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Fast Reactors/Transmutation Technology/SFR

Advanced Structural Materials Development: Accomplishments and Plans

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NEUP Workshop

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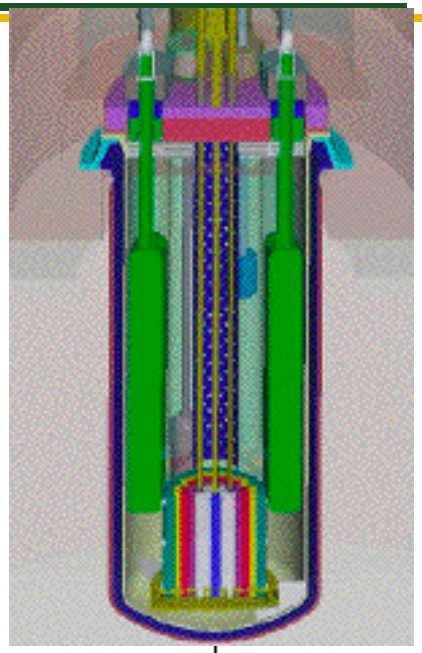
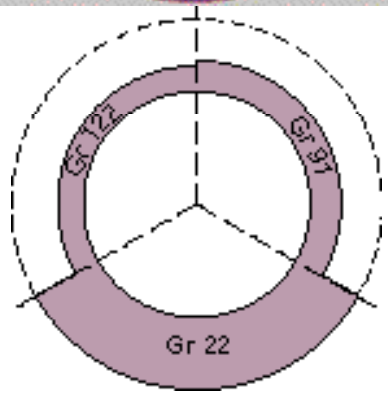
Goal of development effort is to provide qualified, advanced structural materials to enable improved reactor performance

- **Choosing the right materials can impact key requirements for advanced fast reactor development**
  - Economy: reduce capital costs through reduced commodities and simplifications
  - Flexibility: higher material performance allows greater options to designers
  - Safety: higher material performance promotes larger safety margins and more stable performance over longer lives
- **In FY2008, an extensive evaluation of candidate alloys was performed.**
  - National effort (5 labs, 5 universities)
  - Examined past and other ongoing materials efforts (nuclear, fossil, and space)
- **Both austenitic (HT-UPS) and ferritic/martensitic steels (NF616) were chosen for further discussion and development, permitting potential improvement to virtually all structural components**
- **These alloys offer substantial gains over traditional reactor materials.**





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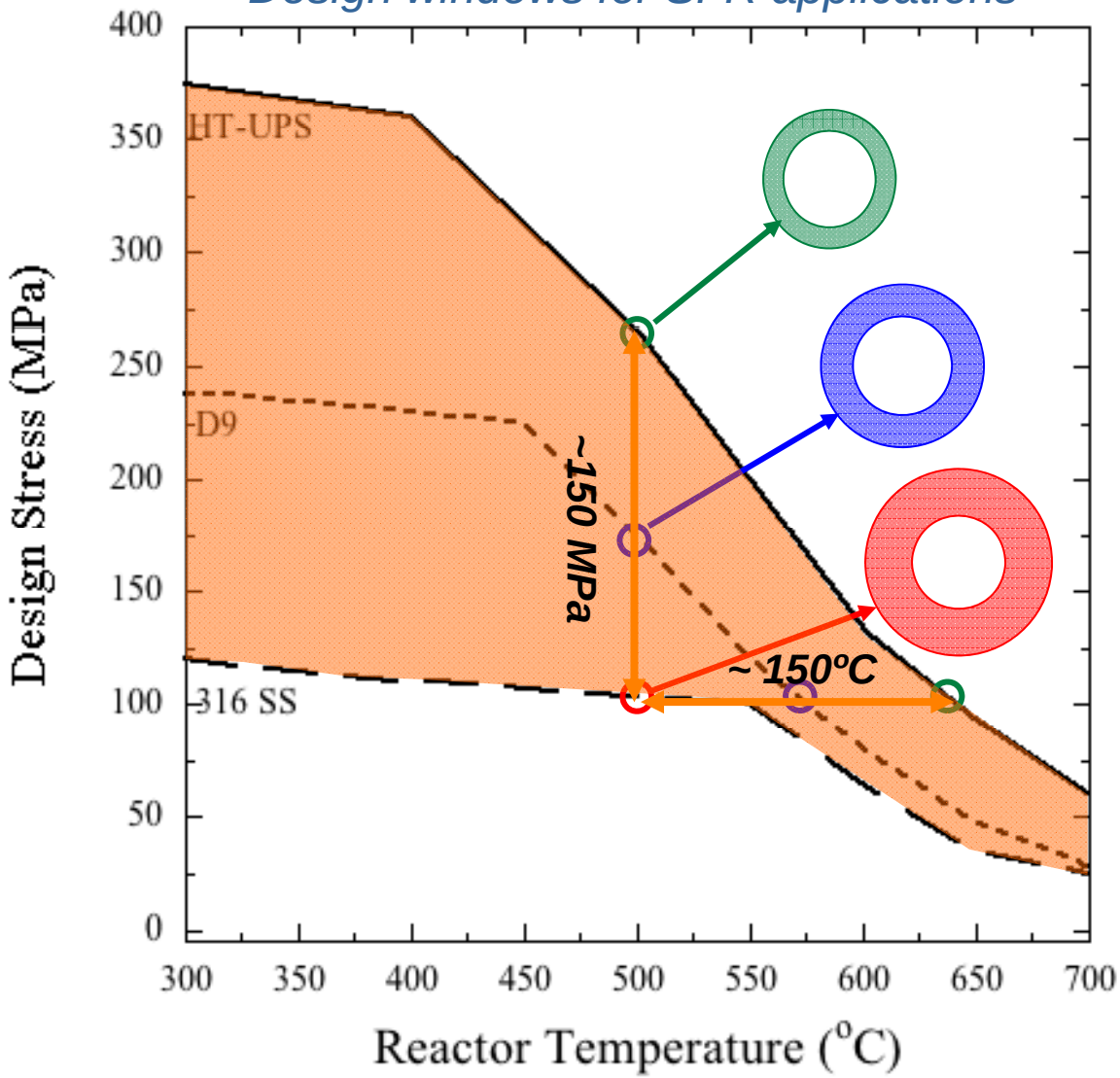
Improved materials can also impact reactor performance

Design windows for SFR applications



- ***Higher strength for constant temperature:***
  - *Reduced commodities*
  - *Greater safety margins*
  - *Longer lifetimes*

