#### **NE 591: Advanced Reactor Materials**

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### **Last Time**

- Austenitic steels undergo excessive void swelling in fast reactor conditions
- F/M steels have good mechanical properties, are cheap, and their microstructure can be tailored through composition and fabrication
- M23C6 and monocarbide precipitate are prevalent both along grain boundaries and within the grains; M2X metallic precipitates form and can be converted to Laves phases
- F/M steels swell very little due to fundamental nature of defects in ferrite, C-vacancy bonding, and dislocation-solute interactions
- Tailoring of alloying elements has allowed for improved creep strength
- Stress induced preferential nucleation/absorption (SIPN SIPA)
- Swelling interaction with creep

## **ADVANCED CLADDING**

### **Irradiation Embrittlement**

- Ferritic steels have these large monocarbides which aid in creep resistance
- The lath boundaries are decorated with Cr rich M23C6 precipitates which increase the thermal stability
- Embrittlement is caused by 1)
   segregation of elements to lath
   boundaries which make the grain
   boundaries decohesive, and 2)
   evolution of carbides and intermetallic
   phases
- For removable components such as clad, which are subjected to high temperature and pressure with a residence time of a few years, creep embrittlement is the issue which decides their design and performance
- For permanent support structures increase in hardening and loss in fracture toughness on irradiation are major issues

### **Irradiation Embrittlement**

- The increase in the ductile to brittle transition temperature, DBTT, is known to be related to irradiation hardening, which is generally observed to saturate with fluence
- Evidence for a possible maximum in DBTT was observed for the 12Cr steel irradiated in the range of 35–100 dpa in the FFTF
- High fluence and/or high temperature are required before a maximum is observed

- Thus, these properties are a balance between the point defect production and irradiation-induced precipitation
- The precipitation during irradiation hardens the steel and irradiation accelerated recovery and aging soften the steel
- The high temperature recovery produces an observable saturation in hardening above ~720K

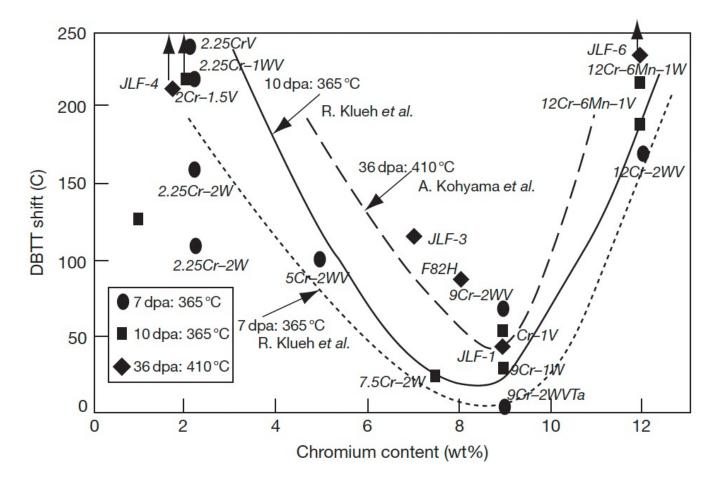
### **DBTT**

- BCC materials can undergo significant increase in the DBTT at low T for even 1 dpa
- The minimum operating temperature to avoid embrittlement F/M steels is ~500 K
- Extensive evaluation of the embrittlement behavior of the ferritic steels for different chemistry has been performed

- Compositions around 9Cr show the least change in the DBTT
- Chemical variation affects on DBTT changes has been thoroughly studied
- Addition of phosphorous, copper, vanadium, aluminum, and silicon increase the DBTT

- The 12Cr steels, HT9, show a larger shift in DBTT as compared to modified 9Cr–1Mo steel
- The balance is always between nearly nil swelling resistant 12Cr steels and 9Cr steel which is less prone to embrittlement than 12Cr steels

