# ANNEX 5: NUCLEAR INNOVATION 2050
# R&D COOPERATIVE PROJECT PROPOSAL

## Innovative Fuels: Acceleration of Industrial Deployment with an Improved Qualification Process

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## 1. The issue to tackle and objectives to reach

The issues associated with the existing fuel qualification paradigm and the objectives for a new paradigm are discussed in the following subsections.

### 1.1. Issues

Fuels and associated materials are critical components of any fission system's performance and safety. The qualification process for any fuel is a lengthy and expensive process, typically requiring 20 to 25 years from concept to commercial readiness for new designs. Sometimes, even a minor modification to a well-understood fuel system requires a decade or more of testing before the fuel is approved for commercial use. A typical experimental program leading to qualification is illustrated in Figure 1. This figure represents a fairly-success oriented optimistic timeline and assumes multiple variations within the design envelope being tested in parallel in each experimental campaign represented by a single line in the schedule. Higher burnup targets require longer testing. Occasionally a failure to meet requirements in Phase III forces the program back to Phase II. Complicated fabrication processes that are not easily scalable to larger-scale are also a major culprit in causing multiple iterations through Phase II and III. A detailed analysis of why fuel qualification takes this long provides the following additional insight:

- The process is based on an approach underpinned by the "observe and qualify" paradigm. Given that each irradiation test takes 3-4 years to complete depending upon the burnup followed by a 1-2 year post-irradiation examination (PIE), each try takes a long time and each failed test results in a complete repeat sometimes including the previously testing series.
- The safety requirements must integrate more and more off-normal or accidental situations. Testing for all the postulated scenarios requires many experiments at different-scales and using different specialized facilities, adding large cost and schedule burdens to the process.
- There is little reliance on modelling and simulation during the development process. Modelling is typically based on macroscopic observations and used after the experimental program is completed to explain the results, as opposed to a predictive modelling approach to guide and optimize (duration and cost) the experimental program. The code validation is based on C/E (calculation/experimental data) comparisons on only few parameters on few spatial and few temporal points.
- Limited data is collected during the irradiation testing resulting in
    - large uncertainties in determining the conditions during the irradiation,
    - missing time-sensitive phenomenological data for the fuel behaviour,
    - conducting tests for longer durations than necessary without intermediate results, and

- making validation of multi-scale, multi-physics predictive codes very difficult (if not impossible).

