Journal of Energy
VOLUME 70 Number 4 | 2021
journal homepage: http://journalofenergy.com/

# Editorial Introduction to the Special Issue of the 13th International Conference of the Croatian Nuclear Society

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***Abstract*— The 13th International Conference of the Croatian Nuclear Society (HND2022) was held in Zadar, Croatia, from 5 – 8 June, 2022. The purpose of the Conference was to present and discuss the most relevant topics concerning the role and position of nuclear option in the current energy balance, with special attention paid to the countries with small and medium electricity grids. In addition, the other important goal was to promote regional co-operation and exchange of experience in use of nuclear power and fuel cycle facilities among the countries with an interest in the nuclear option. Authors' and presenters' contributions were provided in 8 invited presentations and lectures and 66 contributed papers grouped into eight thematic sessions. The Conference also included a panel discussion divided in two parts. The first part discussed the role and the importance of the nuclear option in national energy strategies while the second part was devoted to the challenges of the public relations for the nuclear option. Fourteen papers selected by a program committee are included in the Special Issue. The papers are divided into three categories: nuclear safety analyses and risk assessment (6 papers), operation and maintenance experience (4 papers), reactor physics, nuclear fuel cycle and radioactive waste management (4 papers). Their main conclusions and their relevance to the objectives of the Conference are presented in this paper.**

***Index Terms*—nuclear energy and environment, nuclear option in the context of energy planning, economics and financing, $CO_2$ free energy generation.**

## I. INTRODUCTION

IN the societal context which is considerably marked by dynamic economic growth and concerns which include energy resources and their stability, potential climate changes and increasing greenhouse gas emission the issue of ensuring reliable and sustainable energy is becoming ever more challenging. Nuclear energy, as the $CO_2$ free energy source, should have its place in resolving these concerns and enabling all the countries to cope with challenges under such context [1].

Traditionally, nuclear safety assessment is the most important aspect of the nuclear energy option since the safe and reliable reactor operation is paramount for integration in the electric power system and the positive public perception. Additionally, nuclear option needs to consider other topics from the point of view of the national energy strategies, resources, costs, technological, organizational and educational requirements, as well as environmental advantages. It, also, needs to focus on the matters related to the operation and design safety, fuel cycle, waste management, and decommissioning. All these aspects were covered by the Conference.

The important goal of the HND2022 Conference was to promote regional co-operation and exchange of experience in use of nuclear power and fuel cycle facilities among the countries with an interest in the nuclear option. The importance of international cooperation for the assessment of the nuclear option has been recognized by the International Atomic Energy Agency (IAEA). As a result of this recognition, the Conference was organized in cooperation with the IAEA. European Nuclear Society, and University of Zagreb, Faculty of Electrical Engineering and Computing took considerable part in the preparation and organization of the Conference.

## II. ABOUT THE 13TH INTERNATIONAL CONFERENCE OF THE CROATIAN NUCLEAR SOCIETY

The International Conference of the Croatian Nuclear Society, subtitled "Nuclear Option for $CO_2$ Free Energy Generation", was a 13th event in the successful series of international conferences organized biennially by the Croatian

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Nuclear Society, which was formerly known under the subtitle "Nuclear Option in Countries with Small and Medium Electricity Grids". The purpose of the conference series remains to be presenting and discussing the most relevant topics concerning the role and position of nuclear option in the current energy balance, with special attention paid to the countries with small or medium electricity grids. The conference series was initiated in 1996 with the first conference taking place in Opatija. It was followed by seven conferences in Dubrovnik and the last four which were held in Zadar. This 13$^{th}$ conference, the last one in the series for now, took its place in Zadar again, from 5 – 8 June, 2022.

Topics which were addressed by different sessions at the Conference reflect the above mentioned aspects of safety assessment, facility operation and design, fuel cycle, energy strategies at national level, regulatory practices, radioactive waste management, decommissioning, as well as many others. The papers presented at different sessions promote international exchange of experience and co-operation among the interested parties in these fields.

Authors' and presenters' contributions were provided in 8 invited presentations and lectures and 66 contributed papers.

