

UDK 621.039.534

**Kombinirano hlađenje v jedrski elektrarni Krško**

PREDVIDEVANJA IN IZVEDBA

**Combined Cooling in the Krško Nuclear Power Plant**

PREVISIONS AND IMPLEMENTATION

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*Prvi investicijski elaborat o gradnji jedrske elektrarne v Sloveniji je bil izdelan že davneg leta 1965. Zaradi sorazmerno majhne celotne moči elektroenergetskega sistema je bila izbrana moč 300 MW. Načrtovano je bilo, da bo v uporabi najkasneje do leta 1972. V ožji izbiri so bile tri najprimernejše lokacije; ena ob Dravi v Zlatoličju pri Ptuju in dve ob Savi, v Dolskem pri Ljubljani in v Krškem. V elaboratu je bila najprimernejša lokacija definirana z vidika energetskih, hidroloških, meteoroloških, geoloških, seizmoloških in demografskih okoliščin, in sicer v Krškem [1]. Zaradi več vzrokov je bil začetek gradnje preložen.*

*The first pre-feasibility study on construction of a nuclear power plant in Slovenia was prepared as early as 1965. Considering the relatively low total power of the Slovenian electrical system the power of 300 MW was chosen. The new nuclear plant was supposed to be put into operation in 1972 at the latest. Among several available sites three were chosen as the most suitable: one on the Drava river near Ptuj and two on the Sava river, one in Dolsko near Ljubljana and the other one at Krško. As to the site chosen at the end the pre-feasibility study said: »The most appropriate site in Slovenia is that of Krško taking into account energy supply, hydrological, meteorological, geological, seismic and demographic conditions« [1]. For several reasons the commencement of construction was delayed.*

## 0 UVOD

Strokovnjaki so imeli v tem času veliko manj predpisov, ki so bili vezani na vprašanje topotnega onesnaževanja. V mednarodnem prostoru so bila podana priporočila UNIPEDE iz leta 1971, ki jih je pripravila skupina izvedencev za hladilno vodo na Dunaju. Države so imele zelo različna priporočila oziroma predpise. V preglednici 1 je prikazanih nekaj držav in njihovi predpisi.

Preglednica 1

|   | F  | B  | D <sup>x</sup> | CH | I  | NL  | GB               | USA |
|---|----|----|----------------|----|----|-----|------------------|-----|
| Najvišja temperatura<br>Max. temperature  | °C | —  | 30÷35          | 30 | 30 | 30  | 30 <sup>xx</sup> |     |
| Najvišja teoretična<br>zmesna temp.<br>Max. theoretical temp.<br>of mixture     | °C | 30 | —              | 28 | 25 | —   | 30 <sup>xx</sup> |     |
| Največje zvišanje<br>temp. po mešanju<br>Max. increase of<br>temp. after mixing | K  | 3  |                | 3  | 3  | 2÷3 | —                | 8,5 |
| Zvišanje temperature<br>v kondenzatorju<br>Temperature increase<br>in condenser | K  | —  | —              | 10 | —  | —   | —                | 2,8 |

— ni predpisov

x te vrednosti veljajo samo za vode v 2. razredu čistosti  
xx ni dovoljeno poznejše ohlajevanje, s katerim bi znižali  
temperaturo povratne hladilne vode na dovoljenih  
30 °C

Priporočajo 7-8 K porast temperature v kondenzatorju

Table 1

At the time there were not many regulations referring to the question of thermal pollution. On the international level were the UNIPEDE recommendations from 1971, prepared by a group of experts on water cooling problems from Vienna. Different countries had quite different recommendations or regulations to follow. Table 1 indicates some of these countries and their regulations.

— no regulations

x values apply only to water of 2nd purity category

xx subsequent cooling, reducing the return cooling water temperature to permissible 30° C, is not allowed  
The temperature increase in condenser is recommended to be 7-8 K

Predpisi v Sloveniji so bili približno enaki kakor v sosednjih državah s podobnimi klimatskimi naravnimi okoliščinami. Temperatura po mešanju ne sme preseči  $28^{\circ}\text{C}$  in pri odvzemu vode iz reke mora imeti še nek biološki minimum. Vse drugo je bilo prepričeno vodnogospodarski odločbi, ki jo je izdal po Zakonu o gradnji objektov Vodnogospodarski inšpektorat Slovenije.

### 1 HIDROMETEOROLOŠKI PODATKI IN VODNOGOSPODARSKA DOLOČILA

Opozovanja in meritve pretoka reke Save so bila na voljo od leta 1924 naprej na najbližji vodomerni postaji v Radečah. Ugotovljen je petdesetletni povprečni pretok  $232 \text{ m}^3/\text{s}$ . Za lokacijo JE v Krškem je bilo treba pretok povečati za 7% pri manjših pretokih. Sava ima hudourniški značaj. Katastrofalna poplava leta 1980 je dosegla  $2406 \text{ m}^3/\text{s}$  in močno poškodovala že postavljen jez jedrske elektrarne. Za hlajenje so pomembni podatki najmanjših pretokov in z njimi ugotovijo, ali je dovolj hladilne vode za potrebe pretočnega hlajenja ali moramo računati z zmanjšanjem moči in električne energije ali pa moramo ukrepati z dodatnimi tehničnimi rešitvami.

V preglednici 2 so prikazani nekateri povprečni mesečni podatki o Savi v vodomerni postaji pri Radečah, dobljeni iz opazovanj od let 1924 do 1972 — limnografi.

Preglednica 2: Podatki o Savi pri Radečah  
Table 2: Data on the Sava river at the Radeče

|            |                       | J    | F   | M    | A    | M    | J    | J    | A    | S    | O    | N    | D    |
|------------|-----------------------|------|-----|------|------|------|------|------|------|------|------|------|------|
| $Q_s$      | $\text{m}^3/\text{s}$ | 198  | 197 | 225  | 273  | 260  | 265  | 169  | 146  | 182  | 244  | 353  | 256  |
| $Q_{\min}$ | $\text{m}^3/\text{s}$ | 54,1 | 49  | 77,2 | 84,0 | 87,6 | 71   | 55,2 | 57,7 | 40,0 | 38,4 | 35,2 | 77,2 |
| $T_{\max}$ | $^{\circ}\text{C}$    | 3,6  | 4,1 | 6,3  | 11,2 | 15,6 | 19,5 | 20,3 | 17,5 | 16,5 | 14,2 | 8,0  | 7,0  |
| $T_s$      | $^{\circ}\text{C}$    | 3,4  | 3,9 | 6,0  | 8,9  | 11,6 | 14,2 | 16,2 | 16,6 | 14,2 | 10,9 | 7,9  | 4,9  |

Najmanjši pretoki Save in najvišje temperature, vse v mesečnih povprečjih 49 let, niso v medsebojni zvezi, zato jih je bilo treba še prilagoditi za dimenzioniranje hladilnih naprav.