- ***Higher temperature for constant stress:***
  - *Higher plant performance (?)*
  - *Reduced commodities*
  - *Greater safety margins in accident scenarios*

- ***Combinations of above:***
  - *Greater flexibility*

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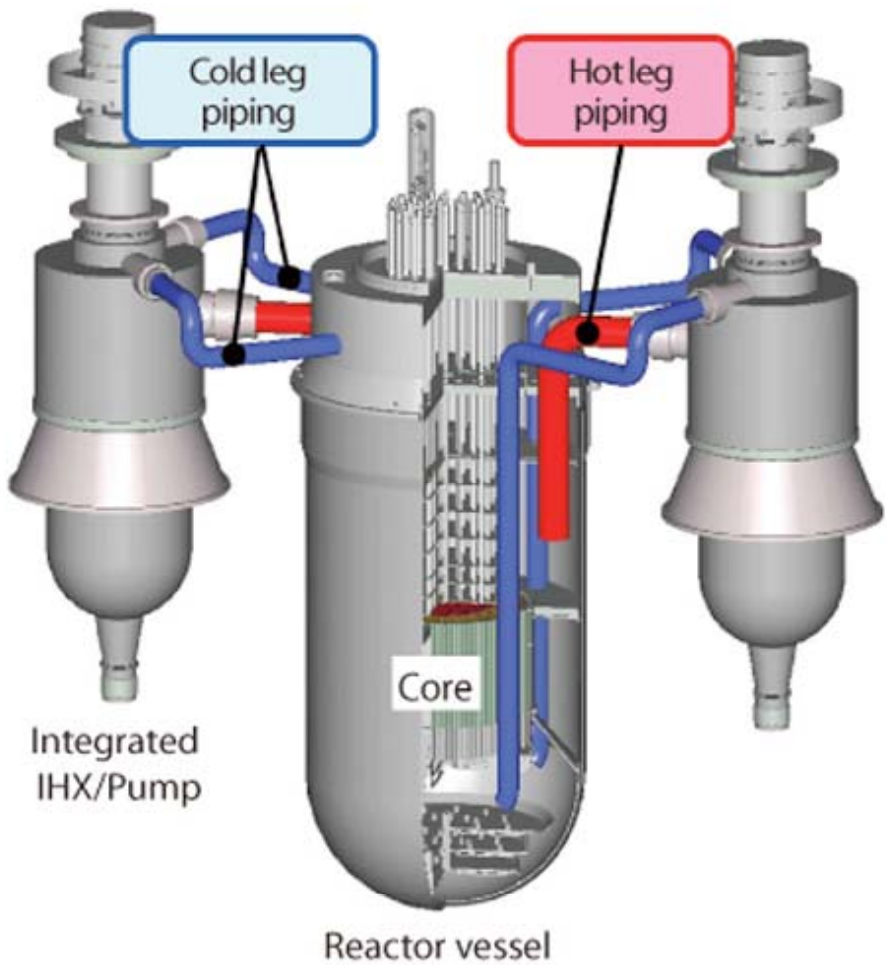
The use of advanced materials may also allow for design simplifications

- The JSFR utilizes 9Cr steels for piping.
- These steels have improved strength and very low thermal expansion, allowing for larger, shorter piping.
- This allows for only 2 IHX instead of four, leading to millions of dollars in potential cost savings.



Schematic of JSFR

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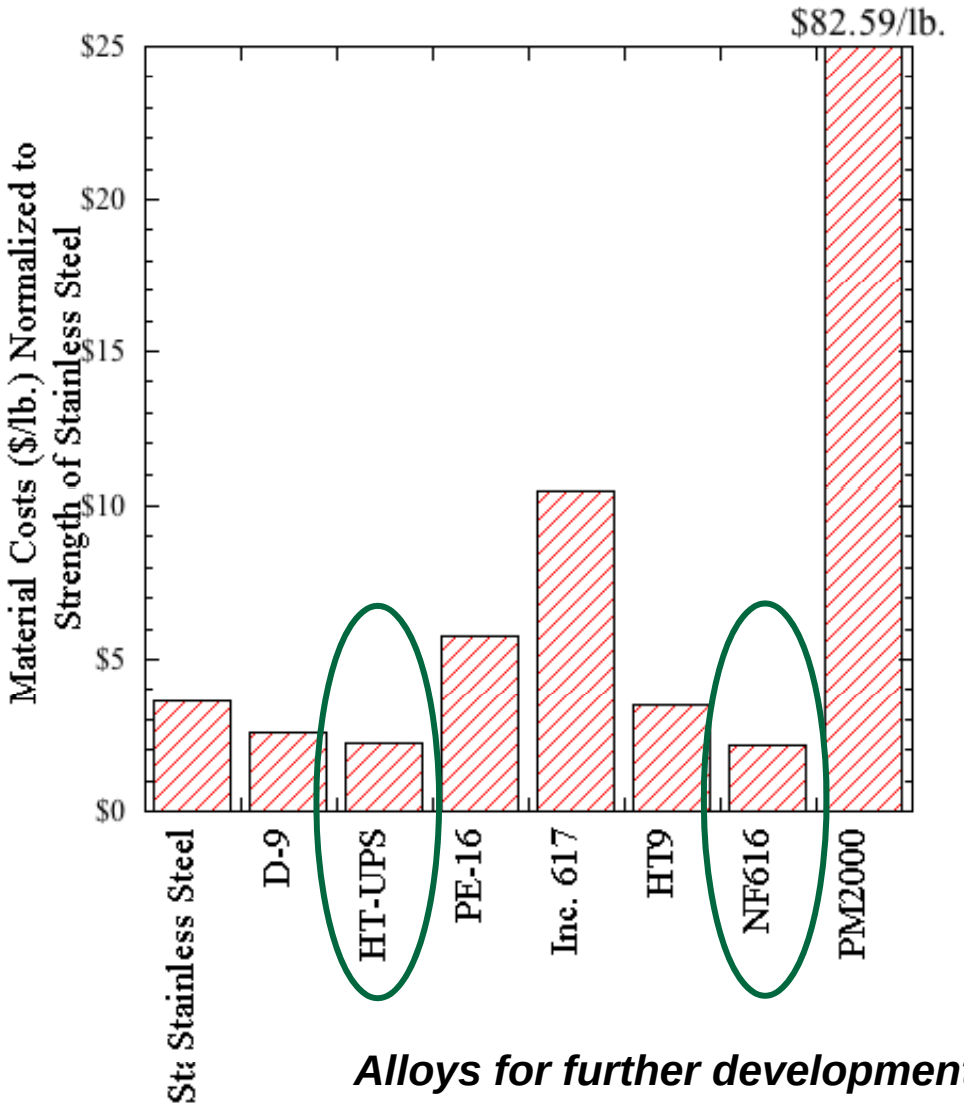
Higher performance can more than offset increased cost of materials



