THE ROLE OF A TECHNOLOGY DEMONSTRATION PROGRAM FOR FUTURE REACTORS

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Abstract

A comprehensive technology demonstration program is seen as an important component of the overall safety case, especially for a novel technology. The objective of such a program is defined as providing objective and auditable evidence that the technology will meet or exceed the relevant requirements. Various aspects of such a program are identified and then discussed in some details in this presentation. We will show how the need for such a program is anchored in fundamental safety principles. Attributes of the program, means of achieving its objective, roles of participants, as well as key steps are all elaborated. It will be argued that to prove a novel technology, the designer will have to combine several activities such as the use of operational experience, prototyping of the technology elements, conduct of experiments and tests under representative conditions, as well as modeling and analysis. Importance of availability of experimental facilities and qualified scientific and technical staff is emphasized. A solid technology demonstration program will facilitate and speed up regulatory evaluations of licensing applications.

1. Introduction

The goal of a technology demonstration program (TDP) is to provide objective and auditable evidence, direct or indirect, that a new technology will meet relevant requirements when deployed in the full scale.

The more novel the technology, the more extensive a TDP would be; nevertheless even for a relatively established technology (such as LWR, for example), each new design must be supported by a systematic effort to “prove” the novel features. This is because, inevitably, new types of hardware as well as software will be used, and operating conditions would be, even if slightly, different. Also, the expectations for safety of new major infrastructure facilities gradually but inexorably change - what was accepted in the past may not be sufficient in the future. The potentially significant safety and environmental risks associated with nuclear installations require high confidence in their safety case. The precautionary principle will instruct the decision-makers to make sure that all practicable steps would be taken to ensure safety. Such steps start with gathering objective evidence in support of claimed safety (and efficiency). In particular when dealing with nuclear power plants, a failure – be it in safety or economics – is not an option that anyone would be willing to entertain.

2. Relationship between Safety Principles and a Technology Demonstration Program

In addition to the already mentioned precautionary principle, there is in place a well established safety philosophy that is valid, by and large, well outside of nuclear applications [1]. Safety principles for current and future nuclear power plants are elaborated, for example in [2 - 5] and unlikely to metamorphose significantly in the next several years. The safety principles vary to some extent among these references but could be summarized along the following lines:

- **Defense in depth**: multiple levels of protection are provided in the design to prevent, with high confidence, occurrence and proliferation of deviations from normal operation.

- **Proven technology**: design relies on the proven technology and engineering practices, with adequate research activities to demonstrate features that are different from the successfully demonstrated technologies.

- **Safety Assessment**: comprehensive evaluation is performed to demonstrate the design capability to withstand challenges to safety without unacceptable consequences to the public and environment.

- **High reliability**: design relies on systems that minimize operator's actions and possesses appropriate redundancy, diversity, independence and inherently safe features.

- **Safety and Security**: design shall provide for an integrated approach to assuring both safety and security.

- **Management of Safety**: plant safety is managed through effective processes and with sufficient technical and financial resources.

Several of the above safety principles, to be compliant with, depend on accumulation of systematic knowledge related to the particular technology and its embodiment in a specific design. First and foremost of the relevant safety principles is the requirement of "Proven Technology". One may say that the ultimate outcome of a technology demonstration program is the "provenness" of a technology. It is thus the role of a TDP to generate, process, and present, the information (or evidence) that will help showing that the safety principles are met. More importantly, however, the TDP allows demonstration of conformance to more detailed, often quantitative, technical requirements in addition to high-level safety principles. The various attributes of a comprehensive TDP are elaborated in the rest of this paper.

We note that, of course, both productivity/efficiency as well as safety aspects will need to be considered in the overall TDP, but, from a regulatory viewpoint, we are only preoccupied with the safety elements.

3. What is a "program" in general and a Technology Demonstration Program in particular?

Technology demonstration will include numerous, sometimes disparate, activities. As the science of management will tell us, a "programmatic" approach will allow increasing efficiency by leveraging the effort and building on common elements. According to Project Management Institute [6] "A program is a group of related projects managed in a coordinated way to obtain benefits and control not available from managing them individually." A program allows maximizing benefits through prioritizing of resources across projects, managing synergies between the projects and controlling of costs and risks of constituent activities. Let us now consider various aspects characterizing a comprehensive technology demonstration program.

3.1 Attributes:

As any program, the TDP should follow the established principles of a management system and meet requirements of the applicable national or international standards, such as or ISO 9004:2009 [7] or CSA N286-05 [8]. In accordance with, for example ISO 9004, a successful TDP is expected to posses the following key attributes:

Strategy and policy:

A TDP is to be built in accordance with the organization's overall management system principles, and support the organization mission and vision.

