the degradations caused by aging are within the allowed limits in order to ensure safe power plant operation for the future period.

The AMP programme usually works in two phases. The first phase is to identify systems, structures and components which are subject to the AMP programme. In the second phase, evaluation is done according to environmental conditions, material properties and aging effects.

The article describes cable aging effects in the nuc-

U članku su opisani učinci starenja kabela u nuklearnoj elektrani uzrokovani prvenstveno povišenim temperaturama i ionizirajućim zračenjem. Kao primjer naveden je program AMP u nuklearnoj elektrani Krško.

lear power plant caused primarily by increased temperatures and ionising radiation. The AMP programme at the Krško nuclear power plant is stated as an example.

2 KLASIFIKACIJA KABELA

2.1 Kabeli u nuklearnim elektranama

Kabeli su vitalna komponenta nuklearnih elektrana (NE) jer osiguravaju napajanje električne opreme i povezuju dijelove sustava s mjernim instrumentima i opremom za nadgledanje i upravljanje pogonom elektrane. Najveći dio položenih električnih kabela može se grupirati prema općim kategorijama:

— srednjonaponski energetski kabeli,
— niskonaponski energetski kabeli,
— signalni i upravljački kabeli,
— instrumentacijski kabeli,
— telekomunikacijski kabeli,
— uzemljivački kabeli.

2 CABLE CLASSIFICATION

2.1 Cables in nuclear power plants

Cables are vital components of nuclear power plants because they ensure the supply of electrical equipment and link parts of the system with measurement instruments and the equipment for the supervision and management of the power plant drive. The majority of installed power cables can be grouped according to the general categories:

— middle-voltage power cables,
— low-voltage power cables,
— signal and control cables,
— instrumentation cables
— telecommunication cables,
— grounding cables.

Tablica 1 – Relativna distribucija strujnih krugova u NE
Table 1 - Relative distribution of circuitry at the nuclear power plant

Električni krug / Circuit	Procijenjeni broj strujnih krugova / Estimated number of circuits	Udio / Share, %
Instrumentacija / Instrumentation	1 0180	20
Upravljanje / Control	3 1500	61
AC napajanje / AC supply	6 580	13
DC napajanje / DC supply	530	1
Komunikacija / Communication	2 560	5
Ukupno / Total	5 1350	100

U tablici 1 prikazana je relativna distribucija strujnih krugova nuklearne elektrane. Kako se vidi iz tablice, najveći udio čine upravljački i instrumentacijski kabeli (80 %) koji su od presudne važnosti za sigurni rad elektrane, a čije se karakteristike preklapaju s karakteristikama niskonaponskih energetskih kabela. Općenito, razmatraju se niskonaponski (< 1 kV) kabeli opterećni malim strujama, s više vodiča i plaštem. Glavna komponenta kabela su vodiči, električka izolacija i plašt. Druge komponente mogu biti različite trake (dodatna električna i mehanička zaštita ili zaštita od požara te trake za grupiranje vodiča) ili različiti materijali za punjenje kojima se poboljšavaju mehanička svojstva kabela.

Pokazalo se da starenje kabela ovisi o starenju električne izolacije, stoga je predmet interesa osnovna električna izolacija. Plašt se ne smatra

Table 1 shows the relative distribution of circuitry at the nuclear power plant:as can be read from the Table, the largest share is made up of control and instrumentation cables (80 %) which are of crucial importance for the power plant's safe operation and which properties overlap with the properties of low-voltage power cables. Generally, low-voltage (< 1 kV) cables are loaded with small currents, with several conductors and a sheet. The main components of the cable are conductors, electrical isolation and the sheet. The other components can be various bands (additional electrical and mechanical protection or fire protection and bands for conductor grouping) or different stuffing materials which enhance cables' mechanical properties.

Cable aging appears to depend on the aging of electrical isolation, so the issue of interest is basic electrical isolation. The sheet is not considered predmetom programa upravljanja starenjem, jer se smatra da je on fizička zaštita osnovne izolacije, iako nam stanje plašta kabela zapravo može poslužiti kao indikator stanja osnovne izolacije. Tim više, jer je plašt kabela obično napravljen od materijala koji ima nešto slabija svojstva od osnovne izolacije, pa su na njemu prije vidljivi negativni utjecaji okoline (ako postoje). Izolacija i plašt napravljeni su od materijala koji se baziraju na polimerima s različitim dodacima kojima se poboljšavaju mehanička, električna svojstva te otpornost na gorenje/požar. Najčešće korišteni izolacijski materijali su engl. cross-linked polyethylene – XLPE (36 %), engl. Ethylene Propylene Based Elastomers – EPR/EPDM (36 %) i engl. *polyvinyl chloride*; polivinil klorid – PVC (najčešće u starijim elektranama). Za plašt se najčešće upotrebljava engl. *chlorosulphonated polyethylene* – CDSP (poznat i kao Hypalon®). Ostali izolacijski materijali koriste se značajno manje, često za posebne primjene koje zahtijevaju specifična svojstva (na primjer, engl. *polyether ether ketone* – PEEK; koristi se u uvjetima visoke radijacije). U novijim elektranama pokazuje se trend prelaska na materijale bez halogena zbog emisija u slučaju požara.

2.2 Kabeli obuhvaćeni programom upravljanja životnim vijekom AMP (engl. *Aging management programme*)

U nuklearnoj elektrani je instalirano mnogo različitih kabela s ukupnom dužinom koja prelazi 1 000 km. Zbog te količine, potrebno je kategorizirati prema važnosti kabele uključene u proces upravljanja starenjem, stoga se navode tri pristupa identifikacije i grupa važnosti kabela:

— uključiti sve kabele iz svih sustava. Ovo je najbrža metoda identifikacije, ali u fazi primjene dovodi do bespotrebnog korištenja resursa s obzirom da se većina kabela nalazi u takvim uvjetima koji neće dovesti do takvog starenja kabela da on izgubi svoju osnovnu funkciju. Također, nisu svi kabeli važni za sigurni rad elektrane,
— isključiti pojedine sustave iz opsega programa. U slučaju ove metode, isključe se neki sustavi za koje smo sigurni da nemaju opremu i kabele važne za siguran rad elektrane. Tako se odrede svi kabeli koji su važni za siguran rad, a imamo i dio kabela koji ne bi trebali biti na našem popisu, ali se zbog pojednostavljivanja u procesu identifikacije oni tu nalaze,
— potpuna identifikacija kabela važnih za siguran rad elektrane. Ovom metodom se dobije točan popis kabela koji su ugroženi, ali je identifikacija tih kabela dugotrajna i često nisu dostupni svi potrebni podaci za ovakav pristup.

the subject of the Aging Management Programme because it is considered to be the physical protection of the basic isolation although the condition of the cable sheet can actually serve as an indicator of the condition of the basic isolation. All the more so because the cable sheet is usually made of materials of somewhat weaker properties than the basic isolation so it will show negative environmental influences (if such exist) sooner. The isolation and the sheet is made of materials based on polymers with various additives which enhance the mechanical and electrical properties and the resistance to burning/fire. The isolation materials which are used most often are the cross-linked polyethylene - XLPE (36 %), Ethylene Propylene Based Elastomers – EPR/EPDM (36 %) and polyvinyl chloride - PVC (most often in old power plants). The sheet is usually made of chlorosulphonated polyethylene – CDSP (also known as Hypalon®). Other isolation materials are used much less, often for special applications which require specific properties (for example, polyether ether ketone - PEEK; used in high-radiation conditions). Newer power plants reveal the trend of transition to halogen-free materials because of the emissions in case of fire.

2.2 Cables encompassed by the Aging Management Programme (AMP)

Many different cables are installed at the nuclear power plant and their total length exceeds 1 000 km. Because of that quantity, the cables included in the aging management process should be categorized according to their significance and therefore three identification approaches and cable significance groups are stated:

— include all the cables from all the systems. This is the fastest identification method but, in the preparatory phase, it leads to an unnecessary exploitation of resources considering the fact that most of the cables are located in such conditions which will not lead to such cable aging that would make it lose its basic function. Moreover, not all cables are important for safe operation of a power plant,
— exclude certain systems from the programme scope. In case this method is used, certain systems which surely do not have the equipment and the cables necessary for the safe operation of the power plant are turned off. In such a way, all safe-related cables are determined and we have a part of the cables which should not be on our list but are so in order to simplify the identification process,
— full identification of cables important for safe operation of the power plant. This method yields an accurate list of endangered cables, but the identification of those cables is lasting and all data necessary for this approach are not always available.

Obično se koristi druga metoda jer je ekonomski najprihvatljivija i za identifikaciju i za kasniju primjenu programa.