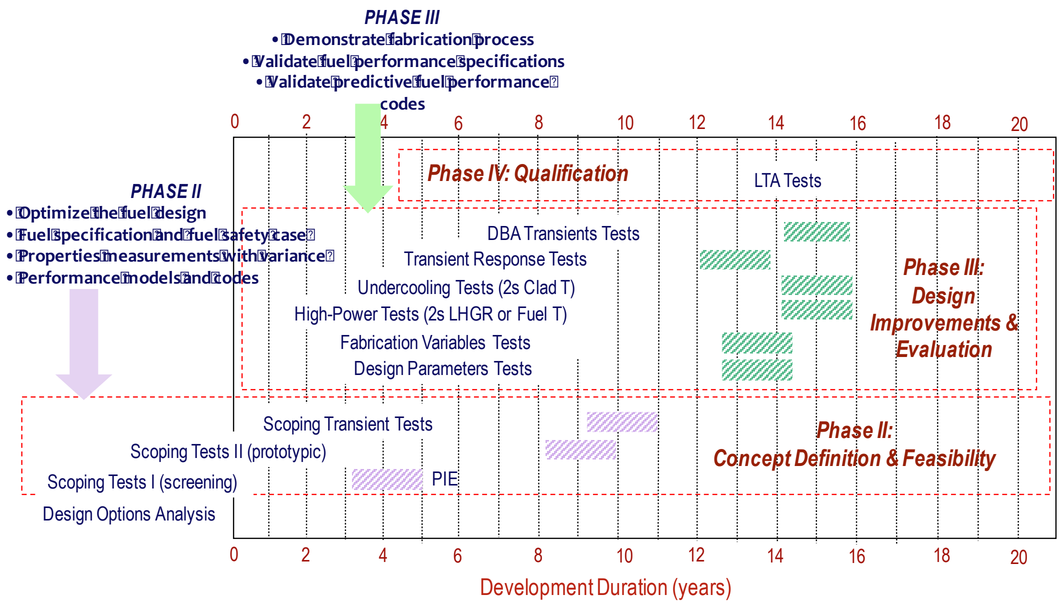


Figure 1 – Representative fuel development timeline

- Limited integral effects data are collected during PIE. The data is primarily used for "Go, No-Go" decisions in comparison with a set of success criteria. A large-quantity of valuable information present in these irradiated samples is typically not collected. The additional information that could be collected at multiple locations of the fuel segments will provide
    - Further insight into the fuel behaviour to explain both the success or the failure,
    - Valuable data for validation of predictive codes (models and models coupling), and
    - Improved chance for success in subsequent tests by understanding the root-causes of failure at a lower-scale.
- There is a strong emphasis on integral experiments. Shorter and simpler phenomenological tests aimed at a fundamental are rarely included in the process. Such tests may accelerate testing for certain behaviour and may use facilities outside the traditional test reactors, including ion-beam facilities and other out-of-pile facilities. The utility of such tests increases considerably when a robust predictive modelling approach is incorporated into the qualification process.
- At the end of the qualification process, the commercialization (licensing) heavily relies on controlling the fuel behaviour by controlling the fabrication processes, as opposed to the relevant properties of the products. This results in a series of lengthy and expensive testing every time the fabrication process is modified to either improve efficiency and to take advantage of new process technologies.

The safety authorities are familiar and comfortable with this traditional empirical approach. Clearly, while it is expensive and very lengthy, the process results in a low-risk commercial product. On the other hand, the process stifles innovation resulting often the commercial sector using the existing technologies at the expense of introducing new technologies that can improve performance as well as safety. This is valid for reactors with fairly well established designs. The situation becomes more severe for reactors with more innovative designs with improved economics, performance and safety. Often these innovative designs require the development of a completely new form of fuel with limited or no historical knowledge base. Mostly because of the cost and duration associated with the fuels and materials development, such innovative concepts seldom move forward beyond the initial paper design and some early small-scale scoping tests. Especially, the time-scale associated with the fuel development is a major impediment to private investment in the area of innovative nuclear technologies.

### 1.2. Objective

To enable timely and cost-effective commercialization of innovative nuclear fuels, a new paradigm is needed. The new paradigm requires a different approach to both the experimental and analytical programs, enabled by the development of a new set of tools. The new set of tools include:

- High reliability predictive modelling and simulation using multi-physics and multi-scale approach coupled with phenomenological validation over a wide range of conditions;
- Experimental capabilities for high-accuracy data collection during carefully designed in-pile and out-of-pile phenomenological experiments; and
- Micro-scale characterization and post-irradiation examination (PIE) over a large range of testing conditions, especially focusing on micro-structural phenomenology.

The new approach is illustrated in Figure 2.

The *objective* of the proposed collaborative work is to develop and demonstrate a new RD&D paradigm that shorten the fuel qualification time to less than 10 years and reduces the cost by 50% compared to the traditional process with an higher reliability, accuracy and predictability.

The challenge is to develop this paradigm that meets this objective for a wide range of fuel and material technologies to enable future innovation. The tools should be available and usable by not only R&D institutions, but also by the industrial sector (reactor vendors, fuel and materials vendors), and technical safety organizations (TSOs). At the end, the success of the new paradigm should be judged based on industrial entities success of commercializing many innovative ideas using the tools made available by the new paradigm. An international harmonization of the methodology brings in additional commercial benefits in terms of supply-chain reliability, extended markets and safety.
The challenge is to get a qualification available whatever the power plant, the fabrication factory and the national drawback : such an international qualification independent of local industries and only dependent to material science and physics should be attractive for industrials as a large – selled product and for SA as a reliable one.

A conceptual fuel qualification schedule is provided in Figure 3.  This is a notional schedule and the exact execution depends on the success achieved in the development of predictive models and the associated experimental programs and the acceptability of the new paradigm by the safety authorities.

