Technology readiness level (TRL) assessment of advanced nuclear fuels

Conference Paper · September 2015

Daniel Shepherd
National Nuclear Laboratory

TECHNOLOGY READINESS LEVEL (TRL) ASSESSMENT OF ADVANCED NUCLEAR FUELS

D.J. SHEPHERD, G.D. ROSSITER, I.D. PALMER, G. MARSH, M. FOUNTAIN
Fuel & Radioisotope Technology, National Nuclear Laboratory
NNL Preston Laboratory, Springfields Works, Salwick, Preston, Lancashire, PR4 0XJ – UK
Correspondence: daniel.shepherd@nnl.co.uk

ABSTRACT

High performance nuclear fuel technology is essential for the safe, reliable, sustainable, secure and economic operation of nuclear stations worldwide. This paper presents a broad ranging technology readiness level (TRL) assessment of potential advanced nuclear fuel concepts relevant for Generation III, III+, IV and small modular reactors (SMRs) including those considered to be potential accident tolerant fuels (ATF).

Assessed fuel concepts include advanced UO_2, advanced MOX, advanced dopants and burnable absorbers, annular and dual-cooled fuel (DCF), carbides and nitrides (U & U,Pu-based), advanced metallic fuels, uranium silicide intermetallics, dispersion and inert matrix fuel (IMF), zirconium hydride matrix fuel, coated particle and microencapsulated fuel, thorium-based fuel, those bearing minor actinides and finally molten salts.

The assessment takes into account the extent of previous nuclear industry experience with these concepts following an extensive literature review combined with conference attendance, relevant facility visits and discussion with key contacts in the international nuclear industry. This paper develops upon a short summary that was published in Nuclear Engineering International in 2014. A similar companion assessment of advanced cladding materials was previously presented at the 2013 OECD NEA SMINS-3 (Structural Materials for Innovative Nuclear Systems) international workshop. This work has been funded by the UK Department of Energy and Climate Change (DECC).

Overall, a sizeable number of advanced fuel concepts are being developed worldwide with some being significantly closer to commercial deployment than others. In particular, in two areas where advanced fuels could potentially provide very significant benefits, ATF for Gen III reactors and fuels for Gen IV reactors, a significant degree of further development is required. In the case of Gen IV fuels, this must take place alongside the development of the reactor system.

1. Introduction

Reliable nuclear fuels are essential for achieving the safe, sustainable and economic operation of nuclear stations. Therefore, this paper presents a worldwide assessment of the technology readiness levels (TRLs) of advanced nuclear fuels. The paper is aimed at highlighting various advanced fuels and their current status with regards to commercialisation in order to allow comparison. This paper develops upon a short summary that was published in Nuclear Engineering International in 2014 [1]. A similar companion assessment of advanced cladding materials was previously presented at the 2013 OECD SMINS-3 (Structural Materials for Innovative Nuclear Systems) international workshop [2]. The work has been funded by the UK Department of Energy and Climate Change (DECC).

The assessment has considered both ‘evolutionary’ fuels (i.e. improvements to existing and past commercial fuels including geometrical improvements) as well as radically different ‘revolutionary’ fuels. The nuclear reactor systems considered to deploy these advanced fuels are current Generation III / III+ light and heavy water reactors (LWRs and HWRs) as well as the more revolutionary Gen IV systems which are aimed at generating nuclear energy in a significantly more sustainable and secure manner [3]. For Gen IV systems, the deployment of the entire reactor designs is dependent on the qualification of advanced fuels in order to fully realise their goals. Small modular reactors (SMRs) are based on either larger Gen III / III+ reactors (i.e. LW SMRs) or on larger Gen IV reactors (e.g. HTR, SFR or LFR). Therefore the fuel concepts for SMRs and their TRLs would be similar to the larger variants. Only TRLs for commercial power applications are assessed and hence marine propulsion, space and research and test reactors (RTRs) are not considered except where RTRs are used as the means to qualify fuels for commercial operation.

