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# Staranje cevi uparjalnikov v Jedrski elektrarni Krško

## Aging of Tubes in the Krško Nuclear Power Plant's Steam Generators

**Leon Cizelj - Ferdo Androjna**

*V prispevku predstavljamo domača prizadevanja, ki so omogočila desetletje varnega in zanesljivega obratovanja JE Krško z imensko močjo v bližini projektne meje uparjalnikov – 18 odstotkov začepljenosti cevi. Podajamo pregled stanja in razvoja procesov staranja. Opisujemo kriterije za popravilo cevi, ki določajo sprejemljivo velikost poškodb. Predstavljamo tudi izbrane rezultate varnostnih analiz, ki smo jih izvedli v podporo obratovanju s poškodovanimi cevmi. Povzamemo lahko, da je JE Krško delovala s poškodovanima, a varnima uparjalnikoma.*

**(Ključne besede: uparjalniki, Inconel 600, varnost, staranje)**

*The paper reviews the domestic efforts devoted to the safe and reliable operation of the Krško nuclear power plant (NPP) at full power, close to the design limit of the steam generators (18% of plugged tubes) for a full decade. This includes an overview of the recent status and history of the degradation processes, discussion of repair criteria, defining the acceptable size of defects and selected results from safety analyses supporting the operation of degraded steam generator (SG) tubes. It is concluded that Krško NPP operated with degraded, but safe, steam generators.*

**(Keywords: steam generators, Inconel 600, safety, aging)**

## 0 UVOD

Cevi v uparjalnikih (SG) predstavljajo večino tlačne meje reaktorskega hladiva v tlačnovodnem reaktorju (PWR). Izpostavljene so toplotnim in mehanskim obremenitvam ter agresivnemu delovanju okolja. Cevi iz Inconela 600 (Ni z dodatkom 15% Cr in 8 % Fe) so občutljive za napetostno korozijo v vroči vodi in pari. Razpoke zaradi napetostne korozije so povzročile večino prezgodnjih zamenjav uparjalnikov tlačnovodnih reaktorjev po svetu [1].

Velike poškodbe lahko povzročijo odpoved cevi in zato pomenijo potencialno zmanjšanje razpoložljivosti in varnosti celotne elektrarne. Najpomembnejša načina odpovedi poškodovanih cevi sta:
- porušitev (razpočenje) ene ali več cevi v uparjalniku (SGTR) in
- prekomerno puščanje reaktorskega hladiva na sekundarno stran.

Razpoložljivost in varnost elektrarne vzdržujemo tudi z rednimi pregledi cevi uparjalnikov. Cevi s prevelikimi poškodbami nato popravijo (npr. vstavijo tulce) oz. izločijo iz uporabe (npr. začepijo).

## 0 INTRODUCTION

The steam generator (SG) tubes represent the majority of the reactor-coolant pressure boundary in a pressurized-water reactor (PWR). They are exposed to thermal and mechanical loads combined with aggressive environmental conditions. The tubes, made of Inconel 600 (Ni with 15% Cr and 8 % Fe), were susceptible to stress corrosion cracking in hot water and steam, the major cause of early retirement of PWR steam generators worldwide [1].

Excessive degradation of tubes might lead to their failure and this leads to a potentially reduced availability and safety of the entire plant. Two potential failure modes of degraded tubing are of particular concern:
- Single or multiple steam generator tube rupture (SGTR),
- Excessive leaking of the reactor coolant to the secondary side.

The availability and safety of the plant is maintained by periodic inspection of SG tubes, which is followed by the repair (e.g., sleeving) or removal from service (e.g., plugging) of the tubes with ex-

Prve cevi so v JE Krško začepili v letu 1985 po komaj treh letih rednega obratovanja elektrarne (od 1982).

JE Krško lahko, v skladu s projektnimi analizami in obratovalnim dovoljenjem, deluje z imensko polno močjo z največ 18% začepljenimi cevmi. Poškodovanost cevi je napredovala dokaj hitro in je dosegla pomemben obseg že med remontom v letu 1990 (sl. 1), ko so se 18-odstotni meji začepljenosti prvič približali. Že takrat je bilo jasno, da zanesljivo in trajno rešitev prinaša le zamenjava uparjalnikov. V obdobju do zamenjave je bilo treba z obsežnimi ukrepi podpreti varno obratovanje s poškodovanimi uparjalniki. Ti ukrepi so:

- spremljanje poškodbe z namenom napovedati kratkoročni in srednjeročni razvoj poškodb in obseg popravil cevi ([3] do [5]);
- primerjalne analize in vpeljava najsodobnejših vzdrževalnih postopkov, dostopnih na trgu, s poudarkom njihovega vpliva na zmanjšanje verjetnosti porušitve cevi in puščanja skozi poškodovane cevi [7];
- ocena tveganj, povezanih s staranjem oz. poškodovanostjo cevi, s sprotnim ocenjevanjem verjetnosti za porušitve cevi in izdatnosti puščanja skozi poškodovane cevi ([7] do [9]).

