High Temperature, Low Dielectric Constant Ceramic Fibers - HTC

Problem Statement

OBJECTIVE: Develop advanced high temperature ceramic fibers exhibiting high strength, low dielectric constant, low loss tangent, high thermal stability, and high oxidation resistance for missile and projectile system applications.

DESCRIPTION: Missile components such as radomes and control surfaces are subjected to tremendous thermal stress during missile flight. Current missiles use high temperature metals for control surfaces and ceramics (such as silicon nitride or silica) for radomes. Future advanced missiles will require components with greater thermal shock resistance with properties such as those exhibited by ceramic matrix composites (CMCs). However, the only fibers available for incorporation into CMCs are fused silica ("quartz" fibers), Nextel aluminosilicate fibers from 3M, and Nicalon fibers. These fibers suffer from a limitation on service temperature, generally about 1000-1200°C for the oxide fibers, and 1400°C for silicon carbide fibers. In the past, there has been insufficient market potential to support commercial development of fibers for higher temperature service. Higher temperature fibers are desired, with the capability of surviving 1500°C or higher. For radome applications, fibers with low dielectric constant and low loss tangent are needed. The desired values for dielectrtic properties, mechanical properties, and thermal properties depend on specifics of the radar system and overall weapon design, and can vary. There is no absolute limit for either, but the concepts are discussed in the reference by Walton [Ref 5]. Examples of possible compositions for high temperature, low-dielectric constant fibers include boron nitride (BN) and silicon nitride (Si3N4). Both types of fibers were produced experimentally in the 1975-1995 timeframe but are not available commercially. Availability of high temperature fibers possessing the desired combination of properties (such as high elastic modulus, low dielectric constant and loss tangent, and high strength to elevated temperatures) will enable the development of ceramic matrix composites with vastly improved high temperature properties compared to current CMCs. Missile components needing these material technology improvements include radomes and control surfaces, since they tend to experience the worst of thermal heat stresses during high-speed flight. As such, the material solutions will need to have electrical properties conducive to radome functionality (e.g., low dielectric constant, low loss tangent) in addition to high thermal stability and high oxidation resistance necessary for both radomes and control surfaces. Possible applications for the desired technology include tactical missiles, long range guided projectiles, and hypersonic vehicles.

For this exam, focus on the following…
Per the instructions below and the additional guidance provided during your Candidacy Exam training sessions, prepare a research and development proposal, that if funded will allow you to ***Develop a concept for high temperature ceramic fiber materials that meets the parameters and applications in the description. Establish concept feasibility of the requirements through analysis, modeling, and experimentation of materials of interest. The Phase I, if awarded, will include the initial design specifications and capabilities description to build a prototype solution during a potential follow-on in Phase II.***

REFERENCES:
1. Kamimura, Seiji; Seguchi, Tadao and Okamura, Kiyohito. 'Development of silicon nitride fiber from Si-containing polymer by radiation curing and its application.' Radiation Physics and Chemistry, Volume 54, Issue 6, June 1999, pp. 575-581.
https://www.sciencedirect.com/science/article/abs/pii/S0969806X97003149
2. Yokoyama, Yasuharu; Nanba, Tokuro; Yasui, Itaru; Kaya, Hiroshi; Maeshima, Tsugio and Isoda, Takeshi. 'X-ray Diffraction Study of the Structure of Silicon Nitride Fiber Made from Perhydropolysilazane.' American Ceramic Society Journal, Volume 74, Issue 3, March 1991, pp. 654-657.
3. Okano et al. US Patent US5780154A. Boron nitride fiber and process for production thereof.
https://okayama.pure.elsevier.com/en/publications/x-ray-diffraction-study-of-the-structure-of-silicon-nitride-fiber

4. Johnson, Sylvia. 'Ultra High Temperature Ceramics: Application, Issues and Prospects.' American Ceramic Society, 2nd Ceramic Leadership Summit, Baltimore, MD, August 3, 2011. http://ceramics.org/wp-content/uploads/2011/08/applicatonsuhtc-johnson.pdf
5. Walton, J.D. 'Radome Engineering Handbook: Design and Principles.' Marcel Dekker, Inc., New York, 1970. https://openlibrary.org/books/OL5077781M/Radome_engineering_handbook

KEYWORDS: Missiles; Guided Projectiles; Radomes; Thermal Shock; Missile Erosion; Hypersonics.