Kabeli izloženi težim uvjetima okoliša (visoka temperatura i radijacija) stare brže. Takvi su uvjeti u reaktorskoj zgradi. Unutar reaktorske zgrade, neki kabeli imaju veću važnost u odnosu na druge. Nakon što se kabeli u reaktorskoj zgradi rangiraju prema kriteriju sigurnosti, potrebno je procijeniti težinu uvjeta okoliša. Treba napomenuti da kabeli koji se već nalaze na EQ (engl. *Equipment/Environmental Qualification* – EQ) listi (lista opreme koja je predmet procesa kvalifikacije za uvjete okoline kako to zahtjeva regulativa) ne ulaze u opseg programa starenja kabela. Za njih vrijede druga, stroža pravila, jer ti kabeli moraju do kraja životne dobi elektrane još izdržati i uvjete u slučaju akcidentalnog događaja (starenje je implicitno uključeno u EQ proces). Nakon toga, identificiraju se kabeli izvan reaktorske zgrade koji su izloženi teškim uvjetima okoliša i stoga ih je potrebno ocijeniti i pratiti njihovo stanje.

Za praćenje starenja kabela najvažnije je poznavanje uvjeta okoliša koji mogu ubrzati starenje (učinci na organske materijale koji se koriste kao izolacija). Dominantni faktori na starenje tijekom normalnog rada nuklearne elektrane su temperatura i doza zračenja (u nekim posebnim slučajevima, vlažnost ili kemijsko zagađenje mogu biti važni) stoga je korisno pratiti njihove vrijednosti unutar reaktorske zgrade. Ukoliko ti podaci nisu dostupni, mogu se koristiti podaci iz projektne dokumentacije.

Identifikacija kritičnih mjesta (engl. *hot spots*; mjerene vrijednosti temperature, radijacije, vlage, kemijskih uvjeta i /ili vibracija su značajno više nego prosječne vrijednosti šireg područja) je vrlo važna. Ti uvjeti će najvjerojatnije uzrokovati degradaciju kabela tijekom životnog vijeka elektrane.

Na slici 1 prikazan je proces identifikacije i dodjeljivanje prioriteta kabelima po fazama.

U svakoj fazi vrši se procjena kojom se smanjuje broj kabela čije se starenje ocjenjuje i prati.

U prvoj fazi identificira se tip strujnoj kruga/sustava kojem kabel pripada. Svi kabeli koji su važni za sigurnost ulaze u procjenu u sljedećoj fazi. Svim ostalim kabelima dodjeljuje se nizak prioritet za upravljanje starenjem. Može se, također, odlučiti da u drugu fazu uđu i određeni pomoćni kabeli važni za rad elektrane.

Druga faza identificira normalne pogonske uvjete (npr. temperatura, zračenje) kabela tijekom životnog vijeka elektrane, ne uključujući i uvjete akcidentnih događaja. Osim tih, identificiraju se i uvjeti

The second method is used more often because it is economically most acceptable both for the identification and subsequent application of the programme.

Cables exposed to more adverse environmental conditions (high temperature and radiation) age more quickly. Such are the conditions in the reactor building. Within the reactor building, some cables are more important than the others. After the cables in the reactor building are sorted according to the safety criteria, it is necessary to estimate the adverseness of the environmental conditions. It should be mentioned that the cables already found on the EQ Equipment/Environmental Qualification List (the list of equipment which is the object of the qualification process for the environmental conditions as required by the regulations) are not included in the scope of the cable aging programme. These are subject to other, stricter rules, because until the end of the power plant's lifespan, these cables still have to endure the conditions in case of accidental event as well (aging is implied in the EQ process). After that, cables outside the reactor building exposed to adverse environmental conditions are identified and therefore need to be evaluated and their condition monitored.

The monitoring of the cables primarily requires the awareness of the environmental conditions which might speed up the aging (effects on organic materials used as isolation). Dominant factors affecting aging during normal power plant operation are temperature and radiation dosage (in some special cases, moisture or chemical pollution might be important) so it is useful to monitor their values within the reactor building. If these data are not available, data from the project documentation can be used.

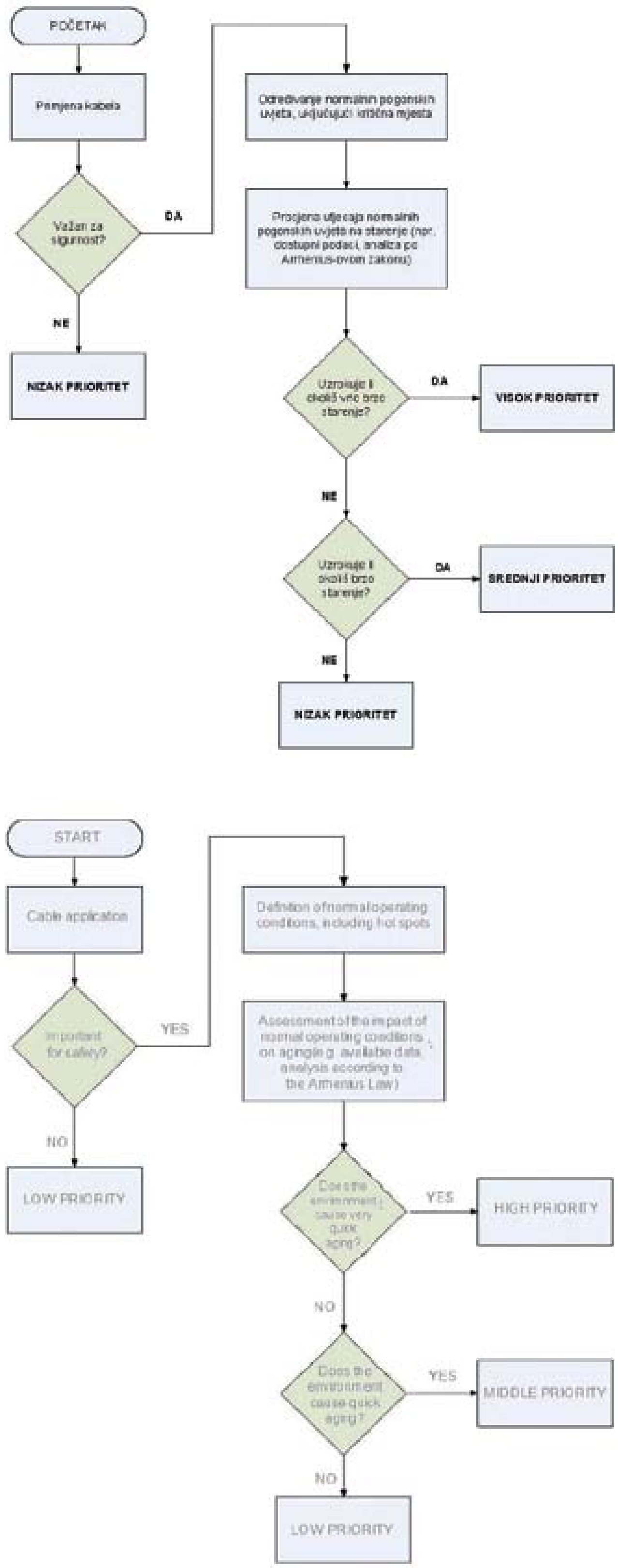
Identification of hot spots (measured values of temperature, radiation, moisture, chemical conditions and/or vibrations are significantly higher than average values of the wider area) is very important. Those conditions will most probably cause degradation of cables during the power plant's lifespan.

Figure 1 shows the process of identification and attribution of priorities to cables according to phases.

In each phase, assessment which reduces the number of cables the aging of which is being assessed and monitored is carried out.

In the first phase, the type of circuitry/system which the cable belongs to is identified. All the safety-related cables are included in the assessment in the next phase. All the other cables are attributed low priority in the aging management. It can also be decided for the second phase to include certain auxiliary cables necessary for the power plant's operation as well.

The second phase identifies normal cable operating conditions (e.g. temperature, radiation) during the



Slika 1 — Proces identifikacije kabela važnih za sigurnost
Figure 1 — Process of identification of safety-related cables

na kritičnim mjestima. Koriste se mjerene vrijednosti, a u slučaju da one nisu dostupne, koriste se podaci iz projektne dokumentacije.

