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# Simulacija domnevne nezgode z izgubo napajanja uparjalnikov v posodobljeni jedrski elektrarni

## Simulation of a Hypothetical Loss-of-Feedwater Accident in a Modernized Nuclear Power Plant

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*JE Krško je v okviru načrta posodobitve v letu 2000 pridobila tudi popolni simulator. Ta je namenjen usposabljanju in vzdrževanju zmožnosti osebja, da zagotavlja varno in zanesljivo obratovanje. V tej študiji smo izračunali odziv posodobljene jedrske elektrarne Krško na nezgodo s popolno izgubo napajanja uparjalnikov, ki vodi do popolne izgube ponora toplote na sekundarni strani. Izračun je bil potreben za preveritev popolnega simulatorja, ki so ga v JE Krško pridobili v okviru načrta posodobitve v letu 2000. Uporabljen je bil že preverjeni vhodni model za program RELAP5/MOD2 za jedrsko elektrarno Krško (JEK), vendar prirejen za 2000 MW toplotne moči (17. gorivni krog) in nova zamenjana uparjalnika.*

*V obravnavani nezgodi se sredica osuši in pregreje, kar vodi v taljenje sredice. Čeprav program RELAP5/MOD2 za opis takih pojavov ni predviden, kljub temu lahko z njim napovemo vse dogodke do tedaj, ko se začne temperatura gorivnih srajčk približevati tališču. Primerjava podatkov, dobljenih s popolnim simulatorjem JE Krško, in izračunanih primerjalnih podatkov kaže dobro ujemanje in potrjuje, da je bila preveritev simulatorja za to vrsto nezgode uspešna.*

**(Ključne besede: elektrarne jedrske, izguba napajanja, simuliranje nezgode, programi računalniški, RELAP5/MOD2)**

*As a part of its modernization plan, NPP Krško (NEK) has obtained the Krško Full-Scope Simulator (KFSS). Simulators of this type are used for training and maintaining competence to ensure the safe and reliable operation of nuclear power plants throughout the world. In this study the response of the modernized Krško nuclear power plant (NPP) to a total-loss-of-feedwater accident, leading to the total loss of the secondary heat sink, was calculated. Based on these results, the validation of the full-scope simulator was performed. The verified plant-specific RELAP5/MOD2 input model of the Krško NPP, adapted for the 2000 MWt power (cycle 17), including the model for replacement steam generators, was used.*

*Core heatup occurred in the analyzed case. Core degradation and melting are outside the scope of the RELAP5/MOD2 best-estimate code simulation, but it can predict all the events up to the moment when the core cladding temperature starts to approach the melting point. The comparison of the Krško full-scope simulator (KFSS) data with the calculated reference data shows good agreement and indicates that the simulator-validation testing for this kind of accident was successful.*

**(Keywords: nuclear power plants, loss of feedwater, accidents-simulations, software package, RELAP5/MOD2)**

## 0 UVOD

Simulatorji jedrskih elektrarn so namenjeni usposabljanju in vzdrževanju zmožnosti osebja, da lahko zagotavlja varno in zanesljivo obratovanje, hkrati pa morajo, kolikor je mogoče, posnemati delovanje pripadajoče elektrarne. Tudi JE Krško je v okviru načrta posodobitve v letu 2000 pridobila tak popolni simulator [1]. Pred začetkom redne uporabe je treba opraviti še postopek preveritve, v katerem preverimo in potrdimo, da se odziva v skladu z odzivi pripadajoče elektrarne.

## 0 INTRODUCTION

As a part of its modernization plan, NPP Krško (NEK) has obtained the Krško Full-Scope Simulator (KFSS) [1]. Nuclear-power-plant simulators are used for training and maintaining competence in order to ensure the safe and reliable operation of nuclear power plants throughout the world. The simulator should be specified to a reference unit and its performance validation testing should be provided.

Popolni simulator JEK upravljata dva programa, od katerih prvi, COMET simulira sredico reaktorja. Ta v dejanskem času rešuje časovno odvisno prenosno enačbo nevtronov, pri čemer uporablja zasnovo teorije ekvivalence, ki omogoča razčlenitev celotne sredice jedrskega reaktorja in reševanje enačb s prevedbo v zapis s končnimi razlikami. Drugi program ANTHEM omogoča simulacijo termo-hidrodinamičnih pojavov v primarnem sistemu jedrske elektrarne. Termohidrodinamični model v programu je nehomogen in neravnovesen ter rešuje pet parcialnih diferencialnih enačb za ohranitev mase in energije za parno in kapljevito fazo, ohranitev gibalne količine pa računa za mešanico kapljevine in pare z modelom gonilnega toka. Dodane so še ohranitvene enačbe za morebitne neukapljive pline in trdne delce, raztopljene v hladivu.

Po definiciji v standardu ANSI/ANS [2] je simulator naprava ali računalniško vodena interaktivna oprema, ki zvesto posnema obratovalne značilnosti komponent, sistemov ali skupine vgrajenih sistemov pripadajoče elektrarne in omogoča ovrednotenje dela operaterja v različnih razmerah. Popolni simulator je po definiciji “simulator z vgrajenimi podrobnimi modeli pripadajoče elektrarne, s katerimi operater upravlja v glavni nadzorni sobi. Vključene so delovne plošče v nadzorni sobi. Tak simulator nazorno prikaže pričakovani odziv elektrarne na običajne in neobičajne dogodke.”

Funkcionalne zahteve za popolni simulator nadzorne sobe jedrske elektrarne so utemeljene s standardom ANSI/ANS-3.5 [2]. Med drugim se zahteva tudi preveritveno testiranje delovanja simulatorja. Namen preveritve je zagotoviti, da ni opaznih razlik, ko primerjamo obnašanje simulatorja nadzorne sobe in simuliranih sistemov z dogajanjem v pravi nadzorni sobi in delovanjem sistemov jedrske elektrarne.

Po načrtu za preveritev in usposobljenost popolnega simulatorja jedrske elektrarne je bil v JE Krško ([3] in [4]) med drugim preverjen odziv popolnega simulatorja v razmerah običajnega obratovanja ter prehodnih pojavov pri različnih močeh reaktorja (zaprtje glavnega osamitvenega ventila parovoda SG-2 [5], delna izguba glavne napajalne vode [6] in test z znižanjem in ponovnim porastom moči). Pri tem so bili uporabljeni podatki iz nadzorne sobe ter iz informacijskega sistema za spremljanje obratovalnih podatkov (PIS). Tak način preverjanja simulatorja je tudi prvi na prednostni listi poglavitnih podatkov za zagotovitev natančnosti simulatorja. Drugi najpomembnejši vir podatkov v postopku preverjanja simulatorja so tisti, pridobljeni iz inženirskih analiz s preverjenimi računalniškimi programi in usposobljenimi modeli. Poleg naštetih dveh virov lahko podatke zberemo še iz elektrarn s podobno zasnovo in delovanjem kakor primerjalna elektrarna ter iz drugih virov, kakor so izkušnje operaterjev, pričakovanja, inženirska presoja in analize iz končnega varnostnega poročila.

To simulate a reactor coolant system (RCS), two types of simulation tools are used. First, the primary core is simulated with COMET. This is a real-time program for calcualting time-dependent neutron-diffusion equations, using the concept of equivalence theory to enable the finite differences to be used as the discretization to deal with the complex reactor core. Second, for the RCS the ANTHEM thermal-hydraulic simulation is used. This is a five-equation non-equilibrium, non-homogeneous, drift-flux model based on the mass and energy conservation equations for liquid and vapor and liquid-vapor mixture momentum conservation. Other transport equations are used for the transport of boron, impurities, radioactive species and non-condensables.

According to the definition in the ANSI/ANS standard [2], the simulator is “a device or computer-driven interactive equipment that replicates the operating characteristics of a component, system, or group of integrated systems of the reference unit; enabling the performance of the operator to be evaluated under varying conditions.” The definition of a full-scope simulator is: “A simulator incorporating detailed modeling of systems of the reference unit with which the operator interfaces in the control-room environment. The control-room operating consoles are included. Such a simulator demonstrates the expected unit response to normal and off-normal conditions.”

