Journal of
Ceramic Science
and Technology

*J. Ceram. Sci. Tech.*, 05 [02] 71-76 (2014)
DOI: 10.4416/JCST2013-00032
available online at: http://www.ceramic-science.com


# Future Research in Refractories: A Roadmap Approach

**A. Geigenmüller*[1], H. Spindler[1], K. Lenk[1], C. G. Aneziris[2]**

[1]Technische Universität Ilmenau, Faculty of Economic Sciences and Media, Department of Marketing, Helmholtzplatz 3, 98693 Ilmenau, Germany
[2]Technische Universität Bergakademie Freiberg, Institute of Ceramics, Glass and Construction Materials, Agricolastrasse 17, 09599 Freiberg, Germany

received October 20, 2013; received in revised form October 21, 2013; accepted December 10, 2013

**Abstract**

**Science and technology roadmaps are valuable instruments for strategic planning in research. Especially for interdisciplinary fields such as materials science and technology, roadmaps are promising instruments for identifying relevant research themes and interfaces between different disciplines and actors. Against this background, this paper aims at developing a roadmap for refractory research in order to strategically promote the field, to initiate ground-breaking research endeavors and valuable collaborations and to advance fundamental and applied refractory research. To this end, the study employs an extensive review of existing roadmaps, strategic papers, reports, and presentations in the fields of materials science and engineering, ceramics, glass, metals, metallurgy, and refractory applications. Furthermore, in-depth interviews with national and international experts from academia, industry and professional associations provide judgments about future research trends and estimates about their time of occurrence. The study identifies four main future research areas, including novel materials compositions as enablers for improved or extended materials properties, new approaches for materials preparation, forming and processing technologies. Moreover, modeling and forecasting of materials properties and performance are identified as important fields for future research.**

*Keywords: Roadmap, strategic planning, refractories, materials synthesis, preparation, processing, testing, modeling and simulation*

## I. Introduction

Refractories' critical importance for many energy-intensive industries, such as iron and steel making, the production of glass, ceramics, or cement, constitutes the demand for novel materials with improved characteristics and superior technological and economic performance [1,2]. To this end, research efforts are needed that span the entire process chain, from raw material preparation to processing, component and system design up to recycling and waste management [3]. This makes refractory research a truly interdisciplinary endeavor requiring knowledge and expertise from diverse academic disciplines as well as contributions from industry and society.

To encourage effective research that translates into technological and economic benefits, research needs, activities and actors have to be aligned in such a way that human and financial resources can be allocated appropriately [4]. Therefore, research institutions, policy-makers and funding institutions are seeking ways to systematically monitor long-term developments and emerging tasks in science, technology and society, to identify future research directions and to derive well-founded strategies for creating appropriate research environments [5].

Against this background, science and technology roadmaps are gaining increasing interest from various stakeholders including scientific communities, firms, and policy-makers. Originating from corporate strategic planning, roadmaps are used traditionally to monitor, forecast and communicate technological developments, in order to link technologies, products, and market opportunities [5,6,7]. Science and technology roadmaps, however, are utilized to predict the long-term future of science and technology, including economic and societal issues. As an important means of prospective technology analysis, they are employed to aid decision-making about *what* to research [8,9]. Forecasting emerging research topics and research directions, science and technology roadmaps are used to prioritize research topics, to align capabilities and requirements as well as to decide on research funding. Thus, science and technology roadmaps support and optimize strategic planning and coordination of research activities and resources in even more dynamic and complex environments [5].

Although the instrument of roadmapping has already been applied to several fields of materials research [10], to our best knowledge, a science and technology roadmap for refractory research is lacking. This, however, limits opportunities to strategically promote the field, to initiate ground-breaking research endeavors and valuable collaborations and to advance fundamental and applied refractory research. By revealing future research trends, relevant actors, and intra- and interdisciplinary interfaces across the entire process chain, strategic allocation of resources for refractory research would be enhanced.

* Corresponding author: anja.geigenmueller@tu-ilmenau.de

Therefore, this paper aims at developing a science and technology roadmap for refractory research. More precisely, the authors identify strategic objectives, market requirements and, consequently, future research needs in refractories. The paper is organized as follows. First, the main methodological aspects and the study design are introduced. Subsequently, attention is turned toward research results as well as measures for implementing science and technology roadmaps. The paper concludes on strategic planning in materials research and refractories and points to future research directions in prospective technology analysis.

