INVAP Nuclear Engineering Department Calculation Suite

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ABSTRACT

INVAP Nuclear Engineering Department (DIN from Spanish acronym) is an interdisciplinary department of the Nuclear Projects Division of INVAP SE. The disciplines involved in DIN are Neutronic, Thermal-hydraulic (steady state and transients), Shielding and Radioprotection. The main reason of this integration is the strong interaction among the different areas during all the design stages of a research reactor and other relevant nuclear facilities like radioisotope production facilities. This interaction is through the engineering data and it handled in an efficient manner. The DIN calculation suite is a set of codes of different disciplines, which are divided in state-of-the-art and production codes. The calculation suite includes also a set of procedures, methodologies to take into account the whole process of design including regulatory aspect, analyst qualification and the computer codes. For this reason, DIN has been on continuous development and validation of the calculation suite used for design and optimization of nuclear facilities.

1   Introduction

The Nuclear Engineering Department (DIN) designs very demanding nuclear facilities [1] (nuclear research reactors, radioisotope production plants, etc.), and better prediction capabilities are needed to reduce the design margins and succeed on the pursued goals. The methodology used in the design process of a nuclear facility takes into account the main characteristic and requirements of the facility and it is based on three main aspects:

- Verification and validation (V&V) of codes integrated in a calculation line
- Analyst qualification.
- Regulatory aspects which are mandatory in any nuclear project.

The Figure 1 shows this design methodology, where it can be seen these three aspects which are independent of any specific project, and they are the main areas of the continuous improvement of the DIN.
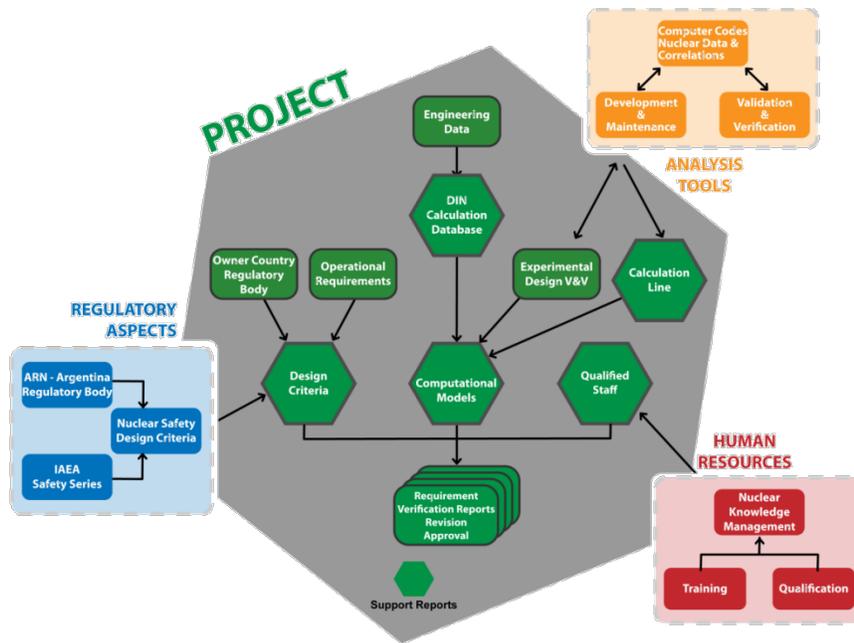
Figure 1: Nuclear Engineering Department Design Methodology

The design of a nuclear research reactor has several interfaces between the different engineering areas, but three of them have strong interaction and for this reason they are integrated in the DIN. These areas are: Neutronic, Thermal-hydraulic for steady state and transients, Radiation Transport, which includes shielding and radioprotection, all of them following the design methodology.

The design is carried out with computer codes, keeping in mind the following important aspects:
- V&V process,
- Qualification of the analyst
- Proper modeling
- Engineering data, and mainly the coupled data (among different engineering areas)

This paper describes the codes used in DIN (most of them are used during the design of a nuclear facility), the V&V process (integrated with the training process of the nuclear analyst) and some V&V examples.

2 DIN calculation suite

The codes used in the DIN are classified in
- Educational packages: Used for academic and training purposes. (out of the scope of this paper)
- Production packages: The codes and tools used to produce high quality results regarding the requirements both for design & production (where computational performance rules must be achieved)
- State-of-art packages: It refers to the codes that are used for Research & Development (where computational performance is not mandatory), and also used for verifications of the production codes in novel design requirements or as an independent calculation requirements.