The functional requirements for a full-scope nuclear-power-plant control-room simulator used for operator training or examination are established in the ANSI/ANS-3.5 standard [2]. Among other requirements, the simulator performance validation testing should also be provided. The aim of the validation is to “ensure that no noticeable difference exists between the simulator control room and the simulated systems when evaluated against the control room and the systems of the reference unit”.

According to the plan for the verification and qualification of the Krško full- scope simulator (KFSS) ([3] and [4]), the source data used were the closure of the SG-2 main steam-isolation valve [5], the partial loss of the main feedwater [6] and the load-swing test. The data recorded in the past and those obtained from the MCR instrumentation and the process information system (PIS) were used. This type of data collection is the first in the baseline data order of preference to ensure simulator fidelity. The second source of data for the simulator validation is that generated through engineering analysis with qualified, best-estimate computer programs and verified models. Other sources of data can be collected from a plant that is similar in design and operation to the reference plant. Finally, these can be data that do not come from any of the above sources, for example, operator experience, expectations, engineering judgment and a safety-analysis-report-type of analysis.

V JEK je bil določen naslednji nabor analiz projektnih scenarijev za preveritev simulatorja, ki naj bi jih izvedli z računalniškimi programi za najboljšo oceno, kakršna je RELAP5/MOD2 [3]: delna in popolna izguba napajanja, delna in popolna izguba primarnega pretoka, prelom parnega voda, nenamerno odprtje razbremenilnega ventila na tlačniku, spekter malih izlivnih nezgod, pričakovani prehodni pojav brez zaustavitve reaktorja, zlom cevi v uparjalniku in hitra ročna zaustavitev reaktorja.

Namen naše študije je bil s programom RELAP5/MOD2 ustvariti osnovne podatke, prvo izmed zgoraj opisanih scenarijev z druge skupine prednostne liste za preveritev simulatorja JEK (podrobnosti so opisane v [7]). RELAP5/MOD2 je termohidravlični računalniški program, ki vsebuje modele, kateri so po dosedanjih dognanjih najboljši približek dogajanja v dvofaznem toku. Uporaba takih programov je v splošnem v praksi, ko gre za preveritev modelov, vgrajenih v simulatorje, kakor je na primer opisano v [8] in [9].

Program RELAP5/MOD2 je bil razvit za čimbolj verodostojne simulacije prehodnih pojavov v lahkovodnih jedrskih elektrarnah med domnevnimi nezgodami. Z njim modeliramo povezan odziv hidrodinamičnih sistemov in dejavnih ter pasivnih toplotnih teles med nezgodami z izgubo hladiva in obratovalnimi prehodnimi pojavi, kakor so pričakovan prehodni pojav brez zaustavitve reaktorja, izguba zunanjega električnega napajanja, izguba napajalne vode uparjalnikov ali izguba primarnega pretoka. Pri modeliranju z RELAP5/MOD2 razdelimo termodinamične sisteme na ločena vozlišča, povezana s spoji. Predpostavljen je dvofazni tok kapljevine in pare. Termohidrodinamični model v programu je nehomogen in neravnovesen ter rešuje 6 parcialnih diferencialnih enačb za ohranitev mase, gibalne količine in energije za parno in kapljevito fazo. Dodane so še ohranitvene enačbe za morebitne neukapljive pline in trdne delce, raztopljene v hladivu. Kot sklepne enačbe so dodane še povezave za prenos toplote med fazama ter med hladivom in toplotnimi telesi in za medfazno trenje ter trenje ob steni. Program vsebuje tudi enačbe točkovne reaktorske kinetike. Generični način modeliranja omogoča simulacije dogajanja v različnih termodinamičnih sistemih. Vključene nadzorne spremenljivke in prožitvena logika ter posebne komponente omogočajo modeliranje nadzornih in krmilnih sistemov elektrarne, odziv turbine, kondenzatorja ter sistema napajalne vode uparjalnikov.

Kot osnovo za analize je JEK zagotovila preverjen vhodni model za program RELAP5/MOD2. Razvoj in potrjevanje specifičnega vhodnega modela elektrarne za RELAP5/MOD2 se je pričel leta 1995 in je bil končan v letu 1999. Vhodni model je dokumentiran, preverjen in usposobljen za ustaljeno stanje in za nekatere prehodne pojave v delovnih poročilih elektrarne ([10] in [11]).

V tej študiji so predstavljeni rezultati izračunov za nezgodo, ki jo povzroči izguba glavne napajalne vode uparjalnikov in se brez pomožnega napajanja uparjalnikov razvije v resno nezgodo, med katero ni

NEK has determined the following set of design-basis scenarios to be analyzed with best-estimate computer codes such as RELAP5/MOD2 [3]: partial and total loss of feedwater, partial and total loss of primary flow, steamline rupture, stuck-open PRZ PORV, spectrum of small-break loss-of-coolant accidents, anticipated transient without scram, steam-generator tube rupture and manual reactor trip.

The purpose of our study was to generate the second-source baseline data for an accident initiated by a total loss of feedwater to the steam generators (SGs) for KFSS validation (for details see [7]). The use of best-estimate codes, such as the RELAP5/MOD2 thermal-hydraulic computer code, is common practice for validating simulator models, and is described in [8] and [9].

The RELAP5/MOD2 code has been developed for the best-estimate transient simulation of light-water reactor's coolant systems during postulated accidents. The code models the coupled behavior of the reactor's coolant system and the core for loss-of-coolant accidents and operational transients such as an anticipated transient without scram, loss of offsite power, loss of feedwater, and loss of flow. The RELAP5/MOD2 is a nodal lumped-parameter two-phase non-homogeneous non-equilibrium thermal-hydraulic code, which solves six differential equations for mass, momentum and energy conservation for vapor and liquid phases. Mass-conservation equations are added for noncondensable gases and soluble species. Interfacial and wall heat transfer and interphase and wall friction correlations are added as closure equations. Point reactor kinetics equations are included. A generic modeling approach is used that permits simulating a variety of thermal hydraulic systems. Control variables and trip logic and secondary system components are included to permit the modeling of plant controls, turbines, condensers, and secondary feedwater systems.

As the basis for the performed analyses, Krško NPP has delivered the verified input model for RELAP5/MOD2. The project of development and verification of the RELAP5/MOD2 plant-specific model started in 1995, and was finished in 1999. The input model is documented, verified and qualified for steady-state and some transients in the plant reports ([10] and [11]).

In this study, the calculated results of an accident initiated by a total loss of feedwater, developing towards the total loss of the secondary heat sink are presented, and were used for the KFSS validation (see plan in [3]). The consequences of such an accident may be very drastic, since core mogoče zagotoviti ponora toplote na sekundarni strani (glej načrt v [3]). Posledice takih nezgodnih dogodkov so lahko zelo resne, pride do taljenja sredice, kasneje celo do pretalitve reaktorske posode in kot skrajna posledica do porušitve zadrževalnega hrama ter širjenja radioaktivnega materiala v okolico. Tu predstavljamo le razvoj dogodkov vključno do odkrivanja in osušitve sredice ter do pregrevanja gorivnih elementov. Podane so grafične primerjave med napovedmi simulatorja in programa RELAP5/MOD2. Izračunani primerjalni podatki so pomembni, ker za JEK ni na voljo dejanskih podatkov za tovrstno nezgodo. To je namreč zunajprojektna nezgoda, za katero se ne pričakuje, da bi se dogodila v dobi obstajanja elektrarne, v kasnejši fazi pa se razvije celo še v resnejšo nezgodo, ki vodi v taljenje sredice reaktorja. V zadnjem desetletju je bil narejen tudi velik napredek na področju analiz težkih nezgod z uporabo računalniških programov za simulacije nezgod z resnimi posledicami. V zvezi s tem je treba omeniti, da ima simulator JEK vgrajeno zmožnost simuliranja nevarnih nezgod vse od pregrevanja sredice, porušitve sredice, poškodbe reaktorske posode, odziva zadrževalnega hrama, interakcije taline sredice z betonom, poškodbe zadrževalnega hrama itn. Z zmožnostjo simuliranja nevarnih nezgod v dejanskem času je simulator tako najsodobnejši izdelek [12]. Razvoj v tej smeri je viden v [13], ki opisuje popolni simulator jedrske elektrarne v Leningradu in je bil izdan leta 1997, kjer so poročali, da je »prvič, da bi kak popolni in analitični simulator zagotavljal simulacijo težkih nezgod«. Poleg tega, da se simulatorji uporabljajo za usposabljanje operaterjev, so lahko namenjeni kot analizatorji ali celo za licenčne varnostne analize [14].