Resource management:

Resources, internal and external, required to achieve the objectives of a program are identified. Risks to the availability of resources are monitored, and research for optimized processes and new resources takes place. For a TDP, in particular, knowledge, information and technology are essential types of resources.

Process management:

Specific processes are put in place and are optimized for the program objectives and suitable for the available resources. The processes will build on the organization management principles and take into account applicable requirements, identified risks, and interactions with other activities.

Monitoring and review:

The program is regularly monitored, evaluated and adjusted based on its performance. Monitoring metrics are implemented based on the program needs and risks. Review activities, such as self assessments or audits are conducted and trends in program performance are identified and used.

Improvement:

Based on the results of the program review the areas for improvement are identified. New options and capabilities are evaluated based on the program outcomes, as well as are drawn from the best practices outside of a particular program. Knowledge and experience generated in the program is preserved and used for continuous learning and improvement.

3.2 TDP objectives

When an innovative technology is being developed, there would be little or no relevant operating experience and, at the beginning, limited knowledge of some phenomena and processes. Novel design or operational features, improvements that go beyond the established standards or practice need to be brought to the level of 'proven technology' through appropriate evaluation, qualification, testing and/or prototyping. Quoting from NS-R-1 [2]:

> *Where an unproven design or feature is introduced or there is a departure from an established engineering practice, safety shall be demonstrated to be adequate by appropriate supporting research programmes, or by examination of operational experience from other relevant applications. The development shall also be adequately tested before being brought into service and shall be monitored in service, to verify that the expected behaviour is achieved.*

The goal of a TDP is to "prove" a technology or, as was already stated in the introduction:

> *To provide objective and auditable evidence, direct or indirect, that a technology will meet relevant requirements when deployed in the full scale.*

This overall goal needs to be developed further into objectives to allow putting in place "monitoring metrics" and making sure that a TDP is aligned with the safety philosophy and principles. A systematic TDP will:

1. Assemble applicable requirements related to performance, safety, security, and other areas.
2. Identify and evaluate known issues of concern.
3. Evaluate available knowledge pertaining to above areas and issues.
4. Identify gaps where the existing technology does not meet requirements (#1 above) or address concerns (#2.
5. Initiate and manage research and development (R&D) projects, as well as evaluation of available operational experience (OpEx), to develop the novel elements of technology.
6. Test and verify the newly developed technology against identified requirements.
7. Develop and validate tools (analytical models, computer codes) and practices (engineering standards and codes) that formalize the obtained knowledge.
8. Document results.
9. Prepare for an independent review by the potential technology users and regulators.

In developing a TDP it is also necessary to recognize that the proof of a technology will need to consider multiple levels, such as:

- Individual components (equipment pieces, structures, as well as design and analysis techniques, methods and software);
- Systems (which are composed of multiple, often diverse in nature, elements – mechanical, electrical, procedural, software, etc);

- Overall plant; and
- The complete technology cycle (the plant, fuel manufacturing, waste disposal) including the interface with coupled applications (i.e., nuclear powered desalination or hydrogen production).

Hence, for each of the specific activities within a TDP, appropriate objectives and success criteria will need to be established, in addition to the above-stated generic objectives and commensurate with the level of novelty and complexity of each level.

To demonstrate technology to stakeholders, dedicated provisions should be made to document the outcomes, including definition of requirements for the TDP activities, results of tests and analyses, OpEx from relevant facilities, operation of the first of a kind facility, and, finally, of the experience with performance of all subsequent plants. Similarly, critical evaluations of the technology, including those by the regulatory agencies, should be documented. These provisions will capture the objective evidence, as expected by a TDP. Utilization of "proven engineering practices[1]" should be treated as an essential element supporting the principle of "proven technology". When there are no applicable standards due to the substantial novelty of the technology, those engineering practices, methods, approaches, etc that were applied, should be codified as the national or international practices.

3.3 Roles of prototyping, testing and analytical "proof"

A technology, and its components, is demonstrated through a prudent combination of

- evaluation of relevant operational experience,
- reliance on proven engineering practices, codes and standards,
- experiments and tests to study phenomena, acquire knowledge, and develop tools
- integral tests to both qualify the technology elements and validate tools,
- comprehensive design and safety modeling and analysis,
- prototype operation.