Alloys for further development under AFCI

- ***Higher performance can come at a premium for raw material costs***
- ***When raw material costs are normalized for improved performance advanced materials provide the best "bargain".***

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Advanced Material Development continues in several key areas

- **Advanced Alloy Development:** Charged with procurement of alloys, defining and testing processing, and acquiring basic properties.
- **Advanced Alloy Testing:** Using the new materials, mechanical testing is performed. This currently includes aging, tensile testing, fracture toughness, impact testing, and creep-fatigue.
- **Materials Performance Criteria and Methodology:** Licensing needs for advanced materials and resolution of design methodology are key long-term needs for application of advanced materials.
- **Environmental Testing (Sodium-compatibility):** There is little information on sodium compatibility of selected alloys. Initial assessments are being provided via an FOA collaboration.

Several composition modifications are being pursued

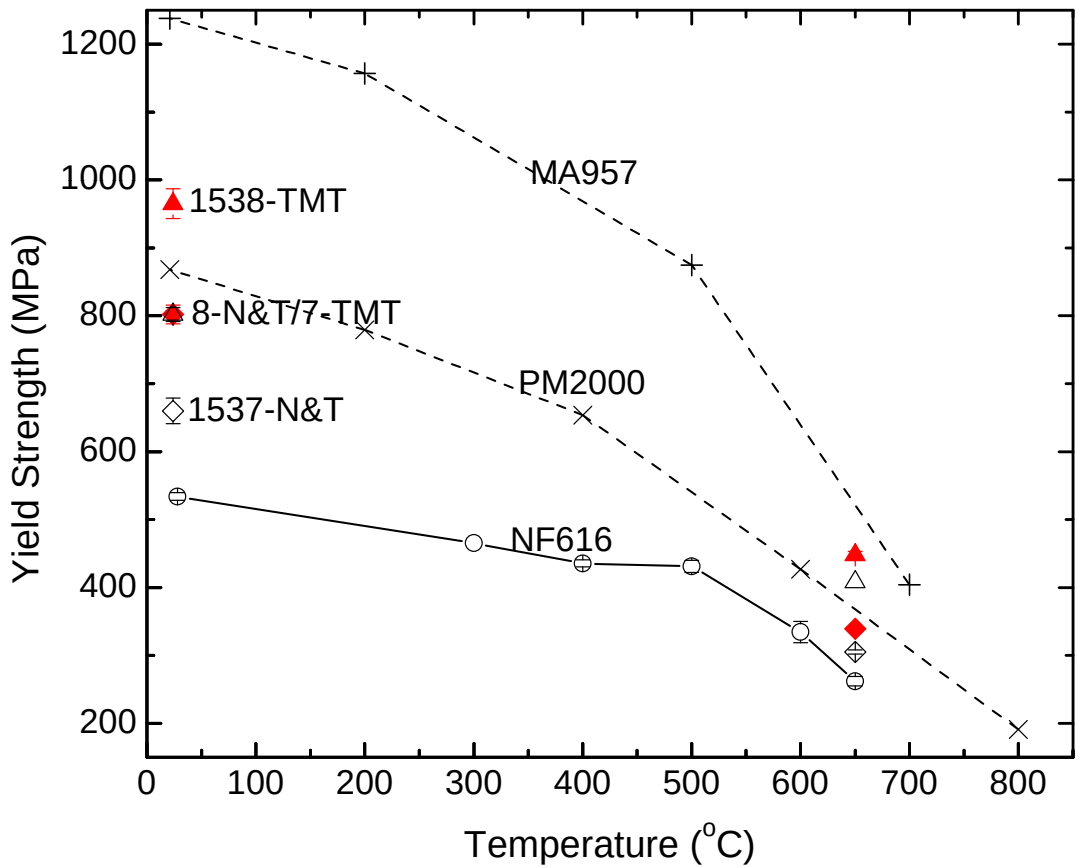
- *A commercial NF616 (Carpenter) and two model alloys were prepared with compositions (wt.%) listed in the following table.*

Alloy	Cr	Mn	Mo	W	Nb	V	Si	Ni	Cu	C	N
NF616	9.0	.45	.45	1.9	.1	-	.2	.2	.05	.1	.02
C3	9.2	.45	.05	2.0	.1	.3	.2	.4	.05	.06	.01
C5	9.3	.05	.05	2.0	.1	.3	.1	.05	1.4	.06	.005

Arc-melted and drop-casted ingots

- *Two TMT treatments, named as TMT1 and TMT2, were applied to the alloys in addition to the conventional normalization and tempering (e.g., 750℃) followed by air cooling, denoted as N&T.*

Effect of TMT on Strength and Ductility



- **Compared to the commercial 9Cr F-M steel NF616 and 12Cr-ODS steels (PM2000 and MA957)**
  - All the 4 heats showed higher strength than NF616.
  - The TMT significantly increased the strength of the 4 heats, which showed comparable (e.g., 1537-TMT) or higher strength (e.g., 1538-TMT) than PM2000 at room temperature and 650°C.