2. Method

2.1 Down-selection of advanced fuel concepts

In order to conduct a TRL assessment, it was first necessary to down-select candidate advanced fuels for deployment in Gen III / III+ and IV systems including Gen III / III+ accident tolerant fuel (ATF) concepts. These down-selections were made by applying pre-existing knowledge of the relevant systems. Dispersion, inert matrix, coated particle fuels and molten salts are considered alongside more traditional bulk material fuel forms. These down-selections are summarised below under a series of broader groupings of these fuels by common characteristics, with standard commercial fuels included for comparison.

- Standard fuels
  - UO_2
  - MOX (mixed uranium-plutonium oxide <12% PuO_2)

- New geometries
  - Annular pellets in LWRs (exc. VVER)
  - Dual-cooled fuel (DCF)

- Evolutionary materials
  - Advanced UO_2
  - Advanced MOX
  - Advanced metal

- New compounds
  - Carbide
  - Nitride
  - Uranium silicide

- Including new elements
  - Thorium-based fuels
  - Minor actinide (MA) bearing fuels

- Including other materials
  - Inert matrix fuel (IMF)
  - Dispersion fuel
  - Zirconium-hydride based
  - Coated particle-based

- Liquid-based
  - Molten salt

2.2 Technology Readiness Levels (TRLs)

The TRL system is a means of measuring technology maturity, with a degree of standardisation, which allows for comparison between different technologies. Originally defined by Mankins (1995) of NASA [4], TRLs have become adopted by many industries around the world. As the technology matures from the lower TRLs to the higher TRLs, it moves from a scientific idea through to a fully developed application that has demonstrated its usefulness by being deployed in an operational situation. Figure 1 illustrates where the development of technologies at different TRLs may be conducted in order to advance their TRL in a typical national technology supply chain.

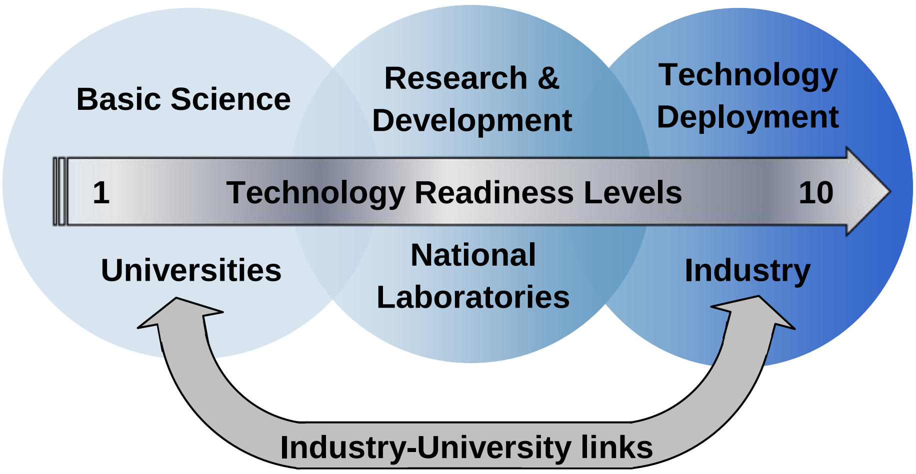

Figure 1. TRLs and a typical national technology supply chain

It should be emphasised that the NASA TRLs were defined for systems for individual space missions (often electronic) and the terminology is not always suitable for nuclear industry applications. Hayes and Porter (2007) of INL (Idaho National Laboratory) [5] reported an adaptation of the TRL system for application to fast reactor fuel.

There is some apparent inconsistency between the NASA and the INL definitions (which both have TRLs 1 to 9). For example, INL TRL 1 seems to correspond more closely with NASA TRL 2, due to INL not including basic principles research at the bottom of the scale. Furthermore at the top of the scale, INL TRL 9 could feasibly correspond to an assumed NASA TRL 10, if their definitions were extrapolated to operation of many actual systems as opposed to single missions. Therefore overall, the INL scale appears to be shifted by one TRL with respect to NASA's.

For the fuel TRL assessments in this paper, a combined approach has been used that includes elements of both the NASA and the INL definitions. Some additional simplification and generalisation was also employed to allow a flexible approach to what is in reality a highly complex situation. Consistency has been maintained with the NASA scale, with TRL 1 still corresponding to basic principles research. In addition, aspects of the more precise INL approach have been incorporated including their guidelines regarding out-of-reactor/in-reactor testing, lead assemblies and core reloads. A TRL 10 has also been defined based on the INL TRL 9 to consider long term operation of many actual systems.

