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Regulatory requirements to the thermal-hydraulic and thermal-mechanical computer codes

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Abstract

The paper presents an overview of the regulatory requirements to the thermal-hydraulic and thermal-mechanical computer codes, which are used for safety assessment of the fuel design and the fuel utilization. Some requirements to the model development, verification and validation of the codes and analysis of code uncertainties are also define. Questions concerning Quality Assurance during development and implementation of the codes as well as preparation of a detailed verification and validation plan are briefly discussed.

1. Introduction

Commitment by utilities to safe, reliable and economical power production is the basis for nuclear energy progress. All these goals are only achievable if the utility is able to accomplish and maintain a successful operation. At the same time the operation of the nuclear power plants are not absolutely free of risk. This requires some principles, requirements and measures for radiological protection of the personnel, the public and the environment to be formulated and adequately implemented so as the risk from the plant operation can be minimized and the society's needs for useful energy can be met. Logical relations between safety objectives and principles for protection should be established to guarantee that the nuclear power plants can be operated safely and reliably. At the other hand the design provisions should include a multibarrier system to protect humans and the environment in a wide range of abnormal conditions. This system is based on series of physical barriers which provide for the containment of radioactive material at successive locations. The reliability of the physical barriers is enhanced by applying the concept of "defence in depth", protecting each of them by a series of measures. The design should also ensure that the different safety systems protecting the physical barriers are functionally independent under accident conditions. To monitor the safe operation of nuclear power plants it is necessary to have an effective and reliable regulatory control which should be based on established regulatory requirements.

The regulatory requirements for safe operation have been developed over time to reflect a collected operational experience of nuclear power reactors. This development has been gradual, but accidents have sometimes introduced a need of new requirements to be defined to satisfy the approved by the regulatory bodies' safety limits. To give stability to regulatory decisions and to ensure objective and consistent interpretations, the requirements have to fit into some logical frame. The main aspects important for safety should be addressed in this frame and the requirements should provide a definition of a safe design and operational envelope. They should also be practical to give relevant guidance for designers and operators. To support the regulatory licensing process it is essential to have reliable tools for performing safety analyses and evaluations. Such reliable tools might be the computer codes, which can provide a more realistic framework for risk-informed regulations and a basis for estimating the uncertainty in understanding normal, transient and accident behaviour of the fuel and the reactor core.

2. Fuel performance codes functions

The principal function of a fuel performance code is to describe the behaviour of nuclear fuel in the most accurate way for normal and off-normal conditions that are required by the licensing authority. To guarantee the safe operation of the reactor all aspects of fuel performance should be treated simultaneously and in-self-consistent manner. The regulatory requirements can define principles for development and conditions for acceptability of the computer codes. A common issue is to write the requirements to be generic and independent of the code type. This is however seldom possible, because detailed requirements are usually coupled to the fuel performance problem they are governing. In writing requirements it is therefore necessary to have a good understanding of the code development process. Requirements also should be coupled to the concepts of ***verification*** and ***validation*** of the computer codes, which can be used to establish the relation between ensuring that a certain requirement is fulfilled and that the entire code is fit for its purpose.

Fuel performance codes accomplish their principal functions by using of models and numerical techniques to analyze a particular event or class of events. An evaluation model is the calculation framework for evaluating behaviour of the fuel and the reactor system during normal operation, a postulated transient or design basis accident. It may include one or more computer programmes, special models and correlations, and all other information necessary for application of the calculation framework to a specific event.

At the same time the results from code predictions for fuel performance should be closely connected with the safety objectives, the safety criteria and the "defence in depth" principle for radiological protection so as to demonstrate that the fuel is utilized in the safest manner. The results should also give some conclusions concerning the integrity of the physical barriers with the aim to estimate their status and quality to ensure that the margins against failure are retained. The relations between safety objectives, physical barriers, and safety function to be performed for protection of these barriers, and the processes that should be monitored to determine the status of the barriers are shown on the following figure.

