Foreword

Dear Colleagues and Friends,

The two years in the run-up to ISRD-17 contained a sequence of uncontrolled events and developments that deeply affected our daily lives. Firstly, we struggled to navigate through the COVID-19 pandemic and secondly, we witnessed the beginnings of the tragic conflict in Eastern Europe and all that that entailed. If there was any word used over and over again throughout this period, it was, perhaps, the word 'unprecedented'.

As a scientific community, it is our responsibility to continue to carry on scientific collaborations without any prejudices and to provide a forum for the interchange of state-of-the-art techniques, databases and standards for radiation metrology and assessment.

The International Symposium on Reactor Dosimetry is held approximately every three years with this seventeenth edition happening five years following its predecessor for the above-mentioned reasons. The symposium is of value to those involved in reactor dosimetry, including researchers, manufacturers and representatives from industry, utilities, and regulatory agencies.

This symposium was organized by EPFL on behalf of the European Working Group on Reactor Dosimetry (EWGRD) and in cooperation with ASTM International Committee E10 on Nuclear Technology and Applications.

The scientific program included the following topics:

- Experimental techniques, measurements, and monitoring
- Calculational methods
- Reactor surveillance, plant life management and decommissioning
- Nuclear data, uncertainties, and adjustments
- Benchmarks and inter-comparisons
- Dosimetry in test and research reactors, including accelerators and fusion

Encompassing these topics, there were 8 oral presentation sessions, 4 workshops and 2 poster sessions.

Because of the factors resulting in the postponement of this seventeenth edition, the number of participants in ISRD-17 was a little lower than usual in this conference series. The symposium was, however, a real success with 64 participants and a total of 49 papers independently peer reviewed and presented in these proceedings. In addition, these proceedings contain the summaries of the four workshops, each of which successfully addressed the key issues in their relevant fields.

We are particularly grateful to our hosts EPFL and the SwissTech Convention Center as well as our Sponsors without whose support this event would not have occurred. We would also like to thank our distinguished keynote speakers, Dr. William Windes (INL) and Prof. Dr. Hamid Ait Abderrahaim; the members of our two supporting committees; session chairs; presenters and all attendees for making this scientific event a great success.

Jan Wagemans Pavel Frajtag Dean Thornton

17th ISRD

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The European Working Group on Reactor Dosimetry (EWGRD) started around 1960, under the sponsorship of EURATOM, with members designated by governments from the European Union's (EU) laboratories working in the field of reactor physics and technology. The goal was to exchange directly experience and know-how in reactor dosimetry and connected programmes. The fields covered were the measurements of thermal and epithermal fluences and fluence rate; the measurement of fast neutron spectra; and fluences of thermal and fast reactors, and later the measurement of fusion and spallation neutron spectra.

A major application of neutron dosimetry in fission reactors was, and still is, the monitoring of irradiation experiments. The knowledge of the neutron and gamma-ray fields and fluences as well as the temperature during irradiation, is necessary to understand and to assess the embrittlement of the structural materials.

Radiation damage units had to be introduced, i.e. dpa, flux > 1 MeV, or flux > 0.5 MeV, to correlate the lifetime of a material under radiation to the exposure dose.

Soon the need for normalization was felt in order to guarantee that specific nuclear data was used, that measurements in different laboratories gave the same results (need for inter-calibration experiments and standards), and that results were expressed such that a comparison with results from other laboratories was possible. Specific topics were discussed in sub-groups resulting in final recommendations. These final recommendations were then discussed in plenary meetings and accepted as recommendations for European use.

ASTM International, formerly known as the American Society for Testing and Materials (ASTM), is a globally recognized leader in the development and delivery of international voluntary consensus standards. Today, some 12,000 ASTM standards are used around the world to improve product quality, enhance safety, facilitate market access and trade, and build consumer confidence.

ASTM's leadership in international standards development is driven by the contributions of its members: more than 30,000 of the world's top technical experts and business professionals representing 150 countries. Working in an open and transparent process and using ASTM's advanced electronic infrastructure, ASTM members deliver the test methods, specifications, guides, and practices that support industries and governments worldwide.

ASTM Committee E10 on Nuclear Technology and Applications was founded in 1951. The Committee has a current membership of approximately 225, including representatives from over 20 countries. E10 has jurisdiction over 105 standards, published in the Annual Book of ASTM Standards, Vol. 12.02. These standards play a preeminent role in all aspects important to the nuclear industry. Committee E10 sponsors scientific and technical symposia such as ISRD and generates publications within the scope of the committee.

