Activation Concerns for Candidate Vacuum Vessel Materials

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VV Steel Should Meet Shielding and Activation Requirements

- Provide shielding function for magnets and externals.
- Water-cooled VV to reduce fast neutron fluence at magnet.
- Structural and filler materials should be recyclable **and** qualify as Low Level Waste (Class C or Class A).
- Preferably Class A LLW to reduce disposal cost.
- Materials generating High-Level Waste should be excluded.
- Low decay heat ($\Rightarrow$ no Mn-based steel).

- Management of ARIES activated materials:
  - Clearance (release to commercial market to fabricate as consumer products) – Bioshield is clearable
  - Recycling (Reuse within nuclear industry) – all fusion components are recyclable
  - Geological disposal:
    - Only Low Level Waste:
      - Class A (such as VV, magnet, bioshield) – lowest disposal cost
      - Class C (such as blanket, divetor, shield) – more expensive to dispose of.

VV Fabrication Requirements
(S. Malang – UCSD)

- Low strength steel, unlike F82H for FW/blanket
- Operate at low temperature (150-200^{o}C)
- No embrittlement at low temperature
- Compatible with water cooling
- Easily rewelded (with TIG or FSW?) with no need for complex PWHT
- Tolerable neutron-induced swelling, particularly behind assembly gaps and near penetrations (> 20 dpa, per El-Guebaly).

Candidate 3Cr-3WV Reduced Activation Steel for ARIES VV (A. Rowcliffe – ORNL)

- Relatively new reduced activation steel: 3.0Cr, 3.0W, 0.25V, 0.5Mn, 0.14Si, 0.1C, Fe bal
- Developed at ORNL over past 10 years.
- Currently undergoing scale-up to 50 ton heats.
- Developing ASME code case for tubing and piping for power generation, chemical and petrochemical industries.
- **Main features**:
  - Superior weldability
  - High toughness microstructure develops during post-weld cooling; tempering probably not necessary
  - Adequate corrosion behavior at 20-300°C
  - Limited irradiation data.

Candidate Steels for ARIES Water-Cooled VV Operating at 150-200°C

Name **Type**	**MF82H** **FS**	**3Cr- 3WV** **Bainitic FS**	**8-9% Cr** **RA F/M S**	**16-18% Cr** **430-FS**	**316-SS** **AS**	**DIN-4970** **RA AS***
Require complex PWHT? (for welding and rewelding)	Y	N	Y	N	N	N
Corrosion resistant in 200°C water?	Y	Y	Y	Y	Y	Y
Need water chemistry control to inhibit IASCC?	TBD	TBD	TBD	TBD	Y	Y
Radiation hardening and DBTT shift @150-200°C, 10 dpa?	High	TBD	Smaller	TBD	#	#
Welding issues for 2 cm thick plates?	TBD	TBD	TBD	TBD	N	N
Thermal conductivity	High	High	High	High	Low	Low
Swelling @ 10-20 dpa and 300°C?	Low[&]	Low[&]	Low[&]	?	Low[&]	Low[&]
Thermal expansion	Low	Low	Low	Low	High	High
Relatively expensive?						yes

• Reduced activation Austenitic Steel: 15% Cr- 15% Ni- 2% W- 1.7% Mn- 0.5% Si- 0.5% Ti- 0.3% Y- 0.1% C (in wt.%) + all other impurities in MF82H. Mo replaced by W.

No DBTT, but reduction in uniform strain.

