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Conference Report

Summary of the 1st International Workshop on Environmental, Safety and Economic Aspects of Fusion Power

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Abstract

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. The workshop was initiated by the International Energy Agency Implementing Agreement on a Co-operative Program on ESEFP. The workshop was well attended with about forty participants representing twelve institutions in ten countries. The presentations covered safety issues and environmental impacts, availability improvement and risk control and socio-economic aspects of fusion power. Safety and licensing gaps between DEMO and ITER were discussed in depth with the consensus output presented as a plenary presentation at the 12th International Symposium on Fusion Nuclear Technology (ISFNT-12). The next workshop is planned to be held in conjunction with the ISFNT-13 in 2017.

Keywords: DEMO safety, safety gaps, IEA ESEFP

1. Introduction

A viable fusion energy system must satisfy a number of goals including a high level of public and worker safety, low environmental impact, high availability, a closed fuel cycle, and the potential to be economically competitive with other energy generation systems. The experience of the ITER project in developing a safety approach, implementing it in a safety design, performing safety analyses under the scrutiny of a nuclear regulator, ensuring the availability of the machine, making provisions for managing the radioactive waste and conducting economic assessments, is all relevant to DEMO. (In this context DEMO is generically defined to represent the class of next-step fusion reactors to be built after ITER.) However, it is recognized that there will be large scientific and technological gaps between the current ITER program and future DEMO programs.

The International Energy Agency (IEA) Implementing Agreement (IA) on a Co-operative Program on Environmental, Safety and Economic Aspects of Fusion Power (ESEFP), 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 IA is intended to play an important role in bridging the scientific and technological gaps between ITER and DEMO, supporting the policy making of government, 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 IA 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 including 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), Edward Stevens (US Department of Energy), Aleksey Kalashnikov (State Atomic Energy Corporation, Russia Federation), Kenji Tobita (National Institutes for Quantum and Radiological Science and Technology, Japan), and David Jackson (McMaster University).

As a result the 1st International Workshop on ESEFP was held at Jeju Island, South Korea, on 13 September 2015, with local organizing committee members led by Zhibin Chen (INEST, CAS) as well as strong support from the local organizing committee of ISFNT-12 (12th International Symposium on Fusion Nuclear Technology) led by Kijung Jung from the National Fusion Research Institute. 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. Ten invited presentations and nine posters 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 identifying the gaps in DEMO safety and licensing which have been presented as a plenary in ISFNT-12.

2. Highlights of presentations

Carlos Alejaldre, formerly an ITER Deputy Director General, reviewed the lessons learned in the safety and licensing of ITER [1], which are valuable not only for future installations but also for the on-going licensing process of ITER including the priority to meet the requirements satisfying a safe design, construction, assembly, operation and dismantling of the nuclear facility. A diligent and conscientious effort must be maintained in order to fulfill the requirements of ASN (the French nuclear regulator). Relationships with the ASN and the other stakeholders must continue on the basis of the mutual confidence achieved during the DAC file examination process. Training of ITER and Domestic Agencies staff should be aimed at the continuous improvement of the common understanding of nuclear safety and the licensing process to be followed in France. An important issue has been showing that the methodology of analysis of fusion systems can be somewhat less stringent compared to fission installations because of fusion's inherent safety features. Indeed, the main effort on the technical side has been focused on convincing the nuclear authorities that a fusion installation is safe. Demonstration of the design effectiveness of the first and second confinement systems was the basis of the success of the licensing process. The robustness of the ITER design has been confirmed by the very low impact of the predicted releases in normal and accident conditions. It was emphasized that the licensing of ITER will produce valuable experience for the licensing of future fusion nuclear installations. Issues specific to fusion such as electromagnetic forces or in-vessel dust explosions must be clearly addressed and followed-up throughout the nuclear installation lifecycle.

Didier Perrault (IRSN) made a presentation about the safety issues to be taken into account in designing future fusion facilities [2]. It was noted that safety should be considered at the earliest stage of DEMO designs, and the concept of ASARA (as safe as reasonably achievable) was presented in the contribution. The main differences between ITER and DEMO were summarized, in terms of four safety issues:

radiation exposure, releases, waste, and accidents, derived from ITER studies, to be considered for DEMO designs. The differing circumstances of ITER and DEMO in terms of these issues were presented. Optimization methods to take into account the characteristics of DEMO, including higher fusion power, longer plasma duration, larger tritium inventory, tritium and new materials in the tritium breeding blanket, additional release routes, new accident scenarios and the differences in the probability of accidents and their consequences were discussed. The presentation concluded with suggestions for including safety issues in designing DEMO, for example: determining if decay heat removal is needed as a safety function; continuing the efforts already undertaken with remote handling and low activation materials for reducing radiation exposure; re-evaluating the accident scenarios considered for ITER and identifying others specific to DEMO; limiting the overall tritium inventory of the facility and optimizing each of the main gaseous tritium release routes; and, integrating constraints related to the requirements of waste disposal routes.

