A Comprehensive Approach to Deal with the Nuclear Waste Problem - 11452

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ABSTRACT

It is desirable to devise a solution for the fuel cycle back-end that is acceptable from the society as well as technologically and economically viable. While satisfactory technological solutions exist, they only address portions of the overall problem. A fully integrated effective solution satisfying all public concerns has yet to be developed. In particular, we aim to establish a comprehensive requirements-driven approach. In this approach, requirements are defined for the high-level wastes with the intent not only to satisfy all technical constraints but also to make them “acceptable” to the public perception. Only then, the best mix of nuclear reactors, reprocessing and fuel forms is examined to determine an effective, viable overall system. One intended benefit of the proposed strategy is that there is no a priori bias for or against any specific nuclear system. In fact, a mix of several different systems will likely provide an optimum solution, promoting collaboration between the relevant industry and research entities in the fuel-cycle back-end activities.

INTRODUCTION

When devising a long-term solution for the fuel cycle back-end, it is necessary to consider not only technical requirements and economics, but also the acceptability from the societal viewpoint, including public acceptance. Technological solutions have been sought for and in many case successfully developed to address specific issues and portions of the fuel cycle. However, a fully integrated solution satisfying all public concerns has yet to be developed.

Two major global requirements are: (i) sustainability; and (ii) effective long-term management of spent nuclear fuel / nuclear waste. This paper focuses on the latter, which has also been the main focus of public attention and a *conditio sine qua non* for public acceptance. Traditionally, a search for an effective solution has focused on a specific reactor type and was driven by the fuel cycle front-end and core residence time. In this work we aim to establish a comprehensive approach where the search for a solution is driven from the fuel cycle back-end, with the primary intent of devising a system that generates “acceptable” wastes.

US HISTORICAL PERSPECTIVE

Spent nuclear fuel (SNF) reprocessing has been pursued and performed on a small scale in the US in 1970’s, then halted for almost 30 years for policy but also economic reasons. In the meantime, efforts have focused on managing the high level waste (HLW) from the once-through fuel cycle. This approach converged in the proposed construction of the Yucca Mountain geologic repository. According to the US NRC website [1] "….On June 3, 2008, the U.S. Department of Energy (DOE) submitted a license application to the U.S. Nuclear Regulatory Commission (NRC), seeking authorization to construct a deep geologic repository for disposal of high-level radioactive waste at Yucca Mountain, Nevada".

While experts generally agree that this solution is technically sound, and would safely resolve the issue of all currently existing US commercial nuclear waste, it does raise some questions – it is not truly sustainable with the current once-through fuel cycle. Yucca Mountain repository would have filled up to its statutory limit around 2010-2014. Even though the actual technical limit may be about double and it would keep it open for another 20 years or so, a new such repository would still be required every few decades thereafter. The exact timing depends on the assumed repository capacity and electricity production growth, but an illustrative sequence is shown in Fig. 1. (To generate Fig. 1, it was assumed that the statutory limit for commercial SNF is 63,000 tHM, reached in 2010, actual capacity is 120,000 tHM, and subsequent repositories are also assumed to have 120,000 tHM capacity. Additionally, annual growth of 2% in nuclear energy generation was assumed.) Each time the SNF mass crosses a horizontal line, it indicates the need for another repository. It is difficult to envision adding multiple repositories at the required rate and demonstrating their performance for the next million(s) of years.

