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Staranje uparjalnikov jedrskih elektrarn

Ageing Phenomena in Nuclear Power Plant Steam Generators

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0. UVOD

Spremljanje obratovanja tlačnovodnih jedrskih elektrarn je že vrsto let povezano z vprašanjem staranja cevi uparjalnikov zaradi korozijskega in mehanskega delovanja, tako primarnega kakor sekundarnega hladilnega sistema. Korozijske in mehanske poškodbe cevi so posledica delovanja več parametrov: kemije vode, termohidrodinamičnih razmer, izbire materiala, izdelave cevi in obratovalnih razmer.

Načela jedrske varnosti za projektiranje zahtevajo celovitost mej primarnega hladila v vseh normalnih, prehodnih in nezgodnih obratovalnih stanjih. Jedrska elektrarna mora obratovati v skladu z obratovalnimi omejitvami in zahtevami za nadzor. Obratovalne omejitve predpisujejo zgornjo mejo puščanja primarnega hladila v uparjalniku in nivo aktivnosti vode sekundarne strani uparjalnika. Zahteve za nadzor predpisujejo redne medobratovalne preglede cevi in merila za popravne posege.

Članek podaja pregled problematike staranja cevi uparjalnikov, njen vpliv na obratovalno zmogljivost elektrarne ter izvajanje preprečevalnih in popravnih posegov. Posebna pozornost naše raziskave pa je seveda namenjena problematiki uparjalnikov jedrske elektrarne Krško (JEK).

1. GLAVNE ZNAČILNOSTI UPARJALNIKOV

V uparjalnikih tlačnovodnih jedrskih elektrarn primarno reaktorsko hladilo predaja toploto vodi v sekundarnem sistemu ter jo uparja. Današnje elektrarne imajo od dva do šest uparjalnikov, odvisno od projekta. JEK ima npr. dva uparjalnika.

Prerez uparjalnika je prikazan na sliki 1. Reaktorsko hladilo na primarni strani teče skozi snop cevi v obliki obrnjenega U; vstopni in izstopni prekat v polkrožnem dnu sta ločena. Sekundarna napajalna voda vstopa v predgrevalnik, kjer se segreje skoraj do vrelišča. V uparjalnem delu se dvofazna zmes med dviganjem ob snopu cevi uparja. Centrifugalni ločevalniki vlage v parnem bobnu nad snopom izločijo v povratni kanal večino kapljevine, sušilniki pare pa še izboljšajo kakovost pare pred izstopom iz uparjalnika. Vračajoča kapljevina se steka na dno uparjalnega dela.

0. INTRODUCTION

Operational monitoring of pressurized water reactor power plants in recent years has been connected with questions related to the ageing of steam generator tubes due to corrosion and mechanical impact on both primary and secondary cooling systems. Corrosion and mechanical tube damages are caused by different parameters: water chemistry, thermohydrodynamic conditions, choice of materials, tube manufacturing processes and operating conditions.

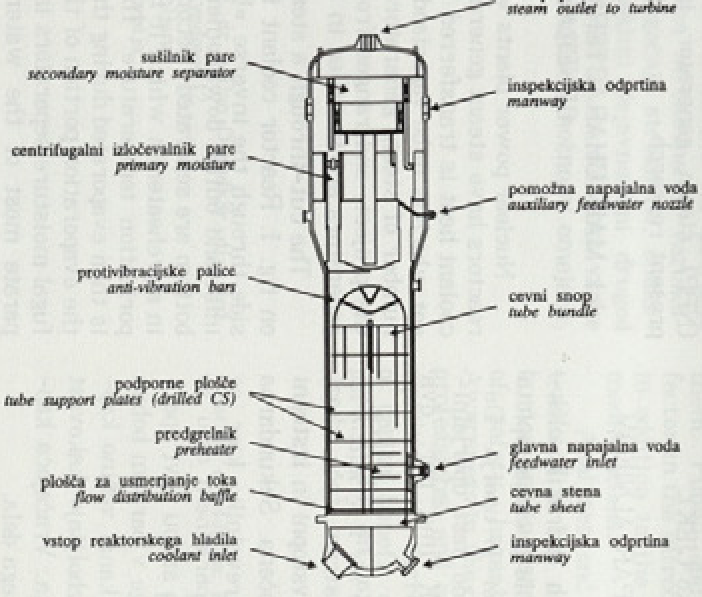
The integrity of the primary coolant boundary is required by nuclear safety criteria for the design in all normal, transient and anticipated emergency operating conditions. Nuclear power plant operation should be in accordance with limiting conditions for operation, and surveillance requirements. The upper limit of the primary coolant leakage through steam generators and the level of secondary water radioactivity are prescribed by limiting conditions for operation. Regular in-service inspections of tubes and criteria for corrective measures are determined by surveillance requirements.

This paper provides an overview of ageing phenomena in steam generators, together with their impact on plant availability and performing preventive and corrective measures. Special attention is paid to the Krško Nuclear Power Plant (NPP) steam generator issues throughout the present research.

1. MAIN CHARACTERISTICS OF STEAM GENERATORS

Nuclear power plants with pressurized water reactors have steam generators in which primary coolant heat is transferred to the secondary coolant which is to be vaporised. Nowdays, the typical number of steam generators per plant depends on the project, and ranges from 2 to 6. Two steam generators are installed in Krško NPP.

The cut-through a steam generator is shown on fig. 1. Reactor coolant flows on the primary side through the inverse »U« shaped tube bundle; inlet and outlet downcomer in the hemispherical bottom are separated. Secondary feedwater enters in a preheater in which it is heated almost to vaporization temperature. The two-phase mixture is then evaporated during the upward flow through the evaporation portion of the tube bundle. Centrifugal moisture separators in the upper section separate most of the water to the recirculation



lokacija *location*	vzrok poškodbe *cause of defect*
cevni lok *tube bend*	zaostale napetosti zaradi zvijanaja *bending residual stresses*
cevna stena - - podr. uvaljanja *tube sheet - - rolling region*	zaostale napetosti zaradi uvaljanja *rolling residual stresses*
cevna stena - - prehodno podr. - podr. usedlin *tube sheet - - transition region - sludge region*	zaostale napetosti v prehodnem podr. *transition region residual stresses*

napetostna medkristalna korozija
intergranular stress corrosion

lokacija *location*	tip poškodbe *defect type*	vzrok poškodbe *cause of defect*
protivibracijske palice *antivibration bars*	stična obraba *fretting - wear*	prekomerno trenje med cevjo in protivibracijskimi palicami *excessive rubbing between tubes and antivibration bars*
podporne plošče *support plates*	stiskanje cevi *denting*	usedanje korozijskih produktov *building of corrosion products*
podporne plošče *support plates*	medkristalno spodjed. *intergranular attack*	lokalna koncentracija jedkih nečistoč *local concentration of aggresive impurities*

značilne poškodbe na sekundarni - zunanji strani cevi
typical defects on secondary - outside tube side

Sl. 1. *Področja značilnih poškodb uparjalnikov.*
Fig. 1. *Regions of typical defects on steam generator tubes.*

Izstopna para vsebuje manj ko 0,25 masnih odstotkov kapljevine v stacionarnem obratovanju v območjih do 100 odstotkov parnega toka polne obremenitve. Enaka kakovost pare je zagotovljena tudi pri prehodnih pojavih: zveznih spremembah do 5 odstotkov polne obremenitve v minuti ali koračnih do 10 odstotkov polne obremenitve, v območju od 15 do 100 odstotkov parnega toka polne obremenitve.

