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Thorium fuel cycle research and literature: Trends and insights from eight decades of diverse projects and evolving priorities

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ABSTRACT

Literature on the thorium fuel cycle spanning eight decades from the 1940s to the 2010s is identified, categorized, and analyzed. The publications are divided among twelve topical categories, and overall thorium literature trends are evaluated using database analysis techniques. In total, 1449 publications are identified, with the most prevalent topics being Reprocessing and Waste Management, Molten Salt Reactors, Fuels, and Light Water Reactors. In aggregate, reactor-oriented categories (five in all) comprise 45.5% of publications. The US is the most dominant thorium-publishing nation with 916 publications, followed next by India with 82 and then eight other countries having 25 publications or more. National laboratories have contributed 45% of thorium publications, with roughly equal shares of the balance split between government agencies, universities, and corporations/companies. Oak Ridge National Laboratory in the US accounts for more than a quarter of all publications. Specialized criteria are developed and applied to identify some of the most important, or "keystone", publications for each category. Across the different categories, and for the study of thorium fuel cycles overall, published research reached an intermediate peak in the 1970s followed by a sharp decline in the 1980s and 1990s; however, interest has been revived moving into the 21st century.

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1. Introduction

Thorium has been investigated as a nuclear energy option for essentially the same duration as uranium. Multiple demonstration reactors and fuel cycle facilities, dozens of irradiation tests and fuel fabrication efforts, and hundreds of important papers and reports attest to the significant experience with thorium that has been accumulated by a variety of nations and organizations. Nevertheless, even at their zenith, thorium-based fuel cycles have not enjoyed the commercial success of their uranium-based counterparts. On the other hand, while interest in thorium has ebbed and flowed, new research efforts have never entirely disappeared, and thorium-related research once again appears to be on the rise. Many of the past and present publications provide valuable insights regarding their specific topics; however, it is difficult to discern a clearly defined and compelling path forward (or on the contrary, an insurmountable shortcoming) for thorium fuel cycles based on the review of a single report.

Vanderbilt University (Vanderbilt) and Oak Ridge National Laboratory (ORNL) have contributed to the revival of the discussion on the outlook for thorium, having investigated various aspects of thorium fuel cycles together since 2012. At the Global 2013 International Fuel Cycle Conference, Vanderbilt organized a thorium fuel cycle track consisting of two technical sessions and a panel session (Krahn et al., 2014a); the following year at the American Nuclear Society Winter Meeting 2014, Vanderbilt and ORNL collaborated to organize a more extensive track with four paper sessions and a panel session (Krahn et al., 2014b), the key findings of which were expanded and organized into a special edition of the journal *Nuclear Technology* (Krahn and Worrall, 2016). One component of Vanderbilt's analysis was to collect literature related to the thorium fuel cycle, consolidate it into a database, and examine the literature to document major findings and trends. This paper presents the key findings of that thorium fuel cycle literature review. Using a combination of quantitative analysis and semi-quantitative categorization methods, augmented by expert judgment, it is intended that this paper serve as a starting point for future examinations of thorium fuel cycle literature dating to 2015 and earlier.

The first portion of this paper (Section 2) briefly describes the methods used to perform the literature review. The paper then

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presents and discusses the primary quantitative results of the analysis (Section 3), based on trends in characteristics such as topic, organizations, publication types, and countries of origin. After these quantitative results, the paper then shifts to summaries of research activity trends by topical category, including the authors' recommendation of "keystone" publications that have been identified as useful starting points for understanding particular topics or time periods within thorium fuel cycle development (Section 4). The paper concludes with some summary thoughts regarding the outlook for the thorium fuel cycle based on the experience with thorium that has been documented to-date (Section 5).

2. Literature analysis methods

This section describes the manner in which thorium fuel cycle publications have been identified (Section 2.1), organized (Section 2.2), and analyzed (Section 2.3).