The production packages contain mainly the deterministic calculation codes and they are used for facility design. These codes must be as fast and accurate as possible with reasonable precision, including as much as it can be the innovative calculation capabilities allowed by the computational system.

The state of art codes contains the Monte Carlo and CFD codes and they are mainly used for verification purposes, specific design (when production codes cannot be applied) and Research and development activities. These codes must be as precise and accurate as possible (with a reasonable calculation cost) and must represent an alternative approach to the problem to be solved.

The calculation line is not only a set of codes, but it also takes care of:

- The analyst (easy to use and analyze)
- The project environment (engineering and models databases, project documentation).
- The traceability of the use, modifications, changes, etc.

The following sections present a brief description of the codes used in each thematic area, of the DIN, as well as the interaction among them.

2.1 Neutronic codes

The Figure 2 shows the neutronic calculation line [2] integrated with third parties codes. The production calculation line is based in CONDOR-CITVAP codes, and the State of Art code is based in the MCNP and SERPENT code.

This calculation line is used for the following neutronic parameters: Reactivity balance, Control Rod Worth, Shutdown Margin, reactivity insertion rates, neutron flux and power distributions, power peaking factor, Xe transients, kinetic parameters, power distribution history, oxide layer growth, reactivity coefficients (fuel and coolant temperature, coolant density, power, etc).
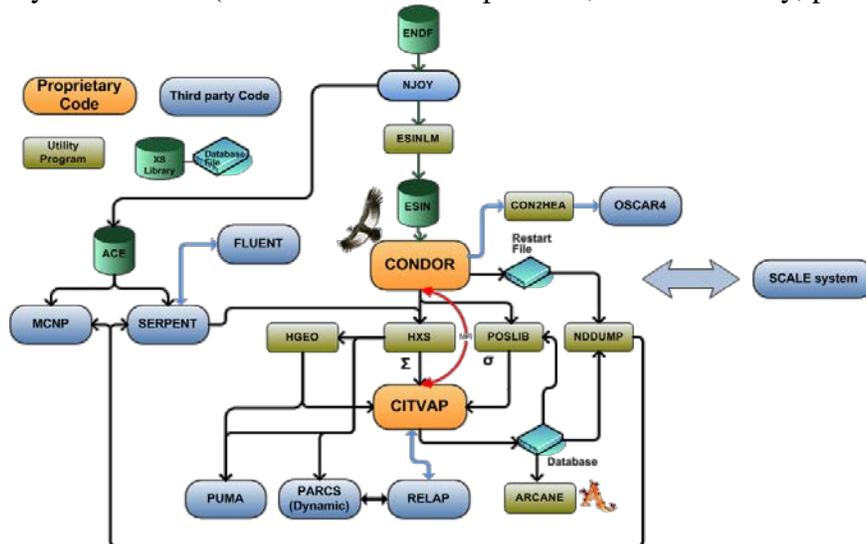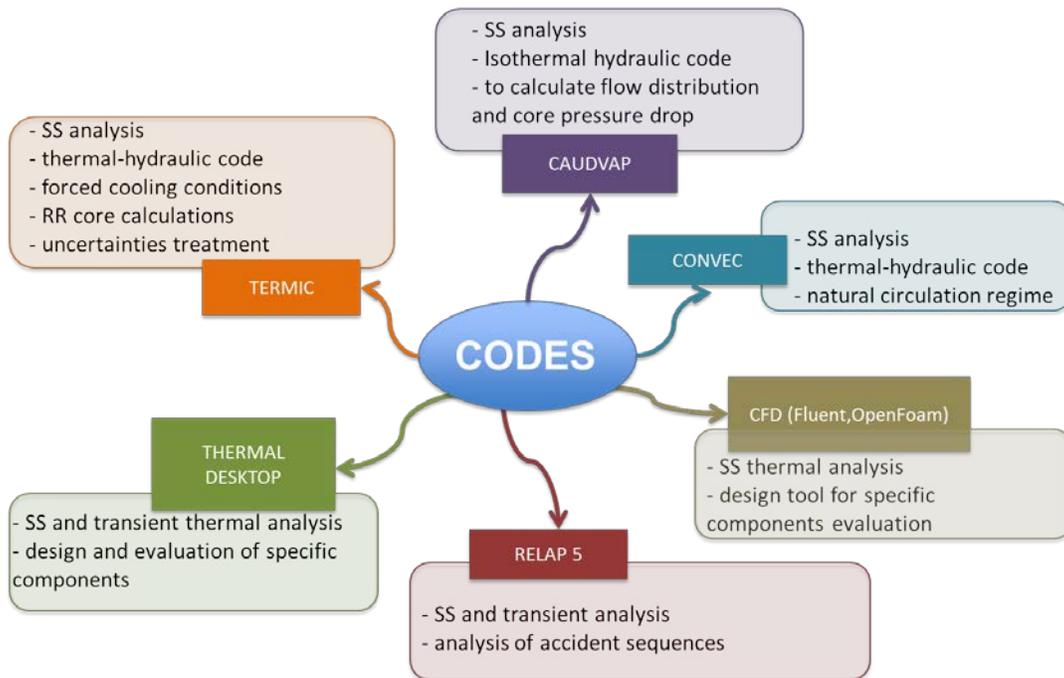

