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Simuliranje preizkusa težke nesreče Phebus FPT1 s programom MELCOR

Simulation of the Phebus FPT1 Severe Accident Experiment with the MELCOR Computer Code

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V okviru sodelovanja v Mednarodnem standardnem problemu OECD št. 46 smo z dvema verzijama programa MELCOR 1.8.5 (QZ in RE) simulirali ključne pojave v gorivnem svežnju in primarnem krogu naprave Phebus med fazo degradacije sredice pri preizkusu Phebus FPT1. Pri razvoju vhodnega modela smo upoštevali priporočila glede nodalizacije in uporabe privzetih parametrov, ki so podana v specifikacijah ISP-46. Posebno pozornost smo namenili modeliranju specifičnosti naprave Phebus.

Primerjava rezultatov izračunov s preizkusnimi meritvami je pokazala dobro ujemanje termohidravličnih spremenljivk in zadovoljivo ujemanje končnih izpustov za večino radioaktovnih snovi, medtem ko je odlaganje v uparjalniku precenjeno. Ključni dogodki so napovedani ob pravih časih. Razlike med rezultati simuliranj z obema različicama programa MELCOR so zanemarljive za termohidravlične spremenljivke, majhne za izpuste radioaktovnih snovi in časovno napoved ključnih dogodkov, vendar pomembne za odlaganje radioaktovnih snovi in degradacijo sredice. V splošnem se rezultati novejše različice RE programa MELCOR 1.8.5 bolje ujemajo z meritvami preizkusa.

(Ključne besede: nezgode reaktorjev, modeliranje, simuliranje, PHEBUS, MELCOR)

As part of the OECD International Standard Problem No. 46, the thermal-hydraulic, fuel-degradation and aerosol phenomena, which occurred in the bundle and circuit of the Phebus facility during the degradation phase of the Phebus FPT1 experiment, were simulated with two versions of MELCOR 1.8.5 (QZ and RE). The input model was developed by strictly following the recommendations on noding and the use of the default parameters provided in the ISP-46 Specification Report. Special attention was given to the modelling of the specifics of the Phebus facility.

A comparison of the simulation results and the experimental measurements showed good agreement for the thermal-hydraulic variables and satisfactory agreement for the total releases for most radio-nuclides, whereas the radio-nuclide depositions in the steam generator were overestimated. The timing of the key events was relatively well predicted. The differences between the simulation results of both MELCOR versions were negligible for the thermal-hydraulic variables, small for the radio-nuclide releases and the timing of the key events, but significant for the radio-nuclide depositions and the bundle degradation. In general, the results of the newer MELCOR 1.8.5 version RE show better agreement with the experimental measurements.

(Keywords: reactor accident, modelling, simulation, PHEBUS, MELCOR)

0 UVOD

V programu Phebus FP [1] raziskujejo ključne pojave med hipotetično težko nesrečo v lahkovodnem jedrskem reaktorju s serijo integralnih preizkusov. Naprava Phebus, ki je na Institutu za zaščito pred sevanjem in za nuklearno varnost (“Institut de

0 INTRODUCTION

The Phebus FP program [1] investigates the key phenomena involved in light-water-reactor severe-accident sequences through a series of in-pile integral experiments. The Phebus facility, which is located at the “Institut de radioprotection et de radioprotection et de sûreté nucléaire" - IRSN), v Cadarache-u, Francija, je sestavljena iz pomanjšane reaktorske sredice, pomanjšanega primarnega kroga z uparjalnikom in pomanjšanega zadrževalnega hrama. Phebus FPT1 [2], drugi preizkus v vrsti, je bil izbran kot osnova za Mednarodni standardni problem OECD št. 46 (MSP-46 ali ISP-46) ([3] in [4]). Preizkus omogoča ocenjevanje zmožnosti sistemskih programov, namenjenih modeliranju težkih nesreč, za celostno obravnavo pojavov, ki zajemajo degradacijo sredice do poznih faz (nastanek bazena taline), nastanek vodika, izpust in transport razcepkov, pojave v primarnem krogu in zadrževalnem hramu ter kemijo joda.

Glavni namen MSP-46 je oceniti zmožnost računalniških programov za celostno modeliranje fizikalnih pojavov med težko nesrečo, od začetnih faz degradacije sredice do obnašanja sproščenih razcepkov v zadrževalnem hramu. Računalniške programe naj bi uporabljali podobno, kakor se uporabljajo pri izračunih za jedrske elektrarne. To pomeni uporabo standardnih modelov in opcij, kolikor je mogoče, ter podobno natančen opis naprave Phebus, kakor se uporablja za opis jedrskih elektrarn. Priporočila glede ustrezne nodalizacije naprave Phebus so predstavljena v specifikacijah MSP-46 [3], kjer je predpisano tudi, na koliko vozlišč je treba razdeliti posamezne dele naprave.

Sodelujoči pri MSP-46 so uporabljali različne računalniške programe, s katerimi so simulirali napravo Phebus v celoti ali njen del [3]. Odsek za reaktorsko tehniko Instituta "Jožef Stefan" je sodeloval v MSP-46 z dvema različicama programa MELCOR 1.8.5 (QZ in RE) ([5] in [6]) (gorivni sveženj in primarni krog) in s programom CONTAIN 2.0 [7] (zadrževalni hram).

1 PREIZKUS

1.1 Naprava Phebus

Preizkusni del naprave Phebus predstavlja v razmerju okoli 1/5000 pomanjšani francoski 900 MW tlačnovodni jedrski reaktor [2]. Na sliki 1 je prikazana shema ključnih delov naprave Phebus.

Reaktorska sredica je 1 m visok gorivni sveženj iz 20 gorivnih palic, ki je obdan s keramičnim izolacijskim ovojem, in je znotraj tlačne cevi (sl. 2). V središču gorivnega svežnja je palica, to je reaktorska krmilna palica. Preizkusna sredica, obdana z večplastno cevjo, je vstavljena v tlačno cev, ki poteka skozi središče bistveno večje 40 MW pogonske

sûreté nucléaire" (IRSN) in Cadarache, France, incorporates scaled-down representations of the reactor core, the primary circuit including the steam generator, and the containment. Phebus FPT1 [2], the second experiment in the series, was selected as the basis for the OECD International Standard Problem No. 46 (ISP-46) ([3] and [4]). The experiment provides the opportunity to assess the capability of systems-level severe-accident modelling codes in an integral manner, covering core degradation through to the late phase (melt-pool formation), hydrogen production, fission-products release and transport, circuit and containment phenomena, and iodine chemistry.

The general objective of the ISP-46 is to assess the capability of the computer codes to model, in an integrated way, the physical processes taking place during a severe accident in a pressurized water reactor, from the initial stages of core degradation through to the behaviour of the released fission products in the containment. The codes are supposed to be used in a similar manner as they would be used for plant studies, employing standard models and options as far as possible, with representations of the facility and similar details as used for plant studies. The recommendations for the appropriate noding of the Phebus facility are given in the ISP-46 specification [3], where the number of nodes in different parts of the facility is prescribed.

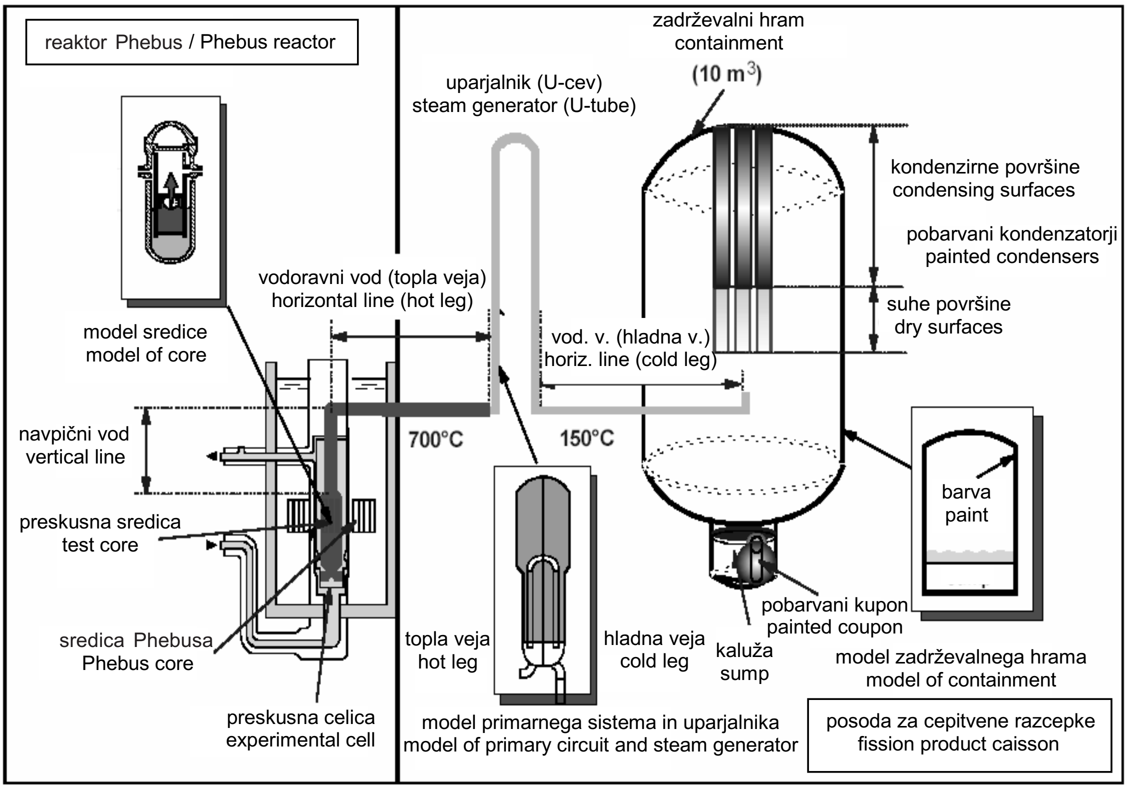
A number of codes were used by the ISP-46 participants, simulating the Phebus facility as a whole or part of it [3]. The Jožef Stefan Institute Reactor Engineering Division participated in the ISP-46 with two versions of the MELCOR 1.8.5 computer code (QZ and RE) ([5] and [6]) (bundle and circuit part) and with the CONTAIN 2.0 computer code [7] (containment part).

1 EXPERIMENT

1.1 Phebus facility

The overall scaling factor of the Phebus facility test train is approximately 1/5000 with respect to the French 900-MW pressurized-water reactor [2]. In Fig. 1 a schematic view of the essential part of the Phebus facility is presented.