Urejen diagram najmanjših pretokov v obdobju 1924 do 1972 je prikazan na sliki 1. Diagram daje samo indikativne podatke. Absolutni mesečni minimum je bil leta 1964 in je znašal  $38,4 \text{ m}^3/\text{s}$ . Med vrednostjo  $40\text{--}50 \text{ m}^3/\text{s}$  je bil v tem času petkrat.

Za ocenjevanje verjetnosti pretokov so projektni upoštevali statistično verjetnostni račun porazdelitev po Parsonovem zakonu — porazdelitev III za lokacijo v Krškem in določili naslednje vrednosti:

$$Q_s 99\% = 132,5 \text{ m}^3/\text{s},$$

$$Q_s 97\% = 147,2 \text{ m}^3/\text{s},$$

V preglednici 3 so prikazani nekateri parametri za zrak iz opazovanega obdobja od 1952 do 1959 leta — mesečna povprečja.

The Slovene regulations were almost the same as those of the neighbouring countries with similar climatic conditions. After mixing the temperature should not exceed  $28^{\circ}\text{C}$  and after the water intake from the waterway a certain biological minimum should be respected. All the rest was regulated by approvals of Water Authorities issued by the Water Management Inspectorate of Slovenia.

### 1 HYDRO-METEOROLOGICAL DATA AND WATER MANAGEMENT PROVISIONS

Data resulting from observations and measurements of the Sava river flow were available from 1924 onwards at the nearest water gauge station in Radeče. An average fifty year flow of  $232 \text{ m}^3/\text{s}$  was recorded. The Krško site required a flow increase of 7% when the flow was low. The Sava river is torrential in nature. In 1980 flood water reached  $2406 \text{ m}^3/\text{s}$  and seriously damaged the already built dam at the nuclear plant. Efficient cooling requires data on the lowest river flows because on that basis it can be established whether there is enough water for the needs of flow cooling or whether the power and electricity have to be reduced or some other additional solution found.

Table 2 indicates some average monthly data on the Sava river as recorded at the Radeče gauge station and which result from observations made during 1924 to 1972 — limnographs.

The lowest flows and the highest temperatures of the Sava river, indicated as average monthly values for 49 years, are not correlated; therefore, they had to be additionally adapted to the capacity of cooling equipment.

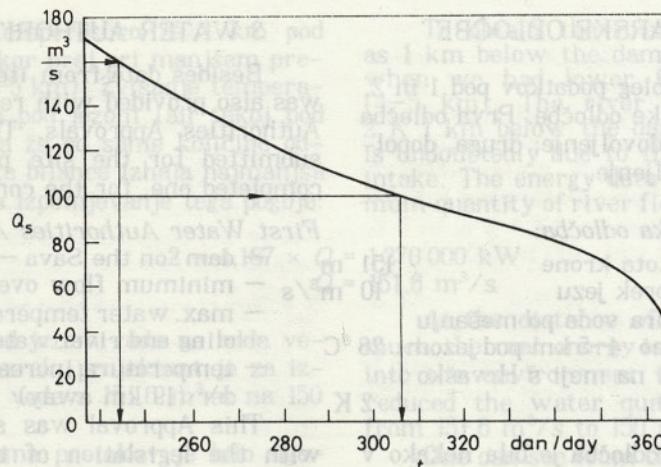
Figure 1 comprises a diagram of the lowest flows from 1924 to 1972. The values from the diagram are only of an informative nature. The absolute monthly minimum of  $38,4 \text{ m}^3/\text{s}$  was recorded in 1964. Flow values of  $40\text{--}50 \text{ m}^3/\text{s}$  were recorded five times in this period.

For the estimation of probable flows at Krško the consultant applied statistical probability calculus according to Parson's Law — distribution III and obtained the following values:

$$Q_s 98\% = 142,2 \text{ m}^3/\text{s}$$

$$Q_s 95\% = 162,3 \text{ m}^3/\text{s}$$

Table 3 indicates some air parameters observed from the period observed from 1952 to 1959 — monthly averages.



Sl. 1. Prikaz minimalnih podatkov – 49-letno povprečje od 1924 do 1972 leta  
Fig. 1. Review of minimum data – 49 years average from 1924 to 1972

Pregledica 3: Parametri zraka v Krškem  
Table 3: Air parameters at Krško

|    | J    | F    | M   | A    | M    | J    | J    | A    | S    | O    | N    | D   |      |
|----|------|------|-----|------|------|------|------|------|------|------|------|-----|------|
| *  | -0,7 | +0,9 | 5,4 | 11,0 | 14,9 | 18,6 | 20,5 | 19,7 | 16,1 | 10,6 | 5,9  | 1,3 | 10,4 |
| ** | 89   | 86   | 80  | 77   | 75   | 78   | 77   | 79   | 84   | 87   | 89   | 92  | 83   |
| x  | 6,9  | 2,7  | 1,1 | 1,4  | 1,6  | 1,4  | 1,7  | 4,1  | 7,2  | 9,9  | 12,9 | 9,3 | 53,2 |
| xx | 0,2  | 0,3  | 0,1 | 2,6  | 5,1  | 7,2  | 6,4  | 3,8  | 3,0  | 0,4  | 0,1  | 0,2 | 29,4 |

\* temperatura zraka °C

\*\* vlažnost %

x št. meglenih dni

xx št. nevihtnih dni

\* air temperature in °C

\*\* humidity in %

x number of foggy days

xx number of stormy days

V mesecu juliju je bil izmerjen v običajnih okolišinah navpični gradient 0,67 K/100 m. Inverzija cona je v višini 40 do 50 m nad Krškim poljem.

In July a vertical gradient of 0,67 K/100 m was recorded under normal statistical conditions. The inversion zone is on the height 40 to 50 m above the Krško Plain.

## 2 PODATKI O ENERGETSKI BILANCI

Dobavitelj jedrske elektrarne Krško podjetje Westinghouse je podal naslednje vrednosti, ki se nanašajo na odvod energije:

|                                   |      |      |
|-----------------------------------|------|------|
| toplota moč reaktorja             | 1975 | MW   |
| moč generatorja                   | 664  | MW   |
| moč na pragu elektrarne           | 632  | MW   |
| količina kondenzata pare          | 604  | kg/s |
| odvedena toplotna energija        | 1270 | MW   |
| količina hladilne vode            | 25   | m³/s |
| temperaturni porast hladilne vode | 12,3 | K    |
| tlačne izgube v kondenzatorju     | 2,6  | MPa  |

V odvedeni energiji je zajeta tudi energija, ki jo odvajamo iz hladilnih sistemov v internem hladilnem krogu, ter bistvene vode in jo ocenujemo na okoli 2 odstotka od skupno odvedene toplotne energije. Temperaturni porast je bil zaradi enostavnosti izračunov vzet enak kakor v pretočnem kondenzatorju, tj. 12,3 K.

thermal reactor power

generator power

net power of the nuclear plant

quantity of condensed water steam

thermal energy discharge

cooling water quantity

increase of cooling water temperature

pressure losses in condenser

The discharged energy also comprises energy removed from cooling systems, namely the internal cooling circuit, and from essential water and is estimated to approximately 2% of the total thermal energy discharged. For the sake of easier calculations the temperature increase was taken from that of flow condenser, i.e. 12.3 K.