## 1 OPIS VHODNEGA MODELA

Uporabljeni osnovni vhodni model elektrarne za RELAP5/MOD2 vključuje vse pomembne komponente reaktorskega hladilnega sistema (RCS) in sekundarne strani, reaktorski varovalni sistem, krmilne in varnostne sisteme, model zamenjanih uparjalnikov in logiko delovanja pomožne napajalne vode (PNV - AFW). Model ne vključuje nove logike delovanja glavne napajalne vode (GNV - MFW), saj v času študije še ni bila znana. MFW je zato modelirana, kakor da bi bilo upravljanje ročno. V posebnem primeru, ki ga predstavljamo v tej študiji, smo predvideli izpad glavnega napajanja uparjalnikov ter nerazpoložljivost sistema za pomožno napajanje uparjalnikov že od začetka preračuna. Model je bil sestavljen iz 309 vozlišč, povezanih s 339 spoji. Strukture elektrarne so v stiku s primarnim in sekundarnim hladivom, zadrževalnim hramom in okolico prek 299 toplotnih teles s 1622 mrežnimi točkami. Merilna oprema, krmilni sistemi in varnostni sistemi so bili predstavljeni s 300 logičnimi pogoji, tako imenovanimi prožitvami in 441 nadzornimi spremenljivkami. Začetne razmere, nastavitvene vrednosti in predpostavke prikazuje preglednica 1. Začetne vrednosti in nastavitve v RELAP in modelu SIM

degradation and melting is a likely consequence of a total loss of the secondary heat sink. Further, this may cause failure of the reactor vessel and possible containment failure and spreading of the radioactive material into the environment. Only the events including the core uncovering and heatup are analyzed here. Some comparison plots between the simulator and the RELAP5/MOD2 thermal-hydraulic computer-code predictions are given. The calculated reference data are very important as no real event of this kind has occurred at Krško NPP. This is a beyond-design-basis accident, which is not expected to occur during the plant's lifetime. The continuation of the scenario leads to an even worse accident plant state, and to core melt. In the past decade, significant progress was made in the area of severe accidents and the use of severe-accident codes. In this regard, it is important to note that the KFSS also has the built-in capability to simulate severe accidents, starting from core heatup, core degradation, reactor vessel failure, containment response, core concrete interaction, containment failure, etc. So the simulator also represents a state-of-the-art product with the capability to simulate severe accidents in real time [12]. Developments in this direction were already indicated in [13], describing the full-scope simulator for the Leningrad NPP, and published in 1997, where it was reported that "it is the first time ever that the full-scope and analytical simulator ensure modeling of severe, beyond-the-design-basis accidents". Otherwise, as well as for operator training simulators, they can also be used as plant analyzers or in licensing safety analyses [14].

## 1 INPUT MODEL DESCRIPTION

The RELAP5/MOD2 basic input model included all the important components of the reactor coolant system (RCS) and the secondary side, the reactor protection system, the control and safety systems, the model of the replacement steam generators and the auxiliary feedwater (AFW) logic. The model did not include the new main feedwater (MFW) logic, since it was not known at the time when the study was performed. The MFW was, therefore, put in "manual" mode. The model consisted of 309 volumes, interconnected with 339 junctions. The plant structure communicated with the primary and secondary coolant, and the containment and environment atmosphere through 299 heat structures with 1622 mesh points. Three hundred trips and 441 control variables represented the measurement equipment, the control and the protection systems. The initial assumptions are shown in Table 1. The initial conditions and setpoints in RELAP5 and the simulator input models correspond to the plant state after modernization and the SG replacement

Preglednica 1. *Začetne vrednosti, nastavitvene vrednosti in predpostavke*
Table 1. *Initial conditions, relevant setpoints, assumptions*

| **Začetni pogoji**<br>**Initial conditions** | **RELAP5/MOD2** | **KFSS** |
|---|---|---|
| moč sredice<br>core power | 1994 MW | 1994 MW |
| povprečna temp. primarnega hladiva<br>average temperature | 578,2 K | 578,25 K |
| tlak v tlačniku<br>pressurizer pressure | 15,51 MPa | 15,506 MPa |
| raven v tlačniku<br>pressurizer level | 55,78 % | 55,53 % |
| tlak v uparjalnikih<br>SG1 / SG2 pressure | 6,25 / 6,22 MPa | 6,24 / 6,24 MPa |
| raven v uparjalnikih (ozko območje)<br>SG1 / SG2 NR level | 69,35 / 69,35 % | 69,30 / 69,30 % |
| pretok na turbino<br>turbine flow | 1088,4 kg/s | 1076,1 kg/s |
| **Nastavitvene vrednosti**<br>**Relevant setponts** | **RELAP5/MOD2** | **KFSS** |
| nizko - nizka raven v uparjalnikih<br>(zaustavitev reaktorja, zagon črpalk pomožne napajalne vode uparjalnikov)<br>low-low SG level<br>(reactor trip, AFW injection) | 13 % NR | 13 % NR |
| nizko-nizek tlak v parovodu<br>(signal za varnostno vbrizgavanje, osamitev parovoda)<br>low-low steamline pressure<br>(SI signal, steamline isolation) | 4,926 MPa<br>lead: 50s, lag: 5s | 4,926 MPa<br>lead: 50s, lag: 5s |
| **Razpoložljivost varnostnih sistemov**<br>**Availability of safety systems** | **RELAP5/MOD2** | **KFSS** |
| visokotlačno varnostno vbrizgavanje<br>HPIS – High Pressure Injection System | **2** /2 | **2** /2 |
| pasivni hidroakumulatorji<br>ACC - Accumulators | **2** /2 | **2** /2 |
| nizkotlačno varnostno vbrizgavanje<br>LPIS – Low Pressure Injection System | **2** /2 | **2** /2 |
| pomožna napajalna voda uparjalnikov<br>AFW – Auxiliary Feedwater | **0** /2<br>**nerazpoložljiva**<br>**unavailable** | **0** /2<br>**nerazpoložljiva**<br>**unavailable** |

ustrezajo stanju elektrarne po modernizaciji in zamenjavi uparjalnikov v letu 2000 in so podani v [15].

Predpostavili smo popolno izgubo napajanja uparjalnikov, ki v kratkem času vodi do popolne izgube ponora toplote na sekundarni strani. Kljub predpostavki, da sta bili razpoložljivi obe progi sistema za zasilno hlajenje sredice, do vbrizgavanja v primarni sistem ni moglo priti zaradi previsokega tlaka, ki se je vzpostavil v primarnem sistemu že v zgodnejši fazi prehodnega pojava. V scenariju niso bili predvideni nikakršni ukrepi operaterja razen zaustavitev reaktorskih črpalk po nezgodnih obratovalnih navodilih. Te operater ustavi ročno po potrebi, to je ob izgubi podhladitve v primarnem sistemu, v skladu z nezgodnimi obratovalnimi navodili, z upoštevanjem 60 s odmika pri ukrepanju.

in 2000, and are summarized in [15].These included the total loss of feedwater into both steam generators, leading to the total loss of the secondary heat sink. In spite of the assumed availability of both emergency core cooling system (ECCS) trains, no cold borated water injection into the primary system occurred due to primary-system overpressurization.

No operator actions were modeled in the scenario specification, except the reactor-coolant pump trip per the emergency operating procedures, due to a loss of primary-coolant subcooling, assuming a 60 s delay for the operator action. The initial conditions, setpoints and assumptions are shown in Table 1.

