Materials Science and Engineering:
a focus on energy, sustainability, and manufacturable devices

A. Executive Summary

This proposal evolved from two "Round 1" submissions in the SAF exercise: *Materials Science and Engineering (MSE) Graduate Group*, and *Materials Science and Engineering (MSE) Undergraduate Program*. It describes MSE as a central discipline within the SAF-defined theme #8 – Matter Science and Engineering: from theory to application, linking fundamental sciences (physics, chemistry, mathematics) and other engineering specialties (mechanical, computing/electrical, environmental, bio). In addition, we indicate ways in which MSE can synergize with *all* of the other themes arising from Round 1 of the SAF exercise.

We emphasize the unique attributes of MSE within the spectrum of MSE-related research (inherently multidisciplinary; multiscale approaches to connecting structure and properties of matter in the solid state; a natural home for research and teaching in nanotechnology; the benefits to our graduated of ABET accreditation). We propose focused growth in the areas of energy materials, sustainability and manufacturable nanoscale devices.

Several recent influential government-funded reports, from agencies in the USA and abroad, have headlined how commitment to materials research and education is vital for technological advancement and future prosperity.

B. Definition of Thematic Area

Materials Science and Engineering (MSE) is a broad field that builds on fundamental chemical and physical principles to design, synthesize, process and characterize materials that have desirable combinations of mechanical, optical, electrical, magnetic, electrochemical and other properties in the solid state. MSE also addresses the environmental impact and financial cost of the ingredients and processes that are used to produce particular materials, seeking to maximize sustainability. MSE has a clear fit in the **SAF-defined theme #8 – Matter Science and Engineering: from theory to application**.

Because of its central role in linking fundamental sciences and other engineering specialties (mechanical, computing/electrical, environmental, bio, chemical, civil), MSE leads to an unusually wide range of academic, industrial and service career choices, within and beyond scientific and technological fields. Employers appreciate the ability of MSE graduates to relate to colleagues across a broad spectrum of expertise. National and international surveys consistently indicate that MSE-related employment opportunities far exceed the supply of suitably qualified individuals with advanced degrees in the subject.

Four particular characteristics of MSE support a central role for the planned MSE graduate group, the MSE major, and proposed MSE minors within the theme:

(i) Even within itself, MSE really does link atoms to appliances, covering *a spectrum of research extending from the basic sciences to engineered devices*.

(ii) MSE theoretically and experimentally addresses the connections between the structure

and properties of matter *over a range of length scales*. Thus *the roles of nano- micro- and macrostructure are all taken into account in a multi-scale approach to the optimization of properties*.
(iii) MSE is a *natural home for the growth of research and teaching in nanotechnology*. Two popular electives in nanotechnology for UCM students across many science and engineering disciplines have been developed by an MSE faculty member.
(iv) The undergraduate MSE programs can be accredited by ABET (and a decision on accreditation of the MSE major is currently pending); this status provides *a route to Professional Engineer (PE) accreditation of our graduates*, and thus to enhanced earning potential and prestige.

MSE seeks to form strong and hopefully seamless ties with the research proposed by other materials-related disciplines. At the time of writing we are aware of – and are enthusiastic about collaborations / integration with – the following materials-focused initiatives being assembled by colleagues: *Nano-Bio Materials* (convened by Sayantani Ghosh), *Multiscale Assemblies of Soft Biological Matter* (convened by Ajay Gopinathan), and *Materials Research Initiative* (convened by Erik Menke). We are recruiting the conveners to join the core group of faculty around which an MSE graduate group proposal is being developed (anticipated submission August 2014); they will also support the teaching of the associated MSE undergraduate major and proposed minor. One of the many potential benefits of these synergies is that we will be able to develop well-structured opportunities for students to take a degree in MSE (both the graduate group and the undergraduate program), or in an MSE-related program, with tailored concentrations in Engineering, Physics or Chemistry.

C. Intellectual Components of the Strategic Initiative

A recent report from an influential research evaluation provider (Ref. 1) envisages the 21st century as an era of revolutionary discoveries in materials research that result in far reaching changes for society and how we live. The authors note that Asian nations and institutions are clearly focusing their research efforts on new materials, and that there does not appear to be a similar commitment to this research on the part of Europe and North America — especially on the part of the USA which has seen its world share of materials sciences research papers not only fall by half in the last three decades but actually decline in output in the late 1990s and in the early years of the last decade. It is only now that the USA's output of such papers is returning to the level of 1996. "*However, materials research in particular is closely tied to economic growth*. Therefore, US and European Commission policy makers and elected representatives may wish to consider whether it is important, even vital, to make a larger commitment to materials research for the sake of future prosperity — even beyond that provided by the US National Nanotechnology Initiative and similar funding by the European Commission."