Glavni namen prispevka je predstavitev domačih prizadevanj, ki so omogočila celo desetletje varnega in zanesljivega delovanja uparjalnikov v bližini njihove projektne meje (18% začepljenost). V prispevku osvetlimo stanje in razvoj procesov staranja (razdelek 1), opišemo kriterije za popravila cevi, ki določajo sprejemljivo velikost poškodb (razdelek 2), in predstavimo izbrane rezultate varnostnih analiz, ki so podprle delovanje s poškodovanimi cevmi (razdelek 3). Povzamemo, da je JE Krško obratovala s poškodovanima, a varnima uparjalnikoma.

cessive degradation. In the Krško steam generators, the first tubes were plugged in 1985, only three years after the commissioning of the plant in 1982.

The nuclear power plant (NPP) in Krško was designed and licensed to operate at full power with up to 18% of the SG tubes plugged. The degradation developed quickly and gained an increased importance during the 1990 outage (see Figure 1), when the 18% limit had already been approached. It was clear that only the replacement of the steam generators could bring a reliable long-term solution. While waiting for the replacement, comprehensive activities were started to support safe operation with the degraded steam generators:

- Assessment of the degradation aimed at short and medium term predictions of the degradation and repair rates ([3] to [6]);
- Comparative analyses and implementation of the most advanced maintenance options available on the market, with emphasis on the impact on the tube rupture probabilities and the leak rates through degraded tubes [7];
- Assessment of risks associated with tube degradation. In particular, routine estimations of tube rupture probabilities and leak rates through degraded tubes were performed ([7] to [9]).

The main aim of this paper is to review the domestic efforts, which enabled safe and reliable operation of the steam generators at their design limit (18% of plugged tubes) for a full decade. This includes an overview of the recent status and history of the degradation processes (section 1), discussion of the repair criteria defining the acceptable size of defects (section 2) and selected results from safety analyses supporting the operation of degraded SG tubes (section 3). It is concluded that Krško NPP operated with degraded, but safe, steam generators.

## 1 ZGODOVINA UPARJALNIKOV V KRŠKEM

### 1.1 Računalniška baza podatkov

JE Krško že od leta 1987 redno pregleduje vse cevi po celotni dolžini s standardnim tipalom s tuljavo (postopek vrtinčnih tokov). V letu 1992 so začeli z rotirajočim tipalom (MRPC) dodatno pregledovati tudi vsa prehodna področja (TTS na sl. 3). V dobrih 14 “dejanskih letih na polni moči (EFPY)” obratovanja uparjalnikov se je nabralo več kot 200.000 zapisov o pregledih cevi. V podporo vzdrževanju uparjalnikov so raziskovalci Odseka za reaktorsko tehniko Instituta “Jožef Stefan” razvili računalniško podprto bazo podatkov [4], ki je bila tudi temelj za vse analize v tem prispevku.

## 1 HISTORY OF THE STEAM GENERATORS AT KRŠKO

### 1.1 Computerized Data Base

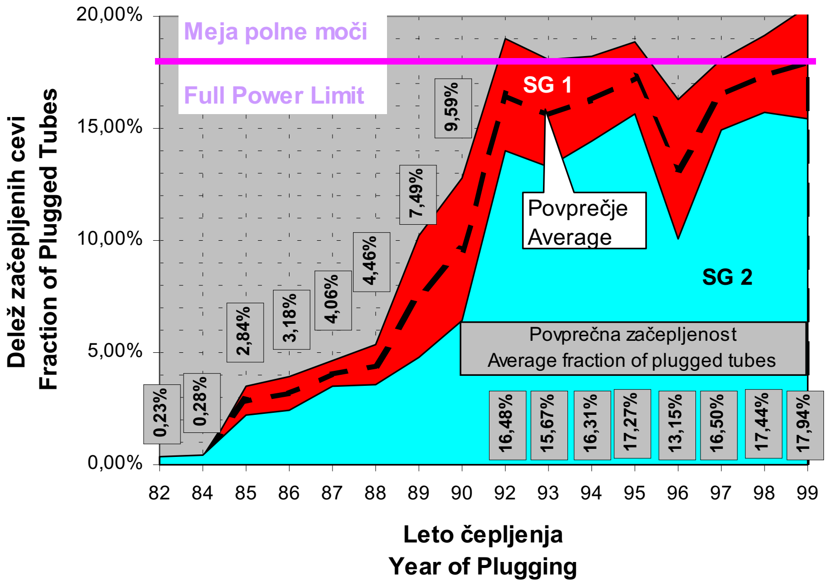
Krško NPP has performed full-length inspection of all tubes by the standard “bobbin coil” (Eddy Current Technique-ECT) method since 1987. In addition, all expansion transitions (TTS, Fig. 3) are inspected by a motorized rotating pancake coil (MRPC) since 1992. More than 200.000 records of inspection results accumulated in nearly 14 effective full-power years (EFPY) of steam generator operation. A computerized database was developed by the Reactor Engineering Division of the “J. Stefan” Institute to support the maintenance of the steam generators [4]. This database was also used for the analyses presented in this paper.

## 1.2 Pregledi in popravila cevi

Slika 1 prikazuje razvoj popravil cevi v obeh uparjalnikih. Polni črti označujeta deleža začepljenih cevi v SG 1 (zgoraj) in SG 2 (spodaj). Črtkana črta označuje povprečni delež začepljenih cevi v obeh uparjalnikih.

## 1.2 Inspection and Repair of Tubes

The history of the tube repairs in both steam generators is depicted in Figure 1. The full lines denote the fraction of the tubes plugged in SG 1 (upper) and SG 2 (lower), while the dashed line shows the average fraction of plugged tubes in both steam generators.