V vsakem uparjalniku JEK je 4586 cevi, njihova površina je več ko polovica vseh površin, ki sestavljajo mejo primarnega hladila. Delovni tlak primarnega hladila je 155 bar pri povprečni temperaturi 305,9 °C. Cevi zunanjega premera 19,05 mm imajo v primerjavi z drugimi mejami izredno majhno debelino stene in sicer 1,06 mm.

Imenska zmogljivost uparjalnika JEK je 510 kg/s suho nasičene pare tlaka 63,4 bar. Temperatura napajalne vode je 221 °C. Specifična toplotna obremenitev cevi je izredno velika in znaša 190,7 kW/m^2. Ta toplotna obremenitev je mogoča le v razmerah dvofaznih tokov in ob izredno tanki steni cevi, izdelani iz INCONEL-600. Z njim je obložena tudi primarna stran cevne stene.

Uparjalnik deluje na naravni obtok sekundarnega hladila, pri čemer je pri polni moči dvižni tok ob ceveh za približno 2-krat večji od toka napajalne vode. Vračajoči tok v veliki meri preprečuje usedanje nečistoč na cevni steni.

Cevi uparjalnika so hladno uvaljane v cevno steno, ki je debela 533 mm. Dolžina ravnega dela snopa cevi je 7181 mm.

Po višini so cevi vodene v sedmih podpornih ploščah skozi izvrtine s premerom, ki je malo večji od premera cevi. Podporne plošče imajo tudi dodatne izvrtine za pretok pare in vode.

Zaradi velike hitrosti pare v področju cevnih lokov in s tem povezanih nihanj so cevni loki posebej opremljeni s protivibracijskimi palicami.

V uparjalnik doteka napajalna voda na dveh mestih. Glavni tok je usmerjen skozi predgrelnik napajalne vode, pomožni tok pa v parni prostor uparjalnika.

Za sprotno odstranjevanje korozijskih in drugih usedlin ima uparjalnik izpustni sistem. Od učinkovitosti tega sistema je v precejšnji meri odvisna doba trajanja uparjalnika.

2. PROCESI STARANJA

Cevi uparjalnikov so izpostavljene kemijskim in mehanskim vplivom, ki so najbolj izraziti predvsem v prehodnih obratovalnih stanjih elektrarne. Ti vplivi se med seboj dopolnjujejo in z leti je treba posamezne cevi popraviti ali celo izločiti iz uporabe.

channels. The steam quality is further improved by steam dryers before leaving the steam generator. Water extracted from the steam is returned to the bottom of the shell.

The outlet steam ciontains less than 0.25 % of water during the steady state operation up to 100 % of full load steam flow. The same steam quality is preserved during transient conditions: continuous changes of up to 5 % of full load per minute and steps under 10 % of full load in the range of 15 to 100 % of full load steam flow.

Each steam generator contains 4586 tubes. Their area is more than half of the primary coolant boundary area. The primary coolant operational pressure is 155 bar at an average temperature of 305.9 °C. The wall thickness of the tubes with diameter of 19.05 mm is only 1.06 mm, which is extremely low compared to other parts of the boundary.

The design capacity of a Krško NPP steam generator is 510 kg/s of saturated steam at pressure of 63.4 bar. The feedwater temperature is 221 °C. The specific heat load on the tubes is extremely high, with a value of 190.7 kW/m^2; this heat load can be achieved only by two phase flow and extremely low tube wall thickness. Tubes are made of INCONEL 600. The primary side of the tube sheet is clad by the same material.

The steam generator uses the natural circulation of secondary coolant, where by full load the riser flow at the tube bundle exceeds the feedwater flow by a factor of two. The recirculated water prevents the formation of sludge on the tube sheet.

The steam generator tubes are cold rolled into the 533 mm thick tube sheet. The straight part of the tubes is 7181 mm long.

Seven support plates with holes of a diameter slightly exceeding the tube diameter are provided at different heights to guide the tube. Additional holes are provided for steam and water flows.

At the tube bends, antivibration bars are provided to reduce vibrations caused by the high speed steam flow.

The feedwater is supplied to the steam generator at two locations. The main flow is directed through the feed water preheater; the auxiliary flow is directed to the evaporation portion of the steam generator.

The steam generator blowdown system performs continuous removal of corrosion and other impurity from the steam generator. The steam generator operating life time considerable depends on steam generator blowdown system efficiency.

2. AGEING PROCESSES

The steam generator tubes are exposed to chemical and mechanical influences, which are mainly expressed during the transient plant operating conditions. The effects are cumulative and, over years, might necessitate repair or even the elimination of the tubes from operation.

S pojmom procesi staranja cevi uparjalnikov tlačnovodnih reaktorjev označujemo naslednje pojave: medkristalno napetostno korozijo, medkristalno spodjedanje, stično-trenjsko obrabo, stiskanje cevi na obodu in točkasto nažiranje.

Med mehanske vplive na cevi uparjalnikov štejemo zaostale napetosti zaradi oblikovanja cevi in obratovalne obremenitve. Kemijski vplivi sekundarnega hladila na materiale komponent in delov so odvisni od načina vzdrževanja kemije hladilne vode, materialov, iz katerih so narejene komponente in deli sekundarnega kroga, ter predvsem od tesnosti kondenzatorja.

JEK vzdržuje kakovost sekundarne vode po postopku s hlapljivimi snovmi. Uporaba teh snovi, kakršna sta hidrazin in amoniak, ki se vezana s prostim kisikom odzračujeta prek ejektorskih črpalk kondenzatorja, ne pušča snovi, ki bi vplivale na povečano električno prevodnost sekundarne vode.

Material komponent in delov sekundarnega hladilnega kroga, npr.: podporne plošče uparjalnika iz ogljikovega jekla, so glavni viri korozijskih snovi. Korozijske snovi nastajajo zaradi kisika, ki vdira v sekundarni hladilni sistem skozi netesen kondenzator. Nastajanje korozijskih snovi se pospešuje s kovinskimi kationi (baker iz kondenzatorja) v sekundarnem hladilu. Skozi netesen kondenzator se vnašajo v sekundarni hladilni sistem tudi nečistoče iz reke Save.

2.1 Oblike staranja

Najbolj pogoste oblike staranja uparjalnikov so prikazane na sliki 1, kjer so označena tudi značilna mesta, na katerih se pojavljajo.

2.1.1 *Medkristalna napetostna korozija*

Medkristalna napetostna korozija je posledica statičnih in dinamičnih obremenitev materiala, ki je izpostavljen agresivnemu mediju. Med statične obremenitve prištevamo tudi zaostale napetosti zaradi hladnega oblikovanja pri uvaljanju cevi v cevno steno in oblikovanju cevnih lokov. Medkristalne razpoke so izhodiščna mesta za začetek širših korozijskih procesov na ceveh.

Kakor je razvidno s slike 1, so značilna mesta za nastanek medkristalne korozije v območju cevne stene in cevnega loka. Za obe področji so značilne popolne in delne razpoke na notranji in zunanji strani stene cevi.