Nakon što su identificirani pogonski uvjeti, u trećoj fazi procjenjuje se njihovo djelovanje na starenje kabela te se dodjeljuju prioriteti:

— **visok prioritet** – kabeli važni za sigurnost instalirani u prostorima čiji uvjeti okoliša mogu uzrokovati ozbiljno starenje tijekom životnog vijeka NE,
— **srednji prioritet** – kabeli važni za sigurnost instalirani u prostorima čiji uvjeti okoliša mogu uzrokovati umjereno starenje tijekom životnog vijeka NE,
— **nizak prioritet** – kabeli važni za sigurnost instalirani u prostorima čiji uvjeti okoliša mogu uzrokovati minorno starenje tijekom životnog vijeka NE.

Evaluacijski proces se može pročistiti i dopuniti novim informacijama. Ukoliko se, na primjer, praćenjem visokorizičnih kabela pokaže da je degradacija manja od očekivane, kabel se može spustiti u grupu niže rizične skupine. Isto tako, ukoliko novije istraživanje pokaže ozbiljniji utjecaj okoliša na starenje kabela, kabel se može smjestiti u grupu više rizičnih kabela.

Očekuje se podvrgavanje kabela iz grupe najvišeg prioriteta daljnjim aktivnostima iz procesa upravljanja starenjem kabela.

3 STARENJE KABELA

Starenje kabela je kemijski (kidanje i/ili umrežavanje polimerskih lanaca, oksidacija, difuzija kisika) ili fizikalni proces (isparavanje i/ili migracija plastifikatora) na molekularnoj razini materijala koji se očituje u nepovratnim promjenama u električkim i mehaničkim svojstvima materijala. Te promjene uključuju smanjenje elastičnosti, povećanje tvrdoće plašta i promjene u električkim svojstvima.

Starenje kabela ovisi o materijalu (sastavu polimera), skladištenju prije instalacije, normalnim pogonskim uvjetima i vremenu. Različite karakteristike okoliša (npr. temperatura, ionizirajuće zračenje, prisustvo kisika i vodene pare) i određeni mehanički uvjeti (npr. vibracije) mogu značajno utjecati na brzinu starenja. Među tim uzrocima starenja, najznačajniji su temperatura i zračenje.

Starenje kabela ovisno o temperaturi može biti opisano Arrheniusovim modelom. U Arrheniusovom modelu brzina reakcija R je opisana prema relaciji:

power plant's lifespan, not including accidental event conditions. Besides those, conditions in hot spots are also identified. Measured values are used, and, in case these are not available, data from the project documentation are used.

After the operative conditions have been defined, in the third phase, their effect on cable aging is assessed and priorities are attributed.

— **high priority** - safety-related cables installed in the spaces which environmental conditions can cause serious aging during the nuclear power plant's life span,
— **middle priority** - safety-related cables installed in the spaces which environmental conditions can cause moderate aging during the nuclear power plant's life span,
— **low priority** - safety-related cables installed in the spaces which environmental conditions can cause minor aging during the nuclear power plant's life span,

The evaluation process can be refined and supplemented with new information. If, for example, the monitoring of high-risk cables reveals that the degradation is lower than expected, the cable can be demoted to the low-risk group. Moreover, if recent research shows serious environmental impact on cable aging, the cable can be placed in the higher-risk cables group.

Subjecting the cables from the top priority group to further activities from the cable aging management process is expected to take place.

3 CABLE AGING

Cable aging is a chemical (breaking and/or networking of polymer chains, oxidation, oxygen diffusion) or physical process (evaporation and/or migration of the plasticizer) at the material's molecular level which is evidenced by irreversible changes in the material's electrical and mechanical properties. Those changes include reduced elasticity, increased sheet stiffness and changes in electrical properties.

Cable aging depends on the material (polymer composition), storage before installation, normal operating conditions and time. Various environmental properties (e.g. temperature, ionising radiation, presence of oxygen and water vapour) and certain mechanical conditions (e.g. vibrations) can significantly affect the aging rate. The most important among those aging agents are temperature and radiation.

Temperature-dependant cable aging can be described by virtue of the Arrhenius model. In the Arrhenius model, reaction rate R is described according to the relation:

$$R = C\,e^{\frac{-E_a}{kT}} ,\qquad (1)$$

gdje je:

C – konstanta,
k – konstanta,
E_a, J/mol – aktivacijska energija za proces,
T, K – apsolutna temperatura.

Promatrajući pokus ubrzanog termičkog starenja kroz širok temperaturni spektar, ponekad se pojavljuje točka loma koja se podudara s promjenom kinetičkog režima. Vrijednost aktivacijske energije nije konstantna u cijelom temperaturnom rasponu. U većini takvih primjera uočeno je da su vrijednosti E_a niže pri nižim temperaturama. U tim uvjetima, ekstrapolacija podataka dobivenih mjerenjem pri višim temperaturama može značajno podcijeniti starenje pri nižim temperaturama. Zato se preporuča da porast temperatura u pokusu ubrzanog starenja ne bude viši od 25 °C. Vrijednost aktivacijske energije važna je za rezultate, a za upute o primjeni Arrhenius-ovog zakona koristi se IEC 216 [2].

Za primjenu na ubrzanom termičkom starenju prikladan je ovaj oblik Arrheniusova modela:

where it is as follows:

C – constant,
k – constant,
E_a, J/mol – activation energy for the process,
T, K – absolute temperature.

In observing the experiment of accelerated thermal aging through a wide temperature spectre, sometimes a breakpoint occurs which coincides with the change of kinetic regime. The value of energy activation is not constant in the entire temperature range. In most of such cases, it has been noticed that the values E_a are lower at lower temperatures. In those conditions, extrapolation of data obtained by measurement at higher temperatures can significantly underestimate aging at lower temperatures. That is why it is recommended that increased temperature in the accelerated aging process does not exceed 25 °C. The value of activation energy is important for the results, and the IEC 216 [2] is used for the instructions on the application of the Arrhenius model.

This form of the Arrhenius model is suitable for application on accelerated thermal aging.

$$t_s \cdot t_a^{-1} = e^{E_a \cdot k^{-1} \cdot \left(T_s^{-1} - T_a^{-1}\right)} ,\qquad (1)$$

gdje je:

E_a, J/mol – aktivacijska energija,
k – Boltzmanova konstanta,
t_a – vrijeme ubrzanog starenja na temperaturi T_a,
t_s – vrijeme pogona koje se simulira na nekoj temperaturi T_s nakon kojeg se postiže degradacija.

Osim vanjskog utjecaja temperature, zagrijavanju izolacije kabela može pridonijeti i ohmsko zagrijavanje samog vodiča. Naravno, ovaj utjecaj se razmatra samo u slučaju energetskih kabela i to kod onih koji su opterećeni više od 80 % vremena.

where it is as follows:

E_a, J/mol – activation energy,
k – Boltzman constant,
t_a – accelerated aging time at the temperature T_a,
t_s – time of operation simulated at a certain temperature T_s after which degradation is achieved.

Besides the outer temperature impact, Ohm's heating of the cable itself can also contribute to the warming of the cable isolation. Of course, this impact is analysed only in case of power cables and that being those which are loaded more than 80 % of the time.

4 UPRAVLJANJE STARENJEM KABELA KROZ KVALIFIKACIJU ZA UVJETE OKOLIŠA

Upravljanje starenjem kabela osigurava njihovo ispravno funkcioniranje tijekom životnog vijeka

4 CABLE AGING MANAGEMENT THROUGH ENVIRONMENTAL QUALIFICATION TESTS

Cable aging management ensures their proper functioning during the life span of the nuclear power

NE. Kroz kvalifikaciju za uvjete okoliša garantira se ispravan rad kabela pod specifičnim uvjetima, kako u normalnim pogonskim uvjetima tako i u akcidentnim uvjetima.

Inicijalna kvalifikacija (engl. *type testing*) koristi se za utvrđivanje uvjeta okoliša novog kabela prije instalacije. Osnovni cilj inicijalne kvalifikacije je dokaz da je kabel kvalificiran za određene uvjete (normalne i abnormalne) i definira granice primjene. Također, definira kvalificiran životni vijek kabela. Alternativni pristup je uspostavljanje kvalificiranih uvjeta.

Kvalificirani životni vijek je vremenski period u kojem, pod normalnim uvjetima, starenje ne utječe negativno na rad (kabela, opreme) u kasnijim uvjetima eventualnih akcidentalnih događaja [2].

Kvalificirani uvjeti su uvjeti okoliša/pogona koji se izražavaju kroz mjerljive indikatore za koje je dokazano da ne utječu negativno na rad (kabela, opreme) [2].

Kvalifikacija za uvjete okoliša postiže se prikladnom kombinacijom inicijalne kvalifikacije, primjenom stečenih iskustava u sličnim primjenama te rezultatima analize (ekstrapolacija inženjerskih podataka i pogonskog iskustva).

