U.S. DEPARTMENT OF ENERGY | Nuclear Energy

UCSB

Advanced Fuels Campaign

Development of Advanced Ferritic Steels for Fast Reactor Cladding

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Advanced Reactor Core Materials Technical Lead for Advanced Fuels Campaign

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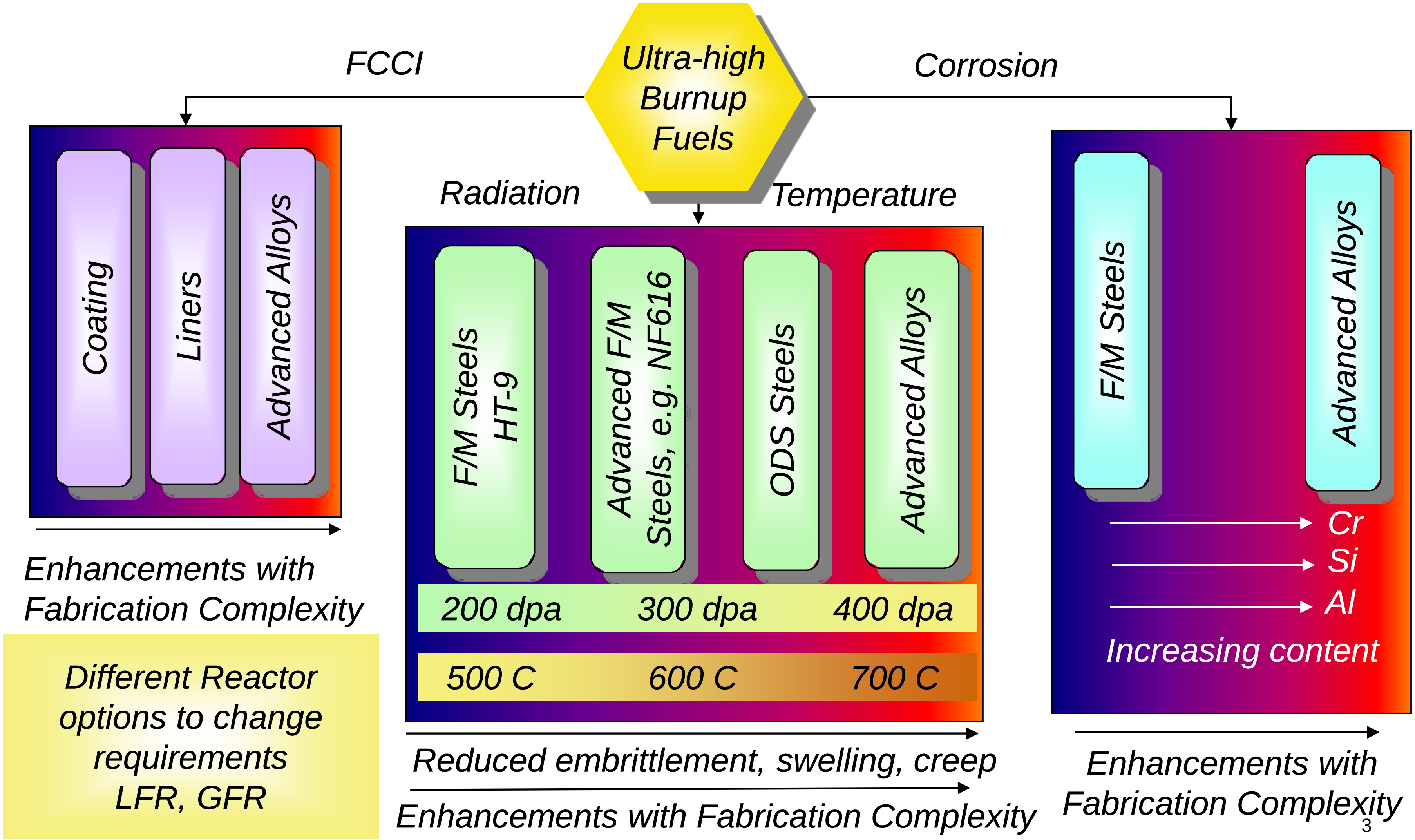
Approach to Enabling a Multi-fold Increase in Fuel Burnup over the Currently Known Technologies

Ultimate goal: Develop advanced materials immune to fuel, neutrons and coolant interactions under specific reactor environments



Ultra-high Burnup Fuels

FCCI

Coating

Liners

Advanced Alloys

Enhancements with Fabrication Complexity

Radiation

Temperature

F/M Steels HT-9

Advanced F/M Steels, e.g. NF616

ODS Steels

Advanced Alloys

200 dpa *300 dpa* *400 dpa*

500 C *600 C* *700 C*

Reduced embrittlement, swelling, creep

Enhancements with Fabrication Complexity

Corrosion

F/M Steels

Advanced Alloys

Cr
Si
Al

Increasing content

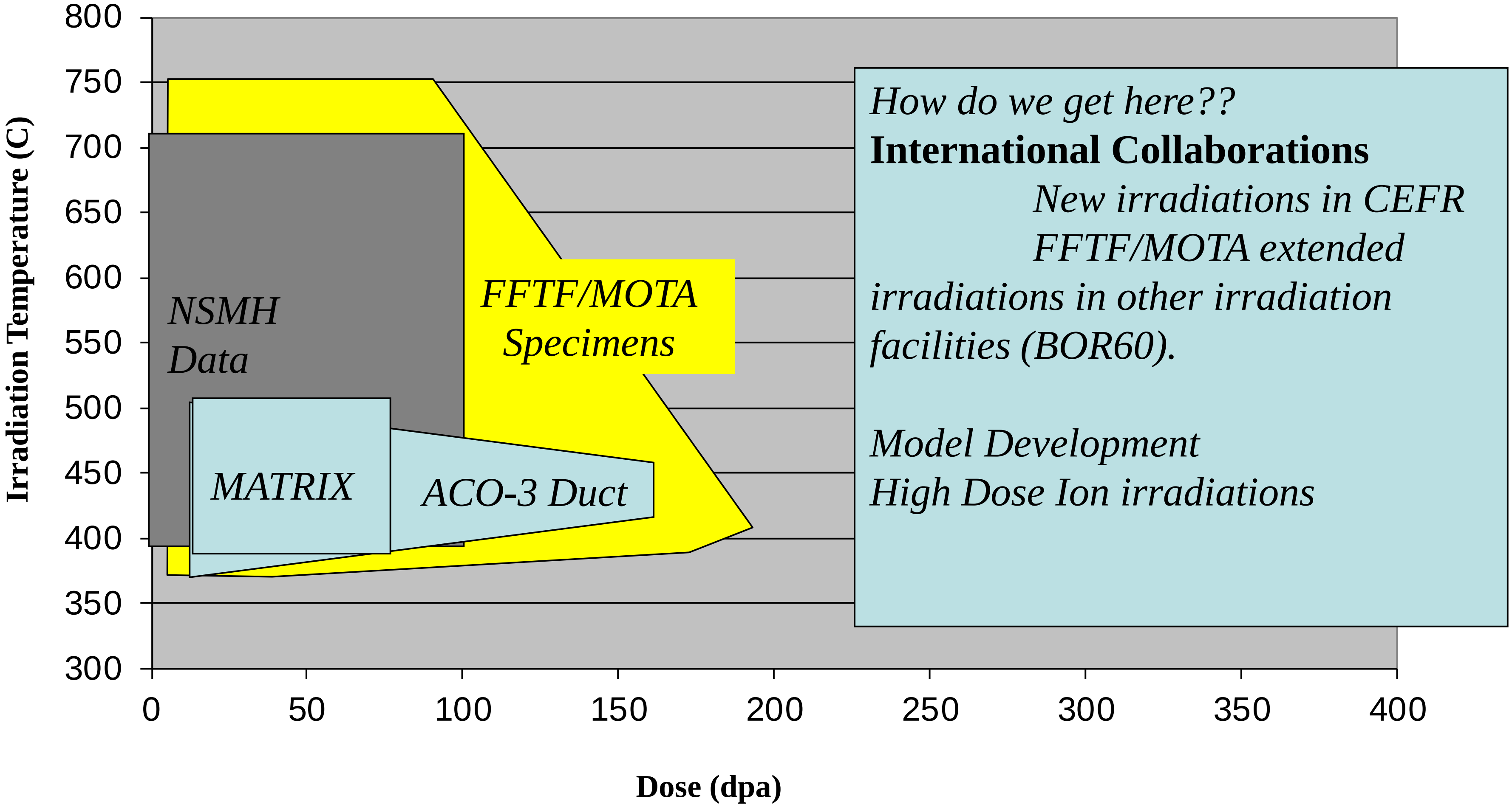
Enhancements with Fabrication Complexity

Different Reactor options to change requirements
LFR, GFR

Outline

- ***Qualify HT-9 to Radiation Doses >250 dpa***
  - *Calculations for CEFR Irradiation*
  - *Development of new heat of HT-9*
- **Develop Advanced Radiation Tolerant Materials**
  - ODS processing of new heat of 14YWT (FCRD-NFA1)
  - Testing of Advanced ODS alloys after Irradiation
  - Progress on Tube Processing
- **Develop Coatings and liners to prevent FCCI**
  - Testing coated tubes in fueled irradiations (CRADA’s with KAERI and Terrapower)

Significant data has been obtained on previously irradiated materials. How do we obtain data to dose levels out to 400 dpa?



How do we get here??