2.1.2 *Medkristalno spodjedanje*

Medkristalno spodjedanje je odvisno predvsem od kemijskega učinkovanja jedkih nečistoč sekundarne vode. Značilna mesta za nastanek medkristalne spodjede so reže med cevjo in podpornimi

The following processes denote ageing of pressurized water reactor steam generator tubes: intergranular stress corrosion, intergranular attack, fretting-wear, denting and pitting.

Residual and operational stresses are considered to be mechanical effects on the tubes. Residual stresses are caused by tube manufacturing. The chemical effects of the secondary coolant on the materials of the components and structures depend on the secondary coolant chemistry control, the materials of the components and structures of the secondary system and especially, the tightness of the condenser.

The quality of the secondary water in Krško NPP is maintained by the use of volatile treatment. Using volatile treatment with hydrazine and ammonia, which can be vented through the ejector pumps in the condenser after bounding the free oxygen, does not leave traces of products which might increase the electrical conductivity of the secondary water.

The main source of corrosion products is the materials of the secondary cooling system components and structures, e.g., the carbon steel support plates in the steam generator. Corrosion products develop under the influence of oxygen, which penetrates into the secondary system through the non-tight condenser. The metal cations (copper from the condenser) in the secondary coolant accelerate corrosion product development. Impurities from the Sava river are also introduced into the secondary cooling system through the non-tight condenser.

2.1 Phenomena of ageing

The most frequent steam generator ageing phenomena are shown on fig. 1, together with their respective characteristic regions.

2.1.1 *Intergranular stress corrosion*

Intergranular stress corrosion cracking develops in material exposed to static and dynamic loads and an aggressive medium. The residual stresses induced by cold material forming during rolling the tubes into tube sheet and manufacturing the tube bends are also considered to be a static load. Intergranular cracks initiate broader corrosion processes on the tubes.

As shown on fig. 1, intergranular stress corrosion typically occurs in the tube sheet and tube bend region. Both area are characterized by through-and part-through wall cracks starting from both the inside and the outside of the tube.

2.1.2 *Intergranular attack*

Intergranular attack conditioned in particular by the chemical effects of aggressive impurities which are part of the secondary water. Typically, it occurs in the crevice between the tubes and the tube supports plates. The tube is locally heated in ploščami. Cev se v območju reže zaradi izrednega toplotnega toka (do 315 kW/m^2) lokalno pregreva nad temperaturo nasičenja. V takih termohidrodinamičnih razmerah pride v režah do dvofaznega toka oz. uparjanja, kar povzroča izmenično močenje in sušenje reže. Izmenično sušenje usedline povzroča nastajanje velikih koncentracij kloridov (do 4 g/ kg) [9].

2.1.3 *Stiskanje cevi*

Pri ohlajanju elektrarne se reža med podporno ploščo in cevno steno veča zaradi različnega raztezanja materialov. V teh razmerah se v režo usedajo korozijske snovi, ki krožijo v sekundarnem hladilu. Najpogostejša korozijska snov je magnetit (Fe_3O_4), ki nastaja ob reakciji kisika z ogljikovim jeklom podpornih plošč. Ob ponovnem segrevanju elektrarne se reža med cevjo in podporno ploščo zmanjša in stisne usedline v steno cevi. Korozijske snovi in druge nečistoče se odlagajo v reži neenakomerno po obodu cevi in s časom širijo svoj prostor tako, da plastično deformirajo steno cevi.

2.1.4 *Stično-trenjska obraba*

Stično-trenjska obraba je posledica relativnega gibanja stičnih površin. Kakor je razvidno s slike 1, je ta pojav opazen v uparjalnikih v območju cevnih lokov, kjer so nameščene protivibracijske palice. Za območje cevnih lokov je značilna velika hitrost pare, ki povzroča nihanje cevi. Hitrost pare in s tem nihanje se z obsegom čepljenja cevi povečujeta. Za stično obrabo je značilno površinsko odnašanje materiala.

2.1.5 *Točkasto nažiranje*

Točkasto nažiranje se pojavlja na ravnih zunanjih delih cevi med podpornimi ploščami in je odvisno predvsem od navzočnosti kisika in delovanja kovinskih kationov (baker).

2.2 **Pogostost posameznih oblik staranja**

Poškodbe na ceveh uparjalnikov JEK so se v večjem obsegu pojavile leta 1985, tj. po treh letih obratovanja. Takrat je bilo treba začepiti 3,6 % cevi na uparjalniku št. 1 in 2,1 % na uparjalniku št. 2. Velikost takratnega vzorca pregledanih cevi je znašala 3 % [1]. JEK je začela s 100 % pregledi cevi po letu 1985.

Prve poškodbe cevi uparjalnikov JEK so bile odkrite v področju cevne stene ter področju prehoda cevi iz cevne stene. Glavnina teh poškodb je na topli strani snopa cevi in ima značilnosti medkristalne napetostne korozije. Z obratovalnimi leti so se začele pojavljati tudi druge oblike procesa staranja, od katerih je najznačilnejši pojav medkristalnega spodjedanja.

the crevice over the saturation temperature by the extremely high heat flux (up to 315 kW/m^2). Vaporization and respectively two-phase flow is induced in the crevice by such thermohydrodynamic conditions, causing alternating drying and wetting of the crevice. The alternating drying of the sludge causes high chloride concentrations (up to 4000 ppm) [9].

2.1.3 *Denting*

During cooling of the plant, the crevice depth between the support plate and the tube increases due to differences in the thermal expansion of materials. This causes the deposition of secondary water corrosion products in the crevice. The most common corrosion product is magnetite (Fe_3O_4), which develops by the contact of oxygen with the carbon steel support plates. At the next plant heatup, the crevice depth between the tube and tube support decreases and the deposits are pushed into the tube wall. Corrosion products and other impurities are deposited in the crevice in a non-uniform manner and extend their space by plastic tube wall deformation.

2.1.4. *Fretting-wear*

Fretting-wear is caused by the relative movement of surfaces in contact. As shown in fig. 1, it usually takes place at the tube bends, where the antivibration bars are located. A high steam velocity is characteristic of the tube bend region, causing vibration of the tubes. The steam velocity and consequently the tube vibrations are increased by the extent of tube plugging. Fretting-wear is characterized by the loss of material on the tube surface.

2.1.5 *Pitting*

Pitting develops along straight portions of the tube between the support plates. It is mainly caused by the presence of oxygen and metal cations (cooper).

2.2 **The likelihood of ageing phenomena**

Major indications of defects on the tubes of Krško NPP steam generators were detected in 1985, e.g. after three years of operation. 3.6 % of tubes in the steam generator No. 1 and 2.1 % in No. 2 were then plugged. 3 % sample of inspected tubes was used at that period [1]. NEK started with 100 % tube inspection since 1985.

The first indications of tube defects in the Krško NPP steam generators were detected in the tube sheet and tube expansion transition region above the tube sheet. The majority of those defects were located on the hot side of the tube bundle and were characterized by intergranular stress corrosion cracking. Over the operational years, other ageing phenomena started, among which the very specific is intergranular attack.

