ADVANCED METROLOGY FOR NEW GENERATION NUCLEAR POWER PLANTS

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Abstract – This EMRP (European Metrology Research Programme) project [1] is looking at solving metrological problems related to a new generation of nuclear power plants. The proposed Generation IV power plants are designed to run safely, make efficient use of natural resources, minimize the waste and maintain proliferation resistance. In order to reach these goals, the reactor operation involves higher temperatures, high-energy neutron fluence, different types of fuel where the minor actinides are also used as fuel etc. In this multidisciplinary project, which has 12 partners in 10 countries, the work is focused on improved temperature measurements, investigation of thermal properties of advanced materials, determination of new and relevant nuclear data and development of measurement techniques for radionuclides suitable for Generation IV power plants.

Keywords
Metrology, Nuclear data, Thermal properties, Instrumentation, Generation IV

1. CONTEXT

Nuclear energy is one of the energies which emit the least greenhouse gases - such as CO_2 - during its lifecycle. With 31% of Europe's electricity produced from nuclear at the moment, this is the most important low carbon technology in Europe's energy mix [2]. Europe can maintain the current level of nuclear energy by long-term operation of existing plants and an ambitious programme of new build. Some European countries have already decided to build new nuclear reactors; Other EU countries are actively considering whether new nuclear power plants should form part of their energy strategy [3], [4].

The nuclear power plants currently in use are first generation Magnox and second generation advanced gas cooled and light water reactors. Generation III type light water reactors of the European Pressurized Water type are currently being deployed, e.g. in Olkiluoto in Finland and Flammanville, France. The near term build will use designs that were essentially developed 30 years ago, because there has been little nuclear build in the last two decades. In terms of safety these designs are significant improvements over second-generation reactors. New builds will involve

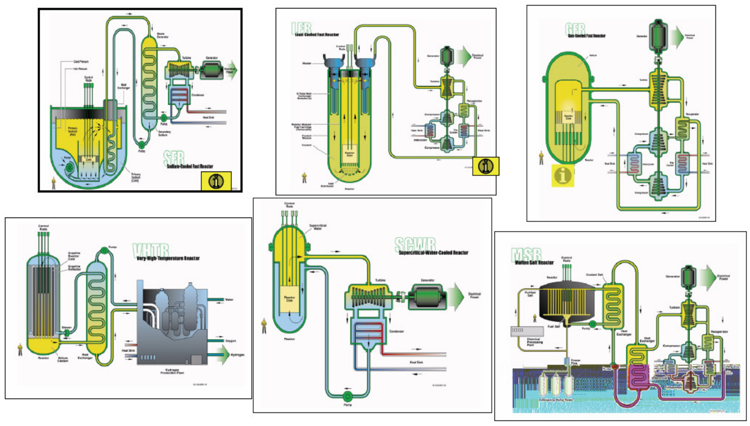

Fig. 1. Next Generation of Nuclear Power Plants

incremental improvements called Generation III+. The purpose of Metrofission is to provide the metrological infrastructure necessary for the design of Generation IV (Gen IV) nuclear power plant. There are, however, some areas where this project will improve Generation III+ power plants.

GenIV aims to improve nuclear safety, improve proliferation resistance, minimize waste and natural resource utilization, and to decrease the cost to build and run such plants. Amongst other, these Gen IV reactors pose the following key challenges [5]:

1. How can the temperatures be measured, since existing thermocouple-based methods will not work in the envisioned temperatures and environments?
2. What materials should be used in these reactors and what are their thermal properties?
3. What are the nuclear data and radionuclide and neutron metrology techniques that will be needed?

2. SCIENTIFIC AND TECHNICAL OBJECTIVES

The present EMRP project aims to address the mentioned challenges by the following specific scientific and technological objectives:

a) Contribute to improved temperature measurements for nuclear power plant applications
b) Contribute to improved thermo-chemical data and modelling for nuclear design
c) Development of reference metrological setups and methods for the measurement of thermal properties of advanced materials at high and very high temperature
d) Characterisation of reference materials for high temperature thermal properties measurements
e) Contribute towards improved neutron cross section data through neutron fluence measurements and standards
e) Measurement of nuclear decay parameters and emission probabilities of priority nuclides.
f) Development of techniques based on Digital Coincidence Counting (DCC) and Triple-to-Double Coincidence Ratio (TDCR) for radionuclide standardisation.