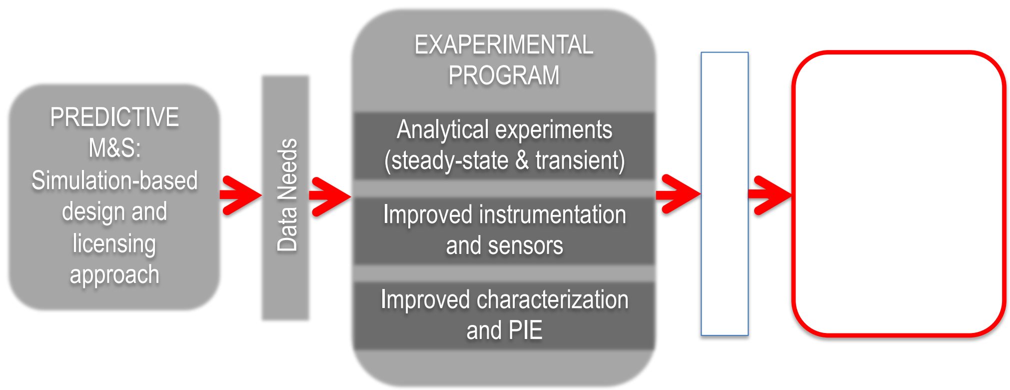


Figure 2: Elements of the new approach for nuclear fuel licensing

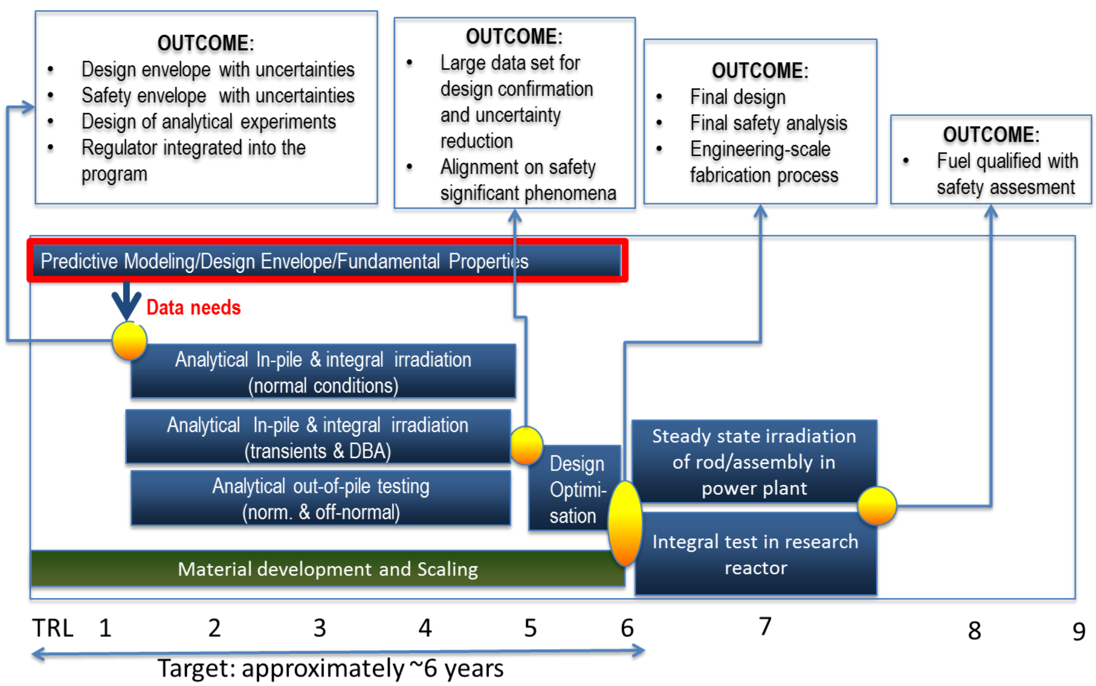


Figure3: Notional execution of the new qualification paradigm

The interest on this new process are identified as follow:

- For the TSO : to participate to the method with the input of their criteria at the starting

- For the stakeholders : If qualification is really based on material and not the process we can expec time and cost reduction. We can also imagine the possibility to enhance the product (process or factory or power plant) without a new qualification requirement.
- For the R&D : to have a complete interaction between their activities (experimental programme, material development and simulation) with the needs.