The TRL definitions used for this paper are presented in Table 1 using a 'traffic light' colour coding that is employed throughout.

TRL	Definition and Description
10	**Widespread, reliable and long-term operation of many actual systems** e.g. long-term use of fuel within a commercial reactor fleet / fleets with many thousands of hours of operating experience and data
9	**Successful operation of actual system** e.g. assemblies have performed successfully under irradiation in reload quantities (demonstrated by surveillance programme)
8	**Actual system constructed and commissioned** e.g. assemblies fabricated in reload quantities; may include irradiation with only limited success
7	**Prototype successfully demonstrated** e.g. lead use assemblies have performed successfully in a prototype or commercial reactor (demonstrated by PIE and/or in-core monitoring)
6	**Prototype construction (much more representative than the basic system)** e.g. lead use assemblies have been fabricated, and potentially irradiated in a prototype or commercial reactor but with only limited success
5	**Basic system successfully demonstrated** e.g. test rods have been irradiated and performed successfully in a test reactor (demonstrated by in-reactor instrumentation and/or post-irradiation examination (PIE) and/or post-irradiation mechanical testing)
4	**Integration of components into a basic system** e.g. representative assembly sections have been manufactured and subjected to out-of-reactor tests and/or test reactor irradiation trials of individual rods have been conducted with only limited success
3	**Basic components fabricated and successfully demonstrated** e.g. fuel and/or cladding components have been manufactured and tested out-of-reactor and/or irradiated as a component only
2	**Practical applications suggested and concepts formulated** e.g. fuel, cladding and/or fuel assembly designs have been established
1	**Research identifies the basic principles that underlie the technology** e.g. promising materials and/or geometry have been identified

Table source: This table represents an amalgamation of those presented in [4] and [5].

Table 1: TRL definitions for nuclear fuels and claddings

2.3 Assessing the TRL of the fuel concept down-selections

For each down-selection, a literature search was performed seeking papers in peer-reviewed journals, conference proceedings and reports produced by international nuclear organisations (IAEA, OECD NEA, WNA) as well as the work of national nuclear institutions. Further information was sought where appropriate through attending various conferences and by contact with partners in the international nuclear community. Using this information, it was then possible to use the TRL definitions in Table 1 to assess the TRL of the down-selections.

The ascribed TRLs in Table 2 represent an international best case scenario for each technology with the TRL being representative of its most developed form in the country or countries that have progressed it to the greatest extent. These international TRLs do not necessarily equate to the TRL applicable to individual countries. Table 2 also considered TRLs with respect to the reactor type(s) for which the fuel concept is most developed. A lower TRL may apply to the use of the same fuel concept in a different reactor type. TRLs with respect to reactor type are given in Table 3.

2.4 Limitations of TRL assessments

It should be emphasised that a TRL assessment is at best a crude measure of a complex and ever changing international technological situation. Interpretation and use of the definitions in a TRL assessment is inevitably somewhat subjective and challenging to apply consistently.

TRL assessment gives no indication of the amount of time/effort/cost required to increase a technology's TRL. For example, if two technologies are currently at the same TRL, then there is no guarantee that these will continue to be developed successfully at the same rate. Indeed, a technology currently with a lower TRL may reach deployment sooner than another technology which currently has a higher TRL due to increased R&D effort, fewer feasibility issues, etc. Importantly, there is no guarantee that any technology will ever reach the highest TRL as it may ultimately be found to be unfeasible during further development. TRLs themselves also give no indication of the relative benefits of the different technologies if they were fully deployed, though this weakness can be overcome by plotting TRLs against appropriate measures of benefit.

In spite of these limitations, a TRL assessment remains useful as a guide for further study. It should be noted that TRL values are potentially more useful for comparisons between technologies than they are when considered individually as absolute values.

3. Results

The full details of the TRL assessment of each fuel concept down-selection are given in an NNL report produced for the UK Department of Energy and Climate (DECC) [6]. Details include a full description of each concept and its benefits, a written justification for each ascribed TRL, and the most important literature references (typically 4-8 per technology). A summary of the assessments from the full report is given in this paper using the same 'traffic light' colour coding as Table 1.