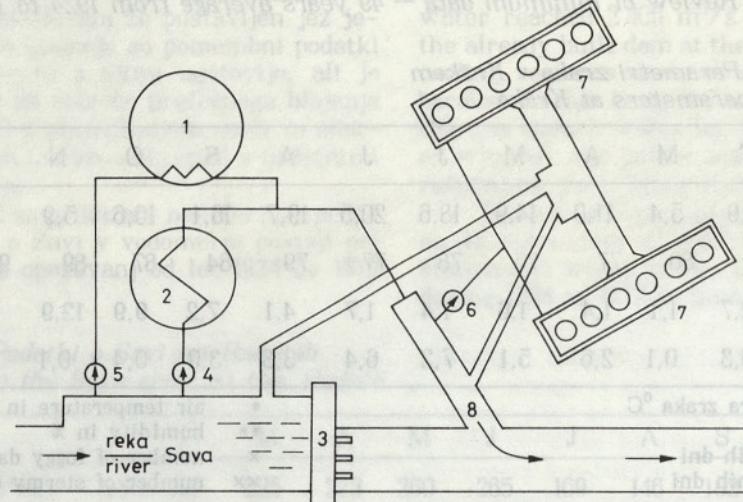
### 3 VODNOGOSPODARSKE ODLOČBE

Projektant je dobil, poleg podatkov pod 1 in 2, še zahteve vodnogospodarske odločbe. Prva odločba je bila dana za lokacijsko dovoljenje; druga, dopolnjena pa za gradbeno dovoljenje.

#### *Prva vodnogospodarska odločba:*

- zaježitev Save — kota krone
- najmanjši pretok prek jezu
- najvišja temperatura vode po mešanju hladilne vode z rečno 4–5 km pod jezom
- porast temperature na meji s Hrvaško (oddaljenost 19 km)

Ta vodnogospodarska odločba je bila nekako v skladu s tedanjem zakonodajo in priporočili sosednjih evropskih držav (preglednica 1).



Slika 2

1 – reaktor, 2 – kondenzator, 3 – jez na reki, 4 – glavne črpalki, 5 – črpalki bistvene vode, 6 – črpalki za hl. stolpe, 7 – hladilni stolpi, 8 – iztok vode

Figure 2

1 – reactor, 2 – condenser, 3 – dam on the river, 4 – main pumps, 5 – pumps for essential water, 6 – pumps for cooling towers, 7 – cooling towers, 8 – water discharge

Druga vodnogospodarska odločba dopolnjuje prvo:

- zaježitev Save kota krone
  - največji odvzem vode
  - najvišja zmesna temperatura  
1 km pod jezom
  - temperaturna razlika reke  
1 km pod jezom
- |       |
|-------|
| 151 m |
| 25 %  |
| 28 °C |
| 2 K   |

#### Razlaga posameznih zahtev:

Višina krone jezu je ostala enaka. Največji odvzem 25% vodnega toka pomeni, da je potreben pretok najmanj  $100 \text{ m}^3/\text{s}$ . V urejenem pretočnem diagramu lahko ugotovimo, da je takih dni, ko je pretok Save manjši od  $100 \text{ m}^3/\text{s}$ , v povprečju 60 dni na leto. Torej je pretočno hlajenje mogoče, toda treba je računati z zmanjšanjem moči in električne energije, ali pa je treba zgraditi navzgorne sezonske zbiralnike z nekaj  $100 \cdot 10^9 \text{ m}^3$  vode.

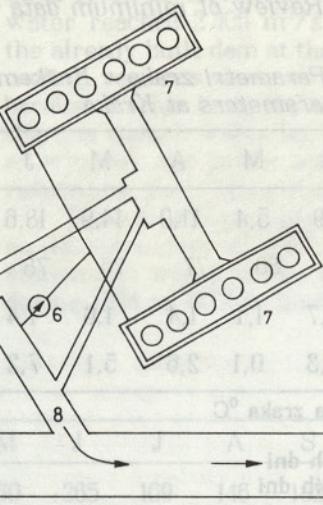
### 3 WATER AUTHORITIES APPROVALS

Besides data from item 1 and 2 the designer was also provided with requirements from Water Authorities Approvals. The first Approval was submitted for the site permit and the second, completed one, for the construction permit.

#### *First Water Authorities Approval*

- dam on the Sava – edge height
- minimum flow over the dam
- max. water temperature after mixing of cooling and river water 4–5 km below the dam
- temperature increase at the Croatian border (19 km away)

This Approval was somehow in accordance with the legislation of the time and with the recommendations of neighbouring European countries (Table 1).



#### *Second Water Authorities Approval (completes the first one)*

- dam on the Sava – edge height
- maximum water intake
- maximum river temperature after mixing 1 km below the dam
- temperature difference  
1 km below the dam

#### Comments to individual requirements:

The height of the dam edge remained the same. The maximum water intake from the river (25%) implies a required flow of at least  $100 \text{ m}^3/\text{s}$ . The diagram shows that there are on average 60 days a year with flow lower than  $100 \text{ m}^3/\text{s}$ . Hence it follows that this makes flow cooling possible but requires either the reduction of power and electricity or seasonal up-stream water storage of some  $100 \cdot 10^9 \text{ m}^3$  of water.

Doseči izenačeno temperaturo že 1 km pod jezom je enako težko kakor prej pri manjšem pretoku in večji razdalji (4–5 km). Zvišanje temperature reke za 2 K, 1 km pod jezom (ali takoj pod jezom) je odvisno seveda že od same količine odvzete vode. Iz energetske bilance izhaja najmanjša količina pretoka Save za izpolnjevanje tega pogoja:

$$2 \times 4,187 \times Q = 1270\,000 \text{ kW}$$

$$Q = 151,6 \text{ m}^3/\text{s}$$

Na razdalji 1 km pod jezom voda ne odda veliko toplotne energije v zrak, projektant je za izračun zmanjšal količino vode s  $151,6 \text{ m}^3/\text{s}$  na  $150 \text{ m}^3/\text{s}$ .

Iz urejenega diagrama pretokov je bilo ugotovljeno, da je celo 120 dni v povprečnem letu, ko je pretok Save v Krškem manjši od  $150 \text{ m}^3/\text{s}$ . Ta pogoj terja razmislek o sezonskem zbiralniku ali pa hladilnih stolpih za uspešnejše hlajenje in izognitev izredno velikim zmanjševanjem moči in izpadu električne energije.