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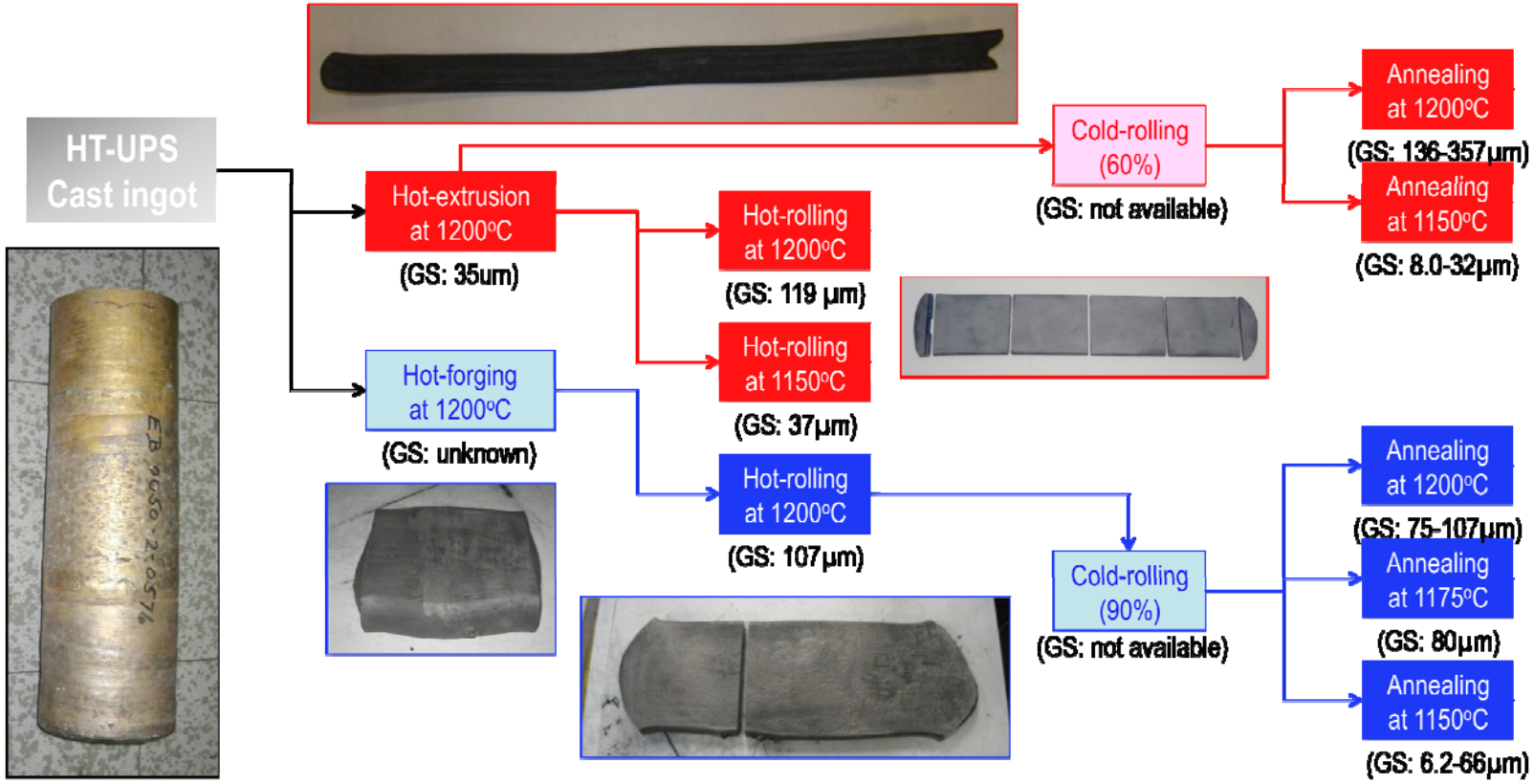
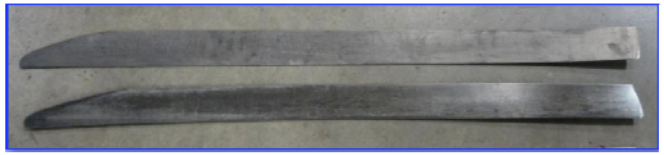
Processing of the HT-UPS alloy is also being pursued

- **Alloy composition (wt%):**

Fe-14.3Cr-16Ni-2Mn-2.3Mo-0.4Si-0.15Nb-0.5V-0.15Ti-0.06C-0.007B-0.003P-0.02N



- No cracking/ tearing during hot-working at 1150 – 1200°C.
- It can be cold-rolled up to 90% thickness reduction without intermediate annealing.



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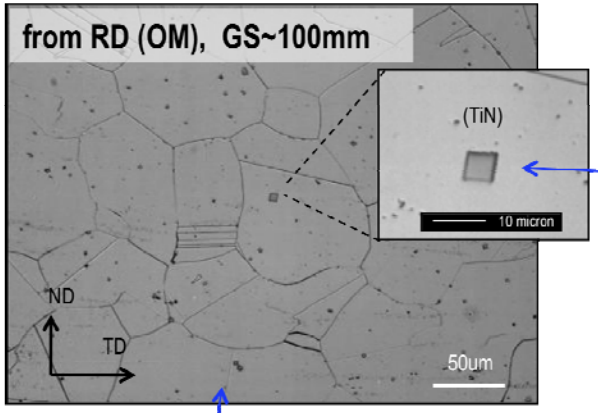
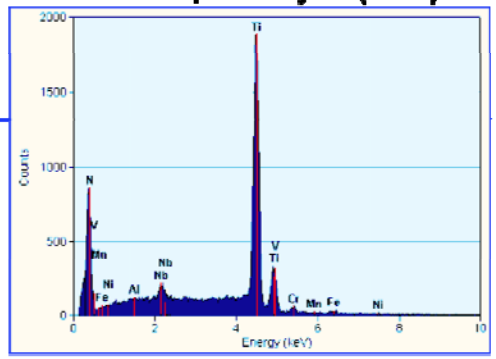
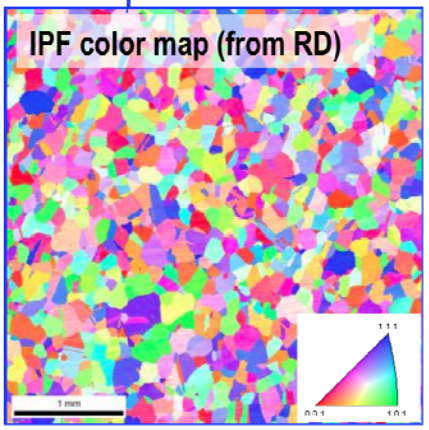
Controlling microstructure is one key to improving performance

❑ Microstructure after hot-forging/rolling

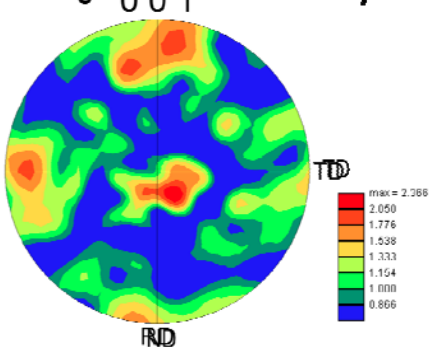


SEM-EDS spot analysis (15kV)





001 Pole Figure
(showing a weak cube-texture)



- As-processed microstructure consists of equiaxed grain together with TiN particles with ~5μm size.
- Grain size can be controlled by selecting hot-roll temperature, and annealing temperature and time after cold-rolling.
- Hot-extrusion and hot-rolling tend to show a very weak cube-texture, whereas cold-rolling + annealing results in strong (011)<100> texture (although the RT/HT strength are quite insensitive to the texture observed).

