FROM NEEDS TO DEVELOPMENT, VALIDATION AND APPLICATION (NEEDS): THE VIRTUOUS CYCLE FOR LFR CORE DESIGN

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Abstract

When dealing with the design of the core of a nuclear reactor, the availability of consolidated expertise, validated simulation codes, and consolidated design and analysis procedures, is a mandatory prerequisite for successful accomplishment.

Concerning lead-cooled fast reactors, the Laboratory for Design and Analysis of Nuclear Systems of ENEA holds a renowned leading position, acknowledged internationally. This derives from a longstanding experience, historically acquired on sodium-cooled fast reactors through the PEC, PRISM and BN-800 projects, and then shifted to systems cooled by heavy liquid metals within the context of Euratom research projects, national programmes and international collaborations.

Despite this, the Laboratory strives to pursue the continuous improvement of its assets, leveraging the activities on which it is engaged to focus the efforts on aspects of primary importance. The identification of the areas of improvement, and the definition of the priorities, are a direct result of the needs emerging as feedback from the activities performed. These needs, generally, involve an extension of the expertise in the pertinent domains (such as neutronics, thermal-hydraulics, thermo-mechanics, fuel performance) and its subsequent consolidation; the development of new codes (as was the case with ANTEO+, TIFONE and TEMIDE) and methods (such as the burnup sensitivity and uncertainty model for ERANOS), and their validation; the execution of new experiments (either by separate or integral effects) and their consequent assimilation.

Examples of the virtuous cycle of improvement of design capabilities, realized by the development of design building blocks, are presented with cases of practical application.

Keywords: *Core Design; Lead-cooled Fast Reactor; Research, Development and Qualification; Simulation and Modeling; Verification and Validation*

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Introduction

The Laboratory for Design and Analysis of Nuclear Systems of ENEA digs its roots in the Fast Reactor Department (Dipartimento Reattori Veloci, DRV), which, until 1987, was in charge – among others – of the design of the core of the PEC experimental reactor, which reached about 85% construction at the Brasimone Research Centre before the nuclear phase out in Italy. At that time, ENEA held the whole and sole responsibility for the design of the core of this reactor, relying on itself for all the competences and manpower for the purpose. Following the closure of this project, a relevant part of the expertise was lost. Despite this, a (small) group maintained determination to work on nuclear, transferring their skills to relevant projects within international collaboration endeavors. Relevant examples of this were the support to the core design of the PRISM reactor, pursued by General Electric in the USA (currently relaunched as NATRIUM with Bill Gates's TerraPower), and a major contribution to the study of a MOX-fueled option for the Russian BN-800 core.
Thanks to these initiatives, the competences were preserved until the late '90s, when – under the propelling action of Nobel laureate Carlo Rubbia, president of ENEA – the Energy Amplifier concept was launched, and followed by a number of collaborative projects on accelerator-driven subcritical systems (ADS), supported by a number of projects funded by the European Commission through its Framework Programmes. With the Energy Amplifier and the subsequent ADS projects, new competences were added, focused on the design of a fast reactor core cooled by a heavy liquid metal (HLM) such as lead or lead-bismuth eutectic (LBE). Despite the commonality of the fast spectrum, the primary cooling by HLM, indeed, changes the frame of technology and safety constraints which are to be accounted for in the design process, compared to those typical of sodium-cooled fast reactors (SFRs), according to the different physical and chemical properties of these liquid metals. It was, however, thanks to the sound expertise formed on SFRs, that the ENEA team managed to master the core design process for HLM-cooled reactors, as proven by the elaboration of ad hoc design processes (such as the so called "42-0" approach for ADSs [1], or the so called "adiabatic reactor" theory for critical systems [2]), and the leading role assumed both in Italian and European research projects, and within collaborations with HLM-cooled reactor vendors such as Westinghouse.