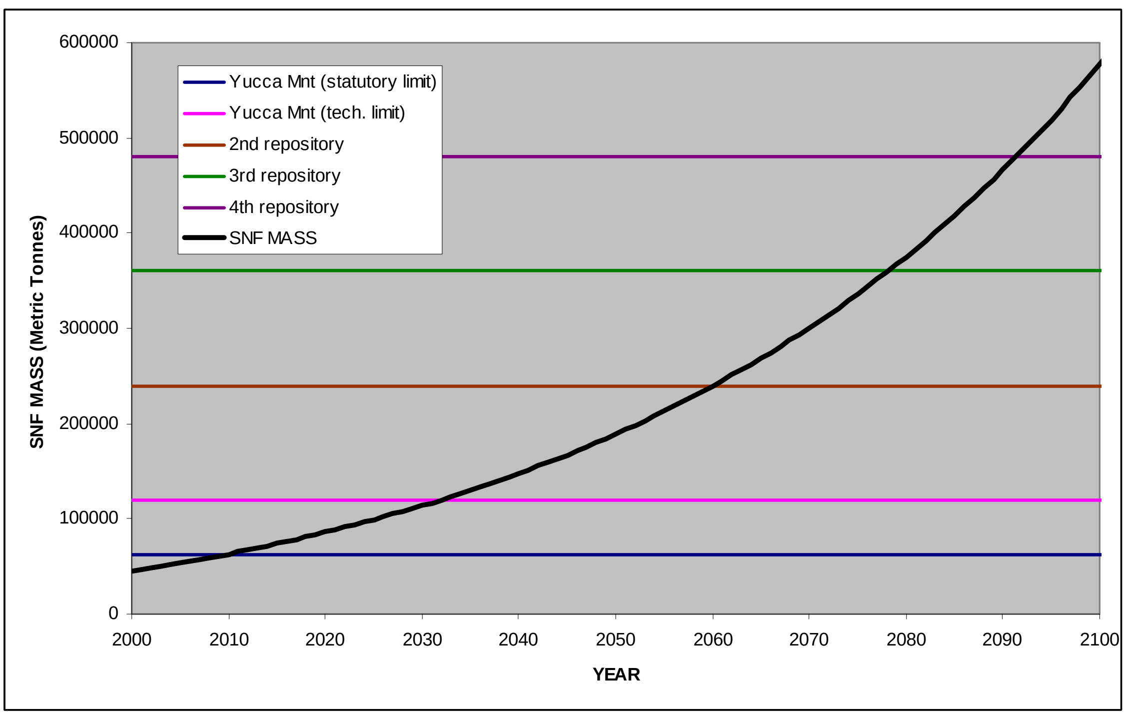

Fig. 1 Illustrative increase in SNF mass in US and the required repositories.

Already in the previous Advanced Fuel Cycle Initiative, fuel reprocessing had been reconsidered in US to reduce the repository load. [2] With the latest US policy change with respect to used nuclear fuel management, DOE has been directed to examine a range of alternative solutions to Yucca Mountain, as demonstrated by the current DOE's Fuel Cycle Research and Development Program (FCR&D Program) and the institution of the Blue Ribbon Commission.[3-5] While instigated by different considerations, the approach proposed in this paper is highly compatible, and also based on understanding and addressing fundamental features and limitations of the nuclear fuel cycle.

OBJECTIVES

To address the discussed concerns, this work proposes to set as the ultimate goal a nuclear fuel cycle that: (i) generates HLW with "acceptable" isolation time requirement and radiotoxicity level, and (ii) "essentially" requires no permanent geological repositories. These top level but vague objectives depends of course on the meaning of "acceptable" and "essential". As the "acceptable" isolation time requirement, Westinghouse proposes to consider 300-500 years. The choice is somewhat arbitrary, but defendable based on the possibility to reliably predict and ensure performance over such a period. The proposed "acceptable" radiotoxicity level is that which (after the isolation period) corresponds to or is lower than the equivalent amount of uranium ore that would have been needed in a typical PWR open cycle to produce the same amount of electricity. This criterion, while not as straightforward as it sounds, does provide a practical mean of comparing wastes without performing a specific risk assessment analysis. While some amount of HLW will be produced under any circumstances in any scenario, the second requirement is intended to indicate that no multiple large repositories would be needed.

METRICS

Radiotoxicity was selected, as noted in the previous section, as perhaps the most practical single parameter. For a more realistic metrics, a compound weighted indicator may be used, accounting among others for the waste volume and mass, radioisotope activity, radiotoxicity, exposure paths and risk, economics, public acceptance, etc. This paper will mainly refer to radiotoxicity, without implying that this is the best factor, and allowing for future refinement of criteria to account for multiple indicators.

APPROACH

It may be observed that traditionally a search for an effective fuel cycle solution would more likely than not proceed by selecting a specific reactor type, then the fuel form, and finally searching for an optimum waste management solution within these bounding conditions. In this work we propose a comprehensive waste-management requirements-driven approach. In this approach, the search for a solution is driven from the opposite direction, i.e. from the fuel cycle back-end, starting with the waste management requirements, as indicated in Fig. 2.

