Material Identification and Prioritization

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AMMT Projects Analysis and Prioritization Process: Material focused

**OUTCOME**
- Provide a current evaluation of the AM materials pipeline for advanced reactors and seeks to prioritize materials based on stakeholder input.
- Full traceability; Working on the right projects at the right time; Prevent duplication; Accelerated progress.

**Input to**
- Workshop/Roadmaps (GAIN, GIF, NEI, EPRI, NRC, ART material, etc)
- Proprietary Project Information
- Suppliers
- Limited Qualtrics Survey Form Distributed
- Program Strategic Plans
- Published Literature (limited)
- Public Vendor Information

**AMMT roadmap**

New Activity Kick off
May 2022
Critical Minerals and Materials

Presentation 4:35
Stakeholder Collaboration and Qualification Methodologies

IVR

AMMT Program Review May 18-19, 2022; Virtual Meeting
Number of times the material type was referenced combined for all the reactor types.

Material type:
- 316SS
- 304SS
- SS316
- SS316H
- SS316 FR
- SS316 CW
- SS304
- D9 Steel
- Alloy 709
- A533B Steel
- A187
- SA213
- HT35 Steel
- ODS Steel
- Grades 92
- SA533B Steel
- SA508B Steel
- 2.25Cr-1.0Mo Steel
- SA508 Steel (Gr. B24)
- Pure Ni
- Inconel 718
- Inconel 617
- Hastelloy X
- Hastelloy N
- Alloy 800H
- Alloy 800H
- Alloy 760
- Alloy 690
- Alloy 820
- Alloy 220
- HEA
- HEAs
- C
- SiC
- C/C
- SiC/SiC
- Carbon
- Mo Alloy
- Nb Alloy
- ZrAl2
- Aluminum Nitride
- Zircaloy
- Concrete
- Other

Number of times Cited:
- 14
- 12
- 10
- 8
- 6
- 4
- 2
- 0

Preliminary Data Sept 2021
Number of reactors the material type was referenced; combined for all reactor types

Material type

- Austenitic Steel
- Ferritic/Martensitic Steel
- Carbon Alloy Steel
- Nickel Alloy
- Other

Preliminary Data Sept 2021
<table>
<thead>
<tr>
<th>ID</th>
<th>Criteria</th>
<th>Guidance</th>
</tr>
</thead>
</table>
| 1  | **Code Availability**                                                    | Codes are available for all areas = 5  
|    | - Material                                                              | Codes are available for two of the three areas = 3                                             |
|    | - Manufacturing Process                                                 | Codes are available for one area = 1                                                          |
|    | - Product application or design code                                    |                                                                                               |
| 2  | **Minimal Gaps in Data Availability for Performance Values and Measurements** | No or few gaps in data availability = 5  
|    | - How do we prove the requirements are met?                            | Moderate gaps in data availability = 3  
|    | - Translated in a specification                                         | Large gap in available data = 1                                                                |
|    | - Irradiation behavior (one example)                                    |                                                                                               |
| 3  | **Technical Maturity for End Use/Development Stage**                    | TRL 8-9 and/or MRL 8-10 = 5  
|    | - Technology Readiness Level (TRL)                                      | TRL/MRL 7-8 = 4                                                                                |
|    | - Manufacturing Readiness Level MRL (DoD)                               | TRL/MRL 5-6 = 3                                                                               |
|    | - Example questions: Can it be fabricated?                              | TRL/MRL 3-4 = 2                                                                               |
|    |                                                                          | TRL/MRL 1-2 = 1                                                                               |
| 4  | **Deployment readiness requirements**                                   | Ready for industry deployment within 2 years = 5                                             |
|    | - 1-5 years                                                             | Ready for industry deployment in 3-5 years = 4                                                  |
|    | - 6-10 years                                                            | Ready for industry deployment in 6-7 years = 3                                                 |
|    | - 10 years plus                                                         | Ready for industry deployment in 8-9 years = 2                                                 |
|    |                                                                          | Ready for industry deployment in \( \geq \)10 years = 1                                        |
| 5  | **Supply Chain Availability**                                           | No anticipated supply chain risks or impacts = 5                                               |
|    | - Resilient to impacts along the supply chain                           | Moderate supply chain risks or potential impacts = 3                                          |
|    |                                                                          | Major supply chain risks and potential impacts = 1                                             |
| 6  | **Programmatic Factors**                                                | Applications across all reactor types and/or multiple industry entities interested in a reactor type = 5 |
|    | - Technology funded by other programs                                   |                                                                                               |
|    | - # of industry entities interested in technology                       |                                                                                               |
Material Score Cards