Po analizi vseh teh vodnogospodarskih pogojev, zveni ugotovitev iz utemeljitve o ugodnosti lokacije Krško malo manj prepričljivo. To razmišljanje velja samo za pretočne hladilne rešitve.

#### 4 MOGOČI NAČINI HLAJENJA

Iz vodnogospodarskih zahtev in danosti okolja je bilo jasno, da ob vseh priložnostih ni mogoče uporabiti samo pretočnega hlajenja. V načrtovanem času delovanja elektrarne bi bil delež moči jedrske elektrarne v slovenskem elektroenergetskem sistemu samo 22% (331 MW : 1520 MW) na koncu obratovalne dobe, tj. leta 2008 (1978 + 30) po srednjem trendu pa še samo 14% (331 : 2432). V sosednji republiki Hrvaški je pomenil delež 331 MW še manjši odstotek v njihovem elektroenergetskem sistemu. V tistem času so začeli tudi izgradnjo visoko napetostnega 400 kV sistema bivše Jugoslavije, kar bi omogočalo medsebojno racionalno izmenjavo v primeru omejitev in drugačnih potreb električne energije.

Poleg bogatitve Save pri nizkih naravnih pretokih s sezonskimi zbiralniki je bilo mogoče zgraditi hladilne stolpe za dodatno ohlajanje ogrete hladilne vode pred izpustom v rečno strugo. Seveda je bila tudi možnost hlajenja celotne odpadne toplotne s hladilnimi stolpi.

Projektanti so imeli na voljo torej naslednje načine hlajenja jedrske elektrarne Krško:

- pretočno hlajenje brez zbiralnika,
- pretočno hlajenje s sezonskim zbiralnikom,
- dodatno hlajenje ogrete vode v stolpih,
- hlajenje samo s stolpi.

Pri teh štirih glavnih načinih so imeli projektanti pri vsakem še nekaj različic. Po dogovorih z investitorjem so ocenili stroške izgradnje in petnajstletne stroške delovanja ter posamezne možnosti primerjali med seboj na podlagi obrestnega računa in predlagali najugodnejšo tehnično rešitev.

To obtain the mixed temperature as little as 1 km below the dam is as difficult as before when we had lower flow and longer distance (4–5 km). The river temperature increase by 2 K 1 km below the dam (or by the dam itself) is undoubtedly due to the quantity of the water – intake. The energy data sheet indicates the minimum quantity of river flow required this condition:

$$2 \times 4,187 \times Q = 1270\,000 \text{ kW}$$

$$Q = 151,6 \text{ m}^3/\text{s}$$

At the distance of 1 km from the dam not much thermal energy is discharged from water – into the environment through air; the designer reduced the water quantity in his calculations from  $151,6 \text{ m}^3/\text{s}$  to  $150 \text{ m}^3/\text{s}$ .

One can see from the diagram that in average year there are 120 days when the Sava river flow at Krško is lower than  $150 \text{ m}^3/\text{s}$ . This requires considering either seasonal water storage or construction of cooling towers if efficient cooling is to be provided and considerable power reductions and electricity cutouts avoided.

After analyzing all of these water management requirements the arguments supporting the choice of Krško as the most suitable site become less persuasive. This applies only for flow cooling.

#### 4 POSSIBLE WATER COOLING PROCESSES

Considering the requirements of Water Authorities and the environmental data it is obvious that flow cooling cannot be applied in all circumstances as the only option. During the envisaged operation period of the nuclear plant its share of power within the entire Slovenian electricity generation system was planned to be not more than 22% (331 MW: 1520 MW) and at the end of its operation, that is in 2008 (1978 + 30) only 14% (331:2432), considering medium trends. In the Republic of Croatia the share of 331 MW represented even a smaller portion of its total electrical production. A new project was also begun in former Yugoslavia, namely construction of 400 kV high-voltage system which was supposed to provide energy in case of reductions or to provide additional energy when required.

Besides compensating for the low flows of the Sava river with seasonal water storage it was also possible to build cooling towers which would provide additional cooling of heated water before its discharge into the river. The cooling towers could also assure cooling of the entire waste water.

The designer could choose among the following cooling processes of the Krško NPP:

- flow cooling without seasonal water storage
- flow cooling with water storage
- additional cooling of heated water in towers
- cooling by cooling towers only.

Among these four variants there were also some other sub-variants available. After making an agreement with both investors the designer prepared a cost estimate for the construction and for 15 year operation cost and made a comparison of individual sub-variants by discount calculation. Then they proposed the best technical solution.

## 5 DOLOČITEV OPTIMALNEGA NAČINA HLAJENJA

Zaradi obsežnih izračunov in velikega števila možnosti naj tukaj navedemo samo poglavite različice v skrajšani obliki. Čeprav so bili izračuni izdelani za več različic temperaturnega ogretja Save, bomo tu prikazali samo za  $\Delta T = 2\text{ K}$  in  $3\text{ K}$ , oziroma ustrezeno količine vode 100 in  $150\text{ m}^3/\text{s}$ .

### 5.1 Investicije za posamezne rešitve

Za današnjo rabo preračunajmo rezultate iz takratnih dinarjev v ameriške dolarje. Tečaj 1 USD = 16 din (v 1974).

| Pretočno hlajenje | 100 m <sup>3</sup> /s | 150 m <sup>3</sup> /s | Flow cooling      |
|-------------------|-----------------------|-----------------------|-------------------|
| gradbeni del      | 2,4 M USD             | 2,4 M USD             | construction part |
| oprema            | 0,8                   | 0,8                   | equipment         |
| drugo             | 0,3                   | 0,3                   | other items       |
| skupaj            | 3,5                   | 3,5                   | total             |

| Pretočno hlajenje s sezonskim zbiralnikom | 100 m <sup>3</sup> /s | 150 m <sup>3</sup> /s | Flow cooling with seasonal water storage |
|---|-----------------------|-----------------------|--|
| gradbeni del                              | 2,4 M USD             | 2,4 M USD             | construction                             |
| + akumulacija                             | 25,2                  | 31,2                  | + water storage                          |
| oprema                                    | 0,8                   | 0,8                   | equipment                                |
| drugo                                     | 2,8                   | 3,4                   | other items                              |
| skupaj                                    | 31,2                  | 37,8                  | total                                    |

| Mešani način hlajenja brez sezonskega zbiralnika | 100 m <sup>3</sup> /s | 150 m <sup>3</sup> /s | Mixed cooling process without seasonal water storage |
|--|-----------------------|-----------------------|--|
| gradbeni del                                     | 2,4 M USD             | 2,4 M USD             | constr.  |
| + razvod vode in<br>hladilne celice              | 0,6                   | 1,3                   | + water distribution<br>and cooling cells            |
| oprema   | 1,8                   | 2,3                   | equipment  |
| drugo  | 0,5                   | 0,6                   | other items  |
| skupaj   | 5,3                   | 6,6                   | total  |

| Hladilni stolp (zajetje 2 m <sup>3</sup> /s) | 100 m <sup>3</sup> /s | 150 m <sup>3</sup> /s | Cooling tower (intake 2 m <sup>3</sup> /s) |
|--|-----------------------|-----------------------|--|
| gradbena dela                                | 8,3 M USD             | 8,3 M USD             | constr. works                              |
| oprema                                       | 1,4                   | 1,4                   | equipment                                  |
| drugo  | 1,1                   | 1,1                   | other items                                |
| skupaj                                       | 10,8                  | 10,8                  | total                                      |

