Developing SiC for Optical System Applications

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Motivation

- Silicon carbide is a new material with potential for making large lightweight mirrors and systems quickly and cost-effectively
- Is this material ready for insertion into future systems, especially in space systems?
- How do we characterize and develop this material for future needs?

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Outline

- Space application requirements
- Existing material overview
- Why SiC?
- SiC descriptions
- Evolution of SiC from substrate to system material
- Future work
- Recommendations
- Summary

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Space Application Needs and Goals

- Build large aperture mirrors
  - Apertures >3 m in diameter are of interest
  - Low areal density, currently ≈ 15kg/m2, goal 1 – 5 kg/m2
- Choose materials that maintain optical performance from launch through on-orbit operations
  - Radiation environment
    - Maintain optical performance even with radiation exposure: AO, UV, electrons, micro debris etc
    - Develop model to predict behavior
  - Material and structural stability
    - Maintain optical performance during launch and temperature variations on orbit
- Reduce risk by using material with extensive space heritage
  - Rely on engineering experience
  - Design systems using established design trades
- Reduce cost of developing new space materials
  - Develop cost-effective substrate production, optical finishing, and coatings
  - Perform space environment testing

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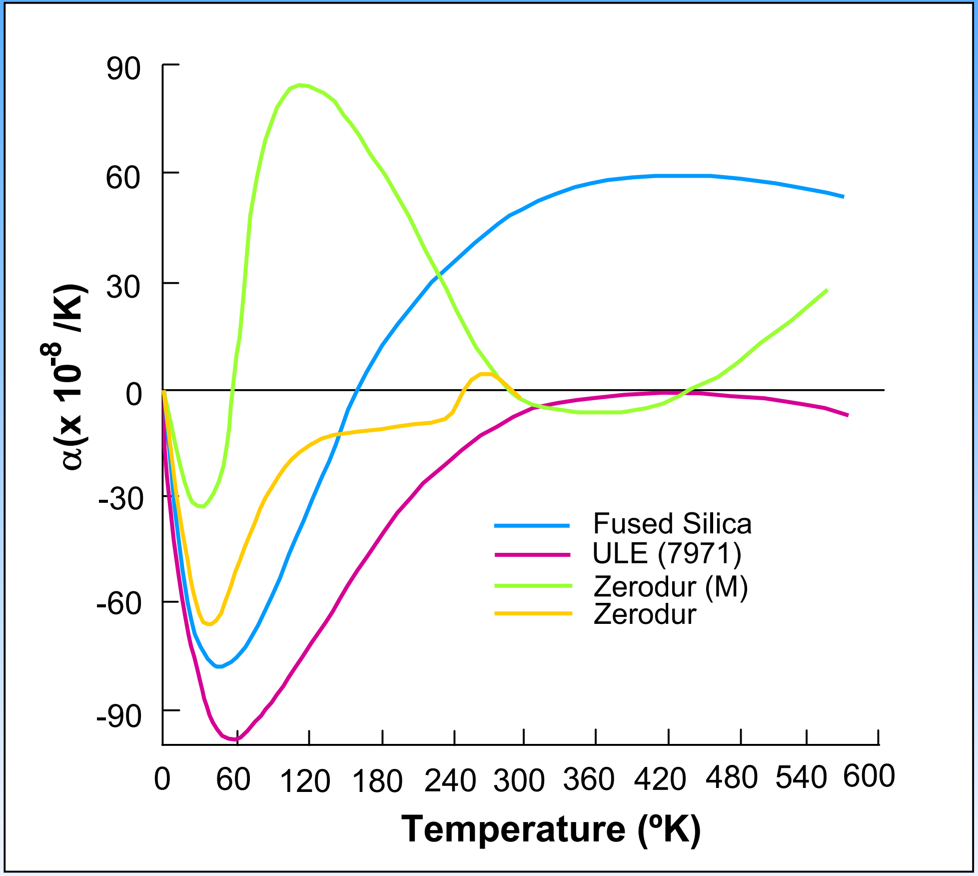
Low CTE Mirror Materials