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Workshop Summaries

The programme included four workshops on topics of key interest to the practice of Reactor Dosimery. The workshops were informal technical discussions of up to two hours duration involving between 15 and 25 participants. Each workshop had two chairs, one of each appointed by the two organising committees. The chairs were responsible for guiding the discussion and producing the summaries, below, which were presented to a plenary session on the final day of the Symposium.

Workshop 1: Reactor Surveillance, Monitoring and Plant Life Management

ASTM chair: Jianwei Chen, Westinghouse, USA
EWGRD chair: Simon Shaw, EDF, UK

This workshop session on Reactor Surveillance, Monitoring and Plant Life Management was attended by approximately 20 people and discussed a number of broad issues. Each issue is summarised below:

Availability of Dosimeter Materials

The availability of dosimeter materials, particularly high purity niobium, was identified as a key risk to continuation of accurate plant dosimetry monitoring. ^{93m}Nb has a half-life of 16.13 years with a fast neutron response energy range from 0.95 to 5.79 MeV, which serves an excellent replacement dosimetry foil for fission monitors, which are difficult to obtain. However, measurement of the ^{93}Nb(n,n')^{93m}Nb reaction can be contaminated by tantalum and requires high purity niobium foils with less than 5 ppm tantalum. Commercially available niobium foils typically cannot meet this requirement. Representatives from the US noted that they had potentially identified a new supplier in China, but that they would only offer very large quantities at large expense. It was proposed that in this case it would be preferable if an international organization could take more responsibility for sourcing dosimeter materials for use by the wider community.

Al-Co dosimeters were also identified as a risk as original stocks of these materials are starting to run out, but current manufacturers are not really prepared to offer to produce such alloys with very low cobalt content (e.g. 0.1%) and guarantee the homogeneity of the material for dosimetry purposes.

Availability of Dosimetry Analysis Capabilities of NPP Residence Countries

The status of practical measurement / assay capabilities within organisations' own countries was also discussed. While it is common practice to transfer irradiated specimens overseas for analysis in dosimetry labs, the absence of national capabilities to perform such measurements also results in a lack of Informed Customer knowledge within those operators' own organisations. Production of new reactors, particularly potentially large numbers of SMRs, will impact the availability of the existing labs to perform analyses on a timely basis, which may damage the accuracy of surveillance programmes that rely on shorter half-life (n,p) reactions for fast neutrons.

Reactor Dosimetry for Advanced Reactors (SMR, MicroReactor, etc.)

The capabilities for dosimetry monitoring of new reactor designs were discussed. Depending on the relevant material properties and possible failure modes, different energy ranges of the neutron spectrum could be more important than the current commonly used reactions, e.g. (γ,n), (n,2n) reactions.

There is currently a sparsity of monitor reactions in the epithermal range (few eV – few 100s keV), although work is ongoing to investigate this (see paper by Grégoire et al.). The epithermal range was noted as potentially being important for the EPR heavy stainless steel reflector design. SMRs, molten salt and other new reactor types may require different treatment; there are difficult engineering problems to provide dosimetry for sealed reactor designs (e.g. microreactors, nuclear batteries), where access to reactor internals is not possible. It was noted that for the advanced reactors, it is expected that the material science community and the reactor dosimetry community are required to work closely at early stages of the advanced reactor design to determine what kind of radiation related material failure mechanisms are important and how to design corresponding reactor surveillance program to monitor them in the future.

Retrospective Dosimetry from Shutdown Nuclear Power Plants

Opportunities exist for irradiated materials to be extracted from recently shutdown plants that are currently defueling and decommissioning. These may be of great benefit to the wider community if material composition data can be combined with irradiation data to inform new reactor design and decommissioning elsewhere; data from irradiated graphite was noted as a potential key material. However, there is likely to be a large cost in constructing such a database and there would be a need for driving organisations to oversee this at international level to ensure that operators were aware of the potential importance to provide samples from their decommissioning plant and to be able to plan this with minimal cost and impact on decommissioning schedules. It was agreed that PWROG and/or EPRI should be approached in the first instance to see if they could support such a scheme.

Proposed Actions:

1. Conduct a demand survey on the high purity niobium foils;
2. Conduct a survey on the potential useful reactor vessel and internals materials to be collected from a shutdown NPP.