1st barrier Fuel matrix 2nd barrier Fuel cladding	Controlling the power	Controlling the power during NO, transients, accidents, shutdown conditions
3rd barrier Primary circuit boundary	Cooling the fuel	Cooling the fuel during NO, transients, LOCA, cold shutdown, refueling
4th barrier Containment	Confining the radioactive materials	Confinement leak-tightness during NO Confining the radioactive materials during LOCA

3. Fuel performance codes classification

According the physical phenomena specificity and reactor systems and components that are modelled, the computer codes are related to the following classes: neutron-physics codes for modelling of neutron-physics characteristics of the reactor core and fuel elements; neutron-kinetics codes for modelling of specific processes into the reactor core with account for the delayed neutrons and the reactivity feedbacks; thermal-hydraulics codes for modelling of thermal-physical characteristics of the reactor core and primary circuit and thermal-mechanical codes for modelling of thermal-mechanical characteristics of the fuel elements.

Concerning origination the computer codes can relate to: development of new codes; adopting and enhancing of already existing codes; and application of approved codes. The regulatory requirements should not be dependent on the code origination.

In accordance with the operational regimes that are modelled, the computer codes can be classified as codes for modelling of: steady-state regimes; slow and fast transients and severe accidents. The majority of the computer codes developed during the last century can model only specific problems, while the modern codes are intended to analyze the complexity of all processes that appears in the fuel, reactor core and reactor systems.

The processes in nuclear fuel are inseparably linked to the processes into reactor core and primary circuit. Therefore calculations and analyses of fuel behaviour usually are performed by two or more computer codes in a complex-consecutive way or in a coupled system. Most often the computer codes are used in consecutive way, which starts with applying of a neutron-physics (NP) code for determining of neutron-physics core characteristics and particularly the power distribution across the core and in the fuel elements, followed by the application of neutron-kinetic (NK), thermal-hydraulic (TH) and thermal-mechanical (TM) codes. Joint calculations and analyses can be performed by combined or coupled computer codes – NP and TH codes, NK and TH codes, TH and TM codes, connected with specific interfaces that ensure proper relations and interactions between intermediate results obtained by a single code in the frame of the system.

In accordance with their defined purposes the calculations and analyses can be classified as best-estimate and conservative. Usually the conservative analyses are used for regulation and licensing purposes. The licensing analyses for nuclear reactors must be conservative to account for the following reasons:

- limited knowledge of the physical phenomena and processes that arise in the fuel and in the reactor core during transient and accident conditions;
- lack of models, which are fully applicable to the phenomena, governed by the code;
- need to cover a great number of similar cases with one analysis – bounding analysis;
- a large number of parameters can affect the results of analysis;
- the quality of the predictions is strongly dependant from the user qualification.

In the past the computer codes had such classification (best estimate or conservative) in relation to their assignment. Nowadays the most modern computer codes are universal and the realistic or the conservative approach can be achieved by compiling and setting up:

- the input data;
- using of proper models and safety margins;
- selection of correct initial and boundary conditions and nodalization details;

- selection of appropriate scenarios for analyzed regimes.

The computer codes for fuel performance should demonstrate their principal capabilities to qualitatively describe most of the governing phenomena in the fuel and in the reactor systems for normal operation modes and for a large variety of accident scenarios.

4. General requirements to the computer codes

To fulfil its functions and to give reliable and accurate results the computer codes should be planned, developed, tested and implemented following some general and specific requirements. The purpose of these requirements is to provide the environment for development of high-quality software which can meet the acceptance criteria for computer code utilization, approved by regulatory authorities.

In that meaning the computer codes should meet the requirements of national and international standards for development, verification, validation and its implementation in analyses for fuel performance during normal operation, transient modes and accident conditions. The quality assurance (QA) programme should be developed and followed by the developer with the aim to check and verify the functional characteristics of the code, such as: accuracy; functionality; reliability; robustness; safety; security; and timing. The software development process characteristics as completeness, consistency, correctness, style, traceability and verifiability should also be include in the QA programme.