Even more recently, the UK Engineering and Physical Sciences Research Council (EPSRC) has recognized (Ref. 2) several contemporary reports from the USA and Europe, highlighting the importance of materials and materials research. These reports include the USA's Materials Genome Initiative for Global Competitiveness (Ref. 3). A majority of the fourteen grand challenges in engineering issued by the National Academy of Engineering require that materials and material systems with properties and performance superior to today's materials be developed (Ref. 2).

A clear consensus emerges on where materials have the potential to impact significantly on societal issues. These areas of significant impact are centered on sustainable economic growth, manufacturing (scalability), energy, healthcare and the environment – encompassing the strengths in *Sustainability* and *Human Health* that UC Merced has been most successful at developing and that have the greatest potential for growth. The reports also tend to agree on the technologies that will be required to realize these goals: they include nanotechnology and advanced materials. There is also agreement on some of the generic requirements to advance the area such as modeling and simulation, as well as on research areas that are especially worth pursuing (areas of existing strength in and related to MSE at UC Merced are in italic font):

- *advanced materials with novel or improved properties*
- *development of rational approaches in the design of advanced materials or in their integration into structures and systems*
- *inspiration by nature (eco-design, bio inspiration and use of natural materials, polymers from non-petrochemical sources)*
- anticipation and control of the performance of materials during the life cycle (including self-sensing and self-healing); replacing scarce elements
- *inorganic materials for photonics and energy (e.g. energy transport, storage)*
- non-organic materials for advanced multifunctional microsystems
- *materials based on novel functionality though molecular organic compounds and polymers*
- meta-materials and *nanostructured materials*
- functional and multifunctional oxide films
- *materials to support healthcare (biomaterials, stem cells, regenerative medicine)*

Within the current five (soon to be six) MSE core faculty, we already have current local expertise in several of the above-listed themes. Specifically looking at the themes of Sustainability and Human Health, we identify expertise that includes:

- "Green" synthesis; all-carbon photovoltaics (Vincent Tung)
- Design and synthesis of materials for energy transduction, transport and storage (Jennifer Lu)
- Characterization of nanomaterials for energy applications, and of nanoparticulate air pollutants (Valerie Leppert)
- Rational design of advanced materials through multi-scale computation (Lilian Davila)
- Bio-inspired and natural materials, and process kinetics (Christopher Viney)
- Biomaterials (tba; appointment in progress).

The proposed MSE graduate group will expand this pool. To date, commitment to participate as founding members of the group has been received from experts in:

- Physics of new materials for applications in energy storage and information processing devices (Sayantani Ghosh, PHYS)
- Electrochemical energy conversion and storage devices (Min-Hwan Lee, ME)
- Control of materials performance: wear and lubrication; materials for extreme environments (Ashlie Martini, ME)

- Materials for regenerative medicine; tissue engineering (Kara McCloskey, BIOE)
- Nanostructures for solar cells; new electrolytes for batteries (Erik Menke, CHEM)
- Characterizing biomolecules for development of artificial functional biomolecular structures and ultra-sensitive biosensors (Tao Ye, CHEM).

Collectively, this group is especially strong in the areas of (i) design and synthesis of novel hybrid materials with focus on energy storage / conversion and biomimetic scaffolds for sustainability applications, (ii) in-depth characterization of structural and mechanistic origin of properties, (iii) focused research efforts in nanoscience (synthesis, characterization, testing, simulations), and (iv) innovative approaches to education (team-based, active learning).

Further growth and consolidation of this research talent pool to achieve signature device fabrication capabilities will occur by recruiting additional members of the current faculty as core or adjunct members of MSE, and by new hires as detailed below.

D. UCM's Role

All nine of the UC campuses that offer both undergraduate and graduate education have programs in or related to MSE. One of our greatest strengths at UCM is our ability to conduct and complete this type of planning exercise that will enable us to uniquely develop research along multidisciplinary lines. In similar vein, we have the maneuverability to expose students to learning opportunities that can only be found in an environment where knowledge is not artificially compartmentalized. We can still implement a uniquely responsive academic culture without having to expend money, time or effort to dismantle deeply rooted pre-existing departmental structures or boundaries.

