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Nova uparjalnika za Jedrsko elektrarno Krško

The New Steam Generators for the Krško Nuclear Power Plant

Krešimir Nemčić

Članek predstavlja nova uparjalnika za JE Krško in opisuje glavne izboljšave projekta in izdelave, ki so kot del stalnega napredka pri razvoju tehnologije uparjalnikov namenjene predvsem večji zanesljivosti in lažjemu vzdrževanju novih uparjalnikov.

Članek tudi podaja osnovne informacije o izdelavi novih uparjalnikov.

(Ključne besede: uparjalniki, Inconel 690TT, ekspanzija, izločevalniki vlage)

This paper presents the new steam generators for the Krško nuclear power plant and describes the main design and fabrication improvements, which are an ongoing research and development effort in steam-generator technology, aimed at improving the reliability and maintainability of the new steam generators.

The paper also provides basic information relating to the manufacturing of the new steam generators.

(Keywords: steam generators, Inconel 690TT, expansion, moisture separators)

0 UVOD

Pogodba za izdelavo novih uparjalnikov je bila sklenjena s Konzorcijem Siemens Framatome. Drugi ponudniki so bili: Westinghouse, ZDA, Babcock & Wilcox, Kanada in Mitsubishi, Japonska. Konzorcij Siemens Framatome je bil izbran na podlagi izpolnjevanja zahtev, ki so bile določene v nabavni specifikaciji in vrednotene na podlagi štirih glavnih kriterijev: dolgoročna zanesljivost tlačne meje, ekonomska upravičenost, zmogljivost uparjalnikov in datum izročitve.

Pred JE Krško so že druge evropske jedrske elektrarne kot nadomestilo za dotrajane Westinghousove uparjalnike izbrale Siemens oz. konzorcij Siemens Framatome. Te elektrarne so: Ringhals 2 in 3 na Švedskem, ASCO 1 in 2 ter Almaraz 1 in 2 iz Španije, Doel 3 iz Belgije.

Nova uparjalnika sta bila izdelana in izročena v 33 mesecih, vključno z njunim transportom iz Santanderja v Španiji do Krškega, kakor je zahtevala pogodba.

Uparjalnika Konzorcija Siemens Framatome sta izdelana v skladu z zahtevami ASME pravilnika o vrelnih in tlačnih posodah, Del III,

0 INTRODUCTION

The contract for manufacturing the new steam generators for the Krško nuclear power plant (NPP) was with the Consortium Siemens-Framatome. The other bidders were Westinghouse (USA), Babcock&Wilcox (Canada) and Mitsubishi (Japan). The consortium Siemens-Framatome was chosen because it best fulfilled the requirements that were specified in the procurement specification and which were evaluated in four areas: long term reliability of the pressure boundary, economy, steam-generator capability and delivery date.

Prior to Krško NPP's decision, other European NPPs had ordered Siemens or Consortium Siemens-Framatome designed steam generators as replacements for the original Westinghouse steam generators. These plants are: Ringhals 2&3 in Sweden, ASCO 1&2 and Almaraz 1&2 in Spain, Doel 3 in Belgium.

The new steam generators were manufactured and delivered in 33 months, this included the transport of the steam generators from Santander in Spain to Krško, as specified in the contract.

The steam generators delivered by Consortium Siemens-Framatome were designed in accordance with the requirements of the ASME Boiler &

Oddelek 1, Podskupina NB, kot komponenti razreda 1. Komponente razreda 1 so tiste, ki sestavljajo tlačno mejo reaktorskega hladila.

Dotrajane stare uparjalnike je treba zamenjati predvsem zaradi velikega števila poškodovanih cevi in s tem povezanimi stroški vzdrževanja. Pri projektiranju in izdelavi novih uparjalnikov smo zato predvideli precejšnje število sprememb, ki bodo povečale odpornost proti poškodbam. Ker na nastanek poškodb najbolj vplivajo: materiali, okolje (tj. predvsem kemija vode) in projekt, je bilo med projektiranjem treba vzpostaviti primerne kriterije, in sicer:

a/ Termohidravlični vidiki
- izogniti se gretju špranj,
- izogniti se zastajanju pretoka,
- izogniti se koncentraciji nečistoč.

b/ Mehanski vidiki
- zmanjšati zaostale napetosti v ceveh,
- zmanjšati vibracije cevi.

c/ Vidiki obratovanja/vzdrževanja
- zagotoviti zadostno rezervo površine za prenos toplote, ki bi se med obratovanjem lahko zmanjšala zaradi čepljenja cevi in usedlin na ceveh,
- zmanjšati delež kapljevine v pari,
- zmanjšati toplotne obremenitve na priključku cevovoda napajalne vode na tlačno mejo (lupino),
- zagotoviti ustrezen dostop osebja za preglede in vzdrževanja.

Da bi izpolnili zelo stroge zahteve nabavne specifikacije, je bilo izvedenih veliko predkvalifikacijskih in kvalifikacijskih testiranj pred uporabo določene tehnologije ali postopkov. Pomembnejše kvalifikacije so bile: kvalifikacija cevi U pred izdelavo, kvalifikacija vrtanja cevne stene, ekspanzije cevi v cevno steno, varjenja, oblaganj z nikljem in drugo, ki se nanašajo na kakovost čiščenja ter kakovost površine.

Zastopniki JE Krško so bili navzoči na različnih lokacijah ves čas izdelave uparjalnikov. Izdelavo in testiranje novih uparjalnikov so neodvisno preverjale tudi slovenske pooblaščene organizacije, npr.: Fakulteta za strojništvo, Inštitut za metalne konstrukcije, Inštitut za kovinske materiale in tehnologije in Inštitut za varjenje.

1 PROJEKTNA ZASNOVA

Nova uparjalnika sta projektirana v skladu s projektnimi kriteriji podjetja Siemens KWU. V naslednjih poglavjih je opisana projektna zasnova novih uparjalnikov za JE Krško (sl. 1).

Pressure Vessel Code Section III, Division 1, Subsection NB, Class 1 Components. Class 1 components are those which form the reactor coolant pressure boundary.