Table 2 gives the ascribed international best case TRLs for the down-selected fuel concepts alongside a brief justification and a reference if appropriate. Figure 2 then plots these international best case TRLs in a more visual manner. Finally, Table 3 shows which reactor types the fuels are relevant to and gives TRLs with respect to each. The reactor types considered are Gen III / III+ reactors (LWRs and HWRs) and the six Gen IV systems as listed below [3]:

- SFR, LFR & GFR – sodium, lead & gas-cooled fast reactor respectively
- HTR/VHTR – high and very high temperature reactor
- SCWR – super critical water reactor
- MSR – molten salt reactor

Fuel categories		Best case TRL	Justification and reference
Standard	UO_2	10	Vast majority of fuel that has been used in almost all commercial reactors worldwide for decades [7].
	MOX (<12%PuO_2)	10	Used in many commercial LWRs [7].
New geometries	Annular pellets in LWRs (exc. VVER)	7	Lead assemblies successfully irradiated in Japanese commercial boiling water reactor (BWR) [8]
	Dual Cooled Fuel (DCF)	5	Test rods irradiated in Korean commercial PWR [9]
Evolutionary materials	Advanced UO_2	9	AREVA Cr_2O_3 doped and Westinghouse Cr_2O_3-Al_2O_3 doped fuel are now commercial products [7].
	Advanced MOX	9	High PuO_2 content MOX used in commercial scale SFR in Russia [7].
	Advanced Metal	7	Hundreds of U-Pu-Zr fuel rods irradiated in prototype SFR in USA [10].
New compounds	Carbide	7	Manufacture and irradiation of (U,Pu)C on a prototype scale for SFR especially in India [11].
	Nitride	7	Manufacture and irradiation of UN on a prototype scale for SFR in Russia [12].
	Uranium silicide	4	U_3Si_2 LWR rodlet irradiation programme by Westinghouse-led consortium [13].
New elements	Thorium	8	Significant amount of Th-bearing fuel irradiated in commercial PHWRs in India [14].
	Minor Actinides (MAs)	4	A number of test irradiations of MA fuel have been carried out, targeting SFR application [10].
Including other materials	Inert Matrix Fuels (IMFs)	5	Successful test irradiations of various IMF types targeting Pu and/or MA disposition [10].
	Dispersion	5	Successful irradiation of dispersion fuels based on research reactor designs have been performed [15].
	Zirconium hydride-based	5	Widespread use in TRIGA research reactors with concept development for LWRs [16].
	Coated particle-based	7	Significant manufacturing and irradiation experience for prototype HTRs [17].
Liquid-based	Molten salt	4	Experience of the use of U-based molten salt fuels in test reactors in the USA in the 1950s and 60s [18].

Table 2: International best case TRL assessments for advanced fuels

4. Discussion

Unlike the cladding materials TRL assessment published previously [2], where maximum operating temperature was considered, it was not appropriate to consider different fuel concepts with respect to a figure of merit that can be easily compared in terms of their relative benefit. This was because fuel concepts are required to perform more complex functions than a cladding material, whose primary function is to contain the fuel and fission products. For example, in addition to the release of nuclear energy, fuel concepts may also be required to perform a fuel cycle function. Such functions can include the breeding of fresh fissile material (Pu, or U-233 in the case of a thorium fuel cycle) for use in recycled nuclear fuel and/or the destruction of transuranics (Pu and/or MAs). As a result, considering a figure of merit for fuel concepts such as heavy metal density or melting temperature was not attempted, as it would not take account of the fuel cycle benefits of adopting a given fuel. Therefore the horizontal axis in Figure 2 has no numerical significance other than ease of presentation, with concepts arranged broadly in order of decreasing TRL from left to right with the exception of the ‘new geometries’ concepts (annular pellets in LWRs and DCF).

For a number of the fuel concepts (advanced UO_2, MOX and metals as well as Th-based and coated particle), such a large range of sub-concepts within these broader types have been proposed, that it was not appropriate to conclude a single TRL and instead a range was more appropriate. These ranges have been plotted on Figure 2 with TRLs of some of the individual concepts within the range identified. No further explanation of these concepts is given in this paper due to space constraints.

