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Invited Article

Research and Development Methodology for Practical Use of Accident Tolerant Fuel in Light Water Reactors

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A B S T R A C T

Research and development (R&D) methodology for the practical use of accident tolerant fuel (ATF) in commercial light water reactors is discussed in the present review. The identification and quantification of the R&D-metrics and the attribute of candidate ATF-concepts, recognition of the gap between the present R&D status and the targeted practical use, prioritization of the R&D, and technology screening schemes are important for achieving a common understanding on technology screening process among stakeholders in the near term and in developing an efficient R&D track toward practical use. Technology readiness levels and attribute guides are considered to be proper indices for these evaluations. In the midterm, the selected ATF-concepts will be developed toward the technology readiness level-5, at which stage the performance of the prototype fuel rods and the practicality of industrial scale fuel manufacturing will be verified and validated. Regarding the screened-out concepts, which are recognized to have attractive potentials, the fundamental R&D should be continued in the midterm to find ways of addressing showstoppers.

1. Introduction

Since the Fukushima-Daiichi Nuclear Power Plant Accident, the research and development (R&D) for improving the safety of light water reactors (LWRs) has been further activated in many countries. Accident tolerant fuel (ATF) is considered to be one of the most attractive concepts for improving safety. There are many candidate concepts of ATF. For example, in Japan, the R&D of accident tolerant cladding of SiC/SiC-composite or advanced stainless steel, advanced fuel based on coated particle concept, and accident tolerant control rods are mainly ongoing. Although there are no specific R&D projects of advanced or coated zircaloy, Mo-cladding, high density fuel, and improved UO_2-fuel in Japan, the R&D of these concepts are being progressed in other countries. A significant concern is pointed out on the technology screening toward the practical use of ATF in LWRs. That is, the potential targets of the accident tolerance, so-called ATF-attributes, obtained from one of these concepts is rather different from those obtained from the other concepts. Hence, a proper methodology is necessary to make consensus among stakeholders for selecting the practical use candidates, which should be clearly shown in the R&D roadmap after achieving a common understanding.

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Table 1 – General definition of practical use of accident tolerant fuel in light water reactors from viewpoints of fuel design and fuel manufacturing.

TRL		General definition for fuel design/fuel manufacturing
Proof of performance	9	Utilization of new fuel concept in commercial reactors
	8	Quality verification for commercial operation Full loading of new concept fuel in a commercial reactor, based on new approval/regulation & new specification/standard
	7	Establishment of final fuel design by vendors Establishment of fabrication technology for commercial fuel assembly Irradiation of lead use assembly (LUA)
Proof of principle	6	Verification of prototype fuel assembly performance Design & irradiation test of prototype fuel assembly (LTA: lead test assembly), based on new approval/regulation & new specification/standard concept Establishment of regulation criteria for safety analysis Design of fuel fabrication plant
	5	Validation of prototype fuel rod performance Finalization of fuel design & irradiation test of prototype fuel rod (LTR: lead test rod) Validation of process performance of fuel fabrication
	4	Establishment of conceptual design of prototype fuel Establishment of fuel design parameters Irradiation test of prototype fuel rod (without fuel, full or long-scale rod) Verification of component technology for fuel fabrication
Proof of concept	3	Verification of new fuel concept Determination of R&D objectives for industrial scale Sample irradiation tests
	2	Embodiment of new fuel concept Evaluation of upper limit to be achieved by new fuel concept Evaluation of technology options
	1	Proposal of new fuel concept Extraction of R&D subjects

R&D, research and development; TRL, technology readiness level.