## II. Methodology

The literature on roadmapping approaches suggests several methodological remedies to address high levels of complexity and uncertainty captured in science and technology roadmaps. First, authors emphasize the value of integrating expert-based and computer-based approaches [5, 11, 12]. Expert-based approaches refer to the subjective evaluation of developments in a field by individuals who possess relevant expertise in a field and who are able to provide potential solutions for a given problem [13]. Computer-based approaches pertain to the investigation of data accessible through published papers, reports, statements, etc. that describe past and present research activities in a generally objective manner [5]. Combining both approaches is recommended to cope with uncertainty without constraining transparency and clarity of a roadmap. Second, prior research supports the notion that forecasting the future of science and technology requires multi-disciplinary working in such a way that knowledge and experiences from different stakeholders is brought together, to enrich the value of such a roadmap [14].

The present study employs both expert-based and computer-based approaches to forecast the long-term future of refractory research. We started with an extensive review of existing roadmaps, strategic papers, reports, and presentations in the fields of materials science and engineering, ceramics, glass, metals, metallurgy, and refractory applications. In total, more than 42 documents on strategic developments in the fields mentioned above were included.

The literature review provided the basis for expert interviews. Between 2010 and 2012, in-depth interviews were conducted with 33 participants from academia and industry across Europe, North America, Brazil, China and Japan. The interviewees held leading positions in universities, companies, scientific institutions, and professional or industry associations (see Table 1). The interviews, which lasted between 60 and 90 minutes, covered main topics, concepts and terms as well as forecasts extracted from a literature review. Participants were asked to provide their judgments on these forecasts in terms of accuracy and relative importance to the future development of the field until the year 2025. The interviews were audiotaped and transcribed verbatim. Content analysis permitted the identification of future trends in refractory research.

In-depth interviews were complemented with citation analysis. Citation analyses are suitable instruments for exploring knowledge evolution, the importance of research topics, and patterns in scientific inquiries. Moreover, data gained from citation analyses discloses individual researchers that influence the development of a discipline [15–18]. In our study, we draw on the Web of Science to search for publications containing the words "refractory" and "refractories" in titles, abstracts or keywords. The search covered a time period from 2000 to 2012. In addition the results were limited to topics referring to materials science and engineering. In total, 2 870 articles and conference papers were included. Core publications and emerging topics were assessed based on citation frequency, citation growth rate, and average citations per year.

## III. Results and Discussion

### *(1) Strategic targets and main functionalities*

Possessing the ability to withstand high temperatures, thermal shocks, chemical and mechanical stresses, refractories are indispensable for many manufacturing processes in high-temperature and/or high-corrosive environments. Not only are refractories important for insulating and protecting manufacturing facilities, they have also a tremendous impact on the quality of metallurgical products. Refractory materials play a crucial role in preventing unfavorable interactions between melts, slags and refractory materials, which decreases inclusions and elevates the purity of metal melts. From an economic point of view, refractories are desirable that enhance a reduction of consumption and maintenance costs as well as energy consumption, for instance due to improved thermal insulation. Although on average consumption of refractories has declined, there is a growing demand for high-performance refractories including multifunctional components and complex geometries that can be tailored to specific applications and environments [19]. Recently, the environmental and health aspects of refractories have also been widely discussed. Novel refractory materials could lower $CO_2$ and other harmful emissions and facilitate waste management and recycling of refractories.

Resulting from that, future research is needed in order to respond to a growing demand for advanced refractories that are materials and components with an extended lifespan that can be tailored in forms and materials to specific mechanical, thermal and chemical stresses, with reduced energy consumption, lower installation and maintenance costs. Controlling materials properties including strength, porosity, density, thermal conductivity, thermal shock resistance, corrosion resistance, dimensional stability and creep will be of utmost importance not only to satisfy basic requirements but also to address the need for functionalized refractory components. In this vein, future research should include all length scales, from nano- and microstructure dimensions up to macroscopic features of components and aggregates, and all levels of the process chain. Closer collaborations, on one hand, between materials science and natural sciences and, on the other hand, between materials sciences and engineering disciplines are vital in order to accomplish significant advances in refractory research.