- **Glass**
  - Fused silica
  - ULE
  - Zerodur
- **Metals**
  - Beryllium
- **Alternatives**
  - Composites
  - SiC



Source: Stephen Jacobs, SPIE Vol 1335

- **Operating parameters dictate material selection**
  - **Room temperature, Zerodur and ULE good choices**
  - **Cryogenic temperatures, less than 123K, fused silica may be better choice**

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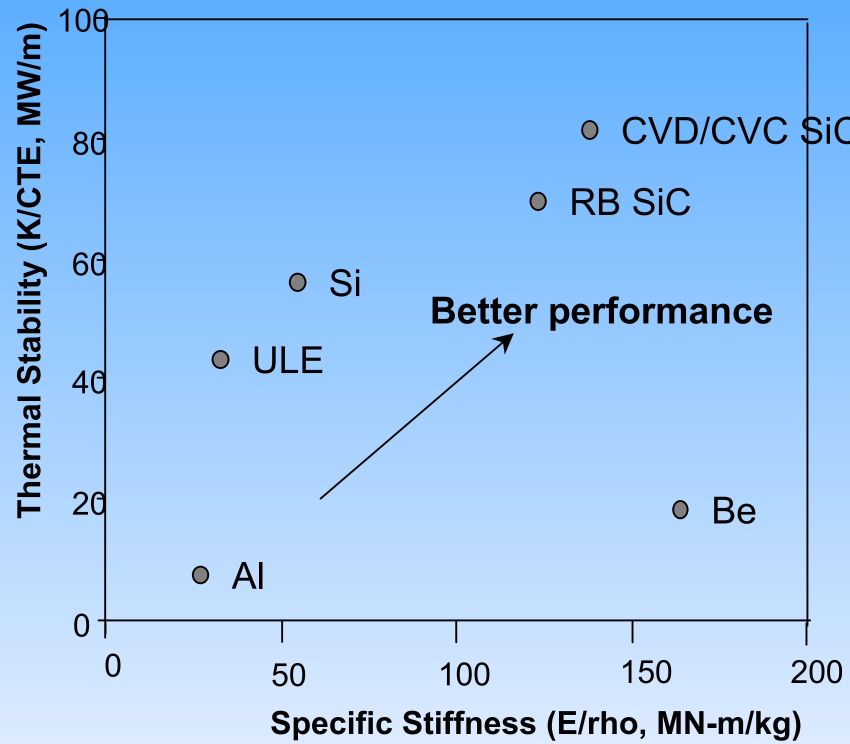
Glass vs Be vs SiC

- **Glass**
  - Extensive space heritage
  - Easily figured and polished
  - Long lead times for large-diameter applications
- **Be**
  - Space heritage, used for structures and mirrors
  - Established material, proven long-term stability
  - Uncertain supply and challenges of toxicity
- **SiC**
  - High thermal conductivity, low thermal expansion, high specific stiffness, can be lightweighted
  - Multiple suppliers, inexpensive substrates
  - Good potential for space applications
  - Limited space heritage and difficult to polish to an optical surface



Source: Trex Enterprises

- **All materials are susceptible to radiation effects to varying extents**
  - Materials have a change in density
  - Compaction or expansion can occur
    - Changes can affect radius of curvature

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Choosing SiC:
Systems engineering approach

- **Using a single property to choose a material must be avoided, must examine all parameters and application**
- **Evaluate replacement of existing materials with SiC on case-by-case basis**
  - **May not be possible to replace only one component of a system with SiC**
  - **Decision may require reengineering of entire system**
  - **Introduction of SiC may be more successful in new projects and technology developments**
- **Resistance may exist when replacement of well-known components with higher risk materials is suggested**
  - **Reengineering and unknown performance**