Figure 2: Neutronic Calculation Line

2.2 Thermal-hydraulic codes

The Figure 3 shows the thermal-hydraulic calculation codes. The production calculation line is based in the Steady State and RELAP 5 codes, and the State of Art codes are based in the CFD codes. The Figure also shows the main calculation parameter calculated by each code.

Figure 3: Thermal-hydraulic Calculation Codes

2.3 Radiation Transport codes

The Figure 4 shows the transport radiation codes and its main application.
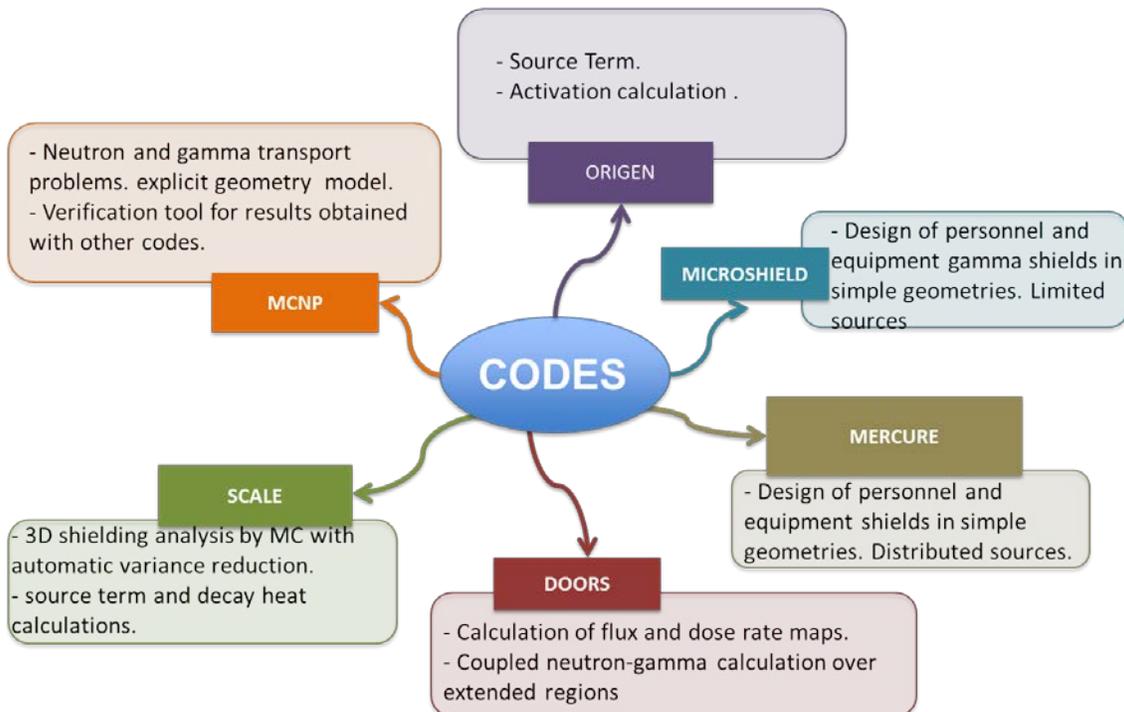
Figure 4: Radiation Transport Codes

2.4 Integration between calculation codes

The integration of the codes is in continuous improvement, and the Table 1 shows the main parameters of this integration.

