Engineering and Materials

Summary
This section identifies four critical scientific grand challenges in materials engineering that will enable the science-based discovery and implementation of high performance materials and engineering processes required for the US to maintain its leadership in advanced manufacturing and technology sectors such as aerospace and defense.

1. **Leverage Advanced Multi-Scale Characterization to Develop True Digital Twins**: Current material characterization techniques lack the precision and integration required for the development of accurate, dynamic digital twins. By leveraging multi-scale voxelated data from atomic through nano to macro levels, this challenge seeks to build comprehensive 3D datasets that enable precise digital twins of engineering materials. These advanced neutron-based characterization techniques will allow for real-time, detailed modeling of material behavior in high-performance applications.
2. **Understand the Evolution of Complex Materials under** operando **Conditions**: Engineering materials undergo complex, time-dependent transformations which are not currently well understood. This challenge proposes instrumentation that can measure the time dependence of voxelated strain tensors creating nD data sets during operando materials processing. This approach in combination with the predictive capabilities of trained AI systems can provide materials insights that are essential for scientific discovery to enable high technology manufacturing.
3. **Discover Materials and Processes for Autonomous Construction Innovations**: The construction industry's reliance on outdated, resource-intensive methods contributes significantly to global CO_2 emissions and inefficiency. Leveraging robotics and additive manufacturing, as well as advances in chemistry and soft matter science enabled by next generation neutron scattering will enable a new epoch for the built environment that is not reliant upon outdated construction methods such as form work and is orders of magnitude more energy efficient. Such developments are an essential requirement for any extra-terrestrial habitat development or interplanetary exploration.
4. **Enabling the Circular Economy and Material Reusability**: Current recycling practices result in downcycling, where material quality degrades with each reuse, limiting its value for high-performance material applications. This challenge seeks to enable a true circular economy by utilizing data from neutron scattering to create materials that can be recycled without quality loss, employing advanced characterization and tensorial tomography will ensure scientists can evaluate and find candidate materials that retain their integrity and performance through reuse cycles. Digital twins will allow for predictive modeling of recycled materials, paving the way for a sustainable system where high-value materials can be reused, significantly reducing resource waste and environmental impact.

These four grand challenges will first be described in more detail, followed by a discussion of why neutron scattering instruments at the Second Target Station are essential to address these challenges.

Grand Challenge #1: Leverage Advanced Multi-Scale Characterization to Develop True Digital Twins:

A grand challenge facing the nation is the development and deployment of science-based certification method(s) for new materials for service in complex, dynamic, and/or extreme environments. Many industries require all new materials and components to be certified, currently based on databases of in-service performance data generated by Edisonian approaches. A canonical example is the qualification of materials for the nuclear power industry, wherein materials used for pressure boundary applications must follow the American Society of Mechanical Engineers (ASME) code qualification process that requires thousands of hours of high-temperature (>300°C) creep data from multiple process heats of the material [1-3].

Consequently, despite recent advancements in materials design and manufacturing processes with engineered structures that offer superior properties and performance over existing materials and components, these high-performance materials have not been deployed since they have not yet been certified or qualified. This has limited reactor designers to just a small number of qualified fuels and materials, certified decades ago, thus hindering the nuclear industry from constructing with the highest-performance materials. Such approaches stifle technological and cultural progress due to the long-lead times and often expensive nature of the exposures, especially for materials, material systems, and components used within extreme environments.

A science-based approach for the certification of materials in engineering applications would leverage the use of digital.twins—virtual tools that **comprehensively encompass both the formation/manufacturing process and in-service performance of the material/component in four dimensions** (i.e., the three spatial dimensions plus time). This paradigm shift would revolutionize the speed and efficiency with which new technologies can be brought to market, enabling rapid innovation and adaptation while also considering the safety, usability, recyclability, and other desirable attributes crucial for fostering a sustainable and technologically advanced society.

Such a revolution in materials certification is a **grand challenge due to the complexity and interconnectivity of intrinsic and extrinsic factors** on materials performance. The interplay of material structure, composition with various stimuli during service, such as stress, temperature, pressure, magnetic fields, and electric fields, further complicates this. Even a small change in a single variable can significantly alter the immediate and/or long-term performance of a material. Capturing the coupled correlation of composition-structure-properties is inherently difficult if not impossible with current means and timelines for materials synthesis and materials interrogation. This grand challenge is the culmination of a decade plus of established priority basic research directions [4].