Sl. 1. *Potek začepljenosti*

Fig. 1. *History of tube plugging*

V letih 1993 in 1996 opazimo pomembno zmanjšanje števila začepljenih cevi, ki je predvsem posledica vstavljanja tulcev v nekatere ponovno usposobljene-odčepljene-cevi.

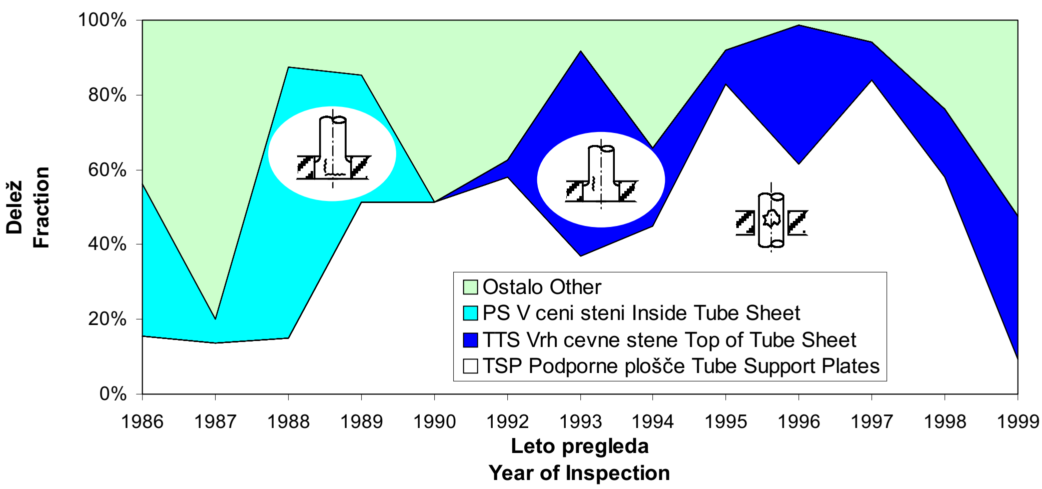
V obdobju po letu 1994 je bilo število na novo začepljenih cevi dokaj stabilno. Izjema je le nenadno povečanje v letu 1997. Pojasnilo je najti v [10].

Slika 2 primerja najpomembnejše vzroke za popravila cevi. Več ko 80% popravil v celotni dobi

A major drop in the number of plugged tubes can be seen in 1993 and 1996. This was a result of the reactivation and sleeving of some of the already plugged tubes.

The repair rates have been relatively stable since 1994, with the exception of in 1997. The explanation for this is attempted elsewhere [10].

The major degradation mechanisms that required the repair of the tubes are compared in Figure 2. More than 80% of tube repairs during the lifetime




Sl. 2. *Glavni vzroki za popravila cevi (SG 1 in SG 2)*

Fig. 2. *Major causes of tube repair (SG 1 and SG 2)*

trajanja uparjalnikov in več kot 90% popravil v zadnjih nekaj remontih pripisujemo le dvema mehanizmoma staranja (sl. 3):

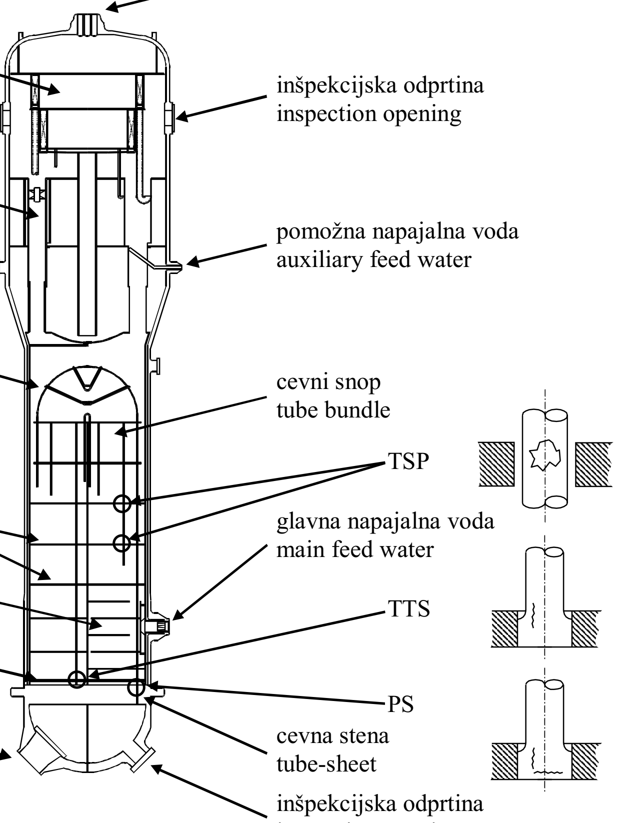
- **TTS:** vzdolžne napetostnokorozijske razpoke v prehodnem področju na vrhu cevne stene (TTS) so povzročile 24% popravil cevi v SG 1 in 17 % v SG 2. Sprejemljiva velikost poškodbe je opisana v razdelku 2.3.
- **TSP:** Napetostno korozijske razpoke na zunanji površini cevi (ODSCC) pod podpornimi ploščami so povzročile 56% popravil v SG 1 in 63 % v SG 2. Sprejemljiva velikost poškodbe je opisana v razdelku 2.4