The invited presentations addressed as diverse subjects as applications of small modular reactors, need for enthusiastic young nuclear professionals in order to ensure the future of nuclear energy, role of nuclear option in achieving net zero, design and safety assessment and verification of different reactor technologies (including the advanced reactors), status of the new nuclear power plant (NPP) project in Slovenia and developments in the field of accident tolerant fuel materials.

As with the previous conference in the series, a topic of particular interest was the role of Small Modular Reactor (SMR) designs in nuclear energy program and possibilities of inclusion of SMRs in the long term energy strategies. This topic was a subject of one among the invited presentations and was additionally addressed under the panel discussion, which was one of the focal points of the conference.

The main topics of the panel discussion were selected to be some basic preconditions needed for the nuclear option to become a relevant part of the solution of the global climate problems. For this purpose, the panel discussion was divided in two parts. The first part discussed the role and the importance of the nuclear option in national energy strategies while the second part was devoted to the challenges of the public relations for the nuclear option.

The contributed papers at the conference were grouped into eight thematic sessions:

S1: Nuclear Safety Analyses (NSA)

S2: Operation and Maintenance Experience (OME)

S3: Nuclear Energy: Planning, Environment and Technologies (NEPET)

S4: Regulatory Practice and Emergency Preparedness (RPEP)

S5: Reactor Physics and Nuclear Fuel Cycle (RPNFC)

S6: Severe Accident Analyses and Risk Assessment (SAA)

S7: Radioactive Waste Management and Decommissioning. Radiation Hazard and Protection. (RWMD)

S8: Safety Culture, Knowledge Management and Public Relations (SCPR)

Following this arrangement of sessions, the selected papers are divided into three categories: nuclear safety analyses and risk assessment (6 papers), operation and maintenance experience (4 papers), reactor physics, nuclear fuel cycle and radioactive waste management (4 papers).

## III. Nuclear Safety Analyses and Risk Assessment

Deterministic and probabilistic nuclear safety analyses for design basis events and severe accidents were presented for selected power plants and experimental facilities with provided appropriate models and nodalizations.

In the paper RELAP5/mod3.3 Analysis of Natural Circulation Cooldown with One Inactive Loop for Nuclear Power Plant Krško [2] the authors aimed to determine the limiting cooldown rates during operator recovery actions to minimize the effect of flow stagnation in inactive loop. Determination of the maximum allowable cooldown rate with one inactive loop for NEK could not be done in straightforward way based on the instructions given in Westinghouse document [3]. The reason is rather different steam generators compared to standard Westinghouse SG types. Since this is typical asymmetrical transient, the RELAP5/mod3.3 NEK model with split reactor vessel model was developed (models of the reactor vessel and core were axially divided in two parts) and used for this analysis. The several transients of cooldown, with one inactive loop, for different time after shutdown (different decay heat) were performed. The extreme conservative assumptions were applied for the analyses, i.e. the complete loss of feedwater (FW) and auxiliary feedwater (AF), including turbine driven (TD) AF pump, and the cooldown has started after the SG is completely dry (inactive). The results show that the cooldown rate shall be significantly reduced, what was expected according to the analysis assumptions and, also, to a certain extent, due to the physical characteristics of NEK steam generators. Based on this analysis and conclusion the procedure ES-0.2 "Natural Circulation Cooldown" was changed as required by DW-04-001 [4].

MAAP 4.07 Analysis of Long Term Containment Heat Removal After Reactor Vessel Failure addressed among other, containment cooling for the period before and after reactor vessel failure with the aim to prevent the operation of passive containment filtered venting (PCFV) system [5]. The analyses considered modification within NEK Safety Upgrade Project - installation of alternative residual heat removal system (RHR) pump and alternative RHR heat exchanger. The containment heat removal was analysed assuming that ARHR pump and ARHR heat exchanger, and also alternative safety injection (ASI) pump, have the actual characteristics as implemented in the plant modifications. The cooling using ASI will initially result in significant containment pressure increase (over PCFVS opening set-point) because the water is spilled through the reactor coolant system (RCS) over the molten core. Therefore, the preferable way of containment pressure reduction, once the vessel has failed, is by using of containment spray (CI). On the other hand, if refueling water storage tank is not available, then the initial water delivery cannot be made from ABWT or other tank via CI system because these options are not foreseen. The fire protection sprays for reactor coolant pumps can also be used for this purpose. Using of RCS injection shall be avoided if enough water is not assured in the reactor cavity to cover the core debris and/or the containment pressure is already high.