An example of the current state-of-art of science-based certification is the on-going effort towards the qualification of additively manufactured (AM) components. Presently, AM products are qualified based on simple test geometries that often overlook spatial and temporal variations in thermal and mechanical strain and the presence of physical defects, leading to standards that cannot quantitatively estimate component life. Federal agencies have recognized these limitations and challenged the community to develop science-based qualification methods using computational modeling and in-situ monitoring [5]. **Timely and reliable certification of failure-critical aerospace components is a strategic industrial and defense need for the United States**. Early defect and fracture detection in component-scale samples will be critical in tuning and benchmarking such numerical models to the point where their results are of sufficiently high quality that they are accepted by certifying agencies in lieu of expensive parametric fatigue experiment series. Multimodal live *in situ* or *operando* measurements in a SANS, imaging or diffraction beamline will provide us with critical insights into the dynamics/kinetics under the relevant environment. **Early fracture detection in advanced components in the void nucleation phase remains the holy grail of engineering mechanics** and may be enabled by dynamic imaging with simultaneous Bragg Edge Imaging (BEI) (strain/phase evolution) and neutron Grating Interferometry (nGI) (porosity/nucleation evolution) modalities [6]

The development of detailed digital twins will enable predictive modeling and real-time monitoring, enhancing the safety, reliability, and longevity of materials used in critical applications. These advancements will significantly reduce the time and cost associated with material certification, facilitating the rapid deployment of high-performance materials and components across various industries. By addressing the limitations of current certification processes, the STS will drive innovation and support the transition to more sustainable and advanced technologies.

Grand Challenge #2: Understand the Evolution of Complex Materials under operando Conditions:

Recent strides at ORNL-SNS VULCAN beam line have created a new state-of-the-art by showing the feasibility of measuring temperature evolution, elastic and plastic strains, texture, and phase fractions under real-time conditions, with the resultant data shown in **Figure 2.1** [7]. Such results are used to verify and validate a computational model, which in turn can be used for predicting residual stress evolution in other complex geometries. However, to understand the long-term stability of these microstructures under loading conditions, there is a need to estimate the partitioning of alloying elements (e.g. carbon, nitrogen, and hydrogen) between phases, as well as the variations close to the small-scale macro defects that control the fatigue life. Extracting such elemental distributions even under *ex situ* conditions across a practical sample volume on the order of cubic centimeters is beyond current neutron diffraction tools, as the sources cannot provide the peak brightness and cold neutron spectrum required for voxelized quantitative imaging required to locate damage zones that are not known *a priori*. **A dedicated multimodal imaging/diffraction instrument or instrument suite on the Second Target Station (STS)**

will enable a tensorization of the stress and strain dataset into a true information volume.