International Collaborations

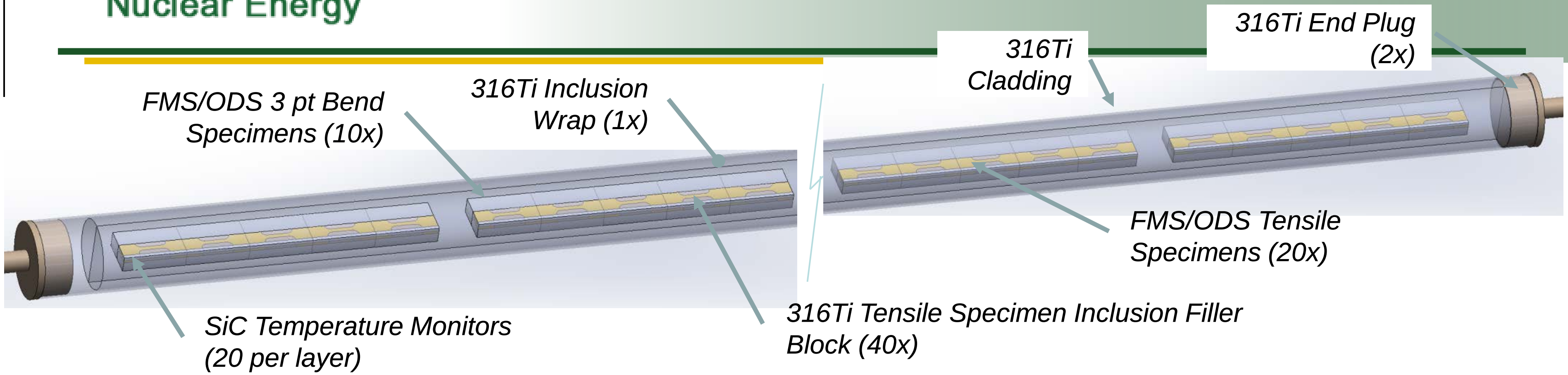
New irradiations in CEFR

FFTF/MOTA extended irradiations in other irradiation facilities (BOR60).

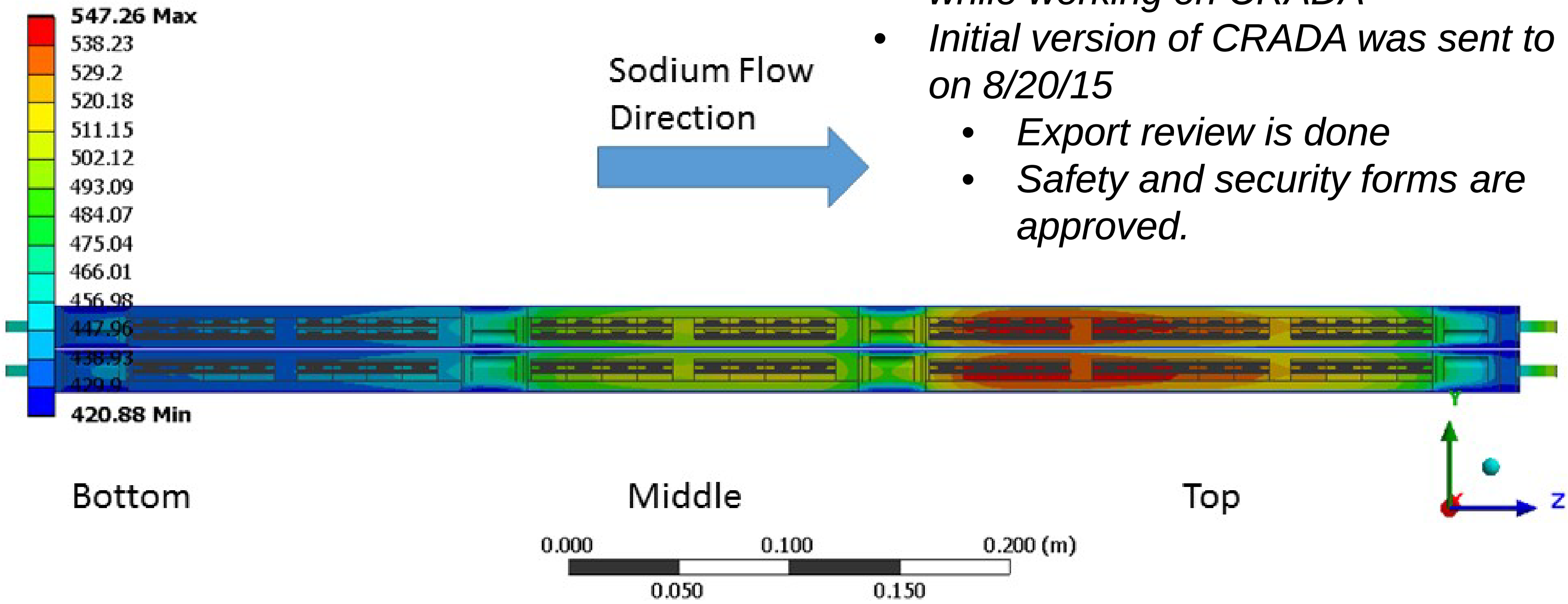
Model Development

High Dose Ion irradiations

Continuing to work toward collaboration agreement with CIAE



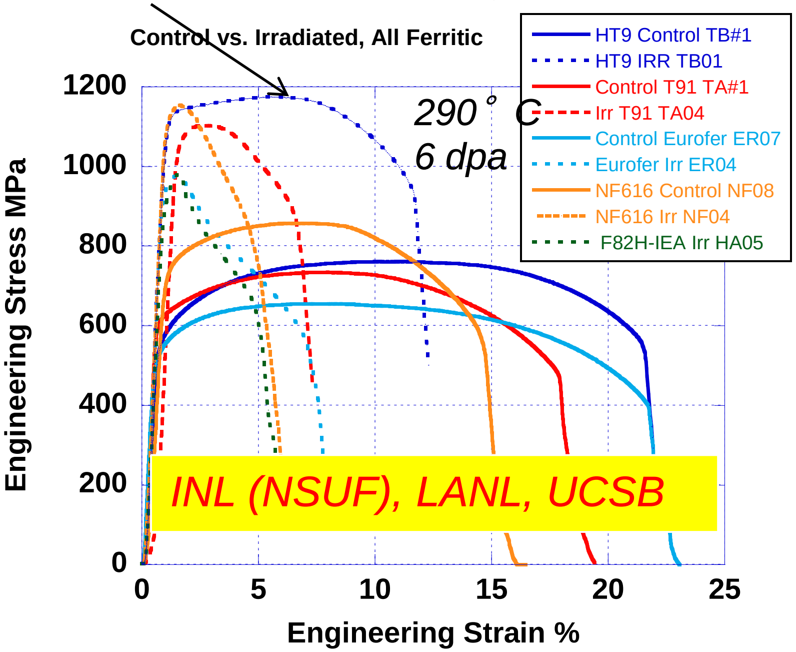
- *Thermal hydraulic calculations continue while working on CRADA*
- *Initial version of CRADA was sent to CIAE on 8/20/15*
  - *Export review is done*
  - *Safety and security forms are approved.*



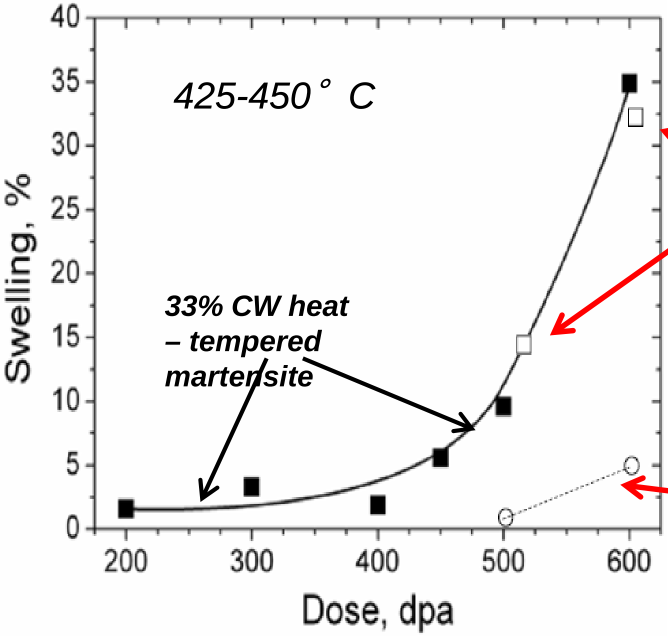
Improved Radiation Response of New NQA1 Heat of HT-9

- **300 lb heat of HT-9 produced by Metalwerks following NQA-1 quality control**
- **Tensile specimens irradiated in ATR to 6 dpa at 290° C**
  - Hardening observed but excellent ductility retained after low temperature irradiation
- **Ion irradiations performed to 600 dpa at 425° C**
  - Minimal swelling observed in tempered martensitic grains after ion irradiation to >500 dpa.
- **Two new heats of HT-9 were produced by Metalwerks with controlled interstitial content.**

INL-HT-9 Heat, best ductility



INL (NSUF), LANL, UCSB



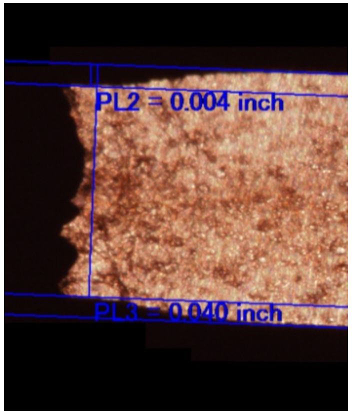
33% CW heat – tempered martensite

INL heat ferrite (<5% volume fraction)