## 2. What is done/exist already, who is doing what, what are the means

There are multiple innovative fuel development activities in many different countries. Many national R&D institutions and industries are focused on development of the so-called accident tolerant fuels (more specifically fuels with better performance characteristics across the operational envelope under normal and off-normal conditions) for light-water reactors. Next generation fast reactors are being pursued in a number of national programs with a variety of innovative fuel types aimed at breeding and/or transmutation (including targets). Also, variations of high temperature reactor fuels also are part of the number of national RD&D portfolio.

While the national development programs appear to be predominantly following the traditional empirical approach (see the existing generic definitions used for TRL in the development process provided in Appendix A), a number of the tools that enable an accelerated development are being pursued individually in these national programs with varying degrees of priorities. It is expected that, over time, these efforts will result in incremental gains towards improving the effectiveness of the process. Also, the licensing process is different in each country, depending on its own safety authorities. One or several irradiations are performed in order to check the behavior up to limits of nominal conditions and an expertise, mostly based on the past experience, is provided for the transients situations. Fuel performance calculations with validated codes are performed to complete these data and to assess this expertise. So the actual situation is in between a full experimental approach and a calculation based approach.

The licensing process also influences the priorities for these incremental improvements as well.

Through different working parties, expert groups and task forces, we know that

- New test reactors are being brought on line (both steady-state and transient test reactors);
- Multi-scale, multi-physics modeling and simulation are being developed, validated and, to a certain extend, benchmarked against each other;
- Characterization and PIE capabilities are being expended to take advantage of advances in material science for non-radioactive materials and include more lower-length scale data for radioactive materials;
- In-pile sensor R&D programs exist in some programs with a wide range in scope from incremental improvements in known measurement techniques to revolutionary techniques with wireless data collection;

- Opportunities to design analytical experiments to explore a multi-physics and multi-scale irradiation effects on fuels and materials,
- There are scattered efforts in exploring accelerated testing using ion-beam facilities; and
- Interactions with local safety authorities are occurring, especially in the area of an increased role for predictive modeling.

These efforts are mostly driven by the national program priorities and the collaborations appear to be limited to information exchange with limited sharing of resources. This is partly driven by the needs and schedules of specific fuel designs pursued by the national programs. To the extent the private sector is involved in the programs, the nature of the collaboration also is strongly influenced by commercial competitiveness and intellectual property issues.

## 3. What can be done to improve/accelerate through cooperation

It is not likely that a revolutionary change in the process to achieve commercial readiness (as defined by more than 50% reduction in schedule and cost) will result from one of the national individual efforts or the existing collaboration frameworks. This is because:

- None of the programs have easy access to all the capabilities and resources needed to develop the comprehensive set of tools discussed above;
- Developing these tools is resource intensive and competes with the resources needed to meet the program schedules for the qualification of a specific fuel type;
- Especially the amount of separate effects data needed to validate the predictive tools require a diversified set of experimental techniques not easily available within a single program; and
- The additional resources and time needed to develop these tools for the first time are not easily justified if applied only to one or two new fuel designs that a single national program might be interested in.
- Current collaborations (with some notable exceptions such as the Halden project) are primarily limited to information exchange
- When focused on specific fuel types, collaborations are hampered by intellectual property and patent right constraints.

Connecting the existing pieces within the existing national programs under an overall collaboration umbrella while optimizing the individual contributions might enable the revolutionary change to the benefit of all the collaborating nations. This requires dedicated resource sharing and project discipline in the collaboration with clear roles and responsibilities. The overall goal would be to enable commercialization of multiple innovative nuclear energy technologies in response to the ever-increasing energy demand and increased global interest in nuclear energy.

An integrated international project might be possible to achieve the desired step-change in the fuel qualification process. The goal of the project would be to deliver on the items (discussed in Section 1) as necessary for a revolutionary change. Also other items may be identified once the project is established. The definition and successful execution of such a project would require multiple steps. Some suggestions are provided in the next section but these are merely suggestions to initiate the discussion. The actual project definition and execution are likely to evolve once the partners are identified.