The decision support tool for severe accidents – called Severa – has been developed within the project NARSIS – New Approach to Reactor Safety ImprovementS [6]. The project has made scientific steps towards addressing the update of some elements required for the safety assessment of nuclear power plants. Severa is a prototype demonstration-level decision support system aimed at supporting the technical support center (TSC) while managing a severe accident. The prediction of future accident progression, if no action is undertaken, is one of its basic functions. The support tool provides a list of possible management recovery strategies and courses of action. For each action, Severa assesses possible consequences in terms of probability of the last barrier (containment) failure and estimated time window for failure. At the end, Severa evaluates and ranks the feasible actions, providing recommendations for the TSC [7].

The core in the vessel is not the only source of fission products as the Spent Fuel Pool (SFP) hosting the fuel removed by the core is, in some NPP, inside the containment and SA conditions can also occur [8]. This is especially important in reactors having proximity between the RPV and SFP such as the VVER-1200. MELCOR code is a widely used, flexible powerful SA code but it is incapable to reproduce a situation in which both the fuel in vessel core and the fuel in the SFP, inside the same containment, are going to experience a severe accident scenario. The current study presents a MELCOR-to-MELCOR coupling method [9] to simulate simultaneously scenarios with both, core and SFP, as sources capable of hydrogen generation, fuel damage and FP release in a VVER-1200 NPP. The results from the proof of concept presented in this paper proved to be encouraging that demonstrated the capabilities of the aforementioned coupling, being able to capture both core degradation independently while continuously managing the data exchange. The future steps involve further validation of the capabilities of the mechanism in order to perform its final implementation in a real VVER reactor nodalization and the analysis of the subsequent accident scenarios involving the SFP as a secondary core.

The determination of minimal cut sets (MCSs) turns out complex even with very simple systems modelled by a coherent fault tree, dealing with at least two basic problems [10]. The first, being the time complexity of algorithms employed for the determination of the complete or partial set of MCSs, while the latter problem relates to a space complexity of the same sets recording. More recently, binary decision diagrams (BDDs) have been developed, enabling indirect recording of fault trees by applying indicator variables for the component failure state within the system. Now, a qualitative and quantitative analysis on a fault tree model may be carried out with BDDs by applying known algorithms for the determination of minimal disjunctive normal form of the logical function presented by the coherent fault tree, which represents the logical recording of a set of minimal cuts. Thus, not only do BDDs show (under the condition of an appropriate variable order) an acceptable time complexity for the implementation of algorithms for determining MCSs but also enable a compact recording of complete or partial sets of MCSs singled out in that way [11]. The exceptional compactness of minimal cut set recordings gained by the BDDs technique makes it possible to ensure the recording of a complete set of MCSs. The accessibility of the complete set of MCSs by means of BDDs allows accurate calculations from a probabilistic model.

Any operating nuclear power plant (NPP), as a facility with potential for radioactive release, is subject to numerous safety reviews with different purposes and objectives [12]. Some of the safety reviews are, by their nature, general and extensive in terms of different safety factors or safety attributes which are covered. An example of such a review is a Periodic Safety Review (PSR) which is promoted by the International Atomic Energy Agency (IAEA) and a number of national safety authorities in Europe and worldwide. The other reviews may, depending on the objective, be targeted at particular safety factor (e.g. ageing management or equipment qualification or safety analyses). Both of the mentioned cases (single general review or multiple targeted reviews over a time period) can generate an inventory of safety issues which need to be addressed but may be very different in their nature and implications, as well as in benefits or resources associated with their resolutions. While some of the issues may be directly related to operational safety (e.g. non-compliance with single failure criterion or aging-related degradation of safety features), for some others the link to operational safety may not be explicit (e.g. comparison of safety bases against the newly emerging methodologies or issues observed with regard to so called "soft factors"). The paper discusses types of safety issues which may emerge from general or targeted safety reviews and outlines some basic principles for comparison and importance ranking of diverse issues, as needed many times in order to develop an action plan for keeping or improving the plant safety level. PSR [13] requires global assessment to provide safety justification for proposed long term operation [14] by evaluating the cumulative effects of both ageing and obsolescence on the safety and reflecting the combined effects of all safety factors (findings and proposed improvements).