Prototyping might seem as the ultimate proof of a technology or its element. This might be the most convincing proof, but it cannot substitute the other activities, because

> Firstly, to build a prototype nuclear reactor, its design must be licensed and be shown to satisfy the same stringent safety requirements as for a "regular" plant. This means that the proof by other means must already be in place.
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> Secondly, the technology cannot be tested in a prototype facility to demonstrate its performance under accident conditions. Initiating an accident in a nuclear reactor to prove safety system performance will not be anyone's idea of an acceptable approach to demonstrate safety.

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[1] NS-R-1 [2] defines a principle of "Proven Engineering Practices" which can be concisely stated as "the design shall be in accordance with the relevant and approved engineering standards and codes".

Thus, the technology proof by necessity occurs before the first, either pilot or full-scale, plant is built. At the same time, prototyping will undoubtedly offer benefits from the operational point of view allowing ironing out wrinkles in design and operation of the process systems.

Another important consideration to be kept in mind when setting a TDP is that both the society's expectations and legal and regulatory requirements develop continuously. Thus, the theoretical understanding of phenomena, robustness of models, coupling of various physical disciplines in computer codes used in design and safety demonstration of advanced reactors are expected to exceed that what was available and accepted for the currently operating facilities. In particular, we expect now that

- challenges to safety functions and physical barriers should be identified and studied with the objective of firmly establishing safety and failure limits for each challenge and each barrier;
- models and correlations should be established over the full range of expected conditions and the associated uncertainties are quantified; normally that would require that high-quality experimental data be available from several independent, different scale experimental set-ups;
- an integral evaluation methodology should be created to allow modeling of the plant and its behavior in transients and accidents. While it is acceptable to use separate qualified codes, they should be able to run together when important feedback effects exist;
- the performance of key systems, structures and components, in particular those important to safety, will need to be demonstrated by tests, most of all in cases where interaction of several components is important.

No matter in what exactly way the technology and its components are proven, this would require time, expertise, investment and availability of experimental facilities, as well as a concerted effort to bring together numerous stakeholders. In particular, the need to develop and conduct R&D activities in support of novel elements of a technology may require a long lead time. It will make sense to take careful stock of the available facilities to get assurances that the experimental base is adequate for technology demonstration or to initiate building of new experimental rigs if required. International cooperation becomes crucially important in this context.

3.4 Stakeholders' roles in a TDP

ISO 9004 [8] indicates that timely and accurate recognition of differing needs of the interested parties (stakeholders) contributes to the success of a program. Those responsible for a TDP should be aware of such needs, and make provisions for accommodating them through a variety of forms, including cooperation, competition, and evaluation of program activities. The table below summarizes what is seen as key stakeholders' roles at various steps of a TDP.

Steps	Key stakeholders		
	Technology proponent	Utilities	Regulator
Assembling applicable requirements	Identify an envelope of constraints (such as legal requirements and performance expectations) related to performance, safety, security, and other areas	Identify performance (as well as other pertinent) requirements	Identify legal requirements as well as provide guidance on aspects where legal requirements are not detailed
Identification of known issues	Assemble and elaborate on the issues of concern, either ongoing or those that have been successfully addressed by competing technologies	Identify safety issues based on the operational experience and other sources	Identify regulatory concerns including areas of lacking knowledge to demonstrate meeting safety requirements
Evaluation of available knowledge	Assemble, systematize and evaluate OpEx, experimental data and analytical results needed to support the technology	Provide operational experience relevant to the technology. Share experimental knowledge where available	Provide input relevant to the interpretation of applicable regulatory requirements and their impact on the expected quality of knowledge
Gap identification	Recognize gaps where the available technology does not meet requirements or address concerns	Provide input as requested by a technology developer	Review and evaluate the (pre)licensing applications against the requirements and identify gaps from the regulatory perspective
Research and Development	Initiate and manage research and development projects, as well as evaluation of available OpEx, to as required to develop novel elements of technology.	Provide expert advise and facilities. Contribute in evaluation of R&D results	On request, assess the adequacy of the R&D effort and outcomes to provide support for technology demonstration
Verifying novel elements	Assess whether the results of R&D address the identified requirements.	Provide input as requested by a technology developer	The regulator will assess TDP outcomes as part of the licensing process
Formalization of information	Develop tools (analytical models, computer codes) and practices (engineering standards and codes)	Provide input as requested by a technology developer	Assess the information submitted in support of the (pre)licensing of the technology applications

	that formalize the obtained knowledge		
Documentation	Document knowledge (results of OpEx and R&D) in a way that allows independent evaluation, for example, by regulatory organizations.	Set utility expectations for design documentation	Set regulatory expectations for documentation in support of the licensing application
Independent review	Respond to critical queries by the reviewing organizations	Undertake review from the user perspective	Undertake regulatory review in accordance with established processes