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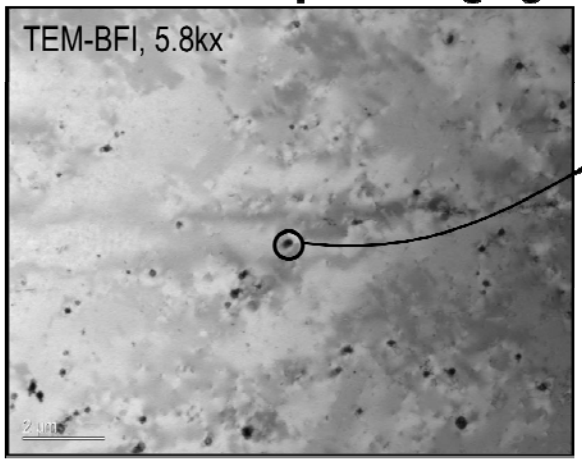
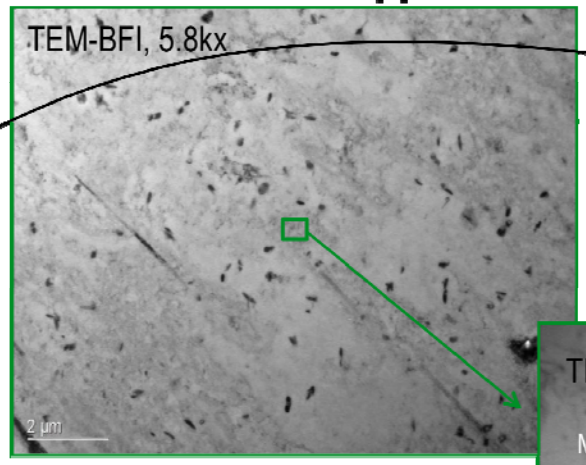
Microstructural analysis indicates that rolling introduces nano-scale carbides which improve strength

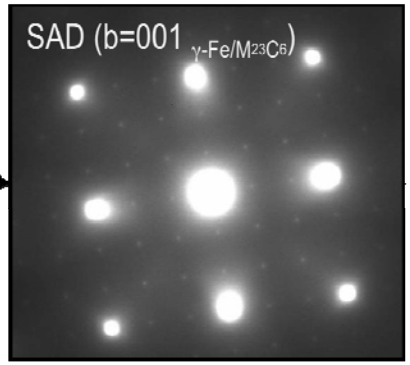
❑ TEM micrographs after aging at 650°C/1000h

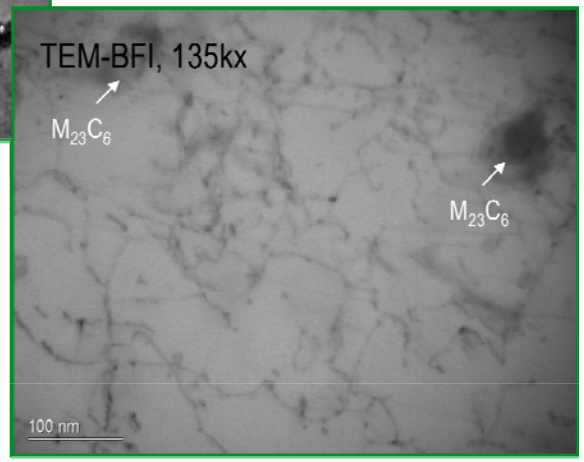
No cold-work prior to aging



20% cold-work applied







- **$M_{23}C_6$** (~200nm size) disperses in the matrix in both specimens. Cold-work may enhance the nucleation of second-phases.
- Dislocations remain without recovery/recrystallization even after 1,000h exposure, possibly due to the formation of nano-scale **MC** pinning dislocation (20%CW).

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Thermal aging studies are also being performed.

- Thermal aging studies to 5000 hours do not show significant changes in strength for the NF616 alloy.
- Microstructural simulations predict some coarsening of carbides
- Initial analysis of aged specimens is consistent

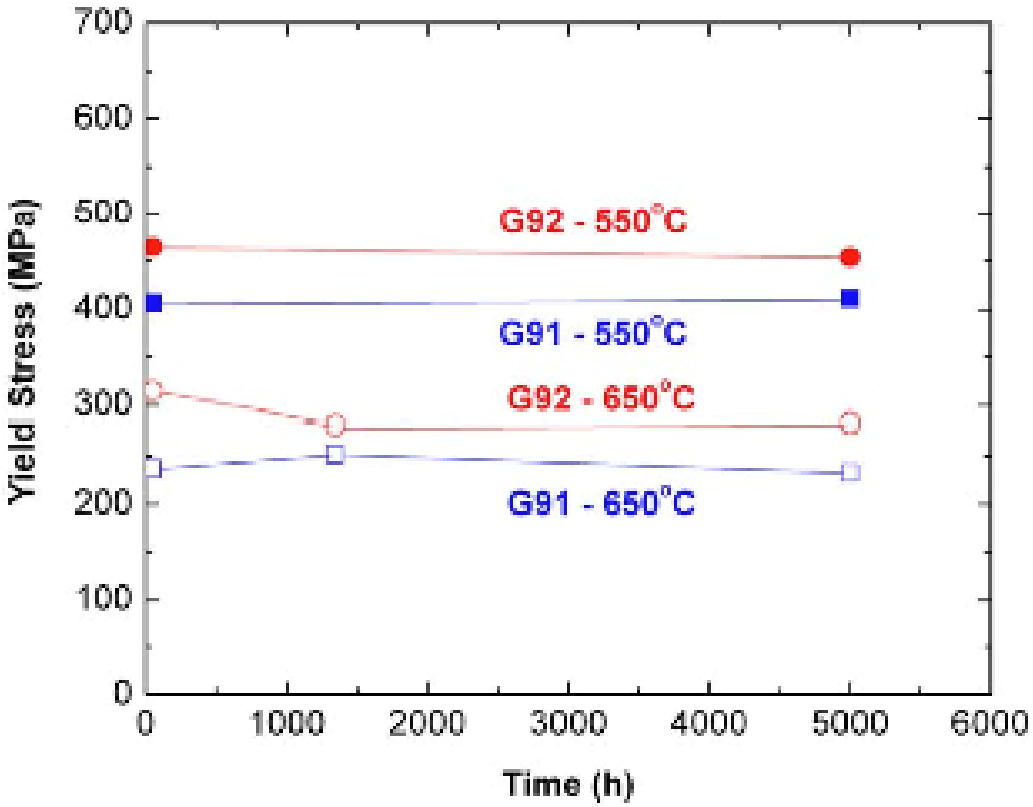

Figure 17. Yield stress as a function of exposure time for NF616 and mod.9Cr-1Mo tested at the aging temperature.