- Prepare material score cards to support DOE-NE’s prioritization and decision-making processes.
- Phase 2 scorecards are revised from Phase 1 scorecards upon detailed analysis of publicly available information.
  - expected to change based on stakeholder input and more research and development information become available.
- Scoring criteria and the knowledge gaps are discussed with the necessary literature for complete traceability of the scores.
- The report mainly focuses on traceability of additive manufacturing technologies of:
  - Austenitic stainless steel SS316, SS304
  - Ferritic/martensitic HT-9
  - Incoloy 800H
  - Inconel 617, Inconel 718
  - Superalloy Hastelloy N
  - Ceramics: Silicon Carbide, Graphite C/C
- Best judgement approach to provide a quantitative evaluation among AM materials for prospective Gen-VI deployment.
- Examples in this presentation: focus on SS316, Inconel 718, & SiC
### Examples of Specific Reactor Type Score Card

<table>
<thead>
<tr>
<th>ID</th>
<th>Criteria</th>
<th>Guidance</th>
<th>MSR</th>
<th>VHTR</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Code Availability</td>
<td>Codes are available for all areas = 5 For two of the three areas = 3 For one area = 1</td>
<td>3 (3)</td>
<td>3 (3)</td>
</tr>
<tr>
<td>2</td>
<td>Minimal Gaps in Data Availability for Performance Values and Measurements</td>
<td>No or few gaps in data availability = 5 Moderate gaps in data availability = 3 Large gap in available data = 1</td>
<td>3 (3)</td>
<td>1 (1)</td>
</tr>
<tr>
<td>3</td>
<td>Technical Maturity for End Use/Development Stage</td>
<td>TRL 8-9 and/or MRL 8-10 = 5 TRL/MRL 7-8 = 4; TRL/MRL 5-6 = 3; TRL/MRL 3-4 = 2; TRL/MRL1-2 = 1</td>
<td>3 (3)</td>
<td>1 (1)</td>
</tr>
<tr>
<td>4</td>
<td>Deployment readiness requirements</td>
<td>Ready for industry deployment within 2 years = 5; In 3-5 years = 4; In 6-7 years = 3; In 8-9 years = 2; In ≥10 years = 1</td>
<td>3 (5)</td>
<td>1 (1)</td>
</tr>
<tr>
<td>5</td>
<td>Supply Chain Availability</td>
<td>No anticipated supply chain risks or impacts = 5; Moderate impacts = 3; Major impacts = 1</td>
<td>3 (3)</td>
<td>1 (1)</td>
</tr>
<tr>
<td>6</td>
<td>Programmatic Factors</td>
<td>Applications across all reactor types and/or multiple industry entities interested in a reactor type = 5</td>
<td>5 (5)</td>
<td>1 (1)</td>
</tr>
</tbody>
</table>