In addition to its clear fit in the SAF-defined theme #8 – Matter Science and Engineering: from theory to application, MSE anticipates connections with all of the other themes arising from round 1 of the SAF exercise, through possible shared interests that include the following examples:

SAF theme #1 – Disparities: Equity, Diversity, Social Inequality.
Progress in MSE plays important roles in the accessibility and affordability of technology, advances in communication and infrastructure, and the equitable distribution of resources such as clean water and energy. It also affects who bears the burden of pollution and waste from materials extraction, processing and disposal.

SAF theme #2 – Cross-cultural Studies and Cultural Production.
MSE characterization techniques and procedures for preventing materials degradation have a role in the preservation of important cultural and historical artifacts.

SAF theme #3 – Human Health
MSE faculty are engaged in health related work, e.g. responsive biopolymers, biosensors, and scaffolding for regenerative medicine, that could leverage and/or be leveraged by other human health efforts on campus. Also, MSE faculty conduct research in air pollution that is highly relevant to the SJV, where 6 of 10 of the worst polluted cities in terms of

particulate matter are located; they have strong ties with other universities and state agencies engaged in similar research.

SAF theme #4 – Innovation and Entrepreneurship
There is a lot of scope for interactions that help innovations in MSE to become marketable reality, with regard to materials selection, materials processing, and devices. A strong research base in innovative materials can provide one means to retain UCMs graduating talent locally, and thus fulfill one of the original purposes of siting UCM in the Central Valley: diversification of the regional economy.

SAF theme #5 – Environmental Sustainability
Synergy between MSE and this theme can promote research into energy materials, and sustainable manufacturing processes (sustainable use of raw materials, finding acceptable alternatives to scarce elements and minerals, and minimizing environmental impact during material extraction, manufacture, and disposal). In dealing with sustainability solutions at this technically foundational level, MSE can be a useful complement to programs that focus more on policy issues (e.g. SNRI).

SAF theme #6 – Energy and Energy Systems
There are numerous MSE-related challenges associated with the large scale harnessing of energy sources as well as the nanoscale transduction of energy. Solar, wind, wave, geothermal and nuclear energy harvesting all impose unique and demanding requirements on materials used in devices that concentrate or collect the energy.

SAF theme #7 – Information, Computational, and Data Sciences, and Engineering
MSE supports the proposal for a Computational and Data Science theme; its scope includes the types of modeling and visualization methodologies that are used to predict the properties of materials across multiple length scales. The development of next generation materials will depend on synergy with this theme.

SAF theme #9 – Life Sciences
MSE can serve as one of the many bridges that link life sciences and human health. Nature can inspire efficient, environmentally sustainable practices in materials selection and processing (self-assembly), and so can inform the design of ideally biocompatible devices and implants.

The breadth and inherent inclusiveness of MSE is such that we look forward to exploring ties with any other SAF themes that emerge from the current round of planning.

E. Faculty Participation

The following bylaw units, graduate groups and programs (listed alphabetically here) might participate in the overall research theme: The list is not exclusive, but is an attempt to round up the main and most likely collaborators.

- Applied Mathematics (unit and graduate group)

- Bioengineering
- Biological Engineering and Small-Scale Technologies (Graduate group)
- Chemistry and Chemical Biology (unit and graduate group)
- Environmental Systems (graduate group)
- Materials Science and Engineering (program and graduate group)
- Mechanical Engineering (program and graduate group)
- Physics (unit and graduate group)

We envisage that a liaison group, consisting of representatives of each of these constituencies, will meet regularly (at least once or twice a semester) to facilitate collaborations, co-ordinate responses to funding opportunities, and develop curriculum.

F. Special Programmatic Needs

The programmatic needs will be served by a new graduate group in MSE and by a strong undergraduate program in MSE. The latter will be augmented by the instruction of MSE minors that enable students who major in related disciplines to obtain recognition for a focus on MSE as it pertains to those disciplines.

We anticipate that as the program grows, additional hiring would take place in areas that include Materials Sustainability, Solid State Structure Characterization (linking molecular design, structure and processing), and Nanodevice Fabrication. Additionally the program would need adequate staffing to support grant writing and program management, student outreach and recruitment, and collection of data for assessment metrics. The program would need IT resources for research, for developing and hosting online courses, and for robust internet and videoconferencing facilities to develop teaching and research collaborations with other institutions. Investment in space for current and future faculty is also needed, especially lab space with fume hoods (that could be shared with related programs).

References

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3. Materials Genome Initiative for Global Competitiveness, National Science and Technology Council, June 2011.
4. The Future of Materials Science and Materials Engineering Education: a report from the Workshop on Materials Science and Materials Engineering Education sponsored by the National Science Foundation, September 18-19, 2008 in Arlington, VA.