### 5.2 Zmanjšanje el. moči in energije

| Pretočno hlajenje                           | 100 m <sup>3</sup> /s | 150 m <sup>3</sup> /s | Flow cooling                                    |
|---|-----------------------|-----------------------|---|
| inst. moč črpalk $4 \times 1.200\text{ kW}$ |                       |                       | inst. power of pumps $4 \times 1.200\text{ kW}$ |
| porabljena moč $3 \times 1.200\text{ kW}$   | 3.600                 | 3.600                 | consumed power $3 \times 1.200\text{ kW}$       |
| porabljena energija GWh/a                   | 25,2                  | 25,2                  | consumed energy GWh/a                           |
| zmanjšana moč kW                            | 17.400                | 59.000                | reduced power kW                                |
| zmanjšana el. energ. GWh/a                  | 122,0                 | 415,0                 | reduced el. energy GWh/a                        |
| skupaj el. energija GWh/a                   | 147,2                 | 440,2                 | electrical energy total GWh/a                   |

## 5 CHOICE OF THE BEST COOLING PROCESS

Due to extensive calculations and a large number of variants this paper will present only the basic variants in the abbreviated form. Although the calculations were made for several variants of the Sava temperature increase you will find here below only those for  $\Delta T = 2\text{ K}$  and  $3\text{ K}$  or the respective water quantities of  $100\text{ m}^3/\text{s}$  and  $150\text{ m}^3/\text{s}$ .

### 5.1 Construction cost for individual solutions

For the sake of today's comprehension the values have been converted from dinars to dollars applying the rate of exchange 1 USD = 16 din (in 1974).

| Pretočno hlajenje | 100 m <sup>3</sup> /s | 150 m <sup>3</sup> /s | Flow cooling      |
|-------------------|-----------------------|-----------------------|-------------------|
| gradbeni del      | 2,4 M USD             | 2,4 M USD             | construction part |
| oprema            | 0,8                   | 0,8                   | equipment         |
| drugo             | 0,3                   | 0,3                   | other items       |
| skupaj            | 3,5                   | 3,5                   | total             |

| Pretočno hlajenje s sezonskim zbiralnikom | 100 m <sup>3</sup> /s | 150 m <sup>3</sup> /s | Flow cooling with seasonal water storage |
|---|-----------------------|-----------------------|--|
| gradbeni del                              | 2,4 M USD             | 2,4 M USD             | construction                             |
| + akumulacija                             | 25,2                  | 31,2                  | + water storage                          |
| oprema                                    | 0,8                   | 0,8                   | equipment                                |
| drugo                                     | 2,8                   | 3,4                   | other items                              |
| skupaj                                    | 31,2                  | 37,8                  | total                                    |

| Mešani način hlajenja brez sezonskega zbiralnika | 100 m <sup>3</sup> /s | 150 m <sup>3</sup> /s | Mixed cooling process without seasonal water storage |
|--|-----------------------|-----------------------|--|
| gradbeni del                                     | 2,4 M USD             | 2,4 M USD             | constr.  |
| + razvod vode in<br>hladilne celice              | 0,6                   | 1,3                   | + water distribution<br>and cooling cells            |
| oprema   | 1,8                   | 2,3                   | equipment  |
| drugo  | 0,5                   | 0,6                   | other items  |
| skupaj   | 5,3                   | 6,6                   | total  |

| Hladilni stolp (zajetje 2 m <sup>3</sup> /s) | 100 m <sup>3</sup> /s | 150 m <sup>3</sup> /s | Cooling tower (intake 2 m <sup>3</sup> /s) |
|--|-----------------------|-----------------------|--|
| gradbena dela                                | 8,3 M USD             | 8,3 M USD             | constr. works                              |
| oprema                                       | 1,4                   | 1,4                   | equipment                                  |
| drugo  | 1,1                   | 1,1                   | other items                                |
| skupaj                                       | 10,8                  | 10,8                  | total                                      |

### 5.2 Reductions of electrical and energy

| Pretočno hlajenje                           | 100 m <sup>3</sup> /s | 150 m <sup>3</sup> /s | Flow cooling                                    |
|---|-----------------------|-----------------------|---|
| inst. moč črpalk $4 \times 1.200\text{ kW}$ |                       |                       | inst. power of pumps $4 \times 1.200\text{ kW}$ |
| porabljena moč $3 \times 1.200\text{ kW}$   | 3.600                 | 3.600                 | consumed power $3 \times 1.200\text{ kW}$       |
| porabljena energija GWh/a                   | 25,2                  | 25,2                  | consumed energy GWh/a                           |
| zmanjšana moč kW                            | 17.400                | 59.000                | reduced power kW                                |
| zmanjšana el. energ. GWh/a                  | 122,0                 | 415,0                 | reduced el. energy GWh/a                        |
| skupaj el. energija GWh/a                   | 147,2                 | 440,2                 | electrical energy total GWh/a                   |

*Pretočno hlajenje s sezonskim zbiralnikom*

|                       |       |       |        |                         |       |
|-----------------------|-------|-------|--------|-------------------------|-------|
| uporabljena moč črpal | kW    | 3.600 | 3.600  | consumed power of pumps | kW    |
| porabljeni energ.     | GWh/a | 25,2  | 25,2   | consumed energy         | GWh/a |
| zmanjšana moč         | kW    | —     | 43.000 | reduced power           | kW    |
| zmanjšana el. energ.  | GWh/a | —     | 301,5  | reduced el. energy      | GWh/a |
| skupaj el. energija   | GWh/a | 25,2  | 326,7  | el. energy total        | GWh/a |

*Mešani način hlajenja brez sezonskega zbiralnika*

|                               |       |       |       |                             |               |
|-------------------------------|-------|-------|-------|-----------------------------|---------------|
| črpanje vode iz Save          | kW    | 3.600 | 3.600 | water pumping from the Sava | kW            |
| porabljeni el. en.            | GWh/a | 25,2  | 25,2  | consumed el. energy         | GWh/a         |
| dodatne črpalki 4–6 × 500 kW  |       | 2.000 | 3.000 | additional pumps            | 4–6 × 500 kW  |
| ventil. za zrak 8–12 × 180 kW |       | 1.440 | 2.160 | air valve                   | 8–12 × 180 kW |
| dodatna el. energija          | GWh/a | 3,1   | 4,6   | additional el. energy       | GWh/a         |
| skupaj el. energ.             | GWh/a | 28,3  | 29,8  | el. energy total            | GWh/a         |