Table 1: Coupling between different calculation codes

Parameter distribution	Neutronic	Thermal-hydraulic	Radiation Transport	Objective
Burnup	←————	————	————→	Analysis of depleted cores (BOC, EOC, etc)
Temperatures	←————	————	————→	Detailed neutronic and radiation transport analysis
Power distribution	←————	————→		Detailed thermal hydraulic analysis
Coupled N-TH	←————	————→		Coupled calculation Power Feedback coefficient Oxide Layer growth
Energy Deposition		←————	————	Detailed Structural materials thermal analysis
Feedback Coeff. & Kinetic parameters	←————	————→		Transient and accident analysis.

3 Verification and validation process

DIN **designs** research reactors; which means that our analysis is used to predict the behavior of a reactor to be built (in 4-6 years). We uses design margins to deal with design uncertainties and we want to have as low as possible design margins (not an "as low as possible calculation error" obtained by adjusting the model).

We use design models for V&V purposes and our design methodology is validated against an as wide as possible universe of reactor designs and experimental data to improve the field of application and safety analysis.

3.1 Types of verification and validation

We have different level of V&V types and its application depends on the following concepts:

- Verification against other codes: This level of V&V is used for:
  - Code development: During the process of developing a new proprietary code or a new version of it. It is also used for the installation of a new (or new version) of an external third party code.
  - User cross checking.
- Theoretical benchmarks (the calculations are as good/bad as other's participants): This level of V&V is used for:
  - Code development.
  - Inexperienced user: Training of a novel nuclear analyst.
- Experimental benchmarks (real world): This is the most frequently used set of benchmarks. They are used for:
  - New reactor design. We use as close as possible design as the new proposal.
  - Analyst training / re-training: To train a new nuclear analyst or re-training an already trained nuclear analyst. In the last case we proposed such a benchmark that is a new challenge for the already trained nuclear analyst.
  - Code development.
- Reactor measurements (real world). This level of V&V is mainly for specific application or novel designs. Normally is a mock-up or specific reactor measurements. The reference [3] shows a very detailed validation of multi-physics measurements based on a mock-up and reactor measurements.

3.2 Previous experience

A few words on previous experience, our calculation codes are validated against a wide universe of nuclear reactors, some of those validations were carried out for specific INVAP projects, but some others were carried out by Balseiro Institute students performing his/her degree, master or PhD thesis. Some examples are (references [4] to [8]):

- Research Reactors: RA-2, RA-3, RA-6, RA-8, (Argentina), NUR (Algeria), TRR (Iran), ETRR-2 (Egypt), OPAL (Australia), MNR (McMaster- Canada), IPEN/MB-01 (Brazil), Triga Mark II Reactor and TRR-1/M1(Thailand), Safari-1 (South-Africa), RSG-Gas (Indonesia), Nuclear power Plants: CNA-1, CNA-2 (PHWR), Candu, PWR, BWR, VVER, FBR, ADS.
- Homogeneous reactor, MSR.

Additionally to the validation work, INVAP's codes and procedures have been acknowledged by several Nuclear Regulatory Authorities: Autoridad Regulatoria Nuclear (ARN, Argentina), Australian Radiation Protection and Nuclear Safety Agency (ARPANSA), Egyptian Atomic Energy Agency (EAEA), Algerian Nuclear Authority (COMENA) and Instituto Peruano de Energía Nuclear (IPEN).

It is worth to mention that during the design process, our clients add value through their independent reviews like ANSTO and CNEA.

3.3 V&V on New release of codes

The implementation of a new release of a code into the set of codes available to be used in a within the frame of a project follows a set of steps which depends if it is a new code or a new version of it and also if it is a third party code or a proprietary code. The next points conceptually describe the planning and V&V steps:

- Release a new third party code:
    - A *verification* process is carried out to check the proper functioning of the code.
    - A *validation* process is carried out in the main area of application of the new code to learn how to use it properly, to detect its capabilities and/or limitations and to establish design margins
- Release a new version of a third party code:
    - A *verification* process is carried out to check the proper functioning of the code.
    - An analysis of the differences with respect to the old version is performed.
    - *Validation* of the new capabilities.
- Release a new proprietary code (or version): In this case, following conceptual plan is performed:
    - The plan takes into account the requirements of the developers, programmers and users.
    - The development program is a live document. It means that the first version of the document is just the plan, and the last version of the document, it is the final implementation. All the intermediates versions provide information regarding the different actions and verifications carried out during the development.
    - The development document, include aspects such as: problem definition, scope and method to solve the problem, estimation of resources, impact on the calculation line (up-stream and down-stream) and procedures, verification and validation plan and acceptance criteria.
    - The plan must focus on design capabilities, like; I/O (easy to use and easy to

analyze), project documentation, project environment integration and traceability.