## **DBTT**



## Features affecting Embrittlement

- There are a number of microstructural features that can impact the embrittlement of F/M steels
- Prior austenite grain size (PAGS)
- The size of martensitic lath and packet (which is sensitive to austenitization temperature)

- Tempering/annealing, which can increase carbide precipitate size
- The generation of helium through (n,alpha) reaction
- For low thickness components, the triaxial stress necessary for the embrittlement does not develop, which reduces the intensity of this otherwise serious problem of embrittlement in ferritic steels

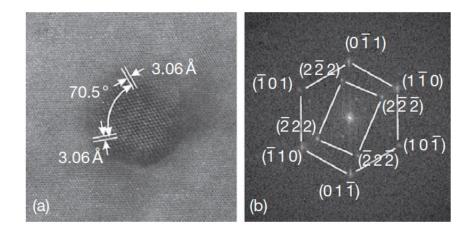
## Ferritic/Martensitic Steels Summary

- Refer to "last time" slide...
- Embrittlement is caused by segregation of elements to lath boundaries and evolution of precipitates
- Maximum DBTT shift occurs in F/M steels for high T or fluence
- DBTT shift is minimized for 9Cr steels
- Microstructure can impact the embrittlement behavior
- In thin-walled materials, such as cladding, the stress state that leads to cladding embrittlement is typically not prevalent

# **ODS STEELS**

## Oxide Dispersion Strengthened

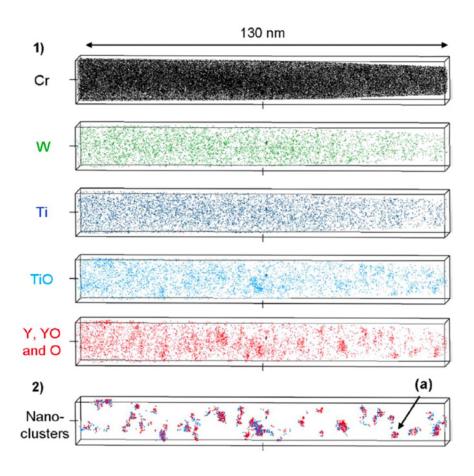
- Thermally stable oxide particles dispersed in the ferritic matrix improve the radiation resistance and creep resistance at high temperature
- ODS steels have a strong potential for high burnup (long-life) and high temperature applications typical for SFR fuels
- Typically, Y2O3 particles or Y2Ti2O7 particles



Y2O3 particle with surrounding matrix

## Y2O3 Decomposition

- The fine distribution of Y2O3 particles is attained by the dissociation of stable Y2O3 particles which are forced to decomposed into the ferritic steel matrix during the mechanical alloying process
- The lattice structure change of Y2O3 in the ODS steel during MA consists of three stages: (1) destruction of the lattice structure, (2) formation of a blurry lattice structure, (3) appearance of amorphous areas



### 9Cr-ODS

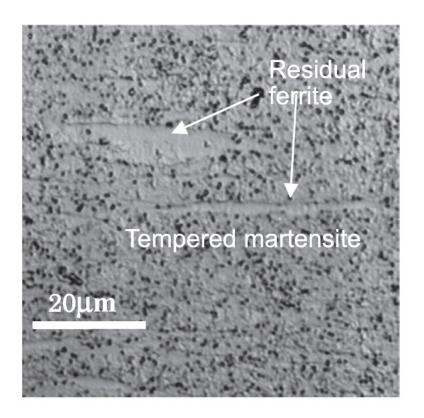
- For nuclear applications, the choice of 9 wt% Cr with a tempered martensitic matrix is preferable to suppress the ductility loss by irradiation hardening and improve the microstructure stability and creep strength at high temperature
- The high-temperature strength of 9Cr-ODS is drastically improved by nano-scale oxide particles dispersion in the matrix

- The standard chemical composition of 9Cr-ODS being developed by the JAEA for SFR application is 9Cr-0.13C-0.2Ti-2W-0.35Y2O3 (wt%)
- The addition of titanium produces the nanoscale dispersion of oxide particles
- Tungsten of 2 wt% is also added in order to improve high-temperature strength by means of solid solution hardening