In the US, a roadmap of the near- and mid-term R&D for ATF was already reported, in which the irradiation test of the prototype lead test rod (LTR) or lead test assembly (LTA) in a commercial reactor will be targeted in 2022 after the technology screening in 2016 [1]. Also, international collaboration between the United States and other countries like China, France, Japan, Korea, etc., is being actively advanced under the roadmap. In the Organization for Economic Co-operation and Development/Nuclear Energy Agency, an expert group of accident tolerant fuel for LWRs (EGATFL) was established in 2014 [2], and identification and quantification of the ATF-attributes are being performed for achieving international common understanding, which includes the recognition of the gap between the present R&D statuses and the targeting practical use for individual ATF-concepts. Publication of several state-of-art reports is planned by the end of 2016. In Japan, a R&D roadmap for the safety technology of LWRs and human resource development was reported in 2015 [3], in which the importance of the evaluation of the effect to various LWR-technologies was pointed out, as well as that of fuel design and fuel manufacturing, when considering the practical use of the ATF. Not only the R&D methodology for fuel design and fuel manufacturing process including the identification and the quantification of ATF-attributes but that for evaluating the effect to the present LWR-technologies like plant performance, core physics, safety analysis method, approval and regulation, quality assurance, transportation, storage, reprocessing, waste disposal, etc., should be clearly shown in the roadmap. The present article attempts to summarize the methodology, so-called R&D-metrics, based on these discussions.

2. Identification of the gap between the present R&D status of various ATF-concepts and practical use

The first step is the identification and the quantification of the gap between the present R&D status and the practical use of candidate ATF-concepts. National Aeronautics and Space Administration originally established the technology readiness level (TRL) methodology for maturity measurement in the technology development process [4], which is recognized as a proper manner for this purpose in many R&D fields. The guideline of the TRL for various advanced fuel concepts was reported in the United States [5]. The TRL is divided into nine steps of three stages and is used as a reference idea in many countries. Table 1 shows an example of the general definition of the TRL for ATF-utilization in the LWRs. The descriptions in the table are mainly from the viewpoints of fuel design and fuel manufacturing. Although the details of the definition for each step must be further discussed, the important point of the TRL is to achieve consensus among specialists on the definition for achievement of each step toward the final goal. The development starts from the proposal of a new ATF-concept and the extraction of the R&D subjects in TRL-1. The region of the practical use, which the new ATF-concept is potentially able to target, is also identified and proposed at the very beginning mainly by inventors of universities, institutes, or other organizations. The various fundamental R&Ds are activated in the proof of concept stage, especially for databasing of the fuel design and the fuel fabrication process. Then, the fundamental performance of the ATF-concept is verified and the upper limit of the benefit, which is achieved by introducing the ATF-concept, are identified and quantified. The various option technologies are identified and the prioritizations are also discussed in this stage. Regarding the fuel manufacturing, the R&D objects for the industrial scale are determined in the last step of the proof of concept stage, as given in TRL-3 in Table 1. The primary screening of the candidates is generally performed in the last step of the proof of concept stage. A keyword for the screening is to search "showstoppers." This point will be discussed in the following section.

The second stage is for the proof of principle. Regarding the fuel design, the R&D from the conceptual design of prototype fuel cladding to the verification of fuel assembly will be performed in this stage. The conceptual design of the fuel rod will be established from the determination of the design parameters and then it will be verified by the sample irradiation test using the prototype fuel cladding, as shown in TRL-4 in the present table. The prototype fuel concept including pellet-cladding interaction will be validated in TRL-5 with the irradiation test of the LTR in the commercial reactors. Then, the performance of the prototype fuel assembly is verified and validated with the irradiation test of the LTA in the commercial reactors. The irradiation test of LTR or LTA is an ambitious target in 2022 of the United States roadmap for ATF. Regarding the fuel manufacturing, the component technologies for fuel fabrication processing is verified in the early step of the proof of principle stage as shown in TRL-4 in the table, based on the individual process tests. Then, the entire process performance is validated in the TRL-5 level, based on so-called unit tests. In the last step of the proof of the principle stage, the industrial scale plant will be designed. In the proof of performance stage, the commercialization will be progressing step by step mainly by vendors.