It is difficult to identify an overall trend from Figure 2. Pre-assessment, it might have been expected that the more revolutionary concepts compared to standard fuels would have a lower TRL. However, whilst this trend is in evidence to an extent, there are significant exceptions in the form of the better developed thorium-based and coated particle concepts. Broadly speaking, the TRL results seem to correspond to the relative amount of international effort that has been put into developing the particular fuel concept. However, this would take a much larger study to confirm.

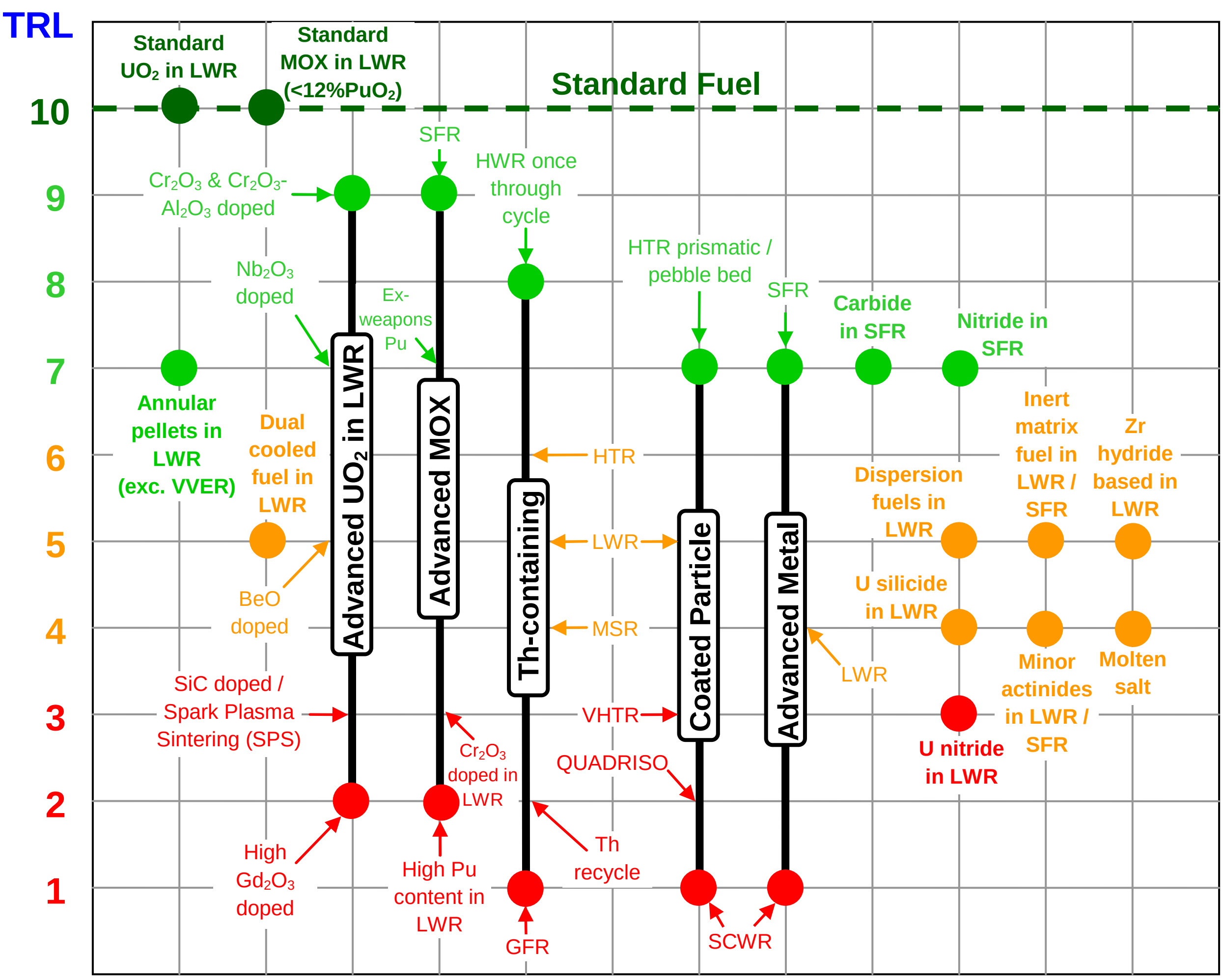

Figure 2. Advanced fuel TRLs

Table 3 shows the complex relationship between fuel TRLs and reactor types. The TRLs for Gen III / III+ L/HWRs show a large range which likely reflects the large amount of R&D effort that has been and continues to be made into developing fuels for these highly successful commercial reactors, with various concepts at different stages in the development pipeline. In general, as might be expected, fuels for Gen IV systems are less well developed, though fuel materials for SFRs and HTRs have quite high technology readiness (TRL 9 and 7 in the best case respectively), as might be expected from the two Gen IV systems nearest to widespread commercial deployment. The fuel concepts for the other Gen IV systems require significant further development if they are ever to be deployed commercially, as these currently score no better than TRL 4.

Ordered by increasing maximum operating temperature	**Generation**	**III / III+**	**IV**					
	Reactor	**L/HWR**	**SFR**	**SCWR**	**LFR**	**MSR**	**GFR**	**HTR / VHTR**
Advanced fuel categories	**Outlet temperature (°C)**	~325 (PWR)	550	510 – 625	480 – 800	700 – 800	850	650 – 1000
Standard	UO_2	**10**		**3**				**7 in coated particles**
	MOX (<12% PuO_2)	**10**		**2**				**4 in coated particles**
New geometries	Annular pellets in LWRs	**7** (10 in VVER)		**1**				
	Dual Cooled Fuel (DCF)	**5**		**1**				
Evolutionary	Advanced UO_2	**9 – 2**		**2**				**2 in coated particles**
	Advanced MOX	**7 – 2**	**9**	**2**	**4**		**3**	**2 in coated particles**
	Advanced Metal	**4**	**7**	**1**	**4**			
New compounds	Carbide	**2**	**7**	**1**	**2**		**3**	**6 as oxycarbide in coated particles**
	Nitride	**3**	**7**	**1**	**4**		**1**	**2 in coated particles**
	Uranium silicide	**4**		**1**				