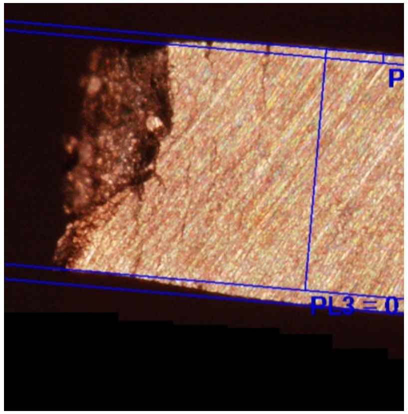
INL heat tempered martensite

Reduction of Area Measurements

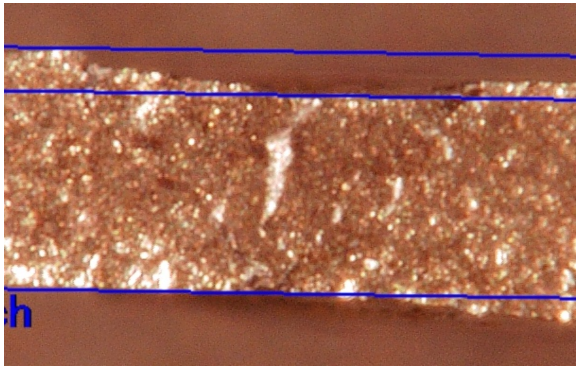
- **HT-9 heat retains UE and reduction of area after irradiation to 6 dpa at 290 C.**
- **In addition, less cracking observed near fracture surface compared to T91 and NF616.**



HT-9



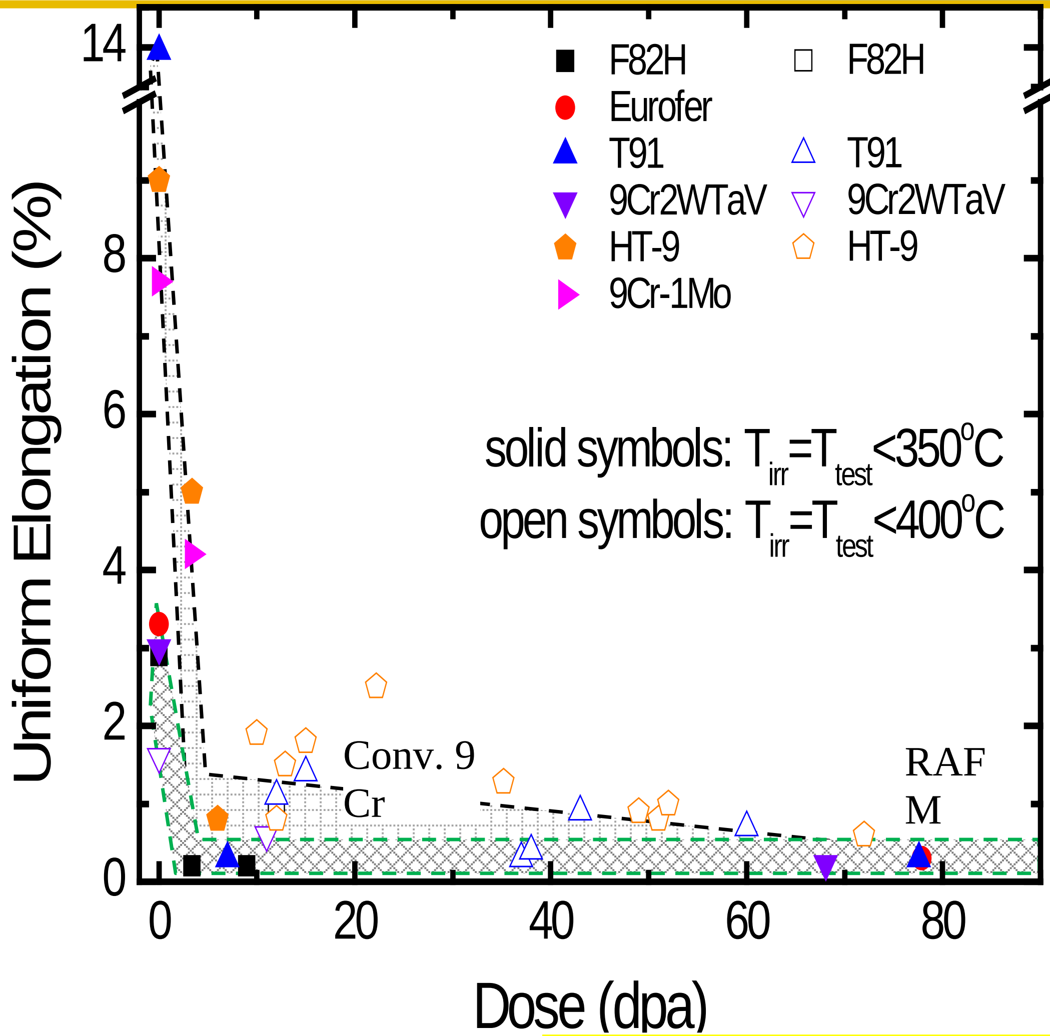
T91



NF616

Material	ID	Type	Yield MPa	UTS MPa	Uniform Elongation %	Total Elongation %	Reduction in Area %
HT9	TB#1c	Control	560	761	9.15	21	55.03
HT9	TB01	Irradiated	1100	1175	4.54	10.9	46.22
T91	TA04	Irradiated	1055	1102	1.07	5.7	39.03
NF616	NF04	Irradiated	1120	1154	0.65	4.7	23.72

Previous Results showing Reduction of Ductility in irradiated F/M steels



Anderoglu, O., Byun, T. S., Toloczko, M. and Maloy, S. A. Mechanical Performance of Ferritic Martensitic Steels for High Dose Applications in Advanced Nuclear Reactors. Metallurgical and Materials Transactions a-Physical Metallurgy and Materials Science, 44A(Jan 2013), 70-83.

Exact Elemental Analysis on Control Materials

Alloy	C	Cr	Mn	Ni	Si	Mo	Nb	V	W	O	N	P	S	Al	Cu	Co	Ti	Fe
HT-9	.201	12.49	.41	.60	.28	1.07	<.002	.29	.52	.002	.001	.007	<.0005	.015	.034	-	-	Bal
Eurofer97	.117	8.69	.47	.024	.056	.005	<.002	.20	.82	.003	.023	.004	.002	.009	.023	.011	.006	Bal
F82H	.093	7.89	.16	.026	.12	.005	<.002	.16	1.21	.003	.008	.004	.002	.002	.028	.007	.002	Bal
NF616	.108	9.71	.46	.064	.056	.47	.043	.20	1.22	.003	.060	.007	.001	.003	.035	.015	.003	Bal
T91	.052	9.22	.46	.18	.24	.96	.063	.24	.013	.002	.057	.016	.001	.009	.087	.021	.002	Bal

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Effects of Interstitial content on Luder’s band formation in Ferritic steels

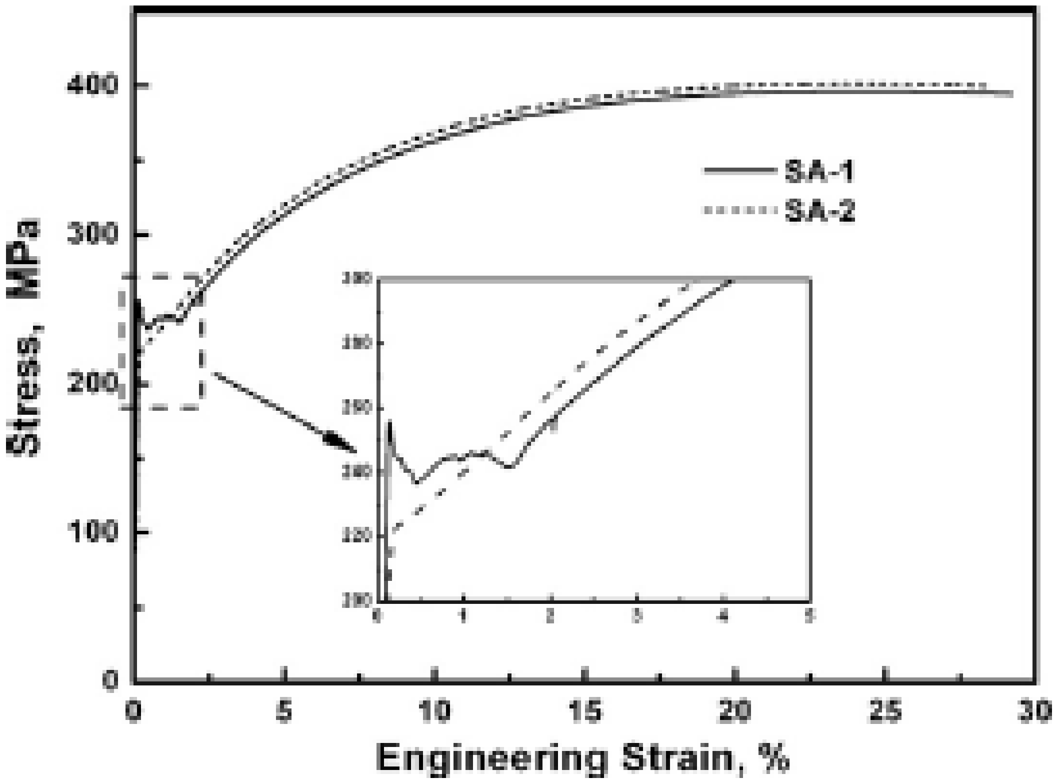

Fig. 3. The stress–strain curve for the specimen along the rolling direction of the experimental steel after different annealing treatments at the strain rate of 0.001 s^{-1}.