The group of experts who participated in our qualitative study provided judgments about emerging research topics suitable for addressing strategic targets and preferred functionalities as well as estimates about specific times of occurrence for each of the topics. The results gained from expert interviews and the citation analysis are shown in Fig. 1. In what follows, we provide brief comments on these results.

**Table 1:** Interview participants

| Interview No. | Position | Institution | Country |
|---|---|---|---|
| 1 | Professor | University | Germany |
| 2 | Professor | University | Germany |
| 3 | Professor | University | Germany |
| 4 | Professor | University | Germany |
| 5 | CEO | Refractory manufacturer | Brazil |
| 6 | R&D Manager | Supplier | Germany |
| 7 | Global Technical. Director | Raw material supplier | Germany |
| 8 | Plant Manager | Refractory manufacturer | Austria |
| 9 | CEO | Refractory user | Japan |
| 10 | Professor | University | Brazil |
| 11 | Professor | University | Brazil |
| 12 | Professor | University | USA |
| 13 | Professor | University | Canada |
| 14 | R&D Manager | Refractory manufacturer | Germany |
| 15 | R&D Manager | Raw material supplier | France |
| 16 | Post-doc researcher | University | Germany |
| 17 | Post-doc researcher | University | Germany |
| 18 | Professor | University | USA |
| 19 | General Manager | Refractory user | Netherlands |
| 20 | Vice President | Minerals supplier | France |
| 21 | Researcher | University | Germany |
| 22 | Researcher | University | Germany |
| 23 | Managing director | Professional association | Germany |
| 24 | Managing director | Research institute | Germany |
| 25 | Managing director | Refractory manufacturer | UK |
| 26 | Managing director | Refractory manufacturer | Netherlands |
| 27 | Managing director | Refractory manufacturer | Netherlands |
| 28 | Professor | University | UK |
| 29 | Professor | University | France |
| 30 | Professor | University | Germany |
| 31 | Professor | University | China |
| 32 | Managing director | Raw material supplier | Germany |
| 33 | CEO | Research institute | Germany |
| 34 | CEO | Refractory user | Germany |