It is necessary to replace worn out steam generators because of the many degraded tubes and the high cost of maintenance. In the design and manufacture of the new steam generators a lot of changes were anticipated which would ensure better resistance to degradation. Because degradation mechanisms are mainly influenced by: materials, enviroment (water chemistry) and design it was necessary in the design phase to establish the following adequate criteria:

a/ Thermal-Hydraulic Aspects:
- Avoid heated crevices,
- Avoid flow stagnation zone,
- Avoid concentration of impurities.

b/ Mechanical Aspects:
- Minimize residual stresses in the tubes,
- Minimize tube vibrations.

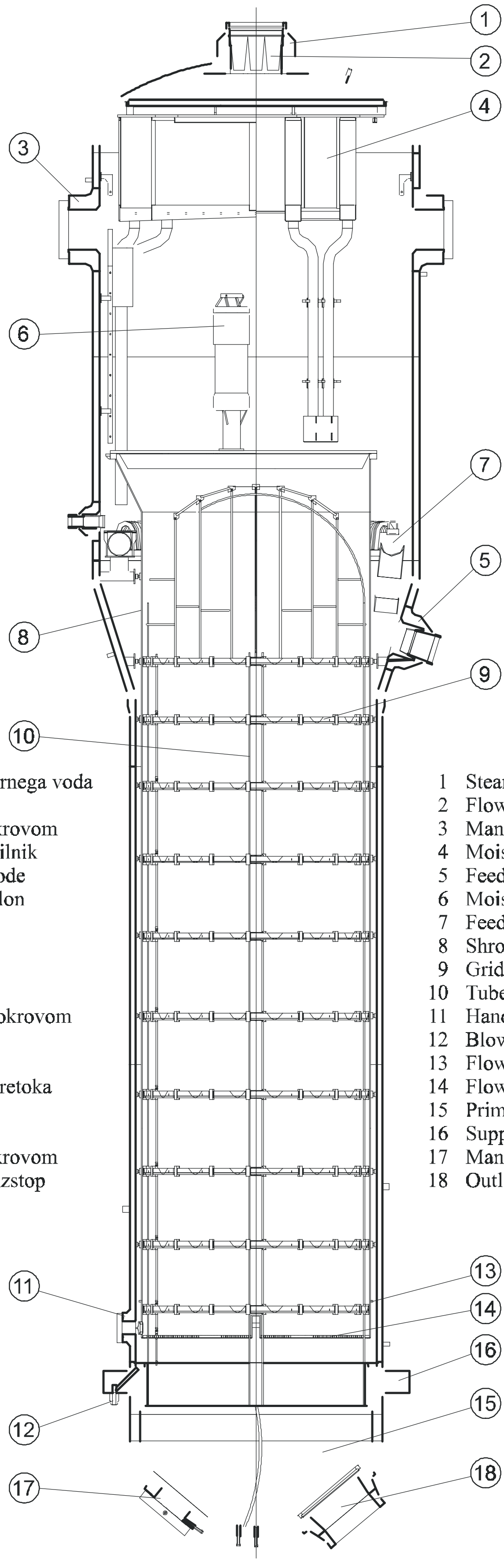
c/ Operational/Maintenance Aspects:
- Provide sufficient margin of heat transfer area, which can be used during operation to compensate for tube plugging and tube fouling,
- Minimize moisture carryover,
- Minimize thermal loading on the feedwater nozzle and pressure boundary,
- Provide adequate access for people during inspection and maintenance.

To fulfill the very stringent requirements of the procurement specification, numerous prequalification/qualification tests were done before a particular technology or operation was applied. The most important qualifications were: preproduction qualification of U-tubes, drilling qualification of tube sheet, expansion of tube inside the tube sheet, welding qualifications, nickel coating qualification and others related to cleaning or surface quality.

At every stage of manufacturing, NE Krško representatives were present at different locations. Additionally, manufacturing and testing of the new steam generators was independently checked by Slovenian Authorized Inspection Agencies, including: the Faculty for Mechanical Engineering, the Institute for Metal Structures, the Institute of Metals and Technology and the Welding Institute.

1 DESIGN CONCEPT

The new steam generators are designed in accordance with the Siemens KWU design concept. The following sections describe the design concept of the new steam generators (NSG) for the Krško Nuclear Power Plant (Figure 1).



1 Priključek glavnega parnega voda
2 Omejilnik pretoka
3 Vstopna odprtina s pokrovom
4 Izločevalnik vlage, sušilnik
5 Priključek napajalne vode
6 Izločevalnik vlage, ciklon
7 Napajalni prstan
8 Notranji plašč
9 Rešetka
10 Cevni snop
11 Pregledna odprtina s pokrovom
12 Drenažni priključek
13 Omejilnik pretoka
14 Plošča za usmerjanje pretoka
15 Primarna komora
16 Podporni obroč
17 Vstopna odprtina s pokrovom
18 Priključek za vstop in izstop reaktorskega hladila

1 Steam outlet nozzle
2 Flowlimiter
3 Manway with cover
4 Moisture separator, dryer
5 Feedwater nozzle
6 Moisture separator, cyclone
7 Feedwater ring
8 Shroud
9 Grid
10 Tube bundle
11 Handhole with cover
12 Blowdown nozzle
13 Flow restrictor
14 Flow distribution plate
15 Primary plenum
16 Support ring
17 Manway with cover
18 Outlet and inlet nozzle

Sl. 1. *Novi uparjanik za JE Krško*
Fig. 1. *New Steam Generator for Krško NPP*

1.1 Tlačne meje na primarni in sekundarni strani

Stene tlačne posode so narejene iz finozrnatih odkovkov iz nizko legiranega jekla (SA 508 CL 3a). Primarno stran sestavljajo primarna komora, valjasti obroč in cevna stena. Ukrivljena plošča iz zlitine Inconel 690TT (SB 168 UNS N06690), ki je privarjena na primarno glavo, valjasti obroč in spodnjo stran cevne stene, ločuje vstopni in izstopni prostor primarne komore. Vstopne in izstopne šobe imajo privarjene avstenitne konce, ki zagotavljajo ustrezen prehod med feritnimi šobami uparjalnika in avstenitnimi cevovodi za reaktorsko hladilo. Znotraj primarne komore sta na področju vstopne in izstopne šobe na nerjavno oblogo primarne komore privarjeni prirobnici za vgradnjo tesnilnih pokrovov. V vsakem od obeh delov primarne komore je vgrajen tudi avstenitni drenažni priključek.