Workshop 2: Experimental techniques, Benchmarks and Intercomparisons

ASTM chair: Bojan Petrovic, Georgia Institute of Technology, USA
EWGRD chair: Ernst Ippel, NRG, Netherlands

The chairs opened the session with the topic of benchmarks for shielding calculations. The question was raised whether Advanced Test Reactors (ATR) could/should be used in shielding benchmarks. Jan Wagemans mentioned that there are quite a lot of benchmarks for LWR's (they had been discussed in the Keynote speech by Prof. Dr. Hamid Aït Abderrahim, e.g., VENUS series), but that not a lot of practitioners are aware of this. Also, there is an ongoing effort to update SINBAD benchmarks within NEA (EGPRS Task Force). It is a volunteer effort, so the progress is slow. The ISRD community is encouraged to volunteer and contribute where they are able. One of the objectives is to classify available experiments/measurements into benchmarks of different levels of completeness and quality to allow users to make selections according to their requirements. IAEA has a database of experiments (CoNDERC, https://www-nds.iaea.org/conderc/) that could also be used in the future. There is within NEA also a task force on Zero Power Reactors that may be of interest. Furthermore, the necessity for UQ (uncertainty quantification) was emphasized; one proposed solution is to adopt the IRPhEP guide for uncertainty quantification. Also, it is important to identify which shielding facilities provide adequate dosimetry capabilities. The conclusion from this part of the discussion was that more experienced practitioners should enlighten the younger generation about the available benchmarks. It was suggested that for the next ISRD, papers about SINBAD could be solicited.

The next topic that was discussed was about the use of ^{93m}Nb dosimetry and the intercomparison thereof. Since the importance of the reaction ^{93}Nb(n,n')^{93m}Nb in determining the fast fluence rate is rising, it is important to reach an agreement within the dosimetry community about how to accurately determine the activity of ^{93m}Nb and its associated uncertainties. An ASTM standard exists (E1297) for ^{93m}Nb measurement methods in which it is also stated which nuclear data to use. This ASTM standard, however, is not very detailed. It was therefore agreed that a more detailed description of how to determine ^{93m}Nb activities is required, where the changes that are implemented should reflect on the lessons learned from previous work. A review of ASTM E1297 is currently being performed, and in parallel ASTM is organizing an inter-laboratory comparison on the determination of ^{93m}Nb activity. The participants were informed that there are 24 niobium samples available for this ILS, and until now only 12 laboratories are participating. The possibility of including additional, potentially intercontinental, participants was therefore suggested. A paper on the ASTM round robin is planned for the next ISRD-18 in 2025.

In the context of the upcoming ILS, it was mentioned by Jan Wagemans that the supply of some dosimeter materials (CoAl, AgAl, and Nb) is limited or non-existent. This problem pertains mostly to alloys (due to more difficult manufacturing). Moreover, the certificates of dosimeter materials should state the tolerances in both the purity and homogeneity. The general consensus was that we, as a community, should push for these materials to be available and certified.

Finally, the question of whether we are ready to perform measurements in more extreme surroundings (i.e., environmental temperatures and gamma heating effects) when keeping in mind possible future reactors, was discussed. This question concerned both the dosimeter materials, as well as the material of the capsules that they are placed in. Stainless steel or ceramics were mentioned as possible packaging materials. The topic was closed by agreeing that we don't have the desired level of knowledge to handle extreme surroundings yet, and that it thus is important to know which materials to use, and where to place them.

Workshop 3: Dosimetry in Test Reactors, Accelerators, and Fusion

ASTM chair: William Windes, INL, USA
EWGRD chair: Mathieu Hursin, EPFL, Switzerland

There is a distinction between low-power research reactors and high-power materials test reactors (MTRs), as follows:

a. Reactor operation and purpose may need different dosimetry requirements.
b. Low-power research reactors:
   i. Most are focused on education/training;
   ii. Low power and/or Pulse operation;
   iii. Potentially lower dosimetry uncertainties during irradiation;
   iv. What deficiencies there are in the material world tend to be communicated to the MTRs so as to improve the MTR results.
c. For High Power MTRs:
   i. High throughput, high dose with focus on providing as much neutron irradiation as possible;
   ii. Continuous (steady-state), high power operation;
   iii. Potentially higher dosimetry uncertainties during irradiations;
   iv. Individual MTRs have specialised dosimetry procedures that are specific to their requirements:
      - This leaves little opportunity to explore new dosimetry methodologies even if they are potential improvements over current practices.
d. The above considerations may alter the dosimetry requirements between the two types of reactors, as follows:
   i. Different types/sizes of wires needed:
      - Low dose verses high dose irradiations;
      - High temperatures (MTR) vs. low temperature irradiation (low power);
      - Wire placement in core/experiment.
   ii. Passive versus active dosimeters used in some low-power reactors.

Accelerators & Fusion reactors have very different irradiation parameters from fissile reactors:

a. Fusion reactors and accelerators publish in units that are confusing to the fission dosimetry community;
b. Guidelines would be a good way to connect their community to the fission community:
   i. Guidelines that would specify the same general concepts of dosimetry.
   ii. Guidelines to encourage the same unit usage.
c. Since there are no primers for how to perform dosimetry across all reactor types such a guideline would be beneficial:
   i. This would benefit training the next generation of dosimetry experts
   ii. This would establish general requirements that would be common across all disparate specific reactor dosimetry procedures.