## IV. OPERATION AND MAINTENANCE EXPERIENCE

Maintenance activities at nuclear power plants are a key to ensuring a safe and resilient long-term operation. The activities are supported by the innovative automated detection, inspection and measurement techniques.

Sludge removal activities at the Krško Nuclear Power Plant take place on the secondary side of the steam generators (SG) on the top of the tube sheet [15]. It always consists of classical Sludge Lancing (SL) which is done by spraying water at different angles (30°, 90°, 150°) between the tube gaps in the steam generator tube bundle with a pressure of around 220 bars. Another method is Inner Bundle Lancing (IBL) which means spraying water directly inside the tube bundle with a traveling lance tape with a spraying nozzle at the end. Another method of sludge removal which was for the first time utilized in 2019 at the Krško site was Chemical Cleaning (CC) of both SG's. During this process, a chemical was injected into the SG's through the Blowdown System and periodically pumped between the two SG's to create a dynamic flow and maximize the cleaning effect. To achieve the best results, a constant temperature of the chemicals had to be maintained at all times. Since the power plant uprate in May 2000, NEK conducted SL on both SG's every outage also starting with IBL in 2013 and 2015, and the same method was used in the 2018 outage. During the outage in 2019, all three methods (SL, IBL, and CC) have been utilized with the main purpose to extend the full load operation of the plant, preventing and/or stopping denting processes in the SG's from occurring, reducing and stopping the build-up of hard sludge area to increase/sustain efficiency and remove foreign objects found in the SG's.

The inspection of the condensate storage tanks is by the book example of managing the aging mechanisms in the NPP Krško [16, 17]. The purpose of the aging management programs is to monitor components and to detect degradation before that degradation can cause the failure of the component. Periodically, the inspections are performed as per program requirements, but in this case, additional effort was taken due to the possibility of leaking and related Corrective Action Program report. The inspection did not reveal holes or degraded areas where leaking is possible, only indications of corrosion underneath the bottom plates at some locations. Corrective measures were taken in a form of welded patches, welds tested, and affected areas treated with the qualified coating. Performance of the job as a whole also presents a good practice of cooperation between organization structures within the NPP Krško for solving such a problem during an outage, when time and resources are limited due to a great number of other activities going on in the meantime. With that job done, NPP Krško has set up a benchmark for inspection and repair of single-hull holdup tanks.

INETEC developed a new remotely controlled TARGET system for bottom mounted nozzles (BMN) inspection [18]. Once submerged, it becomes independent from polar crane or refuelling bridge, thus reducing unnecessary time loss for maintenance operations. Its ease of navigating and operating helps it to move quickly on designated BMN. For ultrasonic testing (UT) data collection, INETEC uses its own Dolphin, phased-array ultrasonic instrument with support for all common ultrasonic inspection techniques. Furthermore, INETEC developed probe "PRO ULTRA TARGET" with multiple variants for different Westinghouse type of BMNs [19]. Probe is composed of three pairs of time of flight diffraction (TOFD) transducers (one axial and two circumferential) and one 0° longitudinal wave probe. Demonstration of examination of bottom mounted nozzles was performed and UT technique was developed on previously delivered flawed mockups given by Electric Power Research Institute (EPRI). In order to prove theoretical presumptions and newly designed probe, INETEC evaluated mockups to document basic flaw detection, location capabilities, characterization and length and depth sizing on representative mockups. All acquired data was evaluated by INETEC and provided to EPRI for independent review. Review showed that INETEC demonstrated capabilities of the system that satisfied demands for proper flaw detection and characterization.