Primarna stran cevne stene je oplaščena z večplastno oblogo iz nikljeve zlitine. Oba dela primarne komore, vključno z notranjimi površinami šob in valjastim obročem, sta v celoti oplaščena z najmanj dvema plastema avstenitnega jekla. Cevna stena skupaj s cevnim snopom ločuje primarni del uparjalnika od sekundarnega, kakor je razvidno s slike 1.

Tlačno mejo sekundarnega hladila sestavljajo: valjasta plašča v spodnjem delu, stožčasti prehod z valjastima koncema, valjasta plašča v zgornjem delu in torisferična glava s šobo za izstop pare na vrhu, ki je opremljena z omejilnikom pretoka. Valjasti plašč, privarjen na cevno steno, ima štiri pregledne odprtine – med njimi je kot 90°. Dve sta usmerjeni v smeri prostora med snopoma cevi. Krožni žleb na obrobju sekundarne strani cevne stene omogoča z obema šobama, privarjenima na spodnjo stran podpornega obroča cevne stene, zelo učinkovito drenažo.

Dva nastavka za zgornji podporni sistem uparjalnika sta privarjena na valjasti podaljšek stožca. Šoba glavne napajalne vode je privarjena na stožčasti prehod. Dve sekundarni vstopni odprtini sta na zgornjem valjastem plašču. Priključek pomožne napajalne vode in priključek za mokro shranjevanje sta privarjena na valjasti plašč nad stožcem. Priključek za mokro shranjevanje je med obratovanjem stalno zaprt s čepom.

1.2 Cevi uparjalnika

Cevi novih uparjalnikov so izdelane iz materiala Inconel 690 TT (UNS N06690), ki so ga razvili za čim boljšo odpornost proti napetostno korozijskim razpokam in proti splošni koroziji v vodi v visokotemperaturnih razmerah uparjalnika.

Inconel 690 je zlitina niklja z zmanjšanim deležem niklja (≥ 58 utežnih odstotkov) in večjim deležem kroma (27 do 31 utežnih odstotkov) v

1.1 Primary- and Secondary-Side Pressure Boundaries

The pressure-vessel walls are made of forgings of fine-grained low-alloyed ferritic steel (SA 508 CL 3a). The primary side consists of the primary head, the cylindrical ring and the tubesheet. A bent plate made of Inconel Alloy 690TT (SB 168 UNS N06690) welded to the primary head, the cylindrical ring and the underside of the tubesheet separates the two chambers of the head. The inlet and outlet nozzles are provided with austenitic safe ends to have a suitable transition between the ferritic nozzles and the austenitic reactor-coolant piping. Inside the primary head, in the area of the inlet and outlet nozzle, each flange ring for the installation of the nozzle dams is welded to the cladding. For drainage, two austenitic drain nozzles are installed in each chamber.

The primary side of the tube sheet is clad with a multi-layer nickel-based cladding. Both chambers of the primary head, including the nozzle inside surfaces and the cylindrical ring, are clad all over with at least a two-layer austenitic cladding. The tubesheet separates the primary from the secondary side as shown in Figure 1.

The secondary side of the pressure boundary consists of: two cylindrical shells in the lower section; the conical transition with cylindrical ends; two cylindrical shells in the upper section and the torispherical head with the integrated steam outlet nozzle on the top, which is equipped with a flow limiter. The cylindrical shell welded to the tube sheet is equipped with four handholes located 90° apart. Two of them are placed in the direction of the tube lane. A circular groove on the periphery of the secondary side of the tube sheet gives, together with the two nozzles welded to the underside of the tubesheet's support ledge, the possibility of a highly efficient blowdown.

The two trunnions for the SG upper support are welded to the lower cylindrical extension of the cone. The main feedwater nozzle is welded to the conical transition. The two secondary manways are welded to the upper cylindrical shell. The auxiliary feedwater nozzle and the wet lay-up nozzle are welded to the cylindrical shell above the cone. The wet lay-up nozzle is closed permanently with a cap during operation.

1.2 Steam Generator Tubes

The NSG tubing is made from Alloy 690 TT (UNS N06690). Alloy 690 TT was developed to resist SCC and general corrosion in the high-temperature aqueous environments associated with nuclear steam generators.

Alloy 690 is a nickel-based alloy with a reduced Ni content (≥ 58 wt%) and a higher Cr content (27 to 31 wt%) compared with Alloy 600.

primerjavi z zlitino 600. V Siemensovi specifikaciji cevi je najnižji delež kroma povečan na ≥ 28,5 utežnih enot, kar povečuje njeno odpornost na medkristalno napetostno korozijo in razjedanje. Delež niklja je od 59,0 do 62,0 utežnih odstotkov. Delež bakra, kobalta, dušika, bora in molibdena je omejen.

Mehanske lastnosti materialov, dobljene s testiranji, so naslednje:

R_{p02} (RT) 276 do 370 MPa (meja plastičnosti pri sobni temperaturi)
Rm (RT) ≥ 586 MPa (natezna trdnost pri sobni temperaturi)
R_{p02} (350°C) ≥ 243 MPa (meja plastičnosti pri 350°C)
Rm (350°C) ≥ 552 MPa (natezna trdnost pri 350°C)

1.3 Spoj cev – cevna stena

Spoj cev – cevna stena je izveden v štirih korakih:

1. uvaljanje koncev cevi zaradi učvrstitve cevi v cevno steno pred varjenjem,
2. varjenje cev – cevna stena,
3. hidravlično raztezanje cevi po celotni višini cevne stene,
4. mehanska razširitev cevi ob obeh koncih hidravlično razširjenega področja.