Considering the practical use of the new fuel concept like ATF in commercial LWRs, the effect to general LWR-technologies, which is attributed from the introduction of the new fuel concept, should be taken into account besides the fuel design and fuel manufacturing. Table 2 proposes the general definition of the TRL for wider technology regions. The last step of the proof of the concept stage, given as TRL-3 in Table 2, is considered to be an important step on evaluating the effect to the general LWR-technologies. The R&D objects in wider R&D regions are targeted and prioritized after extracting potential showstoppers. Regarding the R&D of reactor physics, plant performance, safety analysis method, approval and regulation, the definition of each TRL-step is basically related to that of the fuel performance and the fuel design. For example, the reactor physics and plant performance must be fully validated before the full loading of the selected ATF in the commercial LWRs. Storage and transportation are mainly related to the fuel manufacturing. In some countries like Japan, the effect to reprocessing must be discussed as well as waste disposal of the ATF.

Major ATF-concepts in Japan are SiC/SiC-composite and advanced steel as of fuel cladding, advanced fuel like tristructural-isotropic, and accident tolerant control rod. The R&D level of these concepts is mostly considered to be in the TRL-2 level. A part of the R&D for the advanced steel and the advanced fuel is considered to be progressing in the TRL-3 level.

3. Identification of ATF-attributes and evaluation of easiness to attain the goal

The second step is the identification and the prioritization of R&D metrics based on the identification and the quantification of the attributes of the candidate ATF-concepts. Important aspects for the technology screening are not only identification and quantification of each ATF-attribute but identification of the trade-off between the benefit obtained from each final goal and the easiness to attain the goal. In the roadmap for the safety technology of LWRs and the human resource development of Japan, the benefit and the easiness were selected as indexes for prioritization of the R&D. To evaluate the easiness, searching showstoppers against the practical use by constructing a so-called "attribute guide" is recognized as a proper procedure among the specialists [2]. The search should be performed at the first steps of the R&D and be performed not only for the fuel design and the fuel manufacturing but also for the wider LWR-technologies.

The final goal of the practical use of each ATF-concept based on the attribute is different from each other. Table 3 shows examples. Coated or advanced Zry concepts are considered to be applicable even in the near term, because the characteristics and the fuel performance are mostly the same as those of the conventional Zry-cladding. The high temperature Zry/steam reaction in the early stage of the accidental conditions is suppressed or delayed by coating the surface of Zry or by introducing other advanced technologies [6]. This potentially contributes to widen the safety margin of the accidental conditions, including design base accident conditions. Although the high easiness for the practical use is pointed out from views of getting approval by taking the present regulation manner into consideration, the effect of the accident tolerance is rather limited. There is no significant showstopper to this concept.

Regarding the advanced steel cladding concept [7], the final goal is to obtain so-called "grace time" especially in the early stage of a severe accident, in which the cladding temperature attains at between approximately 1,473 K and 1,773 K. This temperature range is identified from the facts that the melting temperature of stainless steel is approximately 1,773 K and the Zry/steam reaction in Zry/UO_2 system is highly activated in the temperature region higher than 1,473 K. In the case of conventional Zry-cladding, the Zry/steam reaction abruptly progresses when the temperature attains approximately 1,473 K. Then, it causes the sudden increase in temperature and the extreme release of hydrogen. By introducing the advanced steel cladding instead of the conventional Zry-cladding, the heat and hydrogen generation is able to be largely suppressed and then the fuel melting is delayed in the early stage of a severe accident. Since the melting temperature of the advanced steel is lower than that of Zry, this might largely affect the fuel relocation progress in the latter stage of the severe accident after the fuel melting occurs. These discussions point out that quantification of the grace time with respect to the various severe accident scenarios is extremely important to make clear the attribute of the advanced steel concept. Probably, this concept is able to highly improve the accident tolerance in some scenarios but may not be attractive

Table 2 – General definition of practical use of accident tolerant fuel in light water reactors from views of wider light water reactor-technologies.