Druge predpostavke in glavne nastavitvene vrednosti varovalnega sistema reaktorja ter krmilnih in varnostnih sistemov smo v analizi predvideli kot sledi in jih prav tako prikazuje preglednica 1. Začetni dogodek je bila izguba glavnega napajanja uparjalnikov, ki smo jo v vhodnem modelu za program RELAP5/MOD2 dosegli s spremembo logičnega pogoja za delovanje obeh črpalk glavne napajalne vode. Dotok glavne in tudi pomožne napajalne vode v uparjalnik je tam v resnici modeliran le kot časovno odvisni robni pogoj, ki smo ga tako odpravili. Po izgubi napajanja uparjalnikov je pričakovati nagel padec ravni v obeh uparjalnikih, ki povzroči zaustavitev reaktorja na signal za nizko raven v uparjalniku pri 13% ozkega območja merjenja ravni. Zaustavitev reaktorja nadalje sproži signal za zaustavitev turbine. Signal za nizko - nizek tlak v uparjalnikih, ki se ustvari pri nastavitveni vrednosti 4,228 MPa, sproži signal za varnostno vbrizgavanje (SI). Hkrati se osamita tudi oba glavna parna voda. Signal za varnostno vbrizgavanje sproži črpalke za visokotlačno in nizkotlačno varnostno vbrizgavanje. Na signal SI bi se morale vklopiti tudi motorne črpalke pomožne napajalne vode uparjalnikov, vendar je bilo v scenariju zanje predvideno, da jih ni.

The initiating event was the tripping of the main feedwater pumps. Since the feedwater inflow into the steam generators is modeled as a boundary condition in RELAP5, this was achieved by changing the logical condition within the input file. After the feedwater flow interruption, a rapid decrease of both SG levels was expected. This should trigger the reactor trip on the low-low SG level (13% Narrow Range). The turbine is then tripped immediately after the reactor trip. The safety injection (SI) signal was generated on the low-low SG pressure signal, which is set to 4.228 MPa. Simultaneously, the isolation of both SGs was initiated. The SI signal actuated the high- and low-pressure safety-injection pumps. It should also cause the actuation of both motor-driven auxiliary feedwater pumps, but these were assumed to be unavailable.

## 2 REZULTATI IN RAZPRAVA

Primerjalni izračuni za nezgodo z izgubo napajanja uparjalnikov so bili narejeni s stvarnim programom RELAP5/MOD2 za 200 s ustaljenega stanja in predvidoma 5000 s prehodnega pojava. Ker pa se je gorivo v sredici čezmerno pregrelo zaradi izgube hladiva skozi razbremenilne ventile na tlačniku, se je preračun dejansko končal že dobrih 4000 sekund po začetku prehodnega pojava zaradi pregrevanja gorivnih srajčk in zaradi težav pri opisovanju skrajno neravnotežnih pojavov v hladivu v predelu sredice. Analizo prehodnega pojava smo izvedli na podlagi obsežnih parametričnih analiz IJS za JEK iz preteklih let ([16] in [17]) in analiz prehodnih pojavov v celostnih eksperimentalnih napravah [18].

V nadaljevanju je prikazanih nekaj glavnih parametrov preračuna. Čeprav tako RELAP5/MOD2 kakor ANTHEM omogočata opazovanje množice parametrov, so prikazani več ali manj le tisti, ki jih operater lahko spremlja v glavni nadzorni sobi. To so različne temperature po sistemu, tlaki in nekatere ravni. Ti so za operaterja najpomembnejši in smo jih šteli tudi kot najpomembnejše za oceno primerjave med RELAP5 in KFSS.

Za boljši vpogled v simulirane prehodne pojave, najpomembnejše dogodke in bistvene fizikalne pojave za obravnavano nezgodo prikazuje preglednica 2. Zaradi zaustavitve črpalk glavne napajalne vode, ki med običajnim obratovanjem dobavljajo več ko 540 kg/s vode v posamezen uparjalnik in pri nezmanjšani proizvodnji pare, sta ravni v obeh uparjalnikih hitro upadli. Približno po eni minuti od začetnega dogodka se je v reaktorskem varovalnem sistemu ustvaril signal

## 2 RESULTS AND DISCUSSION

The reference calculations of the accident initiated by a total loss of feedwater were performed with RELAP5/MOD2 best-estimate computer code for 200 s of steady-state conditions, and presumably about 5,000 s of transient. The RELAP5 calculation was actually terminated earlier, only about 4,000 s after the transient initiation, due to the fuel cladding overheat and troubles in predicting the highly non-equilibrium fluid state within the core region. The transient analysis was performed at IJS, based on extensive parametric analyses for NPP Krško in the past years ([16] and [17]) and transient simulations in integral experiment facilities [18].

Some of the main parameters are shown next. Although the RELAP5 and ANTHEM codes offer a large number of parameters for observation and analysis, only those that are displayed or indicated in the main control room are shown. These are mainly system temperatures, pressures and levels, and are thus the most important for the operator and were also assumed to be the most relevant for the comparison of the RELAP5 and KFSS results.

To give some deeper insight into the calculated transient, the main events and the relevant phenomena for a loss-of-feedwater accident are shown in Table 2. Due to the main feedwater pumps trip the SG feed flow dropped from the nominal value of over 540 kg/s per SG down to zero in a few seconds. Initially, the SG vapor production remained at the nominal level, so both SG levels dropped very quickly.

Preglednica 2. *Pomembni dogodki in pojavi*
Table 2. *Important events and phenomena*

| **Dogodek ali pojav**<br>**Event or phenomenon** | **RELAP5/MOD2**<br>**Čas (s) / Timing (s)** | **KFSS**<br>**Čas (s) / Timing (s)** |
|---|---|---|
| začetni dogodek - predpostavka<br>(ustavitev črpalk glavne napajalne vode)<br>accident initiation - asumption<br>(main feedwater pumps stopped) | 200 | 200 |
| ustavitev reaktorja<br>reactor trip | 260 | 260 |
| ustavitev turbine<br>turbine trip | 260 | 260 |
| zagon črpalk pomožne napajalne vode<br>auxiliary feedwater pumps start | nerazpoložljive<br>unavailable | nerazpoložljive<br>unavailable |
| delovanje prh v tlačniku<br>pressurizer spray flow | 214 - 263<br>632 - 1570 | 220 - 275<br>660 - 1360 |
| odprtje dušilnega obvoda pare<br>steam dump operation | 260 - 552 | 260 - 560 |
| odprtje razbremenilnih ventilov na parnih vodih<br>SG1 / SG2 PORV discharge | 267 - 281 | ni podatka<br>no data |
| odprtje razbremenilnega ventila št.1<br>na tlačniku<br>pressurizer PORV#1 discharge | 260 - 264<br>940 → | 1385 → |
| uparjalnika prazna (raven v širokem območju pod 3 %)<br>SG1 / SG2 empty (WR level below 3%) | 560 | 529 |
| signal za varnostno vbrizgavanje<br>SI signal | 552 | 507 |
| izolacija vodov pare<br>steamline isolation | 552 | 507 |
| ustavitev reaktorskih črpalk – ukrep operaterja<br>RCP trip – operator action | 1419 | 1360 |
| primarni sistem v stanju nasičenja<br>primary system saturated | 1600 | 1560 |
| enofazni naravni obtok prekinjen<br>single-phase natural circulation interrupted | 2330 | 2280 |
| odprtje razbremenilnega ventila št.2 na tlačniku<br>pressurizer PORV#2 discharge | 1920 - 2970 | 2080 - 3350 |
| dvofazni naravni obtok prekinjen, začne se prenos toplote s kondenzacijo v ceveh uparjalnika in povratnim tokom v sredico<br>two-phase natural circulation interrupted, reflux condensation heat-transfer starts | 2960 | 2450 |
| pregrevanje sredice<br>core heatup | 3230 | 3600 |

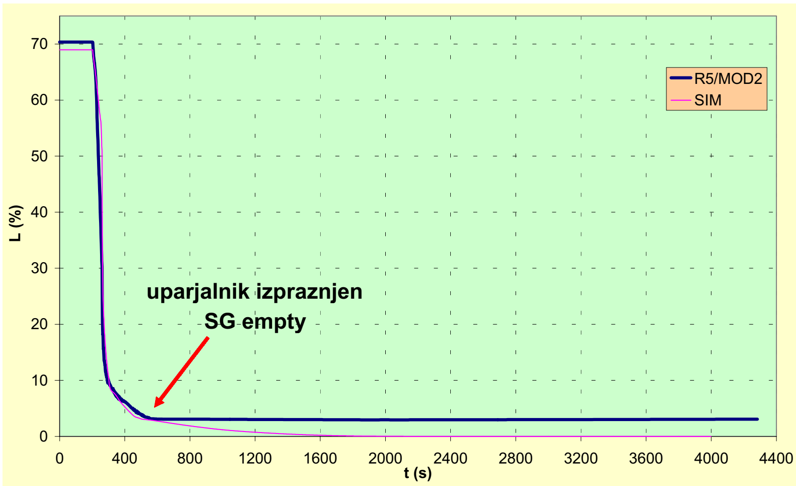
za zaustavitev reaktorja na nizko - nizko raven v uparjalnikih. Ta je sprostil krmilne palice reaktorja, ki so nemudoma padle v sredico in ustavile verižno reakcijo. Hkrati se je začela ustavljati tudi turbina, para pa je začela odtekati v kondenzator skozi dušilni obvod (steam dump). Ob takem razvoju dogodkov se je ustavila le verižna reakcija v reaktorju, ni pa bilo dolgoročno zagotovljeno odvajanje zaostale toplote, ki nastaja zaradi razcepnih produktov v jedrskem gorivu. Zaradi potrebe po odvajanju zaostale toplote na sekundarno stran in od tam v končni ponor toplote, se je proizvodnja pare na sekundarni strani nadaljevala,