3.4 Source of data for V&V

The most valuable source of data for the validation of our codes is the commissioning of the already designed facility, like NUR, ETRR-2, and OPAL, but this valuable data has not the frequency desired and it is not in a range of novel designs.

However, there are several different sources of experimental data, one are the IAEA Coordinated Research Programs (CRP) that allow us to have access to a wide spectra of research reactors, and have a direct contact with different participants from different countries and direct interaction with the experimental data provider. This type of sharing knowledge is a very important aspect for the validation of the code and the training of the analyst. The V&V process during the participation of a CRP allow us to:

- Establish procedures for the qualification of the computational tools and users.
- Transfer know-how in the area of innovative methods in RR and minimization of user effects
    - To enhance the training and knowledge of the INVAP participant's staff through the know-how transference among participants due to: discuss the benchmark, discuss models & results, pursuit small differences and incorporate new codes & methodologies

4 Verification and Validation examples

The following sections shows examples of V&V processes performed for each engineering area of the DIN.

4.1 Neutronic Validation example

Several measurements were carried out in the OPAL reactor during its commissioning. The main parameters measured were the safety related data, besides several performance parameters measurements. Figure 5 shows the First operating core used for the commissioning measurements.
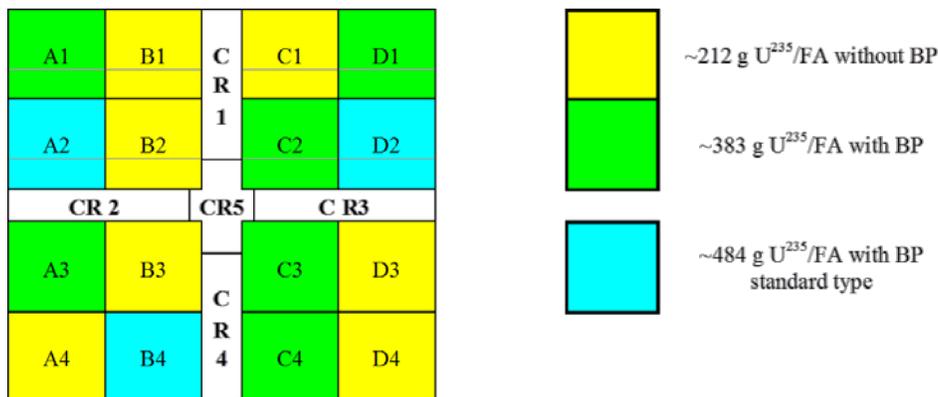

Figure 5: Opal First Core

Table 2 summarizes the main parameters measured and Figure 6 summarizes the control rod worth and flux profile measurements.