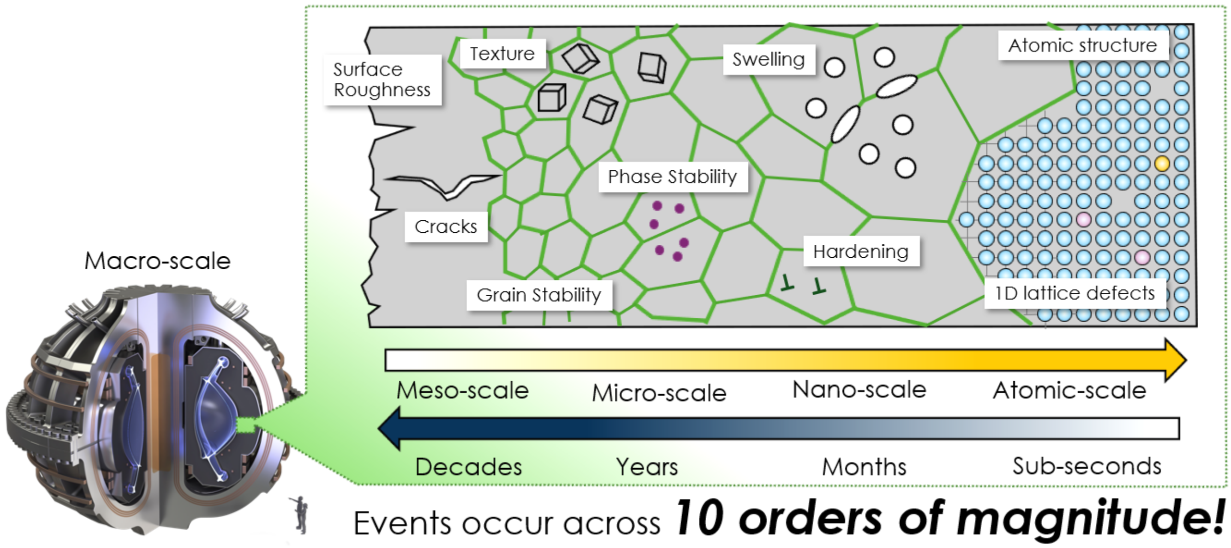

Figure.8¡7¡ *Example of a failure-critical structural cladding component in an experimental fusion reactor. Material kinetics relevant to the performance of each component span ten orders of magnitude in the length scale, from the atomic to the meso scale. An accurate multiscale understanding of not only the material system but the specific part with a specific manufacturing history (casting, extrusion, machining, heat treatment, surface finish, etc.) must be considered for an accurate quantification of component performance [8].*

Advanced neutron characterization capabilities at the STS will enable a detailed understanding of complex, time-dependent transformations crucial for developing transformative manufacturing processes. Taking Additive manufacturing (AM) as an example, the STS would provide critical insights for AI/ML of AM processes (e.g., process optimization and in-process close-loop control), and guidance in post AM processing parameter optimization (e.g, HIP, heat treatment) for AM large components but with very sharp gradients in composition, microstructure and stress (e.g., within submillimeter scales) produced in either ambient or space environment, and component life prediction under extreme service environments (e.g., extreme temperature and fluctuations, corrosive environments). Materials of interest could include superalloys and complex composition alloys (e.g., composites, HEAs). When small samples are extracted as common in conventional characterization, the bulk stress profile is partially lost. In-situ imaging, small- and wide-angle scattering simultaneous measurements at STS with high penetration capability through sample environment and specimen size would enable a fundamental understanding of the interplay of phase transformation and three-dimensional stress evolution during heating and loading, under high pressure, and how they impact defect evolution (micron sized) in large components with extreme complexity in composition, microstructure and residual stress distributions. Multimodal imaging/tomography can simultaneously probe material kinetics at the macroscale while nGI and BEI probe the micro and atomic scales, generating a 4D information volume. Such capabilities critically require the cold and bright neutron flux of the STS.

The scientific impact of the STS will be transformative, bridging the gap between research and practical application, and empowering scientists and engineers to push the boundaries of material science. This will not only accelerate technological progress but also foster a culture of continuous improvement and innovation, ensuring that society can meet the growing demands of modern challenges with confidence and resilience. **Maintaining a position of global leadership in advanced materials manufacturing (aerospace, defense, nuclear) is a strategic national priority and thus requires the utmost support.**

Grand Challenge #3: Discover Materials and Processes for Autonomous Construction Innovations

Motivation

Civil **construction remains one of the most dangerous, inefficient global industries, largely devoid of automation**. Concrete's high strength, flowability during construction and a track record since the Roman empire has led to tens of gigatons being used on an annual basis, requiring more than four gigatons of cement powder (the glue in concrete) to be manufactured annually [1]. The global usage of concrete on a volume basis is second only to society's need for water, which leads to massive resource and energy requirements. Cement production amounts to 8% of global human CO_2 emissions [2]; **the built environment amounts to 37% of global anthropogenic greenhouse gas emissions** [3]. As identified by DOE, transformative manufacturing is fast emerging as a critical area of development in the United States [4]. Innovation and transformative manufacturing are central to the future of construction materials, where efforts will focus on sustainability, additive manufacturing, and high-performance systems [5-6].

The transformation of construction using advanced cements, concrete AM, and robotic construction will revolutionize not only the construction process but the entire built environment, both on-planet and off-planet. A paradigm shift is required in how we construct buildings, considering that the current standard remains dominated by manual labor, with each building being constructed by hand. These inefficiencies have generated not only economic cost of workplace accidents, elevated prices for infrastructure and housing, they have also formatively contributed to the nation's housing shortage. Autonomous, robotic construction is evolving in various forms, although two main areas are currently being investigated in the academic realm. Robotic construction pertains to the erection of structural systems from existing building blocks (masonry units, truss members, etc.). Concrete additive manufacturing (**Figure 3.1**) constitutes the most disruptive advance and is hybridized with the former to yield the most powerful modality. For example, shotcrete (spray-deposited concrete) deposition around a robotically erected reinforcing steel (rebar) allows for fully autonomous construction of reinforced concrete structures.