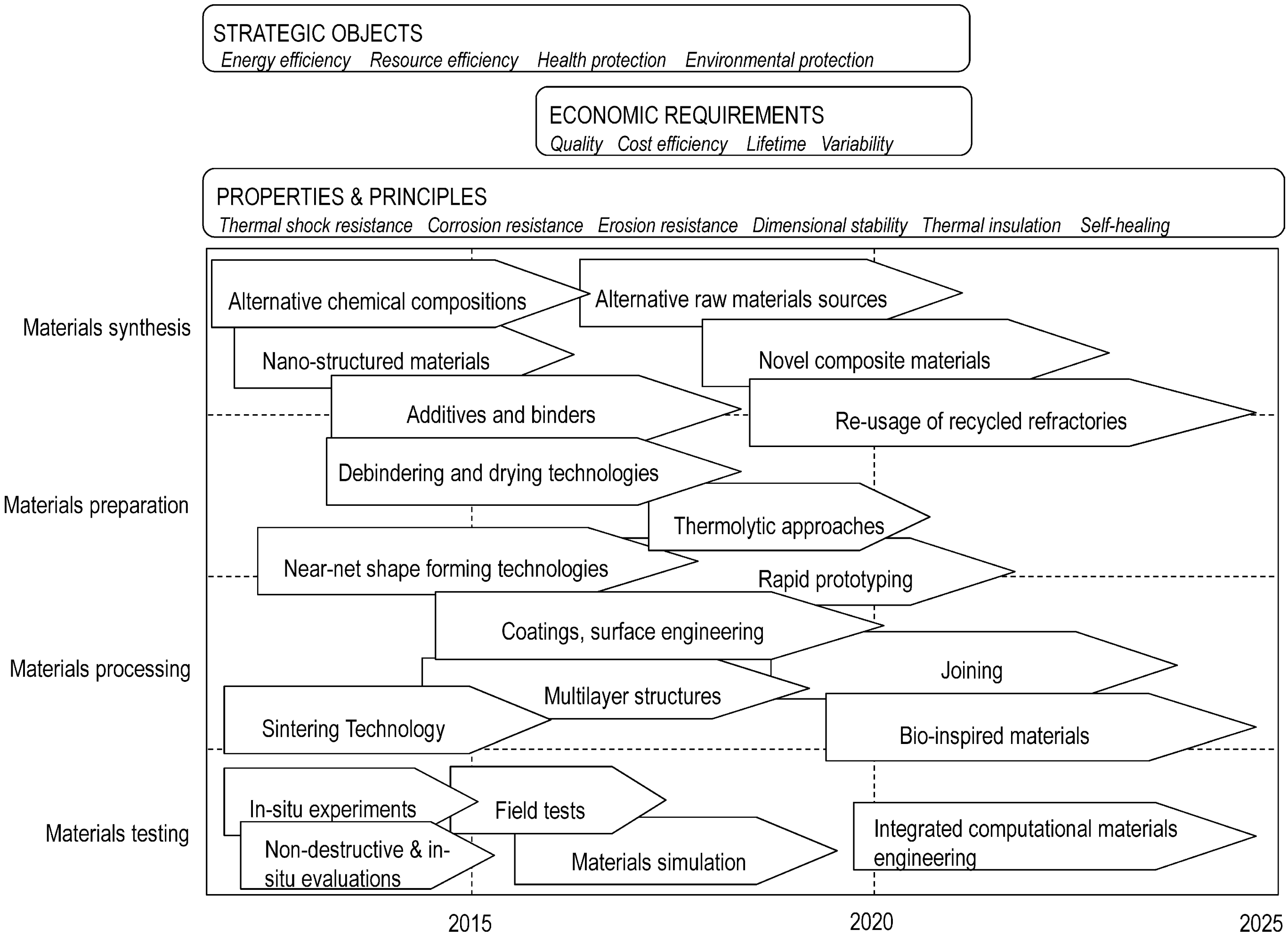

**Fig. 1 :** Roadmap for refractory research

*(2) **Research directions on materials synthesis and preparation***

The demand for advanced refractories with extended functionalities and customized designs poses significant challenges on the selection and composition of refractory raw materials, the development of novel materials compositions, and approaches of materials synthesis and processing. In the face of the serious scarcity of raw materials, such as bauxite, high-grade magnesite, chrome sand or graphite as well as several rare earths, attention turns towards alternative raw materials and recycled refractories. Novel compounds and composite materials provide ways to address the demand for extended functionalities and, hence, higher complexity and superior properties of refractory materials. This includes the integration of different materials classes such as metals and polymers.

Especially regarding the purity of metal melts, further research on chemical compositions of refractory materials was stressed. Deeper understanding of reactions between refractories and other process materials and, hence, a tailored design of novel refractories was identified as an important step towards the improvement of metallurgic products.

Similarly, additives, binders and fillers have a significant influence not only on refractory properties, final shapes and functionalities but also on environmental and health issues of refractory manufacturing processes. Therefore, advances in refractory materials will also emerge from investigations of the roles additives, binder systems and filler materials play in materials design and how green properties of refractories are affected in terms of "green machining technologies".

Finally, in a long-term perspective, approaches for recycling refractory materials were discussed. Besides the exploitation of alternative raw material sources, the re-use of refractories was assumed as a major contribution to improved resource efficiency and to lower dependence on raw material suppliers.

*(3) **Research directions on materials preparation***

In line with the discovery of novel materials, the development of new methods for materials preparation and the advancement of established methods were emphasized. This includes approaches for optimizing formulations in terms of porosity, grain sizes, for comminution and mixing technologies. Moreover, designing refractory materials based on the definition of appropriate precursors at atomic levels, for instance through thermolysis, was suggested as a promising research direction.

Alternative materials compositions as well as requirements of near-net shape forming technologies give rise to appropriate mixing and slurrying technologies. Experts expected growing opportunities for collaborations between chemists, physicists and materials scientists in order to understand and, hence, control crucial parameters especially for preparing dispersions of fine-grained powders and hybrid materials compositions. With regard to prospective developments of mixing technologies, experts pointed to opportunities for knowledge transfer from other industrial technologies such as food technology.