*Hladilni stolp*

Zaradi višje temperature hladilne vode pri hlajenju z rečno vodo, je poslabšan vakuum v kondenzatorju in s tem zmanjšana moč parne turbine:

|  |       |        |   |       |
|--|-------|--------|---|-------|
| moč črpalk za obtok hladilne vode              | kW    | 5.350  | power of pumps supplying the cooling water circuit    | kW    |
| dodatna črpalka za nadomeščanje izhlapele vode | kW    | 500    | additional pump for substituting the evaporated water | kW    |
| porabljeni el. energija 5.850 × 7.000, GWh     |       | 4,1    | consumed el. energy 5.850 × 7.000, GWh                |       |
| zmanjšana moč                                  | kW    | 14.400 | reduced power   | kW    |
| zmanjšana el. energija                         | GWh/a | 101,0  | reduced electrical energy                             | GWh/a |
| skupaj el. energija                            | GWh/a | 142,0  | electrical energy total                               | GWh/a |

**5.3 Pregled vrednosti zmanjšane moči in električne energije**

Investicijski stroški za 1 kW moči so bili ocenjeni s 400 USD in cena električne energije 1,56 centa za kWh (0,25 din/kWh). Vrednost kapitala 14,5% letno.

*Flow cooling with seasonal water storage*

|                       |       |       |                         |       |
|-----------------------|-------|-------|-------------------------|-------|
| uporabljena moč črpal | kW    | 3.600 | consumed power of pumps | kW    |
| porabljeni energ.     | GWh/a | 25,2  | consumed energy         | GWh/a |
| zmanjšana moč         | kW    | —     | reduced power           | kW    |
| zmanjšana el. energ.  | GWh/a | —     | reduced el. energy      | GWh/a |

*Mix. cool. proc. without seasonal water storage*

|                               |       |       |                             |               |
|-------------------------------|-------|-------|-----------------------------|---------------|
| črpanje vode iz Save          | kW    | 3.600 | water pumping from the Sava | kW            |
| porabljeni el. en.            | GWh/a | 25,2  | consumed el. energy         | GWh/a         |
| dodatne črpalki 4–6 × 500 kW  |       | 2.000 | additional pumps            | 4–6 × 500 kW  |
| ventil. za zrak 8–12 × 180 kW |       | 1.440 | air valve                   | 8–12 × 180 kW |
| dodatna el. energija          | GWh/a | 3,1   | additional el. energy       | GWh/a         |
| skupaj el. energ.             | GWh/a | 28,3  | el. energy total            | GWh/a         |

*Cooling tower*

Since the cooling water temperature is higher than when the cooling water is provided from the river the vacuum in the condenser is smaller and the steam turbine power is reduced:

|  |       |        |   |       |
|--|-------|--------|---|-------|
| moč črpalk za obtok hladilne vode              | kW    | 5.350  | power of pumps supplying the cooling water circuit    | kW    |
| dodatna črpalka za nadomeščanje izhlapele vode | kW    | 500    | additional pump for substituting the evaporated water | kW    |
| porabljeni el. energija 5.850 × 7.000, GWh     |       | 4,1    | consumed el. energy 5.850 × 7.000, GWh                |       |
| zmanjšana moč                                  | kW    | 14.400 | reduced power   | kW    |
| zmanjšana el. energija                         | GWh/a | 101,0  | reduced electrical energy                             | GWh/a |
| skupaj el. energija                            | GWh/a | 142,0  | electrical energy total                               | GWh/a |

**5.3 Review of values referring to reduced power and electricity**

The investment cost for 1 kW power was estimated to 400 USD and the electricity price to 1.56 cents for 1 kWh (0.25 din/kWh). The yearly return of the capital invested is 14.5%.

|                      | Stroški zmanj. moči   | Let. str. zmanjšane moči  | El. en. stroški   |
|----------------------|-----------------------|---------------------------|-------------------|
|                      | Cost of reduced power | Yearly cost of reduced p. | Cost of el. power |
| Pretočno hlajenje    | 100 m <sup>3</sup> /s | 8,40 M USD                | 1,22 M USD        |
| Flow cooling         | 150 m <sup>3</sup> /s | 25,00                     | 3,63              |
| Sezonski zbir.       | 100 m <sup>3</sup> /s | 1,44                      | 0,21              |
| Seasonal wat.storage | 150 m <sup>3</sup> /s | 18,64                     | 2,70              |
| Mešano hlajenje      | 100 m <sup>3</sup> /s | 2,82                      | 0,41              |
| Mixed cooling        | 150 m <sup>3</sup> /s | 3,50                      | 0,51              |
| Hladilni stolp       |                       | 8,10                      | 1,17              |
| Cooling tower        |                       |                           | 2,28              |

**5.4 Skupni letni stroški**

Tu je prikazan samo končen rezultat izračuna z obrestno vrednostjo v naslednjih 15 letih stroškov delovanja. Obrestna mera je 10,0% letno. Prikaz je podan samo za zvišanje temperature 2 K v Savi.

Here only the final result of calculations has been indicated taking into account the 15 year discount value of operation cost. The discount rate is 10.0% annually. The table applies only to the temperature increase of 2 K in the Sava river.

**5.4 Total yearly cost**

|  | Pretočno<br>Flow cooling | Akumul.<br>Water storage | Mešano<br>Mixed cooling | Hl. stolp<br>Cooling tower |
|--|--------------------------|--------------------------|-------------------------|----------------------------|
| Investicije v hladilni sistem<br>investment into cooling systems | 3,5 M USD                | 37,8 M USD               | 6,6 M USD               | 10,8 M USD                 |
| zmanjšana nadomest. moč<br>reduced substitute power              | 25,040                   | 18,640                   | 3,504                   | 8,100                      |
| skupaj investicije<br>investments total                          | 28,540                   | 56,440                   | 10,104                  | 18,900                     |
| letni stroški vzdrževanja<br>yearly maintenance cost             |                          |                          |                         |                            |
| gradbeni objekti<br>construct. work                              | 3,0%                     | 0,072                    | 1,008                   | 0,111                      |
| oprema<br>equipment  | 6,0%                     | 0,048                    | 0,048                   | 0,084                      |
| letni stroški za vodo<br>yearly water cost                       | 0,175                    | 0,175                    | 0,175                   | 0,695                      |
| zmanjšana el. energija<br>reduced el. energy                     | 6,875                    | 5,105                    | 0,466                   | 2,219                      |
| skupaj stroški na leto<br>total cost per year                    | 7,130                    | 6,336                    | 0,890                   | 3,267                      |
| skupaj diskontirani stroški<br>discounted cost total             | 54.231                   | 48,192                   | 6,769                   | 24,849                     |
| sedanja vrednost<br>present value                                | 82,777                   | 104,632                  | 16,873                  | 43,749                     |
| indeks<br>index  | 490                      | 620                      | 100                     | 259                        |