3.5 The "demonstration" aspect

A technology demonstration program could be called a "technology development program" – however the use of the word "demonstration" brings focus on an important aspect – the technology must be proven to the stakeholders. Its merits and strengths need to be conclusively shown – "demonstrated" – to the decision makers, including those who will consider utilizing the technology and those who will have to approve its application. To this end, the documented outputs of a TDP shall meet certain expectations that could be summarized as completeness, comprehensiveness and appropriateness. Here is what we understand by these documentation attributes:

- Completeness:
  - The objectives and scope of the documents describing TDP outcomes are clearly stated and matched to the objectives of the overall program
  - The requirements and expectations of all applicable laws, regulations, regulatory documents, codes and standards are identified
  - The presented information is self-consistent and of appropriate level of detail.

- Comprehensiveness:
  - All elements, aspects and activities related to a particular objective are presented
  - Demonstration of conformance/compliance with a stated objective is substantiated by rationale, justifications, discussions or evidence contained in the document, to a depth sufficient to allow making regulatory decisions
  - The rationale, justifications, discussions, and evidence given in the documents are structured, organized and auditable.

- Appropriateness:
  - Relevant requirements and expectations of the applicable laws, regulations, regulatory documents, codes and standards, are shown to be met

- Materials, methods, tools or resources used are applicable, current and accepted by the relevant authorities
- Conclusions and recommendations are consistent and commensurate with the objectives and existing commitments.
- The documents are subject to a formal approval process in accordance with applicable quality management standards.

4. Failure is not an option

Failures of technology, even on a single-component level, can be extremely costly. Costs of replacement of components on an already built nuclear power plant that do not function as they were expected by the designer, could run to tens of millions of dollars. If the whole plant cannot perform to meet the design requirements, the price tag would run up to billions of dollars counting the price of the construction of a nuclear power plant but also the cost of the replacement power and the development expenditures. However, the history of nuclear power engineering knows examples of technologies that were built only to be shutdown several years later because of the deficiencies in design:

> Gentilly-1 (Canada): A prototype CANDU reactor with several unique features, including vertically-oriented pressure tubes and light-water coolant. The operation of the plant was plagued by various difficulties, including control issues due to power instabilities. After recording only 180 on-power days in 7 years of operation, the reactor was permanently shutdown.
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> THTR-300 (Germany): A high-temperature gas-cooled reactor with thorium fuel started full power operation in 1987 only to be shutdown two and half years later, due to high operating costs and an incident with a fuel element getting stuck and releasing fission products.

More importantly, unrecognized failure in safety design could have truly catastrophic consequences both in terms of the impact on the public and environment, as well as by eliminating prospects of this technology. One has only to recall the Chernobyl accident to acknowledge that the demonstration (and, of course, maintenance) of safety requires the upmost attention from the designers, operators and regulators alike. A TDP is expected to provide the evidence that such attention was given to the technology from its conception.

5. Conclusion

The safety case must be robust, transparent to the regulator, and convincing to the informed public. Benefits offered by the already demonstrated elements of the technology are required to be supplemented by clear evidence for the adequacy of the new elements.

A systematic TDP should be seen as a systematic instrument to prove the benefits and safety of a novel design of a system, a plant or a complete technology, to their proposed users or the regulator. Insights from the relevant past operational experience, advanced research and safety management will be fully utilized in a TDP.

A TDP will have identified metrics to measure success in achieving stated objectives; this will also help in the subsequent critical independent evaluations by the licensing authorities. It is important to recognize that a solid technology demonstration program will greatly facilitate and speed up regulatory evaluations of licensing applications.

6. References

[1] "Fundamental Safety Principles", IAEA SF-1.
[2] "Safety of Nuclear Power Plants: Design", IAEA NS-R-1.
[3] "Policy Statement on the Regulation of Advanced Reactors", NRC-2008-0237-0010.
[4] "Safety Objectives for New Power Reactors", WENRA, 2009.
[5] "Basis for the Safety Approach for Design & Assessment of Generation IV Nuclear Systems", Revision 1, 2008, NEA GIF/RSWG/2007/002.
[6] The Standard for Program Management, 2nd Ed. Project Management Institute, 2008.
[7] Managing for the sustained success of an organization – A quality management approach. International Standard ISO 9004, 2009.
[8] Management system requirements for nuclear power plants, CSA Standard N286-05, 2005 (reaffirmed 2010).