Po rednih vzdrževalnih pregledih leta 1990 je število začepljenih cevi v uparjalnikih JEK takšno: v uparjalniku št. 1 je začepljenih 12,8 % cevi, v uparjalniku št. 2 pa 6,3 %. Uspešnost izvedenih varovalnih in popravljalnih posegov je težko oceniti, ker so se v obratovalnem obdobju JEK spreminjali tako merila za čepljenje kakor tudi preiskovalne metode. Lahko le ugotovimo, da je razvoj procesa staranja v uparjalnikih JEK podoben kakor v drugih elektrarnah po svetu. Zanimivost uparjalnikov JEK je nesimetričnost čepljenja, kar kaže na to, da je v veliki meri vsak uparjalnik poseben problem.

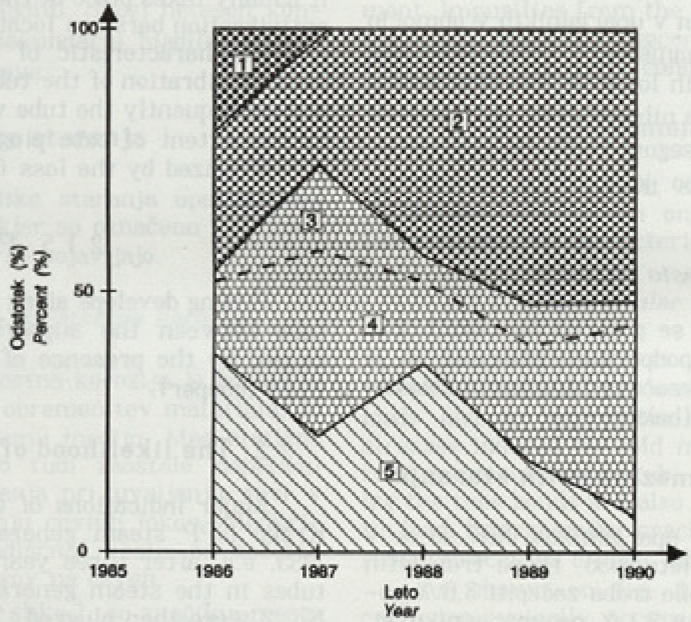
Na sliki 2 je prikazan razvoj za JEK značilnih pojavnih oblik procesa staranja. Slika je narejena na podlagi merskih podatkov in spoznanj o značilnih mestih posameznih pojavnih oblik procesa staranja [3].

S slike 2 lahko ugotovimo, da približno 50 % poškodb kaže na medkristalno napetostno korozijo v območju cevne stene ali tik nad njo. Število poškodb se na primarni notranji strani cevi zmanjšuje, kar še posebej velja v letih po 1987, ko je bilo izvedeno popuščanje napetosti s peskanjem cevi v območju uvaljanja v cevno steno in kaže uspešnost tega posega.

Following inservice inspection performed during outage 1990, the level of plugging of Krško NPP steam generators is as follows: in steam generator No. 1, 12.8 % of tubes are plugged, while only 6.3 % in steam generator No. 2. An estimation of the success of preventive and corrective measures is difficult, mainly due to the change of both plugging criteria and inspection methods during the Krško NPP operational period. The only conclusion which can be drawn is that the trend of the Krško NPP steam generator degradation processes is comparable with the trend in other plants in the world. The interesting point of NEK steam generators is the asymmetry in plugging, showing the specific behaviour of each steam generator.

Fig. 2 shows the history of the characteristic ageing phenomena in NEK. The figure has been produced by the help of measurement indications and a knowledge of the specific locations of ageing phenomenon.

As shown in fig. 2, about 50 % of indications show the existence of intergranular stress corrosion in the tube sheet region or close above it. The number of primary, e.g., inner side, indications is decreasing, especially in the years after 1987, when the relief of residual stresses was performed by means of shotpeening of tubes in the rolling region, showing the efficiency of this measure. The secondary side intergranular stress corrosion



Sl. 2. *Proces staranja cevi uparjalnikov JE Krško.*
Fig. 2. *Degradation process on the tubes of Krško NPP.*

Področje zunanje napetostne korozije na sliki 2 je razdeljeno na dva dela, in sicer: področje indikacij v območju usedlin na cevni steni in druga, za napetostno korozijo značilna področja. Indikacije v območju usedlin so tik nad ali na vrhu cevne stene. Zato smo mnenja, da so indikacije v območju usedlin posledica napetostne korozije. V splošnem pa je za to področje cevi značilen tudi pojav točkastega naziranja, kar pa je za primer JEK redek pojav.

Medkristalna napetostna korozija v območju cevnih lokov je v uparjalniku JEK redka, izjema je le nekaj cevi v 1. in 2. vrsti, kjer je ukrivljenost največja.

Na sliki 2 vidimo, da se v zadnjih letih povečuje število poškodb na sekundarni — zunanji strani cevi, in to v območju podpornih plošč. Te poškodbe kažejo pojav medkristalnega spodjedanja.

3. VPLIV ČEPLJENJA NA DELOVANJE ELEKTRARNE

Z začepitvijo cevi uparjalnika se spremeni geometrična oblika primarne strani uparjalnika. S spremenjeno geometrično obliko uparjalnika ne moremo pričakovati ohranitve imenskih parametrov primarnega in sekundarnega kroga jedrske elektrarne. Posledica začepitve dela cevi uparjalnikov je zmanjšana površina za prehod toplote ter zmanjšan pretok reaktorskega hladila zaradi povečane hidravlične upornosti. Glede na zmanjšan pretok reaktorskega hladila in površine za prenos toplote je JEK za ohranitev imenske moči povečala toplotno moč uparjalnika. To so dosegli z znižanjem tlaka pare pri ohranjeni temperaturi vroče veje primarnega kroga. Tak način ohranitve imenske moči je omogočila predimenzionirana zmogljivost regulacijskih ventilov visokotlačne turbine.

Vsako spremembo obratovalnih parametrov je treba preveriti z vidika jedrske varnosti. Te zahteve so predpisane v domačih in tujih pravilnikih. Preveritev termohidrodinamičnih parametrov je izvedena z ustreznim simuliranjem odziva sistemov elektrarne na vse predpostavljene omejitvene nezgode. V splošnem je vsaka sprememba obratovalnih parametrov sprejemljiva, če varnostne analize pokažejo, da sprememba ne povzroči preseganja varnostnih mej. Kakor so pokazale analize, je glavni omejitveni dejavnik čepljenja temperatura gorivne srajčke med predpostavljeno veliko izlivno nezgodo.

Izkoriščanje zmogljivosti sedanjih sistemov za ohranjanje imenske moči zaradi čepljenja cevi uparjalnikov je omejeno. Za JEK je ta kritična meja 18-odstotna začepitev cevi. Dodatni omejitveni dejavnik je tudi nesimetričnost začepitve uparjalnikov.

cracking region on fig. 2 is divided into two subregions as follows: the sludge region above the tube sheet and other typical intergranular stress corrosion cracking locations. Indications in the sludge region are on or very close to the top of the tube sheet and are result of rolling the tube into the tube sheet. For this reason it is our opinion that these indications are the consequences of intergranular stress corrosion. The sludge region is a typical location for pitting, too, but in the NPP Krško case, this process is uncommon.

Intergranular stress corrosion in the region of the tube bends is rare in Krško NPP steam generators, with the exception of a few tubes in rows No. 1 and 2, which have a minimum bending radius.

Fig. 2 shows the increase in indications of intergranular attack on the tube secondary side in the region of the tube support plates in recent years.

