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Review of Mr **Mikolaj Tarchalski** PhD thesis:

NUCLEAR HEATING MEASUREMENTS IN THE MARIA REACTOR AND IMPLEMENTATION OF NEUTRON AND PHOTON CALCULATION SCHEME

Generation of heat during the operation of nuclear reactor is a complex process depending on many factors. Heat is generated in the process of nuclear fission, in the interaction of radiation inside the reactor core and in secondary interactions resulting from subsequent decays of fission products. The energy deposited in materials surrounding the reactor core depends also on many factors related to the radiation properties (type, intensity and energy spectrum) and on the properties of irradiated materials (material type, its structure etc.) All of it determine the mechanisms responsible for energy deposition.

The complexity of various processes leading to heat generation during the reactor operation, makes difficulties for the measurements of deposited heat. Numerical calculations must also take into account all the contributed effects and their mutual relations. It seems therefore reasonable to combine the calculations with measurements, both performed for the same initial conditions, geometrical configurations, material contents, etc. In this way, a lot of possible sources of systematic errors can be eliminated. This is however the task for two collaborating teams: experts on numerical code application and the reactor exploitation team, knowing the reactor construction and having "know-how" in resolving multiple and sometimes unexpected problems arising during reactor exploitation. The attempt to calculate and measure the nuclear heating in MARIA nuclear reactor is undertaken in this thesis.

The thesis counts 176 pages including 6 chapters and references with 114 positions.

The mechanisms of heat deposition are discussed in the Introduction: nuclear fission and subsequent slowing down of neutrons, photon interactions, decays of activated nuclei, interactions of electrons etc. To describe all of it, the TRIPOLI-4 code developed by CEA (France) is used. The construction of MARIA reactor in Swierk (Poland) is very well suited for heat deposition measurements. On the base of French-Polish agreement the TRIPOLI code was used for MARIA reactor.

In the second chapter "State of the art" the historical review of nuclear heating is shortly presented first. Then the calculation scheme and experimental approaches are discussed. The features of MARIA reactor and the instruments for nuclear heating measurements are described. Most of nuclear fission energy (about 90%) is given by the fission fragments and absorbed in the fission region. The rest of heat is distributed outside the core. Various instruments are used for nuclear heating measurements. Advantages and disadvantages of different types of instruments are discussed. More information is given for the KAROLINA calorimeter designed and developed for the purpose of this thesis.

The calculation tools are discussed also. The WIMS/REBUS scheme is mentioned as used for MARIA reactor operational needs. This is however too simplified approach neglecting the conical shape of MARIA reactor core. For the purpose of this thesis the TRIPOLI-4 and APOLLO2 French calculation codes were used and a conical shape of reactor core was implemented. Calculation scheme is divided into three stages: verification, validation, qualification.

- Verification – this is the first stage where the correctness of important parameters, like geometry or material balance, are verified and compared to the other MARIA models.
- Validation – it is the process performed "until sufficient confidence is obtained and model can be considered valid for application"
- Qualification – it is the last stage in which the nuclear heating calculations are compared to experimental measurements.

Details of all three stages are described and discussed.

The next section of this chapter is devoted to the detail description of the MARIA research reactor. The attention is paid on the specific conical shape of the core and on the procedure of fuel change. The geometrical structure of the reactor core is shown together with the indication of channels selected for measurements and analysis. The structure of existing Maria calculation scheme WIMS-ANL/REBUS code is presented and discussed, showing the needs of improvements in order to obtain the results which can be compared to the results of measurements.

The research hypothesis is formulated in the last section of this chapter. It consists of three main elements:

1. Currently available Monte-Carlo simulations can be used to correct and accurate calculations of prompt nuclear heating.
2. Delayed component of nuclear heating can be determined experimentally.
3. New calculation scheme and improvement of nuclear heating measurements are to be implemented.

Measurements are described in the third chapter. Precise measurements of the heat deposition needs different detector types, to measure neutrons, photons and other particles, having a wide energy spectrum and various forms of interaction with matter. For the purpose of this analysis a dedicated measuring instrument, calorimeter KAROLINA, has been designed and constructed. This calorimeter is described in details as the basic measuring device. Some other instruments like: "Gamma thermometer" and SPND (Self-Powered Neutron Detector) are described also, together with the scheme of their location in the core of MARIA reactor. The activation detectors are used for the measurements of neutron flux density.

In order to assure the precise geometrical configuration of detectors and their location, several detectors were assembled into one probe called "P1". Also the activation detectors formed the probe "P2". The detectors were calibrated before measurements, and the calibration procedure for CAROLINA, using especially designed and manufactured calibration bench, is described in details. Together with theoretical considerations it allowed to obtain and parameterize the dependence of sensitivity and other exploitation parameters on the temperature.