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SiC Mirrors vs. Structures

- Complete SiC system is passively athermal instrument
  - Challenges in mounting and assembly of system
    - Inserts, bonding, SiC screws
- Somewhat different requirements for mirror vs structures
  - Solution is application driven
- Structures
  - High fracture toughness
  - Specific stiffness may not need to be as high
    - Require more weight (Fiber reinforced)
  - Uniformity not as critical, if high fracture toughness is key
- Mirrors
  - High specific stiffness, enables lightweighting
  - Polishable, create optical surface
  - High uniformity, maintain optical performance

Mirrors and structures may require two different forms of SiC

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SiC Production Methods

- Chemical Vapor Deposition (CVD): fully dense single-phase SiC, zero porosity
- Sintering: trace amounts of a second phase from sintering, porosity 2 – 5%
- Reaction bonding: two-phase mixture of SiC and silicon metal (6 to 40%), porosity 0 – 15%
- Graphite or carbon conversion: single-phase (monolithic) structure with porosity up to 20%; if carbon fibers, unconverted Gr or C, or Si present, at least two-phase material
- Hot Isostatic Pressing (HIP): fully dense SiC with minor amounts of a second phase from additive used as a hot pressing aid, porosity <1%
- Foam: fully distributed load paths under mirror surface, easier metrology mount, higher stiffness and first mode frequency, porosity 85 – 95%

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Porosity and Contamination

- Open Pores
  - Increased probability of contamination during fabrication
  - Migration and deposition of outgassed contaminants in vacuum
    - Onto optical surface(s) during coating process
    - Onto critical telescope components (e.g. focal plane arrays) on orbit
- Closed pores
  - Trapped gasses
    - Surface deformation due to pressure difference between fabrication and vacuum/on-orbit environments

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SiC Phase Descriptions and Optical Challenges

- SiC can come in different phases
  - Single phase: pure SiC
  - Two-phase: SiC plus Si
  - Three phase: carbon fibers, SiC, Si example: CeSiC
- SiC with different phases make optical finishing a challenge
  - Single phase is a hard surface, difficult to polish
  - Two phase is more difficult to polish as SiC and Si polish at different rates requiring CVD coating for optic quality
  - Three phase can have fiber print through

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Processing Challenges

- **CVD: time to create monolithic part, limit on size**
- **Sintering: press-limited size, green body integrity during machining, controlled shrinkage during sintering, brazing required for large diameter parts**
- **Reaction bonding: polishing, mold quality**
- **HIP: expensive, limit on shapes**
- **Graphite or Carbon conversion: complete conversion, green body integrity during machining, multiple phases**
- **Foam: polishing optical surfaces, scaling to large diameters**

❖ ***Different methods produce slightly differing SiC properties, which can vary up to 20% in value***

❖ ***Greatest difference among manufacturing methods is costs and processes to make an optical part***

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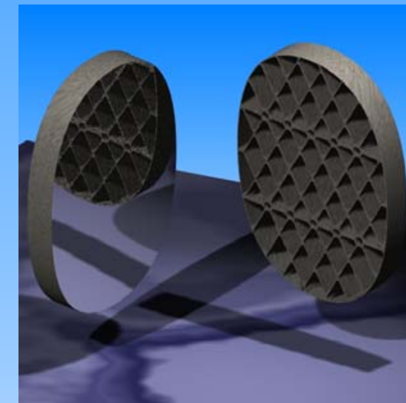
US SiC Manufacturers

Source: CoorsTek

Source: M Cubed



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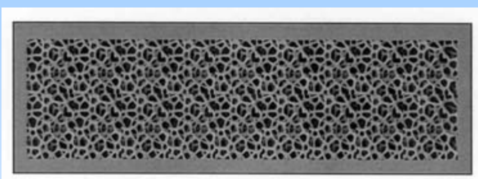

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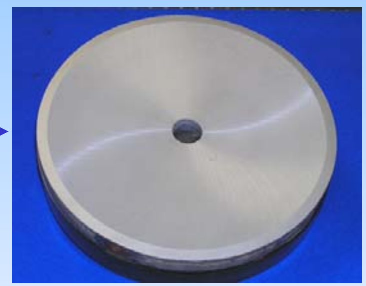

