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Evolution and Structure of the Scientific Basis for Nuclear Waste Management

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ABSTRACT

The final disposal of nuclear waste is at the interface between the technologies of the nuclear fuel cycle that produce the waste and the natural hydrologic and geochemical cycles of geologic repositories. Despite this broad interdisciplinary scope, nuclear waste management, as practiced, remains “balkanized” among the relevant disciplines. The individual subdisciplines continue to work in relative isolation from one another: materials science dealing with the immobilization of nuclear waste; engineering science dealing with the design, construction and operation of the repository; geoscience dealing with the long-term behavior of host rocks and the hydrology; health science dealing with the effects of radiation; social sciences dealing with the issues of trust, risk and ethics. Understanding how these very different disciplines interact is fundamental to creating and managing a nuclear waste organization. Based on a comprehensive review of the scholarly and scientific literature of waste management, we have analyzed the evolution and structure of research in nuclear waste management between 1979 and 2017. Focusing on materials science, we show that some research themes have been isolated from the most central themes of nuclear waste management. Moreover, we observed a relative decline of the fundamental research in materials science. This decline was evidenced by a drop in the number of articles published in the proceedings of the MRS symposia “Scientific Basis for Nuclear Waste Management” since 2000. We argue for the need to more precisely and inclusively define the field of nuclear waste management.

INTRODUCTION

In 2012, the Blue Ribbon Commission on America’s Nuclear Future recommended that a new organization be established for the management of radioactive waste in the United States [1]. The Commission focused their recommendation on the legal and institutional aspects of this organization *vis-à-vis* its responsibilities. However, little

has been said about how the organization should be designed in terms of the type of knowledge required for nuclear waste management. The paper is a first step to understand what the field of nuclear management requires.

We analyzed the papers published in the proceedings of the MRS symposia *Scientific Basis for Nuclear Waste Management* between 1979 and 2017. Using bibliometric methods, we explored the structure and evolution of the MRS corpus. We then performed a comprehensive review and analysis of the scholarly and scientific literature using the Elsevier B.V.’s *Scopus*[®] database of articles published since 1940 about nuclear waste. Focusing on the 1979–2017 period, we compared the structure and evolution of the main academic corpus from *Scopus* to the specialized corpus from MRS. The results show that nuclear waste management has received important contributions from a broad range of different scientific communities—yet they remain in relative isolation from one another.

MRS CORPUS ON NUCLEAR WASTE MANAGEMENT

The first symposium on the *Scientific Basis for Nuclear Waste Management* was held in 1978 at the fall meeting of the Materials Research Society [2]. Over the past forty years, this symposium has brought together nearly 6,000 scientists who jointly published nearly 3,900 proceeding articles (1979-2017). This represents the largest scientific community researching the fundamental and applied science of radioactive waste management, particularly in the materials science. Yet, the number of papers from this community has decreased since 2000 (Figure 1). This occurred despite the total volume of the scientific articles on nuclear waste having increased exponentially during this period.

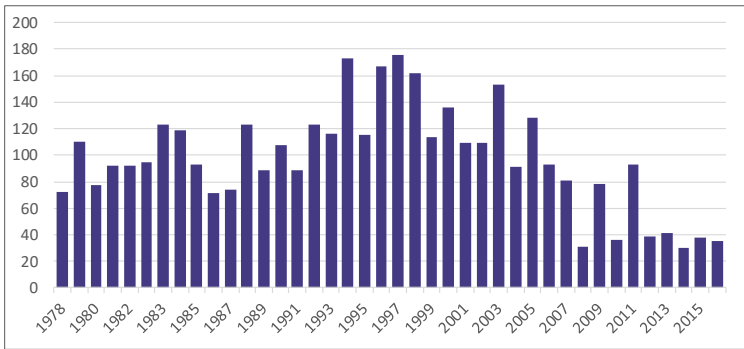


Figure 1: Number of proceeding papers published in the proceedings of the MRS-SBNWM symposia. Note: The figure uses the symposia years, whereas the analysis uses the proceeding publication years. Source: MRS.