Yican Wu (INEST, CAS) gave an overview of fusion safety research and development activities in China and presented a proposed roadmap of fusion nuclear technology and safety with the main programs and projects introduced briefly. The key activities were categorized as: neutron and activation source terms; thermo-fluid behavior and accident mitigation; reliability and risk control; tritium source terms and environmental impact; and, the socio-economic aspects of fusion power. It was shown that significant progress has been made in the development of the SuperMC [3] computer code and in the construction of the high intensity D–T fusion neutron generator (HINEG) [4]. SuperMC, which was selected as an ITER reference code, has been used in more than six hundred institutions in some fifty countries. HINEG-I with an intensity of 10^{12} n/s has been commissioning and the conceptual design of HINEG-II with an intensity of 10^{14}–10^{15} n/s has been completed. Research and development on the key technology of HINEG-II has demonstrated the feasibility of its tritium target. A dual coolant thermal hydraulic integrated experimental loop (DRAGON-V) is under construction to support the engineering design validation of PbLi breeder blankets with parameters covering the design requirements of ITER-TBM as well as China’s DEMO design. The reliability and probabilistic safety assessment program (RiskA 4.0), the tritium analysis program for fusion systems (TAS 3.0) and experimental research on tritium migration, system analysis program continuous development and its application were also presented.

Dobromir Panayotov (F4E) reviewed what can be learned from fission nuclear power plant safety and some needs for further work and challenges to be met on fusion safety. An overview of fusion relevant fission safety studies and methodologies was presented with reference to fission safety development, approaches, methodologies, methods and experience that might be useful and/or could be adapted to fusion safety experimental studies including computer code development, assessment and uncertainty evaluations. These might be further complemented by looking into fission with respect to regulatory framework development, PRA (probabilistic risk assessment) or PSA (probabilistic safety assessment) and their applications, Generation IV cooperation and development, and aspects of CFD (computational fluid dynamics) applications to nuclear safety. It was mentioned that management/preservation of experimental data is crucial for computer codes and safety methods development (knowledge management, reference case, licensing, and so forth). A powerful tool called phenomena identification and ranking tables (PIRTs) was introduced, the effective use of which has been demonstrated at F4E for Fusion Breeder Blankets Accident Analysis [5]. Suggestions for further work and challenges to be met on fusion safety were made particularly to facilitate international cooperation, for example meetings, seminars, and projects on specific subjects, establishing and maintaining a stronger and wider fusion safety community, broader technical exchanges with the fission safety community and industrial engagement.

Brad Merrill (INL) reviewed the computer codes developed by the Fusion Safety Program (FSP) at Idaho National Laboratory. Particular emphasis was placed on three codes which have been widely used in the fusion community: MELCOR modified for ITER—a fully integrated and engineering level thermal-hydraulics computer code; MAGARC—a coupled electromagnetic, radiant energy transport and heat conduction code; and, TMAP—a tritium migration code. The history of MELCOR, MAGARC and TMAP was reviewed as well as recent progress. MELCOR 1.8.6 for fusion [6] has undergone standard benchmarking and was made available to the MELCOR user community through SNL-NM in August 2015. The MAGARC code, developed during the ITER EDA, contains a 3D heat conduction solution for magnetic temperatures and melting, Maxwell’s equations for voltages and currents that develop arcs during an unmitigated coil quench event, and internal arcing and electrical insulation break down models. TMAP treats transport of hydrogen species in materials and was validated with thermal desorption system (TDS) data from the tritium plasma experiment (TPE). Future directions were discussed in fusion safety code development: all fusion modifications will be imported into the latest F95 Fortran version of MELCOR 2.x by request of the US Nuclear Regulatory Commission; MELCOR-TMAP 1.8.6 for fusion will be released after a few improvements are completed; MAGARC will be built into an ANSYS code model as one of the safety assessment capabilities under a contract with the ITER IO; and, TMAP will be eventually coupled to RELAP7.