**PS** označuje tretji najpomembnejši vzrok za popravila cevi (sl. 2), ki je prevladoval pred letom 1988. To so bile napetostnokorozijske razpoke, ki so v celoti znotraj cevne stene. Varnostne analize, opravljene v letu 1990, so pokazale zelo majhno verjetnost odpovedi cevi zaradi takih poškodb (razdelek 2.2 in [4]).

of the steam generators and more than 90% of repairs during the recent outages are attributed to only two degradation mechanisms (Figure 3):

- **TTS:** axial stress corrosion cracking in the expansion transitions at the top of the tube sheet (TTS) caused 24% and 17% of the repaired tubes in SG 1 and SG 2, respectively. The allowable defect size is described in Section 2.3
- **TSP:** outside diameter stress corrosion cracking (ODSCC) at the tube- support- plate intersections (TSP), caused about 56% and 63% of the repaired tubes in SG 1 and SG 2, respectively. The allowable defect size is described in Section 2.4.

**PS** denotes the third major cause of tube retirement shown in Figure 2**.** It stands for stress corrosion cracks located entirely within the tube sheet, which dominated tube repairs until 1988. Safety analyses performed in 1990 showed the very low likelihood of tube failure caused by such defects (see Section 2.2 and [4]).




Sl. 3. *Skica uparjalnika z lego najpogostejših vrst poškodb*
Fig. 3. *Sketch of a steam generator with the locations of dominant degradation mechanisms*

Cevi, ki imajo hkrati več poškodb, so k popravilom prispevale približno 10%.

Podrobnejša razprava o tipičnih procesih staranja, značilnih za JE Krško in druge elektrarne po svetu, je v [11].

Tubes with multiple defects represent about 10% of all repairs.

Further discussion of typical degradation mechanisms found at Krško NPP and elsewhere is given in [11].

## 2 KRITERIJI ZA POPRAVILO CEVI

Pri odločanju o popravilu poškodovane cevi uporabljamo kriterije za popravilo. Tradicionalno uporabljamo splošni kriterij, ki za vse vrste poškodb dovoljuje 40% stanjšanje stene cevi.

V drugi polovici 80. in v 90. letih se je v ceveh uparjalnikov JE Krško in drugih podobnih elektrarnah pojavila napetostna korozija. Ostre in močno razvejane medkristalne razpoke so napredovale skozi steno cevi in včasih povzročile tudi puščanje, še preden so jih odkrili z rednimi pregledi s tradicionalnim tipalom s tuljavo. Sledil je razvoj specializiranih naprav za pregledovanje posameznih vrst poškodb, ki so bile podprte s poškodbam prirejenimi-specifičnimi-kriteriji za popravila cevi. S specifično tehnologijo pregledovanja in analizami porušitev so zmanjšali konzervativnost splošnega kriterija za popravilo cevi.

Osnovni cilj splošnih in specifičnih kriterijev za popravilo je vzdrževanje zanesljivosti in varnosti poškodovanih uparjalnikovih cevi. Kratek opis kriterijev za popravila, ki jih uporablja JE Krško, je v nadaljevanju.

### 2.1 Splošni kriterij za popravilo

Splošni kriterij za popravilo uparjalnikovih cevi določa najmanjšo sprejemljivo debelino stene cevi [15]. Splošno dovoljeno stanjšanje stene cevi znaša 40%. Splošni kriterij je mogoče uporabiti pri vseh vrstah poškodb (npr., druge na sl. 2), razen tistih, za katere veljajo specifični kriteriji, ki so opisani v nadaljevanju.

### 2.2 Kriterij P*

Kriterij P* je namenjen cevem, ki so v celotni dolžini uvaljane v cevno steno. Tako sta bila izdelana tudi prvotna uparjalnika za JE Krško. Kriterij dovoljuje delovanje cevem s poškodbami, ki so najmanj za razdaljo P* oddaljene od vrha cevne stene. Vrsta oziroma usmeritev poškodbe pri tem ni pomembna. Kriterij temelji na naslednjem razmisleku: Cevi so trdno vpete v togo cevno steno, ki lahko v celoti prevzame obremenitve cevi tudi pri 360°obodni skozi stenski razpoki. Dolžino P* pa so določili na podlagi zmožnosti sosednjih cevi, da preprečijo izvlek poškodovane cevi iz cevne stene.

Kriterij P* za popravilo cevi je prvi specifični kriterij, uporabljen v JE Krško. Uspešno ga uporabljajo že od leta 1987 (PS na sl. 2).

### 2.3 Dolžinski kriterij

Dolžinski kriterij je definiran za vzdolžno usmerjene razpoke v prehodnem področju. Prehodno področje je tik nad vrhom cevne stene (TTS), med delom cevi, ki so ga uvaljali - razširili v cevno steno

## 2 TUBE REPAIR CRITERIA

The decision whether to repair a degraded tube or not is based on repair criteria. Traditionally, a generic repair criterion, allowing for 40% of tube wall thinning, is used for all types of defects.

In the second half of the 80s and in the 90s, stress corrosion cracking appeared in the SG tubes of Krško NPP and in other comparable plants. Sharp and highly branched intergranular cracks grew through the tube wall and sometimes caused leaks before being detected by the regular bobbin coil inspection. Specialized defect-specific inspection equipment was developed, accompanied by defect specific repair criteria. Basically, the conservatism inherent in the generic 40% repair criterion was reduced through defect-specific dedicated inspection technology and failure assessment.