The degrading reactor core is represented by a 20-rod, 1-m-high, test-fuel bundle surrounded by an insulating ceramic shroud fitted inside a pressure tube (Fig. 2). A rod simulating the reactor control-rod system occupies the central position. The test device is inserted into a pressurized-water loop,



Sl. 1. *Shema naprave Phebus*
Fig. 1. *Schematic representation of the Phebus facility*

sredice Phebus. Zgornji predel nad preizkusnim gorivnim svežnjem je povezan s preizkusnim primarnim krogom, v katerem je cev v obliki narobe obrnjene črke U, pomeni pa uparjalnik tlačnovodnega reaktorja. Primarni cevovod je povezan s posodo s prostornino 10 m^3, to je zadrževalni hram (simulacija zloma v hladni veji), kamor med preizkusom odtekajo mešanica pare in vodika ter radioaktivne razpršene snovi. Posoda zadrževalnega hrama vsebuje ustrezno pomanjšane pobarvane površine in z vodo napolnjeno kalužo za raziskovanje obnašanja joda v dejanskih okoliščinah.

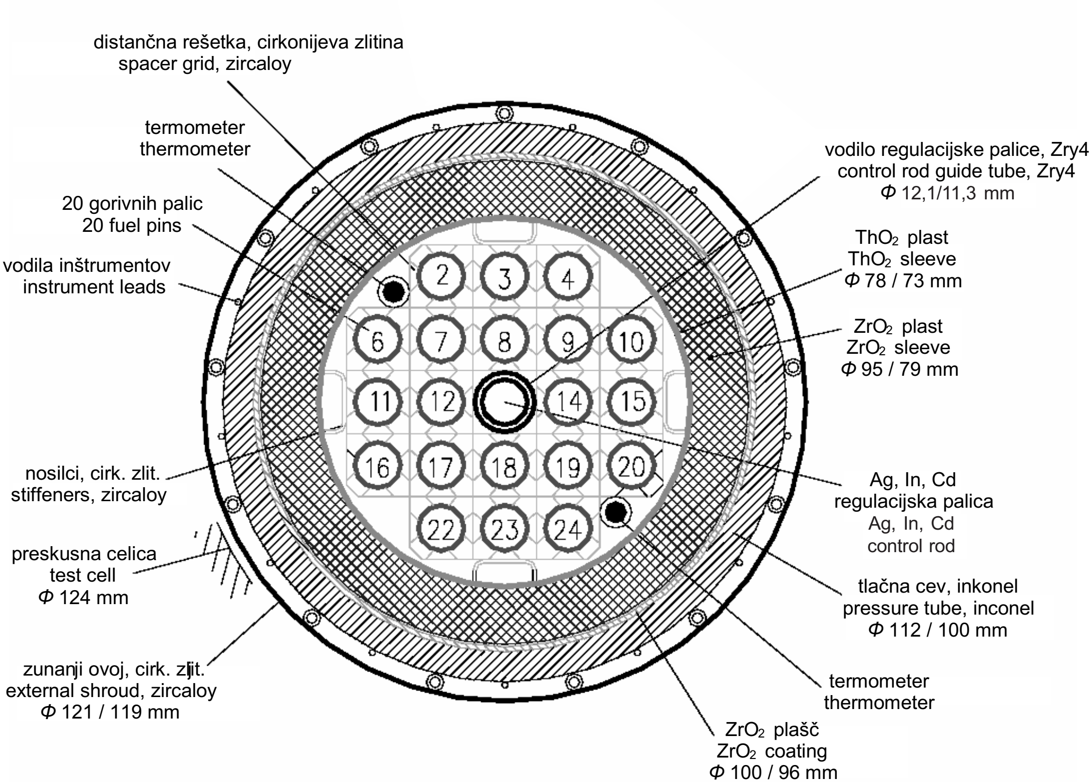
1.2 Opis preizkusa

Preizkusni gorivni sveženj FPT1 je vseboval 18 gorivnih palic tlačnovodnega reaktorja, ki so bile poprej obsevane do povprečne zgorelosti 23,4 GWd/tU, dve instrumentacijski sveži gorivni palici in eno krmilno palico iz srebra, indija in kadmija. Pred začetkom preizkusa so v napravi Phebus gorivni sveženj okoli 7 dni obsevali pri povprečni moči svežnja okoli 205 kW, da bi v gorivu ustvarili kratkožive razcepke. Po tej pripravljalni fazi so

located at the centre of the 40-MW Phebus driver core. The upper plenum above the test-fuel bundle is connected to an experimental circuit, including an inverted U-tube that simulates a PWR steam generator. At the outlet of the circuit, the steam-hydrogen mixture and the radioactive aerosols are injected into a 10 m^3 vessel simulating the containment building of a reactor (cold-leg break simulation). The containment vessel includes scaled painted surfaces and a water-filled sump to investigate the iodine behaviour under realistic conditions.

1.2 Experiment description

The FPT1 test bundle, which included 18 PWR fuel rods previously irradiated to an average burn-up level of 23.4 GWd/tU, two instrumented fresh fuel rods and one silver-indium-cadmium control rod, was pre-irradiated for approximately 7 days with an average bundle power of approximately 205 kW in the Phebus reactor before the experimental phase of the test itself in order to generate short-lived fission products in the fuel. After the pre-



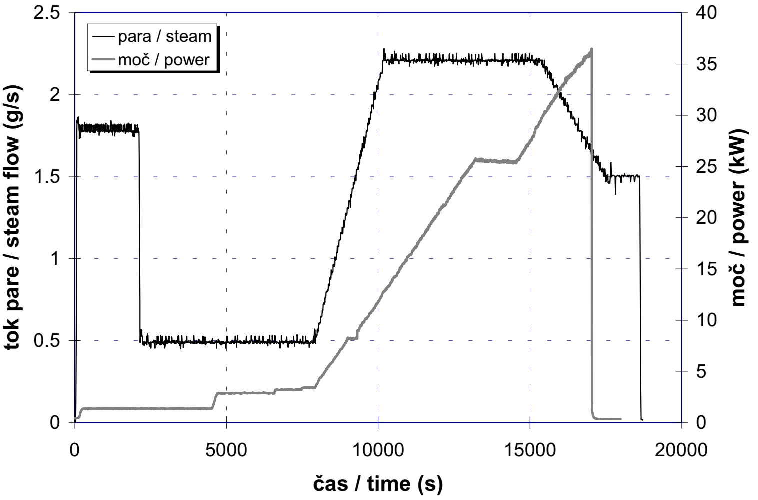
Sl 2. *Prečni prerez FPT1 reaktorske posode z gorivnim svežnjem*
Fig. 2. *Radial configuration of the FPT1 bundle*

potrebovali 36 ur za zmanjšanje zastrupitve reaktorja s ksenonom, za posušitev gorivnega svežnja z nevtralnim plinom ter za nastavitev začetnih pogojev. Dejanski preizkus se je začel z vbrizgavanjem pare v gorivni sveženj in s postopnim dvigovanjem jedrske moči sredice.

Med fazo degradacije gorivnega svežnja, ki je trajala približno 5 ur, so vhodni tok vodne pare, ki so jo v preizkusni cevovod vbrizgavali s spodnje strani, spreminjali od 0,5 do 2,2 g/s in tako ustvarili razmere za oksidacijo, pri tem pa so moč gorivnega svežnja postopoma povečevali od 0,65 kW do 36,5 kW (sl. 3). Fazo degradacije gorivnega svežnja lahko razdelimo na dve obdobji. Prvo obdobje je bilo namenjeno toplotni umeritvi svežnja in meritvam faktorja sklopitve med preizkusnim svežnjem in pogonsko sredico. V tem obdobju, ki je trajalo okoli 7900 s, so moč svežnja in tok pare spreminjali po korakih, da bi preverili toplotni odziv svežnja. Drugo obdobje, ki je trajalo od približno 7900 s do približno 17000 s, predstavlja dejanski temperaturni prehodni pojav in fazo degradacije gorivnega svežnja. Faza degradacije gorivnega svežnja je bila posebej posvečena izpustom razcepkov in snovem goriva, struktur in krmilne palice, da bi lahko raziskovali

conditioning phase, a period of 36 hours was necessary to bring down the reactor xenon poisoning, to dry the bundle using a neutral gas and to establish the initial conditions. The experiment itself then began by injecting steam into the bundle and gradually increasing the core nuclear power.

The fuel-degradation phase lasted about 5 hours, during which time the inlet-steam flow rate injected at the bottom of the test train varied from 0.5 to 2.2 g/s, providing oxidising conditions, while the bundle power was progressively increased from 0.65 kW up to 36.5 kW (Fig. 3). The bundle degradation phase consisted of two main periods. The first one, devoted to the thermal calibration of the bundle and to the measurement of the coupling factor between the experimental bundle and the driver core, lasted app. 7900 s. During this period, the bundle power and the steam flow rate were changed step by step in order to check the thermal response of the bundle. The second period was the real temperature transient and degradation phase of the test, lasting from app. 7900 s to app. 17000 s. The degradation phase was especially devoted to the release of fission products, and bundle, structure and control rod materials in order to study their



Sl. 3. *Vstopni tok pare in moč gorivnega svežnja v FPT1*
Fig. 3. *Inlet steam flow history and bundle power in FPT1*

njihov prenos in zadrževanje v preizkusnem primarnem krogu.

Po fazi degradacije se je preizkus nadaljeval z razpršeno, izpiralno in kemijsko fazo, ki pa jih v prispevku ne obravnavamo.

2 OPIS MODELA NAPRAVE PHEBUS

2.1 Program MELCOR

MELCOR je popolnoma integriran, inženirski računalniški program, ki modelira napredovanje težkih nesreč v lahkovodnih jedrskih reaktorjih [8]. MELCOR razvijajo v “Sandia National Laboratories” za upravni organ ZDA kot orodje za oceno tveganja jedrskih elektrarn. Simulirni program MELCOR je sestavljen iz tako imenovanih modulov, ki modelirajo reaktor ali preizkusno napravo na prilagojen način. Moduli so razdeljeni po pojavih in ne po področjih. Tako je na primer mehanika tekočin v vseh delih modela opisana z istim naborom enačb, izračuni pa potekajo sočasno.

S programom MELCOR je mogoče modelirati naslednje pojave med nezgodo:

- termohidravlični odziv primarnega reaktorskega hladilnega sistema, reaktorske votline, zadrževalnega hrama in izolacijskih zgradb;
- odkrivanje sredice (izguba hladiva), segrevanje goriva, oksidacija srajčk, degradacija goriva (deformacija gorivnih palic) ter taljenje in porušitev sredice;
- segrevanje spodnjega dela reaktorske posode zaradi porušitve sredice, toplotne in mehanične

transport and retention in the experimental circuit.

