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Conference Report

Summary of the 2nd International Workshop on Environmental, Safety and Economic Aspects of Fusion Power

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Abstract

The 2nd International Workshop on Environmental, Safety and Economic Aspects of Fusion Power (ESEFP) was held on 23 September 2017 in Kyoto, Japan. The workshop was initiated by the International Energy Agency Technology Collaboration Program on ESEFP. The workshop was well attended with approximately forty participants representing fifteen institutions in eight countries. The presentations covered safety issues and environmental impacts, availability improvement and risk control and socio-economic aspects of fusion power. Quantitative safety assessment of fusion reactors was discussed in depth with the consensus output presented as a plenary presentation at the 13th International Symposium on Fusion Nuclear Technology (ISFNT-13). The next workshop is planned to be held in conjunction with the ISFNT-14 in 2019.

Keywords: fusion reactors, safety assessment, IEA ESEFP

1. Introduction

Fusion energy as a commercial source of energy should have high level of public and personnel safety, low environmental impact, a closed fuel cycle, and the potential to be economically competitive with other energy generation systems. However, it is recognized that there is still work to be done to close the existing scientific and technological gaps between the current fusion technology and commercial fusion reactors.

The international energy agency (IEA) technology collaboration program (TCP) on Environmental, Safety and Economic Aspects of Fusion Power (ESEFP TCP), with the objective of coordinating aspects of joint research and development on the pathway to implementing fusion power, has been heavily involved in the activities supporting the licensing and construction of the ITER facility. Eight tasks are included in the IEA ESEFP focusing on: (Task 1) In-vessel Tritium Source Terms, (Task 2) Transient Thermo-fluid Modeling and Validation Tests, (Task 3) Activation Production Source Terms, (Task 5) Failure Rate Database, (Task 6) Radioactive Waste Studies, (Task 7) Socio-Economic Aspects of Fusion Power, (Task 8) Magnet Safety, and (Task 9) Fusion Power Plant Studies. In the future, the ESEFP TCP is intended to play an important role in bridging the scientific and technological gaps, supporting the policy making of governments, and raising awareness of fusion energy development programs in the general public.

A proposal to hold an international workshop on topics relevant to the ESEFP was presented to the Executive Committee of the TCP by Yican Wu, the Executive Committee Chair, and unanimously adopted in early 2015 by the committee members, who represent seven contracting parties including the governments of Canada, China, Japan, the Republic of Korea, the Russian Federation, the United States of America and the European Atomic Energy Community (EURATOM). The objective of the workshop was to establish a platform for scientists and engineers to exchange information and further enhance collaboration in order to achieve the stated goals of the ESEFP as given above. The members of the Executive Committee served as the workshop organizing committee. *The 1st International Workshop on Environmental, Safety and Economic Aspects of Fusion Power* (ESEFP) was held on 13 September 2015 at Jeju Island, South Korea, where safety and licensing gaps between DEMO and ITER were discussed [1, 2].

On 23 September 2017, the 2nd International Workshop on ESEFP was held in Kyoto, Japan. The organizing committee included Yican Wu (INEST, CAS—Institute of Nuclear Energy Safety Technology, Chinese Academy of Sciences), Keeman Kim (National Fusion Research Institute, Korea), David Maisonnier (European Commission), Daniel Clark (US Department of Energy), Aleksey Kalashnikov (State Atomic Energy Corporation, Russia Federation), and Yoshiteru Sakamoto (National Institutes for Quantum and Radiological Science and Technology, Japan). Zhibin Chen (INEST, CAS), who has been serving as an assistant to the IEA ESEFP TCP Executive Committee Chair since 2013, led the local organizing committee with the strong support from INEST colleagues such as Zi Meng, as well as the kind support from the organizing committee of ISFNT-13 (*13th International Symposium on Fusion Nuclear Technology*) chaired by Tomoaki Kunugi from Kyoto University. The broad technical areas were: safety and environmental impact, availability increase and risk control, socio-economic aspects of fusion power, and fusion power plant studies. Invitations were made to world leading scientists in the relevant areas. Eight invited presentations were chosen from the submissions received by the organizing committee, the contents of which are described briefly in the following sections. The approximately forty participants contributed to the discussions on quantitative safety assessment of fusion reactors which have been presented as a plenary in ISFNT-13.