2.1. Literature sources and identification

The literature included in this assessment originated from a variety of sources. However, searches of several large information repositories were particularly useful for yielding many of the technical reports and conference papers. Such repositories included:

- ORNL Research Library
- Office of Scientific and Technical Information (OSTI)
- National Technical Information Service (NTIS)
- International Nuclear Information System (INIS)
- American Nuclear Society (ANS)

In addition, journal articles were primarily located using online resources corresponding to the company or organization responsible for a particular journal (e.g., Elsevier). For all of these information repositories, searches were conducted using terms or phrases such as "thorium fuel cycle", "uranium-233", and "thorium nuclear energy", to name a few. Abstracts of papers and reports were briefly reviewed to filter out papers not related to nuclear fuel cycle applications of thorium. Commonly filtered-out subjects included: the presence of naturally-occurring thorium in trace quantities at various sites, the proposed use of thorium in non-nuclear applications such as structural alloys, the role of thorium and thorium compounds in biological or ecological processes, basic chemical sciences, and the use of thorium isotopes in particle physics experiments. Furthermore, general reports on potential thorium-bearing reactor technologies that did not specifically acknowledge thorium-related components or systems were not included. While these stipulations may have reduced the number of publications that would have otherwise have been featured in this review, the relevance of the items that have been included is consistently high as a result.

It is worth noting that two prior thorium literature reviews have yielded larger quantities of "thorium publications"; we observe that in those instances the authors were less specific in their requirements for inclusion. A 1955 review performed by the US Atomic Energy Commission (AEC) includes 2190 entries (Prater et al., 1955), which is about 50% more than the number included in this Vanderbilt-ORNL assessment in spite of the fact that only entries up to the year 1955 are included. However, biomedical studies account for 259 of these, basic chemical property studies (not specific to nuclear fuel cycle applications) account for 894, measurements of macro-scale physical properties (again not specific to nuclear fuel cycle applications) account for 393, and other miscellaneous non-nuclear categories account for most of the rest. Less than 50 entries refer to fission in any capacity, and none explicitly discuss sustained fission for nuclear power applications. More recently, in 2006, a group at India's Bhabha Atomic Research Centre (BARC) downloaded the entire INIS database and located slightly over 10,000 publications that mentioned "thorium" (Kademani et al., 2006). Unlike the AEC study, the BARC did not list each individual publication and only conducted more detailed analyses for the 2399 reports that originated from India. Of these, just over 75% were in categories entirely unrelated to the nuclear fuel cycle. Since a single mention of the word "thorium" retrieved a study from the INIS database, presumably a significant portion of the remaining ~25% involved general statements (e.g., "LWRs can use uranium or thorium") or facts related to the uranium fuel cycle (e.g., the presence of Th-230 as a decay product of U-238). In contrast, in this study, while search terms were still used to locate possible entries, each publication was individually checked for relevance before being include in this assessment – hence the seemingly lower numbers shown in Section 3.

2.2. Literature classification

To facilitate the analysis of the literature examined in this study, each publication was assigned to one of twelve topical categories. Eleven of these twelve topical categories were defined based on logical divisions in subject matter, while the last category was created out of necessity to accommodate multi-topical efforts or reports on relatively uncommon topics. These topical categories, and their corresponding definitions, are shown in Table 1 below.

2.3. Literature organization and index fields

After the thorium publications were collected and classified, the characteristics of each item were documented in a series of tables comprising an SQL-searchable database. An important preliminary effort was the selection of index fields that would be populated for each publication. The development of these fields was partly informed by the structure of existing literature databases, and in some cases by the stated information desires of nuclear fuel cycle researchers. These index fields included:

- Topical Category
- Title
- Author(s)
- Publication Year and Month
- Report Number (if applicable)
- Resource Type – i.e., technical report, conference paper, journal article, thesis/dissertation, or other
- Research Organization(s)
- Research Organization Type (of lead organization) – i.e., government agency, national laboratory, university, corporation, or other
- Country (of lead organization)
- Abstract
- Keywords

Because the information for the thorium publications is stored in a database, it was possible to run SQL queries to analyze certain characteristics of the literature. The results of these analyses are presented below in Section 3.

3. Results of quantitative literature assessment

A total of 1449 thorium publications were identified during the literature review. Since the literature search used to populate the database concluded in 2015, some of the literature from 2015 and most of the literature from 2016 and 2017 is not included in

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