Z.Y. Liu et al. / Materials Science and Engineering A 527 (2010) 3800–3806

Proposed Hypothesis and Future Research

- **Proposed Hypothesis:**
  - Nitrogen attracts point defects under irradiation.
  - This creates stronger pinning centers in ferritic alloys
  - Under stress, when the pinning centers are overcome, defect free channels are formed leading to localized deformation and reduced uniform elongation.
- **Next steps**
  - Procure new heats of HT-9 with controlled nitrogen (two heats produced by Metalwerks)
  - Perform ion irradiations followed by mechanical testing. Investigate deformation microstructure with TEM.
  - Microstructural analysis of irradiated tensile specimens after deformation.

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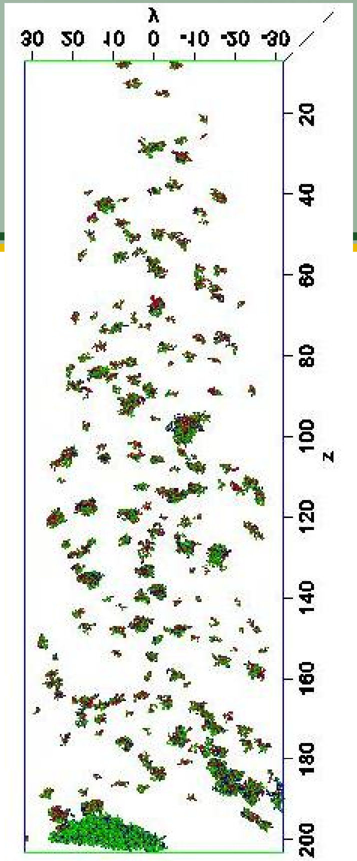
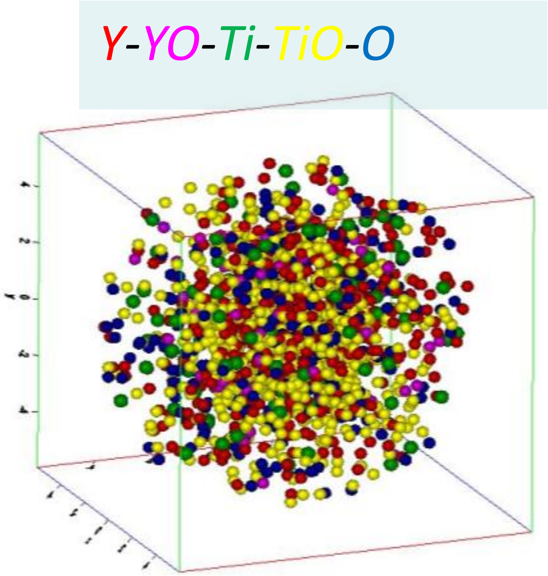
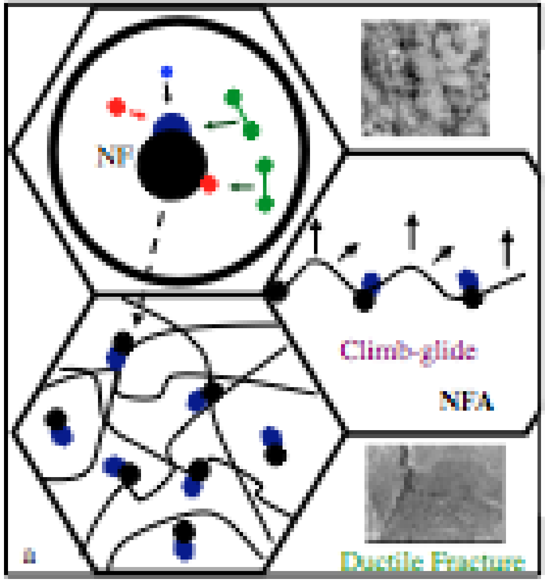
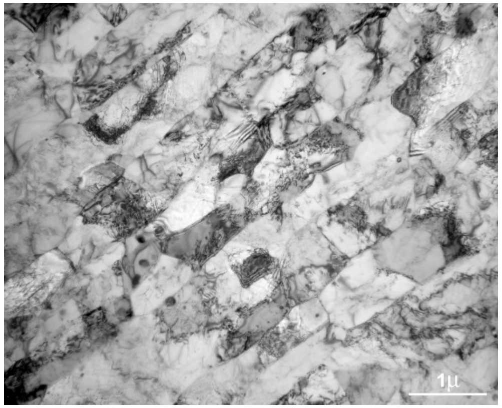
Nanostructured Ferritic Alloys



- *Strength & damage resistance derives from a high density Ti-Y-O nano-features (NFs)*
- *NFs complex oxides ($Ti_2Y_2O_7$, Y_2TiO_5) and/or their transition phase precursors with high M/O & Ti/Y ratios (APT)*
- *MA dissolves Y and O which then precipitate along with Ti during hot consolidation (HIP or extrusion)*
- *Oxide dispersion strengthened alloys also have fine grains and high dislocation densities*



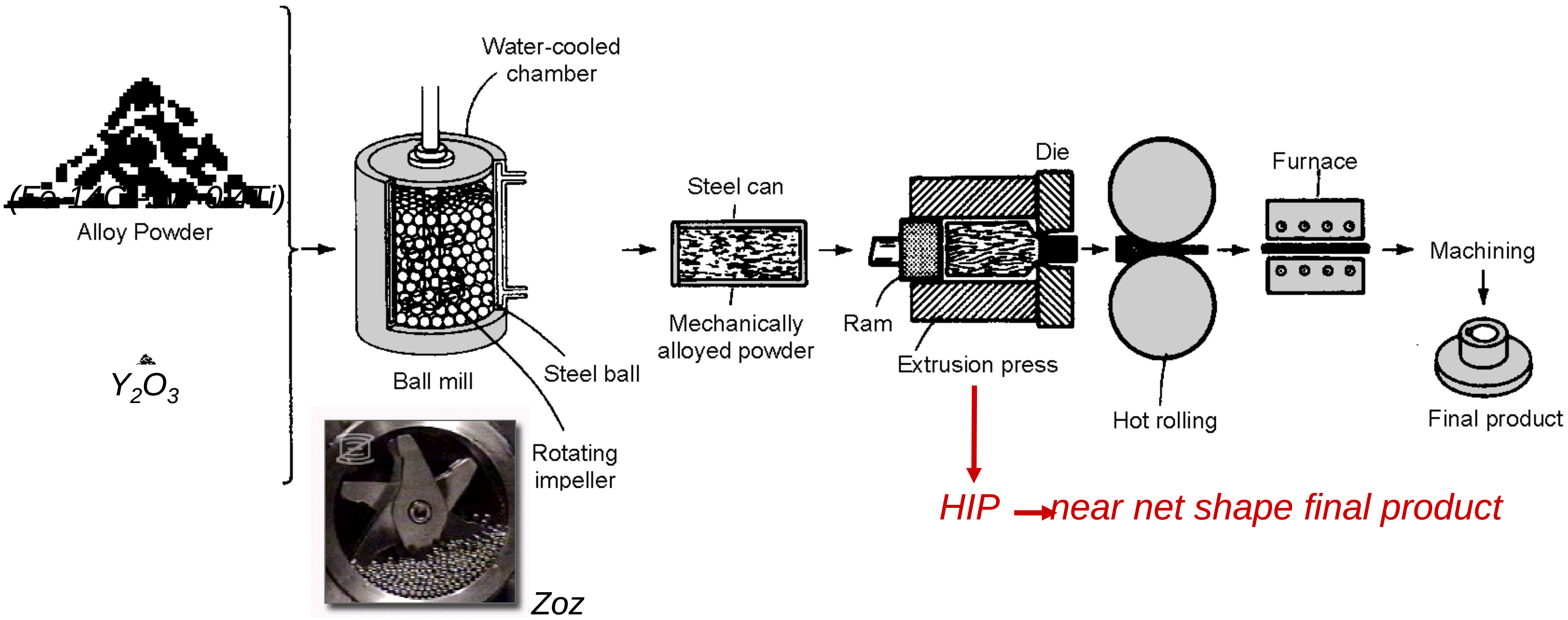




UCSB, LANL, ORNL

Typical Processing Route for ODS Alloys

- *Any desired combination of powders: metals, alloys, and dispersoid, such as oxides, carbides, borides, etc.*



HIP → near net shape final product

Zoz

The <u>conventional approach</u> is to ball mill alloy and Y_2O_3 powders together

Scale Up Production of 14YWT Ferritic Alloy (Heat FCRD-NFA1)

- 4 of 4 ball milling runs completed by Zoz
  - V540-01: 15 kg of coarse (>150 µm) powder
  - V540-02: 15 kg of medium (45-150 µm) and fine (<45 µm) powder
  - V540-03: 15 kg medium, fine and small amount of V540-01 coarse powder
  - V540-04: 15kg medium, fine powder mixed with yttria for the oxide dispersion.

V540-02 Ball Milled 40 h
MET. SPECIMEN NO: 12-0581
LOAD in grams: 200

Indent no.	HV
1	723.57
2	744.47
3	726.78
4	713.14
5	700.18
6	768.03
AVERAGE =	729.36
STD =	23.99

- EPMA showed 40 h ball milling distributed Y uniformly in fine and medium powders
- 40 h ball milling did not distribute Y uniformly in coarse powders
- Mechanical testing underway.