Core Design Methodology

The design of the reactor core – as that of any other system – moves from conceptual to basic to engineering (manufacturing) phases. At the same time – again, as for any system – it focuses on the left branch of the so called "V cycle" (see Figure 1), the one descending from mission to configuration, passing through the definition of objectives, goals and constraints and requirements while progressively detailing the macro into micro.

The right branch of the V cycle rises back from configuration to mission, passing through verification of requirements, constraints and objectives, extending the focus from micro to macro. Verification is aimed at highlighting any possible nonconformance to any of the requirements, objectives and constraints, or mission, the occurrence of which would result in the need for a corrective retrofit to the design, whose process would have to start again.

Therefore, it is the sake of design to be as accurate as possible, so to minimize the possibility of nonconformances, hence of rework. For this, the most appropriate and effective way – whose formalism is due to ENEA – is based on a holistic and predictive approach, which stands on reverting the whole verification problem so as to explicitly convert the objectives, constraints and requirements taken as input, into design parameters returned as output. Basing the configuration on values as close as possible to those obtained by this approach, would permit the design to score at first shot, minimizing (up to potentially zeroing) retrofits, and maximizing the profitability by minimizing the design margins towards the imposed limits.

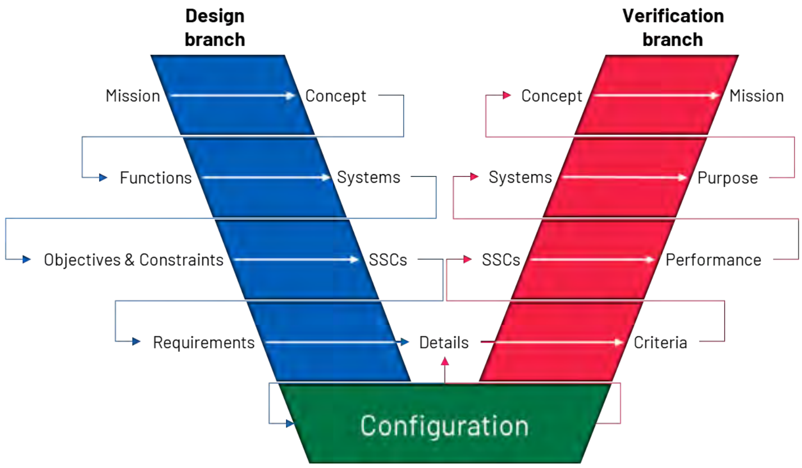

Fig.1: The "V cycle" for reactor design and verification.

Clearly, for this approach to be effective as aimed, two elements are essential: a sound database of experimental evidences, forming a reliable knowledge basis, and a complete portfolio of analytical codes, conceived to be design-oriented and validated upon the same database.

Experiments: the Knowledge Basis

Knowledge is mandatory. Without it, and as in this case, engineers would blindly attempt at designing systems, with the sole chance of stopping the trial-and-fail sequence, by finding a casual combination of things that works, but with no practical hope of making it optimal for the purpose. In science, knowledge stays in data, which comes from experimental results.

Data forms the basis for the quantitative statement of design criteria, which in turn materialize the requirements driving the design. Data also permits the development and calibration of models to reproduce the phenomena of interest, for use in calculation tools. Quality data, then, allows for minimising the uncertainty on phenomena, allowing for reducing margins for safety, hence broadening the design space, and possibly improving reactor performance.

Design-Oriented Codes: the Enabling Tools

The complexity of the problems to be dealt with in designing a reactor core requires the use of analytical tools. While the standard trend of development of such tools is to pursue better and better modelling capabilities, focusing on the micro-scale to capture the most elementary phenomena possible, design imposes rather different needs. The higher zooming capabilities generally imply longer running times, which are hardly compatible with the need for a quick feedback on the viability of an option, as is frequently requested by designers having to move from a blank sheet. Also, the pursuit for the microscopic, and multi-physics scales, generally adds complexity to the codes, hindering their ability to secure the traceability of input to output, i.e., sensitivity considerations, which is a precious information for a designer.

