Energy Policy 53 (2013) 205–217

Contents lists available at SciVerse ScienceDirect

Energy Policy

journal homepage: www.elsevier.com/locate/enpol

The application of systems engineering principles to the prioritization of sustainable nuclear fuel cycle options

Robert R. Price [a,1], Bhupinder P. Singh [a,2], Robert J. MacKinnon [b,*], S. David Sevougian [b,3]

[a] Office of Systems Engineering and Integration (NE-51), U.S. Department of Energy, 19901 Germantown Road, Germantown, MD 20874, USA
[b] Sandia National Laboratories, PO Box 5800, MS 0747, Albuquerque, New Mexico, USA 87185-0747

HIGHLIGHTS

- ► Systems engineering principles applied in U.S. DOE-NE Fuel Cycle Technology Program.
- ► Use of decision analysis methods for determining promising nuclear fuel cycles.
- ► A new screening methodology to help communicate and prioritize U.S. DOE R&D needs.
- ► Fuel cycles categorized by performance/risk in meeting FCT Program objectives.
- ► Systems engineering allows DOE-NE to more rapidly adapt to future policy changes

ARTICLE INFO

Article history:
Received 1 June 2012
Accepted 20 October 2012
Available online 15 November 2012

Keywords:
Nuclear fuel cycle
Systems engineering
Decision analysis

ABSTRACT

We investigate the implementation of the principles of systems engineering in the U.S. Department of Energy's Fuel Cycle Technologies (FCT) Program to provide a framework for achieving its long-term mission of demonstrating and deploying sustainable nuclear fuel cycle options. A fuel cycle "screening" methodology is introduced that provides a systematic, objective, and traceable method for evaluating and categorizing nuclear fuel cycles according to their performance in meeting sustainability objectives. The goal of the systems engineering approach is to transparently define and justify the research and development (R&D) necessary to deploy sustainable fuel cycle technologies for a given set of national policy objectives. The approach provides a path for more efficient use of limited R&D resources and facilitates dialog among a variety of stakeholder groups interested in U.S. energy policy. Furthermore, the use of systems engineering principles will allow the FCT Program to more rapidly adapt to future policy changes, including any decisions based on recommendations of the Blue Ribbon Commission on America's Nuclear Future. Specifically, if the relative importance of policy objectives changes, the FCT Program will have a structured process to rapidly determine how this impacts potential fuel cycle performance and the prioritization of needed R&D for associated technologies.

1. Introduction and context

For the foreseeable future, nuclear energy is the only economic large-scale method to generate electricity with a low carbon footprint, and thus will undoubtedly remain an important part of any energy future for the United States. However, in the near term, challenges exist related to managing used nuclear fuel from the current fleet of reactors and, in the longer term, various technical and economic challenges related to resource and waste management must be solved, specific to the nuclear fuel cycle strategy that is adopted and deployed.

A "fuel cycle" is the progression of nuclear fuel from mining and enrichment to power generation to ultimate disposal of the used fuel or derived waste products. Sustainable fuel cycles are "those that improve uranium resource utilization, maximize

Abbreviations: ABWR, Advanced boiling water reactor; DOE, United States Department of Energy; DU, Depleted uranium; FCT, Fuel Cycle Technologies (Program); FOAK, First-of-a-Kind (nuclear facility); FOM, Figure of merit; Gen III, Generation III Nuclear Energy Systems; Gen IV, Generation IV Nuclear Energy Systems; GTCC, Greater-than-Class-C (Nuclear Waste); GWd/ MTU, Giga-Watt days per metric ton of uranium; HEU, High-enriched uranium; HLW, High-level (nuclear) waste; ISEP, Initial Screening Evaluation Panel; LLW, Low-level (nuclear) waste; LWR, Light water reactor; NE, Office of Nuclear Energy; PWR, Pressurized water reactor; R&D, Research and development; RU, Recycled uranium; SNM, Special nuclear material; TRL, Technology readiness level; TRU, Transuranic elements; UNF, Used nuclear fuel

* Corresponding author. Tel.: +1 505 844 1069; fax: +1 505 844 2348.
E-mail addresses: Robert.Price@nuclear.energy.gov (R.R. Price), Bhupinder.singh@hq.doe.gov (B.P. Singh), rjmacki@sandia.gov (R.J. MacKinnon), sdsevou@sandia.gov (S. David Sevougian).
[1] Tel.: +301 903 2533.
[2] Tel.: +301 903 3741.
[3] Tel.: +702 699 9448.

0301-4215/$ - see front matter © 2012 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.enpol.2012.10.051

energy generation, minimize waste generation, improve safety, and complement institutional measures in limiting proliferation risk.'' (DOE, 2010a, p. 13)

The mission of the Fuel Cycle Technologies (FCT) Program in the U.S. Department of Energy's Office of Nuclear Energy (DOE-NE) is to (1) develop sustainable fuel cycle technologies and options and (2) develop used fuel management strategies and technologies that support the federal government's responsibility to manage and dispose of the nation's commercial used nuclear fuel (UNF) and high-level waste (HLW). It is envisioned, that by mid-century, technologies will be demonstrated and deployed, through a partnership effort between government and industry, to enable viable commercial operation of sustainable nuclear fuel cycle systems and facilities in the U.S., in accord with one or more of the following strategies for used fuel management (DOE 2010b, 2011a):