After about 1 minute the SG low-low level setpoint was reached, triggering the reactor trip signal with the reactor-protection system. Control rods were released and dropped immediately into the reactor core, shutting down the chain reaction. The turbine was tripped simultaneously and the excess steam was directed to the condenser via the steam dump. This sequence of events only ensured that the nuclear power generation due to the chain reaction was terminated, but the residual heat from the fission products' decay remained to be generated. Long-term core cooling was, therefore, not established. Vapor sicer v zmanjšani meri, vendar se je zaradi pomanjkanja črpalk pomožne napajalne vode uparjalnikov zaloga sekundarnega hladiva hitro manjšala.

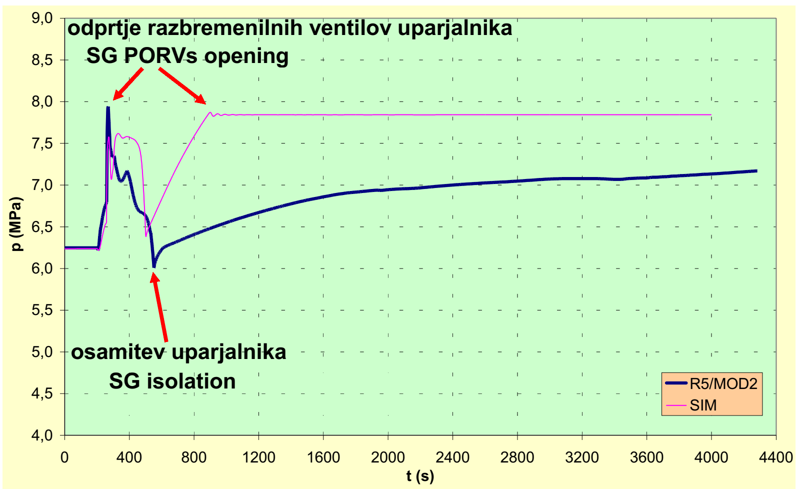
Ob razmeroma hitri osušitvi uparjalnikov (sl. 1), ki ju RELAP5 in simulator napovesta skoraj identično, je padal tudi tlak sekundarne strani (sl. 2), zato se je po nekaj več ko 5 minutah od začetka nezgode ustvaril signal za osamitev parnih vodov ter signal za varnostno vbrizgavanje. Glavni osamitveni ventili v parnih vodih so se zaprli samodejno zaradi signala nizkega tlaka v parnem vodu. Pri tem opazimo nekaj razlik med napovedmi RELAP5 in simulatorja, ki pa izhajajo le iz nekoliko različnega odziva sekundarne strani v prvih 300 sekundah po začetku prehodnega pojava. Signal za varnostno vbrizgavanje je pognal črpalke za visokotlačno in nizkotlačno varnostno vbrizgavanje, ki pa jim zaradi previsokega tlaka v primarnem sistemu ni uspelo dobaviti omembe vredne količine hladne borirane vode. Zaradi tega je bilo onemogočeno hlajenje primarnega sistema z neposrednim vbrizgavanjem hladne vode v hladni

continued to be generated with a reduced rate, since only the residual heat had to be transferred to the ultimate heat sink.

Nevertheless, due to the unavailability of the auxiliary feedwater source, the SG inventory was rapidly depleted (Fig. 1), which is almost the same as that predicted by RELAP5 and the simulator. With the SG emptying, the secondary pressure also dropped quickly (Fig. 2), so about 5 minutes after the start of the accident the SI signal and the steamline isolation signal were triggered when the low-low SG pressure setpoint was reached. Some differences can be observed when comparing the RELAP5 and SIM results, but this is due to a slight difference in the secondary response during the initial 300 seconds of transient. Despite the fact that the safety-injection pumps were started on the SI signal, no significant amount of cold borated water was delivered to the primary system as a result of early overpressurization, so the feed & bleed type of cooling was obstructed. The alternative source for primary system cooling by




Sl. 1. *Raven v uparjalniku št.1 (široko območje merjenja)*
Fig. 1. *Steam generator no.1 Wide Range (WR) level*



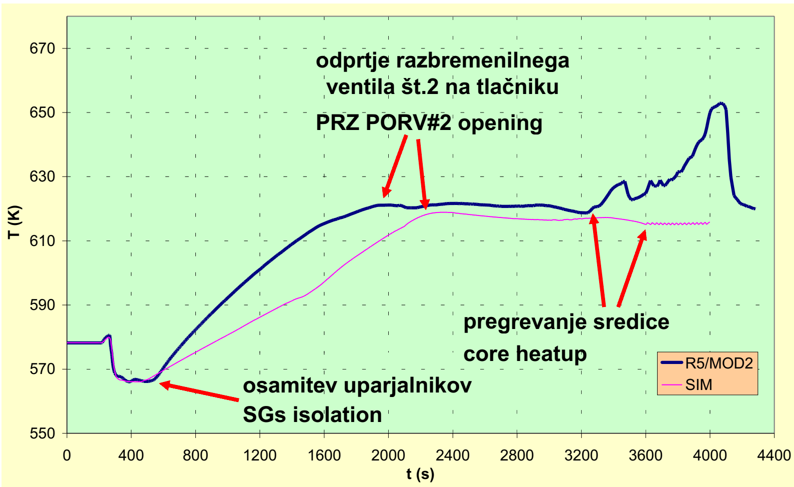

Sl. 2. *Tlak v uparjalniku št.1*
Fig. 2. *Steam generator no.1 pressure*

veji primarnega sistema. Po osamitvi parnih vodov opazimo, da program RELAP5 napove, da se v vsakem uparjalniku po osušitvi raven v širokem območju merjenja (WR) ustali pri vrednosti okoli 3%. Podroben pregled rezultatov preračuna pokaže, da v vsakem uparjalniku ostane okoli 5000 do 5100 kg nasičene pare pri tlaku nekaj nad 7 MPa. Iz rezultatov simulacije s KFSS pa se da ugotoviti, da je program ANTHEM to paro pregrel, tako da se je tlak v uparjalnikih dvignil prek 7,8 MPa in je hladivo ušlo skozi razbremenilne ventile na parnem vodu.