While these kinds of codes perfectly fit the needs for the verification phase of the "V cycle", others should be considered for the first phase, if specifically developed to be design-oriented.

Virtuous Cycle for Continuous Improvement

The PRO laboratory is deeply involved in design activities for liquid-metal-cooled fast reactors, and notably lead-cooled ones, through extensive collaborations at the national and international level. The exercising of its competences permits the continuous challenge of adequateness of the founding bases, and permits also to appreciate – with the variety of cases analyzed – the needs for extending the information already available, so as to enlarge as much as practical (and requested) the application domain of the competences.

A design activity concludes indeed with issuing technical specifications, which provide the reference values (and associated tolerances, in advanced design stages) for the manufacturing of all structures, systems and components of the core. All this information secures that the core systems behave in such a way to comply with the design criteria set as basis for the design itself. Criteria and specifications, thus, stand on the same knowledge data; data, which also form the basis for the validation of all the analytical tools used both in the design and verification phases. Completing and refining such a database is therefore the first and most urgent need for an effective design process, prioritizing the areas and topics to investigate on the basis of the outcomes of the design activities being performed.

Within the PRO laboratory, continuous support is given to the design and/or interpretation of experimental campaigns, providing new data on relevant subjects. This is the case of the newly conceived NETT1 Laboratory [3], the execution of new nuclear data measurements [4,5], or the assimilation of experimental data from NACIE experiments on wire- and grid-spaced rod bundles [6]. However, while some disciplines are relatively easy to investigate, allowing for new experiments to be

arranged with limited use of resources – time, people and money –, other disciplines are more (in some cases, significantly) expensive to investigate. In such cases, the best use of past information is being made, recovering information from the available public databases available (such as the IRPhE, maintained by the OECD/NEA, for reactor physics experiments) or building a new one (such as the FRIDA database for fast reactor fuel performance irradiations) from sparse literature sources, provided the information contained therein is not fragmentary. All this data is used to generate the internal knowledge basis, and (in the short term) to validate the analytical codes in use by the laboratory.
The selection of cases and validation of the codes is based on sensitivity studies, which permit focusing the efforts on the phenomena and parameters of primary importance, so as to get the most benefit for a given effort. The same approach, based on sensitivity studies, also drives the development, or calibration, of design-oriented simulation codes. A complete software package is indeed pursued by the PRO laboratory, to permit the analysis of all phenomena occurring and ruling the behaviour of a liquid-metal-cooled fast reactor core. Following the same successful approach that made available ANTEO+ [7] (an updated version of a proprietary code for fuel assembly thermal-hydraulics), TEMIDE and TIFONE [8] (new codes respectively for fuel performance and whole core thermal-hydraulics), the current efforts involve, mainly, codes for the thermal-hydraulic analysis of a fuel assembly in deformed state (EFIALTE) or for the mechanical analysis of a fuel assembly and of the whole core (respectively, TEIA and FEBE); tools for data management and design optimization purposes (such as the DEMAGAGGER [9], meant at optimizing the core cooling groups); as well as methods extending the capabilities of existing codes to perform the whole spectrum of analyses requested to support and characterize a design (such as the combined deterministic-Monte Carlo method for the neutronic analysis of ADSs [10]).
On top of all this, the laboratory is pursuing the extension of its expertise and competences, aiming at covering all required domains as in its original scope (such as core mechanics and nuclear data evaluation), while consolidating and expanding the areas where an expertise is present and internationally recognized (such as reactor physics and core thermal-hydraulics).

Conclusions

The systematic critical review of the competences and tools that are available vs those that would be needed – as resulting from the extensive core design activities performed – is the key driver in the PRO laboratory for extending and improving its assets. The availability of these new capabilities, in turn, allows providing improved contributions to new projects, offering more chances for the critical review, hence self-growth, in a virtuous cycle towards consolidating a leading position in core design worldwide.

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