After the degradation phase the experiment continued with the aerosol phase, the washing phase and the chemistry phase, which are not treated in this paper.

2 MODEL DESCRIPTION OF PHEBUS FACILITY

2.1 MELCOR code

MELCOR is a fully integrated, engineering-level computer code that models the progression of severe accidents in light-water-reactor nuclear power plants [8]. MELCOR is being developed at Sandia National Laboratories for the U.S. Nuclear Regulatory Commission as a plant-risk assessment tool. The MELCOR simulation code is composed of several so-called “packages” that model a reactor or experimental facility in a modular fashion. The modularisation is by phenomena, not by region. For example, fluid-dynamics calculations for all parts of the model are solved simultaneously, using the same set of fluid equations in all regions.

With MELCOR, the following phenomena occurring during an accident can be modelled:

- the thermal-hydraulic response of the primary-reactor coolant system, the reactor cavity, the containment, and the confinement buildings,
- core uncovering (loss of coolant), fuel heat up, cladding oxidation, fuel degradation (loss of rod geometry), and core-material melting and relocation,
- the heat up of the reactor vessel’s lower head from relocated fuel materials and the thermal and mechanical loading and failure of the vessel lower

obremenitve sten reaktorske posode ter odpoved reaktorske posode, izliv taline iz reaktorske posode v reaktorsko votlino;
- interakcija taline z betonom in nastajanje razpršin;
- nastajanje vodika v reaktorski posodi in zunaj nje, prenos in gorenje vodika;
- izpust razcepkov (razpršine in hlapi), njihov prenos in odlaganje;
- obnašanje radioaktivnih razpršin v zadrževalnem hramu;
- vpliv varnostnih sistemov na termohidravlični odziv in obnašanje radioaktivnih snovi.

Za modeliranje preizkusa Phebus FPT1 smo od 25 modulov, ki so na voljo v programu MELCOR 1.8.5, uporabili naslednjih 17 modulov: CVH – hidrodinamika, CVT – termodinamika, FL – tokovne poti, HS – toplotna telesa, COR – sredica, DCH – razpadna toplota, RN – radioaktivne snovi, MP – snovske lastnosti, NCG – nekondenzirajoči plini, EOS – enačba stanja, H20 – lastnosti vode, CF – krmilne funkcije, TF – tabelne funkcije, EDF – zunanje datoteke s podatki, EXEC – izvršilni modul, UTIL – podporni modul, PROG – knjižnice.

2.2 Termohidrodinamična nodalizacija in modeliranje

Termohidrodinamično nodalizacijo primarnega kroga, ki je predstavljena na sliki 4, smo napravili v skladu s specifikacijami ISP-46 [3], v katerih je predpisano, katero območje naprave Phebus naj obravnavamo in na koliko vozlišč je treba razdeliti posamezne dele naprave. Nadzorne prostornine so označene s CV-xxx, tokovne poti s FL-xxx in toplotna telesa s HS-xxxxx. Geometrijske podatke za vhodni model smo dobili v podatkovni knjigi FPT1 [9], poročilu specifikacij ISP-46 [3] in končnem poročilu FPT1 [2]. Podatke za vhodni tok pare, temperaturo pare in tlak pare smo dobili v končnem poročilu FPT1 [2].

2.3 Vozliščenje gorivnega svežnja in modeliranje

Vozliščenje reaktorske posode in gorivnega svežnja je predstavljena na sliki 5. Nadzorne prostornine so označene s CV-xxx, celice sredice s COR-xxx in toplotna telesa s HS-xxxxx. Enajst osnih ravni na grelnem območju od višine –7,987 m do višine –6,987 m, označenih s COR-x04 do COR-x14, smo določili v skladu s specifikacijami ISP-46 [3]. Gorivni sveženj smo modelirali z dvema prečnima obročema. V prvem prečnem obroču so krmilna

head, and the transfer of core materials to the reactor-vessel cavity,
- the core-concrete interaction and ensuing aerosol generation,
- the in-vessel and ex-vessel hydrogen production, transport, and combustion,
- the fission products' release (aerosol and vapour), transport, and deposition,
- the behaviour of radioactive aerosols in the reactor-containment building,
- the impact of engineering safety features on thermal-hydraulic and radio-nuclide behaviour.

For the modelling of experiment FPT1 from 25 packages, which are available in the MELCOR 1.8.5 computer code, the following 17 packages were used: CVH – hydrodynamics, CVT – thermodynamics, FL – flow paths, HS – heat structures, COR – core, DCH – decay heat, RN – radio-nuclides, MP – material properties, NCG – non-condensable gases, EOS – equation of state, H2O – water properties, CF – control functions, TF – tabular functions, EDF – external data files, EXEC – executive package, UTIL – utility package, PROG – libraries.

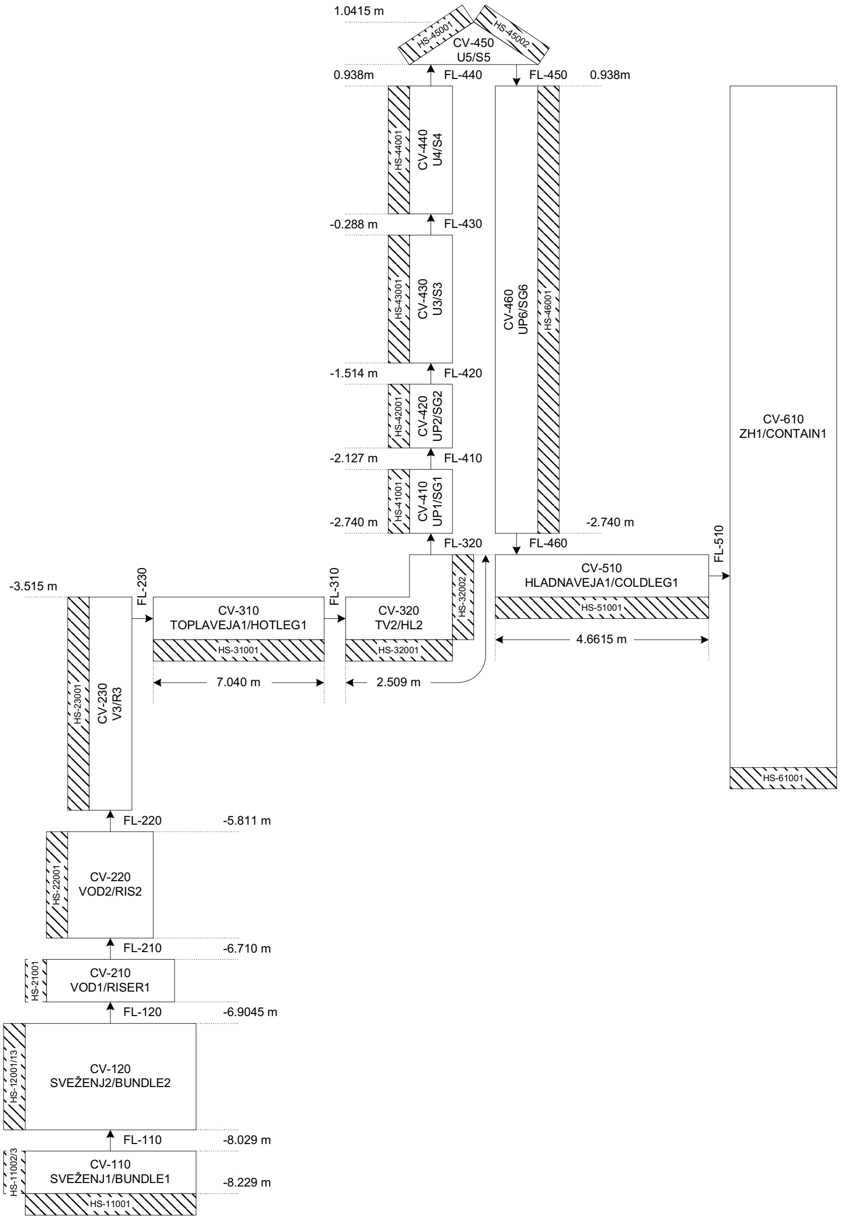
2.2 Hydrodynamic nodalization and modelling

The hydrodynamic nodalization of the bundle and circuit was done according to the ISP-46 specification [3], where the number of nodes in different parts of the Phebus facility and the computational domain is prescribed, and is presented in Fig. 4. The control volumes are denoted with CV-xxx, the flow paths with FL-xxx, and the heat structures with HS-xxxxx. The geometric data for the input model was obtained from the FPT1 Data Book [9], the ISP-46 Specification Report [3] and the FPT1 Final Report [2]. The inlet-steam flow rate, the steam temperature and the steam pressure were obtained from the FPT1 Final Report [2].

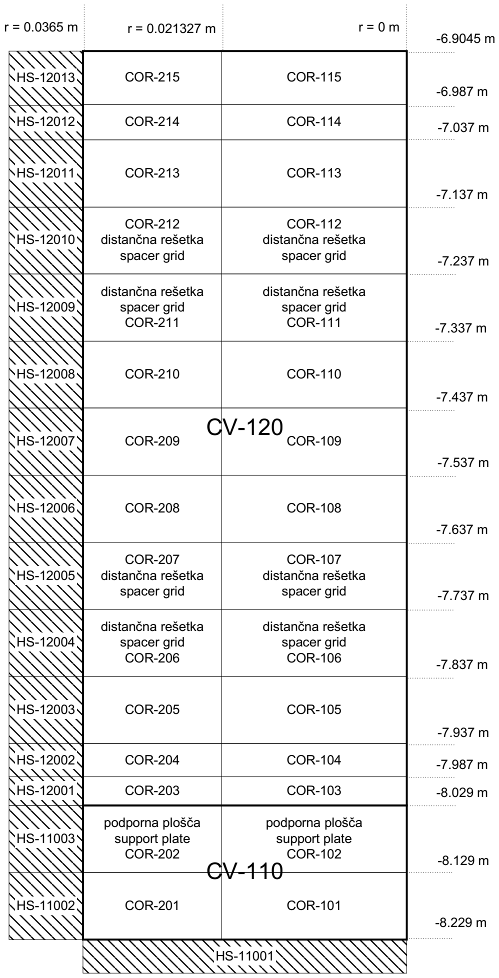
2.3 Core nodalization and modelling

The core nodalization of the bundle is presented in Fig. 5. The control volumes are denoted with CV-xxx, the core cells with COR-xxx, and the heat structures with HS-xxxxx. The 11 axial levels in the heated length from level –7.987 m to level –6.987 m denoted with COR-x04 to COR-x14 were defined according to the ISP-46 specification [3]. The bundle was modelled with two radial rings. In the first radial ring there are the control rod, the control-rod palica, vodilo krmilne palice in 8 notranjih obsevanih gorivnih palic. V drugem prečnem obroču pa je 10 zunanjih obsevanih gorivnih palic, 2 sveži gorivni palici in nosilci. Ker so sveže in obsevane gorivne palice v istih celicah drugega prečnega obroča, jih ne moremo obravnavati ločeno. Zato smo lahko v vhodnem modelu upoštevali le povprečne lastnosti svežih in obsevanih gorivnih palic in zato smo lahko izračunali le povprečne rezultate. Kot podporno

guide tube and the inner 8 irradiated fuel rods. In the second radial ring there are the outer 10 irradiated fuel rods, the 2 fresh-fuel rods and the stiffeners. Since the fresh and irradiated fuel rods are both in the same core cells of the second radial ring they cannot be treated separately. Therefore, in the input model only the average properties of the fresh and irradiated fuel rods could be considered, and for the same reason only the average results can be calcu-