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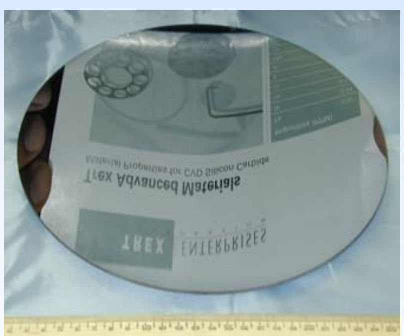

Source: Trex

Source: Xinetics

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Evolution of SiC from Substrate to System Material

- Collaborate with multiple agencies to qualify materials
  - NASA, AFRL, MDA
  - Share resources, develop multi-application requirements
- Verify consistency of SiC production
- Space qualify SiC not only as substrate material but as a system material
  - Develop mirror substrate and structural samples
    - Test variety of SiC such as reaction bonded, sintered, foams, and three phase materials
    - Investigate both coated and uncoated SiC substrates
  - Perform radiation, thermal, and vacuum testing
- Downselect to optimal forms of SiC via testing
- Develop polishing and coating technology
  - Techniques will be SiC-type dependent

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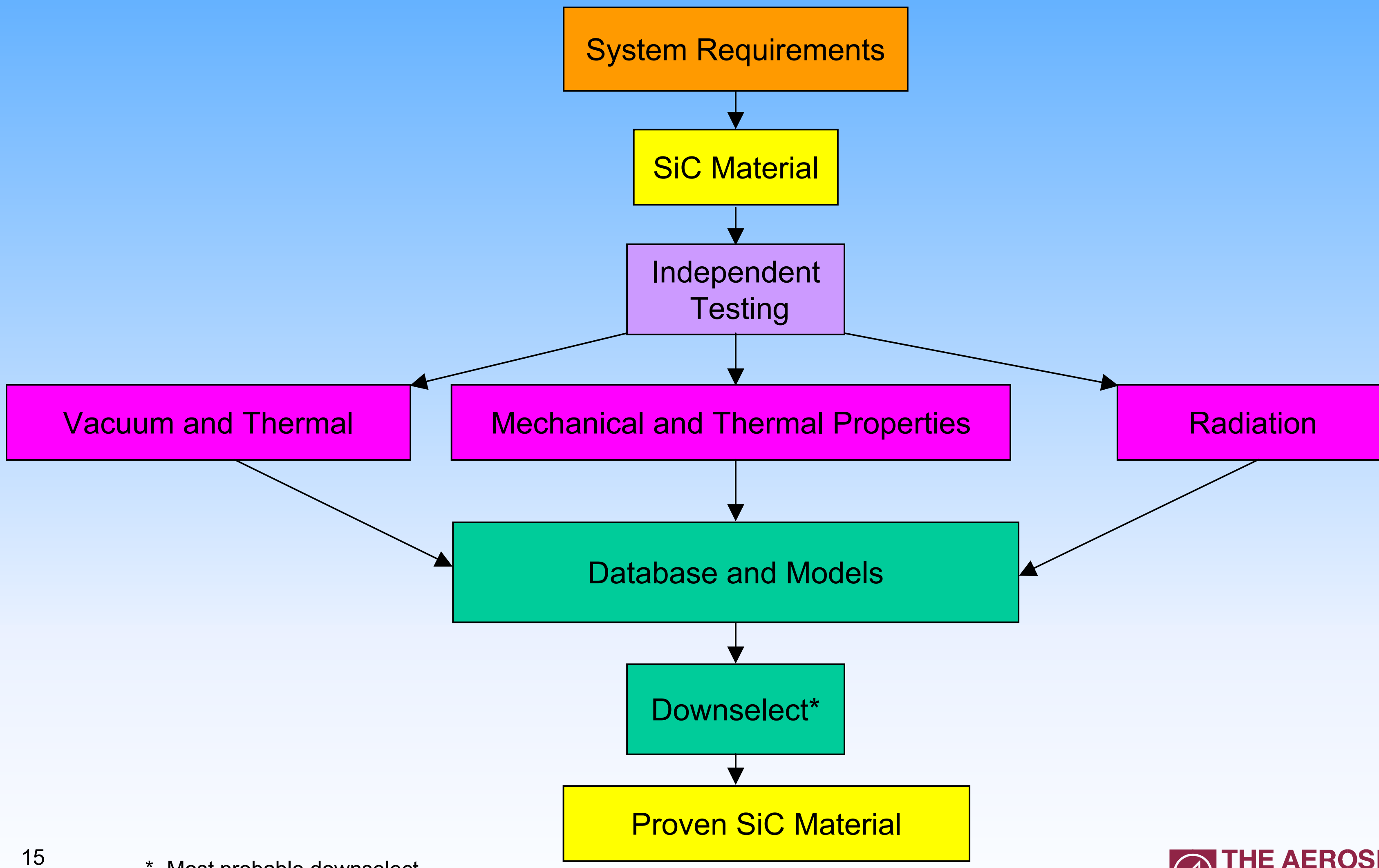
SiC Material Qualification Flow Diagram