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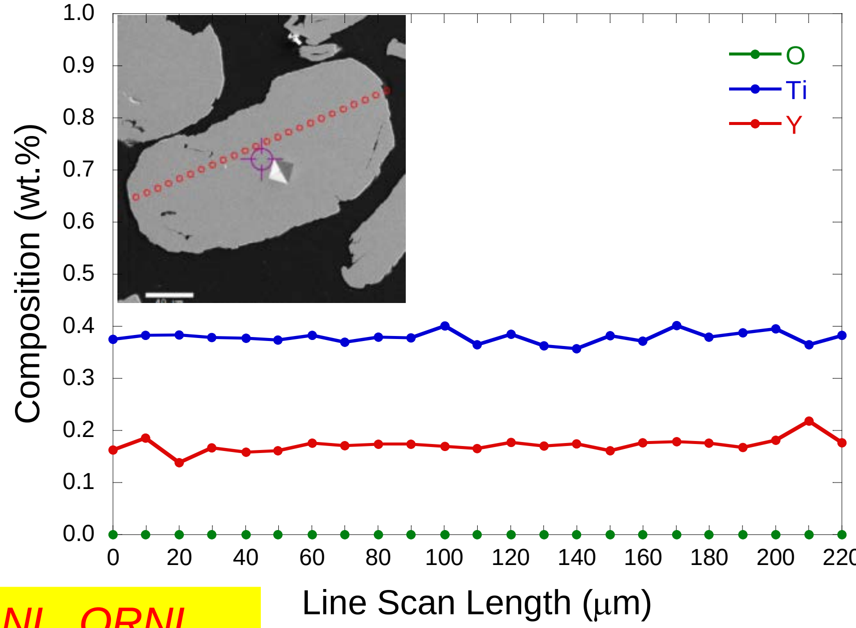


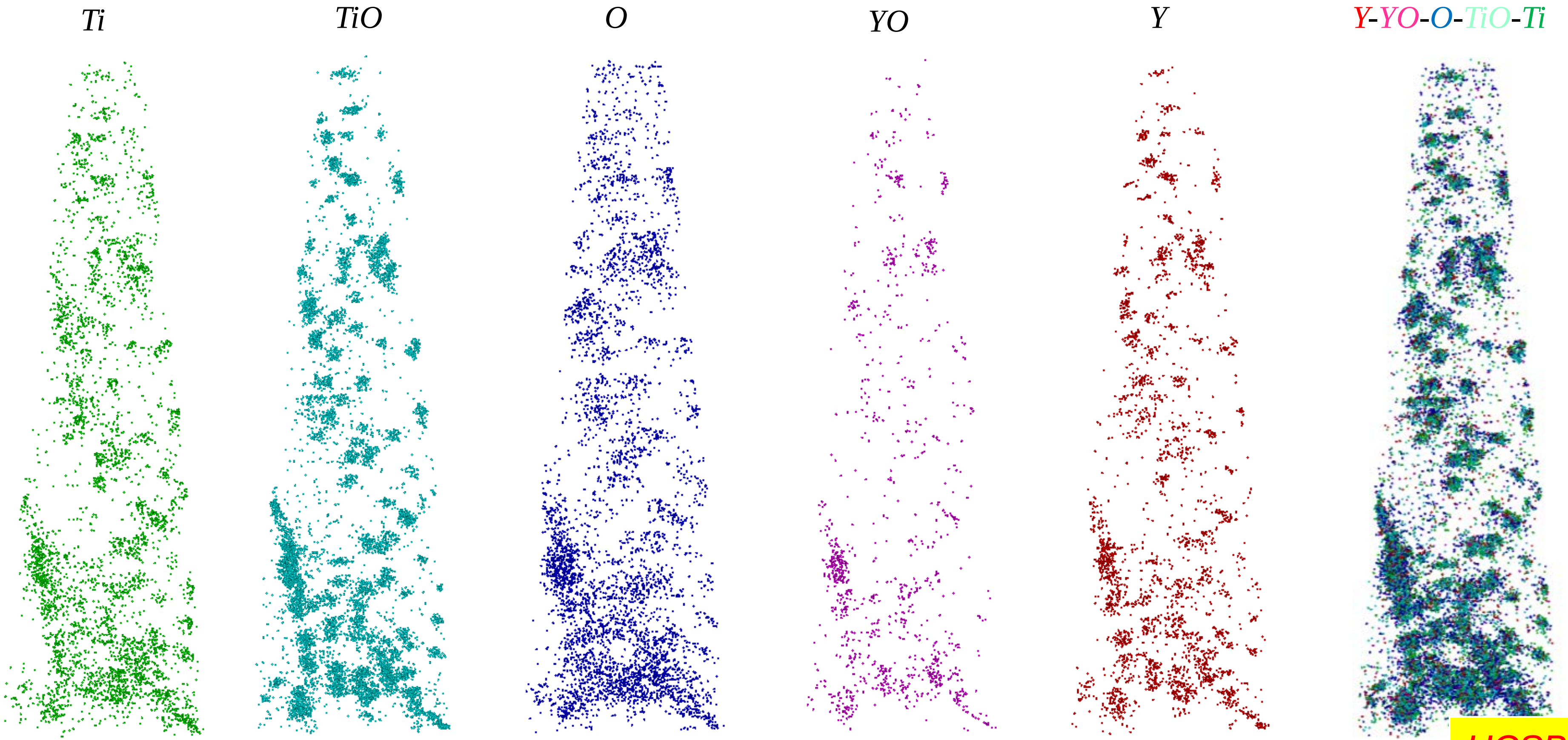
Extrusion and plate fabrication

- 4 new extrusions of FCRD-NFA1 heats were performed
  - 2 extrusions are for EPRI Program
  - 2 extrusion is for FCRD Program
- Each bar section was cross-rolled to 50% reduction in thickness at 1000ºC
  - *12 plates were fabricated (6 for EPRI and 6 for FCRD Programs)*
  - *10 plates were decanned*

ORNL

Characterization of FCRD-NFA1 Material –APT

Y/Ti/O	Y/Ti/Cr/O	Number Density ($10^{23}/m^3$)	Diameter (nm)	Solute Fraction (%)
13.7/41.8/44.5	10.5/32.0/23.6/34.0	6.86	2.02±0.78	0.74



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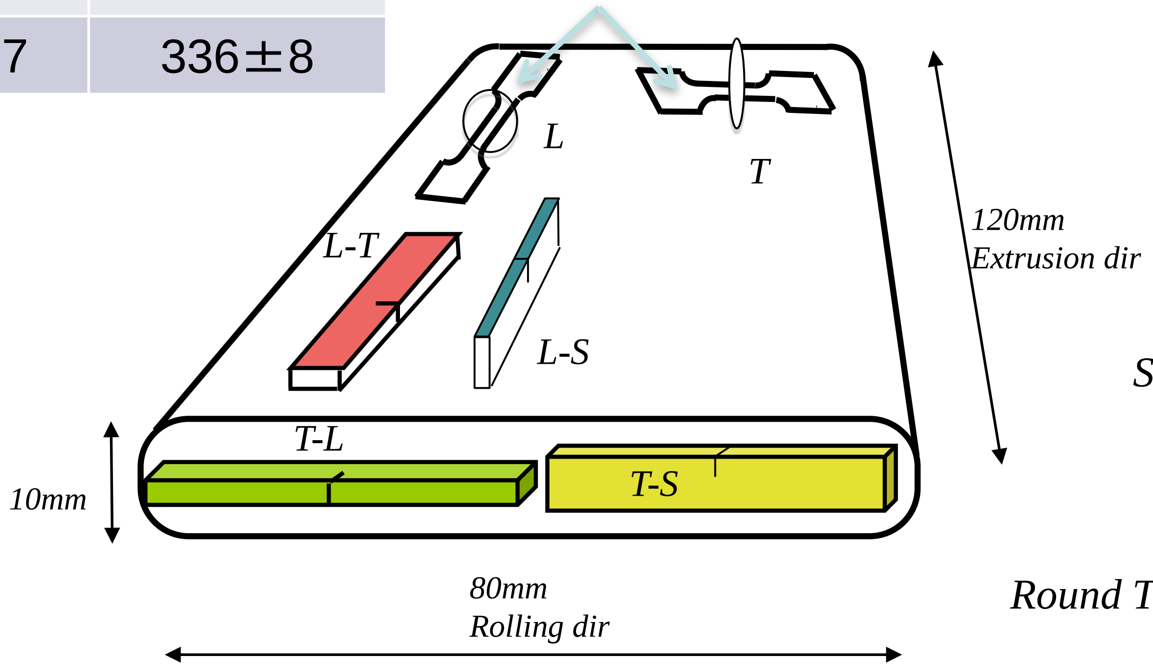
Mechanical Properties