The main goal of generic and defect specific repair criteria is to maintain or improve the reliability and safety of the degraded SG tubes. Brief description of repair criteria applicable for Krško NPP is given below.

### 2.1 Generic Repair Criterion

The generic repair criterion defines the minimum acceptable wall thickness [15]. The generic allowable defect size is 40% of the wall thickness. The defect depth criterion is applicable to all defects (see other in Figure 2), except for those covered by the defect-specific plugging criteria described below.

### 2.2 P* Criterion

The P* criterion applies to tubes, hard rolled into the entire depth of the tube sheet, as manufactured in the original Krško steam generators. The criterion allows that tubes with defects located below a certain distance (called P*) from the top of the tube sheet remain in operation without repair, regardless of the defect size or orientation. It makes use of the following consideration: tubes are fixed into the stiff tube sheet, which is able to support the tube even if it contains a 360°circumferential through-wall crack. The P* distance was established by considering the ability of neighboring tubes to prevent the damaged tubes from being pulled out of the tube sheet.

The P* repair criterion was the first defect-specific repair criterion implemented at Krško NPP and has been successfully used since 1987 (see PS in Figure 2).

### 2.3 Crack-Length Criterion

The crack-length criterion is defined for axially oriented cracks in expansion transitions at the top of the tube sheet. The expansion transitions are located just above the top of the tube sheet (TTS), med izdelavo uparjalnikov, in prostim delom cevi. Razpoke v tem delu cevi so nastale predvsem zaradi dokaj visokih notranjih napetosti [12]. Sprejemljiva velikost poškodbe je definirana kot izmerjena dolžina razpoke. Popraviti je tako treba le cevi z vzdolžno usmerjenimi razpokami, katerih dolžina presega *PL*:

between the portion of the tube which has been expanded into the tube sheet during the manufacture of the steam generators and the free span portion of the tube. The cracks mainly develop here due to the high residual stress [12]. The allowable defect size is defined in terms of the measured crack length. Repair is necessary only for the tubes with axially oriented cracks longer than *PL*:

$$PL = a_c - a_e - a_g \quad (1),$$

$a_c$ pomeni teoretično kritično dolžino razpoke, $a_e$ največjo pričakovano merilno napako in $a_g$ največji napovedani prirastek razpoke do naslednjega pregleda [3].

Dolžinski kriterij v JE Krško je prirejen po belgijskih izkušnjah [1]. Uporabljajo ga od leta 1992 (TTS na sl. 2). Najdaljša dovoljena izmerjena dolžina vzdolžne razpoke znaša 6 mm (za primerjavo: teoretična kritična dolžina znaša 14,2 mm).

where $a_c$ stands for the theoretical critical crack length, $a_e$ for the maximal expected measurement inaccuracy, and $a_g$ for the maximal predicted crack propagation before the next inspection [3].

The defect length plugging criterion has been used at Krško NPP since 1992 (see TTS in Figure 2) and has basically followed the Belgian approach [1]. The longest allowable axial crack length is 6 mm (for comparison: the theoretical critical crack length is 14.2 mm).

**2.4 Kriterij ODSCC**

V začetku 90. se je po vsem svetu pojavilo večje število poškodb ODSCC pod podpornimi ploščami (TSP). Zelo zapletena morfologija, tj. močno razvejane mreže razpok, praktično onemogoča analitične napovedi porušitve. Upravljalci elektrarn v ZDA, Franciji in Belgiji so predlagali rešitev, ki temelji na eksperimentalno določeni povezavi med tlakom razpočenja poškodovane cevi in amplitudo signala tipala s tuljavo, ki pomeni merilo velikosti poškodbe (merjeno v voltih - V!). S podobnim postopkom so določili tudi odvisnost med izdatnostjo puščanja skozi poškodbo in amplitudo signala tipala s tuljavo. Lokalne oblasti (v ZDA Nuclear Regulatory Commission – NRC [13]) so tak postopek sprejele. Seveda pa je treba pri uporabi tega kriterija zagotoviti pregledovanje cevi s tehnologijo, ki je enakovredna tehnologiji, uporabljeni pri določanju odvisnosti.

JE Krško kriterija ODSCC ni v celoti vpeljala. Uporabili so le enakovredno tehnologijo pregledovanja cevi, ki omogoča ločitev za varnost pomembnih in manj pomembnih poškodb. Cevi s poškodbami, ki so pomembne za varnost, še vedno popravijo takoj, ko izmerjena globina poškodbe preseže dovoljenih 40% debeline stene cevi (razdelek 2.1).

Posledice takega postopka za varnost elektrarne so opisane v nadaljevanju. Celovita varnostna analiza je opisana v [6].

**2.4 ODSCC Criterion**

A large number of ODSCC defects under tube support plates (TSP) emerged at the beginning of the 90s on a worldwide scale. The very complex morphology (e.g., the highly branched networks of cracks) of such defects essentially prevents the analytical predictions of failures. A solution proposed by the utilities in the United States, France and Belgium relied on an experimentally determined correlation between the burst pressure of the degraded tube and the bobbin coil signal amplitude, which represents the size of the defect (measured in volts - V!). A similar approach yielded a correlation between the leak rate through the degraded tube and the bobbin coil signal amplitude. Such a criterion was accepted by the local authorities (In the USA by the Nuclear Regulatory Commission (NRC) [13]). Use of non-destructive examination techniques equivalent to those used during the development of correlations is, of course, mandatory.