Furthermore, debinding and drying concepts were pointed out as important research fields. Debinding and drying processes often have a significant influence on major properties of refractories, such as strength and density. Therefore, one focus of future research activities should be on debinding strategies that do not cause any flaws or defects in green bodies and, moreover, prevent hazardous health effects owing to harmful emissions. Another aspect that was stressed is the need for drying concepts that permit efficient and highly productive fabrication processes. A development of appropriate technologies and processes therefore remains a major task in refractory research.

*(4) Research directions on materials processing*

A growing demand for customized designs and superior functional parameters results in a stronger focus on forming techniques that increase the variety of green-state architectures, such as casting, spraying, printing and extrusion, and that reduce the risk of failures by influencing size and distribution of pores, the initiation and propagation of cracks, interfaces, etc. In a long-term perspective, rapid prototyping was mentioned as one way to design refractories with desired geometries and properties according to specific loadings. One major prerequisite for implementing rapid prototyping in refractory engineering is certainly a better understanding of relations between characteristics of suspensions and properties of green bodies. Therefore, major input is expected from closer collaborations with experts specifically in colloidal chemistry.

Likewise, heat treatment has a great influence on materials properties and performance. Although sintering techniques are assumed to be well researched, further advancements and adaptations to new materials compositions are considered as a constant challenge. One interesting route for future research is sintering at lower temperatures and/or shorter sintering times. The development of sintering models and an advanced understanding of related phenomena might help generate high-performance refractory materials and components and, additionally, increase the energy efficiency of production processes.

Coatings and multilayer structures are gaining increasing relevance especially with regard to the resistance against thermal shocks and corrosion. They allow the combination of different materials properties and the use of defects to absorb effects from thermal shocks. Therefore, self-healing refractories come into reach. Coating refractories was seen as an interesting opportunity to influence interactions between refractories, melts and slags, in order to ensure melt purity and to eliminate unfavorable inclusions. In a long-term perspective, natural structures might serve as examples of how to compose multilayer structures for superior materials performance.

Finally, joining was identified as a future research field of interest. Joining of ceramics or ceramics and metals may extend the scope of new refractory materials and properties and, hence, respond to the demand for variable materials and components that can be adjusted to specific operating conditions.

*(5) Research directions on materials testing and modeling*

Experts agreed upon the need for advanced testing methods for refractories that facilitate reproducible results, particularly for evaluation thermal shock resistance, corrosion and dimensional stability. In addition to laboratory tests, the development and validation of field tests that assess the performance of refractory materials up to components under operating conditions closer to reality remains a top research priority. Non-destructive and *in-situ* analyses are expected to provide great support to the ultimate objective of designing and processing new refractory materials and components.

While refractory properties and performance tend to have been investigated empirically, future research should provide theoretic models on relations between microstructure, materials properties and performance, with particular consideration of thermomechanical and thermodynamic properties as well as corrosion. In a long-term perspective, integrated computational materials engineering will enhance the simulation of fabrication processes, the prediction of microstructures and properties as well as materials performance.

## IV. Summary and Conclusions

This paper aimed at developing a roadmap for refractory research. The main contribution is therefore the delivery of an instrument for strategic research planning for various stakeholders including scientific communities, firms, and policy-makers. Based on extensive reviews of existing documents, interviews with actors in refractory research and industry as well as analyses of publications in the field, four major research trends have been identified. Future avenues for refractory research encompass novel materials compositions that enable improved or even extended materials properties. With regard to these novel materials, new approaches for materials preparation are sought. In line with that, research on forming and processing technologies remains a constant challenge. Finally, with the advent of quantitative, computer-aided methods and instruments, modeling and forecasting of materials properties and performance are identified as important fields for research.

This paper postulates that instruments such as roadmaps are important and valuable instruments for strategic planning in materials science and engineering. They can contribute to building consensus among actors in a field or discipline. They help to reduce the complexity of decision-making especially in research and technology management. Finally, roadmaps are powerful tools to identify relevant interfaces between different disciplines, opportunities for knowledge transfer between different scientific domains and relevant actors who are able to manage these interfaces. Thus, considering the multidisciplinary nature of materials science in general and refractory research in particular, this roadmap identifies interesting pathways for future basic and applied research.