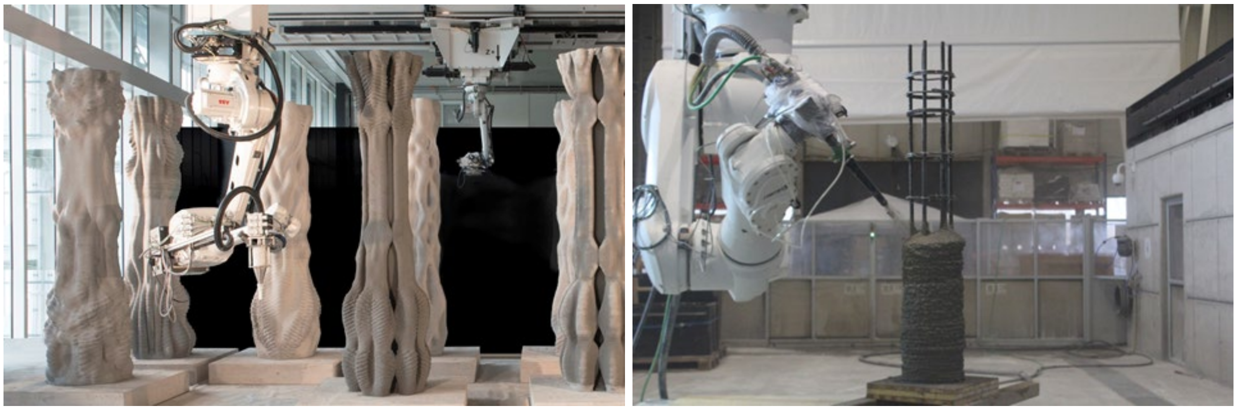

Figure.9¡7¡ *(left) extrusion deposition printing of complex structural members using an inverted robotic gantry system [7] and (right) shotcrete spray deposition printing of a reinforced steel column [8].*

The **grand challenge of revolutionizing how we build will critically require a holistic understanding of that most ubiquitous building material: concrete**. Novel deposition methods of concrete allow for the negation of traditional formwork, removing a major construction expense and decoupling fabrication from the inherent geometric limitations of said formwork [9]. At present, when we build a concrete building, we build it twice: structural formwork is erected, the concrete is placed in the formwork, allowed to cure, and the formwork that was built just days prior is demolished at great cost. Further, additive manufacturing and autonomous construction techniques also allow for the creation of complex shapes at little extra cost to simple geometries, a corollary to polymer and metal powder AM. Concrete structures can be topologically optimized [10], functionally graded (**Figure 3.2**), and printed with voids to accommodate electrical, mechanical services, and insulation in a fully integrated manner [11]. Unlike traditional formwork concrete placement, the stability and mechanical fidelity of the printed structure depends heavily on the printing strategy and, most importantly, on the material being printed. The advantages inherent in additive manufacturing of concrete are countered by a considerable knowledge gap: a truly multiscale understanding of advanced concrete materials fit for additive manufacturing. To date, humanity has largely neglected to gain a holistic understanding of cementitious materials since casting does not require mechanical performance of the mix in the uncured state, as it is both confined and supported by the formwork. A multitude of critical materials challenges remains unsolved that will allow these technologies to be deployed to practice and scaled globally.

Figure.9¡8¡.*Bioinspired functionally graded material with porosity gradient across the depth of the print. The built system allows for strong weather resistance on one surface while integrating both structural efficiency in bending (highest density at outermost fiber of structure) and insulating characteristics into an otherwise highly thermally conductive material.*

Embedded interfaces are found in concrete due to the inclusion of sand and rocks, and with increased AM and the use of material additions, more complex interfaces will be present in these materials in the future. Additively manufactured concrete material must also perform over the service life of the structure on the order of decades, if not centuries. Thus, the performance of structural systems, not just the cementitious matrix but a composite consisting of fibers, macro reinforcement, and other hybrid components, must also be investigated in depth. A **multiscale understanding of the material from fresh mix to virgin hydrated matrix and ultimately to aged system must be established before the material will be accepted into engineering practice**. The high cost of failure (i.e. damage, collapse of countless structures in the nation, i.e., Surfside condominium collapse, 2021) demands this degree of fidelity of study for this disruptive change to gain acceptance in the engineering community and the broader public.