This methodology was, however, not fully implemented at Krško. The equivalent non-destructive examination techniques were implemented to discriminate between the defects which are either important or less important for safety. The defects important for safety are still repaired if they exceed the allowable tube-wall thickness (see section 2.1).

The safety consequences of such an approach are discussed briefly below. A comprehensive safety analysis is given in [6].

## 3 VARNOSTNE ANALIZE

Varnostne analize poškodovanih uparjalnikovih cevi so usmerjene v oba načina odpovedi cevi, ki sta opisana v uvodu. Veliko število pogojno ogroženih cevi in uporaba neporušnih

## 3 SAFETY ANALYSES

Safety analyses of degraded steam-generator tubes are focused on the two failure modes, described in Section 0. The large number of potentially affected tubes and use of non-destructive examinapostopkov za pregledovanje (NDE) stimulirata verjetnostne analize pogojnih odpovedi cevi. Raziskovalci Instituta "Jožef Stefan" smo v zadnjih letih v sodelovanju z JE Krško v ta namen razvili in uspešno uporabili več verjetnostnih metod za ocenjevanje verjetnosti odpovedi uparjalnikovih cevi ([6] do [9]).

Verjetnost za razpočenje in izdatnost puščanja skozi poškodovane cevi smo ocenjevali pri najbolj neugodnem scenariju: pri hipotetični nezgodi z največjo tlačno razliko med primarnim in sekundarnim hladivom, ki se zgodi tik pred pregledom in popravilom cevi. V ta namen ocenimo velikost poškodb ob koncu delovnega obdobja z naključno kombinacijo spodnjih veličin:
- velikosti poškodb ob prejšnjem pregledu;
- negotovosti pregleda z metodo vrtinčnih tokov (ECT)
- večanja poškodb (ocenjeno iz velikosti, izmerjenih v prejšnjih pregledih)

V tem razdelku se posvečamo le napetostnokorozijskim razpokam na zunanji površini cevi (ODSCC) pod podpornimi ploščami (TSP). Poškodbe ODSCC namreč trenutno zahtevajo največ popravil cevi v JE Krško.

### 3.1 Verjetnost porušitve cevi

Slika 4 prikazuje razvoj verjetnosti porušitve ene izmed cevi uparjalnika v obdobju med 1990 do 1999. Prikazana verjetnost je pogojna in predpostavlja, da se je zgodila malo verjetna hipotetična projektna nezgoda zlom glavnega parnega voda. Za vsakega izmed uparjalnikov obravnavamo dva primera: (1) "vse poškodbe", pri katerem v analizi nismo upoštevali popravljenih cevi in (2) "poškodbe pod 1 V", ki predstavlja popravila cevi v skladu s priporočili [13]. Popravila cevi v JE Krško so bila takšna, da je dejansko stanje med obema krivuljama.

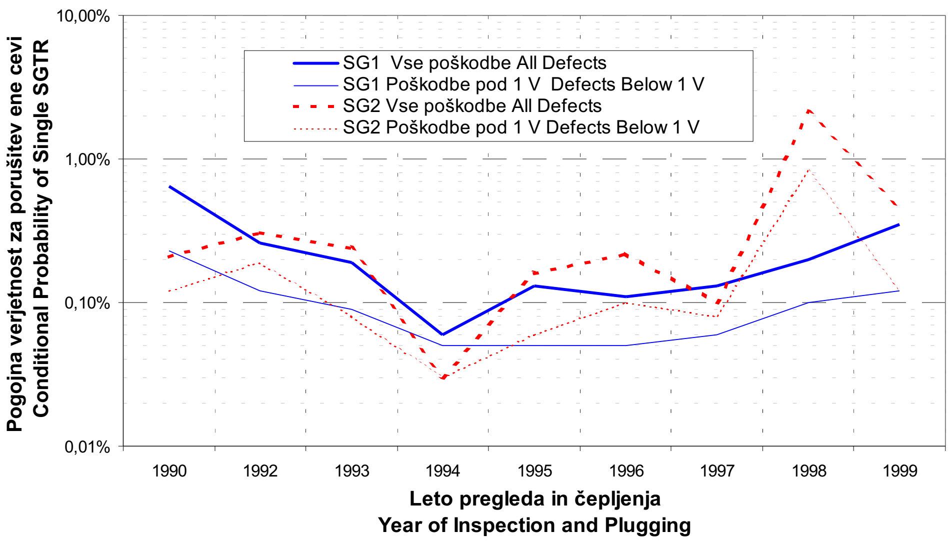
tion (NDE) methods stimulate the probabilistic analysis of potential tube failures. A number of methods aimed at estimating the steam-generator tube failure probabilities have therefore been developed and successfully implemented in recent years in cooperation with the "Jožef Stefan" Institute and Krško NPP (see for example [6] to [9]).

Tube rupture probabilities and leak rates were estimated for a worst-case scenario involving a hypothetical accident with the highest differential pressure across the tube just before the inspection and repair of the tubes. This involves the estimation of the largest defect sizes, estimated by the stochastic combination of the following items:
- Defect sizes at previous inspection;
- Uncertainties of the ECT inspection;
- Defect growth (estimated from the observed defect growth during past inspections).

The particular degradation mechanism addressed in this section is the Outside Diameter Stress Corrosion Cracking (ODSCC) at Tube Support Plates (TSP). ODSCC currently represents the major cause of early tube retirements at Krško.