In this approach, the requirements (technological as well as stemming from the public acceptance) imposed on the ultimate spent fuel or HLW stream are considered first, followed by the fuel form screening. Only then, the best mix of available nuclear systems and reprocessing satisfying these requirements is developed. There is no a priori bias for or against a given system (critical reactors, subcritical ADS, hybrid fusion-fission), fuel cycle (open, modified open, or closed), fuel type or form (U-Pu or Th-U, metal or oxide, Tristructural-isotropic – TRISO fuel particles), coolant (water, liquid metal, molten salt) and so on. The choice should be dictated by how well it satisfies the requirements. Naturally, limitations due to neutronics, safety, fuel performance, radiochemistry, economics and others have to be addressed and satisfied at appropriate time.

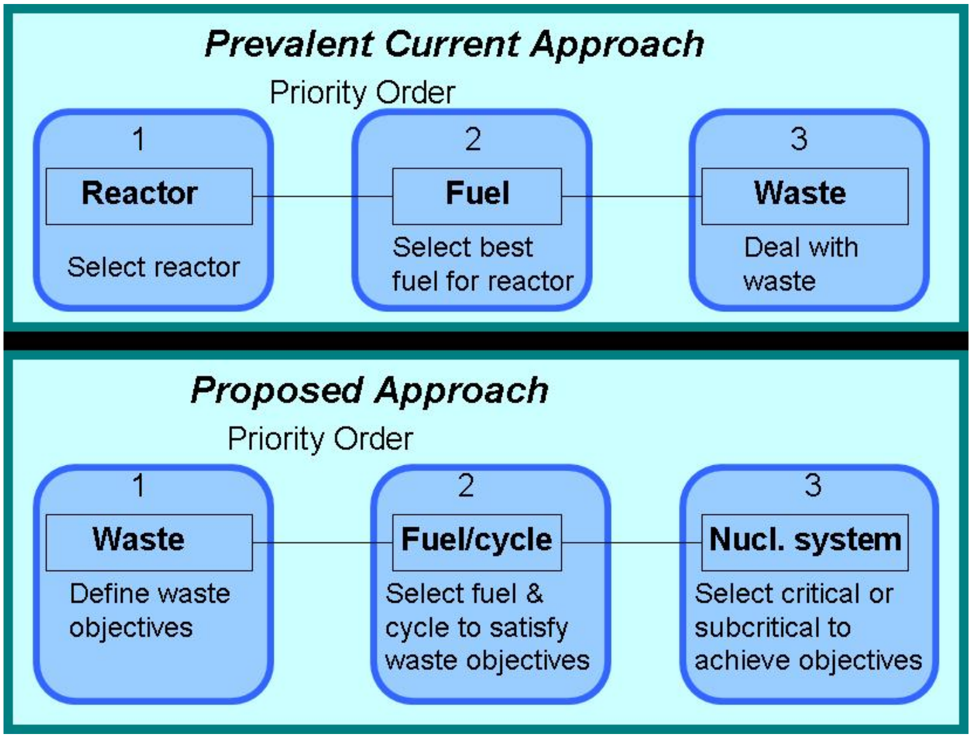

Fig. 2 Proposed approach, driven by the waste management requirements.

One intended benefit is that a mix of several different systems will likely provide an optimum solution, promoting collaboration between the relevant industry and research entities in the fuel-cycle back-end activities. The intent is also to avoid pre-conceived limitations and elimination, and keep all options open as long as meaningful.

Key attributes of the proposed approach are:

- Public acceptance: Addresses concerns on permanent disposal.
- Goal-oriented: Reduction of the waste to ore level radiotoxicity in several hundred years.
- Science-based: Physics, engineering and economics dictates technology choices.
- Solution driven: Each identified technology will be utilized in the most efficient way to support reaching the ultimate goal.
- Unbiased: All present fuel cycle technology (critical reactors, accelerator-driven systems, separation, fabrication) will be utilized as part of the analysis variables to support the evaluation of potentially effective and visible alternatives.
- Forward-looking: New technologies will be developed and introduced as necessary.