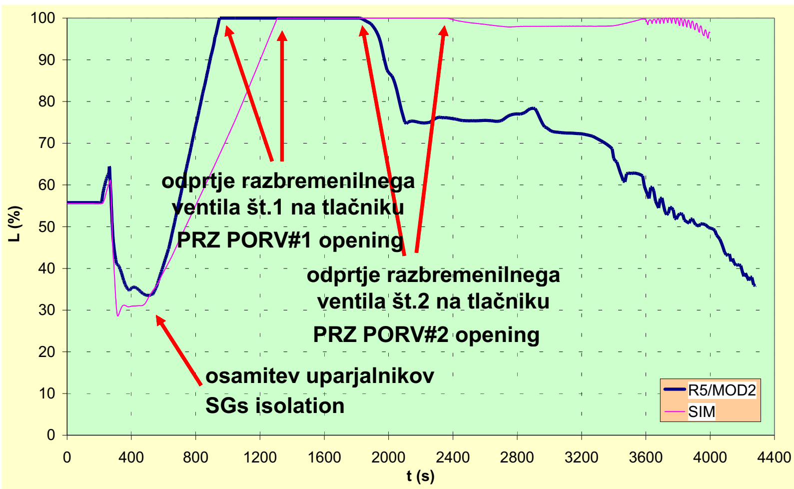
Po izpraznitvi uparjalnikov, ki pomeni popolno izgubo ponora toplote na sekundarni strani, se je primarno hladivo začelo ogrevati (sl. 3) in raztezati (sl. 4). Napovedi se med seboj zadovoljivo ujemajo. Opaziti je nekoliko hitrejše povečanje povprečne temperature primarnega hladiva in ravni v tlačniku po osušitvi uparjalnikov, kar pa je posledica dejstva, da je v vhodnem modelu za RELAP5 upoštevana nekoliko višja, torej bolj konzervativna vrednost zaostale toplote, ki se po ugasnitvi reaktorja sprošča iz razcepnih

injecting cold water directly into the cold legs was thus disabled. It can be seen that the SG WR level stabilized at about 3%, after the SG dryout, and isolation according to the RELAP5 code prediction. A closer look into the RELAP5 results shows that about 5,000-5,100 kg of saturated vapor remained in each steam generator at pressure slightly above 7 MPa. On the other hand, the ANTHEM simulation code overheated this amount of vapor, so that the secondary pressure rose above 7.8 MPa and escaped through the SG relief valves.

After the SG emptying, when the total loss of the secondary heat sink was experienced, the primary coolant started to heat up (Fig. 3) and expand (Fig. 4). Both predictions match satisfactorily. A somewhat faster primary-coolant average temperature and pressurizer level rise can be observed in the RELAP5 prediction. This results from the fact that the residual heat from the fission products was conservatively set to a value somewhat higher than in the simulator calculation. The same is reflected in the primary




Sl. 3. *Povprečna temperatura primarnega hladiva v zanki št.1*
Fig. 3. *Loop 1 average primary-coolant temperature*



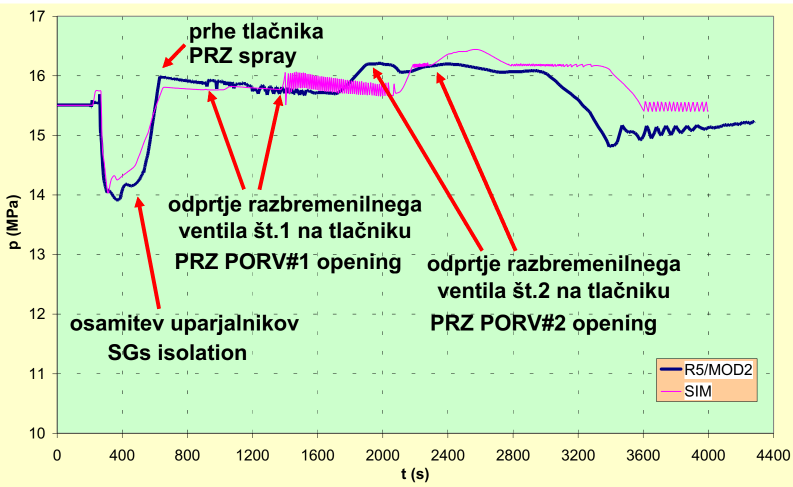

Sl. 4. *Raven v tlačniku*
Fig. 4. *Pressurizer level*

produktov. Enako se kaže tudi v poteku primarnega tlaka po izgubi ponora toplote na sekundarni strani. Tlačnik se je po napovedi RELAP5 in KFSS kmalu po osamitvi parnega voda napolnil. Raztezanje hladiva je po napovedih RELAP5 nekoliko hitrejše. Po vrsti sta se nato odprla tudi oba razbremenilna ventila na tlačniku, kar je ponovno omogočilo nastanek parnega mehurja na vrhu tlačnika. Ta je zaradi izdatnejše izgube primarnega hladiva po rezultatih RELAP5 večji, vendar se obe napovedi pojavov ujemata. Omeniti velja še, da je zaradi hitrejšega raztezanja primarnega hladiva program RELAP5 napovedal nekoliko večjo izgubo primarnega hladiva, kar se je v kasnejši fazi prehodnega pojava kazalo v ravni primarnega hladiva v tlačniku.

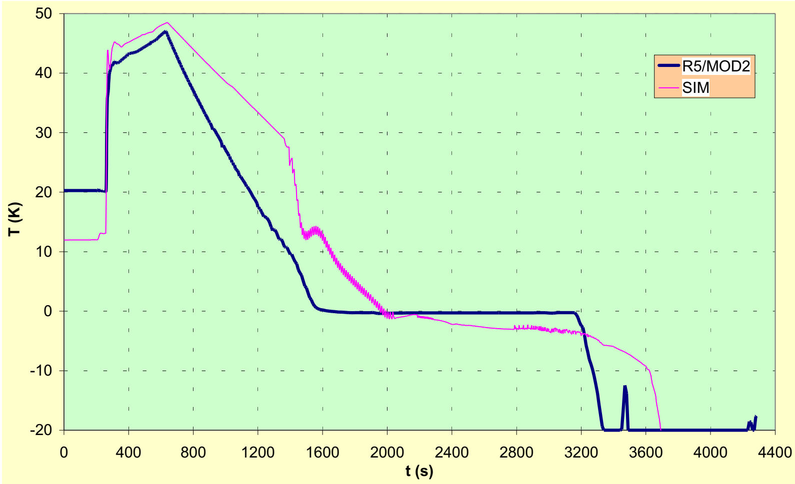
Kakor je bilo že rečeno, se je primarni tlak začel zviševati (sl. 5), zato so najprej ugasnili grelniki v tlačniku, ki med običajnim obratovanjem uravnavajo primarni tlak. Primarni tlak se je namreč hitro zvišal prek meja, med katerimi je predvideno krmiljenje z grelniki. Takoj zatem so se odprli ventili prh in v parni prostor tlačnika je začelo pršeti primarno hladivo iz hladnih vej. Ker tudi to ni ustavilo zviševanja primarnega tlaka, sta se eden za drugim odprla oba razbremenilna ventila na tlačniku. Tako se je začelo izgubljati primarno hladivo in celoten primarni sistem je kmalu prešel v stanje nasičenja. Primarni tlak in temperatura sta se tedaj ustalila. Zaradi izgube podhladitve primarnega hladiva (sl. 6) je moral operater v skladu z obratovalnimi navodili za ukrepanje v sili (EOP) zaustaviti obe črpalki primarnega hladiva. Črpalki namreč ob delovanju s skupno močjo 6 MW dodajata toplotno energijo primarnemu hladivu. Potek krivulj, ki prikazujejo podhladitev primarnega hladiva je v obeh simulacijah podoben, nekaj več razlike je opaziti le v začetni vrednosti. Temperatura na izhodu iz sredice se v modelu za RELAP5 meri le v vozlišču neposredno nad sredico in je pravzaprav povprečna temperatura hladiva nad sredico. Vhodni model v popolnem simulatorju JEK pa vsebuje 3D model sredice, v katerem se temperatura na izhodu iz sredice

pressure development, after the complete loss of the secondary heat sink. The pressurizer become solid soon after the SG isolation. The level rise was faster in the RELAP5 calculation. Both pressurizer PORVs opened as a result, which caused the regeneration of steam bubbles at the top of the pressurizer. This was larger in the RELAP5 prediction due to a more extensive discharge, but the phenomenon was qualitatively described identically in the RELAP5 and KFSS calculations. It should also be mentioned that due to the faster primary-coolant expansion the RELAP5 predicted a larger inventory loss, which was reflected in the pressurizer level in a later phase of the transient.

Consequently, as stated before, the primary pressure rise started (Fig. 5), and soon exceeded the setpoint where the pressurizer proportional heaters were switched off (these control the primary pressure during normal operation). Soon after that the pressurizer spray valves opened, dispersing coolant from the cold legs into the pressurizer steam volume. This also could not prevent a further primary pressure rise, so both pressurizer relief valves opened and started discharging primary coolant. Soon, the primary pressure and temperature stabilized, but the primary system reached saturation. At that time the primary-coolant subcooling was lost (Fig. 6) and a threat that cavitation might damage the main reactor coolant pump (RCP) blades appeared. According to the emergency operating procedures (EOPs) the operator had to stop both RCPs. These operate at 6 MW total power and add thermal energy to the primary coolant. The curves representing primary-subcooling development are similar in both calculations, some difference is observed only between initial values. The core exit temperature in the RELAP5 model is measured in the volume just above the core volumes, which represents the average coolant temperature above the core region. Meanwhile, the simulator input model includes a 3D core model, where the core exit temperature is measured with 39 thermocouples above the core region.