Testovi za kvalifikaciju za uvjete okoliša uključuju funkcionalna ispitivanja, simulaciju ubrzanog starenja (uključujući procjenu dugotrajnog rada) i testiranje rada pri akcidentalnim i post-akcidentalnim uvjetima.

Termičko starenje kabela u nuklearnoj elektrani je uvijek prisutno u nekoj mjeri. Ubrzano termičko starenje postiže se izlaganjem kabela znatno višim temperaturama od onih kojima je izložen u normalnim pogonskim uvjetima (pretpostavlja se primjenjivost Arrheniusovog zakona).

Na određivanje kvalificiranog životnog vijeka utječe [2]:

- temperatura radnog okoliša – manja sigurnosna granica je potrebna ukoliko je temperatura okoliša kontrolirana,
- svojstva izolatorskog materijala – mjerenje aktivacijske energije u određenom temperaturnom intervalu,
- tolerancija testa,
- količina uzoraka.

Ubrzano radijacijsko starenje znači izlaganje kabela dozi zračenja koju bi skupio u cijelom očekivanom životnom vijeku (bez akcidentnih uvjeta) u kratkom vremenu. Ta doza je mnogo viša od radijacijske doze u normalnim pogonskim uvjetima i zapravo ne prikazuje realne uvjete. U literaturi [7]

plant. By virtue of environmental qualification testing, proper cable functioning is guaranteed under specific conditions, both in normal operating conditions and in accidental conditions.

Initial type testing is used for defining environmental conditions of the new cable before installation. The basic aim of the initial qualification is proving that the cable qualifies for certain conditions (normal and abnormal) and it defines application limits. Moreover, it defines the cable's qualified life span. Establishment of qualified conditions is the alternative approach.

Qualified life span is the temporal period in which, under normal conditions, aging does not negatively affect the operation (of cables, equipment) in subsequent conditions of possible accidental events [2].

Qualified conditions are environmental/operating conditions which are expressed through measurable indicators for which it has been proven that they negatively affect the operation (of cables, equipment) [2].

Environmental qualification is achieved by the right combination of initial qualification, application of acquired experiences in similar applications and analysis results (extrapolation of engineering data and operating experience).

Environmental qualification tests include functional testing, simulation of accelerated aging (including the estimate of lasting operation) and testing the operation in accidental and post-accidental conditions.
Thermal cable aging in the nuclear power plant is always present to a certain extent. Accelerated thermal aging is achieved by exposing the cable to significantly higher temperatures than those to which it is exposed in normal operating conditions (the applicability of the Arrhenius law is assumed).

The definition of qualified life span depends on [2]:

- working environment temperature – a lower safety limit is required if the environment temperature is controlled,
- isolation material properties – measuring the activation energy in a certain temperature interval,
- test tolerance,
- number of samples.

Accelerated radiation aging implies the cable's exposure to radiation dosages which it would normally collect throughout the entire expected life span (without accidental conditions) in a short period of time. That dosage is significantly higher than the radiation dosage in normal operating conditions and actually does not indicate realistic conditions. Literature [7] describes accelerated radiation aging and the results reveal that there is a cut-off value of the radiatiopisano je ubrzano radijacijsko starenje i rezultati pokazuju da postoji granična vrijednost radijacijske doze izloženosti ispod koje je utjecaj radijacije na starenje beznačajan i može se zanemariti. Također, rezultati su pokazali da je ta granična vrijednost viša nego se očekivalo.

Kao i u slučaju termičkog starenja, na rezultat utječu doza radijacije u normalnim pogonskim uvjetima, učinak radijacije na izolacijski materijal kabela, tolerancije testa i količina uzoraka.
Kabeli najčešće nisu izloženi uvjetima velike vlažnosti. Velika vlažnost ubrzava termičko starenje kabela jer hidroliza pridonosi degradaciji izolacijskog materijala (ova pojava se manifestira samo u slučaju srednjonaponskih kabela, dok je u slučaju niskonaponskih zanemariva).

Također, kabeli najčešće nisu izloženi značajnim vibracijama. Ukoliko jesu, mogu se pojaviti izuzetno male pukotine koje doprinose starenju. Ovdje treba napomenuti da su kabeli kojima se često manipulira (spajanje i odspajanje opreme za vrijeme remonta, kalibracije opreme) također vrlo podložni oštećenjima i ubrzanom starenju.

Za testiranje akcidentalnih uvjeta koriste se različiti predviđeni događaji (engl. *Design Basis Event* – DBE) koje obično karakteriziraju visoka doza radijacije praćena velikom količinom oslobođene topline. Najčešće se koristi LOCA (engl. *Loss of Coolant Accident*; akcident gubitka rashladnog sredstva) kao najgori scenarij.

Test se izvodi u dva koraka. Radijacijski test se odvija u uvjetima doza radijacije od 1 kGy/h i 10 kGy/h i temperatura značajno viših od temperatura normalnog pogona kako bi se uzelo u obzir zagrijavanje uzrokovano prolaskom struje (iako to zapravo nije relevantno za instrumentacijske kabele). Termodinamički test je projektiran prema posebnostima nuklearne elektrane i uključuje odnos temperature/tlaka pare kao funkciju vremena prema uvjetima predviđenih akcidentnim događajem. Ovo testiranje se vrši samo na EQ kabelima (engl. Eqipment/Enviromental/ Qualification EQ – kvalifikacija za uvjete okoline). Za ostale kabele pretpostavljaju se normalni radni uvjeti (akcidentni događaji ne spadaju u normalne radne uvjete).

Kvalifikacija uvjeta okoliša primarno identificira starenje kabela važnih za sigurnost. Dodatne aktivnosti (praćenje uvjeta okoliša, praćenje starenja kabela, dodatni testovi ubrzanog starenja kabela) služe za dokazivanje graničnih uvjeta primjene i potvrđivanje kvalificiranog životnog vijeka kabela. Održavanje (praćenje i upravljanje) uvjeta okoliša pridonosi kontroli starenja, točnijoj procjeni kvalificiranog životnog vijeka kabela, a time i općenito sigurnosti elektrana.

on exposure dosage under which the radiation effect on aging is insignificant and can be disregarded. Moreover, the results have shown that the cut-off value is higher than expected.

Just as in the case of thermal aging, the result also depends on the radiation dosage in normal operating conditions, radiation impact on the cable's isolation material, test tolerances and sample quantity.

Cables are usually not exposed to high-moisture conditions. High moisture speeds up the cable's thermal aging because the hydrolysis contributes to the degradation of the isolation material (this only occurs in case of middle-voltage cables, while it is insignificant in case of low-voltage cables).

Furthermore, cables most often are not exposed to significant levels of vibration. If they are, extremely small ruptures can appear which contribute to aging. It should be mentioned here that the cables which are manipulated often (connection and disconnection of the equipment during repair or equipment calibration) are also very prone to damages and accelerated aging.

Various Design Basis Events (DBE) are used for the testing of accidental conditions and these are often characterized by high dosage of radiation accompanied with high levels of released heat. The Loss of Coolant Accident (LOCA) is most often used as the worst-case scenario.

The test is performed in two steps. The radiation test takes place in the conditions of radiation dosage between 1 kGy/h and 10 kGy/h and temperatures significantly higher than normal operating temperatures so as to take into consideration the heating caused by passage of current (although that actually is not relevant for instrumentation cables). The thermodynamic test is designed according to the specificities of the nuclear power plant and it includes the relation temperature/vapour pressure as the function of time according to the conditions predicted by the accidental event. This testing is performed on EQ cables only. Eqipment/Enviromental/ Qualification EQ. Normal operating conditions are assumed for the other cables (accidental conditions do not fall under normal operating conditions).

Environmental qualification primarily identifies the aging of those cables which are important for safety. Additional activities (monitoring environmental conditions, monitoring cable aging, additional accelerated cable aging tests) are used to prove cut-off application conditions and confirm the cable's qualified life span. Maintenance (monitoring and management) of environmental conditions contributes to aging control, more accurate estimate of the cable's qualified life span, and thus generally to the safe operation of power plants.

5 PROGRAM AMP U NUKLEARNOJ ELEKTRANI KRŠKO

Kao dio programa PSR (engl. *Periodic Safety Review*; redovno izvješće o sigurnosti) u nuklearnoj elektrani Krško je rađen program AMP. AMP je program koji osigurava praćenje starenja sve pasivne opreme za koju nije predviđena preventivna zamjena ili nije definirana kvalificirana životna dob. Program se provodi u skladu s GALL programom (engl. *Generic Aging Lessons Learned*) [11] američke nuklearne regulatorne agencije (engl. *Nuclear Regulatory Commission* – NRC). U NEK-u je, u sklopu priprema za dobivanje dozvola za produljenje životnog vijeka elektrane, početkom 2009. godine završen AMP. Cilj AMP-a je na sustavan način analizirati učinke i utjecaje starenja. Potrebno je zaključiti da li se degradacije izazvane učincima starenja u elektrani kontroliraju na način da je granica sigurnosti sačuvana.