Sl. 4. *Termohidrodinamična nodalizacija primarnega kroga in nodalizacija toplotnih teles*
Fig. 4. *Thremalhydrodynamic and heat structure nodalization of the bundle and circuit*



Sl. 5. *Nodalizacija reaktorske posode z gorivnim svežnjem in nodalizacija toplotnih teles*
Fig. 5. *Core and heat structure nodalization of the bundle*

strukturo smo modelirali podporno ploščo goriva in obe distančni rešetki, kot nepodporno strukturo pa krmilno palico, vodilo krmilne palice, nosilce ter vzmeti v krmilni in gorivnih palicah. Podporno ploščo in obe distančni rešetki smo razporedili v oba prečna obroča v skladu s površino obročev. Cev, ki obdaja gorivni sveženj, smo obravnavali kot toplotno telo.

2.4 Vozliščenje toplotnih teles in modeliranje

Podatke za snovi, iz katerih je cev, ki obdaja gorivni sveženj, smo dobili iz poročila specifikacij MSP-46 [3]. Vse druge snovske lastnosti smo dobili iz baze podatkov v MELCOR modulu snovskih lastnosti (MP). Zunanjo temperaturo cevi, ki obdaja gorivni sveženj, smo ustalili na 438 K, kar je v skladu s poročilom specifikacij MSP-46. Po specifikacijah ISP-46 naj bi

lated. As a supporting structure the fuel-supporting plate and the two spacer grids were modelled, and as a non-supporting structure the control rod, the control-rod guide tube, the stiffeners and the springs in the control and fuel rods were modelled. The support plate and the two spacer grids were distributed in both radial rings according to the rings' surface area. The shroud was considered as a heat structure.

2.4 Heat structure nodalization and modelling

The data for the shroud materials was taken from the ISP-46 specification report [3]. All other material properties were taken from the MELCOR material properties package database (MP). The outside temperature of the shroud was fixed at the constant temperature of 438 K, obtained from the ISP-46 specification report. The temperature evolution of the circuit walls should be, accordpotek temperature notranje strani cevi primarnega kroga predpisali na podlagi preizkusnih podatkov. V modulu MELCOR toplotnih teles (HS) temperature ni mogoče predpisati na notranji strani cevi, ampak jo je mogoče predpisati le na zunanji strani cevi. Da bi lahko čim bolj natančno predpisali temperaturo na notranji strani cevi primarnega kroga, smo primarni krog obdali z umetnimi tankimi (1 mm) toplotnimi telesi iz nerjavnega jekla. Ker ima nerjavno jeklo veliko toplotno prevodnost, je tako razlika temperatur na notranji in zunanji strani toplotnega telesa zanemarljiva. Temperaturo na zunanji strani teh umetnih toplotnih teles (in s tem posredno temperaturo na notranji strani cevi) smo predpisali na podlagi razpoložljivih preizkusnih podatkov.

2.5 Modeliranje radioaktivnih snovi

Začetno količino radionaktivnih snovi smo določili iz končnega poročila FPT1 [2]. Elemente radioaktivnih snovi smo razvrstili v privzete vnaprej določene skupine radioaktivnih snovi modula MELCOR radioaktivnih snovi (RN) v skladu s privzetimi sestavami [8]. V modulu RN je privzetih 16 skupin radioaktivnih snovi, ki so poimenovane po reprezentativni radioaktivni snovi. V vhodnem modelu smo določili, da takoj po izpustu skupina “jod” reagira s skupino “cezij” in ustvari skupino “cezijev jodid”.

V modulu RN so na voljo trije modeli izpustov: CORSOR, CORSOR-M in CORSOR-BOOTH [8]. Simuliranja smo opravili z vsemi tremi modeli in izkazalo se je, da model CORSOR-BOOTH napove večinoma premajhne izpuste, medtem ko modela CORSOR in CORSOR-M napovesta za nekatere radioaktivne snovi kar dobre rezultate. Izpuste nekaterih radioaktivnih snovi je bolje napovedal model CORSOR, medtem ko je druge bolje napovedal model CORSOR-M. Zaradi različnega obnašanja za različne radioaktivne snovi se je bilo težko odločiti, kateri model je v splošnem boljši. Na koncu smo se odločili, da bomo simuliranja opravili z modelom CORSOR-M, ker so rezultati v povprečju za spoznanje boljši. Izpusta strukturnih snovi (tj. snovi, ki niso gorivo), ki pomembno vplivajo na kemijo in zaradi tega tudi na izvorni člen, ni bilo mogoče izračunati, ker v programu MELCOR ni ustreznega modela za izračun izpusta strukturnih snovi.

2.6 Modeliranje specifičnosti naprave Phebus

Pri visokih temperaturah je toplotno sevanje pomemben način prenosa toplote v sredici, saj se

ing to the ISP-46 specification, derived from the experimental data. In the MELCOR heat-structure package (HS) it is not possible to define the pipe’s inside-wall temperature directly, but it is possible to define the pipe’s outside-wall temperature. To be able to determine the circuit’s inside-wall temperature as accurately as possible, artificially thin (1-mm) heat structures made of stainless steel were provided along the circuit. Since the heat conductivity of stainless steel is high, the difference between the inside and outside temperature of the heat structure is negligible. The outside temperature of these artificial heat structures (and so, indirectly, the circuit’s inside-wall temperature) was derived from the available experimental data.

2.5 Radio-nuclide modelling

The initial radio-nuclide inventory was derived from the FPT1 Final Report [2]. The radio-nuclide elements were grouped into the predetermined, default radio-nuclide classes of the MELCOR radio-nuclide package (RN) according to the default compositions [8]. In the RN package there are 16 default classes, which are named by their representative radio-nuclide. In the input model it was defined that immediately after the release the iodine class reacts with the caesium class and forms the caesium-iodine class.

In the RN package three different radio-nuclide release models are available: CORSOR, CORSOR-M and CORSOR-BOOTH [8]. Simulations were performed with all three models and it turned out that the CORSOR-BOOTH model mostly predicts releases that are too low, whereas the CORSOR and CORSOR-M models give, for some radio-nuclide classes, relatively good results. The CORSOR model gave better predictions for the releases of some radio-nuclide classes whereas the CORSOR-M model gave better predictions for some others. Due to the different behaviour for different radio-nuclide classes it was difficult to decide which model is generally better. In the end it was decided to perform the simulations with the CORSOR-M model since the results are, on average, slightly better. The structural material (i.e., the non-fuel material) release, which significantly influences the chemistry and consequently also the source term, could not be calculated since MELCOR has no appropriate structural-material release model.

2.6 Modelling of specifics of Phebus facility

At high temperatures the thermal radiation becomes an important mode of heat transfer within izsevani toplotni tok zvečuje s četrto potenco absolutne temperature. Prenos toplote s sevanjem med različnimi deli sredice in med sredico ter okoliškimi strukturami je odvisen od geometrijske oblike sredice, emisijskega koeficienta površin in tekočine, v katerem je sredica. V splošnem lahko prenos toplote s sevanjem med ploskvama i in j izračunamo s z naslednjo enačbo:

the core, since the radiated heat flux rises with the fourth power of the absolute temperature. The heat transferred by thermal radiation between the different parts of the core and between the core and the surrounding structures depends on the core geometry, the emissivity of the surfaces and the medium surrounding the core. In general, the heat-transfer rate from surface i to surface j can be calculated with the following equation:

$$q_{ij} = A_i F_{ij} \tau_{ij} \left(J_i - J_j \right), \qquad (1),$$

kjer so A_i površina ploskve i, F_{ij} geometrijski faktor pogleda s ploskve i na ploskev j, τ_{ij} prepustnost sevanja med ploskvama i in j ter J_i celoten sevalni tok s ploskve i. Celoten sevalni tok s ploskve i izračunamo kot vsoto odbitega in izsevanega sevalnega toka:

where A_i is the area of surface i, F_{ij} is the geometric view factor from surface i to surface j, τ_{ij} is the radiation transmittance between the surfaces i and j, and J_i is the radiosity of surface i. The radiosity, which is defined as the total radiation flux leaving the surface i – both reflected and emitted – is calculated as:

$$J_i = \left(1 - \varepsilon_i\right) G_i + \varepsilon_i E_{bi}, \qquad (2),$$

kjer so ε_i emisijski koeficient ploskve i, G_i vpadni sevalni tok na ploskev i in $E_{bi} = \sigma T_i^4$ toplotni sevalni tok s ploskve i, če bi ploskev i sevala kot črno telo.

V modulu MELCOR sredice (COR) se emisijski koeficient površin sredice ε_i in prepustnost sevanja skozi medij τ_{ij} določata z ustreznimi odvisnostmi ob upoštevanju stanja degradirane sredice, geometrijski faktor pogleda F_{ij} pa lahko uporabnik določi sam. V modulu COR vsaka gorivna palica ni modelirana posebej, ampak so gorivne palice združene v prečne obroče sredice, prenos toplote s sevanjem pa se modelira med sosednjima prečnima obročema. Tako pomeni geometrijski faktor povprečno vidljivost gorivnih palic v dveh sosednjih prečnih obročih. Zaradi prečnega temperaturnega gradienta v prečnih obročih sredice je razlika temperatur gorivnih palic ob meji dveh sosednjih prečnih obročev manjša od razlike povprečnih temperatur gorivnih palic v sosednjih prečnih obročih. Ker izračun prenosa toplote s sevanjem temelji na povprečnih temperaturah v posameznih prečnih obročih, ne pa na temperaturah gorivnih palic ob robu prečnega obroča, je tako izračunan prenos toplote s sevanjem precenjen. To odstopanje je mogoče do neke mere izravnati z ustreznim zmanjšanjem geometrijskega faktorja pogleda. Tako dobljeni faktor, ki je prilagojen načinu modeliranja prenosa toplote s sevanjem v modulu COR, imenujemo sevalni izmenjalni količnik.