Values in bracket are phase 1 scores.
## Overview on Results

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Guidance</th>
<th>AM Material for use in Gen-IV Reactors</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>SS316</td>
</tr>
<tr>
<td>Code Availability</td>
<td>Codes Available 1-5</td>
<td>3</td>
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<tr>
<td>Minimal Gaps in Data Availability for Performance Values and Measurements</td>
<td>No or few gaps 1-5</td>
<td>3</td>
</tr>
<tr>
<td>Technical Maturity for End Use/Development Stage</td>
<td>TRL/MRL 1-5</td>
<td>3</td>
</tr>
<tr>
<td>Deployment readiness requirements</td>
<td>Industrial deployment 1-5</td>
<td>3</td>
</tr>
<tr>
<td>Supply Chain Availability</td>
<td>No to major risk 1-5</td>
<td>3</td>
</tr>
<tr>
<td>Programmatic Factors</td>
<td># of Reactor types</td>
<td>5</td>
</tr>
<tr>
<td><strong>Average Score</strong></td>
<td></td>
<td>3.33</td>
</tr>
</tbody>
</table>
## Austenitic SS316

### Composition of various 316SS grades in weight %.

<table>
<thead>
<tr>
<th>Grade</th>
<th>C</th>
<th>Mn</th>
<th>Si</th>
<th>P</th>
<th>S</th>
<th>Cr</th>
<th>Ni</th>
<th>Mo</th>
<th>N</th>
</tr>
</thead>
<tbody>
<tr>
<td>316 (UNS 31600)</td>
<td>0.08</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>316L (UNS S31603)</td>
<td>0.03</td>
<td>2.0</td>
<td>0.75</td>
<td>0.045</td>
<td>0.03</td>
<td>16.0-18.0</td>
<td>10.0-14.0</td>
<td>2.0-3.0</td>
<td>0.10</td>
</tr>
<tr>
<td>316H (UNS S31609)</td>
<td>0.04-0.10</td>
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<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
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</tr>
</tbody>
</table>

### Criteria

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Guidance</th>
<th>Gen-IV Reactor Type for the use of:</th>
<th>SFR/MSR/ Micro/LFR</th>
<th>VHTR</th>
<th>MSR/SFR/GFR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Code Availability</td>
<td>Codes Available 1-5</td>
<td>SS316 &amp; SS316L</td>
<td>3 (3)</td>
<td>1 (3)</td>
<td>0 (1)</td>
</tr>
<tr>
<td>Minimal Gaps in Data Availability for Performance Values and Measurements</td>
<td>No or few gaps 1-5</td>
<td>SS316H</td>
<td>3 (3)</td>
<td>1 (3)</td>
<td>1 (1)</td>
</tr>
<tr>
<td>Technical Maturity for End Use/Development Stage</td>
<td>TRL/MRL 1-5</td>
<td></td>
<td>3 (3)</td>
<td>2 (3)</td>
<td>1 (1)</td>
</tr>
<tr>
<td>Deployment readiness requirements</td>
<td>Industrial deployment 1-5</td>
<td></td>
<td>3 (5)</td>
<td>2 (5)</td>
<td>1 (1)</td>
</tr>
<tr>
<td>Supply Chain Availability</td>
<td>No to major risk 1-5</td>
<td></td>
<td>3 (3)</td>
<td>3 (3)</td>
<td>1 (1)</td>
</tr>
<tr>
<td>Programmatic Factors</td>
<td># of Reactor types</td>
<td></td>
<td>5 (5)</td>
<td>5 (5)</td>
<td>1 (1)</td>
</tr>
</tbody>
</table>

Values in brackets are the phase 1 scores and scores are unchanged for most criteria.
Austenitic SS316

SS316: One of the most investigated alloy using various additive manufacturing techniques (laser powder bed fusion (LPBF) and direct energy deposition (DED))

- most of information for 316L (>50 published papers),
- limited data for 316 (<5) and 316H (<5)

Summary of publicly available information for 316L

- Microstructural conditions: as-built, stress relieved, solution annealed, and hot isostatically pressed.
- Properties: tensile and hardness, creep, corrosion, irradiation resistance, stress corrosion cracking (SCC), and irradiation assisted stress corrosion cracking (IASCC)
Austenitic SS316: Code availability