3. THE IMPACT OF PLUGGING ON PLANT OPERATION

The geometry of the steam generator primary side is changed by plugging a tube. Thus, the preservation of the nominal primary and secondary nuclear power plant parameters can not be expected by this change in steam generator geometry. Plugging a part of the steam generator tubes causes a decrease of the heat transfer surface and reactor coolant flow rate due to the increased hydraulic resistance. Because of the reduced heat transfer surface and reactor coolant flow rate, the thermal power of the steam generator has been increased in Krško NPP to preserve the nominal plant power. This has been achieved by reducing the steam pressure at the preserved primary coolant hot leg temperature. Such an approach to preserve the plant nominal power has been made possible by an overdimensioned capacity of the high pressure turbine control valves.

Any change of the operational parameters should be investigated from the nuclear safety viewpoint. Such requirements are considered in domestic and foreign regulations. The verification of thermohydrodynamic parameters is performed by and appropriate simulation of the plant system response to all hypothetical limiting accidents. In general, any change of operational parameters is acceptable if it is shown by means of safety analyses that the safety limits are not jeopardized by this change. As shown by analyses, the major limiting factor in the case of plugging is the behaviour of systems and components during an hypothetical large break loss of coolant accident, in particular, the temperature of the fuel clad.

Exploitation of the capacity of existing systems and components to maintain the nominal plant power despite steam generator tube plugging is limited. For Krško NPP, the critical limit stands at 18 % of tubes plugged. An additional limiting factor is also the asymmetry of pluging in the two steam generators.

4. PREGLED CEVI

Ozko grlo medobratovalnih pregledov opreme v elektrarni so pregledi cevi uparjalnikov. Medobratovalni pregled opreme se izvaja ob zamenjavi goriva. V tlačnovodnih elektrarnah je to navadno vsako leto ali največ vsakih 18 mesecev.

Medobratovalni pregled 4586 cevi uparjalnika s povprečno dolžino 16 m je dokaj obsežen in zahteven poseg. Minimalni obseg pregledanih cevi je za JEK določen z ameriškim predpisom [1], ki terja tudi sprotno prilagajanje velikosti vzorca ugotovljenemu stanju in razvoju procesa staranja.

4.1 **Postopki pregleda cevi**

Poglavitni in najpogosteje uporabljani postopek pregledovanja cevi uparjalnika je metoda vrtinčnih tokov, ki jo označujemo tudi s kratico ECT (Eddy Current Testing). To metodo navajajo tudi standardi ASME, del V [5]. Dodatno za preverjanje uporabljajo ultrazvok in vizualni pregled.

Pri pregledovanju uparjalnikov je zelo pomembna določitev velikosti vzorca cevi in njegova namestitev. Najmanjša velikost vzorca, ki jo upošteva svetovna praksa, je 3 odstotke cevi. Ta meja izhaja iz zahtev ameriških predpisov in je nespremenjena že 15 let [1].

Staranje cevi uparjalnikov, nova spoznanja o naravi procesov staranja in metodah pregledovanja so narekovali spremembe meril za čepljenje ter s tem povezanim vzorcem cevi, ki ga je treba pregledati. Dandanes po svetu, vsaj v primeru cevi iz INCONEL 600, izvajajo 100-odstotni pregled cevi, ki pa je običajno omejen le na najbolj izpostavljeno področje uparjalnika.

Metoda vrtičnih tokov je utemeljena na spremembi električne prevodnosti stene cevi, ki jo pregledujemo. Najpogosteje se uporablja diferencialna vezava; zato potrebujemo dve tipali, priklopljeni na izmenično napetost. Napetost na sponkah navitja tipala se zmanjša in fazno spremeni s tokom, ki teče po stenah cevi. Tok v steni cevi je odvisen od lokalnih elektromagnetnih lastnosti. V nemagnetnih materialih, kakršen je INCONEL, je pomembna le prevodnost. V primeru nezveznosti cevi se prevodnost zmanjša, napetost na sponkah navitja pa zato poveča in fazno spremeni v skladu z globino poškodbe in spremembo prevodnosti. Z diferencialno vezavo se zniža vpliv pomika tipala ter temperaturnih in geometrijskih sprememb.

Cevi lahko preizkušamo po celotni dolžini v uparjalniku, tudi v območju podpornih plošč in uvaljanem delu, kjer se pojavljajo motilni signali. V območju uvaljanja cevi v cevno steno je razpoke težko odkriti, saj je tu signal zaradi sledi uvaljanja lahko tudi do 30-krat večji. Za učinkovito odstranitev motilnih signalov je v uporabi več frekvenc in merilniki z zelo dinamičnim območjem.

4. TUBE INSPECTION

The inspection of the steam generator tubes is a critical task in the in-sevice inspection of plant equipment. In-service inspection of the steam generator tubes is performed during plant refuelling. In pressurized water reactor plants, this is usualy performed every year, or at least once in 18 months.

The in-service inspection of 4586 tubes with an average length of 16 m is an extensive and demanding task. The minimum extent of tube inspection in Krško NPP is prescribed by American regulations [1], also requiring an immediate update of the sample according to the state and history of the ageing process.

4.1 **Tube Inspection Methods**

The basic and most extensively used steam generator tube inspection method is Eddy Current Testing (ECT). This method is also stated in ASME standards, Section V [5]. Additionally, ultrasonic and visual inspection may be used to verify the ECT results.

The most important task during the steam generator tube inspection is the determination of the tube sample and its location. The minimum sample extent recognized by world praxis is 3 % of the tubes. This limit basically follows American regulations and has not been changed for 15 years [1].

Ageing of the steam generator tubes and new findings about the nature of degradation processes and inspection techniques has required changes in tube plugging criteria and, in this context, in the extent of the tube sample to be inspected. Nowadays, 100 % tube inspection is performed worldwide, at least in case of INCONEL 600 tubes. However, this may be limited to the most exposed regions.

The ECT method is based on the change of electrical conductivity of the tube wall being inspected. In most cases, a differential coil is used; thus, two coils have to be connected to alternating voltage. The voltage in the coil is decreased and its phase changes with the current in the tube walls. The current in the tube wall depends on local electromagnetic properties. In non-magnetic materials like INCONEL600, only conductivity is important. In the case of a discontinuity in the tube, conductivity is reduced, the voltage in the coil therefore increases and changes the phase in accordance with the defect depth and change in conductivity. The differential coil reduces the effects of coil displacement and changes in temperature and geometry.

The tubes can be inspected over their entire length in the steam generator, including the tube support plate regions and rolling region, where some disturbance signals may occur. In the region where the tubes are rolled into tube sheet, the identification of cracks is difficult. This follows from sudden increase of the signal, which may be

Pokazalo se je tudi, da analiza faznega kota signala sama po sebi še ni zadostna v nestandardnih vrstah razpok in vdolbin. Zato se oblikujejo dodatni programi in uporabljajo posebne vrste tipal.

4.2 Merilna oprema

Uporabnost metode vrtinčnih tokov ECT se je zelo povečala z uporabo računalnikov. Avtomatizirane in z računalniki podprte meritve prispevajo k zanesljivemu zbiranju in obdelavi podatkov. Znižala se je tudi obsevanost osebja, čas trajanja in cena medobratovalnega pregleda uparjalnika.