The prognosis for fuel behaviour should be made for all operational modes and accident conditions by using realistic or conservative approach for physical process modelling. The conservative approach must be related to the criteria for safe operation with clear definition for safety margins. The degree of the involved conservatism should guarantee the certainty of the predicted results but should not put them out of the credibility margins of the modelled process. The prognosis results should be interlinked to the design bases, safety limits and operational limits and conditions, which are specific for the given reactor type.

The prediction capability of the fuel performance computer codes largely depends on the success in the development of numerical techniques. The computer codes should be based on numerical techniques, solutions and algorithms for managing of the entire code, providing numerical solution stability and convergence of the iterative procedures. The problems with the time step limitations and numerical stability can be avoided if fully implicit integration techniques are used in the computer codes.

Fuel performance computer codes should have clear definition concerning their applicability and bounding frames that are established on the basis of implemented plan for verification and validation. The compatibility is essential feature for performing a complex analysis using a system from different classes of computer codes. Proper procedures for preparation of input data should be developed to ensure the data correctness and their format. They also should include algorithms and procedures for treatment and visualization of the output data. The users should have a proper level of qualification to perform an adequate nodalization which can ensure a correct evaluation of the performance of the fuel and the reactor system.

4.1. Code development process

The code development process is a very complicated process and requires special attention to avoid errors and to minimize the need for corrective actions later. The process should start with establishing of requirements for code capability followed by the developing of a code assessment base, development of the fuel performance code and finally evaluation of the code adequacy (Fig. 2). To determine the requirements for model capability it is essential to identify and rank the phenomena or physical processes that should be modelled and the reactor components and systems that might be affected by these phenomena or processes.

After that an identification of calculation devices, mathematical modelling methods and parameters needed to evaluate the event behaviour should be made in relation to the figure of merits, which are defined in the regulatory framework. The calculation devices include collections of models and correlations that are empirical in nature. Therefore, it is important to determine the exact application envelope and to identify the importance of constituent phenomena, processes and key parameters within that envelope to assure that they are used within the range of their applicability.

An assessment of the evaluation model adequacy should be made regarding its inherent capability to ensure that the model can analyze the particular event appropriately and that the validation process addresses key phenomena for that event. Since an evaluation model can only approximate physical behaviour, it is important to validate the calculation devices using an appropriate assessment base. The data base may consist of already existing experiments or it may require the performance of new experiments, depending on the results of the requirements determination. At the end of the code development process the adequacy should be evaluated again to assure that all predictions are satisfactory and that the code deficiency is evaluated and corrected.

4.2. Quality assurance and quality management

Because of its complexity, the software for prediction of fuel performance should be developed with an adequate quality control. This control should be managed by implementing of a quality assurance programme. It is recommended to gather a quality assurance team in the earlier stages of code development to review requirements to the code and to evaluate the code adequacy in the final stage. This team should be responsible for implementation of an approved quality assurance programme, which should include as a minimum the following part:

- Introduction, which describes the scope and purpose of the QA programme and gives a brief description of the code characteristics;
- QA management – describes the QA organization and structure, tasks to be performed and responsibilities of the persons in the QA team;
- Documentation – type and control concerning the quality management;
- Standards, norms, practice and dimensions – describes the normative basis for code development concerning documentation, structure of the logic, programme languages and compilators, commentary saving, testing and used dimensions;
- Reviews and audits, which include the requirements to the technical and managerial reviews and audits with the aim to verify that the code is developed in accordance with the development plan and all changes and modifications in the models are accurately involved into the code source;
- Detailed plan for verification and validation of the code and the models;
- Problem reporting and corrective actions – describes the requirements for reporting of the problems and corresponding actions and their documentation for further versions of the code;
- Tools, techniques and methodologies that will be used in the reviews and audits;
- Code and supplier control, which includes control under code versions, configuration and code distribution.