• A data package on AM 316L to ASME submitted by EPRI research team¹.
  • 316L components manufactured by Westinghouse, Auburn University, Rolls Royce, and Oerlikon.
  • A pipe tee section (HIP), a valve body (SA), and a ring flange (both HIP and SA).
  • Chemical, microstructural, and mechanical (Charpy toughness, tensile properties (21-426.6°C), room temperature bend tests, and fatigue (20 and 300°C))
• ASTM F3184-16: Standard Specification for Additive Manufacturing Stainless Steel Alloy UNS S31603 (SS16L) via laser and electron powder bed fusion processes².
  • Covers fabrication of parts using AM, such as manufacturing plan, feedstock, chemical requirements, post-processing, microstructure, and tensile properties.

High temperature codes not available
Score of 3.


HIP: Hot isostatic pressing
SA: Solution anneal
Austenitic SS316: Gaps in data availability for performance values and measurements

**Porosity:** LPBF can produce AM 316L with ~0.2% porosity. HIP can reduce the porosity to below 0.1%.

**Anisotropy:** Can be reduced/removed by post-fabrication heat treatment via recrystallization.

**Tensile properties:** In HIP + SA, LBPF 316L exhibited superior tensile properties vs. wrought 316L.

**SCC and IASCC:** HIP + SA material performed similar or better than conventional forged 316L under simulated Boiling Water Reactor (288°C) conditions.

**Creep:**
- Anisotropy in creep performance (vertically vs. horizontally built) in LPBF 316L SS.
- Creep tests at 600 and 650°C, LPBF 316L had shorter rupture time at all tested stress levels vs conventional 316L.
- Creep (550°C, 275 MPa) of post heat-treated microstructures (650, 700, 750, 800, 900, and 1050°C/1 h). The 650°C heat treated specimen exhibited the longest creep life followed by the as-built sample and the remaining heat-treated samples.
Austenitic SS316: Gaps in data availability for performance values and measurements (cont.)

**Irradiation:** proton irradiation, neutron irradiation, helium irradiation, and ion irradiation.

<table>
<thead>
<tr>
<th>Irradiation conditions</th>
<th>Proton irradiation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>2 MeV proton raster beam at 360°C of stress relieved 316L</td>
</tr>
<tr>
<td>2.</td>
<td>Proton irradiation with 2 MeV protons followed by constant extension rate tensile (CERT) tests in simulated BWR at 288°C and at 10 MPa load</td>
</tr>
<tr>
<td>3.</td>
<td>2 MeV proton irradiation at 360°C</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Irradiation conditions</th>
<th>Ion irradiation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Irradiated with 5 MeV Fe$^{2+}$ ions at temperatures of 500, 550, and 600°C</td>
</tr>
<tr>
<td>2.</td>
<td>Irradiated with 3.5 MeV Fe$^{2+}$ ions at 500°C</td>
</tr>
<tr>
<td>3.</td>
<td>Heavy ion irradiation with Kr$^{2+}$ ions at 400°C</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Irradiation conditions</th>
<th>Neutron irradiation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Neutron irradiation at 300 and 600°C to 1.6 dpa</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Irradiation conditions</th>
<th>Helium</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>500 keV helium ions at temperatures 350, 550, 700, 800 and 900°C</td>
</tr>
<tr>
<td>2.</td>
<td>500 keV He ions at 700°C</td>
</tr>
</tbody>
</table>

Inconsistency in irradiation test results possibly due to differences in composition, fabrication, and test conditions.

AM material exhibits lower creep resistance compared to conventional 316 SS due to composition and microstructural instability.

A systematic investigation of composition-processing-microstructure-performance (consistent test conditions) is required.