Po opisanem izračunu je bila najprimernejša rešitev mešani način hlajenja. Določili so 12 hladilnih celic s prisilnim pretokom hladilnega zraka:

According to the figures indicated here above the most suitable solution was a mixed cooling system. Thus 12 cooling cells have been chosen with forced flow of cooling air.

|                           |                         |                           |
|---------------------------|-------------------------|---------------------------|
| moč ene celice            | 65.000 kW               | power of a cell           |
| količina obtočne vode     | 4.500 m <sup>3</sup> /h | circuit water quantity    |
| dolžina hladilne celice   | 15 m                    | cooling cell length       |
| širina hladilne celice    | 24 m                    | cooling cell width        |
| moč ventilatorja - 12 kom | 180 kW                  | ventilator power - 12 pcs |
| moč črpalk - 6 kom        | 500 kW                  | pump power - 6 pcs        |

## 6 IZVEDBA KOMBINIRANEGA HLAJENJA

Investitor se je na predlog projektantov odločil za izgradnjo kombiniranega hlajenja z dvanajstimi celicami in nominalnim pretokom vode v celici 4500 m<sup>3</sup>/h. Le-ta se lahko poveča za 100% z regulacijo gladine vode na distribucijski ravni.

## 6 IMPLEMENTATION OF COMBINED COOLING

On the basis of propositions made by designers the investor decided on combined cooling with twelve cells, each of them provided with the nominal water flow of 4500 m<sup>3</sup>/h. This flow can be increased by 100% by means of the water level regulation at the distribution point.

### 6.1 Glavni tehnološki podatki – izvedba

#### a) Sistem hlajenja pare v kondenzatorju

Kondenzator:

|  |                          |
|--|--------------------------|
| – pretok hladilne vode 24,86 m <sup>3</sup> /s | 89.500 m <sup>3</sup> /h |
| – temperatura vstopne vode                     | 17,0 °C                  |
| – temperatura izstopne vode                    | 29,2 °C                  |
| – temperaturna razlika vode                    | 12,2 K                   |
| – toplotni tok                                 | 1.270 MW                 |
| – vakuum                                       | 0,05 bar (33,1 °C)       |

Hladilni stolpi:

|                                  |   |
|----------------------------------|---|
| – pretok hladilne vode           | 15 m <sup>3</sup> /s (54.000 m <sup>3</sup> /h)     |
| – število hladilnih celic        | 12  |
| – nominalni pretok vode v celici | 1,25 m <sup>3</sup> /s<br>(4.500 m <sup>2</sup> /h) |
| – vstopna temperatura vode       | 41,2 °C   |

### 6.1 Basic technological data – implementation

#### a) Steam cooling process in condenser

Condenser:

|                                   |
|-----------------------------------|
| – cooling water flow              |
| – inlet water temperature         |
| – outlet water temperature        |
| – difference of water temperature |
| – heat flow                       |
| – vacuum                          |

Cooling towers:

|                                |
|--------------------------------|
| – cooling water flow           |
| – number of cooling cells      |
| – nominal water flow in a cell |
| – inlet water temperature      |

|  |   |   |
|--|---|---|
| – izstopna temperatura vode                                  | 31,1 °C   | – outlet water temperature                                      |
| – temperaturna razlika vode                                  | 10,1 K  | – difference of water temperature                               |
| – temperatura vlažnega termometra                            | 23,3 °C   | – temperature of humid thermometer                              |
| – toplotni tok   | 634 MW  | – head flow   |
| b) <i>Hlajenje zaprtega hladilnega sistema turboagregata</i> |   | b) <i>Cooling in a closed cooling system by turbo-generator</i> |
| – pretok hladilne vode                                       | 0,63 m <sup>3</sup> /s (2270 m <sup>3</sup> /h) | – cooling water flow  |
| – vstopna temperatura vode                                   | 29 °C (maksimum)                                | – inlet water temperature                                       |
| – temperaturna razlika vode                                  | 5,6 K   | – difference of water temperature                               |
| – toplotni tok   | 14,65 MW  | – heat flow   |

### c) *Sistem bistvene oskrbe vode*

Pri zagonu in zaustavitvi reaktorja je ta toplotni tok večji od tistega v običajnih delovnih stanjih, toda takrat pomeni toplotni tok skozi kondenzator 98 odstotkov celotnega odvedenega toplotnega toka. Pri običajnih delovnih stanjih je toplotni tok bistvene oskrbne vode 14,62 MW.

### 6.2 Hidrometeorološki podatki

Opazovanje pretokov Save z limnografi je bilo bolj natančno. Mesečni povprečni pretoki in najmanjši pretoki reke so se izkazali pre malo natančni za korektno izbiro števila hladilnih celic v kombiniranem sistemu hlajenja. Redno se nadzorujeta najmanjši in največji dnevni pretok Save na jezu jedrske elektrarne.

Tudi temperatura vode v Savi se spreminja kot najnižji in najvišji dnevni povpreček. Enako velja tudi za zrak, merjeni sta temperaturi suhega in vlažnega termometra.

### 6.3 Vodnogospodarska določila

Od prvega vodnogospodarskega soglasja do novega iz leta 1990, ki velja sedaj, časovno omejeno samo do konca leta 1995, je minilo skoraj trideset let. Zahteve za varstvo okolja se zaostrujejo. Glavni predpisi tega dovoljenja so naslednji:

a) Sprememba temperature Save po mešanju hladilne vode lahko znaša v povprečju dveh tretjin dnevnih meritev:  $\Delta T = 2$  K, če je temperatura reke pri vstopu v JEK na mestu bistvene oskrbe vode višja od 8 °C, če pa je ta temperatura nižja, lahko znaša temperaturni porast  $\Delta T = 3$  K.

b) Temperatura vode Save po mešanju s hladilno vodo in JEK ne sme presegati 28 °C.

c) Odjem vode iz Save za hlajenje je dovoljen največ 26 m<sup>3</sup>/s pri pretoku Save, večjem od 100 m<sup>3</sup>/s. Pri manjšem pretoku je dovoljen odvzem samo 25 odstotkov.

d) JEK mora v primeru, da bi porast temperature presegel 2 K oziroma 3 K vključiti v obratovanje hladilne stolpe. Če tudi z njimi ne izpolnjuje pogojev pod a), mora sorazmerno zmanjšati obremenitev elektrarne.