2. Highlights of presentations

Sehila Maria Gonzalez de Vicente (IAEA) presented the work done by a number of experts for the IAEA to produce a TECDOC (Technical Document) on Safety Classification of Mechanical Components for Fusion Applications [3]. It has been identified that the safety classification of structures, systems, and components (SSCs) used for nuclear power plants are discussed in various IAEA guides and other international standards which are mostly aimed at fission reactor applications. Whilst the basic principles described in IAEA's SSG-30 [4] remain applicable, there are some important differences between fission and fusion applications. For fusion, the main safety functions are related with confinement and radiation shielding and not with heat removal or power reactivity control. Similarly, various fusion plant states and events and their severity levels are specific to a fusion plant are different than those for fission. In this TECDOC guidance for the classification of SSCs for fusion application is provided. There are still several areas where further work needs to be done for classifying fusion components. Some of the more important areas still lack information and regulatory guidance are as follows:

- Lack of processes and criteria for: classification of shielding function and definition of design pressure for vessel.
- Lack of data for: material properties for structural materials under fusion irradiation conditions (14 MeV neutrons); material properties for ceramics, ceramic to metal joints in irradiated environment (with right spectrum); reliability data for components; uncertainty related with disruption loads and plasma stability.

Yoshiteru Sakamoto (QST) presented ESEFP R&D activities in Japan. Efforts are presently aimed at implemented research activities agreed to under the broader approach (BA) activity, specifically assessing large-scale hypothetical accidents, namely upper bounding sequences, and developing remediation strategies for radioactive waste management. Large-scale loss of coolant accidents (LOCA) were developed for a water-cooled DEMO concept determined to be upper bounding sequences. Hydraulic and thermal analyses of these LOCAs indicated that the IAEA evacuation-free requirement (early dose lower than 100 mSv at the site boundary) would be satisfied even following these large-scale accidents [5]. Radioactive waste management strategy has been developed. Waste disposal assessments based on the decay heat and dose rates from in-vessel components indicated that all radioactive waste could be classified as low-level waste, and could be disposed of in shallow land burial (as L2, relatively lower low-level waste) after allowing for a cooling-down period shorter than 10 years [6]. Future work will improve the strategies and formulate a reasonable accident prevention and mitigation system compatible with a DEMO design.

Brad Merrill (INL) introduced progress on MELCOR for fusion development. A development effort to merge MELCOR and TMAP to create a more complete tool for analyzing fusion accidents began in 2015 [7]. In merging TMAP with MELCOR, several TMAP code modeling deficiencies were addressed:

- Hydrogen species transport in liquids instead of just gaseous atmospheres (initially only liquid metals). This was accomplished by adding T_2, HT, DT and HD as MELCOR user defined non-condensable gases to allow the code to track hydrogen specie gas mixture (note, H_2 and D_2 were already modelled by MELCOR).
- Time-dependent fluid conditions (e.g. temperature, pressure and fluid flow) calculated from conservation of mass, momentum and energy equations instead of user specified to give more realistic time-dependent transport conditions during accident analyses. This was accomplished by adding H, D, T and He conservation of mass equations to track dissolved gases in MELCOR's liquid metal pool flow, including bulk transport to liquid surfaces.
- The number of user defined material defect trap sites was limited. TMAP's diffusion equations was modified for 10 trapping sites for adsorbed gases in metals.

In the next step, equations-of-states (EOSs) for fusion PbLi and SnLi will be improved or developed, and plans are underway to modify this version of MELCOR to allow the user to specify different working fluids, one per heat transport system, in the same user input model. The MELCOR-TMAP will continue to undergo validation and verification, and for the near-term this code will only be available to support U.S. reactor design studies.