PATH TO EVALUATION AND IMPLEMENTATION

The envisioned path to evaluation and implementation includes the list of stages and components:

(1) Develop capability for extended scenario studies, including assessment of sustainability, radiotoxicity, and proliferation resistance characteristics.

(2) Develop models of various reactor and reprocessing options.

(3) Develop isotopic mass balance flow-sheets for various cases.

(4) Determine reactor and reprocessing specifications required to meet the 300-year waste requirement for each case, including the isotopic composition of fuel at reactor discharge, as well as isotopic composition of streams after reprocessing.

(5) Identify technical, proliferation and cost issues for each case.

(6) Generate specifications for nuclear systems development programs, including requirements on the fuel and system performance for the isotopes targeted for incineration.

(7) Generate specifications for reprocessing in terms of elemental recovery ratios that meet the individual process stream specifications.

BASIC CONSIDERATIONS

The well-known relative radiotoxicity profiles for U-Pu cycle are shown in Fig. 3. The once-through cycle takes between one hundred thousand and a million years, significantly longer than a few hundred years, to recede to the uranium ore level. Single plutonium recycle in MOX has only a very limited impact on radiotoxicity reduction. Complete recycle of plutonium has a significant effect, reducing the radiotoxicity by about one order of magnitude, but is still insufficient for reaching the objectives.

The fission products decay below the uranium ore in about 300 years, which makes the 300-500 years objective for the overall radiotoxicity reduction practically coincident with being able to fully recycle all actinides until their final destruction from the recycled fuel. This strategy, besides reducing the volume and radiotoxicity of the waste, has the added advantage of a significant improvement of fuel utilization. A number of conditions would need to be met, however, including:

- Acceptable reprocessing recovery and losses fractions (key requirement)
- Availability of adequate fast spectrum systems (critical, subcritical)
- Feasibility of deep burn of radiotoxic actinides
- Fuel manufacturability and satisfactory performance

- Reliable and safe operation of all systems and facilities

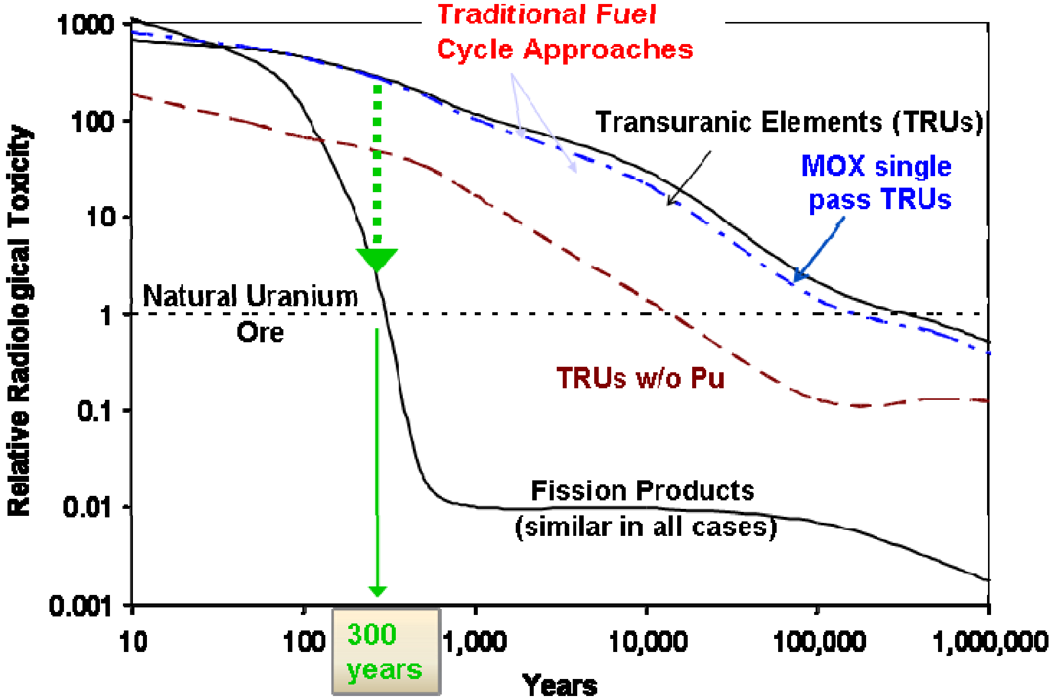

Fig. 3 Relative radiotoxicity for major fuel cycle and reprocessing alternatives.