Tudi pri vrhunsko avtomatiziranih sistemih je končna razlaga rezultatov meritev vedno prepuščena izkušenim strokovnjakom. Orodja, ki jih uporabljajo dandanes, omogočajo natančnost in zanesljivost, kakršnih pri prvotnih pregledih ni bilo mogoče doseči. Na sliki 3 je primer računalniškega izpisa izmerkov vrtečega se tipala pri detekciji razpoke v bližini vrha cevne stene. Samodejna enota omogoča:

— izbiro tipala in pogona tipala za posamezni primer poškodbe, ki jo merimo,

— visoko razmerje signal/šum,

— popolno ločitev enote za zbiranje podatkov in enote za analizo,

— računalniški nadzor vseh posegov, tudi umerjanja,

— računalniško podprte analize,

— učinkovito shranjevanje podatkov,

— diagnozo na podlagi računalniške podatkovne baze.

Z analizo podatkov določimo:

— smer razpok (obodna ali vzdolžna),

— število razpok na istem področju,

— dolžino vzdolžnih razpok,

— globino razpoke z merjenjem faznega kota signala, ob predpostavki, da obliko razpoke že poznamo.

V splošnem se vedno pogosteje uporablja večfrekvenčna preizkusna metoda, ki omogoča izločanje neželenih signalov. Znano je, da metoda ECT ne more dati podatkov o vrsti poškodbe. To lahko ugotovimo le z izvlečenjem in metalografsko preiskavo cevi.

Standardna ECT preiskava cevi uparjalnika se izvaja z notranjim tipalom v obliki navitka. Tipalo se z avtomatsko roko vstavi v cev in nato ga s polgibljivo osjo potiskamo skozi cev. Dodatno k standardnemu notranjemu tipalu se vse bolj uvajajo posebna namenska tipala. Eno takih novih tipal je rotirajoče tipalo, ki je namenjeno ugotavljanju dolžine razpoke. To tipalo se med gibanjem skozi cev vrti. Obstaja tudi posebno tipalo, imenovano profilometer, za ugotavljanje deformacij cevi zaradi stiskanja.

30 times larger because of the rolling traces. To ensure effective filtering of disturbance signals, multifrequency probes with dynamic ranges have been introduced.

It has been shown that an analysis of the phase angle may not be adequate in cases of nonstandard types of cracks and pits. Special types of probes and software are therefore under development.

4.2 Inspection Equipment

The applicability of ECT has been greatly increased by the use of computers. Automatic and computer aided inspection give rise to reliable data acquisition and analysis. The personnel radiation exposure, inspection time and the price of the steam generator in-service inspection have also been reduced.

Even in highly automated system, an experienced expert finally interprets the inspection results. The tools used nowadays enable the operator to achieve an accuracy and reliability which was not possible during early inspections. Fig. 3 shows an example of the computer printout of the measurement results of a crack near the top of the tube sheet as detected by a rotating pancake coil. The automated unit enables:

— the choice of the probe and its drive for the particular defect to be measured,

— high signal to noise ratio,

— complete separation of data acquisition and analysis units,

— computerized control of all tasks, including calibration,

— computer aided analysis,

— efficient data storage,

— data base based diagnostics.

By the analysis of data, the following may be identified:

— crack direction (circumferential or axial),

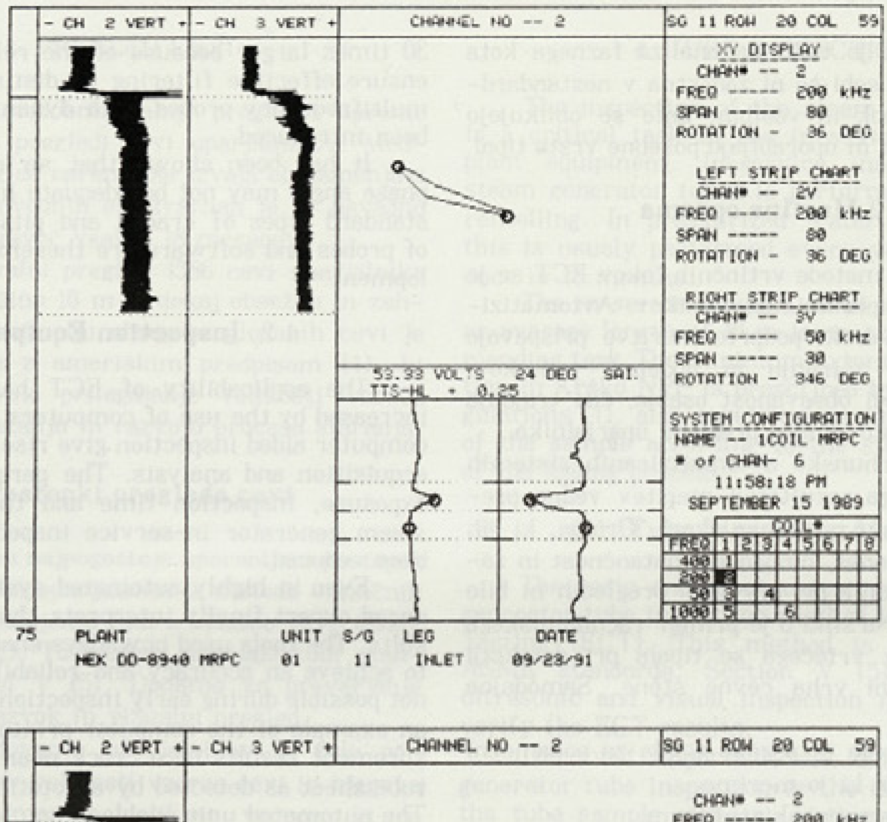
— number of cracks in the same area,

— length of axial cracks,

— the crack depth by measuring the phase angle of the signal, assuming the crack shape.

Generally, the multifrequency inspection method, which enables filtering of some disturbance signals, is more and more used. It is well known that the defect type cannot be fully concluded from the ECT results. Only a metallographic examination of the extracted tubes can serve this purpose.

Standard ECT tube inspection is provided by an inside probe, called a »bobbin« coil. The probe is inserted by a mechanical arm and withdrawn from the tube by a long semiflexible shaft. In addition to the standard inside probe, the use of special probes for specific purposes has been initiated. One such new probe is the rotating probe, developed to measure and evaluate crack length. The rotating probe is rotated as it is withdrawn from the tube inside. A special probe, called a profilometer, has been developed, designed to detect tube deformations caused by denting.



Sl. 3. *Primer izpisa izmerkov vrtečega se tipala pri zaznavi razpoke v bližini vrha cevne stene.*
Fig. 3. *An example of rotating probe inspection results showing a crack near the top of tube sheet.*

5. POSEGI V UPARJALNIKIH

Vsi posegi v uparjalnikih morajo biti v skladu z zahtevami jedrske varnosti in razpoložljivosti elektrarne. V splošnem razdelimo posege na popravne in preprečevalne.

5.1 Popravni posegi

Najbolj razširjen in preprost popravni poseg v poškodovanih ceveh je čepljenje. Običajno so

5. MAINTENANCE ACTIONS ON STEAM GENERATORS

All maintenance actions on steam generators should be consistent with nuclear safety and plant availability requirements. Generally, maintenance actions may be regarded as corrective and preventive.