Christian Grisolia (CEA) made a presentation concerning tritium absorption and release from tokamak-relevant tungsten dust for the evaluation of the consequences on tokamak operation and safety. Concerns about dust in ITER include dust size and shape (specific surface area), dust composition and the dust safety limit in a vacuum vessel. Experimental and model research on tungsten dust were reviewed in particular particle production methods and characteristics, the total quantity of tritium trapped in the tungsten dust, and the behavior of non-tritiated tungsten particles in biologic media. It was noted that dust particles in tokamaks differ in size and shape. The tritium inventory in dust is stable at room temperature but almost all the tritium is released from the dust before it reaches 500 °C. The tritium inventory in tungsten dust is greater than one GBq/g, a level a hundred times greater than the content in a comparable solid piece of tungsten. Tritium release increases in proportion to the dust surface specific area (SSA). From these results, an extrapolation to ITER can be undertaken. If all of the 1000 kg of in-vessel dust is assumed to have the same properties as the dust studied in this work, the tritium inventory in dust will be around 50 g which is much lower than the tritium ITER safety limit. However, if some of this model dust is at low temperature (100 °C) in contact with tritium gas, as it is observed after a plasma shot (~10 Pa for 10 s), then the tritium inventory of this dust will reach a one GBq/g level after less than a 1000 shots. If the model tungsten dust is dissolved in an aqueous solution, tritium release is a slow process with all the tritium released after 10–40 d [7], but more rapidly under acidic conditions (less than 10 d). In terms of biological effects, non-tritiated tungsten dust has a limited impact on the human pulmonary epithelium and tritiated tungsten nanoparticles are now being studied to evaluate the combined effects of chemical and radioactive stress.

Massimo Zucchetti (Politecnico di Torino) unfortunately could not be present at the workshop but his presentation file specially prepared for the workshop was circulated among the participants. Radioactive waste studies were summarized in the framework of ESEFP, and an optimized waste management strategy was presented with the main points: avoid underground disposal as much as possible, maximize recycling of activated materials [8] within the nuclear industry, and/or clearance and release to commercial markets if the materials contain only slight traces of radioactivity. Some technological questions under collaborative study were also reviewed, mainly regarding the recycling option in the US, an assessment of tritiated fusion radioactive materials in Europe and the US [9], the disposal of radioactive waste containing tritium and the rapid disposal method in China. Waste management and safety in Russia was focused on some particular issues. For example, studies there indicate that the potential needs of beryllium for fusion power engineering may exceed global resources if beryllium recycling is not carried out. The concentration of uranium impurities in currently produced beryllium is such that the radioactivity of irradiated beryllium would be mainly determined by the uranium impurities. This situation would prevent conditional clearance of the irradiated beryllium and complicate its burial [10]. In recent years, materials experts have been examining recycling options for several nuclear materials that offer potential solutions for some problems facing the materials community: embrittlement of structural components, erosion of plasma facing components, corrosion of ferritic steels by liquid metals, and other such problems. In the US, the recycling potential of such materials has been investigated [11] and the characteristics of materials for plasma facing components other than tungsten have been examined [12].

Tonio Pinna (ENEA) covered some basic issues concerning reliability and availability for fusion facilities. The presentation was organized under the following topics: reliability/availability as part of risk analysis; correlations between reliability/availability and safety analyses; some techniques and methodologies used in risk analysis, (for example, failure mode and effect analyses (FMEA), failure mode effect and criticality analyses (FMECA), event tree, reliability block diagrams); data on operating experience (e.g. failure modes, failure rates, mean time to repair); guidelines for RAMI (reliability, availability, and maintainability, inspectability) analysis and RAMI assurance program in DEMO and future fusion facilities [13]. It was emphasized that the objectives of reliability/availability research are to identify events and abnormal operating situations that can take place within the plant, to identify and define appropriate solutions in order to avoid system or plant stoppages, to define the likelihood the system or the plant is able to perform its functions for a defined time or for a defined number of cycles, and to define the likelihood the system or the plant is available to perform its functions for a defined time or for a defined number of cycles. Reliability and availability is expected to play an important role in PSA, in particular regarding probabilistic criteria, reliability based assumptions, performance demonstration, and reliability and consequence analysis. Failure rate data have also been introduced especially by considering the operating experience for fusion facilities. Some guidelines for RAMI analysis for future fusion facilities through the experience of existing facilities for which RAMI analysis was proposed.

Didier van Houtte (CEA) made a presentation on the need for improved availability of fusion devices, centered on two questions: 'why make an effort in availability?' and 'how to improve operational availability?' It was mentioned that the inherent availability of current fusion devices is much less than 80% being 15% for operational availability, and the target for ITER is around 46% in the D–T phase but only 15% for operational availability in the D–T phase. The availability target for ITER may be close to the objective of DEMO in its early phase but far from the required value for a fusion power reactor which needs to have an operational availability of at least 75% to be attractive from an economic point of view since the availability directly affects the cost of the electricity generated by a power plant. It was emphasized that both the reliability of components and the maintainability of the system functions are essential for the operational availability of a plant and need to be raised to a higher level in fusion designs with technology choices made to ensure high operational availability for future magnetic confinement devices such as DEMO. It was also noted that an increase of function and component reliability [14] would not be sufficient in itself to obtain a sufficiently high operational availability for ITER due to the long times needed to repair and maintain the machine within the constraints of its highly radioactive environment, requiring both remote handling and hot cell facilities. Thus, an availability-centered maintenance strategy needs to be developed from the conceptual phase of DEMO and recognized as a driver for the commercial success of fusion power plants. The work plan of the IEA RAMI international committee was also presented.