It seems likely that a combination of fast spectrum burners will be required, in combination with accelerator-driven systems or hybrid fusion-fission systems to complete incineration. Two inherent challenges are present. Such multi-tier systems will lead to more complex design of reactors and subcritical and to more demanding requirements on their operation, safety parameters, and target design/performance. At the same time, the overall system would need to address both the "legacy" fuel (that will keep being produced for decades) as well as the "new" fuel(s).

Alternatively, Th-233U cycle, at least at the face value, offers potential to significantly reduce radiotoxicity and satisfy the waste management goals, due to significantly reduced generation of higher actinides. [6]

Finally, "revolutionary" systems and approaches will not be excluded, as long as they offer potential to contribute toward reaching the waste management objectives.

REPROCESSING

Following the general approach philosophy, various reprocessing options will be examined, including PUREX, variants of UREX+, AIROX, melt-refining, Pyroprocessing, Fluorex, Thorex, etc. (see [7] for references and discussion on various reprocessing alternatives) The main discriminating factors leading the selection will be the radiotoxicity of the waste streams, proliferation resistance and economic effectiveness. It is possible that a tandem-combination will be needed in order to meet the recovery fractions enabling the 300-year objective. The current state-of-the-art reprocessing technology could conceivably just meet these objectives for first recycle of LWR SNF. The increasing level of difficulty of recycled fuel, due to the higher Minor Actinide (MA) content, activity and decay heat, will make it unlikely to meet these objectives with the available reprocessing technology.

THORIUM CYCLE CONSIDERATIONS

Various specific features, advantages and disadvantages of thorium-bearing fuel and the Th-^{233}U fuel cycle are discussed elsewhere. Here we briefly remind the reader of the thorium fuel advantage form the waste management standpoint. The interaction/transmutation chain including both ^{232}Th and ^{238}U, as well as transuranics, is shown in Fig. 4. Due to its "lower" position, ^{232}Th requires multiple neutron captures to "progress" to TRU, which would under ideal conditions reduce the concentration of TRU (Pu+MA) by several orders of magnitude. There are however specific issues related to using thorium fuel. These include generation of radiotoxic isotopes from transmutation of Th and U that will require heavily shielded remote reprocessing and low losses in the waste streams (see for instance discussion in [10]).

