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Material Identification and Prioritization

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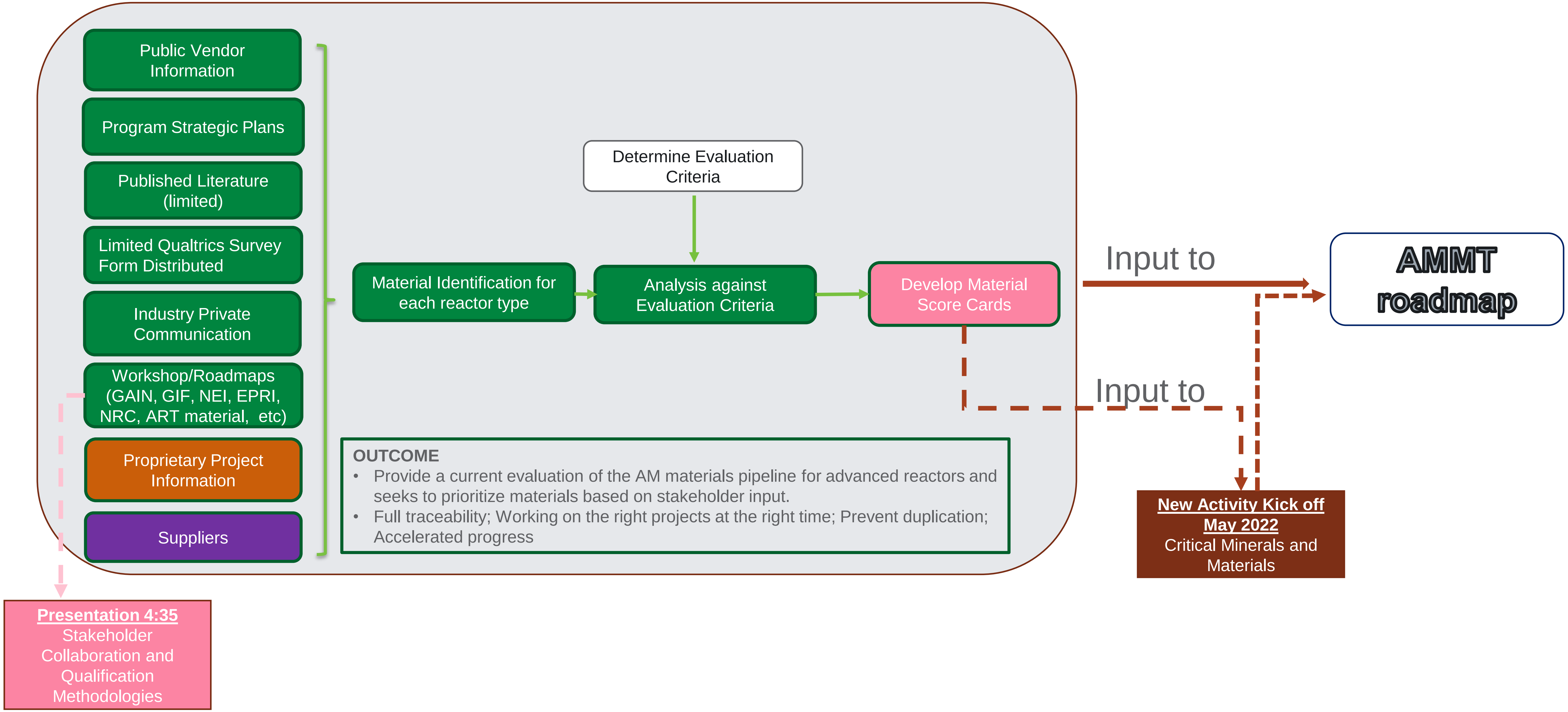
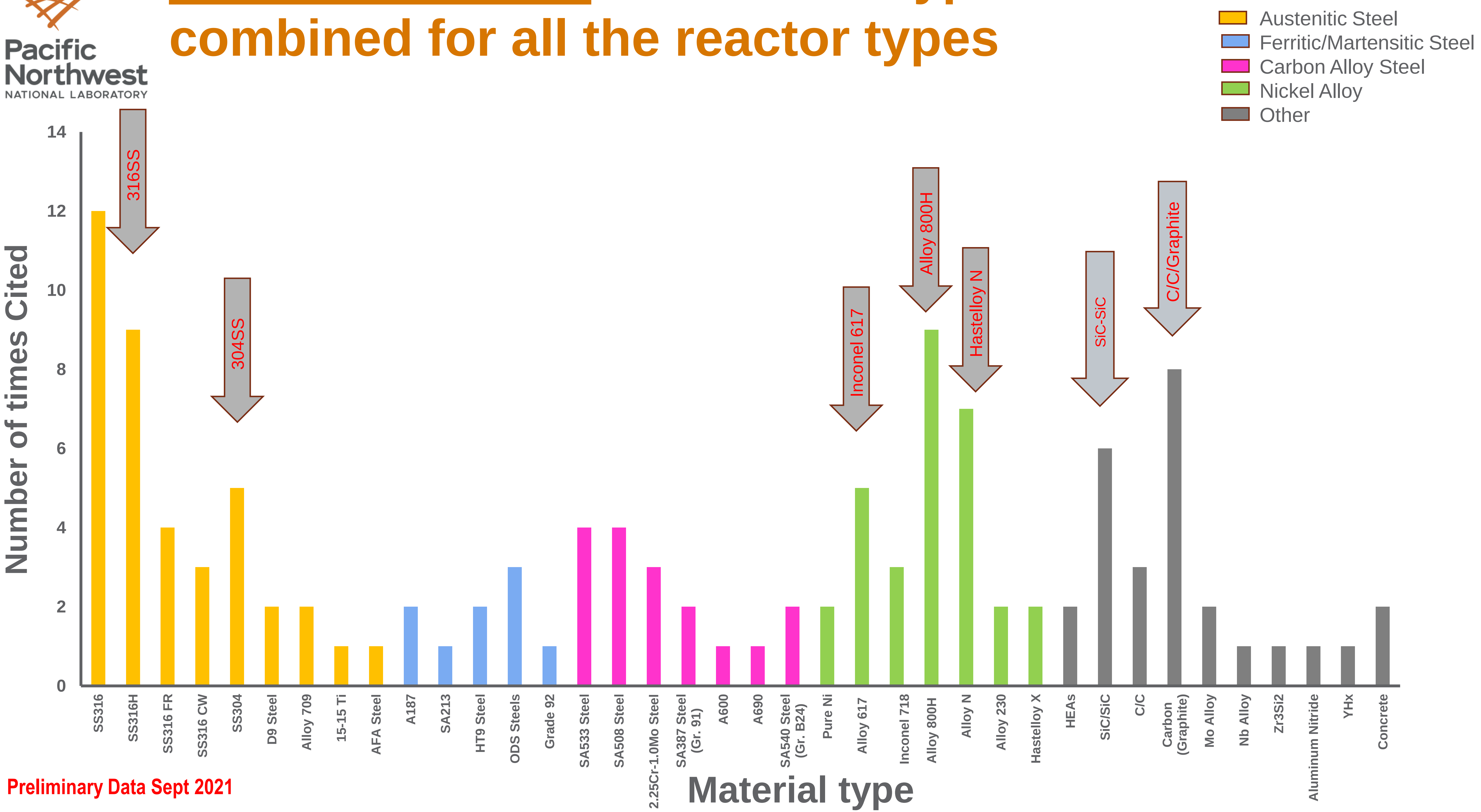
AMMT Projects Analysis and Prioritization Process: Material focused