### 6.4 Posledice dodatnih zahtev vodnogospodarskega dovoljenja

To soglasje je tako zahtevno, da je JEK v času njegovega polnomočja že večkrat morala zmanjšati električno moč. Analiza škode je pokazala, da je treba ob sedanjih stolpih dograditi še dodatne hladilne celice. Vprašanje je, koliko celic in seveda

|                                    |
|------------------------------------|
| – outlet water temperature         |
| – difference of water temperature  |
| – temperature of humid thermometer |
| – head flow                        |

### b) *Cooling in a closed cooling system by turbo-generator*

|                                   |
|-----------------------------------|
| – cooling water flow              |
| – inlet water temperature         |
| – difference of water temperature |
| – heat flow                       |

### c) *Supply system for essential water*

The heat flow is higher when the reactor is started or stopped than under normal operating conditions; however, when flowing through the condenser it represents 98% of the entire heat flow discharged. The heat flow for essential water supply is 14.62 MW under normal operational conditions.

### 6.2 Hydro-meteorological data

The observations of the Sava river flows by limnographs were more accurate. The monthly average and minimum river flows were not accurate enough to enable the correct choice of the number of cooling cells required for the combined cooling system. The highest and the lowest daily flows of the river have been observed from the dam near the nuclear plant.

The lowest and the highest daily average water temperature have also been followed. The same holds for air where temperatures are taken with dry and humid thermometers.

### 6.3 Water Authorities Requirements

Since the first approval of Water Authorities to the latest one, produced in 1990, which applies to a limited time period i.e. till 1995, almost thirty years have passed. The environmental protection requirements have become more and more severe. The main requirements comprised in the above stated approval can be resumed as follows:

a) After mixing with the cooling water the Sava river temperature should not change for more than two thirds of the daily measurements results on average:  $\Delta T = 2$  K if the river temperature at its inlet into the nuclear plant, namely at the essential water supply point, is higher than 8 °C; however, if this temperature is lower, the allowed daily temperature increase is  $\Delta T = 3$  K.

b) After mixing with the cooling water from the nuclear plant the Sava river temperature should not be higher than 28 °C.

c) The permissible water intake for the cooling purposes is 26 m<sup>3</sup>/s provided the river flow is higher than 100 m<sup>3</sup>/s. When the flow is lower the permissible water intake is only 25% of the above quantity.

d) In case the temperature increases by more than 2 K or 3 K the cooling towers have to be put in operation at the nuclear plant. If even then the conditions stated under a are not fulfilled, the operational load of the plant has to be reduced proportionally.

### 6.4 Consequences of additional requirements from the Water Authorities Approval

The requirements stated in this approval are so severe that the nuclear plant, when fully operating, has been obliged to reduce its electric power several times. The analyses of pertaining losses have shown that additional cooling cells are

tudi, kakšne naj bodo. Najprimernejše bi bilo dograditi podobne že delujočim. K sreči je bila že prvotna zamisel hlajenja naravnana na možnost razširitve.

Z matematičnim orodjem lahko postavimo balančne enačbe. Toda pri tem bomo naleteli na sistem, pri katerem je vedno neznanka več kakor je enačb. Sistem lahko rešimo z iteracijo oziroma je izpostavljen analizi verjetnostnega računa.

Jedrska elektrarna bo obratovala s polno močjo še približno dvajset let (če ne bo kakšnega izrednega dogodka — zaprtje z referendumom ali nezgoda), zato bomo tudi pojav neprijetnih dogodkov predpostavili enkrat v dvajsetih letih.

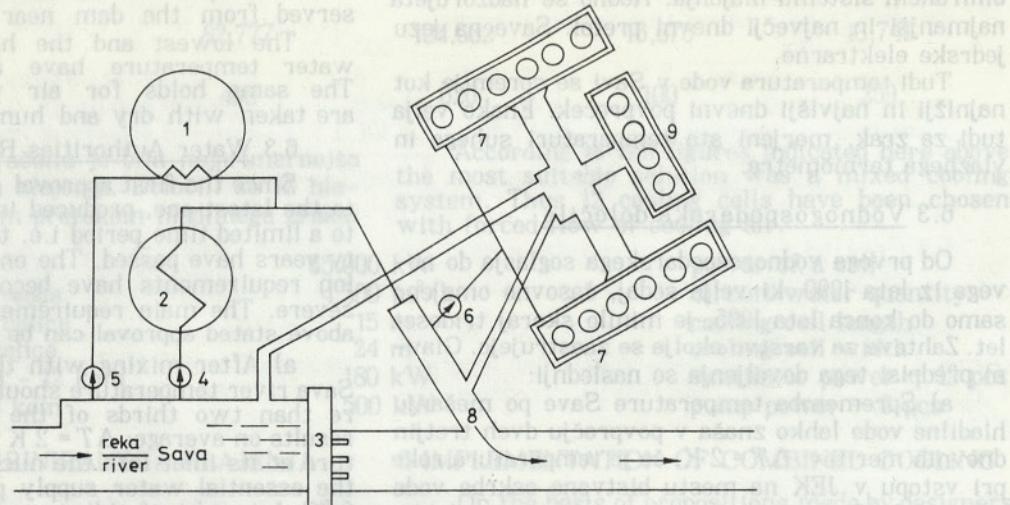
Rezultati analize po zgornjih merilih so pokazali, da bi bilo primerno dograditi še 3 do 6 hladilnih celic z enakimi značilnostmi, kakršne imajo sedanje. Prostor zanje je na voljo med sedanjima hladilnima nizoma. Projekt bi bilo treba še dopolniti z morebitno še ostrejšo vodnogospodarsko odločbo v prihodnje. Če bo ostalo pri dosedanji, bi zadostovale samo štiri dodatne hladilne celice.

required. The question is how many cells and what kind of cells should be built. We believe it would be the best to provide cells similar to the existing ones. Fortunately, the original cooling system concept has already envisaged the possibility of its extension.

The balance equations could be set by applying a mathematical tool. But doing this we would meet with a system in which there is always one unknown more than there are available equations. The system could be solved by iteration, that is by subjecting to the analysis of probability calculation.

The nuclear power plant will presumably be in full operation for another twenty years (unless something unexpected happens, e.g. closing up by referendum or due to an accident) which implies a presumption that unfavourable events could happen once in twenty years.

The analysis results according to the above mentioned criteria indicate that it would be appropriate to build another 3 to 6 cooling cells with the same characteristics as the existing ones. The space is available perpendicular to the existing cooling sets. The project should be also analyzed in consideration of the possibility of even more severe requirements of the Water Authorities in the future. Supposing the requirements remain unchanged, four more cooling cells would be enough.



Sl. 3. Dodatni hladilni stolpi  
Fig. 3. Additional cooling towers

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- [7] Zapis o obratovanju hladilnega sistema v JE Krško od 1980 do 1993.
- [8] Odločbe republiškega sekretariata za varstvo okolja in urejanja prostora o hladilnih sistemih. Zadnja 26.7.1990.
- [9] Osebni zapiski in dokumentacija avtorja tega prispevka.
- [10] Dnevno poročilo JE Krško republiški upravi za jedrsko varnost o hladilnih parametrih.

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