You are the Chief Technology Officer of a company that has specialized in creating low volume customized high reliability nanofibers for specific applications in demanding environments. Your CEO believes that the company's expertise in micro to ceramic nanofiber materials, processing, and devices could provide a research and development path to meet DOD objectives in their solicitation. Your job is to define the research and development needed for new base technologies that would provide the platform for many future ceramic nanofiber technologies, and perhaps even expansion into other harsh environment markets (aircraft, spacecraft, etc.).

While meeting the DOD performance requirements are your priority, the cost of customized systems for ceramic nanofiber improvements could be high, initially, as compared to off the shelf commercial systems. In order to have potential to be competitive in other market applications which value compact, high-performance, it is desirable if your approach can be easily modified or adapted for lower price-point markets.

Your job as CTO is to deliver a complete proposal with your plan for the company to compete in this area to your CEO by your deadline.

YOUR DELIVERABLE

Your task is to write an internal proposal for your corporate officers describing your idea for research and development. The proposal should include all components, sections, etc. per your Candidacy Exam Template and SOP/Guidance documents.

Most Importantly – The fundamental rationality and reasonableness of your proposed solution is of critical importance. The significance and novelty of your creative solution, one that moves the boundaries of knowledge outward, is also of critical importance.

The list below is just a minimum list of issues you might consider and provides additional guidance regarding what you should address in the relevant sections of your proposal (written exam). There may be many more. The point is that your proposal ***should contain the evidence*** needed to make an effective and compelling case to your CEO in order to ensure that they make the right decision.

The guidance below can be used to help you with the preparation of some of the more unfamiliar content required per the Template document. At a minimum, and within the guidelines provided by the SOP and Template documents, be sure you address all of the following additional items where relevant in your written exam response.

Current Science and Technologies – What is already being done in this area by other researchers, companies and governmental institutions? Describe the current state-of-the-art for both the science and the implementation. Use diverse resources such as science literature, journals, conference proceedings, the internet, patents and other sources of existing public knowledge. ***Cite all references you use and use quotes for any word-for-word transfer to your report.***

Your Design Approach – What is the basis for your design approach to the problem? Why is your technology better than existing technologies? What technology attribute(s) make it likely to be selected by DOD? Address scientific *and* engineering aspects of these questions. Where relevant, consider: device size, weight and power (SWAP) requirements; materials of construction; critical components and considerations that comprise the complete device-level or subsystem-level solution; and what are the required prototyping and/or production methods, tools and costs? ***Even***

if you are not an expert in all of the technological areas required to bring the end-product to fruition, you should at least be able to intelligently discuss the other critical components, considerations and R&D requirements.

Research & Development Plan – Describe a set of tasks and/or tests you will complete to demonstrate that your approach is effective and that your implementation of the solution is meritorious of further R&D. ***This is essentially your design of experiments. What are your objectives? What are the tasks required to achieve those objectives?*** Where applicable answer the following:

i) What are the key product specifications that you are targeting and how do they compare to the specifications of the existing solution(s) if any exist?
ii) What mathematical models and/or simulation constructs will you use to validate your approach, especially if prototyping and test trials are costly?
iii) What are the key dependent and independent variables that you must utilize and evaluate to confirm the proposed solution works?

Above all, be specific and detailed about the key tasks to confirm feasibility and validity of what you are proposing.

Cost Analysis – Identify cost and market issues that will impact the pricing strategy of the solution you have proposed. Identify Strengths, Weaknesses, Opportunities and Threats (SWOT) in the market place. If you are unfamiliar with the typical SWOT marketing analysis, I encourage you to 'google it'. Consider such things as: the major cost items that would impact the implementation; which elements of your implementation solution would be handled in-house versus externally-sourced; major risk elements that could drive up costs if the primary path item fails; costs of IP licensing needed, etc. Provide justification and/or reasoning behind your decisions. Avoid subcontracting design, manufacture or assembly of any *proprietary* component outside the company, because the CEO is concerned with potential IP leakage. Utilizing suppliers of common materials or devices is acceptable.

Hint – Clearly state your hypothesized solution. Identify its innovation(s) and advantages relative to state of the art. Describe both existing data, and work needed to support each aspect of the hypothetical solution. Consider theoretical, fabrication, and characterization aspects: for each, identify software/equipment and methods to use, parameters to vary, anticipated outcomes, and possible alternatives in the event of unsatisfactory results. Discuss material, process, device, and systems aspects of your solution. *Refine* your hypothesized solution as you accumulate information and prepare the manuscript. **Remember**: clearly distinguish what is known from what is hypothesized or not known. What is needed to distinguish the important things to know?

Refer to the 2021 MSEN PhD Candidacy Exam SOP and Guidelines and the MSEN PhD Candidacy Exam Template documents for all additional instructions.