## Acknowledgment

We thank the German Research Foundation DFG for supporting this research (project Ge 1273/5 – 2 und 6 – 2). We greatly acknowledge the cooperation of all participants during our interviews and discussions. Finally, we are indebted to our colleagues within the Priority Program for their constant help and support.

## References

1 Headrick, W.L.: Toward a “greener” future with advanced refractories, *Am. Ceram. Soc. Bull.*, **92**, 28 – 31, (2013).

2 Hemrick, J.G.: Improved refractories = energy saving, *Am. Ceram. Soc. Bull.*, **92**, 32 – 35, (2013).

3 Aldinger, J., Baumard, J.F.: Advanced ceramic materials: basic research viewpoint. *European Whitebook on Fundamental Research in Materials Science*. Max Planck Institute for Materials Research, Stuttgart, 26 – 31, (2001).

4 Taylor, J.: Managing the unmanageable: the management of research in research-intensive universities, *Higher Education Management and Policy*, **18**, 9 – 33, (2006).

5 Kostoff, R.N., Schaller, R.R.: Science and technology roadmaps, *IEEE Trans. Eng. Manage.*, **48**, 132 – 143, (2001).

6 Probert, D.R., Farrukh, C.J.P., Phaal, R.: Technology roadmapping – developing practical approach for linking resources to strategic goals, *Proc. Insta Mech. Engrs. Vol. 217, Part B: J. Engineering Manufacture*, 1183 – 1195, (2003).

7 Kappel, T.A.: Perspectives on roadmaps: How organizations talk about the future, *J. Prod. Innovat. Manage.*, **18**, 39 – 50, (2001).

8 Guimaraes, T.A., Borges-Andrade, J.E., dos Santos Machado, M., Vargas, M.R.M.: Forecasting core competencies in R&D environment, *R&D Manage.*, **31**, 249 – 255, (2001).

9 Gerdsri, N.: An analytical approach to building a technology development envelope (TDE) for roadmapping of emerging technologies, *Intern. J. of Innovation and Technology Manage.,* **4**, 121 – 135, (2007).

10 Roedel, J., Kounga, A.B.N., Weissenberger-Eibl, M., Koch, D., Bierwisch, A., Rossner, W., Hoffmann, M.J., Danzer, R., Schneider, G.: Development of a roadmap for advanced ceramics, *J. Eur. Ceram. Soc.*, **29**, 1549 – 1560, (2001).

11 Strauss, J.D., Radnor, M.: Roadmapping for dynamic and uncertain environments, *Res. Technol. Manage.*, **March/April**, 51 – 57, (2004).

12 Möhrle, M.G: Forms of research-related roadmaps of technology (in German). In: Technology-roadmapping. Future strategies for technology companies. (in German). Möhrle, M. G., Isenmann, R. (Ed.), 1 – 15, Wiesbaden, (2008).

13 Kostoff, R.N., Boylan, R., Simons, G.R.: Disruptive technology roadmaps, *Technol. Forecast. Soc.*, **71**, 141 – 159, (2004).

14 Probert, D., Shehabuddeen, N.: Technology road mapping: the issues of managing technology change, *Int. J. Technol. Manage.,* **17**, 646 – 661, (1999).

15 Hattendorf Westney, L.C.: Historical rankings of science and technology: A citationist perspective, *J. Association for History and Computing*, **1**, (1998).

16 Brown, L.D., Gardner, J.C.: Using citation analysis to assess the impact of journals and articles on contemporary accounting research (CAR), *J. Account. Res.*, **23**, 84 – 109, (1985).

17 Garfield, E.: Citation indexing: Its theory and application in science, technology and humanities, New York, NY: Wiley, (1979).

18 Norris, M., Oppenheim, C.: Citation counts and the research assessment exercise: V. Archeology and the 2001 RAE, *J. Doc.*, **59**, 709 – 730, (2003).

19 Deenen, M.A., Gross, A.C.: Refractory Materials: The global market, the global industry, *Business Econ.*, **45**, 288 – 295, (2010).