Program AMP, nakon što se uvede, trajno se održava i služi kao osnova za moguće produljenje životnog vijeka nuklearne elektrane. Regulatorna osnova je US NRC 10CFR Part 54 – Requirements for Renewal of Operating licenses for Nuclear Power Plant.

U sklopu programa provedena je analiza tipova kabela, materijala od kojih je izrađena kabelska izolacija, te uvjeta okoline (temperatura, zračenje, vlaga) u kojima se kabeli nalaze. Zaključeno je da je stanje kabela na vrlo zadovoljavajućoj razini. Najvažniji razlog, zaslužan za to, jest činjenica da po tehničkim specifikacijama za kabele bitne za sigurnost (engl. Safety Related – SR), materijali izolacije smiju biti samo EPR ili XLPE ili materijali koji imaju bolja svojstva od njih. Osim ovih materijala, pronađeni su još i HTK (engl. High Temperature Kerite, koji je ustvari proizvođačko ime za EPR) i Teflon (za uvjete visokih temperatura). Vidljivo je da nisu korišteni PVC kabeli s kojima starije nuklearne elektrane imaju problema, jer su parametri za 60-godišnji vijek trajanja kabela puno lošiji nego za materijale koji su korišteni u NEK. Još je pronađen i CSPE, ali on je korišten samo kao plašt. CSPE ima nešto lošije granične parametre od osnovne izolacije koja je korištena. Ova činjenica je ustvari i povoljna, kao što je već napomenuto, jer običnom vizualnom inspekcijom može se provjeriti stanje kabela i, ako je plašt u dobrom stanju, znači da je i osnovna izolacija uredu. Naravno, neispravnost plašta je indikator za dodatne testove osnovne izolacije.

Za lakšu procjenu stanja kabela postoje tablice s graničnim vrijednostima temperature i zrače-

5 AMP PROGRAMME AT THE KRŠKO NUCLEAR POWER PLANT

As part of the PSR (Periodic Safety Review) Programme, the AMP programme was undertaken at the Krško nuclear power plant. AMP is a programme which ensures aging monitoring of all the passive equipment for which preventive alternative has not been planned or for which the qualified lifespan has not been defined. The programme is being managed in compliance with the GALL (Generic Aging Lessons Learned) programme [11] of the American Nuclear Regulatory Commission (NRC). Within the scope of the preparations for obtaining permits for extending the power plant's lifespan, at the beginning of 2009, the AMP was completed. The objective of the AMP is to systematically analyse the effects and impacts of aging. The conclusion should be drawn whether the degradations caused by aging effects are controlled at the power plant in such a manner that the safety limit remains preserved.

The AMP programme, after being implemented, is permanently maintained and serves as a basis for possible extension of the nuclear power plant's life span. The regulatory basis is US NRC 10CFR Part 54 – Requirements for Renewal of Operating Licenses for Nuclear Power Plants.

Analysis of cable types, materials from which cable isolation was made and environmental conditions (temperature, radiation, moisture) in which cables are located was carried out within the programme. The conclusion was made that cable condition was at a very satisfactory level. The most important reason responsible for this is the fact that, according to technical specifications for safety related (SR) cables, isolation materials must only be EPR or XLPE or materials with better propertiesBesides the new materials, High Temperature Kerite (HTK), which is actually the production name for EPR and Teflon (for high temperature conditions) were found as wellPVC cables, which create problems for older nuclear power plants, evidently were not used because the parameters for the 60-year life span are much worse than for the materials which are used in the nuclear power plant. CSPE was also found but it was only used as the sheet. CSPE has somewhat lower cut-off parameters than the basic isolation which was used. As already mentioned, this fact is actually favourable as well because regular visual inspection can provide information on the cable condition and, if the sheet is in good condition, it also means that the isolation is good. Of course, sheet faultiness is an indicator for additional tests of the basic isolation.

For easier assessment of the cable's condition, tables exist which include cut-off values of temperature and nja za 60-godišnji vijek trajanja kabela iz kojih se može brzo procijeniti (ako znamo materijal i uvjete okoline u kojem se nalazi) stanje kabela. Npr. za XLPE kabel maksimalna konstantna temperatura pri kojoj izolacija traje 60 godina je 86,6 °C, a zračenje $1x10^6$ Gy, za EPR/EDP kabele temperatura je 75,0 °C i zračenje $5x10^5$ Gy, za HTK – N98 kabel 85,2 °C i $1x10^6$ Gy, FEP (engl. *Florinated ethylene propylene*, teflon) 34,17 °C i $5x10^2$ Gy, CSPE kabel 75,0 °C i $2x10^4$ Gy i za PVC kabele vrijednosti temperature i radijacije su 44,2 °C i $2x10^5$ Gy.

Naravno da su rijetki prostori s konstantnom temperaturom (postoji barem razlika u temperaturi zbog godišnjih doba) pa je potrebno i to uzeti u obzir, ako se kabeli nalaze u uvjetima blizu graničnih vrijednosti. Za kvalitetnu procjenu uvjeta potrebno je pratiti parametre okoline barem godinu dana i onda se može odrediti neka srednja vrijednost tih parametara.

6 METODE PRAĆENJA STARENJA KABELA

Praćenje starenja kabela su aktivnosti koje daju informacije o indikatorima koji predstavljaju razinu degradacije. Primjer indikatora su:

— električki indikatori (otpor izolacije, rasipna struja zbog nesavršenosti izolacije (engl. *leakage current*), gubici, pad napona itd.) – nije reprezentativan indikator starenja,
— kemijska svojstva – jer starenje izravno utječe na molekularnu strukturu izolacijskog materijala, pojedina svojstava materijala izravni su indikatori razine starenja,
— mehanička svojstva – prekidna elastičnost je prihvaćeni indikator starenja, tvrdoća i svojstva tlačnih modula su također prihvaćeni indikatori starenja nekih izolacijskih materijala,
— vizualni indikatori – promjena boje (blijeđenje boje ili tamnjenje), ispucanost površine, promjene u dimenzijama su često indikatori promjene svojstava određenih materijala uslijed starenja; mogu se koristiti samo kao početni indikator koji inicira druge, pouzdanije testove.

Različite metode su do sada razvijene i testirane, ali još ima prostora za razvoj novih. Većina tih metoda daje rezultate za točno određenu točku/poziciju kabela i ne daje podatke o graničnim područjima. Mjerenja u intervalima duž kabela daju općeniti trend i ne identificiraju kritična mjesta. Isto tako, većina metoda ograničena je na plašt kabela i svojstva izolacije mogu se testirati samo na krajevima ili priključnim kutijama (ukoliko se ne mogu skupiti uzorci).

radiation for 60-year cable lifespan and from these tables the cable's condition can easily be assessed (if we know the material and its environmental conditions). For example, the maximum constant temperature, for the XLPE cable, at which the isolation endures 60 years, is 86,6 °C, and radiation $1x10^6$ Gy, for the EPR/EDP cables, the temperature is 75,0 °C and radiation is $5x10^5$ Gy, for the HTK - N98 cable it is 85,2 °C and $1x10^6$ Gy, for the FEP (Fluorinated ethylene propylene, Teflon) 34,17 °C and $5x10^2$ Gy, for the CSPE cable 75,0 °C and $2x10^4$ Gy and for the PVC cables, temperature and radiation values are 44,2 °C and $2x10^5$ Gy.

Areas with constant temperatures are, of course, rare (temperature varies at least depending on the season) so that needs to be taken into account as well if the cables are located in conditions near cut-off values. In order for the conditions to be well assessed, parameters need to be monitored for at least a year and then some mean value of those parameters can be determined.

6 CABLE AGING MONITORING METHODS

Monitoring cable aging is an activity which yields information on the indicators which represent the level of degradation. Examples of indicators are:

— electrical indicators (isolation resistance, leakage current due to the imperfections of the isolation, losses, reduced voltage, etc.) – not a representative indicator of aging,
— chemical properties – because aging directly impacts the molecular structure of the isolation material, certain material properties are direct indicators of the aging level,
— mechanical properties – elasticity modulus is an accepted aging indicator; hardness and properties of pressure module are also accepted aging indicators for some isolation materials,
— visual indicators – change of colour (colour fading or darkening), cracked surface and change of dimensions are often indicators of changed properties of certain materials due to aging; these can only be used as initial indicators which initialize other, more reliable tests.