According to the recent breakthroughs in developing automated defect detection algorithms, we can be sure that the automation of non-destructive inspection is a trend that cannot be avoided [20-23]. Industry 4.0 will bring a lot of innovations that will revolutionize the safety inspections of nuclear power plants, oil and gas pipelines, and many more. More and more research papers show that successfully and more importantly, reliably detecting all defects in the inspected material is possible while speeding up the analysis many-fold. Therefore, the industry should prepare and start adapting the protocols toward assisted and even completely automated inspections. Implementation of such algorithms will contribute to the healthy state of the inspected power plants and reduce the downtime of such systems. Inspectors' tasks will become less tedious, and total automation will completely reduce human exposure to harsh conditions such as radiation, high temperature, and high humidity.

## V. Reactor Physics, Nuclear Fuel Cycle and Radioactive Waste Management

An analysis of the neutron transmission through an iron sphere using Monte Carlo and transport theory methods based on ENDF/B-VII.1 general purpose library was given in the paper [24]. In order to benchmark the next-generation ENDF/B-VI iron data, the U.S. Nuclear Regulatory Commission and the former Czechoslovakian National Research Institute have jointly preformed several experiments in 1990s, addressing neutron leakage spectra obtained for a 252Cf fission source in a centre of an iron sphere. It was shown that the ENDF/B-VI iron cross section, containing several improvements over previous evaluations, will not entirely resolve the neutron spectrum discrepancies observed at high neutron energies. Since safety analyses of reactor pressure vessel embrittlement are often based on neutron transport calculations using specific multigroup cross section libraries, simulation of this benchmark was performed using a hybrid shielding methodology of ADVANTG3.0.3 and MCNP6.1.1b codes. Comparison of calculated and referenced dosimeter activation rates are presented for several "standard" nuclear reactions, often used in reactor pressure vessel dosimetry. For that purpose, the new IRDFF-II special library from the IAEA Nuclear Data Services was used as a reference source of dosimetry cross sections.

An updated version of MTV3D program for visualization of the MCNP mesh tally file is presented [25]. The main features of the MTV3D program are 3D visualization of mesh-based results (MC mean values and relative errors), cut-plane results with elevate transformation producing surface plots, and curve plots for selected independent axes. The choice of program modules used for MTV3D development was determined by Windows operating system. The MS Windows SDK 8.1 was used which supports Windows versions from 7 to 10. Application controls are implemented using procedures from Win32 interface and Windows Controls library. Graphical unification of points was done via DirectX11 API collection, including DirectWrite on text rendering. Transformations over matrices and vectors were done using DirectXMath library, while 2D rendering is based on GDI+ class-based API. The MTV3D supports multicore CPU architecture, multithreaded environment processing, and simultaneous work with several open projects. The capabilities of MTV3D were demonstrated for several real-life shielding problems, namely spent fuel dry storage building of NPP Krško. Future work on MTV3D will introduce additional options for mesh tally plotting and possibility to read external WWINP file of MCNP.

TRITON-NEWT and TRITON depletion simulations of the Optimized Fuel Assembly (OFA) model were performed in the framework of GBC-32 cask benchmark [26]. This first phase is addressing accurate source terms characterization, since OFA model contains small modifications compared to the standard Westinghouse 17x17 FA model. Besides quantification of neutron-gamma source terms, during burnup and cooling time periods, this methodology provides ability to generate cross-section database (ft33f001 file) for each depleted material as a function of burnup in ORIGEN-S format. The obtained time-dependent databases can be directly used with ORIGEN-ARP interpolator to produce comprehensive source term characterization. The obtained results will be used in preparation of specific neutron-gamma source terms for the future MAVRIC/Monaco shielding calculations of GBC-32 cask. The presented calculations utilize symmetry of the OFA model, so only 1/4 of FA was modeled with reflective boundary conditions. On top of that, each fuel pin had the same UO2 matrix as the only depleted material, which is a gross approximation for modern FA designs. In practice, considerable CPU time goes on cross-section processing (CENTRM module) prior to NEWT calculations if one chooses to deplete a large number of fuel mixtures [27]. Moreover, this CPU time becomes prohibitively large with multiple unit cells, which are necessary for capturing spatial effects of fuel depletion. This problem is a well-known issue in depletion of modern, heterogeneous FA designs, that even with symmetry inclusion one typically gets dozens of fuel pin locations which need to be independently depleted. To simplify cross-section processing paradigm, it has been recognized that the macroscopic response of spent fuel is much more sensitive to the number densities of constituent nuclides than the nuclide cross-sections [28, 29].