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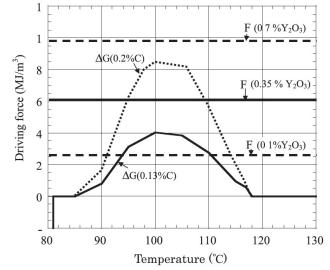
### 9Cr-ODS microstructure

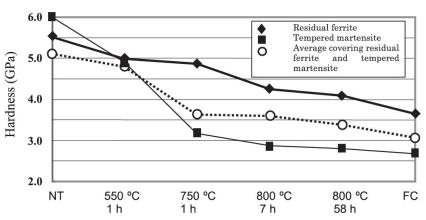
- The microstructure of 9Cr-ODS steel cladding is basically tempered martensite, but includes some residual ferrite phases
- Only the full martensite phase can be expected in 9Cr-ferritic steel without yttria under the same conditions
- The high temperature strength is greatly improved with the ferrite, and thus control of ferrite is key in ODS fabrication



## **Residual Ferrite**

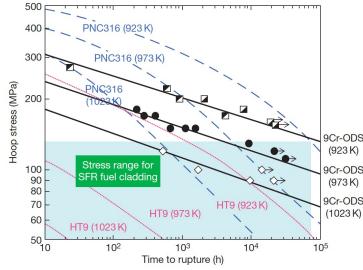
- Annealing results in the formation and precipitation of Y—Ti complex oxide particles at elevated temperatures of 700C or higher
- Since the reverse transformation of alpha (ferrite) to gamma (austenite) takes place at a temperature over 850C, alpha ferrite is attributed to the presence of the Y-Ti-O particles
- These particles block the motion of the alpha-gamma interface, there by partly suppressing the reverse transformation from alpha to gamma-phase

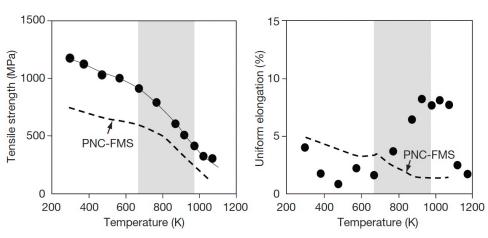




## **Mechanical Properties**

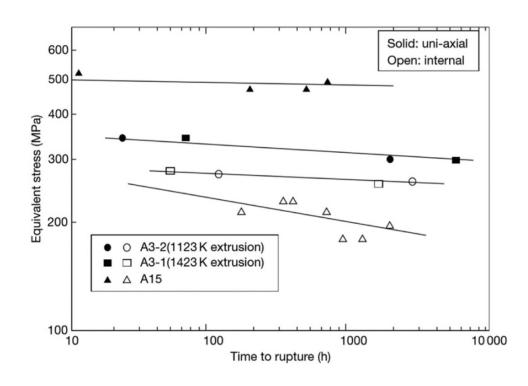
- The lifetime of a SFR cladding is mostly determined by the internal creep rupture strength with the internal pressure of the fission gas at a temperature of ~700C
- PNC316 is austenitic steel used developed by JAEA for fast reactors
- PNC-FMS is a F/M steel
- 9Cr-ODS steels have superior creep resistance and higher tensile strength





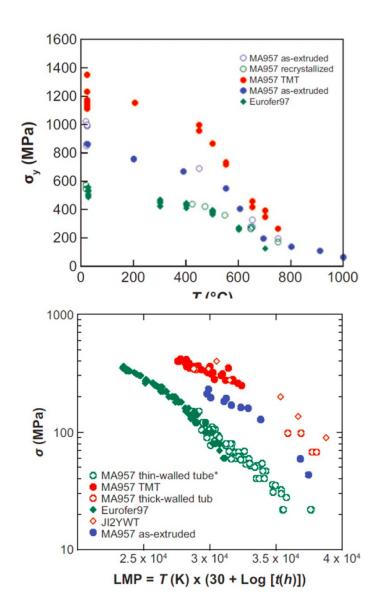
## Ferritic 12Cr-ODS Steel

- Development of ODS steels began with purely ferritic types, similar to MA957
- While these types of steel exhibit excellent creep rupture resistance, there is anisotropy of the rupture strength
- If the Y2O3 content is kept sufficiently low, an equiaxed grain structure can be maintained, providing more isotropic mechanical properties