Various methods have been developed and tested so far, but there is still space for development of new methods. Most of those methods yield results for the exactly determined cable spot/position and do not yield data on cut-off areas. Measurements in intervals along the cable yield a general trend and do not identify hot spots. Moreover, most of the methods are limited to the cable sheet and isolation properties can be tested only at the ends or terminal boxes (if samples cannot be collected).

Trenutačno najraširenije metode su mjerenje dubine otiska (engl. *Indenter Modulus – IM metoda*), mjerenje produljenja pri prekidanju (engl. *Elongation at Break* – EAB metoda) i termička analiza mikro uzoraka mjerenjem vremena (engl. *Oxidation Induction Time* – OIT) ili temperature (engl. *Oxidation Induction Temperature* – OITP) potrebnih za induciranje oksidacije. Novija LIRA (engl. *Line Resonance Analysis*) metoda daje dobre rezultate za identificiranje kritičnih mjesta. Druge poznate metode su termo-gravimetrijska analiza (TGA) koja mjeri gubitak težine uzorka pri zagrijavanju, mjerenja torzionog momenta (mjeri se krutost materijala) i mjerenja gustoće. U istraživačkim laboratorijima su testirane i neke druge metode (engl. *Fourier Transform Infrared Spectoscopy* – FTIR, foto-akustična spektroskopija, kemijska luminiscencija) koje se značajnije ne primjenjuju.

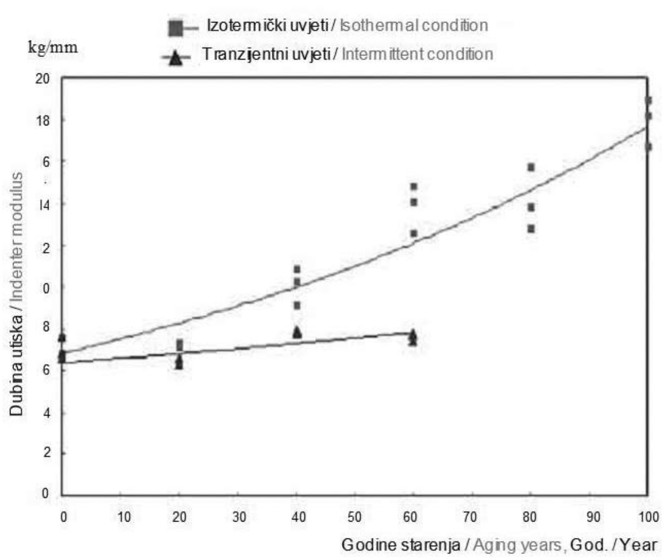
6.1 Mjerenje dubine otiska

Mjerenje dubine otiska je dobar pokazatelj starenja kabela; pokazuje kompresivnost (stlačivost) materijala pod kontroliranim uvjetima. Sonda se utiskuje u površinu materijala i mjeri se krivulja pomaka. Nagib krivulje se uzima kao vrijednost IM (engl. *Indenter Measurements*) modula. Izmjerene vrijednosti ovise o parametrima testa (brzini i sili utiskivanja sonde, temperaturi), stoga za usporedbu rezultata treba još navesti proceduru kalibriranja. Metoda pokazuje dobru korelaciju izmjerenih vrijednosti IM modula i starenja kabela.
Rezultati mjerenja IM modula opisanih u literaturi [8] prikazani su na slici 2.

Currently, the most wide-spread methods are the indenter modulus (IM) measurement method, elongation at break (EAB) measurement method and the thermal analysis of micro samples by measuring oxidation induction time (OIT) or the oxidation induction temperature (OITP). The more recent LIRA Line Resonance Analysis method, yields good results in the identification of hot spots. Other familiar methods are thermo-gravimetric analysis (TGA) which measures the sample's weight loss at warming, measurements of torque (material rigidity is measured) and measurements of density. Some other methods have also been tested in research laboratories (Fourier Transform Infrared Spectroscopy – FTIR, photo-acoustic spectroscopy, chemical luminescence) which are not applied to a significant extent.

6.1 Indenter measurement

Indenter measurement is a good indicator of cable aging; it shows material compressibility under controlled conditions. The probe is pressed into the material surface and the shift curve is measured. The curve pitch is taken as the value of the indenter measurements modulus. Measured values depend on test parameters (speed or probe impressing force, temperature), therefore, the comparison of results also requires the calibration procedure. The method shows good correlation of the measured values of the IM modulus and cable aging.
Results of the IM modulus measurement described in literature [8] are shown in Figure 2.



Slika 2 — Rezultati mjerenja IM modula
Figure 2 — Results of the IM modulus measurement

Za potrebe pokusa, simulirano je ubrzano starenje kabela zagrijavanjem. U jednom slučaju, zagrijavanje na 130 °C je kontinuirano, u drugom se periodi zagrijavanja na 130 °C izmjenjuju s periodima u kojima je temperatura 80 °C. Obje krivulje kontinuirano rastu, nema kritičnih i/ili prekidnih točaka. Nagibi krivulja su različiti (različita brzina starenja), stoga kontinuirano zagrijavanje u periodu od 60 godina daje dvostruko veće vrijednosti nego u slučaju kada se periodi zagrijavanja izmjenjuju.

Zaključak je da uzimajući u obzir redovne remonte (koji se odvijaju svakih 12 ili 18 mjeseci) kada nema opterećenja na kabel, postoji mogućnost oporavka materijala te se životni vijek nuklearne elektrane može produžiti na 60 godina.

6.2 EAB metoda

EAB metoda, odnosno mjerenje prekidne elastičnosti, smatra se pouzdanom metodom za procjenu starenja kabela. Vrijednost od 50 % apsolutne vrijednosti produljenja pri prekidu se činio kao granična vrijednost kvalificiranog životnog vijeka materijala. Kasnije studije su pokazale da rezultati nekih materijala (većinom kod PVC) znatno odstupaju, stoga IEC standard 544 preporuča 50 % početne vrijednosti kao graničnu vrijednost kriterija. Također, preporuča se korištenje dostupnih informacija o određenom materijalu za definiranje kriterija (50 % apsolutne ili 50 % relativne vrijednosti).

Rezultati mjerenja EAB metode opisanih u literatu-

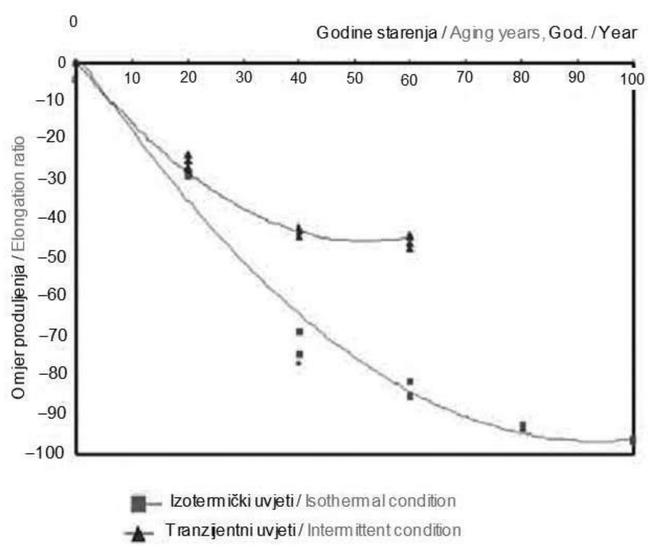
For the purpose of experiment, accelerated cable aging has been simulated by warming. In one case, warming to 130 °C was continuous and in the other, warming to 130 °C alternated with periods in which temperature was 80 °C. Both curves have been rising continuously, there were no hot spots and/or cut-off points. Curve pitches are different (different aging rate) so continuous warming in a 60-year period yields a value twice as high as in the case of intermittent warming periods.

The conclusions is that, taking into consideration regular repairs (which take place every 12 or 18 months) when the cable is not loaded, there is possibility of material recovery and the nuclear power plant's lifespan can be extended to 60 years.

6.2 EAB Method

The EAB method, that is, elasticity modulus measurement, is considered to be a reliable method for the estimate of cable aging. Value of 50 % of the absolute value of elongation at break seemed as the cut-off value of the material's qualified lifespan. Later studies showed that the results of some materials (mostly with PVC) deviate significantly, so the IEC standard recommends 50 % of initial value as the cut-off criteria value. Moreover, it is recommended to use available information on a certain material for the definition of criteria (50 % absolute or 50 % relative value).