New elements	Thorium	**8 – 5**	**4**	**2**	**2**	**4 in molten salt**	**1**	**6 in coated particles**
	Minor Actinides (MAs)	**4**	**4**	**2**	**3**	**2 in molten salt**	**2**	**2 in coated particles**
Including other materials	Inert Matrix Fuels (IMFs)	**5**	**5**	**2**	**3**		**2**	**2 in coated particles**
	Dispersion	**5**		**1**				
	Zirconium hydride-based	**5**		**1**				
	Coated particle	**5**		**1**			**2**	**7 – 2**
Liquid-based	Molten salt					**4**		

Table 3: TRLs of advanced fuels vs. reactor systems

5. Conclusions

A number of the fuel concepts were found to have higher TRLs than their associated cladding materials, assessed previously [2], which suggests that cladding material development may be the more limiting factor in terms of the deployment of some advanced fuel concepts and possibly even reactor designs. However, such a conclusion should be treated with caution as potential fuel-clad interaction (FCI) must also be investigated in operating and credible accident conditions.

For Generation III / III+ reactors, a number of proposed accident tolerant fuel (ATF) concepts still have relatively low TRLs and hence represent an urgent development priority if their potential safety benefits are to be realised in the shortest possible timeframe in current and soon to be operating reactors.

Finally, the R&D effort required to deploy higher radioactivity fuel concepts – those containing plutonium, minor actinides and recycled thorium – should not be underestimated. Consideration should be given to the widely reported difficulties that have been experienced in deploying new commercial-scale production facilities for even relatively well developed fuel materials with higher radioactivity such as MOX. Deployment may be even more difficult for non-oxide forms of such highly radioactive fuels as some production methods require inert atmospheres.

6. Acknowledgements

This work has been funded by the UK Department of Energy and Climate Change (DECC) under an 'Initial UK National Nuclear R & D Programme'. The authors would also like to thank the following for their assistance:

- **NNL** – Walter Weaver, Dr. David Goddard, Andy Nickson, Dr. Emma Johnston, Alex Brooke, Dan Mathers, Paul Glenville, Aiden Peakman, Robbie Gregg, Mike Thomas, Kevin Hesketh, Dr. Richard Stainsby, Carol Bullen, Paul Smith and Keith Miller.