Uvaljanje

Med uvaljanjem cev namestijo v izvrtino cevne stene in uvaljajo na razdalji približno 20 mm. Tako zaprejo režo med cevjo in izvrtino. Optimalne varilne razmere dosežejo s primernim, vrtilnim momentom stroja za uvaljanje, ki je nastavljen tako, da se med nadaljnjim delom cev ne more premakniti. Material cevi se pri tem relativno malo preoblikuje, kar pomeni sorazmerno malo zaostalih napetosti.

Varjenje cev – cevna stena

Pri varjenju cev – cevna stena se uporablja avtomatski proces varjenja ozkega zvarnega roba s kovinskim polnilom. Varilnik se namesti z uporabo centrirne naprave. To in natančna priprava varjenja z valjanjem in strojno obdelavo zvarnega roba zagotavljajo enotno geometrijsko obliko zvarov. Neprepustnost spoja so preverili s helijevim testom prepustnosti.

Hidravlična razširitev

Hidravlična razširitev cevi po celotni višini cevne stene je izvedena z vodnim tlakom. Hidravlični sistem je bil elektronsko nadzorovan. Oblika orodja s tesnili na obeh straneh omogoča gladek prehod med razširjenim in nerazširjenim delom cevi.

In the Siemens KWU material specifcation for the tubes the minimum Cr content is increased to ≥ 28.5 wt% to improve the resistance against intergranular stress corrosion and pitting. The Ni content is specified as 59.0 to 62.0 wt%. The content of Cu, Co, N, B and Mo has also been restricted.

The mechanical values according to the material test sheet were:

R_{p02} (RT) 276 to 370 MPa (Yield strength at room temperature)
Rm (RT) ≥ 586 MPa (Tensile stress at room temperature)
R_{p02} (350°C) ≥ 243 MPa (Yield strength at 350°C)
Rm (350°C) ≥ 552 MPa (Tensile stress at 350°C)

1.3 Tube-to-Tubesheet Joint

The tube-to-tubesheet joint is made in the following four steps:

1. Tack rolling of the tube ends to position and fix the tubes in the tubesheet in preparation for welding.
2. Tube-to-tubesheet welding.
3. Hydraulic expansion of the tube over the entire height of the tubesheet.
4. Local mechanical expansion at both ends of the hydraulic expanded region.

Tack Rolling

During tack rolling the tube ends are positioned in the tubesheet hole and expanded slightly over a length of approximately 20 mm. This eliminates the gap between the tube and hole. To achieve optimum welding conditions the torque of the expansion tool is adjusted in such a way that the tube will not be dislocated during the subsequent work steps. The tube material receives a relatively low transformation and therefore relatively low residual stresses.

Tube-to-Tubesheet Welding

The tube-to-tubesheet welding utilizes an automatic welding process applying a single-pass pulsed gas tungsten arc (GTA) weld with filler metal. The welding gun was positioned by means of a centering device. This, together with the precise weld preparation by tack rolling and machining of the chamfer, ensures a uniform weld geometry. The leak-tightness of the joint was verified by a helium leak test.

Hydraulic Expansion

Hydraulic expansion of the tubes over the full height of the tubesheet was performed by hydroswaging. The hydraulic system was electronically controlled. The design of the mandrel with the seals at both ends ensures smooth transitions from the expanded to the unexpanded tube area.

Lokalna mehanska razširitev

Da bi lahko trdno pritrdili cevi na cevno steno in v celoti zatesnili špranjo na sekundarni strani, se cevi mehansko razširijo na obeh koncih hidravlično razširjenega področja. Dolžina razširitve na vsaki strani je 50 mm.

1.4 Podporni sistem cevnega snopa

Sistem cevnih podpor sestavljajo trije osnovni elementi: rešetkaste podpore ravnega dela cevi (sl. 2), vodoravni in navpični trakovi v loku cevnega snopa (sl. 3) in valoviti trakovi, ki so na vrhu cevnih lokov.

Projektiranje cevnih podpor izpolnjuje osnovne zahteve:
- izdelavo z zelo majhnimi tolerancami,
- zagotovitev preproste vgradnje cevi,
- prenašanje obremenitev med izdelavo, prevozom in vgradnjo,
- prenašanje obremenitev zaradi normalnega obratovanja in nezgodnih situacij, posebej tistih, ki nastanejo zaradi:
  - vibracij med stabilnim obratovanjem in prehodnimi pojavi, ki so posledica povečanega pretoka pare,
  - deformacij zaradi toplotnih in tlačnih obremenitev,
  - pospeškov zaradi naravnih tveganj in nezgod, ki jih povzroči človeški dejavnik,
- zmanjšanje tlačnih izgub, kar prispeva k večji recirkulaciji pare,
- zmanjšanje nalaganja usedlin na cevnih podporah,
- povečanje odpornosti cevi in njihovih elementov na korozijo, obrabo zaradi trenja in na utrujenost materiala,
- preprečenje stiskanja cevi zaradi oblog v špranjah.

Vsak izmed novih uparjalnikov je opremljen z 10 rešetkami (sl. 2), ki so približno enakomerno razporejene po ravni dolžini cevi med cevno steno in cevnimi zavoji.

Pri lokih cevi U je bilo še posebej treba paziti na:
- zagotovitev trdnosti sestave, ki je praktično brez zračnosti med cevmi in podpornimi trakovi (gibanje cevi je blokirano),
- valoviti trakovi postavijo loke v navpično smer in tako vzdržujejo stalno razdaljo med sosednjimi cevmi.

1.5 Rešetke

Rešetko (sl. 2) sestavljata dve vrsti trakov iz nerjavnega jekla, ki so na robu vpeti v notranji obroč. Kot med trakovi je 60°, vsake cevi pa se dotikajo štirje trakovi. Robovi trakov so vpeti v zarezanem notranjem obroču iz nerjavnega jekla, ki je vpet v zunanji okvir iz feritnega jekla. Vsak osmi

Local Mechanical Expansion

To fasten the tubes firmly to the tubesheet and to completely seal the gap on the secondary side the tubes are locally mechanically expanded at both ends of the hydraulically expanded area. The length of this expansion was 50 mm at each end.