5.1 Corrective Actions

The most extensively used and simple actions on defected tubes is plugging. Steam generators are uparjalniki tlačnovodnih reaktorjev prav zaradi čepljenja in usedlin na prenosnih površinah predimenzionirani za 10 do 20 odstotkov. V primeru, ko obseg čepljenja cevi uparjalnika preseže projektno zalogo, je treba zmanjšati moč reaktorja, izvesti popravne posege ali morda zamenjati uparjalnike.

V nekaterih primerih je mogoče čepljenje cevi nadomestiti z vstavljanjem tulcev. Ta poseg je uporaben pri poškodbah v območju cevne stene in tik nad njo. Tulec je hidravlično natisnjen znotraj cevi ter dodatno zatesnjen z zvari. Material in obdelava tulca morata ustrezati cevi.

Problem vgradnje tulcev so zvari, kjer se zaradi pregrevanja pojavljajo obodne razpoke. Da bi se izognili težavam pri varjenju, so začeli izdelovati tulce iz mehkejšega materiala (niklja) in jih pritrjevati z eksplozivnim natisnjenjem, ki ne terja dodatnega segrevanja cevi.

5.2 Preprečevalni posegi

Preprečevalni ukrepi so namenjeni preprečevanju in širjenju posameznih vrst procesov staranja. Sem sodijo:

— vzdrževanje ustrezne kemije vode primarnega in sekundarnega hladila,
— medobratovalno čiščenje uparjalnikov,
— popuščanje zaostalih napetosti,
— izbira najprimernejših materialov za sestavne dele sekundarnega hladilnega kroga,
— tesnost kondenzatorja.

Zaostale napetosti v ceveh odpravljamo s toplotno ali mehansko obdelavo. Za cevni lok je primerna le toplotna obdelava, pri kateri se kot vir toplote uporablja električno uporno navitje. Cev se pri tem segreje za nekaj minut (do 10 minut) na temperaturo 593 do 760 °C [14]. Takšna toplotna obdelava zmanjša notranje napetosti na 50 MPa in manj, s čimer povečamo odpornost materiala pred napetostno korozijo.

Peskanje je mehanski način popuščanja notranjih napetosti v materialu pri temperaturi okolice. Postopek je uporaben na mestih uvaljanja v cevno steno.

Poznamo dva načina peskanja: neposredno na notranji površini cevi in z vrtečo se ročico, na katero so pritrjene jeklene kroglice. Postopek z vrtečo se ročico se redkeje uporablja. Nadzor nad postopkom peskanja izvajajo z zvočnimi signali [10].

Iz diagrama na sliki 2 je razvidna tudi stalna korozija materiala pod usedlinami na cevni steni. Za zmanjševanje korozijskega vpliva usedlin so v uporabi različni postopki čiščenja uparjalnika, ki se opravljajo ob rednem medobratovalnem pregledu cevi. Cev se čisti le na sekundarni strani cevi uparjalnika.

usually overdimensioned by 10 to 20 % to allow for sludge and tube pluging. In cases where the design reserve is exceeded, reactor power should be decreased, corrective actions should be performed, or steam generators may be replaced.

In some cases, tube plugging may be replaced by tube sleeving. This may be applicable for defects in the region of the tube sheet or just above it. The sleeve is hydraulically expanded inside the tube and, additionally, tightness is achieved by welding. The material and the make of the sleeve must be consistent with the tube.

The major sleeving problem are welds, whereby circumferential cracking is initiated because of overheating. To overcome the welding problems, the sleeves may be made of softer material (nickel) and fixed by explosive expansion, which does not require additional tube heating.

5.2 Preventive Actions

Preventive actions are organised to preclude or stop the ageing process. They include:

— maintaining the appropriate primary and secondary water chemistry,
— in-service steam generator cleaning,
— relieving residual stresses,
— choice of most appropriate materials for the components of the secondary cooling loop,
— tightness of condenser.

Residual stresses in the tubes may be relieved by heat or mechanical treatment. For the tube bends, only the heat treatment may be applied. An electrical resistant coil is used as the heat source. The tube is heated for a short time (up to 10 minutes) to a temperature of 593 to 760 °C [14]. Such heat treatment reduces the residual stresses to 50 MPa or less, thus increasing the stress corrosion resistence of the material.

Peening is a mechanical treatment used to relieve residual stresses in the material at room temperature. It has been designed to relieve residual stresses in the tube to tube sheet rolling regions.

Two methods of peening are recognized: direct bombardment of the tube internal surface and peening by rotating beam with small steel spheres attached. The second methods is rarely used. Sound signal control over the peening process is provided [10].

The sustained presence of corrosion under sludge on te tube sheet is shown in fig. 2. Different steam generator cleaning methods have been applied to diminish the sludge corrosion effects, being carried out during regular in-service inspections of the steam generator tubes. Tube cleaning is performed only on the secondary side of the steam generator.

Chemical and mechanical cleaning are both used. Chemical cleaning is a very demanding task with possible negative effects on the steam generator.

Poznamo kemično in mehansko čiščenje. Kemično čiščenje je zelo zahteven postopek z mogočimi slabimi posledicami za uparjalnik.

JEK uporablja mehansko čiščenje z vodnimi curki v kombinaciji z dinamičnim uparjanjem vode, ki povzroča rahljanje usedlin. Usedline odvaja iz uparjalnika izpustni sistem. Vseh usedlin ni mogoče odstraniti, ker se strdijo. V usedlinah je veliko kovinskih ostankov, npr. baker, ki kot kovinski kationi pospešujejo korozijo stene cevi. Kemično čiščenje je pomembno predvsem zato, ker lahko iz usedlin odstrani kovinske delce [9].

6. MERILA ČEPLJENJA

Merila za čepljenje temeljijo na dopustni poškodbi cevi, ki mora zadostiti načelom jedrske varnosti. Glede na vrsto poškodbe poznamo dolžinska in globinska merila čepljenja cevi uparjalnikov. Dolžinska merila se nanašajo na dopustno dolžino popolne razpoke cevi. Temeljijo na načelu »puščanje pred zlomom«. Globinska merila čepljenja pa so utemeljena na dopustni nepopolni poškodbi, ki ima površinski značaj. Obe navedeni vrsti meril čepljenja upoštevata:

— trdnost poškodovane stene cevi,

— napako meritve ECT,

— oceno napredovanja poškodbe do naslednjega pregleda.

Analize trdnosti cevi so izvedene za najneugodnejše obremenitvene primere, tj. zlom cevi napajalne vode ob upoštevanju mehanike loma [16]. Ocena napake meritev ECT je izvedena na podlagi umerjanja tipal ECT. Napoved napredovanja poškodb do naslednjega medobratovalnega pregleda cevi pa je utemeljena na statistični analizi poprejšnjih rezultatov meritev.

Dolžinsko merilo terja stalni in sprotni nadzor puščanja uparjalnika in bistveno znižano mejo dopustnega puščanja ter radioaktivnega onesnaženja sekundarnega hladilnega kroga.

V JEK je bil razvoj meril čepljenja naslednji:

Od začetka obratovanja leta 1982 do leta 1990 je bilo uporabljano merilo 40 odstotkov poškodbe stene cevi, ki pa se je z leti deloma spremenilo. Najprej se je to merilo dopolnilo z merilom P*, ki v nekaterih ceveh dopušča vse poškodbe za razdaljo P* pod vrhom cevne stene. Sledile so še manjše sprostitve, ki pa so bile vedno utemeljene s povečano natančnostjo kazanja tipal ECT.