* Most probable downselect

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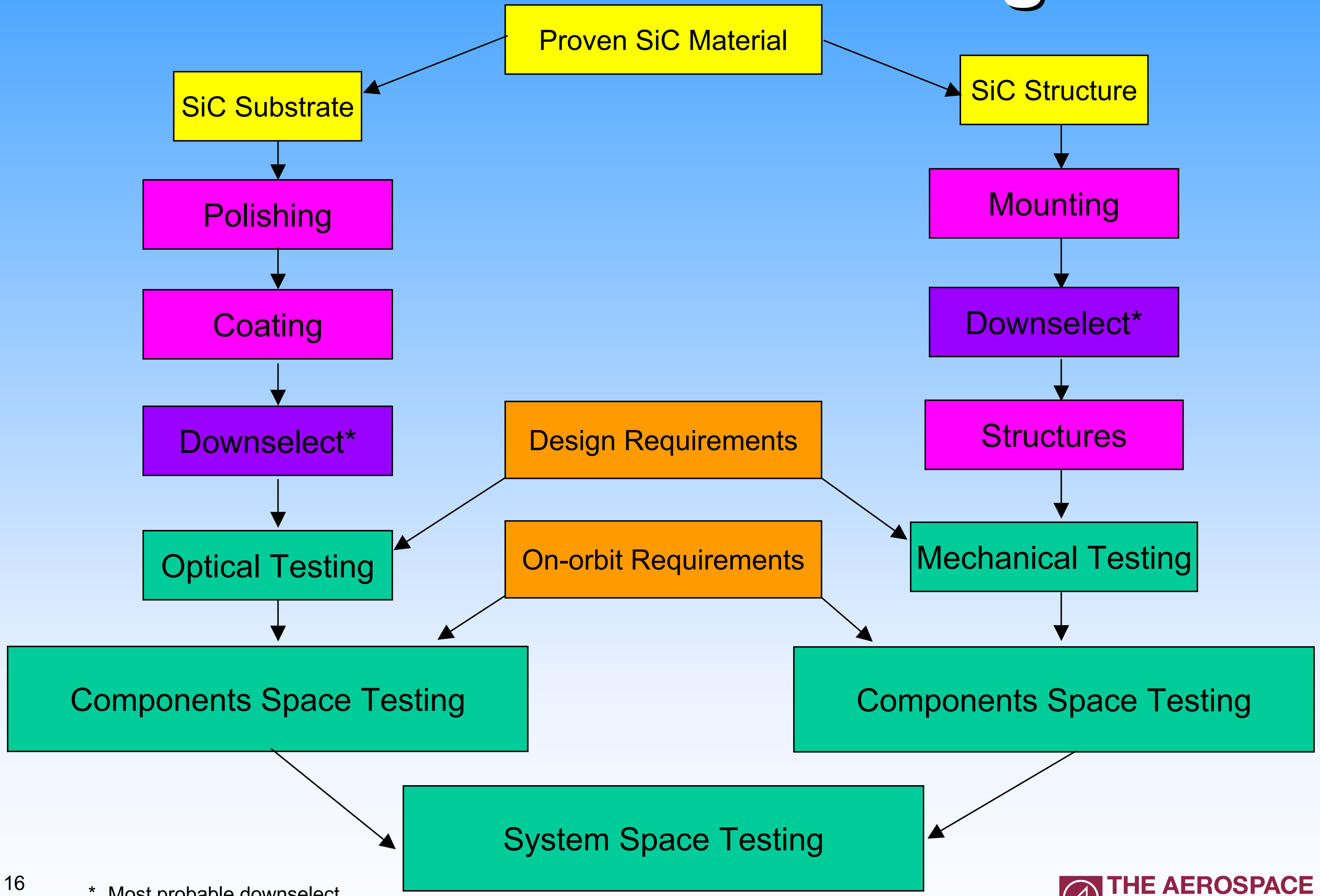
SiC Evolution Flow Diagram