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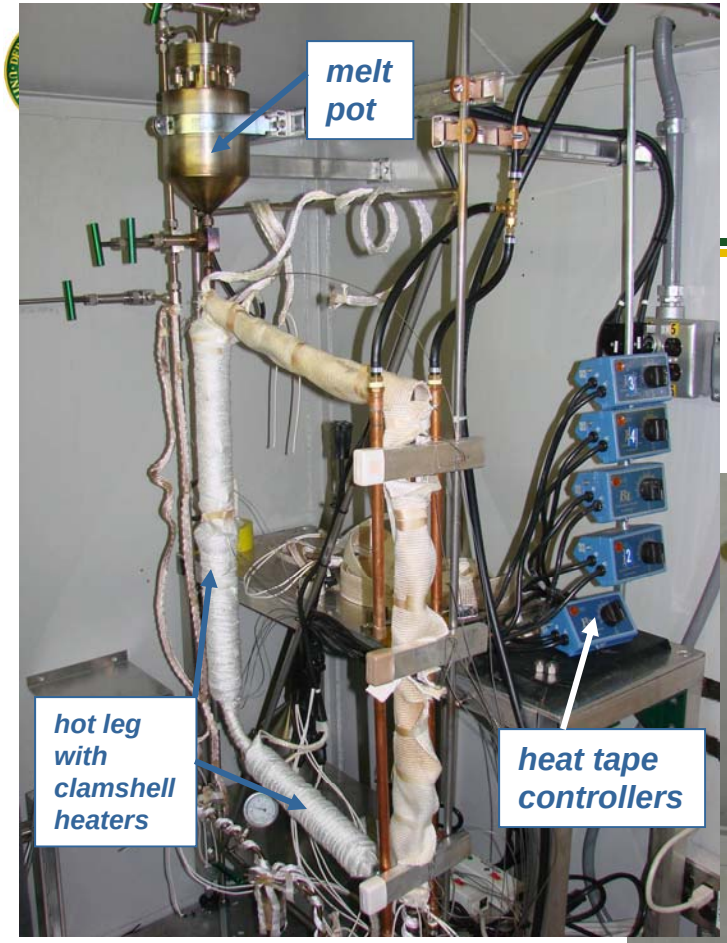
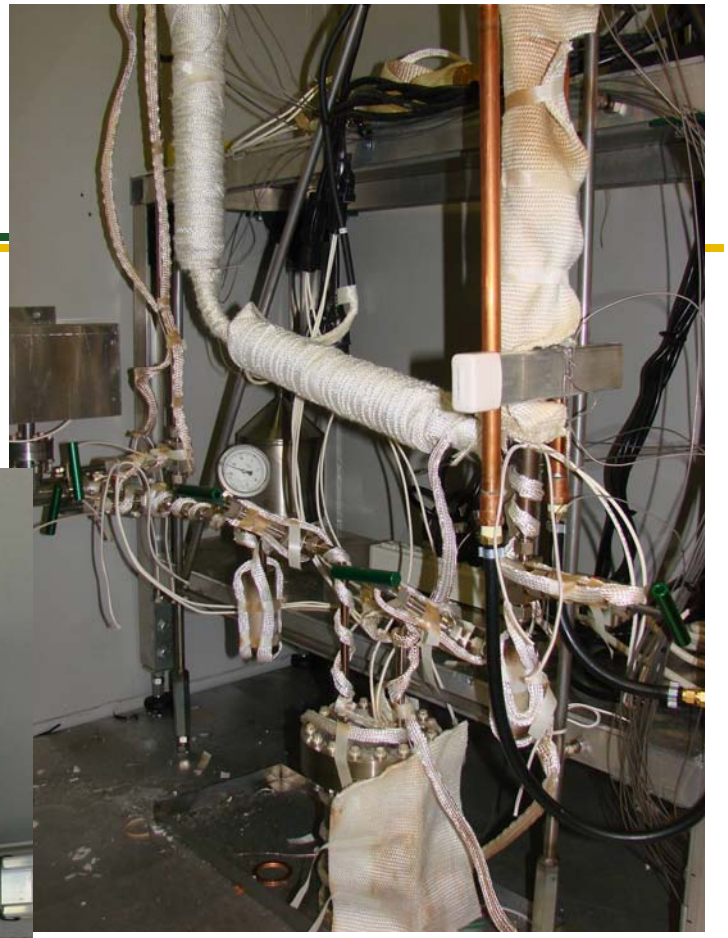
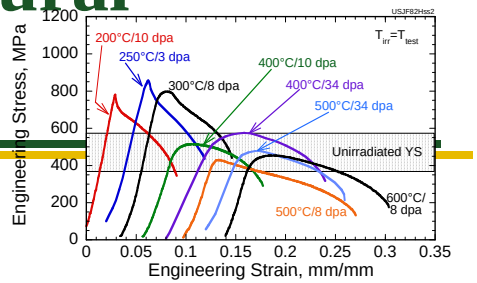
Environmental testing was initiated with an emphasis on sodium compatibility

- **Task objectives:** ***provide an initial assessment of sodium corrosion compatibility of the improved materials being considered for advanced fast reactor applications***
- **Research effort also provides an opportunity to rebuild sodium testing expertise and infrastructure**
- **A collaborative research effort has been initiated to examine sodium compatibility for advanced materials.**
- **Utilizing a combination of capsules, thermal convection loops, pumped loops, and accelerated testing in gas loops will provide a more detailed and varied database.**

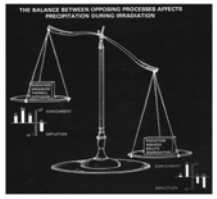

melt pot
hot leg with clamshell heaters
heat tape controllers

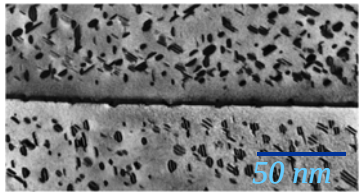


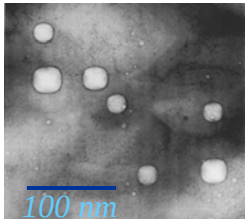
Radiation Damage can Produce Large Changes in Structural Materials