Sl. 5. *Tlak v tlačniku*
Fig. 5. *Pressurizer pressure*



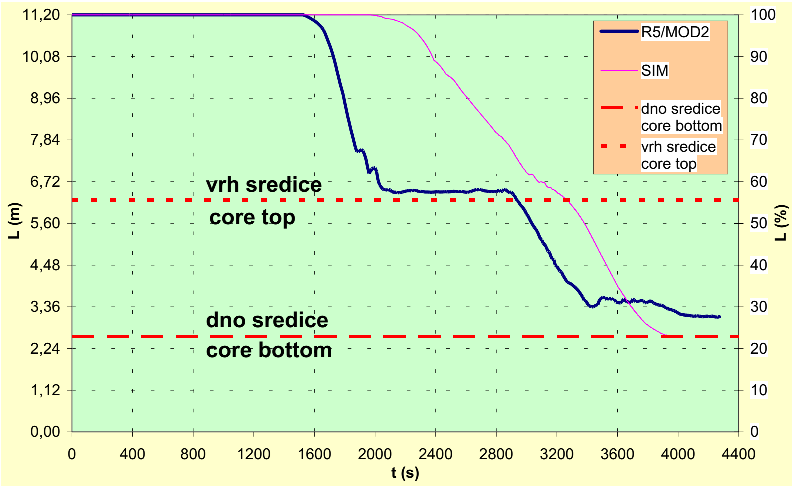

Sl. 6. *Podhlajenost primarnega hladiva na izhodu iz sredice*
Fig. 6. *Primary-coolant subcooling at core exit*

meri z 39 termočleni. V izračunu podhladitve se upoštevajo odbitki iz petih najbolj vročih termočlenov, to je po en najbolj vroč iz posameznega kvadranta sredice ter iz termočlena v centru prečnega prereza sredice. 3D modeliranje sredice je z vidika reaktorske kinetike in termohidravlike bolj stvarno. Vendar velja ponovno poudariti, da KFSS temelji na petih osnovnih enačbah, kar je manj natančno kakor v RELAP5/MOD2, ki rešuje tudi gibalni enačbi za vsako fazo posebej. Primerjave in sklepe je zato treba delati še posebej previdno.

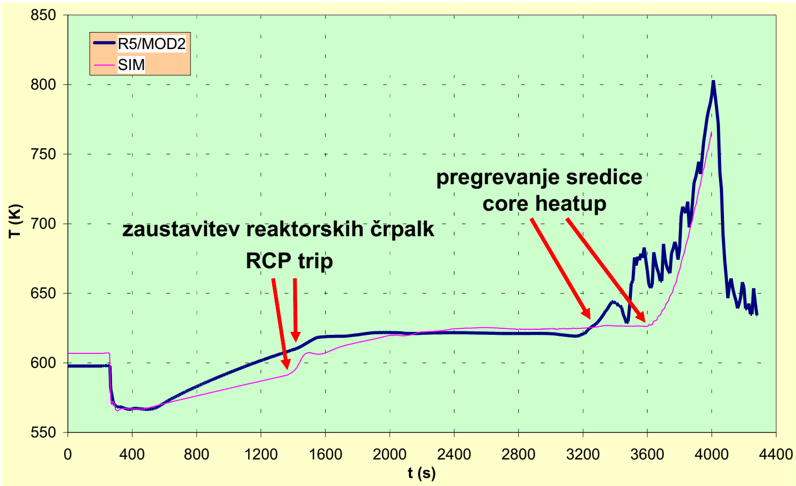
Zaradi postopne izgube primarnega hladiva se je po primarnem sistemu začel širiti parni mehur, ki je prekinil dvofazni naravni obtok primarnega hladiva. Kmalu je primarno hladilo ostalo le v hladnih vejah in v reaktorski posodi. Primerjava poteka parametrov na naslednjih dveh slikah (sl. 7 in 8) še podkrepi nekatere prejšnje ugotovitve. Zaradi bolj zgodnje in hkrati izdatnejše izgube primarnega hladiva RELAP5 napove v povprečju hitrejše znižanje ravni hladiva v področju sredice, zato se sredica tudi nekoliko prej začne pregrevati. Prepričamo se tudi, da razlike v izračunu začetne podhladitve primarnega hladiva izvirajo iz različnih vrednosti izstopne temperature primarnega hladiva iz sredice. Ob postopnem nižanju ravni v reaktorski posodi (sl. 7) so se začeli zgornji deli sredice osuševati in pregrevati (sl. 8), zato se je začela višati temperatura goriva in gorivnih srajčk [16]. Po približno 3000 sekundah se je delno odzračil eden izmed sifonov v hladnih vejah, kar je prispevalo k znižanju primarnega tlaka. Vendar pa to ni bilo zadosti, da bi hladna voda iz sistema ECCS lahko prodrla v primarni sistem, zato se je pregrevanje sredice nadaljevalo. Ko se je temperatura gorivnih srajčk v izračunu z RELAP5 zvišala na okoli 1530 K, je prišlo do napake v izvajanju programa zaradi previsokih temperatur toplotnih teles v sredici ter izrazitih neravnovesnih stanj v primarnem hladivu, ki je občasno še oblivalo nekatere dele sredice. Iz poteka različnih parametrov je bilo tedaj sklepati, da je taljenje

The core exit temperature is then calculated, taking into account the readings from the five hottest thermocouples, i.e. the hottest in each quadrant plus the thermocouple at the center of the core exit cross-section. The 3D core modeling in the KFSS is more realistic from the point of view of reactor kinetics and thermal hydraulics. Nevertheless, it has to be stressed again that the KFSS model is based on only five constitutive equations, while the RELAP5/MOD2 solves the momentum equation separately for each phase. Therefore, any comparison and conclusion has to be made carefully.

Due to the gradual primary-coolant discharge, steam bubbles started growing in the primary system and the two-phase natural circulation was soon interrupted. The primary coolant remained confined only within the cold legs and the reactor vessel. The comparison of the parameters on the next two figures, (Fig. 7 and 8), supports the previous conclusions. On average, due to an earlier and larger primary coolant loss, RELAP5 predicted a faster core-level depletion and, consequently, a slightly earlier start of the core dryout and heatup. It can be proved that the difference in initial subcooling values results from the differences in the method of the core-exit temperature calculation in both input models. During gradual inventory depletion in the core region (Fig. 7) the top parts of the core dryout and heatup started (Fig. 8), so the fuel and fuel-cladding temperatures started rising rapidly [16]. After about 3,000 s one of the loop seals in the cold legs had partly cleared, which caused the primary pressure drop. But this was not sufficient for the cold water from the ECCS to penetrate the primary system, so the core heatup continued. When the core cladding temperature exceeded 1,530 K in the RELAP5 calculation, the calculation was aborted due to high material temperatures and water property errors, when highly non-equilibrium metastable fluid states were calculated during occasional core flooding. The development of several parameters indicated that core




Sl. 7. *Sesedena raven v reaktorski posodi*
Fig. 7. *Reactor-vessel collapsed level*




Sl. 8. *Temperatura hladila na izhodu iz sredice*
Fig. 8. *Core exit temperature*

sredice neizbežno, zato smo s tem primerjalno simulacijo nezgodnega scenarija s programom RELAP5 proglasili za končano. Približno ob istem času je bil ustavljen tudi izračun s simulatorjem, saj so različni parametri jasno nakazovali osuševanje in pregrevanje gorivnih palic.