Mechanical Testing of FCRD-NFA1

Alloy	μH
FCRD	359±18
PM2	401±15
MA957	336±8

SSJ2 and
Round SSJ2
tensile specimens



<u>Machined Specimens</u>

1/3-1/2 bend bars

T-S: 17
L-S: 20
T-L: 20
L-T: 20

SSJ2 Tensile

T: 36
L: 30

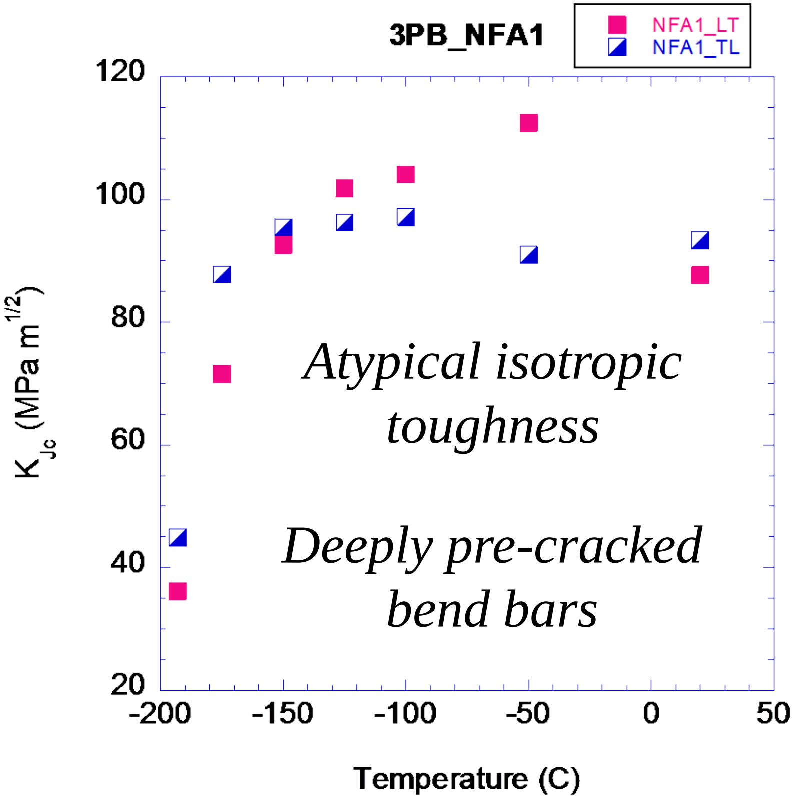
Round Tensile (Creep)

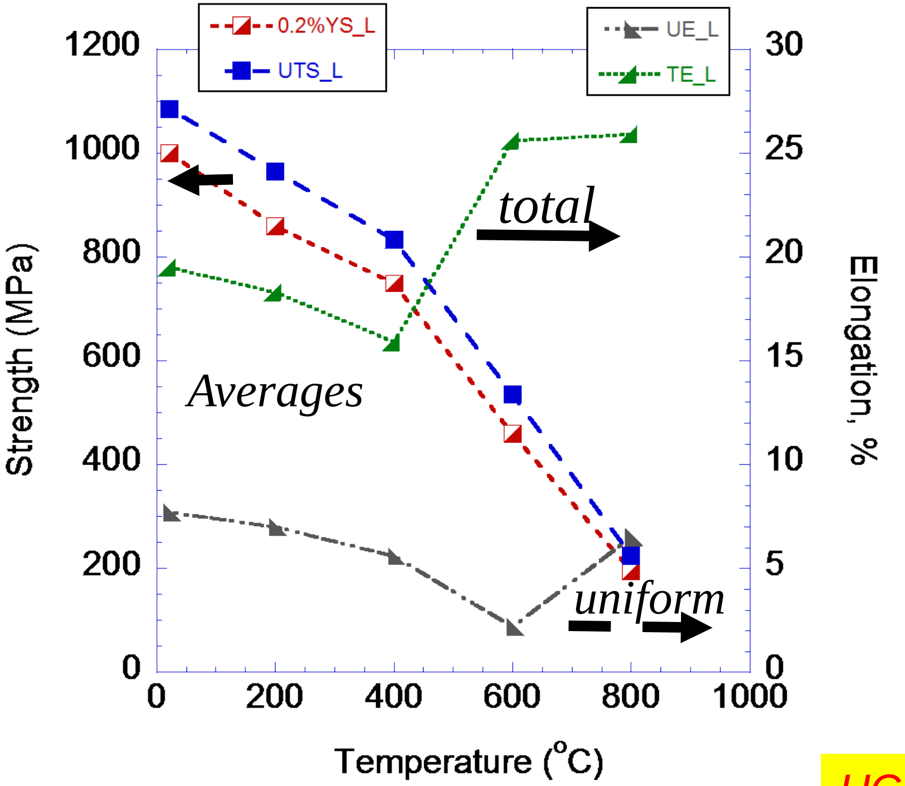
T: 8
L: 8

Round tensile specimens will be used for high temperature strain-rate jump tests

NFA-1 Strength, Ductility and Toughness

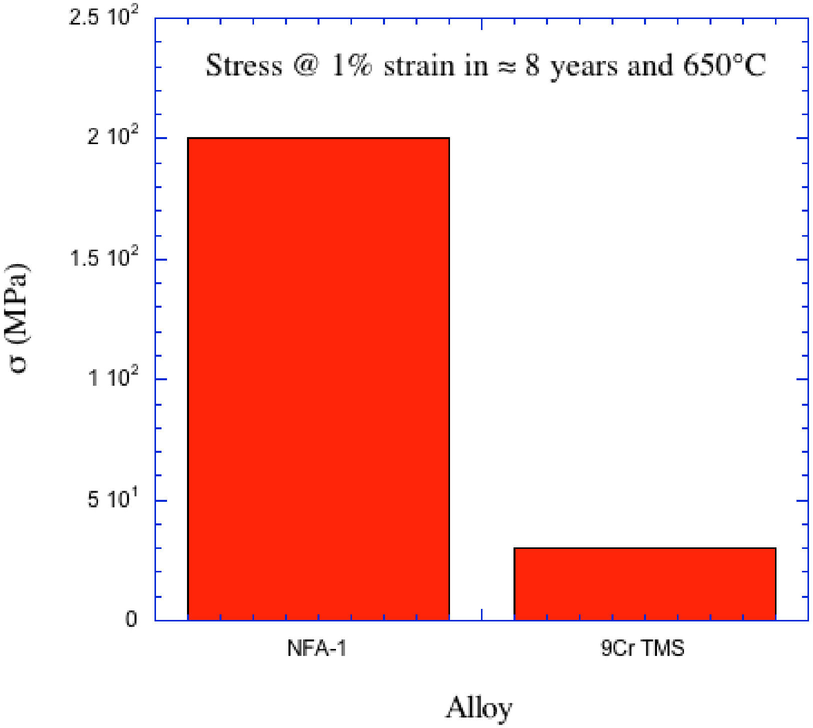
- *Unusual combination of high tensile strength and ductility*
- *Very low brittle-ductile transition temperature (-150 to -175° C) –> high isotropic strength and ductility in the presence of deep-sharp cracks (toughness)*



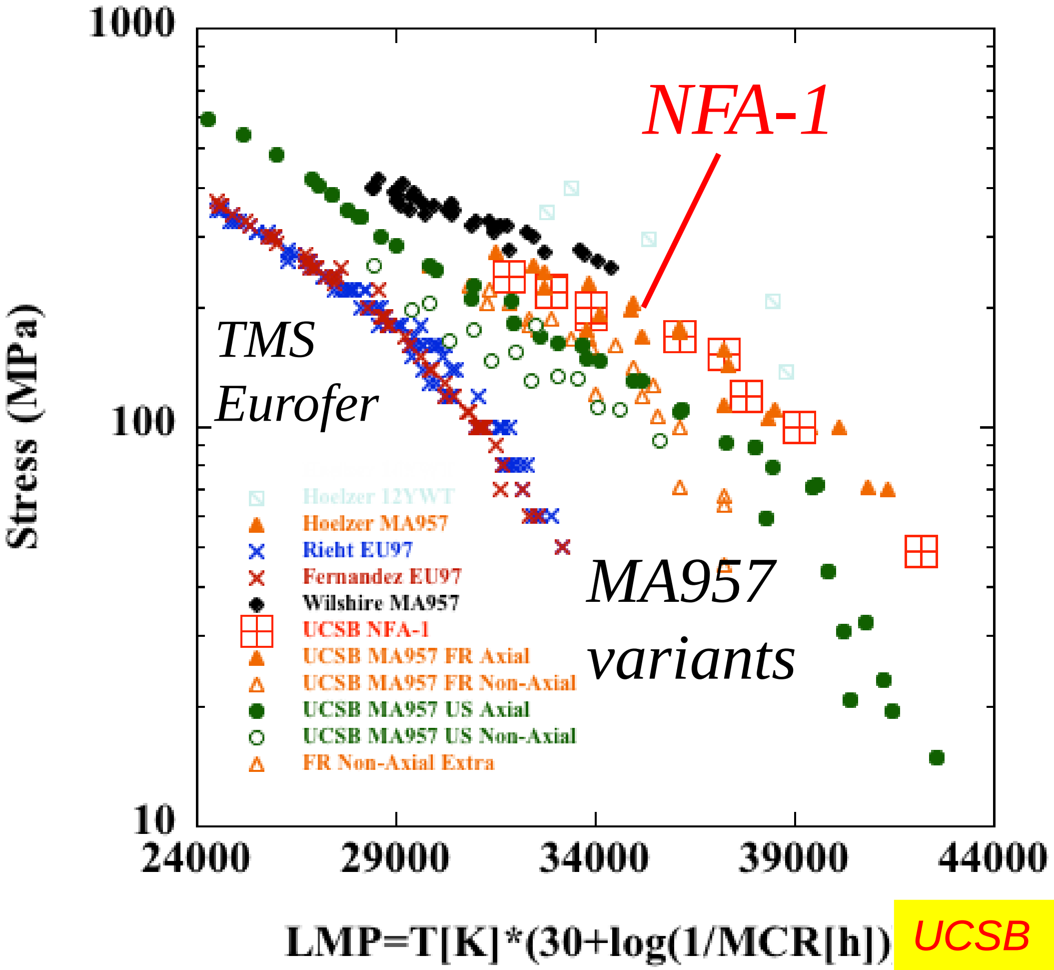


High Temperature Creep

- *The high temperature creep strength of NFA-1 is comparable to that of the stronger variants of MA957*