- **Others** – Dr. Megan Cooper and Rob Arnold of DECC; Prof. Tim Abram, Joel Turner, Matthew Gill, Dr. Maria-Luisa Gentile of Manchester University; Maxime Zabiego, Marion Le Flem, Christian Poette of CEA; Lars Hallstadius and Ed Lahoda of Westinghouse; Prof. James Marrow and Prof. Steve Roberts of Oxford University.

7. References

[1] D. Shepherd (NNL), "TRLs for fuel and cladding", Nuclear Engineering International, p32-33, January 2014.

[2] D. Shepherd (NNL), "Technology readiness level (TRL) assessment of cladding alloys for advanced nuclear fuels", NEA/NSC/WPFC/DOC(2015)9, p108-116, Structural Materials for Innovative Nuclear Systems (SMINS-3), Idaho Falls, USA, 7-10th October 2013.

[3] US DOE and GIF, "A Technology Roadmap for Generation IV Nuclear Energy Systems", GIF-002-00, 2002.

[4] J.C. Mankins (NASA), "Technology Readiness Levels", NASA White Paper, 6th April 1995.

[5] S.L. Hayes and D.L. Porter (INL), "SFR Fuel Performance and Approach to Qualification", Presentation to DOE/NRC Seminar Series on Sodium Fast Reactors, 27-28th November 2007.

[6] D. Shepherd, G.D. Rossiter, I.D. Palmer, G. Marsh, M. Fountain (NNL), "Technology Readiness Level assessment of advanced fuels, cladding and associated manufacturing technology", NNL (13) 12502, 2013.

[7] IAEA, "Manufacturing technology of uranium and mixed uranium plutonium oxide fuels", Experiences and Trends of Manufacturing Technology of Advanced Nuclear Fuels", IAEA-TECDOC-1686, Chapter 2, 2012.

[8] H. Oguma et. al. (Hitachi, Toshiba and JNC), "Technology developments for Japanese BWR MOX fuel utilization", IAEA-TECDOC-941, p155-170, Technical Committee meeting on Recycling of plutonium and uranium in water reactor fuel, Windermere, UK, 3rd–7th July 1995.

[9] Y.H. Koo et. al. (KAERI), "Status of Dual Cooled Annular Fuel Development in KAERI", Enlarged Halden Programme Group Meeting, March 2013

[10] OECD-NEA, "State-of-the-art Report on Innovative Fuels for Advanced Nuclear Systems", NEA No. 6895, 2014.

[11] IAEA, "Carbides and Nitrides", Status and Trends of Nuclear Fuels Technology for Sodium Cooled Fast Reactors, Nuclear Energy Series, NF-T-4.1, Chapter 4, 2011.

[12] V.M. Poplavsky et. al. (IPPE, VNINNM and RIAR), "Fuels for advanced sodium cooled fast reactors in the Russian Federation: State of the art and prospects", IAEA, Proceedings of Fast Reactors and Related Fuel Cycles (FR09), p261-275, Kyoto, Japan, 7-11th December 2009.

[13] S. Bragg-Sitton (INL/US DOE), "Overview of International Activities in Accident Tolerant Fuel Development for Light Water Reactors", Presentation to IAEA Technical Working Group on Fuel Performance and Technology, 24th April 2014

[14] D. Greneche (Nuclear Consulting) and M. Chhor (AREVA), "Development of the thorium fuel cycle", Nuclear Fuel Cycle Science and Engineering, ISBN 978-0-85709-073-7, Chapter 8, 2012.

[15] IAEA, "Development status of metallic, dispersion and non-oxide advanced and alternative fuels for power and research reactors", IAEA-TECDOC-1374, Chapters 5 and 6, 2003.

[16] K.A. Terrani et. al. (University of California), "Investigation of liquid metal bonded hydride fuels for LWRs: a review", Advanced Fuel Pellet Materials and Fuel Rod Design for Water Cooled Reactors, IAEA-TECDOC-1654, p215-228, 2009.

[17] IAEA, "High Temperature Gas Cooled Reactor Fuels and Materials", IAEA-TECDOC-1645, 2010.

[18] J. Uhlir (UJV Rez), "Chemistry and technology of Molten Salt Reactors – history and perspectives", Journal of Nuclear Materials, Volume 360, Issue 1, p6-11, 2007.