Extraterrestrial Robotic Construction

The apex of this grand challenge lies with the **complete replacement of traditional Portland cement**. New materials must be developed for us to transition greener materials that can be deposited by autonomous, robotic, extrusion-based systems. Cement substitutes will realize substantive CO_2 reductions. A key benefit in terrestrial concrete printing will be the ability to hyper-localize the supply stream, i.e., print with materials found at the construction site. Deep learning algorithms, trained by rich neutron voxelized neutron data will help to enable such a paradigm shift.

These developments will facilitate extraterrestrial robotic construction, which is essential for the fabrication of habitats (**Fig. 3.3**) before the arrival of human habitants. Shielding of extraterrestrial habitants from cosmic radiation will rely heavily on robotically printed structures. Material recipes for such prints will be deduced from fully integrated multiscale/multiphysics models that have been established on Earth, derived in part from STS neutron data, in years preceding the launch to the Moon and, ultimately, to Mars.

Figure.9¡9¡ *Artist's rendering of Mars habitats, robotically constructed before the arrival of the Martian astronauts [12].*

The transformation of how we build and what we build with will effectively disrupt societal change and may well **solve the housing crisis while substantively decarbonizing the national economy and provide a means for expansion of human habitation off-world.**

Grand Challenge #4: Enabling the Circular Economy and Material Reusability

The transition towards a sustainable, circular economy relies heavily on developing and adopting the materials that will support a circular economy. Despite best practices and guiding principles, implementing circular economy materials yields significant challenges regarding control of composition, which impacts performance, reliability, and reuse of the materials-in-design. Furthermore, the complexity of material composition necessitates building multiscale models to support the emerging machine learning platform in the inverse design of circular materials. A comprehensive approach is needed, starting with the design and synthesis of materials that meet performance and reliability requirements. To achieve this goal, we must understand fundamental material behavior across multiple scales throughout the chain of use, recycling, regeneration, repurposing, and reuse.

Creating a sustainable, circular economy requires sustainable materials such as green steels, concrete, energy materials, and green composites. Many of these materials are

hierarchical in structure and require methods that allow observation of multiscale phenomena over an expanded range of wavelengths. The following three examples are presented where the STS can support development of such materials.

The materials supporting sustainable energy infrastructure are not sustainable in their current formats. Many of the key systems supported by these materials are being established, but the full impact from **decommissioning established technologies such as batteries and solar cells** will be increasingly felt over the next 10-20 years [1,2]. These established technologies will advance to new compositional make-ups that must meet higher standards of sustainability. We must apply lessons learned from these established systems to produce next generation energy materials that are truly sustainable. Realizing this capability will require instruments that capture fundamental material behaviors within the context of a full device on practical time scales. Access to longer wavelengths, as shown for representative battery materials in **Figure 4.1**, is critical for this fundamental understanding.

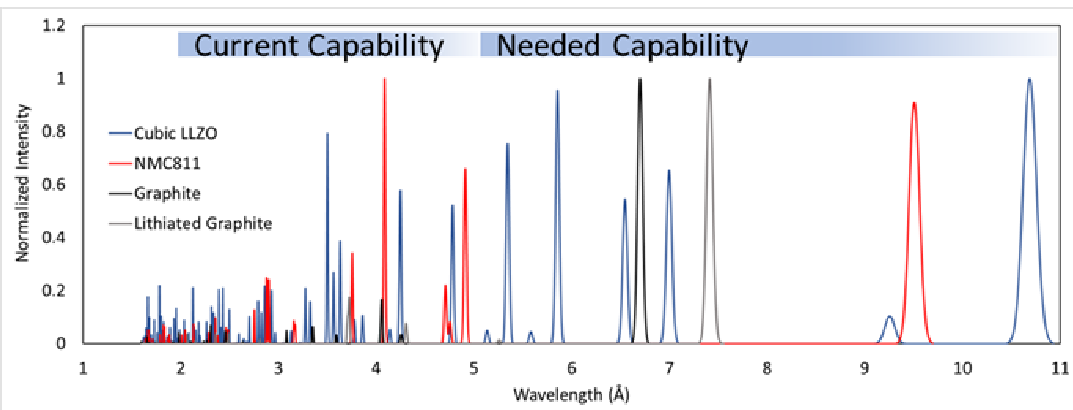

Figure.0¡7¡ *Example of neutron wavelengths needed to probe/understand the structure of four key lithium battery materials. "Needed Capacity" will be addressed by the STS.*