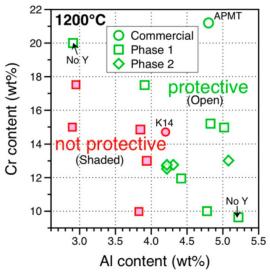
### **NFAs**

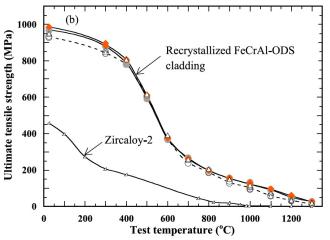
- Nanostructured ferritic alloys (NFAs) are 12%–20% Cr ferritic stainless steels that are dispersion strengthened by a very high density of ultrafine Y-Ti-O nanofeatures
- This high density can yield excellent strength and radiation resistance, but make fabrication processes very difficult
- MA957 and Eurofer are examples of NFAs



## **FeCrAl-ODS Steel**

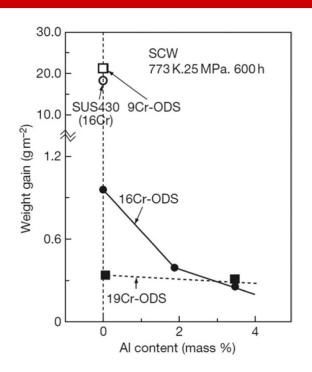
- FeCrAl steels, with and without ODS are of interest since Al-containing steels produce the stable alumina (Al2O3) scale to prevent direct reaction of Fe with steam
- A nominal composition of Fe-10Cr-6.1Al-0.3Zr (wt%) with 0.3wt%
   Y2O3 has been studied by ORNL
- Zr is added to prevent Y-Al oxide particle formation

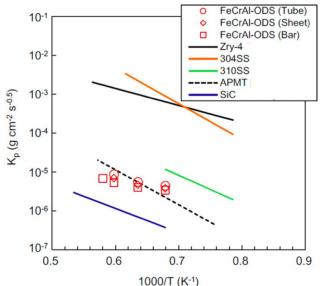




## Corrosion

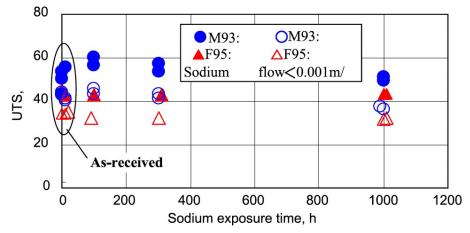
- Hot steam oxidation tests are fairly limited in ODS steels
- Additional Cr improves corrosion resistance, and Al content greater than 2 wt% provides a protective barrier
- Excess oxygen content in the alloys can serve to suppress corrosion
- In systems with high amounts of excess oxygen, Zr content can further aid in corrosion resistance