2.1. New high-temperature references, sensors and validation methods

New temperature sensors and methods for in-situ measurements in nuclear power plants are investigated and developed with an emphasis on extending the measurement range to higher temperatures and characterising, limiting, or completely eliminating the sensor drift in a high temperature, high-neutron-flux environment.
Reference fixed points above the copper point will be rapidly developed to perform post-irradiation studies of thermocouples. In the first months of this project significant progress has been achieved in the realisation of the Fe-C fixed point (1154 °C). In a joint effort between NPL and LNE-Cnam, different combinations of materials and designs have been tested and a comparison of different realisations has been performed. The first results show a promising repeatability of this fixed point.

Suitable thermocouples from the Mo/Nb family will be identified, constructed, and studied with respect to their reference functions, stability, and thermoelectric homogeneity [6].
The practicality of self-validation methods for thermocouples will be examined as a means to reduce or eliminate drift related problems. In order to achieve a proof of concept of an innovative driftless thermodynamic method of temperature measurement, an acoustic thermometer is under study for possible application under ionising environment at temperatures up to 1000 °C.

The first experiments on the acoustic thermometer developed at NPL were conducted to highlight weaknesses in the measurement protocol. Several effects linked to imperfect compensation of the thermal gradient along the acoustic waveguide leading to the measurement region were identified. Two different designs are to be tested to cope with this shortcoming and to take the system to higher temperatures.

2.2. Improved thermo-chemical data and modelling

In terms of modelling, a range of major and minor actinide containing systems relevant to fuels (both in-reactor and during reprocessing) and coolants potentially used in Gen IV nuclear plant will be defined. Thermodynamic models will be developed to represent the variation of the thermodynamic properties of the various phases of these materials, which could form with temperature and composition. These will be parameterised [7] through critical assessment of all the related experimental thermodynamic and phase diagram data. This will result in a thermodynamic database. The combination of models and assessed data will allow predictions to be carried out related to the high-temperature phase equilibria (such as phase transformation temperatures, vapour pressures or the potential interaction between the fuel and coolant) of these materials, which can partly be validated by comparison with experimental observations.

The thermodynamic database(s) arising from this work will be compatible with the major software packages used to calculate phase equilibria from thermodynamic data.

2.3. Thermophysical properties of advanced materials

This research project aims at implementing a European metrological infrastructure in the field of thermophysical properties in order to provide reliable and traceable high temperature measurements for materials having thermal properties similar to those used in fission reactors. In terms of measurements and measurement techniques, all important properties related to heat transfer will be addressed. This includes specific heat capacity, thermal diffusivity, thermal expansion, and emissivity. In some cases, these properties can already be measured at high temperatures [8] [9] [10]. However, often these measurements lack traceability to the SI above 800°C. Therefore, reference metrological setups and methods will be implemented or improved for measurements up to 2000°C (1500°C in the case of specific heat of solids). Suitable candidate materials to be used by nuclear research laboratories as “transfer reference materials” for high temperature thermal properties will be identified and characterised. The feasibility of applying a laser-flash technique to thermal diffusivity measurements of molten salts up to 1000 °C will be investigated.

The availability of accurate facilities and reference materials will improve the traceability of the measurements performed by nuclear research laboratories.

2.4. Improved cross sections through neutron metrology

New fast reactor designs will involve materials exposed to higher-energy neutron fields. The current nuclear databases concentrate on thermal energies. Work will need to be done to determine and/or achieve lower uncertainties of nuclear data at higher energies. Advantage will be taken of the experience of National Metrology Institutes (NMIs) in neutron metrology, particularly fluence measurements, to improve cross section measurements of interest to new generation power plants and fuel cycles. In this respect, an important objective of this EMRP project is to establish an easy-to-use secondary fluence standard and to demonstrate its potential for the determination of cross sections of actual interest and the improvement of nuclear data standards in the form of reduced measurement uncertainties.

Practically the project aims at improving neutron interaction data measurements beyond the present state-of-the-art, which is set by self-normalizing methods and the neutron data standards used at laboratories where the data are measured [11] [12]. The program of work includes

1. the establishment of an easy-to-use secondary fluence standard at the JRC-IRMM GELINA facility along with a procedure for reliable determination of the efficiency of fluence measurement devices used in neutron data measurements at JRC-IRMM and elsewhere,
2. the demonstration of the potential of these fluence measurement devices for the determination of cross sections of actual interest, and also for the improvement of nuclear data standards
3. transfer of these improvements in measurement uncertainties to other labs where such data are measured.

2.5. Nuclear decay data

The minor actinides and their decay products have generated increased interest in recent years because of their significant role in the foreseen development and adoption of nuclear fuel. A list of specific needs for improved actinide decay data has recently been outlined in a review by the IAEA [13] [14]. Responding to those needs, an objective of the present project will be to measure the alpha-particle emission probabilities of U-238 with certified isotopic composition.