Another emerging concept relevant to US Department of Energy goals is the sustainable synthesis and manufacturing of high value-added components using **local materials** [3]. These local material resources may have mixed streams containing virgin ores and recycled materials. As a result, there is a need to perform rapid evaluation of elemental and phase distribution of these feedstocks and their distribution. The ability to perform structure identification in the long Q-range will allow for rapid evaluation of material feedstocks, thereby accelerating the sustainable manufacturing.

Circular economy materials for civil infrastructure presents one more opportunity for significant impact. For example, the US has 2.8 million miles of paved roads and 3,330 airport runways, 94% of which are surfaced with asphalt [4]. The use of **reclaimed asphalt pavement** (RAP) presents an opportunity for significant cost and CO_2 emission reductions, but the adoption of RAP has been limited [5-7]. The critical scientific issues limiting the amount of RAP stem from the mixing of the new and recycled asphalt binder, the impact of this imperfect mixing on the interface with the aggregate, and its subsequent effects on fatigue behavior as a function of temperature, hydration, and complex mechanical loads. This is an inherently hierarchical problem involving light elements that can be uniquely addressed by the new capabilities provided by the STS. Comparable multiscale materials challenges with significant societal impact are abundant within civil infrastructure.

How can neutrons uniquely address these grand challenges?

Neutron techniques stand apart from competing techniques for their ability to detect light elements and molecules (hydrogen, lithium, water, hydrocarbons) and their distribution throughout materials. This means that neutrons provide a means to acquire data essential for future advances in hydrogen-based fuel cells, lithium-based batteries, hydrogen-containing polymers, hydrogen-based embrittlement in metal alloys, water diffusion in geological materials, etc.

The proposed Second Target Station (STS) presents a unique opportunity to expand and enhance the neutron scattering capabilities and instruments in the United States for the coming several decades. As already discussed, for the field of materials science there are numerous grand challenges that can only be addressed by new instrumentation at such a facility.

<u>Materials certification and Transformative Manufacturing</u>: The advanced neutron characterization capabilities enabled by the STS hold immense potential to revolutionize the field of science-based certification of materials and manufacturing processes. Utilizing high-fidelity and rapid data sources, integrated with high-throughput synthesis techniques and sophisticated digital twins, STS will provide unprecedented accuracy and detail in understanding material behavior with real-time, in-situ, and multiscale (multimodal) data. The ability to perform simultaneous diffraction, small-angle scattering, Bragg-edge imaging, elemental contrast imaging, and other spectroscopic measurements will generate comprehensive datasets that capture the intricate interplay of material properties and environmental factors. Probing component-scale volumes requires high neutron fluxes at wavelengths ~3-15 Å, which will only be available at STS. Detection of mechanical failures in metals and ceramics at component scales - a necessary consideration in certification of load-bearing materials - requires global tensorial tomography, a transformational capability in materials mechanics. This is only possible at STS through fast neutron imaging coupled with AI. Additionally, quasi-in situ neutron exposure and diagnostics can uniquely inform the evolution of materials that must be qualified against irradiation performance.

<u>New alloy development and advanced nuclear materials</u>: to understand the long-term stability of alloy microstructures under extreme environmental conditions, including mechanical loading, temperature, and radiation, there is a need to estimate the partitioning of alloying elements (e.g. carbon, nitrogen, and hydrogen) between fcc and bcc phases, as

well as the variations close to the small-scale macro defects that control the fatigue life. Current neutron diffraction tools are not capable of extracting such elemental distributions even under ex-situ conditions across a practical sample volume on the order of cubic centimeters. For materials certification science, current neutron sources cannot provide the peak brightness and cold neutron spectrum required for voxelized quantitative imaging required to locate damage zones that are not known a priori. Multimodal imaging and/or diffraction instruments at the STS will enable a tensorization of the stress and strain dataset into a true information volume. These advancements will significantly reduce the time and cost associated with material certification, facilitating the rapid deployment of high-performance materials and components across various industries. STS data will empower the creation of true digital twins of manufactured components, providing detailed descriptions of macroscopic defects, crystal structure, elemental constitution, dislocation/twin density, and phase fractions within representative volume elements (<1 mm^3) of engineered components (>1 m^3). The development of detailed digital twins will enable predictive modeling and real-time monitoring, enhancing the safety, reliability, and longevity of materials used in critical applications. By addressing the limitations of current certification processes, the STS will drive innovation and support the transition to more sustainable and advanced technologies.