Dobromir Panayotov (F4E) discussed challenges of uncertainties evaluation in fusion safety studies. An approach to uncertainty evaluation based on the uncertainty identification and phenomena identification and ranking table (PIRT) and utilizing sensitivity studies has been reported as part of the comprehensive methodology for fusion breeding blanket (BB) accident analyses [8]. The proposed method consists of an expert review of areas of uncertainties followed by the performance of sensitivity analyses. It addresses both the different sources of uncertainties—computer code models, system model representations, plant operating parameters and effect of scale as well as the specificity of the BB designs, materials, and phenomena. The applicability and robustness was demonstrated by the qualification of the models by comparison with finite element analyses and code-to-code comparisons and executed thus for sensitivity studies in HCLL [8] and HCPB [9] ITER test blanket systems (TBSs) specific accident scenarios: 32 h LOOP, LOFA and LOFA with aggravating failure of in-box LOCA. The reported advantages of the proposed method are its flexibility, practicality and progressive direct improved understanding. Although there are a number of challenges in the uncertainty evaluation, he believed that through the ITER operation and operation of a number of satellite tokamaks and experimental facilities the fusion safety community would collect the needed data, and would be able to take a more systematic approach in the uncertainties assessment and thus progressively move into best estimate analyses with uncertainty evaluation.

Massimo Zucchetti (Politecnico di Torino) and Boris Kolbasov (NRC 'Kurchatov Institute') summarized the radioactive waste studies in the frame of ESEFP [10]. In Japan, impurities in beryllides as neutron multiplier in Japan's DEMO blanket for shallow land disposal were studied. It was found that the uranium content in $Be_{12}Ti$ needs to be less than approximately 0.7 wppm in order for the total radioactive concentration of α nuclides, such as Np, Pu, Am and Cm, produced in $Be_{12}Ti$ to be less than 10^{10} Bq/ton, which qualifies for shallow land disposal under regulations in Japan. Neutron activation of impurity gases in the divertor material of Japan's DEMO was also discussed and found that there is a risk of these gases diffusing in the reactor hall in case of certain accidents. In the US [11, 12], material radiation damage and activated corrosion product characteristics were investigated for a liquid metal plasma facing component (PFC) system that removes heat from its Li reservoir by an in-vessel heat exchanger (HX). The DANTSYS code modeled the vertical build in cylindrical geometry to generate the radial neutron flux within the Li reservoir and the radiation damage parameters for the HX material, including: atomic displacement, helium production, and hydrogen production. In the EU, a feasibility assessment study was carried out, regarding the integration of tritium breeding units in the divertor cassette for DEMO. Activation calculations and shut-down radioactivity levels of relevant isotopes were performed with the EASY activation analysis system and found that there are no long-term waste management questions raised by this approach for the divertor cassette regarding any change in production of long-lived activated materials [13]. In Russia, the use of molten salt blankets in hybrid fission-fusion reactors was investigated [14]. At the equal thermal power hybrid reactors can produce at least ten times more fissile isotopes, than fast breeders even, if their breeding ratio will reach value 1.5–1.6. This means that the number of hybrid reactors can be fewer than the number of fast breeder reactors.

Didier van Houtte (CEA) estimated inherent availability of ITER cask and plug remote handling system during nuclear maintenance operations. The ITER nuclear maintenance strategy is based on the removal of components from the vacuum vessel, and remote transfer within casks to the Hot Cell facility where the sub-systems/components will be cleaned, repaired and tested by common and dedicated RH equipment, or replaced with new components. The availability of the ITER Cask & Plug Remote Handling System (CPRHS) in charge to install and remote transfer the port plugs between Port Cell to Hot Cell facility, and the deduced duration of its workflow have been estimated [15]. By introducing failure modes of basic functions in a failure modes, effects and criticality analysis, a CPRHS inherent availability of 22% has been obtained, leading to an operation time of 1471 h for transporting two equatorial port plugs to be maintained in Hot Cell (compared to 321 h with 100% availability—i.e. no failure). Statistic tests using a Monte Carlo approach with Primavera risk analysis tool, gave a similar result (repairing probability of 80% at t ~ 1150 h). This CPRHS operation time which would lead to decrease the ITER operational availability down to unacceptable value must be strongly reduced through risk mitigation actions (design, spare parts, etc) knowing that any additional time to the time currently allotted by the project will be less time for ITER operational availability and thus its ITER scientific program.