Score of 3.
Austenitic SS316

Deployment readiness requirements  
**Score of 3**
- A research team led by GE has fabricated a BWR debris filter.
- AM Thimble plugging device installed into Byron Unit 1 reactor core in March 2020
- Additional data to better understand processing-structure-property relationship

Supply chain availability  
**Score of 3**
- Sustained bulk scale powder production and components fabrication when the technology matures, and deployment opportunity arises.

Programmatic factors  
**Score of 5**
- SS316 is the most cited austenitic stainless steel for nuclear application and considered for all types of GEN-IV reactors.

Technical maturity for end use/development stage
- Structure-properties relations depend on powder composition, LPBF machines, process parameters, and numerous post-processing variations.
- More cohesive effort to collect data on selected compositions, powder vendors, LPBF machines, process parameters, and detailed microstructure-property correlations.
- Research teams led by GE and the EPRI covered many of the important points in that regard
- AM 316L in HIP+SA condition: better or similar tensile, SCC, and IASC properties however, creep and impact toughness of stress-relieved AM 316L was inferior to conventional 316L.

Additional research is needed for optimizing the AM microstructure for better critical properties such as creep-fatigue and IASSC.  
**Score of 3.**
Inconel 718

Code availability

- ASTM F3055-14a: Standard specification for AM nickel alloy (UNS N07718) by Powder Bed Fusion
  - Feedstock, manufacturing process, chemical composition, microstructure, mechanical properties, post thermal processing, and HIP.

  A very few publications on nuclear relevant properties are available. Score of 1.

Gaps in data availability for performance values and measurements

Anisotropy: As-built microstructure can be completely recrystallized via post heat-treatment leading to isotropic properties.

Tensile Properties: Higher tensile strength along transverse direction compared to build direction and conventional IN718.

Fatigue testing: Exhibits similar fatigue properties at 25 °C to 650°C compared to conventional IN718.

Creep: Some studies reported improvement in creep performance while others reported inferior resistance.

Irradiation behavior: No irradiation experiments of AM IN718.

- Wrought IN718: instability of strengthening precipitates in form of disordering or dissolution under irradiation.
- Oxide dispersion strengthened (ODS) IN718: IN718 modified with 0.2 wt.% Y₂O₃ and 0.5 wt % Ti6Al-4V
- Irradiation (200 and 450°C up to 3 dpa) of ODS IN718: no significant changes in matrix or particles (450°C irradiation)

SCC: No published literature is available.

Significant gap in nuclear relevant properties exists for AM IN718 Score of 2.
Inconel 718

Deployment readiness requirements  Score of 2
• Fabrication issues need to be solved and relevant mechanical and nuclear data are lacking.
We expect a longer than 10 years period until AM IN718 can be deployed in Gen-IV systems.

Supply Chain availability  Score of 3
• AM IN718 is rapidly advancing therefore, procurement of powder and subsequent component manufacturing may not have major limitations.
• Effort is needed to produce ODS IN718 powders.

Programmatic factors  Score of 4
Three reactor designs such as micro-Reactors, GFR, and VHTR are looking into the potential use of IN718 components for high temperature applications.

Technical maturity for end use/development stage
• Proof of concept testing of various nuclear relevant properties is lacking.
• Therefore, a systematic investigation of creep, high temperature fatigue, creep-fatigue, irradiation fatigue, and IASCC under GEN-IV relevant condition is essential.

Many nuclear relevant properties of AM Inconel 718 remains unknown.
Score of 2.
Silicon Carbide SiC

**Code availability**

ASME code cases are unavailable

The fabrication process of AM SiC is rather mature and AM SiC shows good performance under neutron irradiation.

- **CVD SiC:**
  - ✓ shows low irradiation induced volume swelling of up to 2% at high neutron damage of 100 dpa.
- Combination of binder jetting (BJ) and chemical vapor infiltration (CVI), 3D objects with complex features have been produced.
  - ✓ Used to fabricate a core component for in-reactor testing at ORNL.
  - ✓ acceptable strength of 300 MPa, parallel and perpendicular to the printing plane,
  - ✓ thermal conductivity 37 W/m K at 25 °C (12.5 mm disc with 1.9 mm thickness)

Literature data indicate that crystalline AM SiC with high dimensional stability and minimal degradation under neuron irradiation can be fabricated.