Optimalna vrednost sevalnega izmenjalnega količnika je odvisna od velikosti sredice in njenega

where ε_i is the emissivity of surface i, G_i is the radiation flux incident on surface i and $E_{bi} = \sigma T_i^4$ is the blackbody emissive power of surface i.

In the MELCOR core package (COR), the emissivity of the core surfaces ε_i and the radiation transmittance of the media τ_{ij} are calculated using appropriate correlations considering the state of the degraded core, whereas the geometric view factor F_{ij} can be set by the user. In the COR package each fuel rod is not modelled separately, but the fuel rods are grouped in radial core rings, and the heat transfer by thermal radiation is modelled between adjacent radial rings. So, the geometric view factor presents an average view of fuel rods in two adjacent radial rings. Due to the radial temperature gradient in the radial core rings, the difference between the fuel-rod temperatures at the boundary of two adjacent radial rings is smaller than the difference between the average fuel-rod temperatures in adjacent radial rings. Since the calculation of the heat transfer by thermal radiation is based on the average fuel-rod temperatures in the radial rings and not on the fuel-rod temperatures at the boundary of the radial ring, the so-calculated heat transfer by thermal radiation is overestimated. This overestimation can be, to a certain degree, compensated by reducing the geometric view factor. The so-established factor, which takes into account the specific treatment of heat transfer by thermal radiation in the COR package, is called the radiative exchange factor.

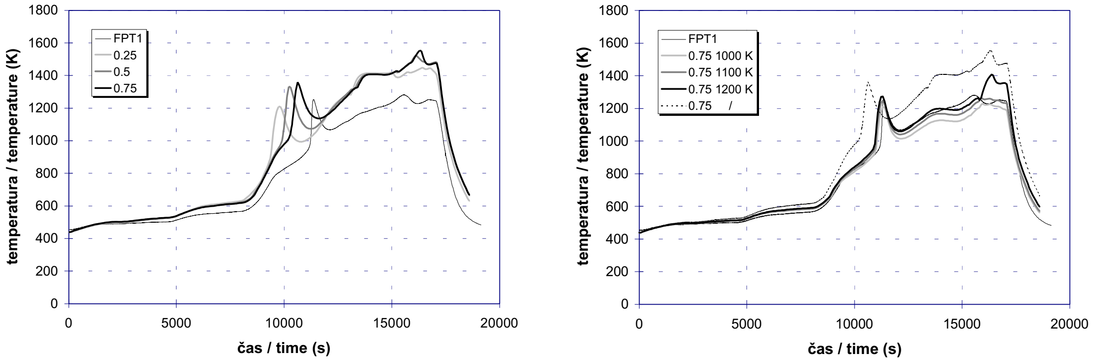
The optimum value of the radiative exchange factor depends on the core size and the nodalization.

vozliščenja. Zaradi majhne velikosti gorivnega svežnja v napravi Phebus je v vsakem obroču vozliščene sredice le ena prečna »plast« gorivnih palic. Tako ima »povprečna« gorivna palica v obroču precej boljšo vidljivost sosednjega obroča, kakor bi jo imela v primeru reaktorske sredice v naravni velikosti. Poleg tega gorivne palice v notranjem obroču ne vidijo le gorivnih palic v zunanjem obroču, ampak vidijo neposredno tudi cev, ki obdaja gorivni sveženj. Zato je treba sevalni izmenjalni količnik za sevanje v prečni smeri med dvema sosednjima prečnima obročema sredice (privzeta vrednost: 0,25) občutno povečati.

Na slikah 6 do 8 so prikazani izračuni temperatur cevi MELCOR 1.8.5 RE okoli gorivnega svežnja, srajčke in goriva za različne sevalne izmenjalne količnike (0,25; 0,5; 0,75) v primerjavi s preizkusnimi meritvami (FPT1). Valovanje (sl. 7) in nenadne spremembe (sl. 8) v preizkusnih krivuljah so posledica odpovedi termočlenov. Nenaden padec

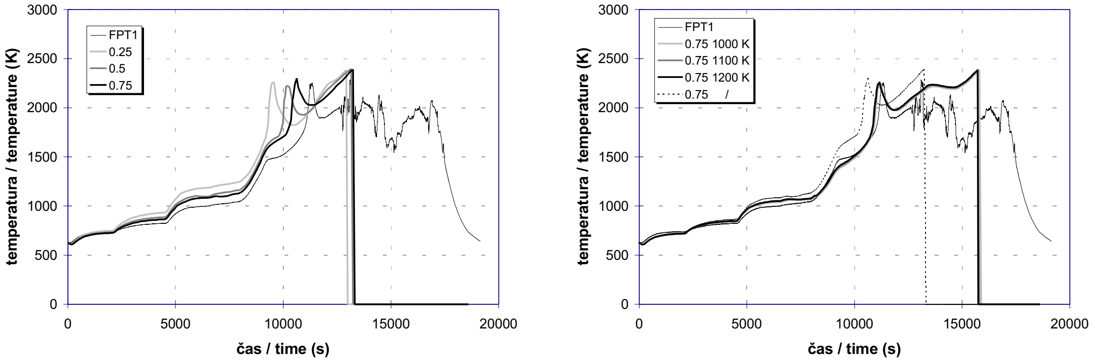
Because of the small size of the bundle in Phebus, each ring of the core nodalization contains only one radial layer of fuel rods. Thus, the “average” rod in a ring has a much better view of the adjacent ring than would be the case in a full-scale reactor core. In addition, the fuel rods in the inner ring can see not only the fuel rods in the outer ring but also directly the shroud. Therefore the radiative exchange factor for radiation radially outward from the cell boundary to the next adjacent cell (default value: 0.25) has to be significantly increased.

In Figures 6 to 8 the MELCOR 1.8.5 RE calculated temperatures of the shroud, clad and fuel are presented for different radiative exchange factors (0.25, 0.5, 0.75) in comparison with the experimental measurements (FPT1). The fluctuations (Fig. 7) or abrupt changes (Fig. 8) in the experimental curves are due to the failure of thermocouples. The abrupt fall in the calculated curves (Fig. 7 and 8) indicates a component failure, since in MELCOR it is defined



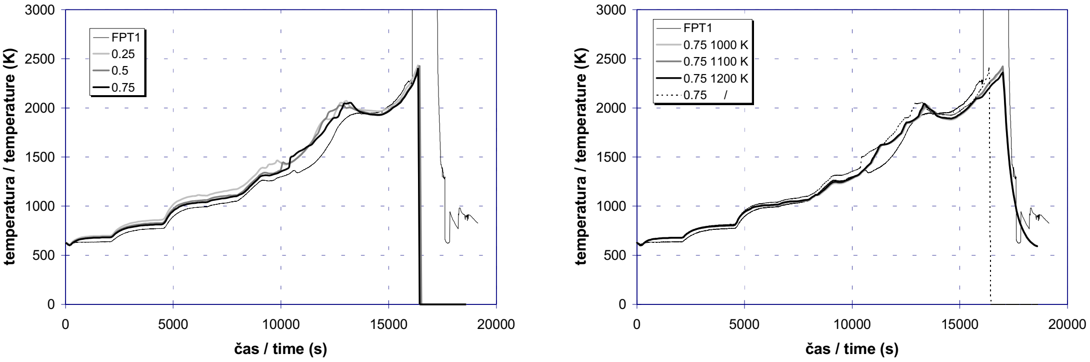
Sl. 6. *Temperatura na notranji strani cevi okoli gorivnega svežnja na višini 800 mm za različne sevalne izmenjalne količnike (levo) in za različne temperature zapiranja parnih rež (desno)*

Fig. 6. *Inside shroud temperature at level 800 mm for different radiative exchange factors (left) and for different steam gaps closure temperatures (right)*



Sl. 7. *Temperatura srajčke v zunanjem obroču sredice na višini 600 mm za različne sevalne izmenjalne količnike (levo) in za različne temperature zapiranja parnih rež (desno)*

Fig. 7. *Clad temperature in outer core ring at level 600 mm for different radiative exchange factors (left) and for different steam gaps closure temperatures (right)*



Sl. 8. *Temperatura goriva v zunanjem obroču sredice na višini 300 mm za različne sevalne izmenjalne količnike (levo) in za različne temperature zapiranja parnih rež (desno)*

Fig. 8. *Fuel temperature in outer core ring at level 300 mm for different radiative exchange factors (left) and for different steam gaps closure temperatures (right)*

(sl. 7, 8) v preizkusnih krivuljah pa označuje porušitev komponente, saj je v programu MELCOR definirano, da je temperatura komponente, ki je v celici ni, 0 K. Kakor je bilo pričakovati, se temperatura srajčke in goriva zmanjša, če sevalni izmenjalni količnik povečamo (sl. 7, 8), saj se več toplote odvaja s sevanjem. Posledično se tudi temperaturni vrh srajčke, ki je posledica eksotermne oksidacije cirkonija, pojavi kasneje (sl. 7). Če povečujemo sevalni izmenjalni količnik, se krivulje temperatur približujejo preizkusnim meritvam, vendar tudi za ocenjeno vrednost sevalnega izmenjalnega količnika 0,75, ujemanje še vedno ni zadovoljivo.

Na sliki 6 vidimo, da je izračunana temperatura na notranji strani cevi, ki obdaja gorivni sveženj, precenjena, kar kaže, da bi lahko bila toplotna prevodnost cevi podcenjena. In res, v večplastni cevi sta dve 0,5 mm debeli parni reži - med plastema ThO_2 in ZrO_2 ter med plastjo ZrO_2 in ZrO_2 plaščem (sl. 2), ki močno vplivata na toplotno prevodnost cevi. Med segrevanjem cevi se zaradi toplotnega raztezanja notranjih toplejših plasti debelini obeh parnih rež zmanjšujeta, dokler se obe parni reži popolnoma ne zapreta in pride do neposrednega stika posameznih plasti. Ob neposrednem stiku posameznih plasti cevi se toplotna prevodnost cevi občutno poveča. Ker v programu MELCOR zapiranja obeh parnih rež ni mogoče neposredno simulirati, smo zapiranje parnih rež modelirali s temperaturno odvisno dejansko toplotno prevodnostjo pare v obeh režah:

that the temperature of a component that does not exist in the considered cell is 0 K. As expected the temperature of the clad and fuel decreases when the radiative exchange factor is increased (Fig. 7 and 8), since more heat is transferred by radiation. Consequently, the clad-temperature peak caused by the zirconium's exothermic oxidation reaction also occurs at a later time (Fig. 7). When the radiative exchange factor is increased the temperature curves move towards the experimental measurements, but also for an estimated value of the radiative exchange factor of 0.75 the agreement is still not satisfactory.