R&D phase	TRL	R&D field: Fuel performance fuel design	Fuel manufacturing	Reactor physics plant performance	Safety analysis	Approval regulation	Storage transportation	Reprocessing waste disposal
Proof of performance	9	Commercial operation of LWRs	Commercial operation of fuel manufacturing plant	Commercial operation of LWRs	Commercial operation of LWRs	Commercial operation of LWRs	Storage & transportation of commercial fuel assembly	Reprocessing & waste disposal of spent commercial fuel assembly
	8	Full loading in commercial LWRs	Mass-production of commercial fuel assembly	Validation of reactor physics & plant performance	Establishment of safety analysis for commercial LWRs	Approval of commercial operation	Establishment of storage & transportation of commercial fuel assembly	Establishment of reprocessing & waste disposal of spent fuel
	7	Irradiation test of lead use assembly (LUA)	Fabrication of LUA	Establishment of static & dynamic characteristics of plant	Establishment of safety analysis for DBA/BDBA/SA	Approval of LUA	Validation using fuel assembly	Validation using spent fuel assembly
Proof of principle	6	Irradiation test of lead test assembly (LTA) Validation of fuel performance code Establishment of fuel design	Fabrication of LTA Establishment of process control/monitoring technology Establishment of fuel fabrication process	Establishment of reactor physics & plant operation code	Establishment of criteria on DBA/BDBA/SA for LTA	Approval of LTA irradiation test Establishment of LTA regulation	Storage & transportation of LTA	Establishment of industrial process for reprocessing & waste disposal
	5	Irradiation test of lead test rod (LTR) Out-of-pile tests for prototype fuel	Fabrication of LTR Industrial scale unit test	Analysis of commercial plant characteristics	Establishment of SA analysis method LOCA/RIA simulation test using irradiated specimens	Establishment of guideline of regulation	Establishment of storage & transportation technology of LTA	Establishment of process technology for individual steps of reprocessing and waste disposal
	4	Irradiation test of prototype fuel cladding	Fabrication of full scale fuel rod Establishment of quality assurance technology	Improvement of neutronics/core/hydro-thermic analysis codes	LOCA/RIA simulation test using non-irradiated specimens	Analysis of regulation guideline	Improvement of storage & transportation technology	Improvement of reprocessing & waste disposal technology
Proof of concept	3	Sample irradiation tests Establishment of database Improvement of fuel performance code	Fabrication of samples Targeting of R&D objects for industrial scale fuel manufacturing	Prioritization of R&D subjects Targeting of R&D objects for commercial plant	Prioritization of R&D subjects Targeting of R&D objects for commercial plant safety analysis	Prioritization of R&D subjects Targeting of R&D objects for commercial plant regulation	Prioritization of R&D subjects Targeting of R&D objects for storage & transportation	Prioritization of R&D subjects Targeting of R&D objects for reprocessing & waste disposal
	2	Databasing Extraction of R&D subjectsEvaluation of upper limit of R&D target Research of option technologies	Databasing Extraction of R&D subjects Evaluation of upper limit of R&D target Research of option technologies	Databasing Extraction of R&D subjects	Databasing Extraction of R&D subjects	Databasing Extraction of R&D subjects	Databasing Extraction of R&D subjects	Databasing Extraction of R&D subjects
	1	Proposal of new ATF concept Literature survey Definition of ATF-attributes Evaluation of potential benefit						

ATF, accident tolerant fuel; DBA/BDBA/SA, design basis accident/beyond-design-basis accident/severe accident; LOCA/RIA, loss of coolant accident/reactivity initiated accident; LTA, lead test assembly; LTR, lead test rod; LUA, ; LWR, light water reactors; R&D, research and development.

Table 3 – Final goal targeting based on accident tolerant fuel-attributes.