Advanced Reactor Material Failure Modes:

a. Participants agreed to share a list of potential materials used in new advanced reactor designs.
b. Dosimetry community must determine how to implement dosimetry to these advanced materials and reactor designs:
   i. They need to know how the dosimetry analysis for the new materials may change;
   ii. For example, how does high temperature affect the cross section of resonances?
c. Molten salts are potentially a large area of development:
   i. There is a dearth of experimental information on dosimetry within all the molten salt compositions.

ii. MTRs are beginning to conduct static corrosion experiments on materials immersed within molten salt. This may be an opportunity to begin developing the dosimetry background information necessary for molten salt applications.
iii. Is there a need to perform dosimetry experiments on all the salt compositions to ascertain differences in dosimetry response?
   - There is the perception that additional information is required before there can be an accurate understanding of what kind of dosimetry practices must be implemented for these new applications.

d. More communication is needed between Dosimetry and Advanced Reactor material scientists as well as advanced reactor Designers:
   i. Need to understand new material failure modes;
   ii. Need to understand new reactor designs, for example, in order to recommend where to locate surveillance packages.

Workshop 4: Calculational Methods, Nuclear Data, Uncertainties, and Adjustments

ASTM chair: Thomas Quirk, Sandia National Laboratory, USA
EWGRD chair: Mladen Mitev, IRNE, Bulgaria

This workshop largely followed the session title, in terms of topics addressed. The discussion began with calculation methods. After a brief discussion of recent SERPENT releases, the conversation quickly turned to code-to-code comparisons. In short, agreement coalesced around "we have a lot of codes" and "blind predictions are difficult." Therefore, making common, non-proprietary benchmarks is very important. The community is long overdue for a Round Robin exercise. Roughly a dozen workshop participants expressed interest in joining such a Round Robin effort. EWGRD-ASTM will continue effort to identify a small working group. It was suggested that a framework for this inter-comparison effort be presented at the next ISRD conference.

The execution of this Round Robin necessitates answering many questions. Using a power reactor or research reactor? Dosimetry or activation estimates? However, the question of who will spearhead this work remains unanswered. With EURATOM 2023 proposal deadlines upcoming, vessel fluence calculations for plant life extension may create a natural leadership opportunity within this group. Defining the goal will be paramount, showing code agreement is an important first step, with the intention of later including experiments. Decommissioned plant data might be a promising avenue for benchmark data. It was suggested that the next EDF decommission may include some releasable data. A few questions arose about regarding active members in the community: What is being done in terms of boiling water reactor component activation? Does any public data exist (even power history)?

Nuclear data was next discussed. This topic began on a practical note. From an industrial point of view, "if it works, it is good enough." However, from a scientific perspective several deficiencies and concerns were identified. More specifically, the ENDF-B 8.0 Fe-56 transport cross sections still have questions surrounding the quality of the evaluation as there is poor agreement in some benchmark studies. In spite of its improved high-energy fission data and improved covariance data, it remains unclear which are valuable. Some of these concerns will likely be addressed in the upcoming (estimated February 2024) ENDF-B 8.1 release, based on some beta user experience. Generally speaking, the same issues exist with JEFF libraries, although its documentation is good. Elastic scattering angular distribution from oxygen: JENDL4 is different from all others, which had a significant impact on LWR. Newer evaluations of carbon cross sections are not as good as those performed many decades ago. This could have an impact on future/proposed reactor systems. Lastly, aside from only, perhaps, thermal neutron capture, gamma ray data remains a significant nuclear data need.

Some improvements in uncertainty reduction were reported. Work has been undertaken to compare standard methodologies to higher fidelity calculations, but power sources and history remain the largest source of uncertainty. Total Monte Carlo methods were discussed, and best practices for the application of uncertainties in transport and in dosimetry calculations. Assessing cross correlations remains a challenging task and can lead a practitioner to use multiple libraries to determine a best estimate.

Finally, the meeting discussed spectral adjustment methods. All attendees agreed that the upcoming REAL exercise is important to the community and there were expressions of great interest in seeing it conducted, especially given the recent IDRFF update. From this a possible action emerged seeking IAEA support in concluding the REAL exercise. The inclusion of novel genetic and machine learning algorithms into this benchmark was noted as a primary validation for broader adoption.

Overall, this workshop session was a fruitful forum for identifying needs within the calculation community to begin addressing historical shortcomings on joint efforts. At the meeting's conclusion its participants left hopeful for more collaborations in the near future.