- The first step would be to identify the partners interested in a equitable cost-shared project. In order to define an improved methodology, that could accelerate a fuel qualification for an industrial deployment, a working group should be constituted with the following stakeholders:
    - R&D experts on fuel, materials, simulation, instrumentation and sensors, test design
    - Industries/stakeholders (reactor and fuel vendors and power plants' operators)
    - Safety authorities: experts on safety evaluation and responsible of safety requirements and rules
- Once the partners are identified, an executive team from representatives of the partner states and a high-level execution plan with a detailed collaboration framework will be developed. The execution plan can be broken to sub-projects under various task forces, each corresponding to one of the deliverables for the project. The sub-project teams (task forces) would include the expert representatives from the project partners and would be responsible to define:
    - Scope (based on an analysis of drawbacks)
    - Schedule (with a 5-year goal to achieve the final outcome)
    - Necessary expertise
    - Software requirements
    - Access needs to existing data
    - Facility requirements and facility schedules
    - Funding needs including in-kind contributions

A notional organization chart is provided in Figure 4. Figure 4 also provides the expected outcomes of various sub-project teams (task forces). Some salient points associated with the notional organization structure are as follows:

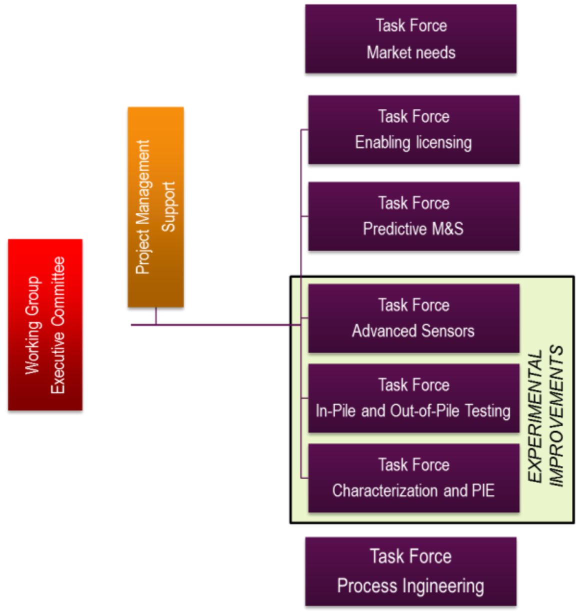


Figure 4 - Notional project organization chart and task forces

- The executive team would be responsible in assuring that the sub-project scopes, schedules and funding are integrated to achieve the overall goal of delivering the tools for revolutionary paradigm shift at the end of 5 years. The executive team defines the challenges for the sub-teams.
- Some sub-teams may require integration across multiple facilities (test reactors, hot-cells, beam lines, etc.) that would be under agreement to deliver based on international project schedule.
- Some sub projects may be in the form of the expert groups engaged in analytical studies (e.g. TRL definitions that needs to include industry and investment community and LRL definition including regulators). The definition of predictive codes, tools validation and validity will be included.
- The intellectual property and patent issues must be addressed at the executive committee level. This may be particularly tricky for in-pile sensors development and demonstration and M&S software.
- Each partner does not need to participate in each sub-project but the overall contributions must be equitable to benefit from the results of each sub-project.
- In defining the scope, we must be careful in not focusing in one specific fuel/clad design (specific composition, geometry, etc.) that may be of interest to only a single partner or may easily encroach into IP and patent issues. The key is to find a number of generalized examples of interest to multiple partners. After all, the goal is NOT to qualify a given fuel design but to deliver a toolbox and a framework that can subsequently be used to accelerate the commercial readiness of multiple innovative designs or substantial improvements on existing designs.
- Actual execution of the tools for specific designs may be the subject of subsequent projects with smaller set of partners and preferably with private sector engagement and funding.

## 4. Action plan and necessary means (resources and infrastructures)

A detailed action plan or an execution plan can only be generated once the project is defined and the partners are identified. However, the following are offered as some initials thoughts as we move forward.

The potential tools that can result in a revolutionary change are

1. Revision to technology readiness level (TRL) and licensing readiness level definitions (LRL) definitions incorporating the role of predictive modelling
    a. TRL and LRL detailed description
    b. Objectives for each level of TRL synchronized to LRL objectives
    c. Define metrics and criteria for each item of each TRL for a quantitative evaluation.