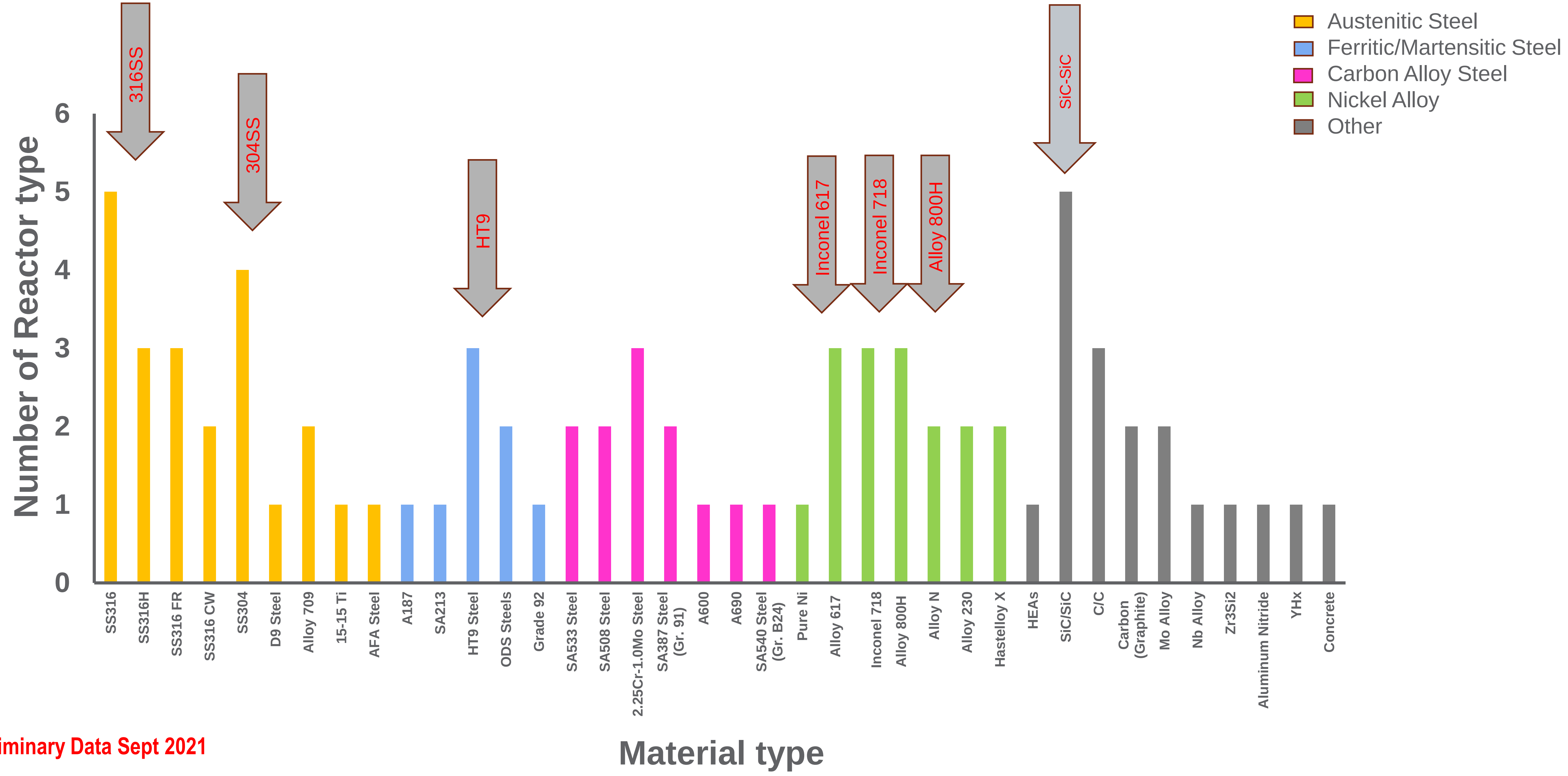


Number of times the material type was referenced combined for all the reactor types



Preliminary Data Sept 2021

Number of reactors the material type was referenced; combined for all reactor types



Preliminary Data Sept 2021

Score Criteria

Score criteria developed by collaborative effort by DOE-NE(5, NE4); AMM program, ART-program materials lead)

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

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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

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Examples of Specific Reactor Type Score Card