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Testing and Future Work

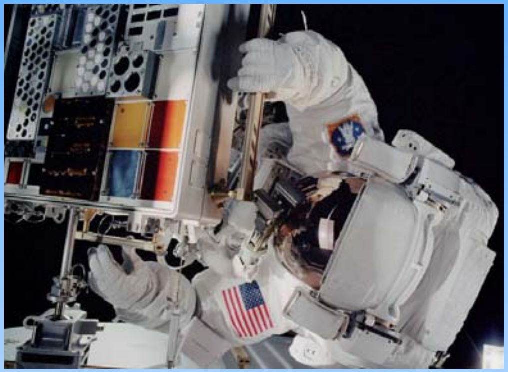
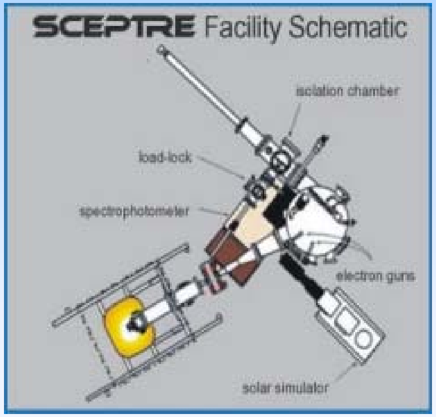


Photo courtesy of NASA/MSFC



Drawing courtesy of AFRL/ML

- Characterize SiC as a substrate and structural material
  - Perform material and optical testing
    - 2-stage test matrix
      - Screening – most critical properties: CTE, stiffness
      - Characterization – full materials testing
    - Reduce cost of materials development
      - Identify manufacturers with greatest potential early
      - Invest consolidated funds into companies that meet space environment requirements
        - Pursue SiC system development
- Perform space environment testing
  - Earth simulation of atomic oxygen, radiation effects
  - On-orbit testing, combined effects
- Develop and validate models of radiation effects on SiC
  - Compare on-ground orbit simulation with on-orbit exposure

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Recommendations

- Continue funding development of various forms of SiC
- Encourage collaboration with various government agencies and non-profit organizations for independent evaluation of SiC
- Develop groundwork for development of established polishing and coating techniques, will vary with SiC type
- Characterize various forms of SiC from material, optical, and structural perspective
- Fund demonstration program that uses a SiC system
  - Validate material, optical, and structural characteristics of SiC
  - Produce multiples of a system to validate production processes
  - Increase diameters to meter class or greater

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Summary

- SiC has attractive qualities for space applications
- Several US SiC manufacturers producing various forms of SiC
- US programs are interested in pursuing SiC as an alternate material
- SiC must evolve from substrate material to systems engineering material for full implementation
- Develop radiation effects modeling
  - Required to predict behavior of future systems

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