ATF-concept	Final goal targeting based on attribute of each ATF-concept
Advanced/coated Zry as of fuel cladding	This concept is applicable even in the near/mid-terms due to relative easiness for the practical use in LWRs including approval & regulation point of view, which is attributed from the fact that the fuel characteristics & the fuel performance of the advanced or coated Zry are mostly the same as those of the conventional Zry with the exception of Zry/steam reaction in high temperature. The safety margin in the accidental conditions is able to be widened by suppressing or delaying the Zry/steam reaction based on coating or other advanced technologies.
Advanced steel as of fuel cladding	In the early stage of severe accident, in which cladding temperature attains at ~1,473–1,773 K, "grace time" is obtained from the delay of fuel melting & suppression of hydrogen generation by introducing advanced steel cladding instead of the conventional Zry. Taking the maturity of the conventional stainless-steel cladding previously used in the commercial reactors into consideration, this ATF-concept is potentially able to be introduced in relatively early stages than other advanced ATF-concepts. By widening the safety margin in the accidental conditions, improvement of plant operation efficiency is potentially able to be achieved by introducing this concept. Furthermore, integrity of the fuel assembly for long term storage is potentially improved. The most important concern is identified as the penalty of reactivity for stainless steel base cladding.
SiC/SiC-composite as of fuel cladding	In the severe accident conditions, "grace time" is obtained from the delay of fuel melting & suppression of hydrogen generation by introducing SiC base cladding instead of the conventional Zry cladding. In some severe accident scenarios like station black out, fuel melting is evaluated to be prevented & hence catastrophic accident progression potentially does not happen. This suggests that the quantification of the "grace time" related to various illustrative scenarios is especially important for this concept. However, there are many potential "showstoppers" from views of the practical use in commercial LWRs. The construction of proper R&D scheme & prioritization of the R&D subjects are highly necessary in the early stage of the R&D.
Coated particle fuel	By introducing coated particle fuel, suppression of fission product release & delay of fuel melting are potentially achieved in the severe accident conditions. By combining with SiC base cladding concept, catastrophic accident progression for wider severe accident scenarios is potentially prevented. The most important concern is identified as the penalty arising from lower fissile density than conventional UO_2-fuel.
Other advanced fuels	There are various kinds of advanced fuel concept. High density fuel is targeting to solve various concerns of other ATF-concept & to improve the LWR economy by increasing fissile density. Furthermore, the amount of enthalpy accumulating in the fuel is able to be decreased than conventional UO_2 fuel by introducing nitride, carbide or silicide fuels with the high thermal conductivity, which is potential able to widen the safety margin. Regarding doped fuel concept, by doping Cr, Th, & other candidates into UO_2, the pellet-cladding interaction is able to be suppressed. This potentially contributes to decrease the risk of fuel failure. There are many potential showstoppers. Since ATF-cladding is highly effective than ATF-fuel from viewpoints of improving safety, the main role of the advanced fuel concepts is recognized to improve the LWR economy in the conditions of improving the safety by introducing ATF-cladding.
Accident tolerant control rod	In the severe accident conditions, the earlier melting of control rod than fuel is able to be prevented by introducing various ATF-materials as control rod cladding. Also, neutron absorber materials are able to be homogeneously melted with fuel after fuel melting. By using these phenomena, risk of recriticality in case of debris reflooding is able to be lowered in various stages of the severe accident. The safety margin of normal operation is potentially widened.

ATF, accident tolerant fuel; LWR, light water reactors; R&D, research and development.

in other scenarios. Taking the maturity of the conventional stainless-steel cladding into consideration, which was used as fuel cladding in the commercial reactors mainly in the United States, the advanced steel concept is recognized to be introduced in the relatively early stages, maybe in the midterm. Not only the accident tolerance to the severe accident but the