ID	Criteria	Guidance	MSR									VHTR						
			316	316H	304	Alloy 800H	Alloy N	Graphite	SiC	HT9	IN617	316	304	Alloy 800H	Graphite	SiC	IN617	IN718
1	**Code Availability**	Codes are available for all areas = 5 For two of the three areas = 3 For one area = 1	3 (3)	0 (1)	3 (3)	1 (2)	0	1 (2)	2 (2)	2	1 (2)	1 (3)	2 (3)	1 (2)	1 (2)	2 (2)	1 (2)	1 (1)
2	**Minimal Gaps in Data Availability for Performance Values and Measurements**	No or few gaps in data availability = 5 Moderate gaps in data availability = 3 Large gap in available data = 1	3 (3)	1 (1)	3 (3)	1 (2)	0 (1)	1 (1)	2 (2)	2	1 (2)	1 (3)	2 (3)	1 (2)	1 (1)	2 (2)	1 (2)	2 (2)
3	**Technical Maturity for End Use/Development Stage**	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	3 (3)	1 (1)	3 (3)	2 (3)	0 (1)	2 (2)	2 (2)	2	2 (3)	2 (3)	2 (3)	2 (3)	2 (2)	2 (2)	2 (3)	2 (3)
4	**Deployment readiness requirements**	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	3 (5)	1 (1)	3 (5)	2 (5)	0 (1)	2 (3)	3 (3)	3	2 (4)	2 (5)	2 (5)	2 (5)	2 (3)	3 (3)	2 (4)	2 (4)
5	**Supply Chain Availability**	No anticipated supply chain risks or impacts = 5; Moderate impacts = 3; Major impacts = 1	3 (3)	1 (1)	3 (3)	3 (3)	1 (3)	2 (4)	2 (4)	2(3)	3 (3)	3 (3)	3 (3)	3 (3)	2 (4)	2 (4)	3 (3)	3 (3)
6	**Programmatic Factors**	Applications across all reactor types and/or multiple industry entities interested in a reactor type = 5	5 (5)	1 (1)	5 (5)	4 (4)	4 (1)	5 (5)	4 (4)	4	4 (4)	5 (5)	5 (5)	4 (4)	5 (5)	4 (4)	4 (4)	4 (4)

Values in bracket are phase 1 scores.

Overview on Results

Criteria	Guidance	AM Material for use in Gen-IV Reactors								
		SS316	SS304	Alloy 800H	Graphite	Hastelloy N	SiC	HT9	IN 617	IN 718
Code Availability	Codes Available 1-5	3	3	1	1	0	2	2	1	1
Minimal Gaps in Data Availability for Performance Values and Measurements	No or few gaps 1-5	3	3	1	1	0	2	2	1	2
Technical Maturity for End Use/Development Stage	TRL/MRL 1-5	3	3	2	2	0	2	2	2	2
Deployment readiness requirements	Industrial deployment 1-5	3	3	2	2	0	3	3	2	2
Supply Chain Availability	No to major risk 1-5	3	3	3	2	1	2	2	3	3
Programmatic Factors	# of Reactor types	5	5	4	5	4	4	4	4	4
Average Score		**3.33**	**3.33**	**2.17**	**2.17**	**0.83**	**2.5**	**2.5**	**2.17**	**2.33**

Austenitic SS316

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

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

Composition of various 316SS grades in weight %.

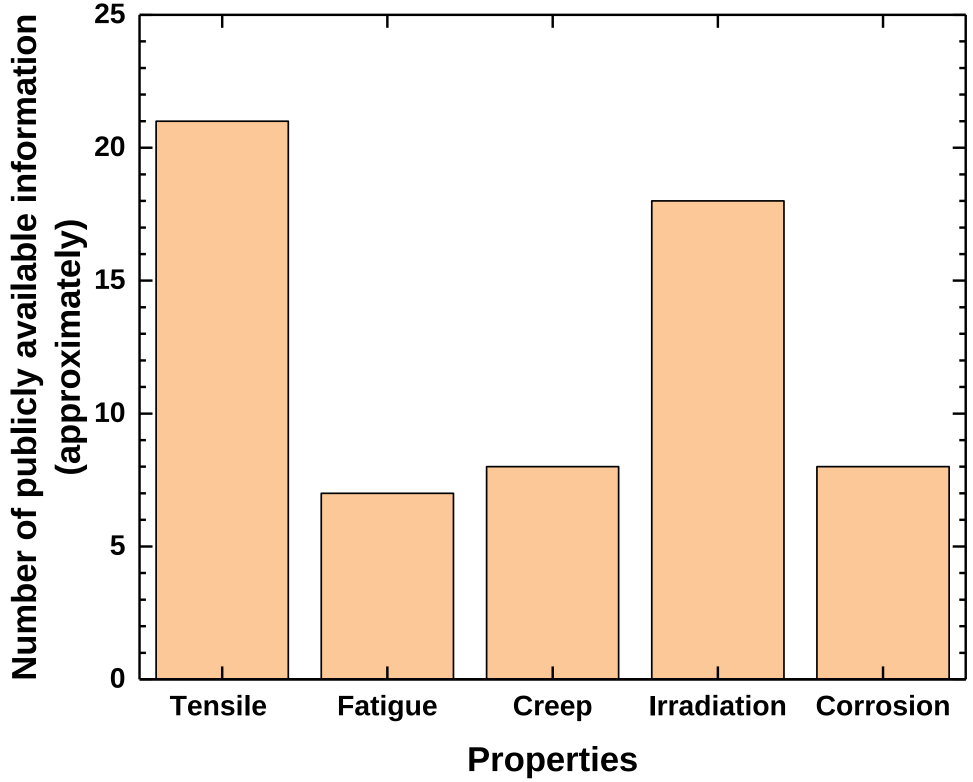
<table>
<tr><th>Grade</th><th>C</th><th>Mn</th><th>Si</th><th>P</th><th>S</th><th>Cr</th><th>Ni</th><th>Mo</th><th>N</th></tr>
<tr><td>316 (UNS 31600)</td><td>0.08</td><td rowspan="3">2.0</td><td rowspan="3">0.75</td><td rowspan="3">0.045</td><td rowspan="3">0.03</td><td rowspan="3">16.0-18.0</td><td rowspan="3">10.0-14.0</td><td rowspan="3">2.0-3.0</td><td rowspan="2">0.10</td></tr>
<tr><td>316L (UNS S31603)</td><td>0.03</td></tr>
<tr><td>316H (UNS S31609)</td><td>0.04-0.10</td><td>0.0</td></tr>
</table>