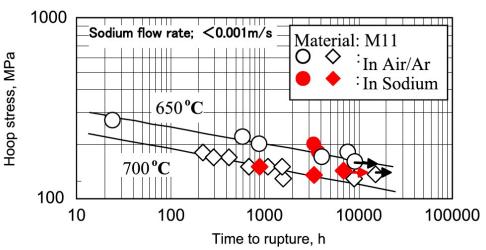




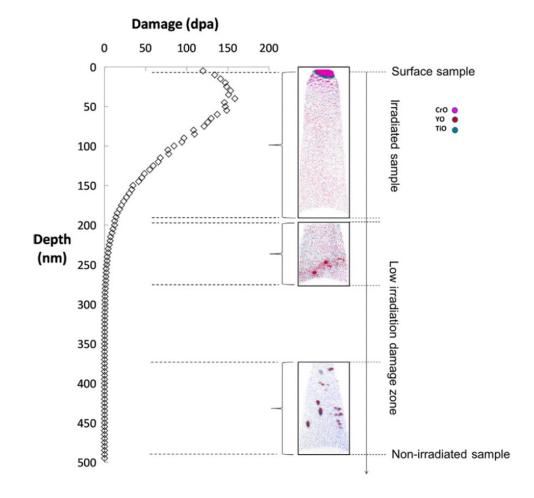
# **Liquid Na Compatibility**

- OSD-steels display excellent compatibility with liquid sodium
- Both 9Cr and 12Cr ODS steels show no degradation in UTS after prolonged exposure to Na
- Creep rupture behavior of ODS steels in air is identical to that in liquid Na
- Under irradiation, this corrosion behavior may change, but has not been thoroughly studied





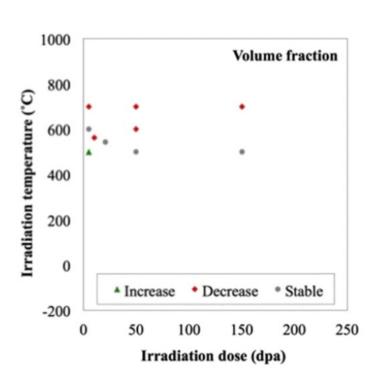
- The stability of the oxide particles under irradiation is the key factor in these alloys maintaining their advantageous mechanical properties under operation
- Ballistic dissolution is the ejection of atoms from oxide particles due to high energy PKAs and the disordering of the particles

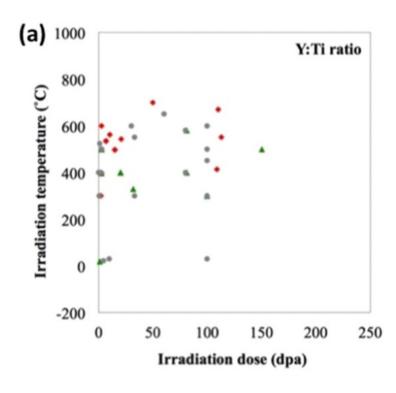


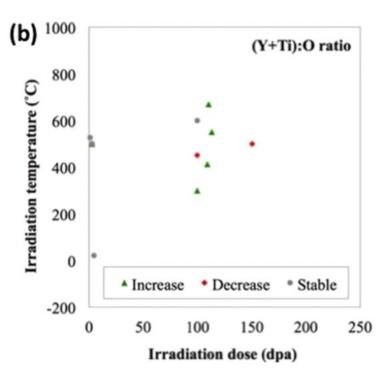
- At higher temperatures where vacancy diffusion is possible, ballistic dissolution works in conjunction with irradiationassisted diffusion and changes the dispersion of oxide particles
- The atoms ejected from oxide particles can diffuse back to the original oxide particles, stay in the matrix, or reach other oxide particles
- Most research groups have reported that the size and number density of the oxide particles hardly change compared to how they were before irradiation
- The predominant mechanism of these results are the recovery arising from back diffusion to the original oxide particles or re-join to other existing oxide particles

- A large number of irradiation experiments have been performed and analyzed to study the evolution of oxide particles
- It appears that there is no correlation between irradiation dose, irradiation temperature, and the trend of change in size or number density of oxide particles