In Fig. 6 we see that the calculated inside-shroud temperature is overestimated, which is an indication that the shroud's heat conductivity could be underestimated. Indeed, in the shroud there are two 0.5-mm-thick steam gaps – between the ThO_2 and ZrO_2 sleeves and between the ZrO_2 sleeve and the ZrO_2 spray coating (Fig. 2) – which significantly influence the shroud's heat conductivity. During the shroud's heating up the thickness of both steam gaps reduces due to the thermal expansion of the inner hotter sleeves until both steam gaps completely close and there is a direct contact between the different shroud layers. At a direct contact between the shroud layers the heat conductivity of the shroud significantly increases. Since in MELCOR it is not possible to simulate the closure of the two steam gaps directly, we decided to model the steam-gaps closure with the temperature-dependent effective thermal conductivity of the steam in both gaps:

$$\lambda_{effective} = \begin{cases} \min\left(10\frac{\mathrm{W}}{\mathrm{mK}}, \lambda_{steam}\left(1-\frac{T-300\mathrm{K}}{T_{close}-300\mathrm{K}}\right)^{-1}\right) & \text{če/if } T < T_{close} \\ 10\frac{\mathrm{W}}{\mathrm{mK}} & \text{če/if } T \geq T_{close} \end{cases} \quad (3),$$

ki temelji na predpostavki, da se med dvigom temperature od 300 K do T_{close} debelini obeh parnih rež linearno zmanjšujeta do popolnega zaprtja. Zaprti parni reži smo modelirali kot reži, v katerih je para z zelo veliko dejansko toplotno prevodnostjo $\lambda_{effective} = 10\,\mathrm{W/mK}$, ki tako ne zmanjšujeta več toplotne prevodnosti večplastne cevi. Na slikah 6 do 8 je prikazan vpliv predpostavljene temperature T_{close} (1000 K, 1100 K, 1200 K, brez zapiranja rež), pri kateri se parni reži popolnoma zapreta, na rezultate simuliranj s programom MELCOR 1.8.5 RE. Vidimo, da model zapiranja parnih rež občutno izboljša rezultate simuliranj in da se rezultati simuliranj pri temperaturi zapiranja parnih rež 1100 K skoraj popolnoma ujemajo z izmerjenimi temperaturami.

3 REZULTATI SIMULIRANJ

Opravili smo dve primerjalni simuliranji z različnima različicama programa MELCOR, to je z različico MELCOR 1.8.5 QZ (v nadaljevanju QZ), ki smo jo posodobili z najnovejšim uradnim popravkom (oznaka “Patch 185003”), kar je zadnja uradna izvedba, ter z izboljšano verzijo MELCOR 1.8.5 RE (v nadaljevanju RE), ki smo jo prejeli na uporabniški delavnici “MELCOR Users’ Workshop 2002”. Glavne razlike med različicama RE in QZ, ki zadevajo simuliranje preizkusa Phebus FPT1, so naslednje: v izvedbi RE so izboljšali doslednost hidrodinamičnega modula in modula sredice (CVH/COR), odpravili so nekaj programerskih hroščev v modulu sredice (COR) in v modulu radioaktivnih snovi (RN) so izboljšali interpolacijo koeficientov razpršin.

Simuliranji smo opravili pri ocenjeni vrednosti sevalnega izmenjalnega količnika za sevanje v prečni smeri med dvema sosednjima celicama sredice 0,75 in pri vrednosti temperature zapiranja parnih rež T_{close} = 1100K, kjer so se rezultati izračunov najbolje ujemali z meritvami. Kakor je prikazano na slikah 6 do 8, je tako mogoče dobiti dobro ujemanje temperaturnih razmer v gorivnem svežnju s preizkusnimi meritvami, kar je potrebno, če želimo ocenjevati zmožnost programa MELCOR za napovedovanje drugih preizkusnih rezultatov, to so nastanek vodika, izpust in odlaganje razcepkov, degradacija sredice idr. Ker so razlike med QZ in RE izračuni temperatur cevi okoli gorivnega svežnja, srajčke in goriva zanemarljivi, teh rezultatov za simuliranje QZ ne bomo opisovali.

Na sliki 9 sta prikazana preizkusni (FPT1) in simulirani (QZ, RE) masni tok vodika. Vodik nastane med oksidacijo cirkonijevih srajčk gorivnih palic v

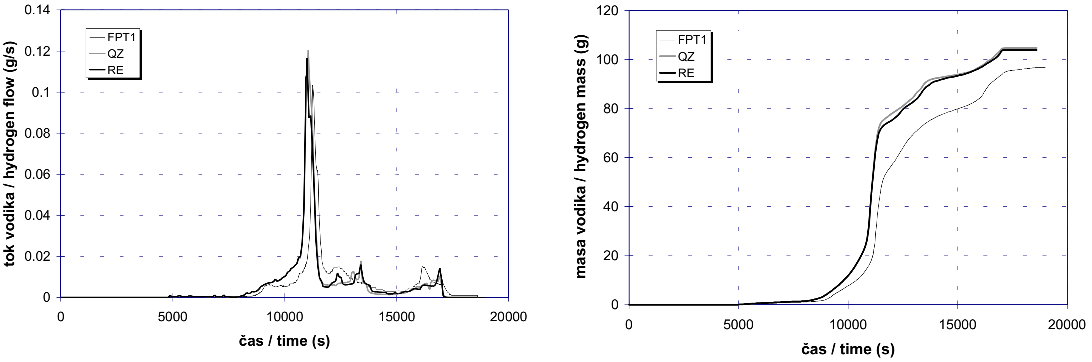
which is based on the assumption that during the temperature rise from 300 K to T_{close} the thickness of both steam gaps linearly reduces until complete closure occurs. The closed steam gaps were modelled as gaps filled with steam that has a very high effective heat conductivity $\lambda_{effective} = 10\,\mathrm{W/mK}$, so that the gaps do not reduce the heat conductivity of the multi-layer shroud anymore. In Figures 6 to 8 the influence of the assumed steam gaps’ closure temperature T_{close} (1000 K, 1100 K, 1200 K, no gaps closure) on the MELCOR 1.8.5 RE simulation results is presented. We see that the steam gaps’ closure model significantly improves the simulation results, and that the results for the steam gaps’ closure temperature 1100 K are in nearly perfect agreement with the measured temperatures.

3 SIMULATION RESULTS

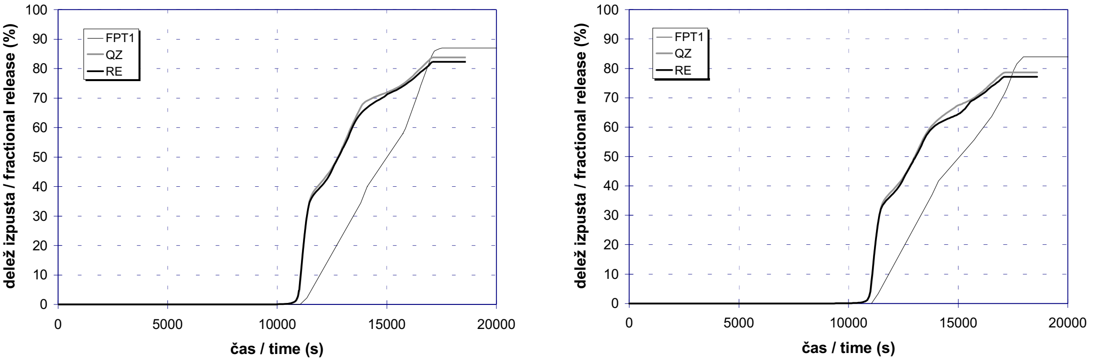
Two simulations were performed with different versions of MELCOR, i.e., with the MELCOR 1.8.5 QZ version (denoted QZ) updated with the newest patch (label “Patch 185003”), which is the latest official version, and with the improved MELCOR 1.8.5 RE version (denoted RE), which was distributed at the MELCOR Users’ Workshop 2002. The main differences between the RE and QZ versions, which affect the Phebus FPT1 experiment simulation, are that in the RE version the consistency of the hydrodynamics package and the core package (CVH/COR) was improved, that some core-package (COR) bugs were fixed, and that in the radio-nuclide package (RN) the aerosol-coefficient interpolation was improved.

The simulations were performed with the estimated value of the radiative exchange factor for radiation radially outward from the cell boundary to the next adjacent cell 0.75 and the best fit steam gaps closure temperature 1100 K. In this way, as shown in Figures 6 to 8, a good agreement of the temperature conditions in the bundle with the experimental measurements was achieved, which is needed to be able to assess the capability of MELCOR to predict other experimental results, like the hydrogen generation, the fission-products release and deposition, the core degradation, etc. Since the differences between the QZ and RE calculated temperatures of the shroud, clad and fuel are negligible, these QZ simulation results will not be presented.