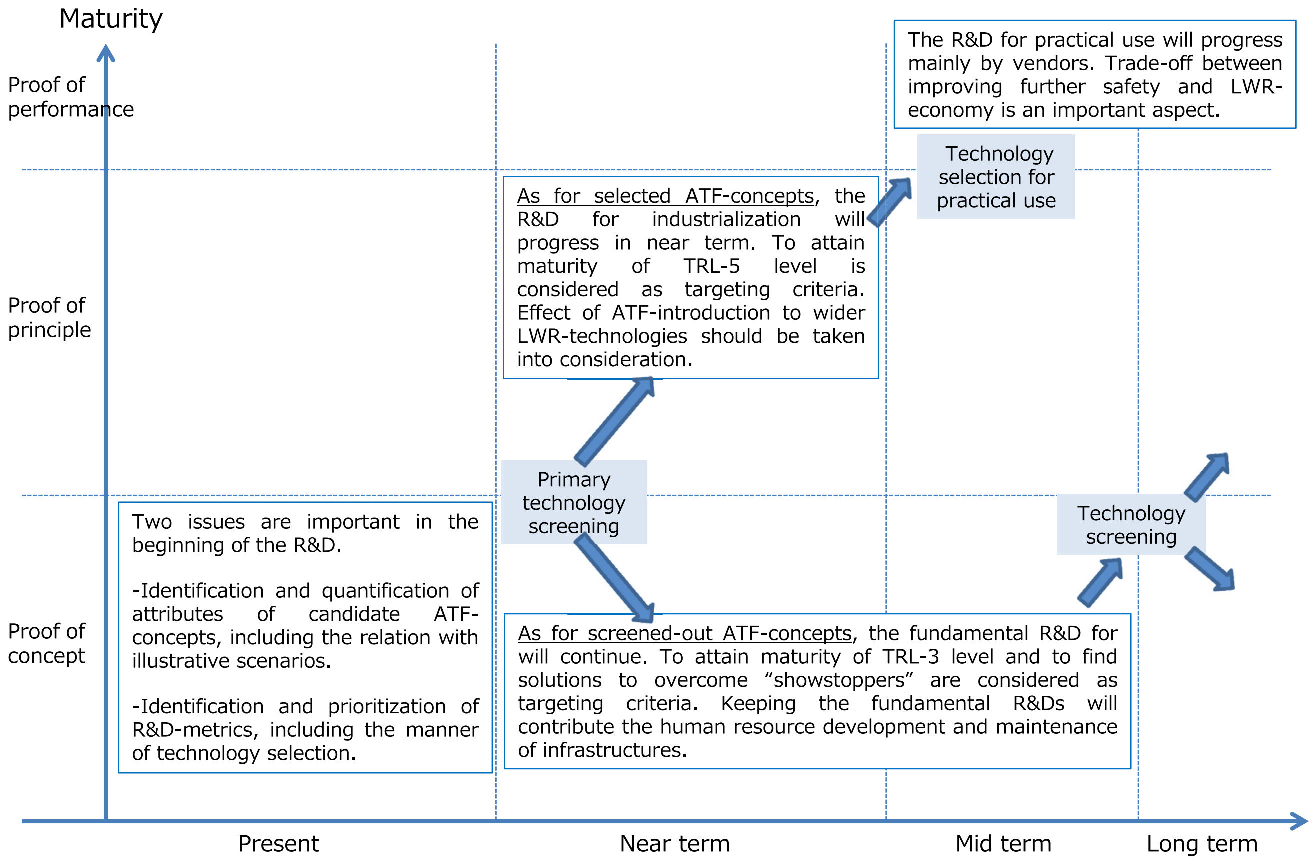

Fig. 1 – Research and development methodology toward practical use of accident tolerant fuel in light water reactors. ATF, accident tolerant fuel; LWR, light water reactors; R&D, research and development; TRL, technology readiness level.

widening of the safety margin in the design base accidental conditions is another attractive benefit of this concept, which improves the plant operation efficiency. Improvement of the integrity of fuel assembly is another benefit from a view of long-term storage. A major concern of the advanced steel concept is, however, the reactivity penalty. Development of the fabrication process of thin cladding and confirmation of the fuel integrity even using thin cladding are major concerns of the advanced steel concept. Also, to make a consensus on the trade-off relation between improving safety and decreasing in LWR economy is highly important for this concept.

The R&D of SiC/SiC-composite is being progressed in many countries because of the attractive potential of accident tolerance arising from the utilization of SiC [8]. In severe accident conditions, "grace time" is obtained from the delay or suppression of fuel melting and hydrogen generation by introducing SiC base cladding. Furthermore, in some severe accident scenarios like station black out, this concept is able to prevent fuel melting following catastrophic accident progression. This suggests that the quantification of the grace time with respect to the various illustrative severe accident scenarios is extremely important to identify the attribute of the SiC/SiC-cladding concept. Many potential showstoppers have already been pointed out from various views of the practical use of SiC-cladding in the commercial LWRs. The construction of a proper R&D scheme and prioritization of the R&D subjects are important from the early stages of the R&D.