4.3. Documentation

To provide comprehensive, accurate and up-to-date documentation is an obvious requirement for fuel performance code development process. Since the code development and assessment process may lead to changes in the importance determination, it is most important to develop and keep the code documentation on the earlier phase. All activities concerning code development, verification and validation and code actualization requires to be documented. The code document package should include:

- Document defining the requirements to the code;
- Methodology documentation, which should describe the internal relations, computational devices (algorithms, programmes, subroutines) and full description of the input and output data;
- Code handbook, which should give the detailed description of the code and its components, and some details for theoretical bases and applied models or correlations;
- Manual for users, which should include the code applicability, code limitations, preferable options for the models and correlations; choosing of scheme for nodalization, tool for input data preparation, tools for output preparation and visualization of results;
- Report for code applicability or scaling with results from verification and validation of the code against the experimental data;
- Code assessment report with respect to the adequacy, accuracy, effectiveness, compatibility with other fuel performance or neutronic codes;
- Manual for collection and arrangement of input data, initial and boundary conditions and plant operational status;
- Uncertainty analysis report, which describes the uncertainties of the code and models and their exact values.

5. Verification and validation plan

5.1. General aspects

The assessment process of the fuel performance computer codes aims to verify their quality by comparing code predictions against experimental data gained mainly by tests performed on experimental facilities. There are three sources of information for maintenance of the code assessment:

- Benchmark calculations;
- Experimental facilities;
- Plant transients.

Verification is a process of evaluation of the code software, which demonstrates fulfilment of the requirements established during the initial and previous phases of its development and guarantee that code performs correctly the calculations defined in the mathematical model and is applied through all life cycle [1]. Usually the verification is applied to the mathematical models and correlations, which describe the specific process or phenomena. Verification can be performed by testing of the software components and modules comparing the numerical results with exact solutions for specific conditions. Verification can also be performed by comparing with data from experiments and irradiations. These experimental data should be well-qualified and should illustrate specific aspects of fuel performance.

Validation is a process of software evaluation at the end of the code development process to ensure compliance with the code requirements [1]. The validation should demonstrate the code adequacy with the specified objectives in accordance with the code requirements and should guarantee that the physical processes and phenomena included in the code are modelled correctly and adequately. The purpose of validation is to demonstrate that the codes may be used for a specific application.

The processes of verification and validation usually cover each other during the code life-cycle because the modelling requires, in an iterative consequence, both – verification of the model during its development and validation of the entire code with the aim to demonstrate the model's characteristics and the code applicability. At the end of the code development process a final validation should be made to demonstrate the ability of the code to predict correctly the physical processes and phenomena, which are the object of the modelling [1, 2].

5.2. Verification and validation (V&V) planning

To perform a successful code verification and validation it is essential to develop a verification and validation plan, which ensures evaluation of the code during all phases of its development, adoption, modification and implementation. The V&V plan should ensure that:

- the observed errors will be eliminated in the earlier phases;
- the risk for cost increasing will be reduced;
- the quality and reliability of the software will be higher;
- the management of the code development will be provided;
- the traceability of changes and modifications will be ensured.

Proper tasks of the V&V planning should be established to:

1. Verify that the software of each fuel performance code development phase:
   - Comply with previous life-cycle phase requirements for correctness, completeness, consistency and accuracy;
   - Satisfy the standards and practices of the phase;
   - Establish the proper basis for initiating the next life-cycle phase activities.
2. Validate that the completed end fuel performance code complies with established code requirements.

The V&V plan should cover all life-cycle phases of the code development including concept, requirements, design, implementation, test, installation and checkout, operation and maintenance. For each phase should be defined the following:

- Verification and validation tasks;
- Methods for verification and validation and acceptance criteria;
- Required inputs and outputs;
- Tasks schedule;
- Anticipated risks and assumptions;
- Roles and responsibilities of the members of the team.

V&V usually performs in parallel with the code development. Each V&V phase finishes when the V&V tasks of that phase are completed and the code development products are determined to be adequate. V&V tasks are iterative: as changes are made to the code product, selected V&V tasks from the previous life-cycle phases are performed, or additional V&V tasks are performed to address the changes. V&V tasks should be re-performed if errors are discovered in the V&V inputs or outputs. The complexity and scope of changes determine the level of detail covered by the iteration. The criteria for performing the iterative tasks should be identified in the scope of the V&V plan.