- *MA957 rupture time @ 100 MPa & 800 ° C > 38,000 h!*



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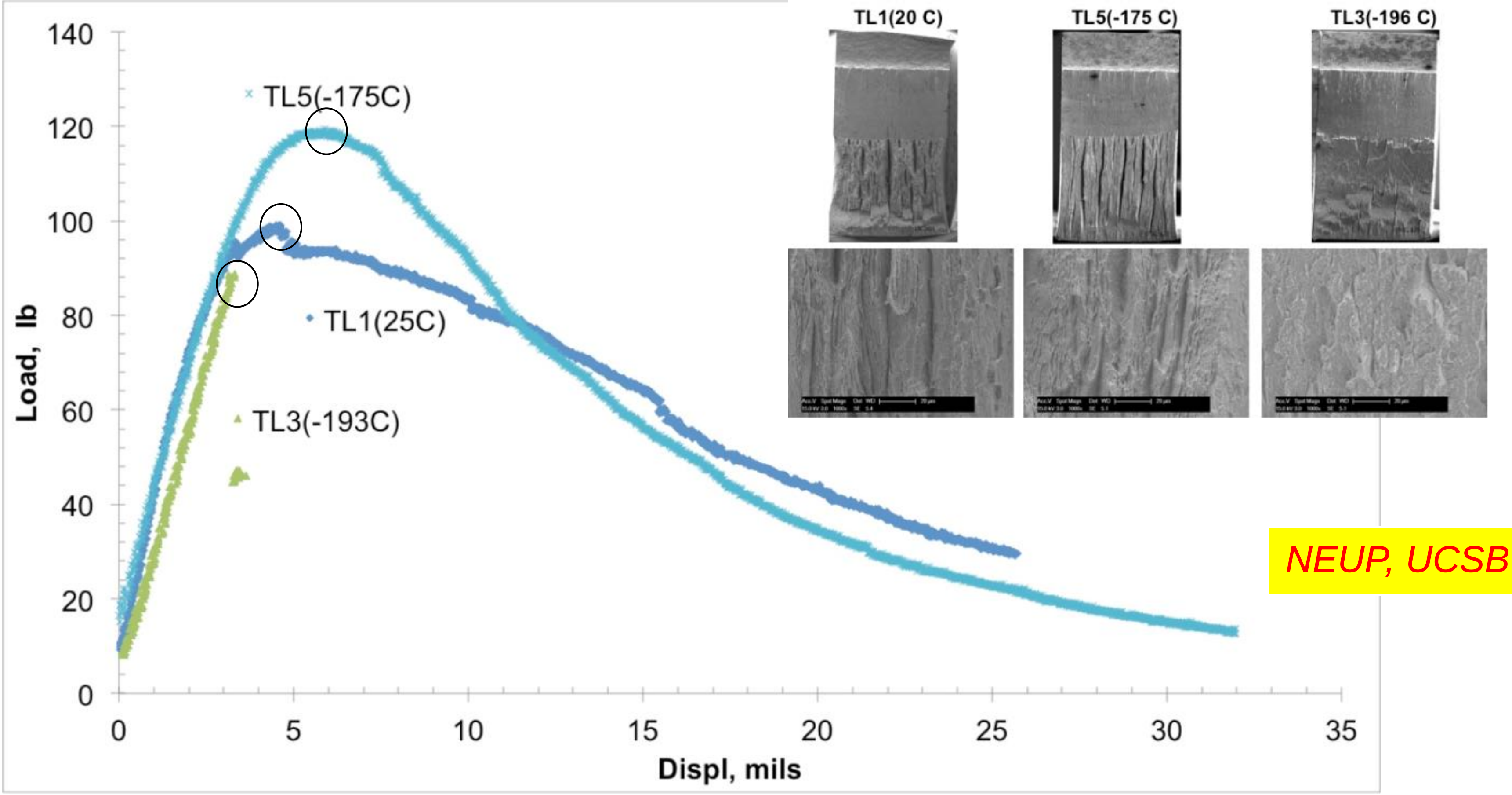
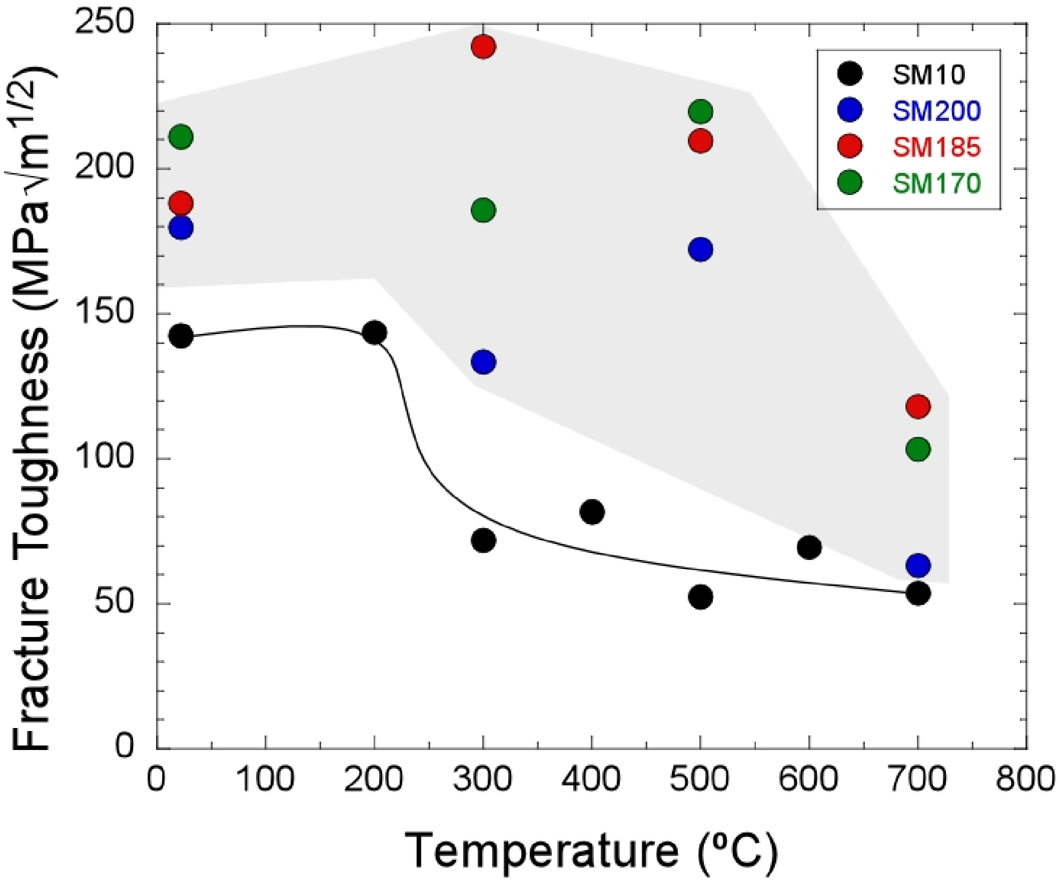
"Best Practice" processing of NFA1: ***Stable crack growth toughness***

- High *tensile strength* controlled stable crack growth ductile tearing toughness and very high "ductility" down to -175° C
- Behavior due to a delamination toughening mechanism



NEUP, UCSB

"Best Practice" Processing of 14YWT: *Significant increase in high-temperature fracture toughness (FT)*