Zaradi nepredvideno hitrega napredovanja števila razpok zaradi medkristalne napetostne korozije in s tem povezanega obsega čepljenja je JEK leta 1990 delno prešla k uporabi dolžinskega merila. To merilo dopušča obratovanje uparjalnikov z omejenimi razpokami, vendar terja sprotno spremljanje naslednjih parametrov:

Mechanical cleaning, using water jets combined with dynamic water vaporization, aimed at loosening the sludge, is used in Krško NPP. The sludge is removed from the steam generator by means of a blowdown system. the removal of all sludge is not possible since it hardens. A lot of metal particles, such as copper in the form of cations, are contained in the sludge, thus accelerating tube wall corrosion. Chemical cleaning is important mainly because of the possibility of removing the metallic parts from the sludge [9].

6. PLUGGING CRITERIA

Plugging criteria are based on the allowable tube wall defect, which should satisfy nuclear safety principles. Length and depth steam generator tube plugging criteria relate to the type of defect. Length criteria are related to the allowable through-wall crack length; this is based on the »leak-before-break« approach. Depth criteria are based on a part-through-wall defect, having surface characteristics. Both types of criteria consider:

— the strength of the degraded tube,

— the ECT sizing error,

— an estimate of defect propagation until the next inspection.

Structural analyses are performed for the most unfavourable load cases, e.g., feedwater line break, considering fracture mechanics [16]. The ECT sizing error is based on an ECT probe calibration data. The prediction of defect propagation until the next in-service inspection is based on a statistical analysis of past measurement results.

The length criterion requires continuous on-line monitoring of the steam generator leak rate and significantly reduced allowable leak rate and secondary cooling system activity.

In the Krško NPP case, the development of plugging criteria has been as follows:

From the beginning of operation, since 1982 until 1990, a criterion of 40 % tube wall degradation was used, with minor modifications over the years. First, a P* criterion was added, allowing for all defects in some tubes, provided that defects are located at least P* below the top of the tube sheet. Some minor relaxations also followed, based on improved ECT probe accuracy.

Due to an unexpected fast growth in the amount of intergranular stress corrosion cracking and consequently an increased plugging extent, a partial use of length criterion was introduced by Krško NPP in 1990. The operation of steam generator tubes containing limited through-wall cracks was allowed by this criterion. However, continuous monitoring of the following parameters is required:

— leak of the primary coolant into the steam generator,

— the length of cracks and their propagation,

— puščanje primarnega hladila v uparjalnik,
— dolžine razpok in njihova rast,
— natančnost kazanja tipal ECT in
— povečan obseg vzorca (100 %).

Uporaba dolžinskih meril je v JEK omejen le na področje tik nad cevno steno. Za druge poškodbe, ki nimajo značilnosti razpoke, ta merila niso primerna.

7. SKLEP

Obratovalne izkušnje s cevmi iz INCONEL-600 kažejo na to, da doba trajanja teh uparjalnikov ne ustreza dobi trajanja jedrske elektrarne, ki je ocenjena na 30 do 40 let. Desetletne izkušnje iz JEK kažejo, da je proces staranja, kljub obratovanju jedrske elektrarne v okviru zahtev tehničnih specifikacij le delno obvladljiv. Iz razvoja pojavov različnih vrst procesov staranja sten cevi je razvidno, da ukrepanja učinkujejo selektivno, saj se z zmanjšanjem intenzivnosti nekaterih procesov staranja pojavljajo druge oblike procesov.

Z ustrezno izbiro meril čepljenja poškodovanih cevi uparjalnika lahko pomembno vplivamo na dobo trajanja uparjalnika. Prvotna merila čepljenja 40-odstotkov poškodovane cevi lahko na podlagi novih spoznanj s področja trdnosti in verjetnostne mehanike loma [16], preizkusov ter stalnega nadzora puščanja uparjalnika sprostimo. Z uvedbo dolžinskih meril je podaljšano obratovanje uparjalnikovih cevi z razpokami. To je ekonomski ukrep, ki omogoča podaljšanje razmeroma kratke dobe trajanje obravnavanih uparjalnikov.

Z uporabo dolžinskih meril se tako izognemo po eni strani čepljenju oziroma izločenju cevi in po drugi zelo dragemu postopku vstavljanja tulcev, ne da bi pri tem zmanjšali obratovalno varnost. Pri tem pa ne smemo zanemariti resnice, ki govori v prid dolžinskim merilom, da se z večanjem obsega čepljenja veča potencialna nevarnost utrujenostnega loma cevi v področju cevnega loka zaradi vibracij.

Glede na dosedanja spoznanja o procesu staranja uparjalnikov JEK bi lahko v najneugodnejših razmerah število začepljenih cevi doseglo zgornjo mejo čez nekaj let. Vsaka začepitev cevi uparjalnikov vpliva na spremembo geometrijskih in termohidrodinamičnih razmer v primarnem hladilnem sistemu, kar narekuje preveritev varnostnih mej sredice.

Da bi upočasnili staranje cevi uparjalnikov, izvaja JEK preprečevalne ukrepe, npr. popuščanje zaostalih napetosti in čiščenje sekundarne strani uparjalnikov. Izvedeni ukrepi kažejo določene pozitivne rezultate, saj je razpoložljivost JEK v zgornji tretjini svetovne lestvice razpoložljivosti jedrskih elektrarn.

— accuracy of the ECT probes,
— increased extent of inspection sample (100 %).

Usage of length steam generator tube plugging criteria is allowed only for the transition zone at the top of the tube sheed. Length criteria are not appropriate for tube defects which are not typical cracks.

7. CONCLUSION

The operating experience with INCONEL—600 steam generator tubes indicates that the life time of such steam generators does not match the life time of a nuclear power plant, which is estimated to be 30 to 40 years. Ten years of NEK experience indicate limited control over the ageing processes, despite operation within the technical specification requirements. The history of different ageing phenomena shows a selective effectiveness of preventive activities, the decrease of some phenomena intensity thus causes the appearance of other similar phenomena.

The appropriate choice of tube plugging criteria may significantly influence the steam generator life time. The initial conservative 40 % of the tube defect may be relaxed, based on new knowledge in the field of strength of materials and fracture mechanics [16], inspection and contiuous on-line leak rate monitoring. By the implementation of length criteria, an extension of the operational life of through-wall cracked steam generator tubes has also been allowed. This is an economical measure, allowing for a prolongation of the relatively short steam generator life time.

By using the length criteria, first, the plugging or deactivisation of tubes and second, very expensive sleeving insertions are eliminated without reducing operational safety. However, the increased potential danger of tube fatigue cracks by increasing the extent of plugging in support of the lenght criteria implementation should not be overlooked. Increased extent of tube plugging caused increased tube bend vibration.

Considering the trend of progress of the ageing phenomena in the Krško NPP steam generators and the case of the most unfavourable conditions, the limit of the number of plugged tubes may be reached in a few years. Each plugged SG tube effects the geometrical and thermohydrodynamical conditions in the primary colling system, requiring verification of the core safety limits.

To slow down the expansion of ageing phenomena in the steam generator tubes, some preventive measures have been implemented by Krško NPP, e.g. relief of residual stresses and cleaning of the steam generator secondary side. The preventive measures implemented show certain positive results, considering that the Krško NPP availability is in the upper third of the world nuclear power plant availability scale.

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