### 3.1 Probability of Tube Rupture

Figure 4 depicts the development of a single tube rupture probability in both steam generators during the period 1990 to 1999. The depicted probability is conditional and is assumed to follow a rather unlikely occurrence of a hypothetical design accident Steam Line break. Two cases are considered for each steam generator: (1) "All defects", which means that no credit was taken for tube repair and (2) "defects below 1 V", which represents the tube repair following the recommendations of [13]. The tube repair performed at Krško NPP was between both




Sl. 4. *Pogojna verjetnost porušitve ene cevi med hipotetičnim zlomom parnega voda*

Fig. 4. *Conditional probability of single SGTR given a hypothetical SLB accident*

Zato konzervativno privzamemo krivuljo “vse poškodbe”.

Slika 4 kaže dve različni usmeritvi. Za obdobje med 1995 in 1999 je značilno naraščanje verjetnosti porušitve ene cevi, kar je v skladu z naraščajočim pojavom poškodb ODSCC. Po drugi strani kaže obdobje med 1990 in 1994 zmanjševanje verjetnosti porušitve ene cevi. Glavni razlog za to je sprememba tehnologije za neporušne preglede: nova, s priporočili [13] usklajena tehnologija pregledovanja cevi je bila prvič uporabljena v letu 1994. Dosledni rezultati so tako na voljo le za obdobje med 1995 in 1999.

Povprečna pogojna verjetnost porušitve ene cevi v obeh uparjalnikih (“vse poškodbe”) je bila v opazovanem obdobju daleč pod mejo 1%, pri kateri je v skladu s priporočili NRC GL-95-05 [13] stanje treba prijaviti upravnemu organu. Verjetnost za porušitev več ko ene cevi je bila v vseh obravnavanih primerih za najmanj dva velikostna razreda manjša. Povzamemo torej lahko, da je JE Krško delovala s poškodovanima, a varnima uparjalnikoma.

Podrobnejši pregled uporabljenih metod in vhodnih podatkov je v [6] in [7].

### 3.2 Puščanje skozi poškodovane cevi

Slika 5 prikazuje razvoj ocenjene izdatnosti puščanja v obdobju med 1990 do 1999. Prikazana izdatnost puščanja je pogojna in predpostavlja, da se je zgodila malo verjetna hipotetična projektna nezgoda zlom glavnega parnega voda. Za vsakega izmed uparjalnikov obravnavamo dva primera: (1) “vse poškodbe”, pri katerem v analizi nismo upoštevali popravljenih cevi in (2) “poškodbe pod 1 V”, ki predstavlja popravila cevi v skladu s priporočili

curves. In further discussion it is therefore conservative to rely on the “All defects” curve.

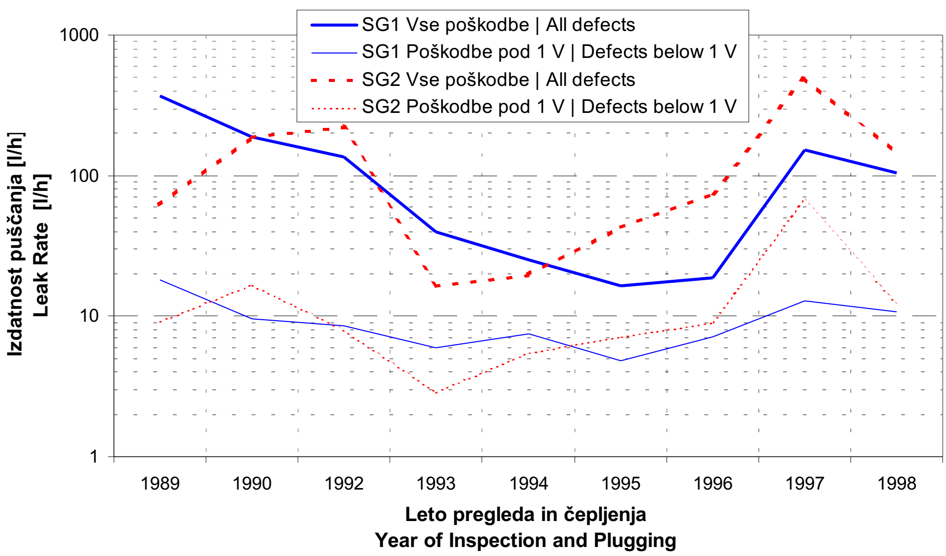
Two different trends may be observed in Figure 4. In the period 1995 to 1999, the probability of tube rupture decreases, which is consistent with the growing population of ODSCC defects. On the other hand, the period 1990 to 1994 exhibits a decreasing probability of tube rupture. The main reason for this is a change in the non-destructive examination technology: the first implementation of [13] compliant NDE methods dates back to 1994. Consistent results are therefore obtained only for the period 1995-1999.

The average conditional single-tube-rupture probability of both steam generators (“All defects”) was well below the reportability threshold of 1% which is foreseen in NRC GL-95-05 [13] during the period depicted in Figure 4. The probability of multiple tube rupture was at least two orders of magnitude lower in all the analysed cases. It may therefore be concluded that Krško NPP operated with degraded, but safe, steam generators.

Details about the methods and input data can be found in [6] and [7].