Score of 2
AM SiC as a promising material for nuclear applications.

- Crystalline SiC with high purity can be fabricated by (1) binder jet printing followed by CVI, (2) LCVD, and (3) selective laser sintering of SiC powders.

- High-pure AM SiC showed excellent nuclear properties with minimal secondary phase formation and low irradiation-induced strength degradation.

- High dimensional stability after neutron irradiation to high neutron damage levels of up 100 dpa.

Nuclear property data for AM SiC are available, data on mechanical property and corrosion are sparsely available

Score of 2
Silicon Carbide SiC

Technical maturity for end use/development stage

• The processing route has a significant influence on the resulting properties and irradiation resistance.
• There are currently three generations of SiC fibers that have been commercially produced, and only the Gen-III fibers are suitable for nuclear applications.
• For matrix densification, chemical vapor infiltration is the best method, and nano-infiltration and transient eutectic-phase process are improving and may be considered.
• In crystalline SiC, the matrix must be stoichiometric with high-purity for adequate irradiation resistance.
• The technical maturity for fabricating AM SiC for nuclear application is high due to intensified research at Oak Ridge National Laboratory over the last decade.
  • A core component of BJ-CVI fabricated AM SiC is deployed in a test-demonstration under nuclear conditions in nuclear reactor at Oak Ridge National Laboratory (ORNL).
  • AM SiC showed acceptable mechanical strength of 300 MPa with little anisotropy.

The technical maturity for deployment:
Score of 2 with a trend to 3.
Silicon Carbide SiC

**Deployment readiness requirements**

Deployment of AM SiC in nuclear facilities within this decade is projected.

New fabrication routes, such as binder-jetting in combination with chemical vapor infiltration (BJ-CVI) have been developed for the purpose of providing nuclear-grade AM SiC for core application.

**Supply chain availability**

Materials for the fabrication of AM SiC are commercially available as standard chemical supply or as SiC microparticles (Thermo Fisher, Sigma Aldrich, GNM, Oocap Inc.).

**Programmatic factors**

Nuclear grade SiC is proposed for deployment in Gen-VI systems such as MSR, GFR, VHGR, and Micro Reactors. The programmatic factor of AM SiC is high.
### Summarized Information on 3 selected Gen-IV AM materials

<table>
<thead>
<tr>
<th>Material/ Information</th>
<th>SS316L</th>
<th>Inconel 718</th>
<th>SiC</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>AM Fabrication</strong></td>
<td>LPBF, SLM, LENS</td>
<td>SLM, LPBF, DED, EBPBF, LENS, LDMD, LRF, DLF</td>
<td>CVD</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>BJ-CVI</td>
</tr>
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<td></td>
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<td></td>
<td>Lithography &amp; sequential pyrolysis</td>
</tr>
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<td></td>
<td>Direct-Ink writing/pyrolysis</td>
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<td></td>
<td>LCVD</td>
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<td></td>
<td>Selective laser sintering</td>
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<td><strong>Post-Processing microstructure</strong></td>
<td>Dozens solution annealing</td>
<td>2 study on normalization</td>
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</tr>
<tr>
<td></td>
<td>(SA) studies including TTT</td>
<td>1 study on recrystallization,</td>
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<td>1 study on HIP with solution</td>
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<td></td>
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<td>annealing</td>
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<tr>
<td><strong>Corrosion resistance</strong></td>
<td>&gt;5 Pitting potentials</td>
<td>Hydrogen embrittlement</td>
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<tr>
<td></td>
<td>&gt; 3 IGC</td>
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<td>&gt;5 Stress corrosion cracking</td>
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<td>Hydrogen embrittlement</td>
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<td>&gt;5 studies on tensile</td>
<td>1 study on high-temperature strength</td>
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<tr>
<td></td>
<td>7 Studies on fatigue</td>
<td>4 studies on creep fatigue</td>
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<tr>
<td></td>
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<td></td>
<td>8 Studies on creep</td>
<td>Fracture toughness</td>
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<tr>
<td><strong>Irradiation Damage</strong></td>
<td>Proton to $5.4 \times 10^{19}$ p/cm$^2$</td>
<td>Krypton to 3 dpa @ 200 and</td>
<td></td>
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<tr>
<td></td>
<td>3 MeV Fe to 200 dpa</td>
<td>400 °C on Y$_2$O$_3$ modified</td>
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<tr>
<td></td>
<td>1 MeV Kr</td>
<td>Inconel 718</td>
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<td>1 study on neutron irradiation</td>
<td>1 study on neutron irradiation</td>
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<tr>
<td><strong>Neutron-Irradiation</strong></td>
<td>$1$ dpa $=1 \times 10^{21}$ n/cm$^2$ for E$&gt;0.1$MeV</td>
<td>$9$ studies up to $100$ dpa</td>
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<td>1 study on in-reactor testing</td>
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Conclusions