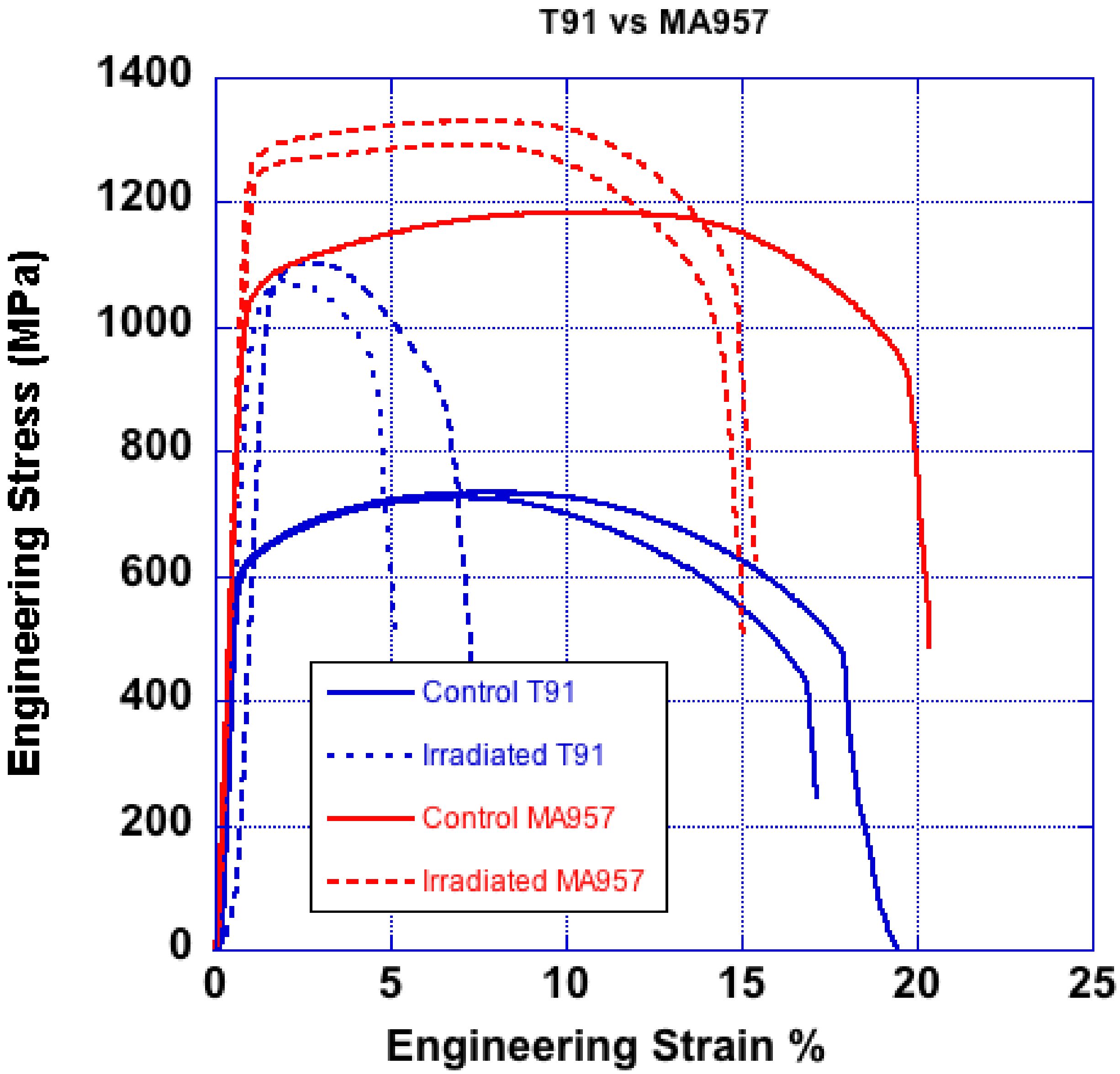


- *FT of the three 14YWT heats is higher than that that of SM10 from 25º to 700ºC and up to* ***4x higher*** *than SM10 at 500ºC*
- *FT of SM170 and SM185 are above 100 MPa√m$^{1/2}$ at 700ºC*

- *The improvement in high-temperature fracture toughness is unprecedented for ODS ferritic alloys*

Radiation Resistance

Ductility Retention in MA957 after irradiation to 6 dpa at 290C

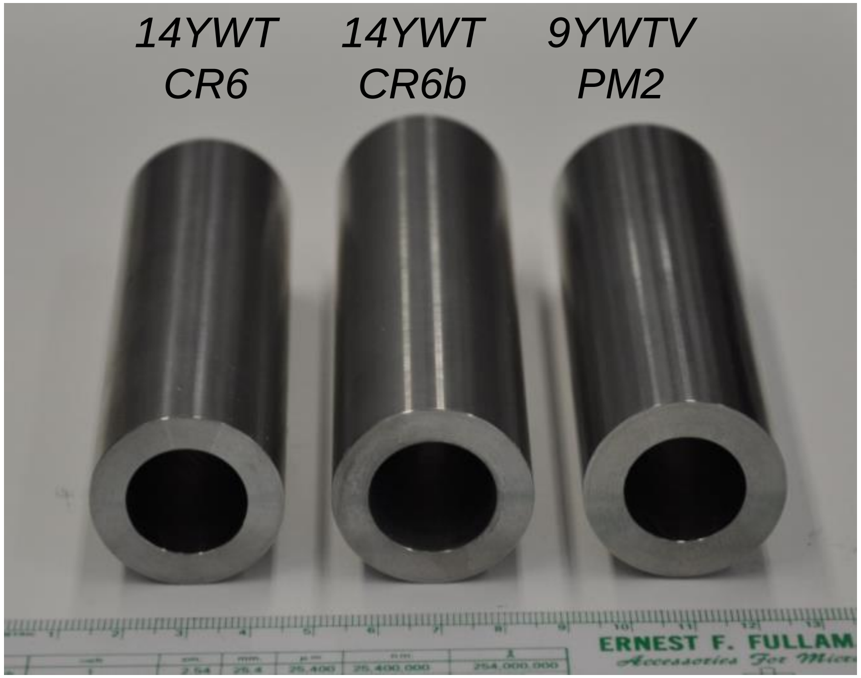


LANL, UCSB,

Fabrication of Cladding Tubes from ODS alloys

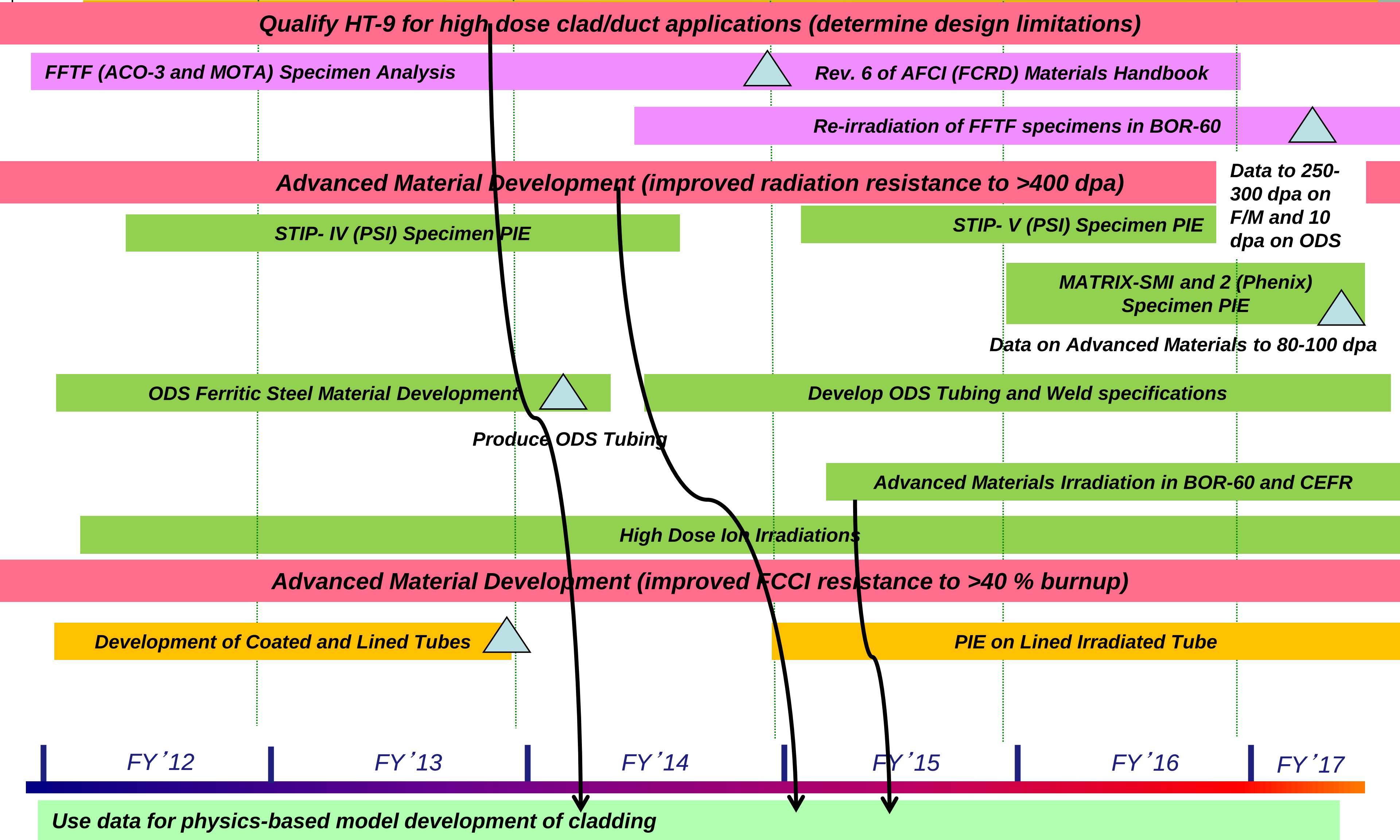
- 3 cans were extruded with mandrel at 850ºC and decanned
  - *6-7 mm wall thickness; 31-32 mm diameter; 10.5-11.3 cm long*
- Working with PNNL (Curt Lavender) and CEA on Pilger processing of starting thick walled tubing and J. Lewandowski (CWRU) on hydrostatic extrusion

1. *Hydrostatic EXTRUSION TEMP: 1500F (815C)*
2. *RAM SPEED: 0.5 in/min, however 1st 0.5” of extrusion, speed was 0.7 in/min*
3. *SOAK TIME: 10 min*
4. *OVERALL EXTRUSION: 25 min*
5. *ER: 4:1, 45 DEG TAPER DIE (actual 0.495 diam)*
6. *CLAD/MANDREL DESIGN DIFF FROM PREVIOUS*



LANL, PNNL, ORNL, CWRU

Core Materials Research and Development – 5 Year Plan



Qualify HT-9 for high dose clad/duct applications (determine design limitations)

FFTF (ACO-3 and MOTA) Specimen Analysis

Rev. 6 of AFCI (FCRD) Materials Handbook

Re-irradiation of FFTF specimens in BOR-60

Advanced Material Development (improved radiation resistance to >400 dpa)

Data to 250-300 dpa on F/M and 10 dpa on ODS

STIP- IV (PSI) Specimen PIE

STIP- V (PSI) Specimen PIE

MATRIX-SMI and 2 (Phenix) Specimen PIE

Data on Advanced Materials to 80-100 dpa

ODS Ferritic Steel Material Development

Develop ODS Tubing and Weld specifications

Produce ODS Tubing

Advanced Materials Irradiation in BOR-60 and CEFR

High Dose Ion Irradiations

Advanced Material Development (improved FCCI resistance to >40 % burnup)

Development of Coated and Lined Tubes

PIE on Lined Irradiated Tube

FY’12 FY’13 FY’14 FY’15 FY’16 FY’17

Use data for physics-based model development of cladding