1.4 Tube Bundle Support System

The tube support system consists of three basic elements which are the egg-crate-type supports in the straight run of the tubes (Fig. 2), the horizontal and vertical strips in the bend portion of the tube bundle (Fig. 3) and the corrugated strips which are located in the apex of the tube bends.

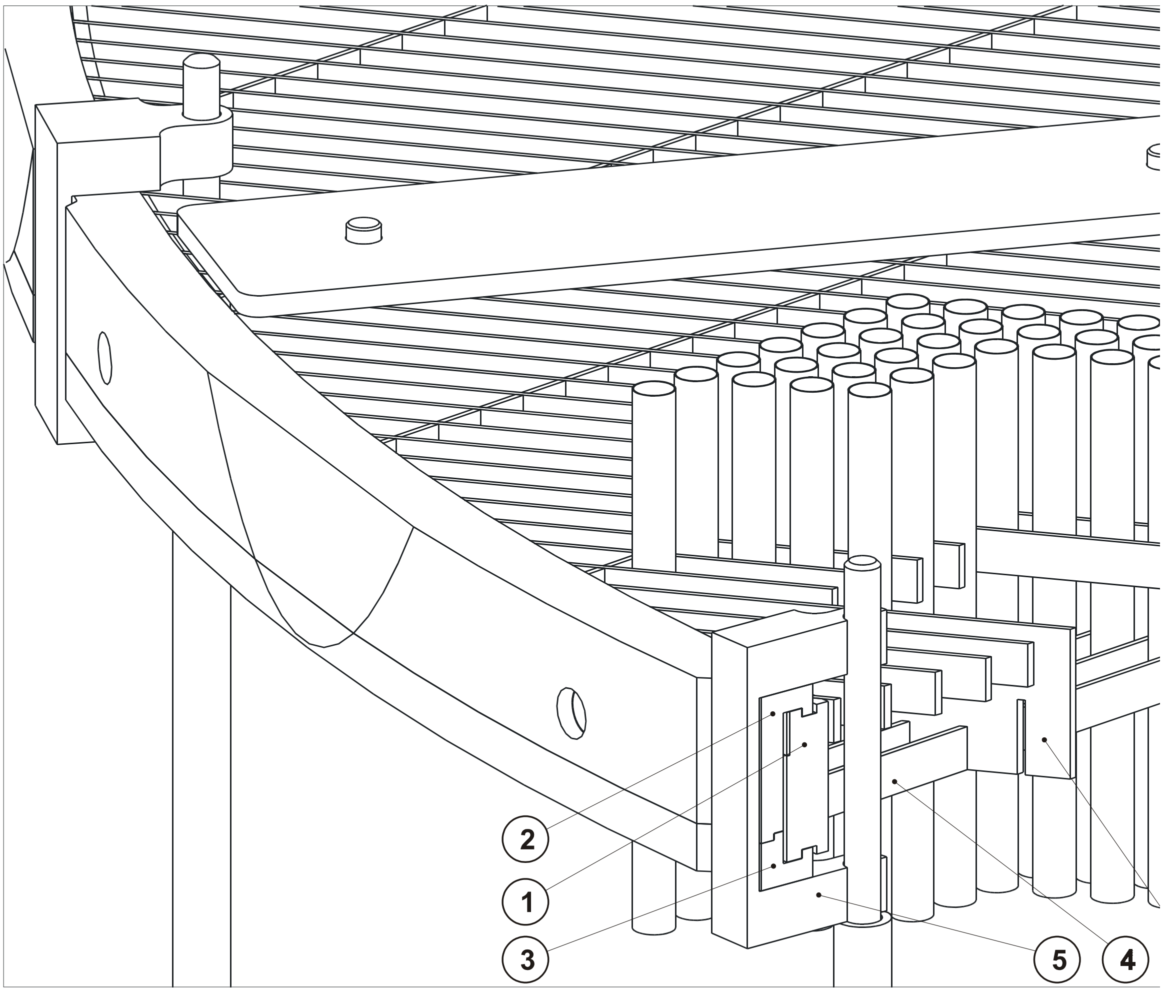
The design of the tube supports (grids) fulfils the basic requirements to:
- facilitate manufacture with very tight tolerances,
- ensure ease of tube insertion,
- accommodate all loads imposed during manufacture, shipment and installation,
- accommodate all operational and accident-induced loads, especially those due to:
  - steady-state and transient flow-induced vibration,
  - thermal and pressure-induced expansion,
  - accelerations due to natural and extemal manmade hazards,
- minimize flow pressure losses (contribute to high circulation ratio),
- minimize accumulation of crud deposits on the tube supports,
- maximize resistance of tubes and their supporting elements against corrosion, fretting and fatigue,
- avoid denting.

Each NSG is equipped with 10 full grids which are appoximately equally distributed over the straight tube length between the tube sheet and U-bend.

For the U-bend the following requirements have also to be taken care of:
- ensuring a compact assembly with nearly no clearances between the tubes and support strips block-type tubing).
- corrugated strips locate the U-bends in their vertical direction, thereby preventing contacts between tubes.

1.5 Egg-crate-Type Supports (Grids)

The egg-crate-type grid (Fig. 2) consists of two rows of stainless steel strips standing on edge and set at 60° to each other; four strips hold the tubes. The ends of the strips are engaged in a slotted stainless steel inner ring, which is engaged in an outer frame of ferritic material. Every eighth strip in the grid consists of a higher



1 – notranji obroč
2 – zgornji okvir
3 – spodnji okvir
4 – nižji trak
5 – spona
6 – višji trak

1 – inner ring
2 – upper frame
3 – bottom frame
4 – low bar
5 – spacer
6 – high bar

Sl. 2. *Podporna rešetka*
Fig. 2. *Egg-crate-type support (grid)*

trak v rešetki je višji podporni trak (69,5 x 3 mm) iz nerjavnega jekla, ki povezuje sicer po višini razmaknjene nižje trakove. Visoki podporni trakovi so vpeti z zarezami, speti med sabo, kar omogoča trdnost podpore v vodoravni smeri. Dve vrsti nižjih trakov (20 x 3,0 mm) sta vstavljeni v zareze ob zgornjih in spodnjih robovih višjih podpornih trakov. Med obročem iz nerjavnega jekla in feritnim zunanjim okvirom je zaradi različnega toplotnega raztezanja načrtovana ustrezna zračnost.