6. Analysis of uncertainties

Computer model uncertainties can arise from errors in the computer code used to develop the model, input data errors, misapplication of the code (for example through application of the code to problems beyond the range for which the code was developed), and approximations in the solution of the mathematical model (for example due to discretisation of a domain when solving a differential equation through a numerical method such as the finite difference or finite element method).

Uncertainty means the number(s) defining an interval supposed to contain the true value of the calculated quantity [3]. The relation between error and uncertainty is a matter of convention; it is not unique. At the highest level, a rather usual distinction is made between:

1. the random uncertainty: arises from random and locally systematic errors;
2. the systematic uncertainty : arises from strictly systematic errors.

Uncertainties of the fuel performance computer codes can be considered to arise from three inter-linked sources (hypotheses/scenarios that are made, selection/development of the models and preparation of the input data/parameter and initial and boundary conditions). Each of these is discussed and illustrated below.

6.1. Hypothesis/scenarios

It is usual practice to use a hypothesis to simplify the physical processes and phenomena that should be analyzed (to conceptualize the phenomena or processes). The phenomena can be simulated in details or can be partially simulated. This simplification involves uncertainty in the developed models. The feedbacks and relations between the processes and systems also involve additional uncertainty due to their simplifying. When experimental data from test facilities are used their suitability for phenomena modelling should be analyzed to avoid involving of additional uncertainties. Some tests have a limited application (limited suitability) related to phenomena that should be modelled.

6.2. Models

Model uncertainty relates to the uncertainty in the conceptual, mathematical and computer models used to simulate the fuel behaviour and also approximations that are made in the models. All models will encompass some simplification of reality, and there will be choices concerning model types (deterministic or probabilistic), processes to be included, their sophistication, and state variables (block averages or point values). Such simplification results in the model uncertainty. The model should be as complete and as appropriate to the scenario as possible, based on the information and data available and on previous experiences with similar types of problems. The formulation of the conceptual model can lead to uncertainty in a number of ways. The origin of uncertainties can be listed as below:

- Uncertainties due to the choice of the basic models;
- Uncertainties in the experimental data that are used to develop a semi-empirical model;
- Uncertainties due to the geometrical approximation: one-dimensional or three-dimensional;
- Uncertainties due to the numerical methods: spatial and time discretisation;
- Uncertainties due to the closure relationships;
- The phenomena not taken into account in the models.

Regarding the model used, the strict uncertainty method requires to satisfy the four assumptions, i.e. realism, modelling of all relevant phenomena, identified and quantified systematic uncertainties, and verification with acceptable confidence. A workable approach to achieve that purpose should in general include the following steps.

- The model structure is analysed and the model is recursively decomposed into basic elements.
- The ability of the model and model elements to correctly describe the physics inside the model validity domain and at the required accuracy level is verified. Conservatism is acceptable provided that it does not reduce the impact of uncertainties (this property is addressed under the terms of “controlled conservatism”).
- The realistic behaviour of model components and the correct modelling of relevant phenomena are verified by comparison with separate effect tests.
- The global model behaviour is verified to be realistic by comparison with integral tests.
- The representativeness of the performed tests is verified by comparison with the actual reactor situation.
- The coverage of the model validity domain is verified by the performed tests.
- Systematic uncertainties can be identified and quantified through the different verification steps.

6.3. Input data and parameters

Data/parameter uncertainty relates to uncertainty in the data (i.e. directly measurable quantities) and parameters (i.e. quantities derived from material properties handbooks) used as inputs in the modelling process. These can arise from a number of sources: lack of sufficient data; instrument errors (mainly caused by the imprecision and malfunctioning of the available measuring devices); human errors; and the data used to derive a parameter may not be representative of the parameter due to scale and geometric effects.