As fission fragments containing more beta-decay isotopes will result from proposed fast reactors, developing beta spectrometry using cryogenic detectors is an objective of our project aimed at improving the measurement of beta spectra and verifying theoretical models, particularly for those of the forbidden type. This will lead to improved calculations of decay heat produced by nuclear fission, a quantity important for safe reactor operation (reactor shutdown, post irradiation handling of nuclear fuels).

Thus two major objectives steer this part of the research at improving

1) our knowledge on decay data for radionuclides playing a major role in power-related fields. It is proposed to measure some nuclear data that have been identified as incomplete or inconsistent, and in which NMIs could provide a major impact with their dedicated facilities for primary standardisation of activity. NMIs have a proven record of providing accurate decay data such as half-lives and alpha-particle emission probabilities. Alpha-particle emission probabilities will be determined for one of the important nuclides for which an explicit demand for better decay data has been expressed: U-238 [13].

2) the knowledge of beta spectra, through experimental determination using the technology of cryogenic detectors, which is innovative in that field of application and offers exceptional characteristics in terms of energy resolution and detection efficiency in a wide energy range. The development of such beta spectrometry systems could lead to significant improvements in the experimental determination of beta spectra and to the verification of theoretical models, especially for beta spectra of the forbidden type. This task relies on the experience already acquired by CEA-LNHB in activity and spectrometry measurements using cryogenic detectors and on a study of beta spectrometry using that technique, with positive results. This improvement could have impact in several fields of application, including decay heat calculation.

2.6. TDCR : Metrology for in-situ activity measurements

The general aim of this work is to enhance operation of new generation nuclear power plants (NNPP) by enabling on-site determination of low-energy beta-emitters created in the fuel cycle (e.g. Pu-241) and/or as activation products in the reactor and its enclosure (e.g. S-35, Ni-63, Ca-41, H-3 etc.).

Addressing the demand of nuclear power plants for on-site activity measurements of pure beta emitters, the objective for this part of the project is therefore to develop a miniature size Triple to Double Coincidence Ratio (TDCR) system, clearly advancing technology beyond the current state-of-the-art [15] [16] [17]. Present systems are metrology instruments not suitable for use on-site, partly due to their large size and weight. One step in this direction will be the miniaturisation of the instrument's detection chamber itself by selecting newer, smaller, more efficient photomultiplier tubes.

2.7. Digital Coincidence Counting for radionuclide metrology

The work will focus on the provision of a means of on-site activity standardisations for various photon-emitting radionuclides that may be readily standardised using the $4\pi\beta-\gamma$ coincidence counting technique. This will proceed via the modernisation of data acquisition techniques for the provision of primary standards of radioactivity, with the development of high-speed digital acquisition systems and associated digital signal processing techniques. Specific attention will be paid to providing Digital Coincidence Counting (DCC) systems with high sampling speeds allowing improved pulse-shape discrimination (e.g. different types of radiation) [18].

The work will also:

- Enable the provision of an in-situ detector and analysis system (analogue electronic systems are too cumbersome to be defined as portable).
- Create a cost-effective DCC system that is less labour intensive to operate than existing analogue techniques.
- Facilitate a means of employing and improving pulse shape discrimination, for partitioning of events from different radiation types.
- Increasing the dynamic range of source activities that may be standardised.

3. CONCLUSION

This paper presents ongoing work in an EMRP Joint Research Project, which started in September 2010. This project is aimed at providing solutions to metrological challenges in relation to nuclear new build and specifically Gen IV reactors so that these reactors can be designed, built and operate safely. The project proposes innovative temperature measurements in order to satisfy the need for measurements at the higher temperatures experienced in GenIV reactors and possible solutions for long-term stability of such equipment. The project will deliver thermo physical and thermo chemical data by experimental methods as well as modelling in order for new nuclear power plans to have suitable construction materials. It also addresses the issue of nuclear fuel and how accurate and traceable methods of measurements of neutron flux and nuclear data can improve cross-section measurements, crucial for the calculation of the fission yield and the reactor efficiency. The nuclear data will furthermore benefit the operation of the power plant, once realised, as such data is required for calculations of for example the radiation heat. With methods for radionuclide metrology that previously was designated to specialist primary conditions, this project is investigating the possibility of realising an in-situ measurement facility that will enable accurate determination of difficult to measure radionuclides, in the fuel and during operation. In summary, this project is working towards the realisation of a low-carbon emission source of energy that will provide Europe with a source of sustainable energy. And, with the benefit that these new types of reactors use a closed fuel cycle, will increase resistance to proliferation of nuclear weapons.

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