Chiara Bustreo (ENEA) presented the latest progress of EUROfusion Socio Economic Studies (SES). Along the development of fusion research, SES contributes, within international collaborations, to assess the role of fusion technology in a future global energy system by studying energy scenarios over a long term (up to 2100). Recent studies [16] demonstrate that fusion is likely to give a large contribute for electricity generation in a world with a strong environmental responsibility and a stringent global carbon emissions target. However, the technology penetration in the energy market is sensitive to the investment costs so that the share of fusion electricity production decreases by ~10% in the reference case with a 30% investment cost increase. Further, research activities are on-going to study how fusion could contribute for a sustainable energy system. Besides the economic aspects of fusion, SES studies [17] public perception of fusion as a research endeavor and as a future energy source, stakeholder engagement, and media analysis and framing. What emerges is that people have generally little knowledge about 'fusion' and that there is often confusion between fusion and fission. Therefore, a fundamental SES social research challenge deals with how to provide information on fusion and whether, and if so how, it generates changes in perceptions and attitudes. The on-going SES research is particularly focusing on the development of more sophisticated research methods to both providing information on fusion and evaluating the related public perceptions.

Youbean Kim (NFRI) studied the economic benefits of big science R&D program: with a focus on fusion R&D program in Korea [18]. He investigated three spillover effects of fusion R&D program.

- Market spillover effect: the contribution ratio of nuclear fusion R&D projects to the sales of the 24 enterprises that participated in KSTAR and ITER projects increased 19.1% on average. Total amount of sales increase was estimated to be 1538 600 M KRW (1322 M$). The 24 participating enterprises have created a sales-increasing effect greater than the financial input to the KSTAR and ITER projects (762 600 M KRW/669 M$).
- Knowledge spillover effect: 238 new jobs were created in the 24 participating enterprises through participation in the KSTAR and ITER projects. A total of 527 human resources in the industrial enterprises have experienced nuclear fusion. The new created skilled human resources in the field of nuclear fusion technology may be effectively used in the future construction of the K-DEMO.
- Network spillover effect: 15 enterprises (62%) out of the 24 enterprises have extended their businesses to other relevant technological fields. In particular, power supply (ultra-high heating, inverting, and converting), vacuum vessel, precision assembly and welding, ultra-low temperature, and superconducting technologies have been used to receive overseas contracts for ITER Project. Technology has been extended to fields of particle accelerators and space science, as well as to electric subway motor cars in the private sector.

3. Discussions

The workshop discussions were mainly focused on quantitative safety assessment of fusion reactors. Zhibin Chen, on behalf of Chair Yican Wu, made a short introduction of a quantitative safety assessments of fusion reactors for comments and suggestions, and participants were actively involved with the discussions.

Occupational radiation exposure (ORE) related: numbers of loops/components in the primary cooling, fuel cycle and diagnostics systems should be reduced. Remote handling technologies should be developed and widely used to cover nearly all the repair and maintenance. Advanced coolant purification technologies should be developed.

Accidents related: methods for reducing the assumed at risk tritium inventories in VV/tritium plant system should be investigated. Different blanket design options using gas or liquid coolants need to be assessed for their potential safety impact on fulfillment of safety objectives and criteria. R&D of the fusion emergency shutdown and residual heat removal systems should be carried out to reduce the frequencies of in vessel LOCA accidents. Tightness and reliability of ultimate confinement barrier, e.g. reducing the failure rate of ventilation system isolation or loss of detritiation function, should be enhanced. The possibility of using the cryostat vessel as the second confinement barrier was also discussed.

Radioactive waste related: specific activities of structural materials should be further reduced and advanced technologies of recycling should be investigated. Clearance levels for fusion radioactive waste should be considered.

Nuclear proliferation related: the IAEA safeguard system may be extended to cover the fusion reactors at due time. Fusion reactor designs should incorporate special technical barriers developed to prevent malicious modification.

4. Summary

The workshop is well attended with around 40 participants representing 15 institutions from eight countries. The presentations mainly include a review on safety issues and environmental impact, availability growth and risk control, socio-economic aspects of fusion power. A quantitative safety assessment of fusion reactors was deeply discussed, which provides in-depth suggestions for fusion safety towards an ideal nuclear energy source. It is highly expected that the IEA ESEFP technology collaboration program will continue by combining international efforts to promote fusion energy as the commercial nuclear energy source, to support the governmental policy, and to raise public and political awareness of the sophisticated fusion energy development program. It was agreed by the Executive Committee of IEA ESEFP to be held in conjunction with the ISFNT-14 in 2019.

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