The goal of the measurements was "to determine experimentally vertical and horizontal distribution of neutron and photon field in MARIA reactor core". The measurements were performed for the detector locations selected in this way that their positions form a line symmetric with respect to the core center. The procedure of measurement was complicated and the reactor core was emptied of all target materials before. Such arrangement allows to better compare the results of measurements and calculations.

A special procedure was applied to study the delayed nuclear heating. The time dependence of temperature was measured for two cases:

– reactor was rapidly shut down by all safety and control rods drop,
– entire probe P1 with all instrumentation was rapidly taken out of the core.

A clear difference was observed. However, some additional effects can also contribute to the measured time dependence and it was necessary to make a deconvolution of the obtained distributions.

The calculation scheme for MARIA reactor is presented in the next (fourth) chapter. The TRIPOLI-4 code vas used for reactor simulation and the fuel material balance was calculated by APOLLO2.8-3 code. Both codes were developed by CEA-Saclay and were used for the simulation of JHR reactor in France. In order to use them for MARIA, it was necessary to reconstruct the reactor geometry, what was a difficult task due to the conical shape of the reactor core. A special code EVA was created to prepare the data with the MARIA geometry for TRIPOLI allowing for simple and quick modification in the case of reactor elements location or material composition changes.

Many factors were taken into account for the adaptation of TRIPOLI code for MARIA conditions. Let’s mention some of them: conical core shape, geometry of fuel elements, composition of materials in different reactor elements, fuel elements poisoning during campaign, change of water density with temperature, material balance in depleted fuel, and many, many others.

Last chapter presents the comparison of calculated and experimental results. In order to do such comparison properly, both results should refer to the same quantity (“compare apple to apple”). In this case, the measured values include prompt and delayed neutron and photon components together, while the calculations allow to determine them separately, but for the prompt component only. The delayed one need to be added using another data. Two kind of data were used: experimental and taken from numerical analysis for JHR reactor.

It turned out that the differences between the results form CAROLINA and from Gamma Thermometer depends on the sensor location with respect to the center of the core. This difference can be attributed to the relations between the different material using for the core of each sensor (graphite and stainless steel) and to difference between the neutron and gamma flux density and different energy spectrum in different locations.

Comparison of calculations and measurements show a general agreement. Some systematic differences appeared in dependence on the detector position with respect to the reactor center (for different channel numbers and the core height) and for different type of detector used (KAROLINA or Gamma Thermometer). Keeping in mind that the mean gamma energy is related to the position and that different sensors have different material of the sensor core, some interesting conclusions were drawn from these dependences:

1. Significant difference is seen for the reaction of low energy photons with different materials: carbon or iron.
2. Location close to the fuel elements corresponds to higher energies of photons.
3. Good agreement for the sensor location close to the fuel elements, prove the correctness of calculation for prompt and high energy photons.
4. Fraction of low energy photons is larger for larger distance from the fuel elements.

5. Calculations and measurements show significant difference in the results for different material of the sensor core.

The general conclusions can be expressed in the following way:

1. The calculation scheme based on TRIPOLI and APOLLO codes can be successfully used for nuclear heating description of MARIA nuclear reactor.
2. CAROLINA calorimeter is a proper device for the nuclear heating measurements.
3. Detailed analysis of differences between the results of calculation and measurements indicates the needs to continue studies performed in this thesis, but with more precise measuring instruments. It will be useful to have the sensors like KAROLINA, but with different core materials.

Concluding remarks:

The title of this thesis, and the thesis itself, consists of two parts: nuclear heating measurements and development of calculation scheme.

The first part - measurement of nuclear heating – is in fact a complete physics experiment with all the elements of experimental procedure: definition of goals, preparation of measuring instruments, measurement campaign, data analysis and results interpretation. The author has applied the existing measuring devices, e.g. the SPND detectors, adapted to the needs of this thesis measurements, as well as new instruments, e.g. KAROLINA calorimeter, designed, constructed, calibrated and installed in the selected positions inside the reactor core. The thesis contain the detailed description of all the stages of this work.

The second part - development of neutron and photon calculation scheme use the existing codes, but implemented and adapted to the conditions of MARIA reactor. Launching and conducting of such calculations was also a well-defined scientific task, and the results were obtained and interpreted.

In the reviewer opinion, each of these parts can be seen as a PhD thesis. Here both are joined together and their mutual relations are extensively discussed. New measuring devices are designed, constructed and tested, reactor MARIA is equipped with a new calculation scheme. **All of it justify the award of this thesis by the honorable mention of highest degree.**

Last but very important – the realization of this thesis shows the author as a high level expert on the reactor physics, instrumentation and exploitation, a person with a deep knowledge and experience, with a firm position in the reactor physics community and with the enthusiasm to the subject of his activity.

The thesis meets all the requirements for doctoral dissertations. The author can be admitted to the further stages of the PhD procedure.

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