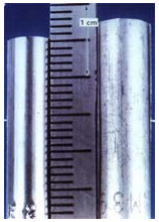


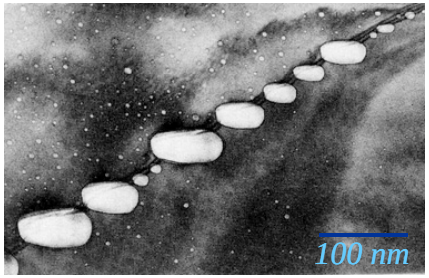
- **Radiation hardening and embrittlement (<0.4 T_M, >0.1 dpa)**
- **Phase instabilities from radiation-induced precipitation (0.3-0.6 T_M, >10 dpa)**
- **Irradiation creep (<0.45 T_M, >10 dpa)**
- **Volumetric swelling from void formation (0.3-0.6 T_M, >10 dpa)**
- **High temperature He embrittlement (>0.5 T_M, >10 dpa)**











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Advanced Material Development in FY11 will continue to build upon previous work

- **Advanced Alloy Development:** Continued development of optimized conditions, testing, and analysis
- **Advanced Alloy Testing:** Using the new materials, mechanical testing is performed. This will continue thermal aging, tensile testing, fracture toughness, impact testing, and creep-fatigue.
- **Environmental Testing (Sodium-compatibility):** Sodium testing will continue at all partners, building upon FOA testing and equipment investments.
- **Materials Performance Criteria and Methodology:** Key testing needs will be initiated using FY09 report and FY10 progress as basis.

- **Key needs for university partners include**
  - Microstructural stability during lifetime (compatibility, thermal stability, or irradiation)
  - Predictive capability of microstructure changes (life time model)

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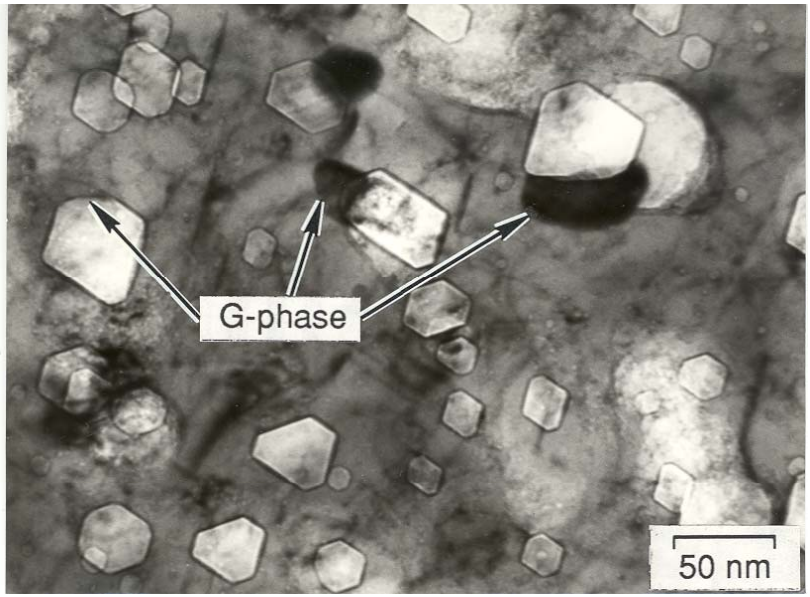
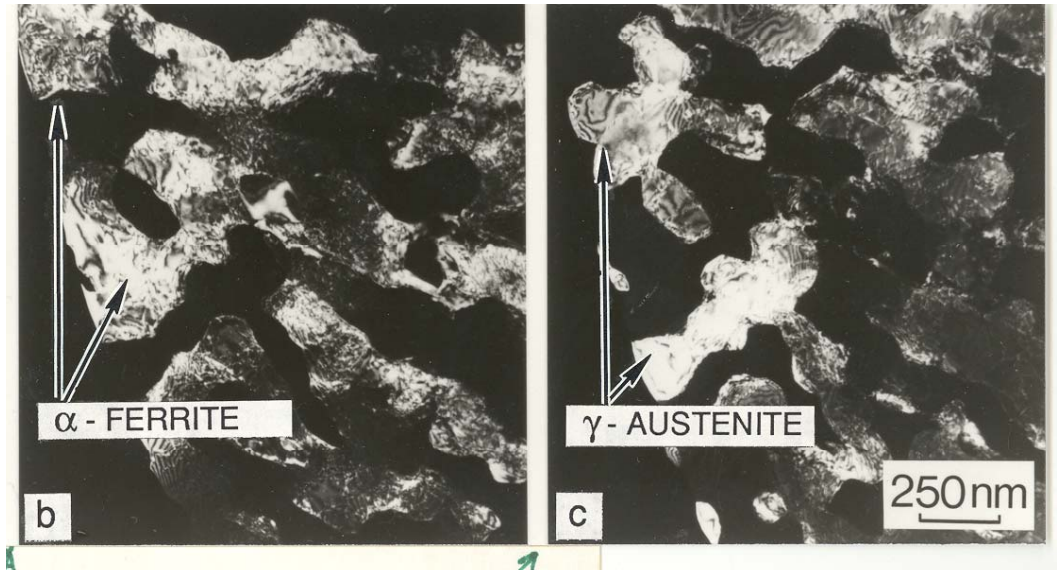
Radiation-Induced Segregation Can Lead to Local Concentrations That Exceed Solubility Limits in SFR materials



- *Microstructure of SA Fe-12Cr-15Ni-1Si austenitic stainless alloy irradiated in EBR-II at 575℃ (<20 dpa), with TEM showing*
- *RIS causes the initially homogeneous γ-austenite matrix to decompose into Fe-Cr-Si ferrite and Fe-Ni austenite.*

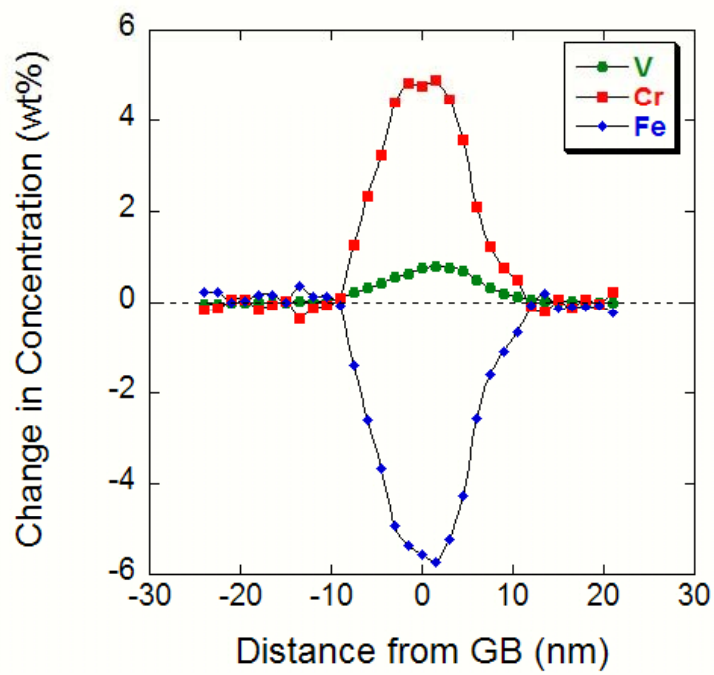
SA PCA steel irradiated at 500 C in ORR to 11 dpa (200 appm He), showing the association between radiation-induced G-phase silicide ($Mn_6Ni_{16}Si_7$) particles and the largest voids