There are many advanced fuel concepts. Although these concepts show various kinds of potential attractiveness for improving safety and LWR economy, the maturities are recognized mostly in the TRL-2 level or below. Searching the showstoppers and finding a way to overcome them are recognized to be important for the practical use of these concepts. The attribute of several typical advanced fuel concepts is shown in the table. By introducing a coated particle fuel [9] instead of the conventional UO_2-fuel, significant suppression of fission product release and fuel melting are potentially achieved in severe accident conditions. By combining this advanced fuel concept with SiC base cladding concept, catastrophic accident progression for wider severe accident scenarios is potentially prevented. Since the decrease in fissile density is a significant concern of this concept, the R&D on the combination of the coated particle fuel concept and the high density fuel concept are being progressed. High density fuel [10,11] is targeting to improve various concerns of other ATF-concept, such as reactivity penalty, fissile loading amount, etc. by increasing the fuel density. Furthermore, the amount of enthalpy accumulated in the fuel is able to be decreased than conventional UO_2-fuel by introducing high density nitride, carbide, or silicide fuels with their high thermal conductivities. Regarding doped fuel concepts, by doping Cr, Th, and other candidates into UO_2, the pellet-cladding interaction is suppressed and risk of fuel failure is potential decreased [12].

Accident tolerant control rod is a relatively new concept and the R&D is still in the fundamental stage [13]. In severe accident conditions, the earlier melting of the control rod than the fuel is able to be prevented by introducing various ATF-materials as control rod cladding. Also, neutron absorber materials are able to be homogeneously melted with fuel after fuel melting by introducing rare-earths or hafnium absorbers instead of the conventional Ag–In–Cd or B_4C. By using these functions, the risk of recriticality in case of debris reflooding is able to be lowered in various stages of the severe accident. Also, the safety margin of normal operation is potentially widened.

In the EGATFL, the attribute guide of each ATF-concept is being discussed among specialists, in which potential showstoppers will be extracted. The state-of-art report will be published by the end of 2016. This must show a proper guideline for the ATF-attributes.

4. R&D scheme for practical use of ATF

The third step is to draw a roadmap for the practical use of ATF. Fig. 1 illustrates an outline image of the R&D scheme. The scheme of technology screening and the R&D steps for the selected ATF-concepts should be clearly shown in the roadmap. Also, the policy to the presently screened-out concepts should be given. Proper indices for the technology screening are the TRL and attribute guides, as discussed above. To show the manner of technology selection is beyond the discussion in the present review.

From the technological point of views, proper construction of the R&D scheme for TRL-3–5 levels is considered to be extremely important. A relatively large amount of R&D resources is required in these levels for the irradiation study in research reactors or in commercial reactors, prototype fuel manufacturing, out-of-pile tests using industrial scale fuels, improvement of severe accident codes, etc., although a significant degree of the R&D risk still exists in these levels for the selected candidates. These R&Ds will be efficiently progressed by setting a primary technology screening at the last step of the proof-of-concept stage and by showing proper routes to overcome major potential showstoppers. The R&D on screened-out concepts is not necessary to be terminated. After quantification of the attributes and identification of the showstoppers even for the screened-out concepts, the fundamental R&Ds should continue using a proper amount of the R&D resource to overcome the showstoppers. These fundamental R&Ds are considered to be very useful for human resource development and for maintaining fundamental R&D infrastructures.

5. Summary

R&D methodology toward the practical use of ATF in commercial LWRs is discussed. TRL is a proper tool to show the gap between the present R&D status and the goal of the practical use of each ATF-concept. Identification and quantification of the attribute of each ATF-concept are very important even in the early stages of R&D for proper technology screening and prioritization of the R&D, including the identification on the relationship with illustrative scenarios of severe accidents. Some ATF-concepts are potentially able to contribute to widen the safety margin in accidental conditions. The quantification of this ATF-attribute is necessary.

Conflicts of interest

This methodology is a kind of guideline to built consensus among experts beyond their specializations. The details should be improved in the roadmap of each country.

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