hor Mate		terial Irrad. Particle		Irrad. Temp. (°C)		Irra7d. Dose	(dpa)	Dose Rate (dpa/s)	Method	Structure	Chemistry		Size	Number density	
sak r	Mathon <sup>141</sup> Menut <sup>142</sup>	MA957 DY	Therm. r Fast n	325 400~480	2.0, 5.5 75.4	5	$2.9\times10^{-7}$	TEM, SANS XAFS, TEM	Stable Disordering	n.s. n.s.		table ot specified	table table	Stable n.s.	
	Miller <sup>143</sup>	MA957	Fast n	600	3		$3.7\times10^{-7}$	APT	n.s.	Y:Ti decrease	Stable S	able	ecrease	Increase	
	Monnet <sup>144</sup> Monnet <sup>145</sup>	DY EM10	Kr electron	RT 300 ~ 500	100		$3-6 \times 10^{-3}$	STEM HRTEM	Amorphize n.s.	Stable		able s.	table	Stable	
y 1	Vonnet <sup>146</sup>	DY, EM10	He	400	0.05		0 0 1 10	HRTEM	n.s.	Stable		able	table	Stable	
	Monnet <sup>146</sup> Monnet <sup>146</sup>	DY, EM10	Ar	400	33			HRTEM	Amorphize	n.s.	Decrease D	ecrease	ecrease	Decrease	
		Yamashi	ta <sup>115,170</sup>		Fast n	450~560	2.5~15			HRTEM	Stable	Y:Ti decrease	Stable	Stable	
in !	Monnet <sup>146</sup> Pareige <sup>147</sup>	Yamashi			Fast n	500, 700	100	1	$1.2 \times 10^{-6}$	TEM	n.s.	n.s.	Increase	Decrease	
	Pareige 148	Yu <sup>172</sup>			electron	500	10			TEM	Stable	n.s.	Decrease	Stable	
XIIII		Yutani <sup>173</sup> Zhanbing			Fe electron/H	300, 500 350~550	1 ~ 10 15	1	$1 \times 10^{-3}$ $2 \times 10^{-3}$	TEM TEM	n.s.	n.s.	Stable Stable	Stable Stable	
ain F	Pasebani <sup>149</sup> Pasebani <sup>149</sup>		)	12.501	electron/H	350~550	15	4	2 × 10 -	IEW	O/M interface become irregular	S II.S.	Stable	Stable	
12	Ramar <sup>150</sup>	Yano <sup>175</sup>			Fe	500	3, 100	1	$1 \times 10^{-4}$	APT	n.s.	n.s.	Decrease	Decrease	
ro1	Jung 176		PM2000 Fast n, He		500	21			EFTEM	Amorphization faceted shape becomes spherical	Cr-rich shells	n.s.	n.s.		
	Ribis <sup>152</sup> Ribis <sup>152–154</sup>	<sup>a</sup> Aydogar	177	14YWT	Fast n	360 ~ 370	7	f	$3.5 \times 10^{-7}$	TEM. EFTEM	n.s.	n.s.	Stable	Stable	
is	HIDIS	<sup>a</sup> Aydogar			Fe	450	585		$1.7 \times 10^{-3}$	TEM, APT	11.0.	Stable	Decrease	Decrease	
F	Ribis <sup>155</sup>	aBrooks1	78	SS310	Kr	520	1.5		$\sim 1.25 \times 10^{-3}$	STEM-EDS	n.s.	Y:Ti decrease	Stable	n.s.	
	Robertson <sup>156</sup>	aChen179		12Cr	Fe	475	~800		$\sim 1.74 \times 10^{-3}$	TEM	Destroyed incoherent	n.s.	Decrease Dis		
on 8	Rogozhkin <sup>157,15</sup>	В									particles		appear >		
													Saturation		e 20°
	Rogozhkin <sup>159</sup> Rogozhkin <sup>160</sup>			<sup>a</sup> Skuratov <sup>11</sup>	88 KP4	Bi	RT	$4.8 \times 10^{-4}$ 1.2	× 10 <sup>-3</sup>	TEM, HRTEM	Erosion > 5 nm Else no change	n.s.	n.s.	n.s.	
130 F	Rogozhkin <sup>160</sup>	aGetto <sup>180</sup>		N <sup>a</sup> Skuratov <sup>11</sup>	88 KP4	Xe	RT	$1.0 \times 10^{-3}$ 1.5	$\times 10^{-2}$	TEM, HRTEM	Amorphization Crystal	Mixing of the	n.s.	n.s.	ba
	Saito <sup>161</sup>										inclusion in	elements Dis-			eas