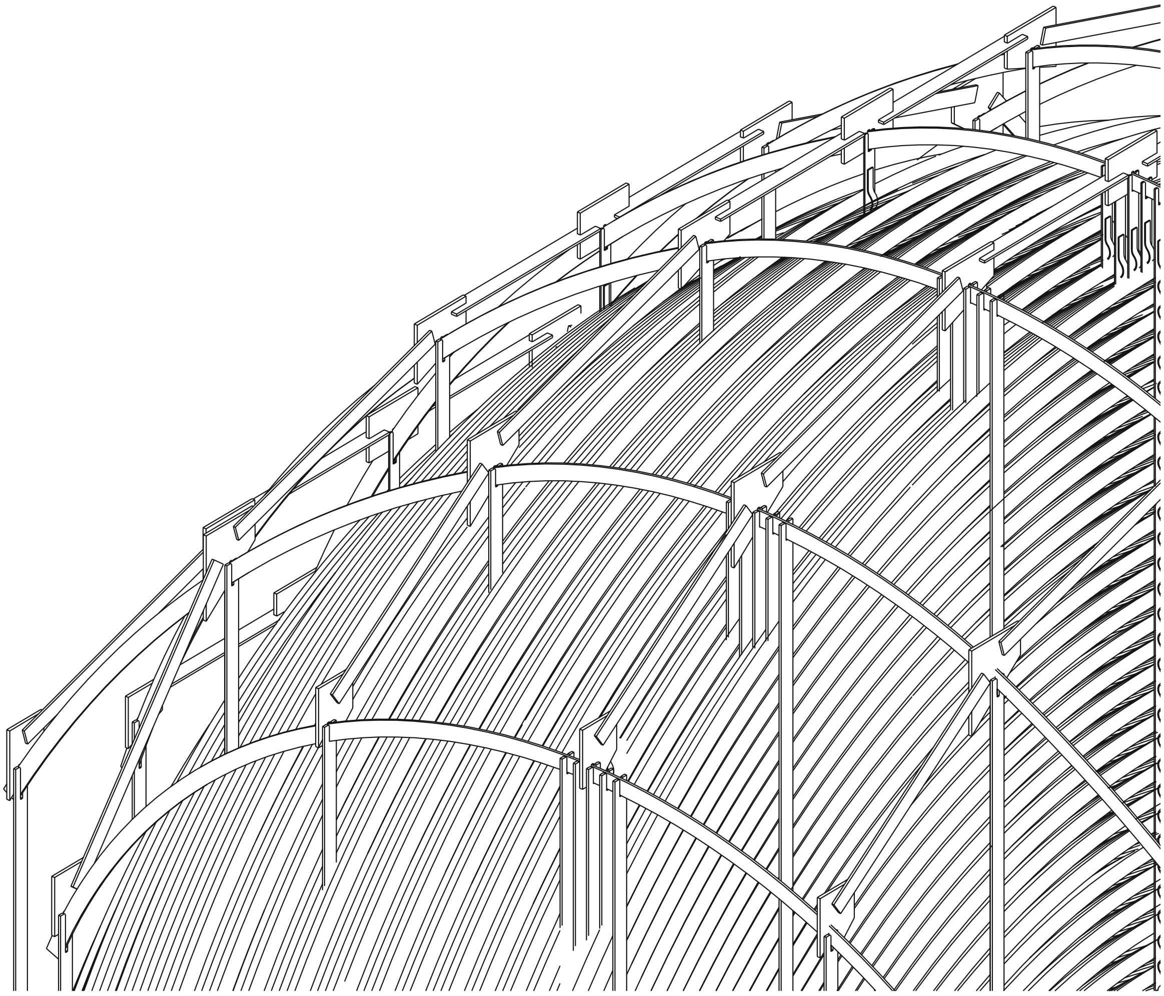
Oblika rešetk in podpor cevnih lokov onemogočajo ohlapnost in medsebojno premikanje trakov. Vse vijačne zveze so zavarovane s podložkami ali zavarjene.

Togost rešetke povečujeta avstenitni palici, ki sta nameščeni na zgornji in spodnji strani rešetke, ki se v prostoru med cevmi raztezata prek celotne rešetke. Palici sta privarjeni in pomenita

support strip (69.5 x 3 mm) also made of stainless steel and spanning the height of both low strip rows. The high-support strips are engaged into each other at the slotted points of the intersection, thus providing structural rigidity in the horizontal direction. The two rows of low-strips (20 x 3,0 mm) engage in slots along the top and bottom edges of the high support strips. To accommodate differential thermal expansion, suitable clearance is provided at the interface between the stainless steel ring and the ferritic frame.

The design of the egg-crate-type supports and the tube bend supports makes it impossible for the strips to work loose or move out of position. All screwed connections in the tube-support system are secured either by lock washers or by lock welds.

Additional stiffness is provided for the grid by two austenitic bars on the top and bottom side of the grid, which stretch over the grid diameter at the tube lane loca-



Sl. 3. *Podpore lokov cevi*
Fig. 3. *U-bend tube supports*

tudi oviro za tok v prostoru med cevmi (zmanjšan obvodni tok).

1.6 Podpora cevnih lokov

V področju snopa cevnih lokov je nameščena podporna struktura iz avstenitnega nerjavnega jekla (sl. 3), ki cevi podpira na optimalnih lokacijah. Podporne lokacije so določene na podlagi konzervativnih projektnih študij vibracij, rezultatov testiranj in odličnih obratovalnih izkušenj.

Podpora cevnih lokov je narejena iz trakov, neodvisnih med sabo, to so:

- navpični valoviti trakovi na vrhu cevnega zavoja,
- navpični ravni trakovi na obeh straneh valovitih trakov,
- vodoravni ravni trakovi na obeh straneh valovitih trakov.

tion. Welded pins connect the bars tightly. In addition, these bars form the tube lane block (reduced bypass flow).