Fig. 9 shows the experimental (FPT1) and simulated (QZ, RE) hydrogen mass-flow rate. Hydrogen is generated during the oxidation of the zirconium fuel



Sl. 9. *Masni tok vodika na izhodu sredice (levo) in skupna masa vodika (desno)*
Fig. 9. *Hydrogen mass flow rate at core exit (left) and total mass of hydrogen (right)*



Sl. 10. *Delež izpusta I (levo) in Cs (desno) iz sredice glede na začetno stanje*
Fig. 10. *Fractional release of I (left) and Cs (right) initial inventory*

ozračju vodne pare, do katere pride v večji meri pri temperaturah nad 1100 K. Med oksidacijo cirkonijevih srajčk se sprošča toplota, zaradi česar se cirkonijeve srajčke dodatno segrevajo (sl. 7), kar lahko zaradi pozitivne povratne zanke privede do samostojnega stopnjevanja oksidacijskega postopka, kar se je zgodilo pri preizkusu FPT1 (sl. 9). Med degradacijo sredice se spreminja velikost površine cirkonijevih srajčk, ki je v stiku z vodno paro, ter debelina oksidne plasti, ki prekriva cirkonijeve srajčke, kar pomembno vpliva na nastanek vodika. Oboje je v modulu MELCOR sredice (COR) ustrezno upoštevano. Na sliki 9 vidimo, da je izračunan vrh masnega toka vodika nekoliko precenjen in da se pojavi nekoliko prezgodaj. Eden izmed razlogov za to bi lahko bila predpostavka, da naj bi bile srajčke na začetku simuliranja popolnoma neoksidirane, kar je splošna praksa, medtem ko so bile srajčke verjetno nekoliko oksidirane že pred pričetkom preizkusa. Kot posledica precenjenega masnega toka vodika, je tudi skupna masa vodika precenjena (sl. 9), a je še vedno v okviru natančnosti preizkusne meritve ±10 %. Razlike med simuliranji QZ in RE so majhne.

rods' cladding in the steam atmosphere, which occurs to a greater extent at temperatures over 1100 K. During the zirconium-cladding oxidation heat is released, thereby additionally heating up the zirconium cladding (Fig. 7), which can lead, due to the positive feedback, to a self-excursion of the oxidation process, as happened in the experiment FPT1 (Fig. 9). During the core degradation the area of the zirconium cladding in contact with the steam and the thickness of the oxide layer covering the zirconium cladding are changing, which significantly influences the hydrogen generation. In the MELCOR core package (COR) both processes are appropriately considered. In Fig. 9 we see that the hydrogen mass-flow-rate peak is slightly overestimated, and that it occurs slightly too early. One of the reasons for this could be that it was presumed that at the beginning of the simulation the cladding is completely unoxidized, as is an overall practice, whereas the cladding was probably somewhat oxidized already before the experiment started. As a consequence of the overestimated hydrogen mass-flow rate also the total hydrogen mass is overestimated (Fig. 9), but is still inside the experimental measurement accuracy band of ±10 %. The differences between the QZ and RE simulations are small.

Na sliki 10 je prikazan delež izpusta joda in cezija. Za izračun izpustov smo v modulu MELCOR radioaktivnih snovi (RN) izbrali model CORSOR-M, ki temelji na eksperimentalnih meritvah in predpostavlja, da je hitrost izpusta posamezne radioaktivne snovi preprosta funkcija temperature [8]. Končni deleži izpustov so kar dobro napovedani, medtem ko so začetni izpusti precenjeni. Iz preglednice 1, ki prikazuje rezultate ključnih dogodkov, je razvidno, da niso izpusti vseh radioaktivnih snovi napovedani tako dobro. Izračun RE napove v splošnem nekoliko večje izpuste iz gorivnega svežnja kakor izračun QZ (za nekatere radioaktivne snovi je prav nasprotno).

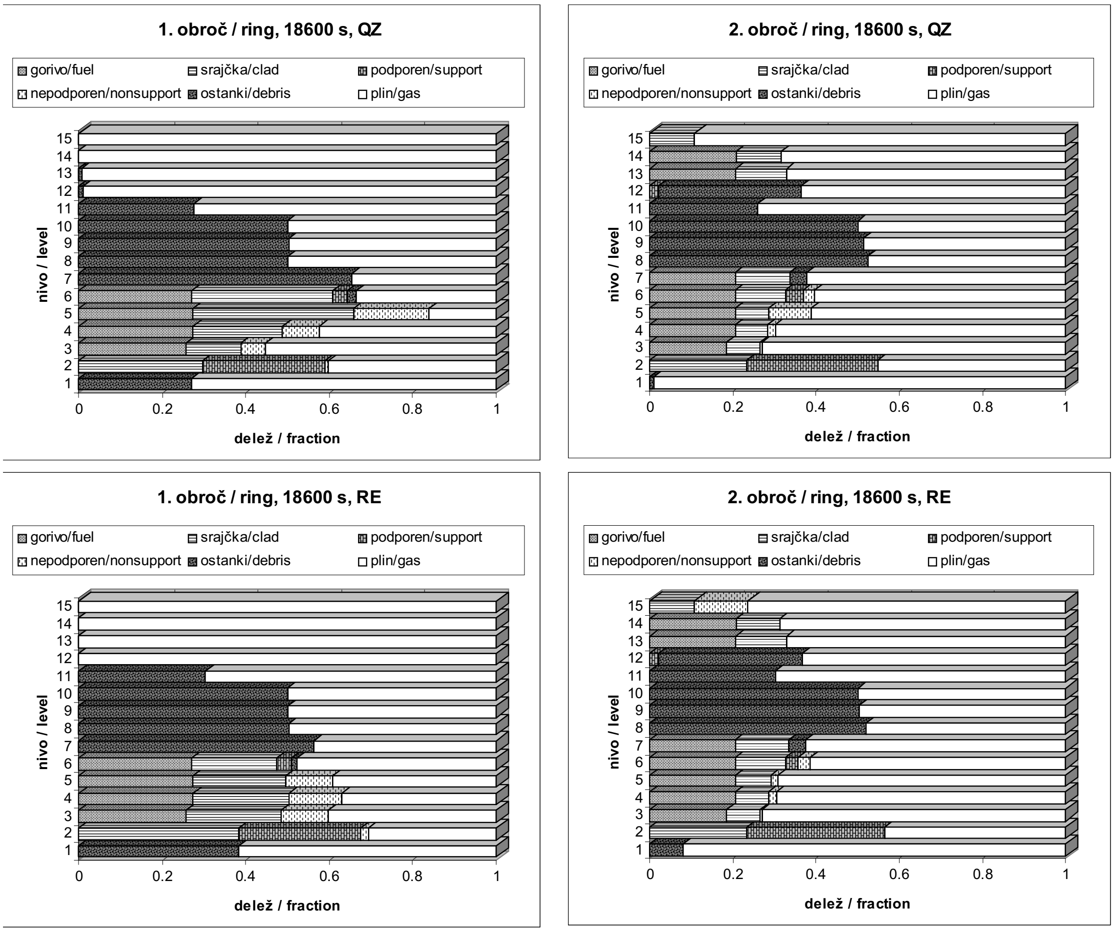
Preglednica 1 prikazuje rezultate obeh simuliranj za ključne dogodke v primerjavi s preizkusnimi meritvami. Vidimo, da je ujemanje časovnih napovedi ključnih dogodkov s preizkusnimi meritvami kar dobro in da so razlike med obema simuliranjema majhne. Končni deleži izpustov iz gorivnega svežnja in cevovoda so zadovoljivo napovedani za večino radioaktivnih snovi, toda za nekatere, npr. rutenij in uran, so razlike med izračuni in meritvami več velikostnih razredov. V splošnem lahko ugotovimo, da se rezultati novejše različice RE programa MELCOR bolje ujemajo s preizkusnimi meritvami.

In Fig. 10 the fractional releases of iodine and caesium are presented. For the calculation of the releases in the MELCOR radio-nuclide package (RN) the CORSOR-M model was chosen. In the CORSOR-M model, which is based on experimental data, it is presumed that the fractional release rate of a particular radio-nuclide is a simple function of temperature [8]. The final fractional releases are relatively well predicted, whereas the initial releases are overestimated. From Table 1, showing the results for key events, it is evident that not all radio-nuclide class releases were predicted as well. The RE simulation predicts, in general, slightly lower bundle releases than the QZ simulation (for some radio-nuclide classes it is just the opposite).

Table 1 provides the results of both simulations for some key events in comparison with the experimental measurements. We see that the timing of key events is relatively well predicted and that the differences between both simulations are small. The total fractional releases from the bundle and circuit are satisfactory for most radio-nuclides, but for some, like ruthenium and uranium, the difference between the simulation results and the experimental measurements is more orders of magnitude. In general, one can state that the results of the newer MELCOR version RE are in better agreement with the experimental measurements.

Preglednica 1. *Ključni dogodki za simuliranji MELCOR 1.8.5 QZ in RE v primerjavi s preizkusnimi meritvami*
Table 1. *Key events for MELCOR 1.8.5 QZ and RE simulations in comparison with experimental measurements*

Pojav / Event		**FPT1** [2,3]		**QZ**		**RE**	
Prva porušitev srajčk / First cladding rupture		5700 s		5332 s		5332 s	
Začetek oksidacije srajčk Start of cladding oxidation		~ 8580 s		8415 s		8415 s	
Začetek izpusta razcepkov iz goriva Start of fission products release from fuel		11170 s		10810 s		10806 s	
Prvo premikanje goriva / First fuel movement		~ 11000 s		11039 s		11025 s	
Prvi oksidacijski temperaturni vrh First oxidation temperature peak		11260 s		11058 s		11046 s	
Končni odstotek izpusta iz svežnja in cevovoda Total percentage release from bundle and circuit		sveženj bundle	cevovod circuit	sveženj bundle	cevovod circuit	sveženj bundle	cevovod circuit
žlahtni plin / noble gas	Xe	77,4	77,4	84,3	84,3	82,7	82,7
hlapljivi razcepki volatile fission products	I	87,0 ± 4,0	64,1	83,9	43,5	82,3	51,3
	Cs	84,0 ± 0,8	43,8	78,6	35,1	77,2	44,7
	Te	83,0 ± 1,0	52,5	76,5	32,6	78,2	48,6
	Mo	56,0 ± 4,0	23,0	13,2	4,26	14,8	8,62
slabo hlapljivi razcepki low volatile fission products	Ba	< 5	0,65	3,21	1,06	3,08	1,42
	Ru	< 5	0,50	5,16E-4	1,64E-4	5,21E-4	2,99E-4
gorivni sveženj / fuel bundle	U	> 0,14	0,119	1,98E-2	4,03E-3	2,09E-2	1,06E-2



Sl. 11. *Diagrama stanj gorivnega svežnja za simuliranji QZ in RE pri času 18600 s*
Fig. 11. *Bundle state diagrams for the QZ and RE simulations at time 18600 s*

Na sliki 11 sta za obe simuliranji prikazana diagrama stanj gorivnega svežnja ob koncu faze degradacije sredice. Stanji gorivnega svežnja sta prikazani s prostorskimi deleži različnih komponent sredice (gorivo, srajčka, podporna struktura, nepodporna struktura in ostanki) v vseh osnih vozliščih obeh prečnih obročev. Zaradi omejitve uporabljenega programa za risanje diagramov so vsa osna vozlišča narisana enakomerno. Prave velikosti celic sredice so prikazane na sliki 5. V modulu MELCOR sredice (COR) so modelirani vsi ključni postopki degradacije sredice, to so oksidacija kovinskih komponent sredice, kemijske interakcije med snovmi sredice (raztapljanje, nastanek evtektikov itn.) in porušitev sredice (deformacija, taljenje, tvorba staljenih gmot, ostanki itn.) [8]. Na sliki 11 vidimo, da sta stanji gorivnega svežnja za simuliranji QZ in RE zelo različni, čeprav so bile temperaturne razmere v svežnju pri obeh izračunih

In Fig. 11 the bundle state diagrams at the end of the degradation phase are presented for both simulations. The bundle states are presented with the volume fractions of different core components (fuel, clad, supporting structure, non-supporting structure and particulate debris) in all axial levels of both radial rings. Due to limitations of the used diagram-plotting program the axial levels had to be plotted as equidistant. The correct sizes of the core cells are presented in Fig. 5. In the MELCOR core package (COR) all the key processes of the core degradation are modelled, like the oxidation of metal core components, the core material chemical interactions (dissolution, eutectics formation, etc.) and the core relocation (deformation, candling, melting, debris formation, etc.) [8]. In Fig. 11 we see that the bundle state diagrams for the QZ and RE simulations are significantly different, despite the fact that the temperature conditions in the bundle were the same for enake. Razlog za razlike bi bilo lahko dejstvo, da so v izboljšani izvedbi MELCOR 1.8.5 RE v modulu COR odpravili nekaj programerskih hroščev.