Measurement results of the EAB method described in literature [8] are shown in Figure 3. In case of con-



Slika 3 — Rezultati EAB metode za kontinuirane i periodične uvjete starenja
Figure 3 — EAB method results for continued and periodic aging conditions

ri [8] prikazani su na slici 3. U slučaju kontinuiranog zagrijavanja, može se vidjeti brzo propadanje u prvih 40 godina; granična vrijednost od 50 % postiže se u 30-im godinama. Za slučaj izmjena u zagrijavanju, krivulja je nešto blaža i granična vrijednost dostignuta je u 60-oj godini. Zaključak je da, isto kao i za metodu mjerenja dubine utiska, životni vijek nuklearne elektrane se može produžiti na 60 godina uzimajući u obzir realne uvjete starenja (remont).

6.3 OIT/OITP metoda

Termička analiza mikro uzoraka mjerenjem vremena ili temperature potrebnih za induciranje oksidacije mjeri razinu anti-oksidansa u materijalu koji su dobri indikatori starenja materijala. Za uspoređivanje rezultata OIT metode, potrebno je definirati formu i veličinu uzorka, količinu kisika kojem je uzorak izložen, vrijeme stabilizacije dušika prije prihvaćanja kisika, tip i kalibraciju ispitne opreme, temperaturnu krivulju do postizanja temperature oksidacije, metodu određivanja početne vrijednosti oksidacije. Za OITP metodu potrebno je sve navedeno uz malu izmjenu; umjesto informacije o temperaturnoj krivulji do postizanja temperature oksidacije potrebno je definirati početnu temperaturu i nagib krivulje po kojoj temperatura raste.

7 UPRAVLJANJE ŽIVOTNIM VIJEKOM KABELA

Kabeli su izvor potencijalnih rizika za siguran rad NE. Proaktivnim upravljanjem starenja kabela osigurava se praćenje i kontrola funkcioniranja kabela kroz životni vijek elektrane. S obzirom da održavanje kabela nije planirano, sustavni pristup upravljanja životnim vijekom kabela postaje vrlo važno i donosi nekoliko dobrobiti: potvrđuje funkcionalnost opreme u svim pogonskim uvjetima (uključujuću i akcidentne događaje), osigurava projektiran životni vijek postrojenja i dostavlja podatke potrebne za odluku o produženju životnog vijeka, odnosno za obnavljanje licence za rad. Na slici 4 shematski je prikazan proces upravljanja životnim vijekom kabela, ali isti pristup primjenjuje se i za ostalu opremu važnu za sigurni rad nuklearne elektrane.

Proces upravljanja životnim vijekom kabela sastoji se od pet faza:

1. razumijevanje mehanizama starenja kabela,
2. koordinacija aktivnostima u procesu upravljanja,
3. aktivnosti upravljanja procesom starenja instaliranog kabela,

tinuous warming, quick deterioration is visible in the first 40 years; cut-off value of 50 % is achieved in the 30ies. In case of intermittent warming, the curve is somewhat milder and the cut-off value is achieved in the 60th year. The conclusion is that, just as with the method of indenter measurement, the nuclear power plant's lifespan can be extended to 60 years taking into consideration realistic aging conditions (repair).

6.3 OIT/OITP method

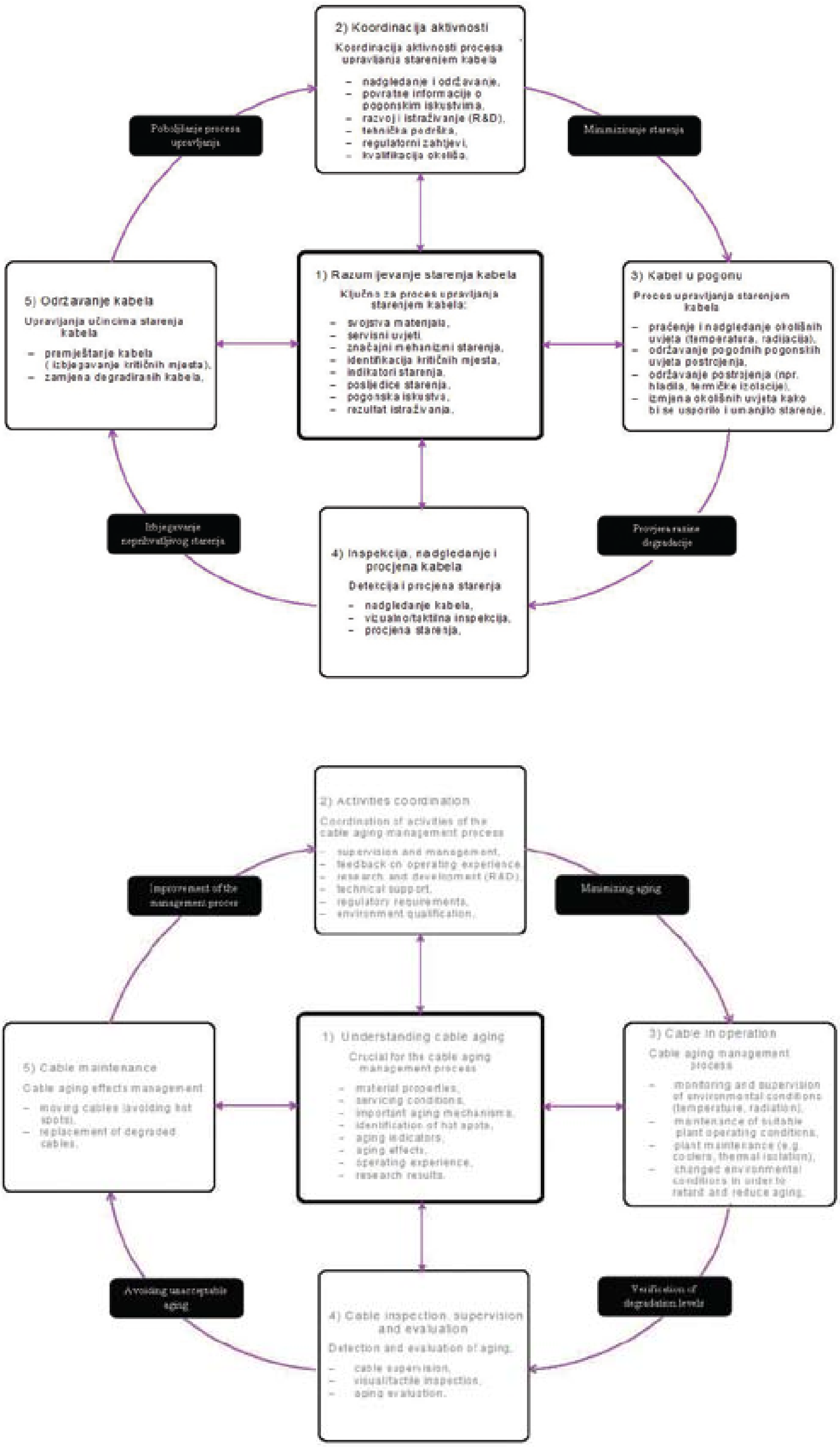
Thermal analysis of micro samples by measuring time or temperature necessary for oxidation induction measures the level of anti-oxidants in the material which are good indicators of material aging. For the purpose of comparison of the OIT method results, it is necessary to define the form and size of the sample, the volume of oxygen to which the sample is exposed, nitrogen stabilizing time before oxygen acceptance, type and calibration of the test equipment temperature curve up to the achievement of the oxidation temperature and the method of determination of the oxidation initial value. The OITP method requires all of the above with a small modification; in place of the information on the temperature curve up to the achievement of the oxidation temperature, it is necessary to define the initial temperature and curve pitch along which the temperature rises.

7 CABLE LIFESPAN MANAGEMENT

Cables are a source of potential risks for the safe operation of a nuclear power plant. Proactive management of cable aging provides for monitoring and controlling the functioning of cables throughout the power plant's lifespan. Considering the fact that cable maintenance was not planned, systematic approach to cable's lifespan management becomes very important and yields several advantages: confirmation of the functionality of the equipment in all operating conditions (including accidental events), ensuring the plant's engineered lifespan and provision of data necessary for the decision on extended lifespan, that is, for the renewal of the operating permit. Figure 4 schematically depicts the process of the cable's lifespan management, but the same approach is also applied to other safety-related equipment at the nuclear power plant.

Cable lifespan management process consists of five phases:

1. understanding cable aging mechanisms,
2. coordination of activities in the management process,
3. activities of installed cable aging management process,



Slika 4 — Shematski prikaz procesa upravljanja životnim vijekom kabela
Figure 4 — Schematic overview of the cable's lifespan management process

4. inspekcija, nadgledanje i procjena kabela,
5. održavanje.