2. Validation of the multi-physics and multi-scale (minimum engineering and meso-scale) codes
    a. Detailed description of tools or code:
        i. Validation
        ii. Applicability
        iii. Predictive capabilities
    b. Identification of critical issues or lack of knowledge for improvement of robustness
        i. identification and definition of safety issues
        ii. experimental checking on specific safety issues
        iii. additional R&D to offset the lack of knowledge in models and input data
        iv. feedback on codes and extrapolation to power reactor conditions
    c. Improved modelling with dependency of initial fuel and clad characteristics (properties) with its irradiation behaviour. The objective is to make the link between initial material characteristics (properties) and irradiation behaviour instead of specifying specific fabrication process parameters. The added advantage is that the licensing is based on materials properties/product specifications decoupling the licensing from the process parameters.
    d. Wide data base with spread feed-back (international contribution needed to take advantages of past experiences in different reactors configurations (e.g. Phénix, EBR2, FFTF, FBTR, BOR60, BN600, JOYO, etc.)
    e. Conclusion / expected results: predictive & physical models + extension of validation data base

3. Design and implementation of experiments guided by the modelling tools : separate-effect irradiation & coupled effects/steady state irradiations & transients tests
    a. To perform in-pile tests :
        i. description of requested conditions,

        ii. type of irradiation device,
        iii. improved irradiation process (simplified safety demonstration),
        iv. multiscale (rodlet to pin and pin to bundle)
        v. multipurpose (from nominal to off-normal) irradiations
        vi. multiphysics (materials & fuel behaviour, thermal-hydraulic, neutronic, etc.)
    b. Advanced in-pile instrumentation to collect in-situ data during testing (especially during irradiation tests)
        i. High-resolution data
        ii. Big-data assessments
    c. Intermediate and final NDE on reactor side (objective to have one irradiation in several steps instead of several irradiations with intermediate PIE with interpretation):
        i. supplemental data
        ii. adjusted irradiation conditions in order to fulfil all the objectives

4. Characterization and PIE equipment that can characterize fresh and irradiated fuels and materials at micro-structural scale for inter-granular and inner-granular phenomena. The objectives are to extend the C/E comparison to larger data with: a complete spatial description, record new physical data, the reduction of measurement uncertainties, automation
    a. High resolution radiography
    b. Fast and automated sample preparation
    c. Fast and automated data collection
    d. Data bases with big-data assessments
    e. Technics coming from other fields than nuclear materials : characterisations of materials (micro-electronics, …) as well as qualification methods (space, medicine, …)
    f. furnace testing

These tools for the most part are applicable to almost all fuel types (at least for the solid fuels and to some extend for liquid fuels with some variations).

## Appendix 1 : TECHNOLOGY READINESS LEVEL

In using TRL as an effective progress-tracking tool, the first step is to define quantitative definitions with specific criteria for different TRLs. The attributes to defining the quantitative definitions specifically for transmutation fuels are discussed in the following section.

Full maturity requires long-term routine operations of commercial fabrication plant(s) supplying fuels to operating reactors. At this point, adequate statistical data are available for fuel performances; and the system is optimized within the constraints of the performance envelope. This level of maturity is assigned a numerical score of 9 for the corresponding TRL.
At the other end of the spectrum, when a new concept is proposed and it is shown that the concept is viable based on first principles assessment, a numerical score of 1 is assigned for the corresponding TRL. The intermediate steps are defined based on the logical progression of the research and development towards demonstration and deployment and the corresponding criteria are shown in Table 1. The criteria in Table 1 determine the completion of the corresponding TRL level.

TRL Completion Criteria:

| TRL | Criteria |
|---|---|
| 9 | Routine operations with licensed fuel established |
| 8 | Reactor full-core conversion to new licensed fuel completed |
| 7 | All qualification steps completed and fuel is licensed |
| 6 | Fuel safety basis established |
| 5 | Process parameters defined |
| 4 | Fuel design parameters and features defined |
| 3 | Success criteria and technical specifications are defined as a range |
| 2 | Technical options evaluated and parametric ranges are defined for design |
| 1 | Initial concept verified against first principles and evaluation criteria defined |

Also, as discussed in Ref. 1, another way of describing the fuel development process will be in 4 phases:

| | |
|---|---|
| Selection Phase: | TRL 1 – 3 |
| Development Phase: | TRL 3 – 5 |
| Optimization Phase: | TRL 5 – 7 |
| Qualification phase: | TRL 7 - 9 |