1.6 Tube-Bend Support

In the U-bend region of the tube bundle an austenitic stainless steel support structure (Fig. 3) is used to support the tube bends at optimally spaced locations. The support locations are established in a conservative way after consideration of vibration design studies, experimental results and excellent operational experiences.

The tube-bend support is made up of independent strip elements, namely:

- Vertical corrugated strips located at the apex of tube bend,
- Vertical flat strips located at both sides of the corrugated strips,
- Horizontal flat strips located at both sides of the corrugated strips.

1.7 Razdelilni sistem glavne napajalne vode

Razdelilni sistem glavne napajalne vode v novih uparjalnikih sestavljajo: šoba glavne napajalne vode s toplotnim tulcem, cevovodi z razteznim elementom in razpršilnik napajalne vode.

Razdelilni sistem glavne napajalne vode izpolnjuje vse toplotne in hidravlične zahteve glede: majhnih toplotnih napetosti, onemogočanja razplastitve toka tekočine, enakomerne porazdelitve pretoka v povratnem kanalu in preprečevanja vodnega udara.

1.8 Sistem pomožne napajalne vode

Poleg sistema glavne napajalne vode je uparjalnik opremljen tudi s pomožnim sistemom napajalne vode. Pomožna napajalna voda teče skozi šobo pomožne napajalne vode do prhe, ki je projektirana kot površinski kondenzator. V prhi se voda intenzivno meša s prihajajočo paro. Toplota pare poveča temperaturo napajalne vode in tako bistveno omili toplotne udare tlačne meje in notranjih delov uparjalnika.

1.9 Razdelilnik pretoka

Namen razdelilnika pretoka (sl. 4) je povečati pretok kapljevine in zmanjšati parne praznine med cevmi nad cevno steno. S tem zmanjšamo odlaganje in zbiranje gošče. Sistem razdelilnika pretoka je sestavljen iz dveh plošč z izrezano odprtino.

1.10 Sistem izločevanja vlage

Siemensov sistem izločevanja vlage sestavljajo prvostopenjski in drugostopenjski izločevalniki vlage.

Ta sistem so razvili in testirali v različnih obratovalnih razmerah. Testiranja s paro in vodo so določila podatke o izločevanju vlage, to so: prenos kapljic, tlačne izgube in prenos kapljic pri različnih tlakih pare, nivojih vode in pretokih pare ter napajalne vode. Prvostopenjski izločevalniki (sistem: Siemensovi cikloni) so projektirani tako, da izločijo čim več vode iz mokre pare, ki zapušča cevni snop. Uparjalnik ima 48 prvostopenjskih izločevalnikov.

Drugostopenjski izločevalniki so privarjeni na torisferično glavo in imajo štiri privarjene podporne okvire za valovito pločevino (sistem: Peerless). Drenažne cevi na dnu vsakega izmed podpornih okvirov usmerijo izločene vodne kapljice na dno vodnih pasti. Te vodne pasti pari preprečijo, da bi jo odpihnilo navzgor proti drenaži, kadar nivo vode pade pod dno drenaž. Velikost drenažnih cevi je projektirana tako, da odvajajo vodo, ne da bi zmanjšale učinkovitost sušilnikov.

1.7 Main Feedwater Distribution System

The design of the NSG internal feedwater distribution system consists of the feedwater nozzle with thermal sleeve, piping with expansion bellows and a feedwater sparger.

The main feedwater distribution system fulfills all thermal and hydraulic requirements with respect to: low thermal stresses, destratification effect, equal flow distribution into downcomer and water hammer prevention.

1.8 Auxiliary Feedwater System

In addition to the main feedwater system the steam generator is equipped with an auxiliary feedwater system. The auxiliary feedwater is fed via the auxiliary feedwater nozzle to the auxiliary feedwater distributor, designed as a surface condenser. In the distributor the water is mixed intensively with the upcoming steam. The condensing heat of the steam increases the temperature of the feedwater and so thermal shocks of the pressure boundary as well as of the internals are prevented.

1.9 Flow-Distribution Plate

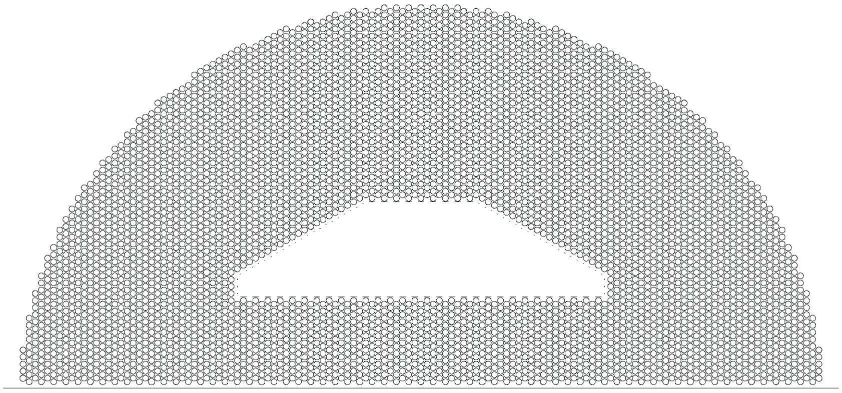
The purpose of the flow-distribution plate (Fig. 4) is to increase the liquid flow and to minimize steam voiding zones in the tubed region above the tubesheet so as to reduce sludge deposition or accumulation. The flow distribution baffle system consists of two orifice plates, each with an integrated cutout.

1.10 Moisture-Separation System

The Siemens KWU moisture separation system consists of first-stage separators and second-stage separators.

This system was developed and tested under a variety of operating conditions. The steam/water tests included obtaining separator performance data such as moisture carry-over, pressure loss and carry-under as a function of steam pressure, water level and steam and water mass flows. The first-stage separators (System: Siemens cyclones) are designed to separate as much water as possible out of the wet steam leaving the tube bundle. The steam generator accommodates 48 first stage separators.