Na slikah so prikazani le pomembni sistemski parametri, kakor so primarni in sekundarni tlak, raven v tlačniku in uparjalnikih, povprečna temperatura primarnega hladiva, temperatura hladiva na izhodu iz sredice reaktorja in podhladitev primarnega hladiva. Ta niz parametrov ne vsebuje tistih značilnih, ki smo jih uporabili v analizi RELAP5/MOD2 kot npr. temperature srajčk, pretoki skozi ventile, padci tlakov po zankah itn., ker elektrarna ni opremljena za meritev teh parametrov in ti parametri niso na voljo operaterju pri odločanju. Ti parametri tudi niso na seznamu za test usposobljenosti simulatorja po navodilih, dodanih standardu ANSI/ANS-3.5 [2]. Po tem standardu je eno najpomembnejših meril za preveritev, da vsaka opazna sprememba simuliranega parametra po smeri ustreza tisti, ki bi jo pričakovali

degradation and melting became unavoidable, so we assumed that the reference RELAP5 simulation was completed. The simulator calculation was terminated at approximately the same time, when the development of various parameters clearly indicated core dryout and heatup.

In the figures, important plant parameters like the primary and secondary system pressure, the pressurizer and secondary level, the primary-coolant average temperature, the core exit temperature and subcooling are shown. This set of parameters does not include typical parameters used in the RELAP5/MOD2 analysis, like cladding temperatures, various valves' flow, pressure drops across the loop, etc. because the plant is not instrumented for measuring such parameters and thus these parameters are not available for operator decision-making. Besides, such parameters are not proposed in the guidelines for the conduct of simulator operability testing included in ANSI/ANS-3.5 [2]. According to this standard, one of the most important criteria for the validation is that any observable change in simulated parameters od dejanskega odziva elektrarne na nezgodo ali odziva na nezgodo izračunanega s programom za najboljšo oceno.

Zgoraj opisani rezultati analiz se lahko uporabijo tudi za izobraževanje operaterjev in neodvisno ovrednotenje licenčnih preračunov nezgode z izgubo napajanja uparjalnikov. Trenutna svetovna praksa kaže, da se nekateri programi za najboljšo oceno že uporabljajo v popolnih simulatorjih jedrskih elektrarn [14].

## 3 SKLEPI

Program za najboljšo oceno RELAP5/MOD2 je bil uporabljen za analizo nezgode z izgubo napajanja uparjalnikov, zaradi česar pride do popolne izgube ponora toplote na sekundarni strani. V prispevku so opisani glavni elementi vhodnega modela za program RELAP5, ki smo ga uporabili za analizo, navedeni so začetni pogoji ter predpostavke pri simulaciji prehodnega pojava.

Napovedani rezultati nezgode s popolno izgubo napajanja uparjalnikov za jedrsko elektrarno Krško s programom RELAP5/MOD2 so bili uporabljeni za preverjanje delovanja simulatorja JEK. Primerjava je pokazala, da simulatorski model dovolj zvesto posnema odziv elektrarne za primer obravnavane domnevne projektne nezgode in da se rezultati s simulatorja dobro ujemajo s preračuni, izvedenimi s programom RELAP5/MOD2. Tovrstna analiza projektne nezgode se lahko uporabi poleg preveritve simulatorja tudi za izobraževanje operaterjev o ključnih fizikalnih pojavih in zaporedju dogodkov v jedrskih elektrarnah med različnimi nezgodnimi pojavi.

Primerjavo rezultatov RELAP5 in KFSS je treba gledati tudi z vidika, kateremu namenu sta namenjena oba programa. RELAP5/MOD2 je predvsem orodje za znanstvene in inženirske analize prehodnih pojavov v lahkovodnih jedrskih elektrarnah, popolni simulator pa je podrobno prilagojen stanju posamezne elektrarne. Vhodni model za KFSS do potankosti obsega modele vseh sestavin elektrarne, kakor so različni ventili in črpalke ter logika krmiljenja posameznih komponent, medtem ko je v programu RELAP5/MOD2 bolj podrobno opisano termohidrodinamični odziv primarnega in sekundarnega sistema, večina pomožnih sistemov pa je zajeta le prek robnih pogojev. Prav tako so nekateri krmilni sistemi opisani le do določene ravni natančnosti ali zastopani le v obsegu, ki je pomemben za obravnavanje posameznega prehodnega pojava. Povsem smiselna je le primerjava odziva glavnih parametrov sistema in ne tistih, ki so odvisni od posegov operaterja oziroma podrobnega načina delovanja posameznih ventilov in črpalk.

Analiza bi bila lahko temelj za oceno licenčnih preračunov nezgode z izgubo napajanja uparjalnikov, ki jih je opravil izvirni projektant in dobavitelj jedrskega sistema za proizvodnjo pare. Seveda pa je uporaba rezultatov omejena zaradi neupoštevane negotovosti preračuna ([19], [20] in

corresponds in the direction of those expected from an actual or best-estimate response of the reference plant to the malfunction.

The above results of the best-estimate calculations can also be used for operator education and independent evaluation of the licensing loss-of-feedwater calculations. The best practice in the world also shows that simplified best-estimate codes are used in full-scope NPP simulations [14].

## 3 CONCLUSIONS

The RELAP5/MOD2 best-estimate computer code was used for the analysis of an accident initiated by a total loss of feedwater, leading to a total loss of the secondary heat sink. The RELAP5 input model used for the analysis, the assumptions used and the modifications to the input model were described.

The predicted results of the accident with the total loss of feedwater for Krško NPP with RELAP5/MOD2 were used for the KFSS performance-validation testing. The comparison shows that the simulator model reproduces plant response satisfactorily in the case of the analyzed hypothetical design-basis accident. The simulator results are in good agreement with best-estimate calculation performed with RELAP5/MOD2. Besides the simulator validation, the best estimate analysis of such a design-basis accident can be used for operator education on the physical phenomena and processes.

The comparison between the RELAP5 and KFSS predictions must take into account for which purpose each of the tools was developed. RELAP5/MOD2 is primarily a scientific and engineering analysis tool for studying the transient phenomena in light-water nuclear power plants, while full-scope simulators are adapted in detail to the design of a particular plant. The KFSS input model includes detailed models of every plant component, such as valves, pumps or control logic, while the RELAP5/MOD2 models thermo-hydrodynamic plant response more in detail (the interference with various other systems is represented only through boundary conditions). Moreover, some control systems are modeled only to the requied level of detail or to the extent relevant for the analysis of the particular transient. Thus, it is reasonable to compare only the main plant parameters and not those which result from various operator actions or the detailed response of certain valves and pumps.

This analysis can also be used as an independent analysis to the license loss of feedwater calculation performed by original nuclear steam supply system designer-supplier. However, the conclusions about the results would be limited because uncertainty was not evaluated ([19], [20] and [21]). The supplier

[21]). Dobavitelj je namreč opravil zadržane analize, predstavljena analiza pa je opravljena s programom za najboljšo oceno, vsebuje stvarni model in temelji na stvarnih predpostavkah, zato bi bilo treba pred primerjavo z rezultati zadržane analize seveda nujno ovrednotiti negotovosti posameznih parametrov.

has performed a set of conservative analyses, while the presented analysis was performed using a best-estimate computer code and was based on a realistic plant model with realistic assumptions. Before comparing the results of the presented analysis with the results of the licensing conservative analysis, the uncertainty of the parameters should be evaluated.

## 4 KRATICE
## 4 ABBREVIATIONS

| | | |
|---|---|---|
| pomožna napajalna voda uparjalnikov | AFW | Auxiliary Feedwater |
| ameriško združenje jedrskih strokovnjakov | ANS | American Nuclear Society |
| ameriški inštitut za standardizacijo | ANSI | American National Standards Institute |
| obratovalna navodila za ukrepanje v sili | EOP | Emergency Operating Procedures |
| sistem za visokotlačno varnostno vbrizgavanje | HPIS | High Pressure Injection System |
| popolni simulator jedrske elektrarne Krško | KFSS | Krško Full Scope Simulator |
| sistem za nizkotlačno varnostno vbrizgavanje | LPIS | Low Pressure Injection System |
| glavna napajalna voda uparjalnikov | MFW | Main Feedwater |
| jedrska elektrarna | NPP | Nuclear Power Plant |
| ozko območje | NR | Narrow Range |
| informacijski sistem za spremljanje obratovalnih podatkov | PIS | Process Information System |
| reaktorski hladilni sistem | RCS | Reactor Coolant System |
| reaktorski računalniški program | RELAP | Reactor Excursion and Leak Analysis Program |
| uparjalnik | SG | Steam Generator |
| varnostno vbrizgavanje | SI | Safety Injection |
| simulator (KFSS) | SIM | Simulator (KFSS) |
| široko območje | WR | Wide Range |

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