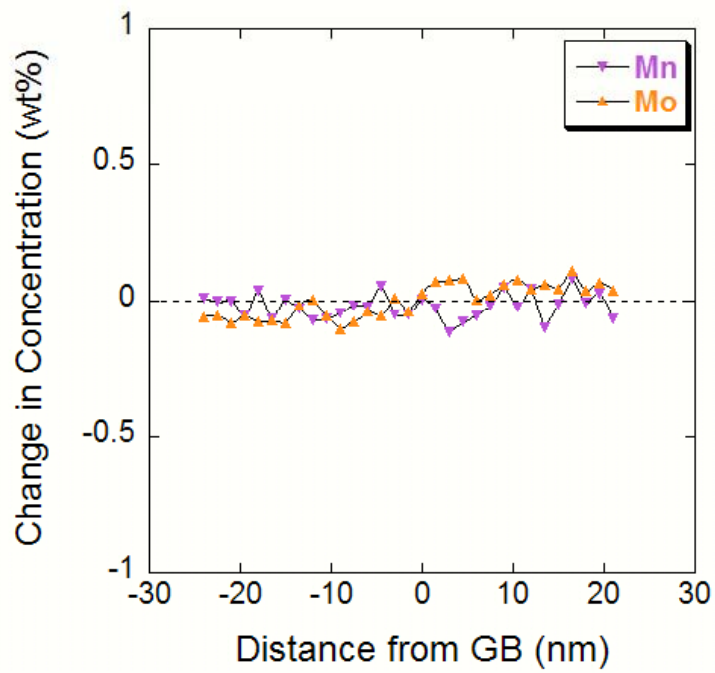


Segregation has also been observed in F/M steels identified for SFR applications

- *RIS is extremely difficult to measure in F/M steels.*

T91 to 10 dpa, 450°C, 2 MeV H+





- *Cr enrichment could lead to precipitation of additional phases.*

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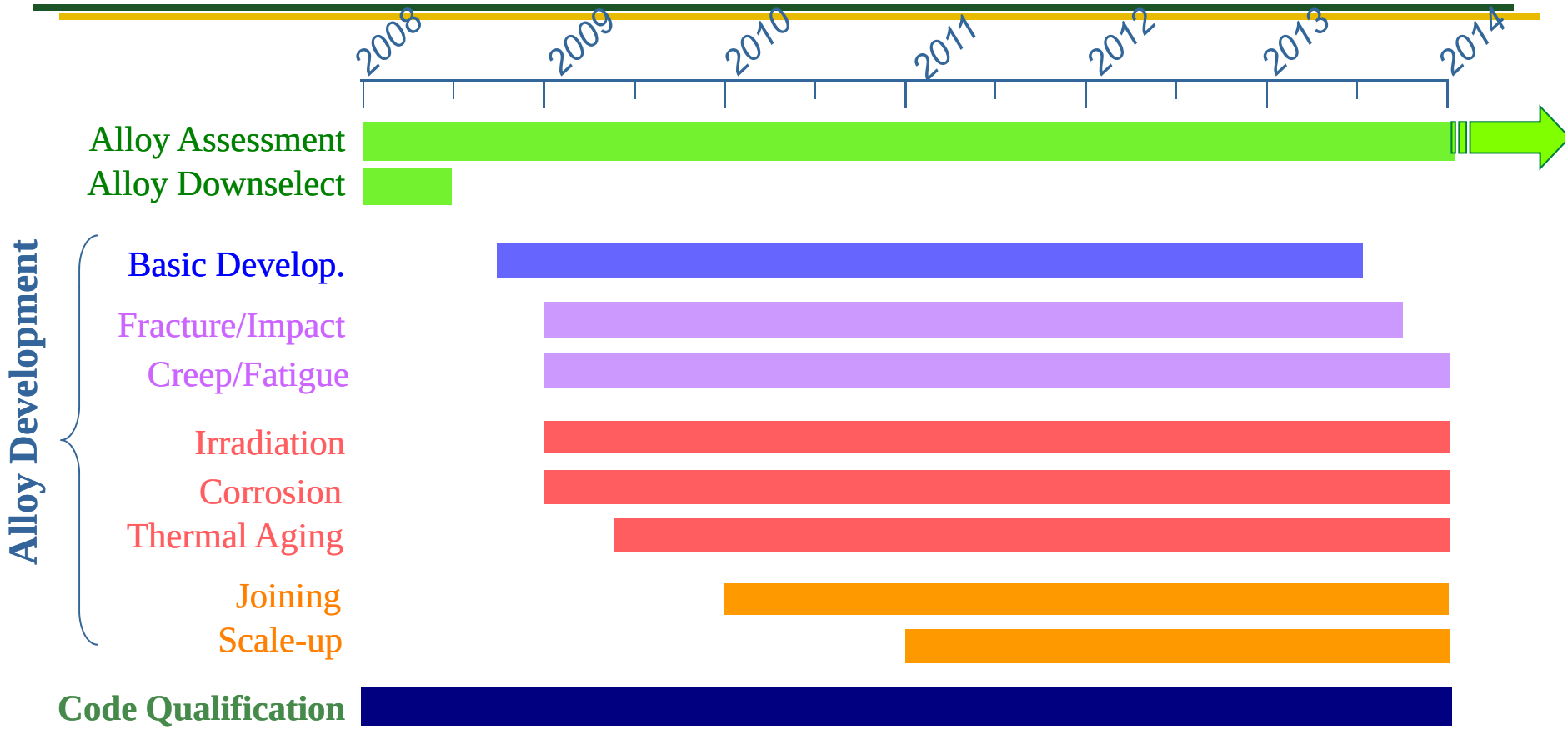
Alloy Development Plans: 5-year Plans and Needs