The second-stage-separator assembly is welded to the torispherical head and consists of four welded support frames that accommodate the second-stage-separator plates (System: Peerless). Drain tubes in the bottom of each end of the support frames direct the separated water droplet downward into connected water traps. These water traps prevent steam from blowing up through the drains when the water level drops below the bottom of the drains. The drain tube sizes are designed to ensure that the water drains off without affecting drier efficiency.



Sl. 4. *Razdelilnik pretoka*
Fig. 4. *Flow-distribution plate*

V drugostopenjskih izločevalnikih je preostala vlaga v pari , ki zapušča prve izločevalnike, izločena do takšne mere, da iz uparjalnika do turbine potuje praktično suha para. Suhost pare na izstopu iz uparjalnika je najmanj 99,9 %, največji prenos vlage na izhodu omejilnika iztoka pare je 0,1 odstotek.

In the second stage separators the residual moisture in the steam leaving the first stage separators is removed to such an extent that almost dry steam flows from the steam generator to the turbine. The quality of extracted steam is 99.9%, the maximum moisture carry over is 0.1% at the outlet of the steam flow limiter.

1.11 Splošni podatki

1.11 General Data

UPARJALNIK STEAM GENERATOR	Stari D4 Old D4	Novi 72W New 72 W
toplotna moč thermalpower per SG	941MWt	1000 MWt
površina prenosa toplote heat transfer area	4487 m²	7177 m²
material cevi tube material	Inconel 600MA	Inconel 690TT
število cevi number of tubes	4578	5428
zunanji premer cevi outer diameter of tube	19,05 mm	19,05
tlak pare steam pressure	6,35 MPa	6,50 MPa
največja vlažnost max. steam moisture	0,25	0,10
obtočno razmerje circulation ratio	2,06	3,7
masa suhega uparjalnika total dry weight	330 t	345 t

2 IZDELAVA

Izdelava uparjalnikov je bila zelo zapletena naloga, ki so jo uspešno opravili v Španiji (ENSA). Konzorcij Siemens/Framatome je kot glavni izvajalec dobro vsklajeval dela s številnimi soizvajalci. Odkovki za tlačno mejo so bili izdelani na Japonskem (Japan Steel Works). Izdelava cevi U je potekala na Švedskem (Sandvik Steel). Glavne podkomponente: primarna glava, notranji plašč, zunanji plašč, rešetke, razdelilnik napajalne vode so bile izdelane v Italiji (ANSALDO). Tudi vijaki, matice, podaljšani tulci so bili izdelani v Italiji (OME). Iz Nemčije so dobili: primarne izločevalnike (Mechanic Center), tesnilne obroče

2 MANUFACTURING

Manufacturing of the steam generator was a very complex task which was very successfully completed in Spain (ENSA). Consortium Siemens-Framatome, as the main contractor, coordinated the numerous subsuppliers. The forgings for the pressure boundary were manufactured in Japan (Japan Steel Works). Manufacturing of the U-Tubes was performed in Sweden (Sandvik Steel). Major sub-assemblies such as: primary head, shroud, shell, grids, feedwater distribution, were manufactured in Italy (ANSALDO). Studs, nuts, extension sleeves were also manufactured in Italy (OME). Some parts came from Germany: primary separators (Mechanic Center), sealing discs (Kempchen) and

(Kempchen) in raztezne elemente (Witzenmann). Peerless izločevalniki (GSS Sarre Union) in material za pokrove (CLI) so iz Francije.

3 IZBOLJŠAVE

V primerjavi s sedanjima uparjalnikoma sta nova v zasnovi drugačna. Glavna razlika je vidna pri izbiri materialov, pri izdelavi in projektiranju.

a. Materiali
   Zlitina Inconel 690TT za cevi nadomesti zlitino Inconel 600MA.
   Material za tlačno mejo SA 508 CL.3a, prej SA 533 Gr.B.
b. Izdelava
   Odkovki, prej varjena pločevina (v novih uparjalnikih ni vzdolžnih zvarov).
   Natančnejša izdelava cevi.
   Vpetje cevi v cevno steno (minimizacija zaostalih napetosti).
   Kakovost površine obloge primarne glave (minimizacija obsevanosti osebja).
   Nikljeve obloge na omejilniku pretoka pare.
c. Projektne značilnosti
   Projekt cevnega snopa (bistveno povečana površina za prenos toplote, rešetke, učvrstitev proti vibracijam).
   Koncept napajanja z vodo (lega priključkov napajalne vode, razdelilni sistem napajalne vode).
   Valjasti obroč med cevno steno in primarno glavo.
   Povečani premer vstopnih odprtin.

4 SKLEP

Nova uparjalnika sta bila z ladjo pripeljana iz Santandra (Španija) do Kopra, iz Kopra v Krško pa brez težav s cestno-transportno kompozicijo. Spravljena sta v posebnem prostoru, kjer čakata na zamenjavo.

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expansion compensators (Witzenmann). Peerless separator vanes (GSS Sarre Union) and material for opening covers (CLI) came from France.

3 IMPROVEMENTS

The NSG is different from the existing steam generator. The essential differencies are visible in the chosen materials, manufacturing and design.

a. Materials
   Tubing material, alloy 690TT, replaced alloy 600MA
   Pressure boundary material, SA 508 Cl.3a, replaced SA 533
b. Manufacturing
   Forging vs. plate (no longitudinal welds in the new steam generators)
   More precise tube processing
   Expansion of tubes
   Quality of channel head cladding surface finish (Principle As Low As Reasonable Achievable, ALARA, for radiation exposure of personnel))
   Steam flow limiter nickel coating
c. Design features
   Tube bundle design (enlarged heat exchanger area, grids, AVB)
   Feedwater concept (position of feedwater nozzle, feedwater distribution system)
   Internals design (auxiliary feedwater, separators, shroud and deckplate)
   Cylindrical ring between tubesheet and channel head
   Manway opening diameter enlarged.

4 CONCLUSION

The new steam generators were transported from Santander (Spain) to Koper by ship and from Koper to Krško by truck without any damage. They are sited in the Krško storage area and are waiting to replace the existing generators.

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