• **Stainless Steel**
  - AM austenitic steel grades SS316L and SS304 most promising for near-term nuclear deployment and levels of maturity and readiness are high.
  - Martensitic/ferritic HT9 ranks high, but fabrication-structure-property data on AM fabricated HT9 less available.

• **SiC**
  - AM SiC scores high on one fabrication hybrid method such BJ-CVI : in-core testing of AM SiC with is currently performed at ORNL.
  - SiC-Composite materials still low maturity for deployment

• **Nickel Alloys and Super Alloys:**
  - Maturity and readiness level of AM IN718 higher compared with AM IN617. The fabrication of crack-free high-performance Ni-based alloys using AM technology challenging because of their susceptibility to hot cracking.
  - Maturity of AM Incoloy 800H for high temperature deployment is jeopardized by its affinity for carbide precipitation and sensitizing.
  - Data on AM Hastelloy N must yet become available. Data on related AM Hastelloy X are available. AM Hastelloy X shows susceptibility for hot cracking, which could be mitigated by the addition of TiC nano powders. High concentration of refractory metals in AM alloys lead to phase segregation and solutionizing remains incomplete.

• **Graphite:**
  - Fabricating nuclear grade graphite by AM is a real challenge.
  - A novel process to combines binder-jetting & sequential impregnation-drying-pyrolysis cycles was developed which has the potential to fabricate graphite acceptable for nuclear deployment.
To achieve the desired properties for nuclear application, phase transformation and microstructural alteration of the as-built AM materials during post-fabrication heat treatment must be studied.

Need central database: processing conditions, resulting microstructure, post processing thermal treatment, mechanical properties, nuclear performance.

Develop time-temperature-transformation (TTT) diagrams for AM fabricated steels and alloys:

- Optimize solutionizing.
- Control the formation of carbides (MC, M_{23}C_6, \gamma'/\gamma'\''', G-phase, and ordered Laves phases.
- Minimize the content of \delta-ferrite (in austenitic alloys).
- Homogenize microstructure and achieve normalization.
- Achieve isotropic behavior of physio-mechanical properties similar of those of wrought material.

Phase transitions of AM alloys have to be understood to:

- Decrease additional ASME qualification requirements for AM materials.
- Allow their deployment within this decade and without undergoing lengthy testing of mechanical and nuclear properties.
- Heat treatment will deplete some properties such as mechanical strength, resistance to grain boundary embrittlement and IGC, as well as corrosion resistance.

Campaign on nuclear properties of AM alloys regarding void swelling, radiation-induced precipitation (RIP) and radiation-induced segregation (RIS) might be necessary to allow for a full deployment of AM materials in nuclear reactor systems.
Thank you

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