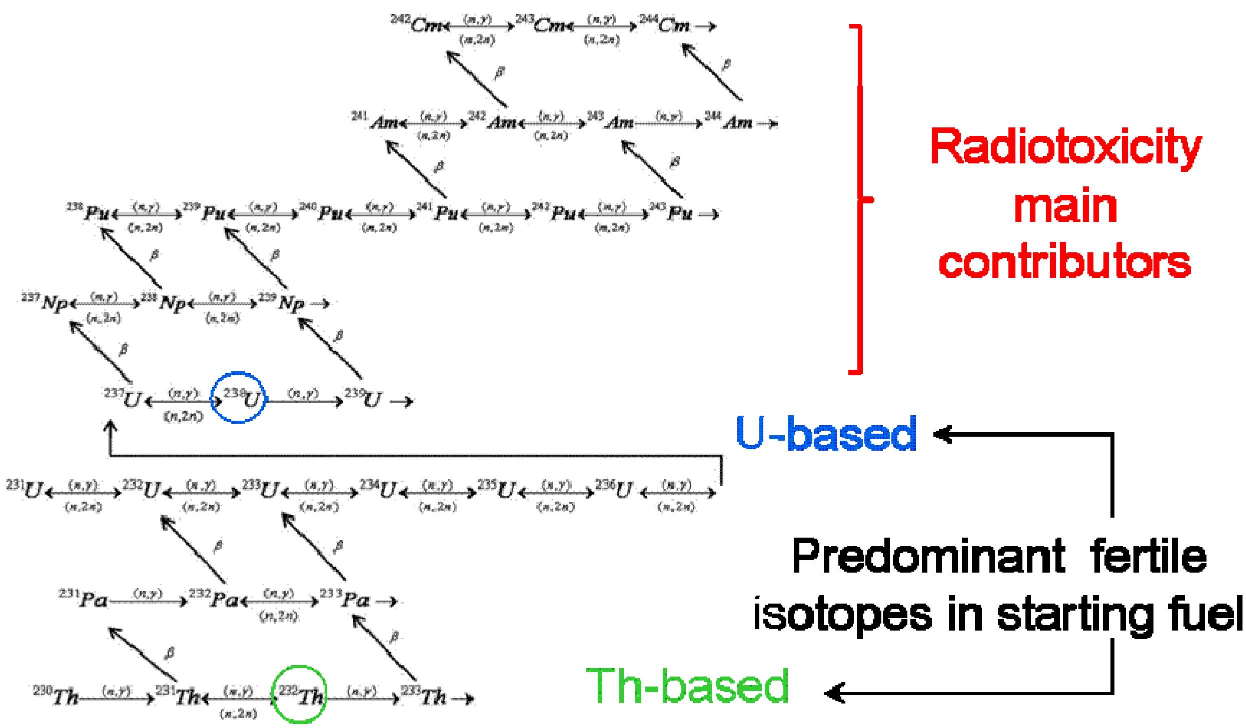

Fig. 4 Chain depicting nuclear reactions and decay leading to buildup of higher actinides (adapted from [8]).

Thorium has been considered for many decades and proposed by various organizations, with some development programs underway in various countries, such as India and China [9].

Considering the front-end and core residence time only, Thorium has had not much chance to economically compete with the U-Pu cycle. The reason is that the latter can rely on well established industrial infrastructure and low price and availability. However, if the criterion is waste reduction/elimination, a Th-^{233}U cycle due to its significantly lower TRU/radiotoxicity, may become overall less costly, i.e., more economical. The radiotoxicity of the wastes from UOX and U-^{233}Th recycle assuming equivalent separation efficiency is shown in Fig. 5, showing the potential advantage of Th vs. U. This only illustrates thorium fuel potential and does not imply a priori selection of thorium cycle. The ultimate selection will be requirements driven, as previously discussed.