The cause and effects of hydrogen embrittlement have been difficult to establish in the absence of data about hydrogen concentrations and dynamics in steels. STS has two features essential for hydrogen atom velocity field mapping, high brightness and cold neutrons. The high brightness is needed for the spatial resolution, as the area of interest around the crack is on the order of tens of microns. Cold neutrons, to 15 Å, are needed to tune the center-of-mass of neutron-hydrogen scattering to access a wide range of hydrogen velocities. Doppler shift anisotropy in small angle neutron scattering with neutrons at velocities near that of the target atom have been used to measure velocity. The combination of grating interferometry and Doppler shift anisotropy in small angle scattering for the purpose of hydrogen atom velocity field mapping has not yet been demonstrated, but the STS has the unique features favorable for a successful implementation. Instrumentation at the STS that enable hydrogen atom velocity field mapping would provide this critical data and thus enable informed designs and material choices for metal structures in the hydrogen economy.

Construction materials: The performance of complete structural systems, not just the matrix but the full composite consisting of fibers, macro reinforcement, and other hybrid components, must be understood in depth. The STS will provide the necessary cold neutron flux to study crystalline constituent components within the matrix, as well as porosity and defects, impurities and trace elements. Advanced neutron methods will be absolutely pivotal in formulating an understanding of complex concrete-based materials system, from the fresh paste (soft matter) of wide-ranging compositions to the fully cured state (hard matter) into a hierarchical material. The porosity and pore structure of concrete – ranging from nm to mm – and the fact that it tends to be in a semi-saturated state makes it well-suited for characterization by neutron scattering. The STS could open an entirely new area of research focused on the impact of environmental stressors on the permeability and pore structure of monolithic concrete, enabling the development of new types of high-performance concrete mixes using a materials-driven design methodology to develop novel concrete AM systems.

Embedded interfaces are found in concrete due to the inclusion of sand and rocks, and with increased AM and the use of material additions, more complex interfaces will be present in these materials in the future. nGI combined with nCT will reveal how the pore structure and associated mesoscale morphology is augmented by such interfaces, enabling for direct links to be made between macroscopic performance and the material's heterogeneous structure. The performance of structural systems, not just the cementitious matrix but a composite consisting of fibers, macro reinforcement, and other hybrid components, must also be investigated in depth. Here, the STS will provide the necessary cold neutron flux to perform (Bragg Edge Imaging) BEI on crystalline constituent components within the matrix (reinforcing steel), nGI to detect porosity and defects, as well as polarized imaging to detect impurities and trace elements.

Advanced neutron methods will be absolutely pivotal in formulating an understanding of the concrete and concrete-like materials systems, from the fresh paste (soft matter) of wide-ranging compositions to the fully cured state (hard matter) into a hierarchical material (**Figure 5.4**). The porosity and pore structure of concrete – ranging from nm to mm – and the fact that it tends to be in a semi-saturated state makes it well-suited for characterization through SANS [13,14]. The dark field imaging signal (DFI) from nGI will effectively generate a 3D SANS information volume (rather than one point), opening a whole new area of research focused on the impact of environmental stressors on the permeability and pore structure of monolithic concrete specimens. This capability will enable the development of new types of high-performance concrete mixes using a materials-driven design methodology to develop novel concrete AM systems. An example would be bioinspired, functionally-graded cementitious materials with inherent insulation characteristics, as shown in **Figure 2.2** [10-15]. Neutrons are also central for studying transport-dependent processes in concrete, and similar materials, due to the aqueous environment found in its pores and associated free and hydrated H_2O molecules.