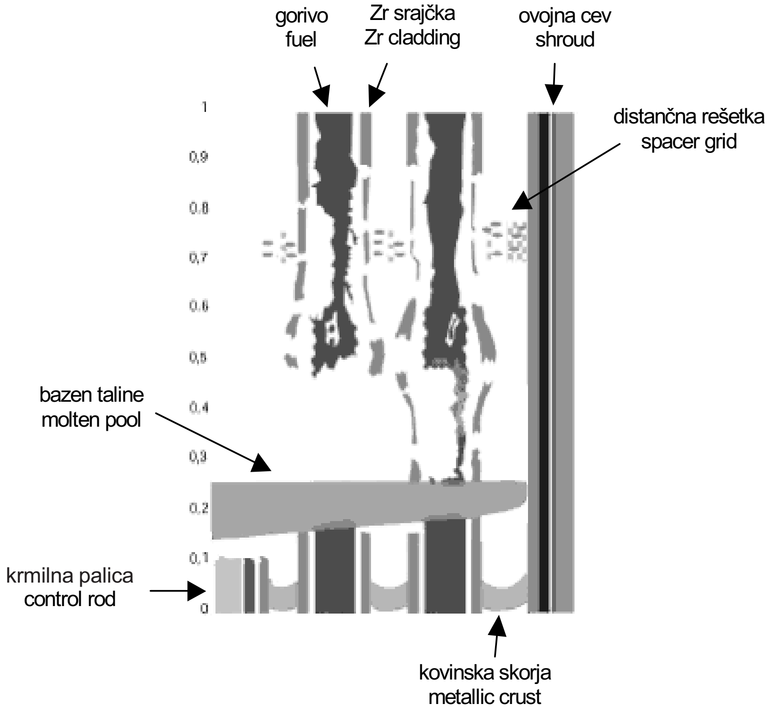
V simuliranjih se ostanki sredice nabirajo na višini 300 mm (sl. 11), medtem ko se pri preizkusu bazen taline oblikuje na višini 200 mm (sl. 12). Votline, ki se oblikuje v preizkusu nad bazenom taline, s programom MELCOR ni mogoče napovedati, ker se v programu MELCOR gorivne palice v zgornjih celicah sredice pomaknejo navzdol, če je pod njimi prostor in jih ne podpirajo nepoškodovane gorivne palice (ali podporna struktura) v nižjih celicah sredice.

Na sliki 13 je prikazano izračunano odlaganje joda in cezija vzdolž primarnega kroga od zgornjega predela nad preizkusnim gorivnim svežnjem (-6,78 m) do zgornjega dela uparjalnika (0,26 m). Preizkusne meritve so predstavljene le za vročo vejo uparjalnika. Odlaganje radioaktivnih snovi je obravnavano v modulu MELCOR radioaktivnih snovi (RN), kjer so modelirani vsi ključni mehanizmi odlaganja radioaktivnih snovi, to so težnostno odlaganje, Brownova difuzija, termoforeza, difuzoforeza in kondenzacija [8]. Vidimo, da so razlike med simuliranji QZ in RE pomembne, čeprav so bili izračunani izpusti podobni (sl. 10). Pri simuliranju RE je odlaganje joda kar dobro napovedano, medtem ko je odlaganje cezija

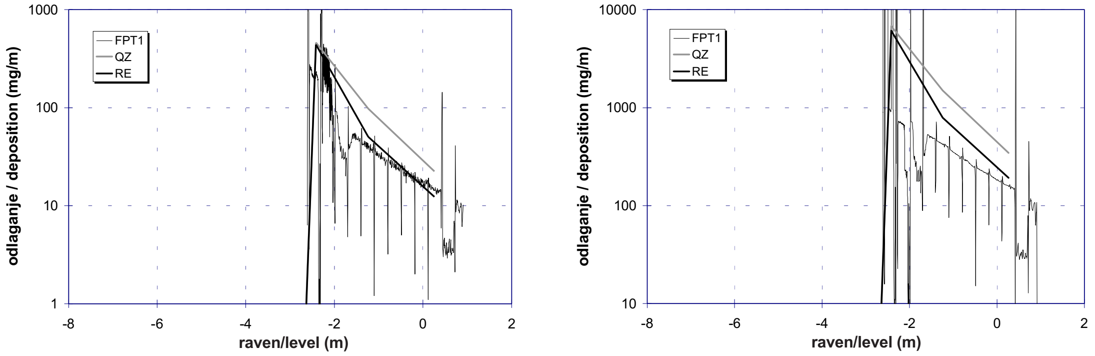
both calculations. The reason for the differences could be that in the improved MELCOR 1.8.5 RE version some core bugs were fixed.

In the simulations the debris accumulates on level 300 mm (Fig. 11), whereas in the experiment the pool forms on level 200 mm (Fig. 12). The cavity that formed in the experiment above the pool could not be reproduced with MELCOR since in MELCOR the fuel rods in the upper core cells relocate if there is place and they are not supported by intact fuel rods (or a supporting structure) in the core cells below.

In Fig. 13 the calculated depositions of iodine and caesium along the circuit from the upper plenum (-6.78 m) to the upper part of the steam generator (0.26 m) are presented. The experimental measurements are shown only for the steam generator's hot-leg region. The deposition of radio-nuclides is treated in the MELCOR radio-nuclide package (RN), where all the key radio-nuclide deposition mechanisms, like gravitational deposition, Brownian diffusion, thermophoresis, diffusiophoresis and condensation, are modelled [8]. We can see that the differences between the QZ and RE simulation are significant, despite the fact that the predicted releases are similar (Fig. 10). In the RE simulation the iodine deposition is quite well predicted, whereas the caesium deposition



Sl. 12. *Shema na podlagi meritev ocenjenega stanja gorivnega svežnja pri času 17039 s [2]*
Fig. 12. *Scheme of the estimated state of the bundle at time 17039 s based on measurements [2]*



Sl. 13. *Odlaganje I (levo) in Cs (desno) v primarnem krogu*
Fig. 13. *Deposition of I (left) and Cs (right) in the circuit*

precenjeno. V splošnem je odlaganje radioaktivnih snovi v uparjalniku precenjeno.

4 SKLEP

Primerjava izračunov s preizkusnimi meritvami je pokazala, da je mogoče dobiti dobro ujemanje termohidravličnih spremenljivk v gorivnem svežnju, če pravilno upoštevamo sevanje v gorivnem svežnju in toplotne izgube skozi cev, ki obdaja gorivni sveženj. Glede izpustov radioaktivnih snovi se je izkazalo, da model CORSOR-BOOTH napove večinoma premajhne izpuste, medtem ko modela CORSOR in CORSOR-M napovesta za nekatere radioaktivne snovi kar dobre rezultate. Izpuste za nekatere radioaktivne snovi je bolje napovedal model CORSOR, medtem ko je druge bolje napovedal model CORSOR-M. Končna simuliranja smo opravili z modelom CORSOR-M, ker so rezultati v povprečju za spoznanje boljši. Izpusta strukturnih snovi, ki pomembno vplivajo na kemijo in posledično tudi na izvorni člen, ni bilo mogoče izračunati, ker v programu MELCOR 1.8.5 ni ustreznega modela za izračun izpusta strukturnih snovi.

V splošnem lahko ugotovimo, da je ujemanje termohidravličnih spremenljivk dobro, da je ujemanje končnih izpustov za večino radioaktivnih snovi zadovoljivo ter da je odlaganje radioaktivnih snovi v uparjalniku precenjeno. Ključni dogodki so napovedani ob pravih časih. Razlike med rezultati simuliranj obeh različic programa MELCOR 1.8.5 (QZ in RE) so zanemarljive za termohidravlične spremenljivke, majhne za izpuste radioaktivnih snovi in časovno pojavljanje ključnih dogodkov, vendar pomembne za odlaganje radioaktivnih snovi in degradacijo gorivnega svežnja. V splošnem se rezultati novejše izvedbe RE programa MELCOR 1.8.5 bolje ujemajo s preizkusnimi meritvami.

is overestimated. In general the depositions of radionuclides in the steam generator were overestimated.

4 CONCLUSION

The comparison of simulation results and experimental measurements showed that good agreement of the thermal-hydraulic variables in the bundle can be achieved if the radiation inside the bundle and the heat losses through the shroud are correctly considered. Regarding the radio-nuclide releases, it turned out that the CORSOR-BOOTH model tends to underestimate releases, whereas the CORSOR and CORSOR-M models give, for some radio-nuclide classes, relatively good results. The CORSOR model gave a better prediction for the releases of some radio-nuclide classes, whereas the CORSOR-M model gave better predictions for some others. The final simulations were performed with the CORSOR-M model, since the results are, on average, slightly better. The structural material release, which significantly influences the chemistry and consequently also the source term, could not be calculated since MELCOR 1.8.5 has no appropriate structural material release model.

In general, one can state that the agreement of the thermal-hydraulic variables is good, that the agreement of the total releases for most radio-nuclide classes is satisfactory, and that the radio-nuclide depositions in the steam generator are overestimated. The timing of the key events was relatively well predicted. The differences between the simulation results of both MELCOR 1.8.5 versions (QZ and RE) are negligible for the thermal-hydraulic variables, small for the radio-nuclide releases and the timing of key events, but significant for the radio-nuclide depositions and the bundle degradation. In general, the results of the newer MELCOR 1.8.5 version RE show better agreement with the experimental measurements.

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