Table 2. Measured parameters in OPAL reactor

Parameter	Measured value	Calculated value
Critical Cores (reactivity) (pcm)	0 $\pm$ 5	-380 $\pm$ 80
CRW #3 (pcm)	3727 $\pm$ 150	3594
Isoth. FC (pcm/°C)	-15.7 $\pm$ 0.8	-19.0
Void FC.(pcm /%)	-223 $\pm$ 9	-206
Power FC(pcm /Kw)	-0.74 $\pm$ 0.1	-0.60
PPF	2.48 $\pm$ 0.12	2.31
FSS SDM (pcm)	10070 $\pm$ 500	11500
SSS SDM (pcm)	10460 $\pm$ 500	10640
FSS at 0.5 Sec(pcm)	9970 $\pm$ 500	10980
SSS at 15 Sec(pcm)	8490 $\pm$ 400	8290
Irr.Fac. worth(pcm)	240 $\pm$ 24	220
α (sec^{-1})	38.1 $\pm$ 2.0	37.2
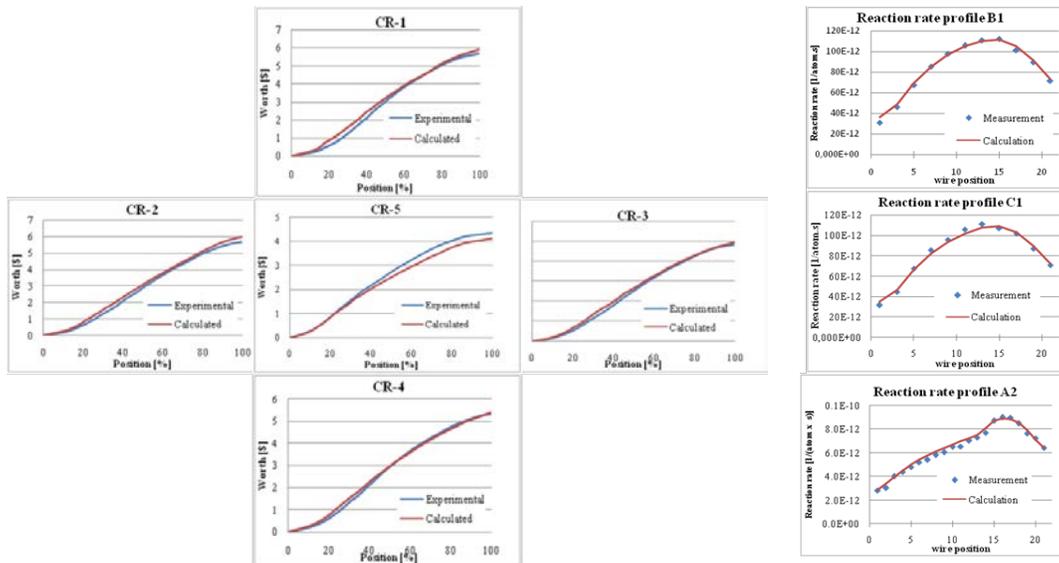
Figure 6: CRW and flux profiles measurements

4.2   Thermal hydraulic Validation examples

Several measurements were carried out for different experiments to validate the different types of codes regarding steady state and transient analysis Figure 7 shows the CAUDVAP validation against hydraulic measurements on a dummy of an OPAL fuel assembly. Figure **8** shows the TERMIC validation for the Redistribution power with the SUPER BOB measurements [10] and Figure 9 shows a RELAP validation against the coast-down flow and cladding temperature measurements performed at the IPEN/IEA-R1 5 MWatt reactor, from Brazil [11] .
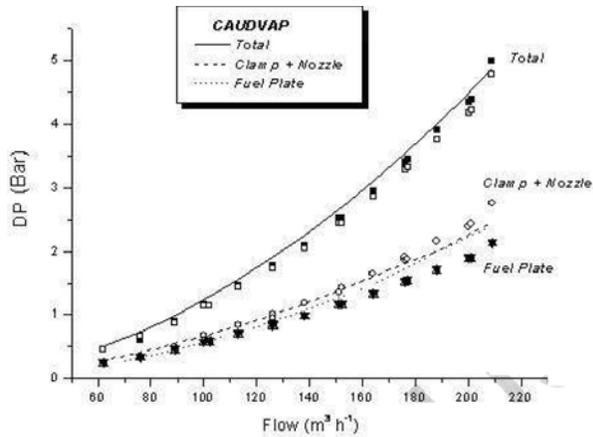
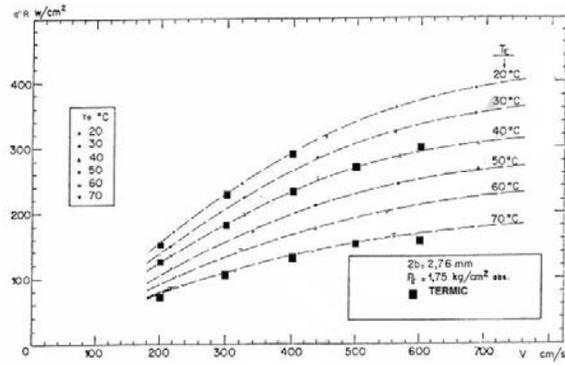Figure 7: OPAL FA (Dummy) pressure drop measurement