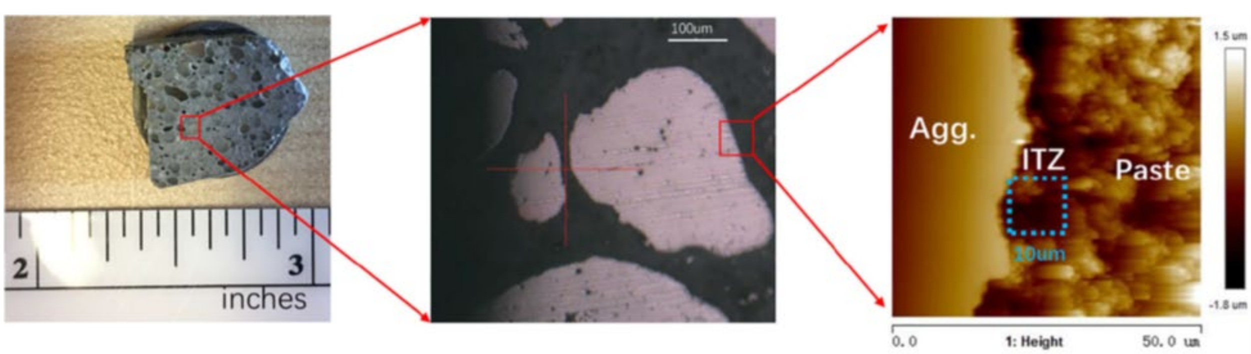

Figure.❶0¡ *Cement with C nanofibers and aggregate imaged and probed with AFM QNM to analyze interfacial mechanical properties [16]. At the STS nCT with nGI will elucidate the relationship between the microscale morphology and macroscale performance of concrete.*

The stiffness of Portland cement evolves over time with the ongoing hydration reaction of the cement forming a hydrated Calcium-Silica-Hydrate (C-S-H) gel, which ultimately acts as the binding agent in concrete. A better understanding of the features of the statistics of the phase formations and behavior under loading environments must be understood to design **lasting alternatives to Portland cement** [17]. The cold spectrum features of the STS will provide nano- to meso-structure data of the C-S-H gel in bulk and at the interfaces to reinforcement structures. The complex dynamics of concrete material evolution - be it hydration, microfluidity, self-healing capsule deployment, or microstructural evolution under load, temperature, or pressure - will require a *holistic* measurement approach. **Dynamic imaging, enabled by bright cold neutrons of the STS, will provide an ideal platform for in situ in operando simultaneous multiscale hyperspectral imaging**. An imaging instrument will allow for the voxelization of the data volume and allow for the localization of damage domains which are not known a priori. Here, **AI-assisted computed tomography that internalizes the information tensor of BEI, nGI, polarized imaging, isotope contrast, and traditional attenuation contrast will provide the ultimate information volume.**

<u>Mixed materials and Polymers</u>: characterizing materials for a circular economy using neutron scattering techniques provides valuable insights into these materials' structure, dynamics, and behavior. At increased neutron flux this characterization can be achieved for highly dynamic systems and long wavelengths (5-15 Angstrom) within the context of engineering components at practical time scales. This capability enables the dynamic multiscale observation of materials to understand performance, degradation, and lifecycle. Furthermore, since neutrons are effective in studying the spatial arrangement of atoms and the interactions between polymer chains/crystals, stress/chain relaxation, and segmental motions, the use of neutron scattering technique helps understand the various impurities and contaminants that are impacting these features within the circular economy material system.

In conclusion, **the scientific impact of the STS will be transformative**, bridging the gap between research and practical application, and empowering scientists and engineers to push the boundaries of material science. In-situ imaging, small- and wide-angle scattering simultaneous measurements at STS with high penetration capability through sample environment and specimen size would enable a fundamental understanding of the interplay of phase transformation and three-dimensional stress evolution during heating and loading, under high pressure, and how they impact defect evolution (micron sized) in large components with extreme complexity in composition, microstructure and residual stress distributions. Multimodal imaging/tomography can simultaneously probe material kinetics at the macroscale while nGI and BEI probe the micro and atomic scales, generating a 4D information volume. Such capabilities critically require the cold and bright neutron flux of the STS. This will not only accelerate technological progress but also foster a culture of continuous improvement and innovation, ensuring that society can meet the growing demands of modern challenges with confidence and resilience. **Maintaining a position of global leadership in advanced materials (aerospace, defense, nuclear) is a strategic national priority and thus requires the utmost support.**