### 3.2 Leaking of Reactor Coolant Through Degraded Tubes

Figure 5 depicts the development of estimated accidental leak rates in both steam generators in the period 1989 to 1998. The depicted leak rates are conditional and are assumed to follow a rather unlikely occurrence of a hypothetical design accident Steam Line break. Two cases are considered for each steam generator: (1) “All defects”, which means that no credit was taken for the tube repair and (2) “defects below 1 V”, which represent the tube repair




Sl. 5. *Ocenjene izdatnosti puščanja ob hipotetični nezgodi zlom parnega voda*
Fig. 5. *Estimated leak rates given a hypothetical SLB accident*

[13]. Popravila cevi v JE Krško so bila takšna, da je dejansko stanje med obema krivuljama. Zato lahko konzervativno privzamemo krivuljo "Vse poškodbe".

Slika 5 prikazuje dve različni usmeritvi. Za obdobje med 1995 in 1999 je značilno rahlo naraščanje izdatnosti puščanja skozi poškodovane cevi , kar je v skladu z naraščajočim pojavljanjem poškodb. Obdobje med 1990 in 1994 pa kaže na rahlo zmanjševanje izdatnosti puščanja. Glavni razlog za to je sprememba tehnologije za neporušne preglede: nova, s priporočili [13] usklajena tehnologija pregledov je bila prvič uporabljena v letu 1994. Dosledni rezultati so tako na voljo le za obdobje med 1995 in 1999.

Konzervativno ocenjene največje izdatnosti puščanja v obeh uparjalnikih so v velikostnem razredu 0,2 $m^3$/h v SG 1in 0,5 $m^3$/h v SG 2 (1997). To je daleč pod priporočeno največjo izdatnostjo puščanja med projektno hipotetično nezgodo zloma glavnega parovoda 19 $m^3$/h [14], ki zagotavlja še dovoljene obremenitve okolja. Za primerjavo povejmo, da sme JE Krško v skladu z veljavnim obratovalnim dovoljenjem obratovati z izdatnostjo puščanja največ 40 l/h na uparjalnik. Sklepamo torej lahko, da je JE Krško delovala s poškodovanima, a varnima uparjalnikoma.

Podrobnejši pregled uporabljenih metod in vhodnih podatkov je v [6] in [8].

following the recommendations of f13]. The tube repair performed at Krško NPP was between both curves. It is therefore conservative to rely on the "All defects"curve.

Two different trends may be observed in Figure 5. In the period 1995 to 1999, the leak rate through both steam generators was increasing, which is consistent with the growing population of ODSCC defects. On the other hand, the period 1990 to 1994 exhibits a decreasing leak rate. The main reason for this is a change of the non-destructive examination technology: the first implementation of [13] compliant NDE methods dates back to 1994. Consistent results are therefore obtained only for the period 1995-1999.

The conservatively predicted highest accidental leak rates for both steam generators are in the order of 0.2 $m^3$/h in SG 1 and 0.5 $m^3$/h in SG 2 for 1997. This is well below the recommended maximum leak rate of 19 $m^3$/h [14], allowed during a hypothetical SLB. For comparison, the Krško NPP is licensed to operate normally with a leakage of up to 40 l/h through any of the steam generators. It may therefore, again be concluded, that Krško NPP operated with degraded, but safe, steam generators.

Details about the methods and input data can be found in [6] and [8].

## 4 SKLEPI

V prispevku so predstavljena najpomembnejša domača prizadevanja za zagotavljanje varnega in zanesljivega delovanja uparjalnikov v JE Krško. Še posebej smo se posvetili zadnjemu desetletju obratovanja elektrarne. Za to obdobje je značilno, da sta uparjalnika obratovala v bližini njune projektne meje 18% začepljenosti, in je postalo jasno, da lahko le zamenjava uparjalnikov prinese trajno in zanesljivo rešitev.

Pregledali smo trenutno stanje in razvoj procesov staranja, opisali smo kriterije za popravila cevi, ki določajo sprejemljivo velikost poškodb, in predstavili izbrane rezultate varnostnih analiz, ki so podprle delovanje s poškodovanimi cevmi.

Povzeli smo, da je JE Krško z veliko pomočjo domačega znanja delovala s poškodovanima, a varnima uparjalnikoma.

## 4 CONCLUSIONS

The main domestic efforts devoted to the safe and reliable operation of the Krško steam generators are reviewed in this paper. The main focus is given to the last decade of plant operation. In the beginning of this period, the steam generators approached the limit of 18% plugged tubes and it became clear that only the replacement of the steam generators could bring a reliable long-term solution.

The main topics include an the overview of the recent status and the history of degradation processes, discussion of repair criteria defining the acceptable size of defects and selected results from safety analyses supporting the operation of degraded SG tubes.

It is concluded that Krško NPP's operation with degraded, but safe, steam generators, was to a significant extent, based on domestic knowledge.

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Naslova avtorjev: doc.dr. Leon Cizelj
Institut Jožef Stefan
Odsek za reaktorsko tehniko
Jamova 39
1000 Ljubljana

Ferdo Androjna, univ.dipl.inž.str.
Nuklearna elektrarna Krško
Vrbina 12
8270 Krško

Authors' Addresses: Doc. Dr. Leon Cizelj
Institut Jožef Stefan
Reactor Engineering Division
Jamova 39
1000 Ljubljana, Slovenia

Ferdo Androjna, Dipl.Ing.
Nuclear Power Plant Krško
Vrbina 12
8270 Krško, Slovenia

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