- *Once-through*—Develop fuels for use in reactors that increase the efficient use of uranium resources and reduce the amount of used fuel requiring direct disposal for each megawatt-hour of electricity produced. The existing once-through fuel cycle with light water reactors utilizes less than one percent of the energy in the uranium that is mined (MIT, 2011).
- *Modified open cycle*—Investigate fuel forms and reactors that would increase fuel resource utilization and reduce the quantity of long-lived radiotoxic elements in the used fuel to be disposed, with limited or no separations steps, using technologies that substantially lower proliferation risk.
- *Full recycle*—Develop techniques to enable the long-lived actinide elements to be repeatedly recycled rather than disposed. The ultimate goal is to develop a cost-effective and low-proliferation-risk approach that will dramatically decrease the long-term risk posed by the waste, reducing uncertainties associated with its disposal.

Each of these fuel cycles strategies, or a combination of these strategies, may be appropriate depending on future conditions and societal demands. Furthermore, within each of these strategies, there are hundreds of possible combinations or system ''options'' comprised of differing reactor technologies, separations technologies, and various fuel types. Thus, to most effectively utilize taxpayer dollars, DOE-NE must make decisions to focus its research and development (R&D) efforts in the most promising directions for each of these strategies and related fuel cycle technologies. In combination with the lengthy time period needed for research and development, and the cost and complexity of the technologies to be developed and demonstrated, this presents a challenging integration and management problem.

To solve this multi-dimensional integration and management problem, the FCT Program is applying the principles of systems engineering to develop a structured, open, and objective decision-making framework that will help the program focus R&D on high-potential opportunities and help better explain decision-making to stakeholders. This framework employs a ''screening'' methodology that rates the potential ability of alternative fuel cycle options to achieve desired characteristics, measured as objectively as possible using approved evaluation criteria and metrics (DOE, 2010c). As shown in Fig. 1, the decision-making framework has two major components that are iterative in time: a policy component (outer loop) and an FCT Program R&D component (inner loop). The inner R&D loop represents both (1) the key elements of the screening methodology (in green) and (2) the use of the screening results to inform R&D planning and data/knowledge management (in yellow).

Information from a screening evaluation that is useful for R&D planning includes identification of the fuel cycle system options that are most promising for achieving program objectives as well as those options that do not warrant further development. Such

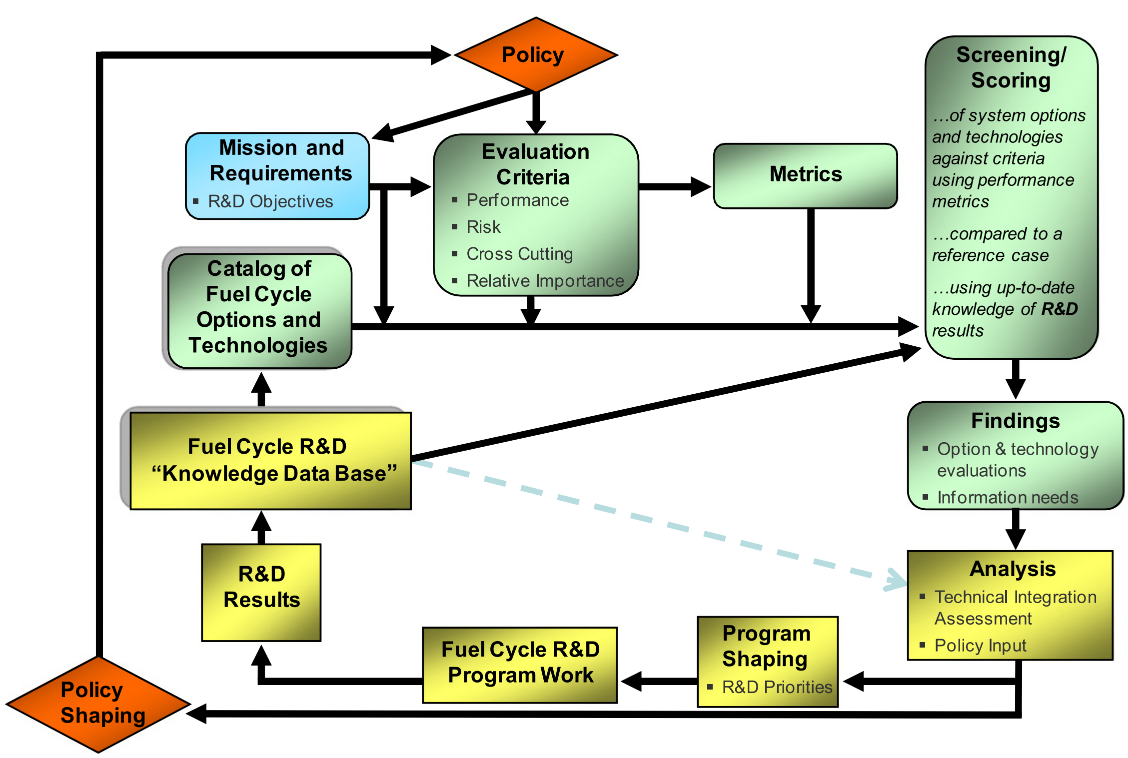

Fig. 1. A schematic representation of the steps for decision making (adapted from Frazier 2011). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)