MAIN ACADEMIC CORPUS ON NUCLEAR WASTE MANAGEMENT

Nuclear waste management is not a well-defined research field despite the thousands of scientific papers published on this topic since 1940. The lack of an explicit definition makes it difficult to define the scope of the corpus that we want to analyze. We built a main corpus on nuclear waste management articles using *Scopus*, an abstract and citation database of peer-reviewed literature commonly used in bibliometric analysis. We

used a search query tested to return documents relevant only to nuclear waste management, broadly defined. The search query was applied to both title, abstract, and keywords and was limited to articles in scientific journals.

The data collected using this search query generated a database of the main academic corpus. The data was downloaded from *Scopus* API between February 14, 2018 and August 31, 2018 via <http://api.elsevier.com> and <http://www.scopus.com>. A series of treatments was applied to the corpus before being analyzed. We fixed the analysis to 1979–2017 which covers the overlapping period with the MRS corpus. Over this period, we collected a total of 30,828 articles, 48,873 authors, and 362,155 citations, including 52,407 within the main corpus (co-citations). We then divided the data into four sub-periods: 1979–1987, 1988–1997, 1998–2007, 2008–2017. There has been a sharp increase in the scientific production on nuclear waste management between the last two periods—from 7,421 articles in 1998–2007 to 14,255 in 2008–2017.

Journals were then categorized by their main scientific disciplines using Thomson-Reuters’ *Essential Science Indicators*SM (ESI) journal list (version as of November 9, 2017). Out of the 21,699 articles published in a journal of the ESI list (70% of the corpus), 29% were in engineering, 18% in chemistry, 12% in geosciences, 12% in environment/ecology, and 7% in materials science (Figure 2). Engineering has been, by far, the most active field on nuclear waste management. Materials science also has been central, despite the relatively small number of publications. However, the impact of materials science declined in the 1990s, when fundamental research focused on engineering applications and waste forms (Figure 3). Applied research on nuclear waste continued to grow through the 2000s—particularly in the geosciences, environment/ecology, and chemistry—as countries started to develop their geological repositories.

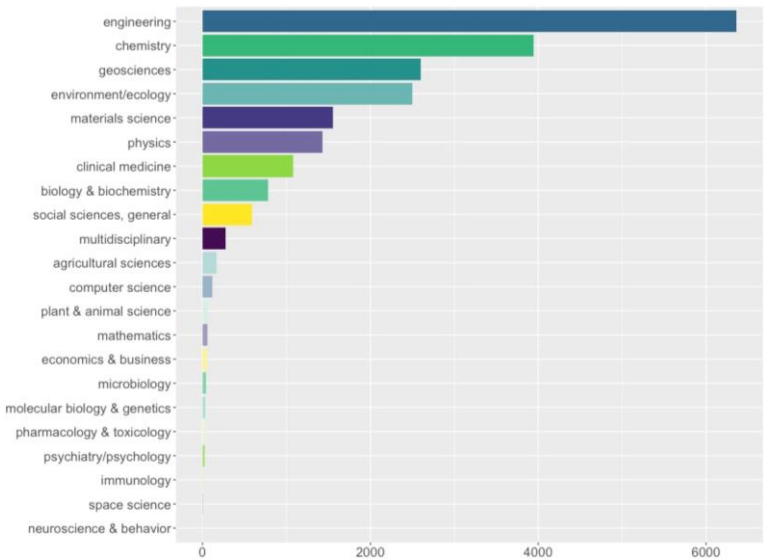


Figure 2: Scientific articles on nuclear waste management counted by ESI journal category (1979–2017). Source: *Scopus*.