Selected data about spent fuel (SF) and radioactive waste (RW) management at global and EU level are presented in the paper [30]. Two latest sources were used: IAEA status report and EU progress reports on Waste Directive implementation. The paper first briefly presented highlights related to SF and RW management frameworks, developed practices and technologies. The paper is about SF and RW inventory at world regions (including values related to SF reprocessing, type of storage and final disposal). Majority of RW by volume is disposed of (80% globally and 70% in the EU). However, this percentage is so high only for the Low-level radioactive waste (LLLW and LLW categories) while high-level waste (HLW) and SF are not yet disposed of in any country. Presented data and normalization illustrate how cumulative amounts of SF and RW are both absolutely and relatively not so large and significantly smaller in comparison to amounts of yearly treated hazardous waste (HW). Yearly treated HW average per capita, for nuclear EU MSs, is >200 kg, which is about 40 times larger than average of accumulated RW from the beginning of nuclear power use. Management of RW seems more strictly regulated (e.g., export restrictions) and certainly is way much more controversial than for HW. The amount of every year traded HW between countries is larger than total amount of accumulated RW (~40 vs ~38 million t, assuming $1m^3 \approx 1t$). Transport of RW and SF between countries is rare and dominantly related to treatment and reprocessing with return of resulting RW to origin country.

## VI. Conclusion

The papers selected for the publication in the Special Issue of the 13th International Conference of the Croatian Nuclear Society cover the core areas of interest of the HND2022 conference: nuclear energy and the environment, power reactors and technologies, operation and maintenance experience, nuclear safety analyses, probabilistic safety assessment and severe accident analyses, nuclear fuel cycle and reactor physics, radioactive waste management and decommissioning. These topics of the HND2022 Conference have followed the developments and main points of interest in nuclear energy and industry sector considering also scientific research in the field and current regulatory requirements, as well as the role of the nuclear option in the societal context.

The subtitle “Nuclear Option for $CO_2$ Free Energy Generation” emphasizes the fact that nuclear energy is contributing significantly to climate change mitigation and adaptation while supporting sustainable development. Nuclear energy is one of the most important sources of low carbon electricity and at the same time it is characterized by its high reliability, availability, and safety standards.

A new key factor that is going to become more important in the years to come is the resilient electricity generation. This will be the next main topic in the conference series development. Nuclear power’s resilience follows general definition of resilience as the ability to limit the extent, severity, and duration of system degradation following an extreme natural or man-made event. The resilience is already closely integrated in concept of nuclear safety, making the nuclear power reliable energy source and helping the global community to overcome potential challenges in near future. Another future conference focus will also be on matters related to Long Term Operation (LTO). Successful LTO should be considered in the light of plant generation of reliable, safe, low-cost, low-emission electricity for decades longer than originally envisioned.

## Acknowledgment

We would like to express our gratitude to almost 200 authors and co-authors who put a large effort into completing their full camera-ready papers. We would also like to thank the sessions’ coordinators and chairs, reviewers, and all those who gave a hand in organizing the Conference.

Special acknowledgments are given to the International Atomic Agency and the European Nuclear Society for their provisions.

Last but not least, we are particularly grateful to all the sponsors and donors whose help has been essential for the success of this International Conference. We express our thanks to all those who, through their efforts and participation, have contributed to the Conference’s success.

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