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1 8	Schäublin 163	aKim <sup>181</sup>		1							Chromite formation				ore
ıra	Skuratov <sup>164</sup> Skuratov <sup>165</sup>	944 1 11	10	<sup>8</sup> Šćepanovi	ić <sup>189</sup> 14Cr	Fe	- 80	15		TEM, STEM- EDS, EFTEM	Disk, rod shape increase	Stable	Decrease <5 nm	Increase	bh
11111	Swenson 166, 167	aKondo <sup>18</sup>		<sup>3</sup> Šćepanovi	ic <sup>189</sup> 14Cr	Fe/He/H	600	30		APT TEM, STEM-	Disk, rod shape	Stable	Ostwald ripening	Stable	
ime	Swenson 166, 167			оссраноч	1401	TOTTOTT	000	50		EDS, EFTEM		OBDIC	(decrease	Otabic	
oat ,	Villiams <sup>168</sup>									APT			<5 nm and		
	/amashita <sup>169</sup>	aLescoat	183	С									increase larger particles)		
oat	/amashita169			<sup>8</sup> Song <sup>190</sup>	14Cr	Fe	RT	2, 10, 50	$6.4 \times 10^{-4}$	TEM	n.s.	n.s.	Decrease	Decrease 2 orders	
	/amashita <sup>115,170</sup>	<sup>a</sup> Liu <sup>184</sup>		N *Swenson*	91 9Cr	Fe	500, 400	1, 3, 50, 100	$2.2 \times 10^{-4}$	TEM, APT	n.s.	Y: O increase	Decrease	Decrease	
oat <sup>24</sup>	180	3D 1 18	15	]								(Y + 0): Ti stable			
	9Cr	<sup>a</sup> Parish <sup>18</sup> <sup>a</sup> Parish <sup>18</sup>	15	<sup>3</sup> Swenson <sup>1</sup>	91 9Cr	Н	500	1, ~3, 7	$1.2 \times 10^{-5}$	TEM, APT	n.s.	Y: O increase		Increase < 50 dpa,	1
138	DY	aPasebar	186	1								(Y + 0): Ti	else decrease	else decrease	
		aRogozh	kin <sup>187</sup>	aZhang <sup>192</sup>	SS31	6 Kr/He	500	0.05~8		TEM	n.s.	stable n.s.	Shrinkage <10 nm	n.s.	1
	F82			Linuing	5501	- 14,,,,0	000	0.00					else stable		
												+ V), (Y →			
<sup>39</sup> don <sup>140</sup>	140	<sup>a</sup> Skurato	188	Cr16	Bi	RT		$0^{-4} 1.2 \times 10^{-3}$		TEM. HRTEM	Amorphous ion tracks	+ V)/0 sta	ible n.s.	n.s.	







- Swelling:
  - ODS steels are very swelling resistant, as the oxide particles trap vacancies and gas atoms, resulting in very small and homogeneously dispersed voids/bubbles
- Hardening:
  - hardness increases due to irradiation in ODS steels are smaller than in non-ODS steels
  - Oxide particles dominate hardness, and act as sinks for generated point defects

## **Summary**

- ODS is fabricated through mechanical alloying and subsequent annealing
- 9Cr-ODS steel has a unique structure consisting of tempered martensite and residual ferrite that induces superior strength through finely dispersed oxide particles
- NFAs have a very high density of oxide particles, producing very high strength and creep resistance, at the cost of workability
- FeCrAl-ODS can provide superior corrosion resistance while retaining the ODS influenced mechanical properties
- Further in-reactor studies on ODS steels need to be performed
- While performance of ODS steels is widely studied, current production is limited to laboratory scale, with prohibitive costs for large scale production