The following items should be accounted in the code accuracy:

- Uncertainties due to plant specific data as operational history, plan status at the beginning of the event, parameters of the primary circuit and reactor core, power peaking factors, boundary conditions;
- Selection of parameters that will be correlated;
- Uncertainties due to scaling of the experimental data used for verification and validation of the code;
- Errors in preparation of input data – improper formats and dimensions;
- Uncertainties due to human errors as a result of the insufficiency in the qualification level of the users.

6.4. Management of uncertainties

In order to build confidence in an assessment and to assist the decision-making process, it is important that these uncertainties are identified and managed appropriately. According to Savage [4] management of uncertainties have four main components:

- **Awareness** - Uncertainties cannot be managed if they are not known about. A safety assessment should identify all major potential sources of uncertainty.
- **Importance** - Some uncertainties have significant effects on the safety case, whilst many others are unimportant. Before attempting to reduce uncertainties it is first necessary to determine whether the uncertainty has a significant effect on the overall outcome of the safety assessment. This can involve the use of scoping calculations and sensitivity analysis.

- **Reduction -** Having the importance of particular uncertainties, measures can then be undertaken to reduce them.
- **Quantification -** The effect of uncertainties on the final safety assessment needs to be quantified using uncertainty analysis. Some uncertainties are more difficult to quantify than others, but an attempt should be made to quantify the most important uncertainties.

The results of calculations including uncertainties should indicate that the safety criteria are met with a high level of confidence. Several methodologies have been developed to take into account the propagation of uncertainties from the basic parameter uncertainties (physical models, numerical models, fuel data, and facility's data) to the relevant responses of the code. Thus, whatever methodology is used, the basic uncertainties due to code have to be evaluated and managed.

7. Specific requirements to the TH and TM computer codes

7.1. Thermal-hydraulic codes

Depending on the tasks the thermal-hydraulic codes are divided into two groups: TH system codes and TH subchannel codes. System codes are developed to simulate behaviour of the complete reactor system and they are composed of a number of models, which model separate physical processes. Computer codes of that type can model the integral behaviour of the reactor system and feedbacks between physical processes during off-normal and accident conditions. Prediction of nuclear reactor thermal-hydraulic behaviour under off-normal conditions can be made by the:

- analysis of the thermal-hydraulic behaviour in smaller scale facilities and extrapolation to real plants;
- assessment of large computer codes and application of qualified versions to plant situations.

TH subchannel codes are developed to predict the departure from nucleate boiling ratio, coolant flow velocity, pressure, thermal energy fields and fuel rod temperatures for single and two-phases flow in the reactor core. They solve equations for mass, energy and momentum conservation for laterally interconnected array of parallel flow channels assuming incompressible thermal expandable homogenous flow. Channel may represent a true subchannel within rod array or a larger flow area representing several channels or rod bundles.

A prognosis for thermal-hydraulic characteristics of the reactor, heat conduction, reactor kinetics and status of the systems for control and protection of the reactor can be obtained as a result of the codes running. To perform a successful code running the following requirements should be applied to the TH codes:

1. Input data – the input data should include information about: thermal power of the reactor; pressure and water level in the pressurizer; coolant average temperature; fuel average temperature; position of the control rods; boric acid concentration; pressure into the steam generator; hydraulic characteristics of the primary circuit; characteristics of the main feed water pumps and est.
2. Output data – the output data should include the information about: fluctuation of the decay heat across the reactor core at the time of the reactor shut-down; radial and axial distribution of the coolant flow; changes in the coolant flow velocity during the time; status of the coolant phases; pressure in the primary circuit; mechanical condition of the fuel cladding; cladding oxidation; the amount of the zirconium which is react with the water.