Satoshi Konishi (Kyoto University) presented the evaluation of the socio-economic aspects of fusion. Most current fusion power plant designs assume large and stable electrical grids to which the plants will be connected. However, the majority of future electricity markets may be significantly different from that expectation. Under these circumstances, the objectives of the presentation were to identify a possible scenario for fusion deployment in grids with limited size and stability and to suggest a possible solution with viable electricity storage to accommodate fusion and future carbon-free sources. It was emphasized that socio-economic considerations are essential and should be reflected in the plant design in order to maximize the possibility of the adoption of fusion power for future energy markets. Some improved socio-economic features would be that fusion must: have minimal impacts on the grid (small scale, flexibility, controllability and stability in power generation) and the capability to produce alternative fuel particularly bio-based, and have significant relevance to CO_2 emission reduction. In the future fusion has a chance to succeed only under strong environmental constraints, such as under the A1T scenario described in the Special Report on Emission Scenario (SRES) [15] by the Intergovernmental Panel on Climate Change (IPCC), in which the global population peaks in the middle of the twenty-first century with rapid economic growth and CO_2 emission reduction.

Poster presentations were also made during the workshop: Nobuyuki Asakura (QST), 'Investigations of the Divertor and Power Exhaust for 1.5 GW Fusion Power DEMO Reactor and Design Issues'; Dehong Chen (INEST, CAS), 'Development and Validation of System Analysis Program for Parameters Optimization and Economic Assessment of Fusion Reactor (SYSCODE)'; Gyunyoung Heo (Kyung Hee University), 'Initiation of Failure Rate Database Development Project for KSTAR'; Jiangtao Jia (INEST, CAS), 'Challenges and Strategies of Safety Analysis of Helium Cooled Ceramic Breeder Test Blanket System'; Muyi Ni (INEST, CAS),'Tritium Safety Assessment for Fusion Reactor Based on Environmental Dispersion Modelling'; Masashi Shimada (INL), 'Current Status and Research Needs for In-Vessel Tritium Source Term Assessment in DEMO in Future Fusion Reactor'; Hiroyasu Utoh (QST),'Design Issues of Remote Maintenance on Fusion DEMO Reactor'; Jin Wang (INEST, CAS), 'Preliminary RAMI Analysis of DFLL TBS for CFETR'; Zhiqiang Zhu (INEST, CAS), 'Construction and Experiment in DRAGON PbLi Loops for Fusion Material Testing'.

3. Discussions

The workshop discussions were mainly focused on DEMO safety and licensing gaps. Yican Wu made a short introduction with a preliminary summary of these gaps for comments and suggestions, and participants were actively involved with the discussions. The consensus output is summarized in broad areas of relevance as follows:

Accidents: large lack of failure rate data; hydrogen/dust explosion needs to be fully addressed to protect confinement barriers (e.g. vacuum vessel, building walls); electromagnetic loads due to plasma disruptions need to be well understood; decay heat removal may be become a safety function; comprehensive consideration of DEC (design extension conditions) and enhanced confinement measures to meet the 'no off-site emergency response' criterion.

Radioactive material releases: tritium operational release limit in ITER never verified leaving this limit in DEMO unknown; research and development on the fuel burning fraction needs to be further enhanced to reduce the tritium inventory.

Occupational radioactive exposure: remote handling maintenance needed for the minimization of occupational radiation exposure

Radioactive waste: low-activation materials and good understanding of tritium inventory in material are needed.

Other important points were also raised: code development needs to be well verified and validated; development of safety assessment methodology for fusion installations should be conducted; there is a great lack of industry involvement; the feasibility of adapting fission safety approaches to DEMO needs to be further investigated; and still many unknowns due to the immature design of DEMO.

4. Summary

The workshop was well attended with around forty participants representing twelve institutions from ten countries. The presentations concentrated on safety issues and environmental impacts, availability improvement and risk control, and the socio-economic aspects of fusion power. DEMO safety and licensing gaps were discussed in depth with consensus output useful for guiding the safety design of DEMO. The ESEFP implementing agreement will continue to facilitate international efforts to bridge the scientific and technological gaps between ITER and DEMO, to support the development of governmental policy, and to raise public and political awareness of the sophisticated fusion energy development program. It was agreed by the Executive Committee to hold the next workshop in conjunction with the ISFNT-13 in 2017.

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