Ključno za proces upravljanja je poznavanje mehanizama i razumijevanje procesa starenja. Nužno je poznavanje svojstava materijala, pogonskih uvjeta, postojanje kritičnih točaka, mehanizama starenja, prikladnih indikatora starenja i drugih podataka važnih za procjenu starenja. Podaci su većinom dobiveni iz projektne dokumentacije (na primjer, tehnička specifikacija kabela), rezultata nadzora, općeg pogonskog iskustva i rezultata istraživanja. Podaci bi se trebali povremeno osvježavati kako bi se omogućilo kontinuirano poboljšanje procesa upravljanja životnim vijekom kabela.

Programi upravljanja uključuju kvalifikaciju za uvjete okoliša, programe nadgledanja i održavanja pogona, povratne informacije o pogonskim iskustvima, istraživanje i razvoj te programe tehničke podrške. Iskustvo pokazuje da se učinkovitost procesa upravljanja povećava koordinacijom aktivnosti i sustavnim pristupom.
Koordinacija aktivnosti uključuje:

— dokumentaciju:
    · propisane regulativne zahtjeve i kriterije sigurnosti,
    · odgovarajuće programe i aktivnosti,
— opis mehanizama korištenih za koordinaciju i poboljšanje procesa upravljanja,
— koordinaciju prikladnih programa i aktivnosti,
— kontinuiran rad na poboljšanju.

Pogonski uvjeti značajno utječu na brzinu propadanja komponenti instaliranih u NE. Izlaganje kabela određenim uvjetima okoliša (temperatura, radijacija) može uzrokovati ubrzano starenje. Dakle, nadgledanjem i upravljanjem karakteristikama okoliša tijekom normalnog pogona značajno se može pridonijeti čuvanju opreme od ubrzanog starenja. To se postiže održavanjem određenih vrijednosti unutar pogonskih ograničenja.

Inspekcija, nadgledanje i procjena daju informaciju o postojanju i razini degradacije kabela prije kraja životnog vijeka na temelju kojih se, uz informacije iz prethodnih faza, donosi odluka o potencijalnoj zamjeni kabela.

8 ZAKLJUČAK

Produljenje životnog vijeka nuklearnih elektrana aktualna je tema nuklearne energetike pa su u okviru toga procjene starenja i upravljanje životnim vijekom komponenata važnih za sigurnost osobito značajne.

4. cable inspection, supervision and evaluation,
5. maintenance.

What is crucial for the management process is being acquainted with the mechanisms and understanding the aging process. It is necessary to be aware of material properties, operating conditions, of the existence of hot spots, aging mechanisms, suitable aging indicators and other data necessary for the evaluation of aging. Data have mostly been obtained from project documentation (for example, the cables' technical specifications), supervision results, general operating experience and research results. Data should be refreshed periodically in order to enable continued improvement of the cable lifespan management.

Management programmes include environmental qualification, plant supervision and maintenance programmes, feedback on operating experience, research and development and technical supervision programmes. Experience shows that the efficiency of the management process increases with the coordination of activities and systematic approach.
The coordination of activities includes:

— documentation:
    · prescribed regulatory requirements and safety criteria,
    · adequate programmes and activities,
— description of mechanisms used for coordination and improvement of the management process,
— coordination of adequate programmes and activities,
— continuous effort to improve.

Operating conditions significantly impact the speed of degradation of the components installed in the nuclear power plant. Exposing cables to certain environmental conditions (temperature, radiation) can cause accelerated aging. Therefore, the supervision and management of environmental conditions during normal operation can contribute significantly to the preservation of the equipment from accelerated aging. That is achieved by maintaining certain values within operating limits.

Inspection, supervision and evaluation provide information on the existence and level of degradation of the cable before the end of the lifespan based on which, with the information from the previous phases, decision is adopted on potential cable replacement.

8 CONCLUSION

Extension of nuclear power plant's lifespan is a current issue of the nuclear energy industry and for this reason evaluation of aging and the management of safety-related components' lifespan are extremely significant.

Iz perspektive sigurnosti, degradacija sustava, struktura i komponenti mora biti ispod kritičnih vrijednosti, u normalnim i abnormalnim pogonskim uvjetima. S obzirom da kabeli imaju dug životni vijek (40 godina), starenje kabela se nije razmatralo u kontekstu održavanja nuklearne elektrane. Međutim, radi produljenja životnog vijeka nuklearne elektrane, potrebno je utvrditi je li životni vijek kabela duži od projektom predviđenog.

Opisani su mehanizmi i učinci starenja kabela, prikazane su metode kojima se procjenjuje stupanj degradacije. Uočena je vrijednost procesa upravljanja starenjem kabela. Također, naglašena je važnost praćenja uvjeta okoliša za preciznu procjenu životnog vijeka kabela.

From the perspective of safety, degradation of systems, structure and components must be under critical values, in normal and abnormal operating conditions. Since the lifespan of cables is long (40 years), cable aging was not observed in the context of nuclear power plant management. However, for the purpose of extension of the nuclear power plant's lifespan, it is necessary to determine whether the cable's lifespan is longer than the engineered.

Mechanisms and cable aging effects were described, methods by which the degradation level are evaluated were shown. Importance of the cable aging management process has been noted. Moreover, the importance of supervision of the environmental conditions for the evaluation of the cable lifespan is stressed.

LITERATURA / REFERENCES

[1] Management of Ageing of I&C Equipment in Nuclear Power Plants, IAEA-TECDOC-1147, Vienna, 2000

[2] Assessment and Management of Ageing of Major Nuclear Power Plant Components Important to Safety: In-containment Instrumentation and Control Cables, volume I & II, IAEA-TECDOC-1188, Vienna, 2000

[3] Management of Life Cycle and Ageing at Nuclear Power Plants: Improved I&C Maintenance, IAEA-TECDOC-1402, Vienna, 2004

[4] Ageing Management for Nuclear Power Plants, IAEA Safety Guide, NS-G-2.12 Vienna, 2009

[5] ANUP K. BAHERA, CHARLES E. BECK, AIHAM ALSAMMARAE, Cable Aging Phenomena under Accelerated Aging Condition, IEEE, 1996

[6] JONG-SEOG KIM, Evaluation of Cable Aging degradation Based on Plant Operating Condition, Atomic Energy Society of Japan, Tokyo, 2005

[7] PAOLO F. FANTONI, GARY J. TOMAN, Wire System Aging Assessment and Condition Monitoring Using Line Resonance Analysis (LIRA), NPIC&HMIT, 2006

[8] JUAN CARLOS CANO GONZALES, PAOLO F. FANTONI, Experiments on Cable Aging Assessment and Fault Detection Using Modern Techniques, 2008

[9] USNRC, Generic Aging Lessons Learned (GALL) Report, NUREG-1801, September 2005

Adrese autora:

Prof. dr. sc. **Nikola Čavlina**
nikola.cavlina@fer.hr
Sveučilište u Zagrebu
Fakultet elektrotehnike i računarstva
Zavod za visoki napon i energetiku
Unska 3
10000 Zagreb
Hrvatska

Irena Jakić, dipl.ing.
Irena.Jakic@hep.hr
HEP d.d. Sektor za održivi razvoj i unaprjeđenje kvalitete
Ulica grada Vukovara 37
10000 Zagreb
Hrvatska

Renato Barbarić, dipl.ing.
renato.barbaric@enconet.hr
Enconet d.o.o.
Unska 3
10000 Zagreb
Hrvatska

Mr. sc. **Bruno Glaser**
bruno.glaser@nek.si
NE Krško. d.o.o.
Vrbina 12
8270 Krško
Slovenija

Authors' Adresses:

Prof. **Nikola Čavlina**, PhD
nikola.cavlina@fer.hr
University of Zagreb
Faculty of Electrical Engineering and Computing
Institute for High Voltage and Energy Science
Unska 3
10000 Zagreb
Croatia

Irena Jakić, dipl. ing.
Irena.Jakic@hep.hr
HEP d.d. Sustainable Development and Quality Improvement Sector
Ulica grada Vukovara 37
10000 Zagreb
Croatia

Renato Barbarić, dipl. ing.
renato.barbaric@enconet.hr
Enconet d.o.o.
Unska 3
10000 Zagreb
Croatia

Bruno Glaser, MSc
bruno.glaser@nek.si
NE Krško d.o.o.
Vrbina 12
8270 Krško
Slovenia

Uredništvo primilo rukopis:
2009-05-20

Prihvaćeno:
2009-07-02

Manuscript received on:
2009-05-20

Accepted on:
2009-07-02