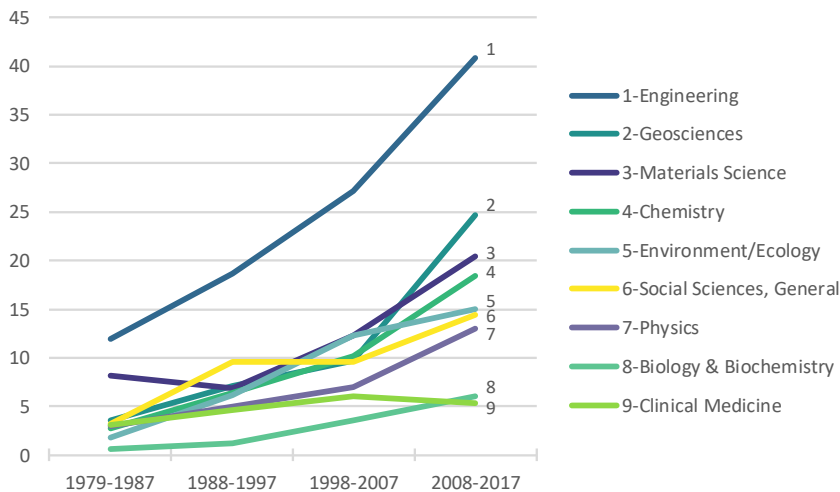


Figure 3: *H*-index (normalized) values of the 9 most active disciplines by sub-period. Note: *h*-index values were normalized for each discipline to account for different publication and citation standards [3,4]. Source: *Scopus*.

THEMATIC EVOLUTION OF THE MAIN ACADEMIC CORPUS

We then performed a co-word analysis of the main corpus to reveal the main themes within each sub-period. Networks detected by the co-occurrence frequencies of keywords in a corpus can be represented using different measures [5]. We used the eigenvector centrality and degree. Eigenvector centrality is a measure of node importance in a network based on a node's connections; whereas, the degree of a node is the number of edges that are adjacent to the node. Table 1 shows the main themes in materials science.

Table 1: Top keywords in the materials science discipline for each sub-period obtained from the co-word analysis. Abbreviations used: EC: eigenvector centrality; D: degree. Note: Several keywords had same EC and D values although they were not within the same network (theme). Source: *Scopus*.

| Period | Keyword 1 | Keyword 2 | Keyword 3 | Keyword 4 | Keyword 5 |
|-----------|--|--|--|--|---|
| 1979-1987 | ruthenium; lanthanides EC: 1.0 D: 5 | monoclinic perovskites; oxidation; nickel EC: 0.907955 D: 4 | fluorite-like compounds EC: 0.476464 D: 2 | | |
| 1988-1997 | nuclear materials EC: 1.0 D: 17 | glass EC: 0.931158 D: 26 | titanates EC: 0.739284 D: 16 | sodium EC: 0.732279 D: 13 | phases EC: 0.575432 D: 11 |
| 1998-2007 | microstructure EC: 1.0 D: 34 | mechanical properties EC: 0.924119 D: 34 | yag lasers; co2 lasers EC: 0.803524 D: 22 | ^(a) EC: 0.67585 D: 14 | pitting corrosion EC: 0.519948 D: 25 |
| 2008-2017 | immobilization EC: 1.0 D: 629 | corrosion EC: 0.1539 D: 125 | microstructure EC: 0.14919 D: 83 | concrete EC: 0.110262 D: 61 | adsorption EC: 0.109614 D: 52 |

Note: (a) There were 11 keywords with eigenvector centrality = 0.67585: comparisons; consumables; dp600 high strength steel; gap; hardness tests; high strength steels; hot cracking; hybrid laser welding; joint preparation; laser welding; mag welding.

Figure 4 reveals that several peripheral themes appeared in the last period. Some themes were important, but they occurred in relative isolation from other research themes. For instance, research on ‘reprocessing’ was made in relative isolation, which may be explained by the shift to direct disposal of spent fuel in a number of Western countries following the U.S. suspension of their civilian reprocessing program [6]. Another isolated theme concerned the ‘nuclear power’ and ‘carbon dioxide emissions’. For materials research, ‘microstructure’ and ‘corrosion’ were central themes in materials science (Table 1) and were isolated from the main academic corpus. Similarly, ‘immobilization’ and ‘adsorption’ were also peripheral topics not well connected to the main corpus.