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 team[1].
  - 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 processes[2].
  - 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.

[1]D.W. Gandy, S. Tate, F.A. List III, R. Dinwiddie, K. Carver, C. Hensley, K. Sisco, A. Godfrey, S. Babu, ICME and In-Situ Process Monitoring for Rapid Qualification of Components Made by Laser-based Powder Bed Additive Manufacturing Processes for Nuclear Structural Applications, Electric Power Research Institute, 2020
[2]F3184-16 Standard Specification for Additive Manufacturing Stainless Steel Alloy (UNS S31603) with Powder Bed Fusion, 2016.

HIP: Hot isostatic pressing
SA: Solution anneal

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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.

	Irradiation conditions
Proton irradiation	1. 2 MeV proton raster beam at 360°C of stress relieved 316L 2. 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 3. 2 MeV proton irradiation at 360°C
Ion irradiation	1. Irradiated with 5 MeV Fe^{2+} ions at temperatures of 500, 550, and 600°C 2. Irradiated with 3.5 MeV Fe^{2+} ions at 500°C 3. Heavy ion irradiation with Kr^{2+} ions at 400°C
Neutron irradiation	Neutron irradiation at 300 and 600°C to 1.6 dpa
Helium	1. 500 keV helium ions at temperatures 350, 550, 700, 800 and 900°C 2. 500 keV He ions at 700°C

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 IASCC 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.% Y_2O_3 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.

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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

Silicon Carbide SiC

Gaps in data availability for performance values and measurements

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 a 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 Score of 3

Deployment of AM SiC in nuclear facilities withing 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 Score of 2

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 Score of 4

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

Material/ Information	SS316L	Inconel 718	SiC
AM Fabrication	LPBF, SLM, LENS	SLM, LPBF, DED, EBPBF, LENS, LDMD, LRF, DLF	CVD BJ-CVI Lithography & sequential pyrolysis Direct-Ink writing/pyrolysis LCVD Selective laser sintering
Post-Processing microstructure	Dozens solution annealing (SA) studies including TTT	2 study on normalization 1 study on recrystallization, 1 study on HIP with solution annealing	
Corrosion resistance	>5 Pitting potentials > 3 IGC >5 Stress corrosion cracking Hydrogen embrittlement	Hydrogen embrittlement	
Mechanical Properties	>20 Studies on tensile 7 Studies on fatigue Fracture toughness 8 Studies on creep	>5 studies on tensile 4 studies on creep fatigue testing Fracture toughness	1 study on high-temperature strength
Irradiation Damage Neutron-Irradiation 1 dpa $=1\times10^{21}$ n/cm^2 for E>0.1MeV	Proton to 5.4×10^{19} p/cm^2 3 MeV Fe to 200 dpa 1 MeV Kr 1 study on neutron irradiation	Krypton to 3 dpa @ 200 and 400 °C on Y_2O_3 modified Inconel 718 1 study on neutron irradiation	9 studies up to 100 dpa 1 study on in-reactor testing

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.

Outlook

- 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, $M_{23}C_6$), γ'/γ'', G-phase, and ordered Laves phases.
  - Minimize the content of δ-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.

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Thank you

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