3. Verification and validation – for the purpose of code development and code validation there are developed two databases with the phenomenologically well founded sets of experiments for which comparisons of the measured and calculated parameters forms a basis for establishing the accuracy of the predictions. These two code validation matrixes (Integral Effect Tests and Separate Effect Tests) are collected and maintained by the OECD/NEA Data Bank [5]. The first matrix SET contains data from the individual experiments performed on small experimental facilities to study “separable” physical processes similar to those expected in nuclear power plants typical conditions or characterise the behaviour of a single component. The second matrix IET contains data from integral tests performed on relatively large scale test facility, where the overall behaviour of a plant can be simulated during accident conditions. The V&V plan should include all initiating events which can lead to an accident.
4. Capability and applicability – they are defined by the validation matrix for steady-state, transient and accident conditions.
5. Assignment – TH codes are designed to analyze the normal and off-normal operational conditions, to perform licensing analyses to ensure compliance with the regulatory goals, to study the plant modifications and equipment qualification. They also can be used for data collection for probabilistic and statistical safety analyses, for training of the reactor personnel and for preparation of operational instructions.

7.2. Thermal-mechanical codes

The thermal-mechanical codes are designed to model the fuel behaviour taking into account the thermal, mechanical, physical and chemical processes in the fuel elements in dependence on the fuel element design, the material properties of the fuel and cladding, operational parameters, power history, burnup effects, fission products generation, presence of chemical aggressive environment. The following requirements are applicable to these codes:

1. Input data – the input data should include: geometrical dimensions of the fuel and the cladding; gap size; free volume in the fuel element; fuel initial enrichment; open porosity of the fuel pellets; material properties of the fuel and the cladding in dependence on the temperature and the burnup; power history; temperature and temperature gradient of the coolant in the core; neutron flux density in the core; and power peaking factor through the core height.
2. Output data – the output data should include information for: fuel and cladding temperature; fuel burnup; fission gas release; gas pressure under the cladding; cladding elongation; changes in the fuel diameter and gap size; mechanical strains in the fuel and in the cladding, degree of the cladding oxidation, possible pellet-cladding mechanical interaction.
3. Verification and validation – the V&V of the models usually performs by comparison of the predicted results with experimental data from specific experiments for measurements of the fuel temperature, fission gas release, gas pressure under the cladding, cladding elongation, changes in the fuel diameter in the prefabricated fuel elements. Validation of the entire code performs by comparison with data from post-irradiation examinations of irradiated fuel. Similar comparison can be made with data from experimental operation of the fuel, which is equipped with measurement devices replaced in the reactor core. For the purpose of code development and validation the OECD/NEA, the IAEA and the IFE/OECD/Halden Reactor Project are assembled data sets from various sources including PWR, BWR, WWER and PHWR reactor systems (NEA/IAEA International Fuel Performance Experiments Data Base – IFPE) [6]. The aim of this assembling is to provide a comprehensive and well-qualified database on Zr clad UO_2 fuel for model development and code validation for the public domain.

4. Capability and applicability – they are defined from the validation matrix for steady-state, transient and accident conditions.
5. Assignment – the TM codes are designed to give a reliable prognosis for the fuel and the cladding status under steady-state and transient regimes that can be used for utilization of a new or modified fuel, its loading into the reactor core. Such codes can be used for safety assessment of prolonged utilization of the fuel in the reactor core, when the high burnup effects become limiting concerning fuel safety criteria.

Conclusions

The present fuel performance computer codes have sufficient capability to provide a more realistic framework for risk-informed regulations and a basis for estimating the uncertainty in understanding normal, transient and accident behaviour of the fuel and the reactor core. To a large extent these codes synthesize the experience gained over a period of more than thirty years from extensive reactor safety research programmes as were carried out in many countries. Although the enhanced requirements for quality management, verification and validation there still remain shortcomings in these codes. There are often related to limitations of the basic modelling approach or the applied numerical methods and as such cannot always be solved by minor changes to the code. These more basic deficiencies are in many cases partially compensated by simplified highly empirical solutions which are usually tuned to the experimental data from experimental fuel irradiation, separate effects and integral test programmes. These engineering models largely contribute to the uncertainty of the prediction if the code is applied outside the validity of the experimental database from which these models have been derived. The long term perspective of these codes is certainly connected to the future of nuclear energy in general.

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