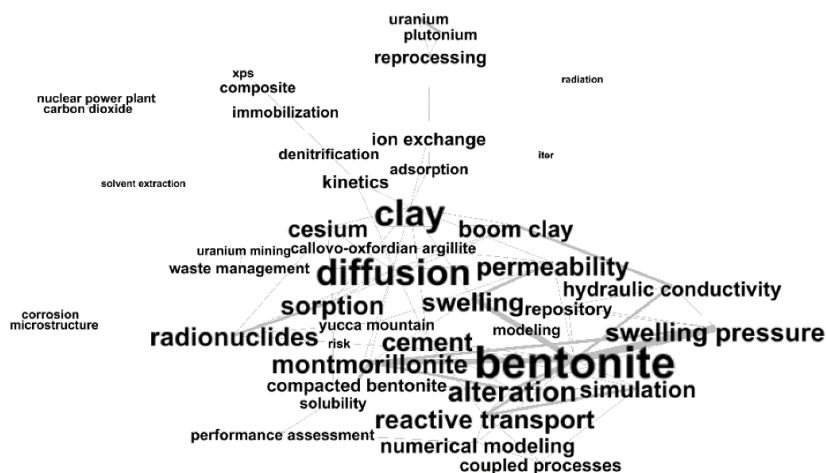


Figure 4: Main themes of the main corpus (2008–2017) based on co-word analysis (52,624 keywords). Note: 45 clusters represented by their central node (keyword) and inversely distanced by number of times keywords from two clusters appear in one document. Keyword size is by the number of edges coming in/out from the cluster. Source: *Scopus*.

DISCUSSION AND CONCLUSIONS

The various subdisciplines dealing with nuclear waste management shall be recognized as just different ways of looking at the same issues. Whereas the unification of very diverse subdisciplines does not appear possible, efforts for their integration should be pursued. A more well-defined scientific basis for nuclear waste management shall start by recognizing the importance of working at the interfaces between these disciplines. We suggest that a nuclear waste management organization should have three main activities:

- Science—focusing on the fundamental understanding of the mechanisms involved in radioactive materials in storage and disposal conditions;
- Engineering—dealing with the design, construction and operation of nuclear waste storage and disposal facilities, including deep geological repositories;
- Social science—building and maintaining trust through the decision-making and monitoring processes.

These three activities should work in a coordinated way with one another. The sciences should provide the adequate fundamental scientific basis used in the engineering applications. In turn, the engineering applications should follow the scientific method by assessing the level of validity or falsification of the models and hypotheses based on new

data from the site characterization. These models and hypotheses should be revised when falsified by data. Finally, the social sciences shall provide the epistemological principles for the conduct of the decision-making process. Particularly, they should address the perception gap between experts and non-experts by supporting the search for an agreement on strategies and proposals.

The study showed that such interactions between the subdisciplines have not occurred in the scientific literature about nuclear waste management. Instead, there has been a relative disconnect between the fundamental research in most of the relevant sciences, *e.g.*, materials science, and the applied research in engineering. The same was observed between sciences and social sciences. The disconnect between subdisciplines prevents the development of technical solutions in conjunction with societal demands [7]. A new organization that effectively includes these three types of knowledge—science, engineering, and social science—would have important implications on the way scientific information is produced and solutions are implemented. This is mainly because of the different cultures of the scientific, engineering and social science communities involved. These cultural differences are evidenced by the relative disconnect between the disciplines involved in the scientific literature about nuclear waste. We suggest that learning how to re-connect the diverse scientific cultures into one organization could help to “reset” nuclear waste management programs that have been stalled for decades—as is the case of the US repository program [8].

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