Figure 8: Comparison of heat flux redistribution for different coolant temperatures and velocities
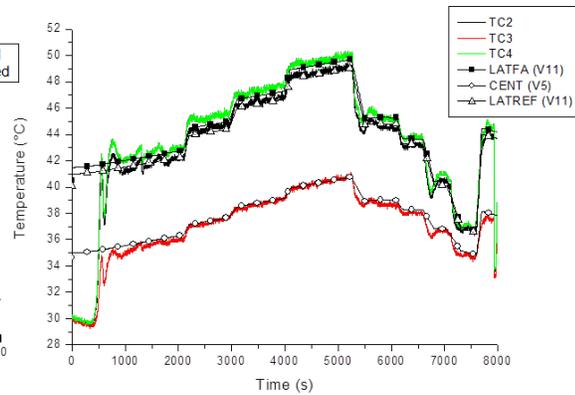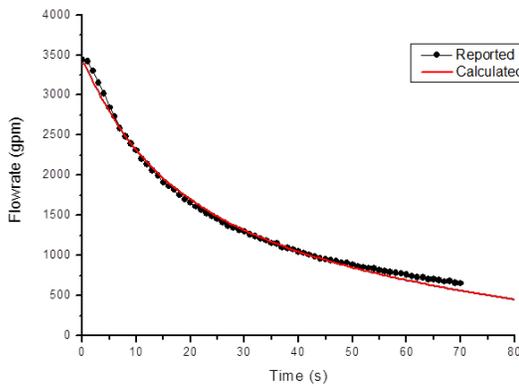

Figure 9: IEA-R1 Coast down measurements (flow and cladding temperature).

4.3   Radiation Transport Validation examples

The IPEN/MB-01 Mo99 activation measurements were selected as an example of activation validation. This benchmark not only shows the capability of the INVAP codes to calculate this parameter, but also how INVAP uses the benchmarks to analyze user effects and trains the analyst in a working environment. Figure 10 shows the core configuration and the Figure 11 summarizes the results.
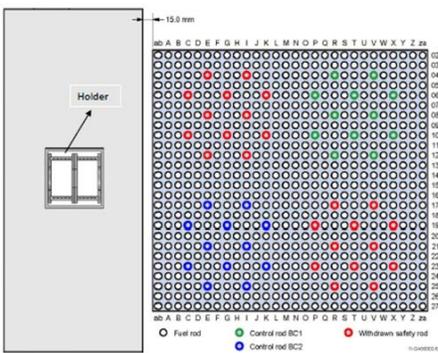

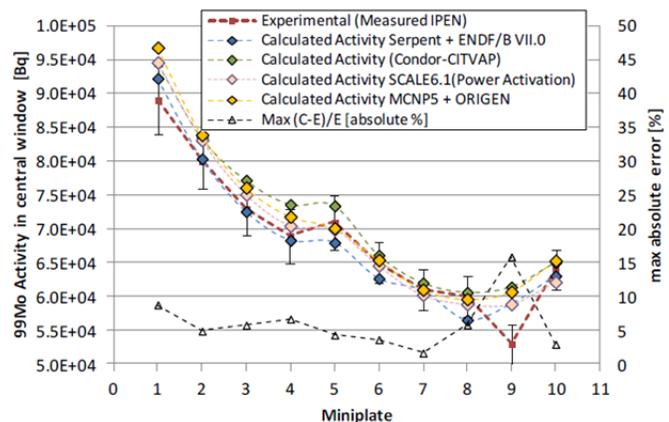**Figure 10: IPEN/MB-01 Mo99 experiment.**

Figure 11: IPEN/MB-01 Mo99 activation measurements

5   Conclusion

The INVAP calculation suite integrates the three different engineering areas which have a strong interaction during the different design stages. The codes and utilities are in continuous improvement following a V&V process which takes into account not only its calculation capabilities but also the user and the project environment. According to the use of the code and the purpose of application, different types of V&V are followed, also giving the code user the adequate training. The steps for the implementation of new releases of in-house or third party codes or versions are properly established ensuring they are properly verified and validated. To have data, either calculated results or measurements are essential for the V&V of codes and users and commissioning experience and IAEA coordinated research programs are invaluable sources of this activity. Finally, although the calculation suite is focused on design, state of art codes is also included.

A continuous and extensive V&V effort is carried out taking into account not only the V&V results but also the user qualification and training

6   References

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