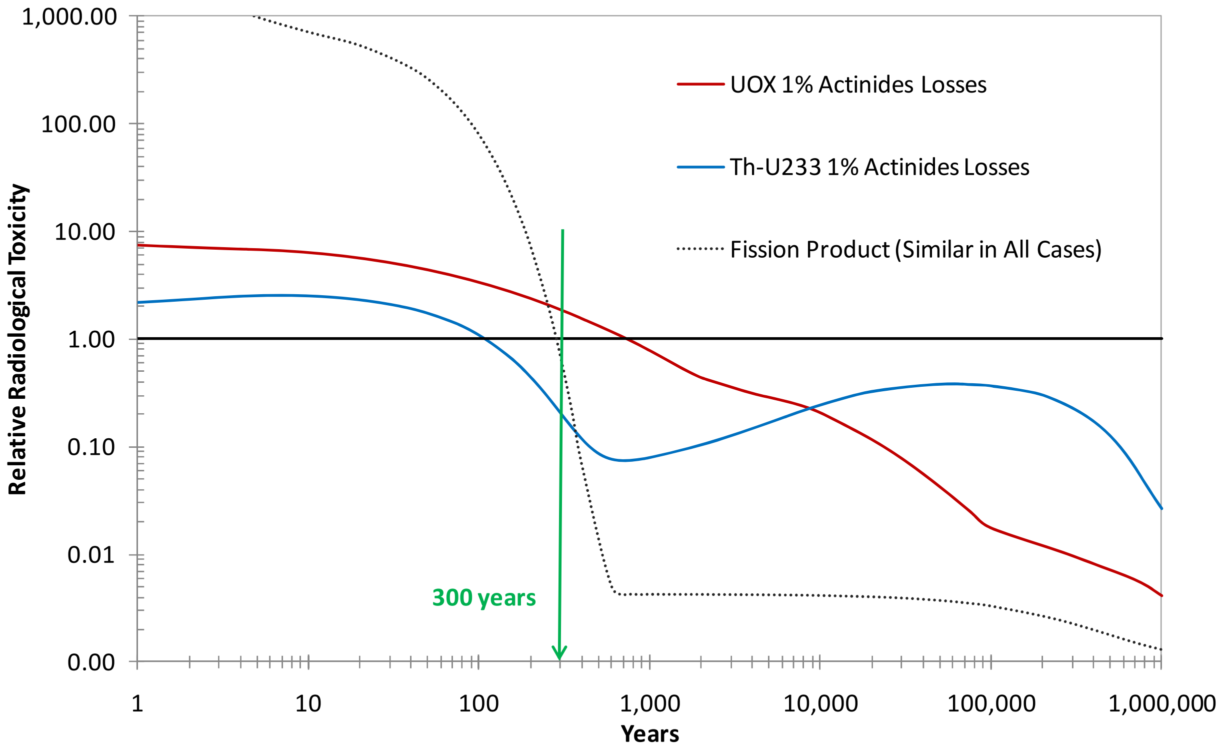

Fig. 5 Illustrative waste radiotoxicity from UOX or Th-U233 SNF recycle with different reprocessing efficiencies.

PROGRESS TO DATE

The progress to date may be summarized as follows. A novel waste requirements driven approach has been developed. Establishing of simulation capabilities and analytic tools is either underway or completed. Core physics tools are being benchmarked or extended as needed. Preliminary calculations and benchmarks have been performed.

We have devised preliminary fuel cycle scenarios and are performing preliminary analyses to scope alternatives from the standpoint of satisfying the waste requirements, primarily expressed through radiotoxicity evolution, but also accounting for economics and proliferation resistance. Specific analyses are being performed on thorium fuel implementation in multi-tier systems. Potential role of fission-fusion hybrids and ADS in multi-tier systems is considered for the next stage of analysis as well.

SUMMARY AND CONCLUSIONS

A new approach to fuel cycle optimization has been proposed. Rather than being based on the reactor type selection, it starts from and it is driven by the waste management requirement, since this is one of essential requirements for both the fuel cycle long-term sustainability and public acceptance. In this preliminary stage, tools for analysis are being established and exploratory analyses performed.

It is important to note that the methodology aims to eliminate any predetermined solution or a priori bias for a specific reactor or fuel. The decisions will be based solely on the match to requirements, and the spent fuel and high level waste management will effectively guide the development of the fuel cycle and reactors. Consequently, these efforts are open to any technology that could contribute to accomplishing the stated goals.

REFERENCES

[1] Retrieved online from NRC website on 10/15/2010: http://www.nrc.gov/waste/hlw-disposal/yucca-lic-app.html

[2] Advanced Fuel Cycle Initiative Mission, retrieved online from DOE website on 10/15/2010: http://www.ne.doe.gov/AFCI/neAFCI.html

[3] DOE Roadmap, retrieved online from DOE website on 10/15/2010: http://www.ne.doe.gov/pdfFiles/NuclearEnergy_Roadmap_Final.pdf

[4] Blue Ribbon Commission Charter, retrieved online from DOE website on 10/15/2010: http://www.ne.doe.gov/fuelcycle/neFuelCycle.html

[5] US DOE Motion to withdraw licensing application for a permanent geologic repository at Yucca Mountain, retrieved online from DOE website on 10/15/2010 http://www.energy.gov/news/documents/DOE_Motion_to_Withdraw.pdf

[6] Various Authors, "Thorium fuel cycle — Potential benefits and challenges", IAEA-TECDOC-1450, International Atomic Energy Agency (2005)

[7] "Processing of Used Nuclear Fuel", retrieved online from the World Nuclear Association website on 10/15/2010: http://www.world-nuclear.org/info/inf69.html

[8] D. J. COATES and G.T. PARKS, "Actinide evolution and equilibrium in fast thorium reactors," *Annals of Nuclear Energy*, **37**, 1076-1088 (2010).

[9] "Thorium", retrieved online from the World Nuclear Association website on 10/15/2010 http://www.world-nuclear.org/info/inf62.html

[10] M. BENEDICT, T. H. PIGFORD AND H W LEVI, "Nuclear Chemical Engineering" (2nd Ed.), 1981, McGraw-Hill(ISBN: 0070045313)