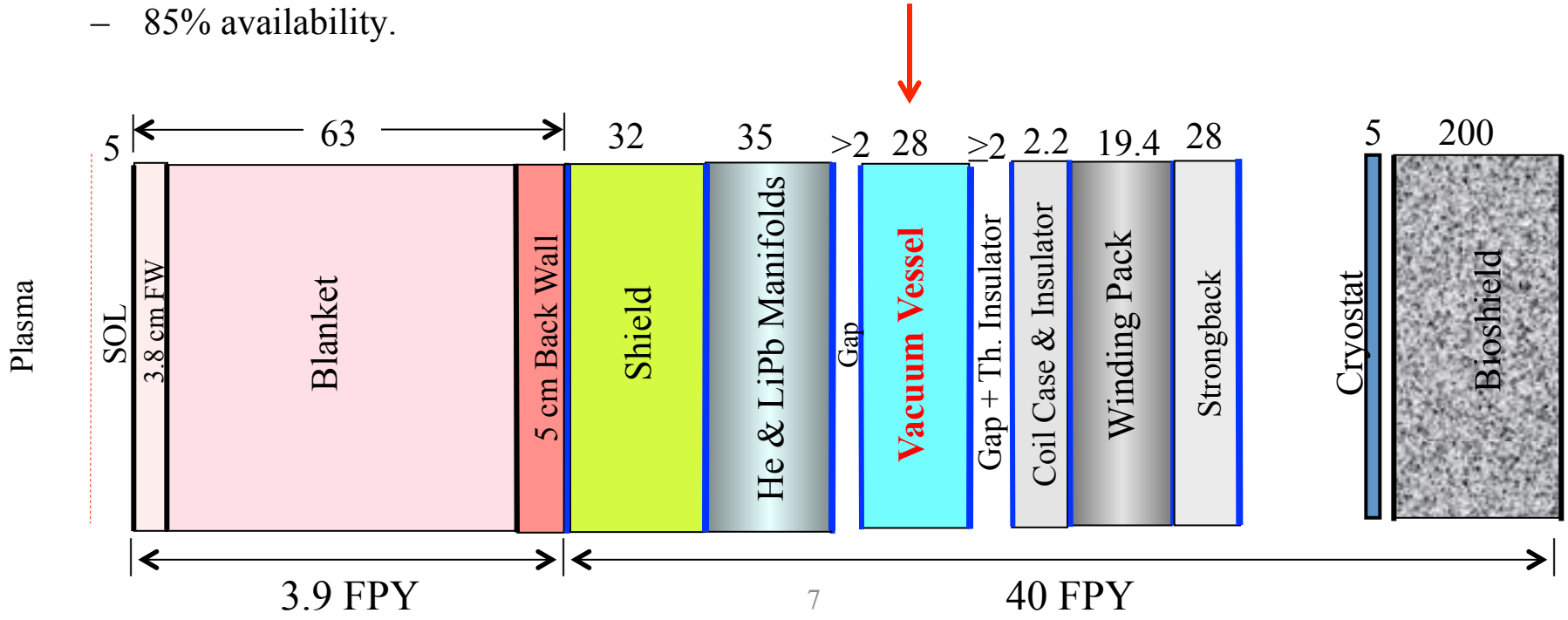
[&] Less than 5%.

Nominal Impurities

Alloy	MF82H	3Cr_3WV_FS	ORNL-FS	430_FS	316_SS	RAAS
Density (g/cm^3)	7.89	7.89	7.78	7.7	7.966	7.966
Composition in wt%						
B					0.001	
C	0.1	0.1	0.1	0.12	0.0225	0.1
N					0.07	
O					0.002	
Na						
Mg						
Al	1.40E-03	1.40E-03		1.40E-03	0.05	1.40E-03
Si		0.14	0.25	1	0.5	0.5
P					0.025	
S					0.0075	
K					5.00E-04	
Ti					0.15	0.5
V	0.2	0.25	0.025		0.004	
Cr	7.5	3	9	17	17.5	15
Mn		0.5	0.5	1	1.8	1.7
Fe	90.11586	92.945858	88.073862	80.815858	64.938	64.883258
Co	2.80E-03	2.80E-03	3.40E-03	2.80E-03	0.05	2.80E-03
Ni	4.74E-02	4.74E-02	4.02E-02	4.74E-02	12.25	15
Cu	1.00E-02	1.00E-02		1.00E-02	0.1	1.00E-02
Y						0.3
Zr					0.002	
Nb	3.30E-04	3.30E-04	4.00E-04	3.30E-04	0.01	3.30E-04
Mo	2.10E-03	2.10E-03	7.00E-03	2.10E-03	2.5	2.10E-03
Pd	5.00E-06	5.00E-06	1.80E-05	5.00E-06		5.00E-06
Ag	1.00E-05	1.00E-05	1.60E-05	1.00E-05		1.00E-05
Cd	4.00E-05	4.00E-05	5.00E-06	4.00E-05		4.00E-05
Sn					0.002	
Ta	0.02		7.00E-06		0.01	
W	2	3	2		0.001	2
Os	5.00E-06	5.00E-06	2.00E-06	5.00E-06		5.00E-06
Ir	5.00E-06	5.00E-06	5.00E-06	5.00E-06		5.00E-06
Pb					8.00E-04	
Bi	2.00E-05	2.00E-05	5.00E-06	2.00E-05	8.00E-04	2.00E-05
Eu	5.00E-06	5.00E-06	5.00E-06	5.00E-06		5.00E-06
Tb	2.00E-06	2.00E-06		2.00E-06		2.00E-06
Dy	5.00E-06	5.00E-06	5.00E-06	5.00E-06		5.00E-06
Ho	5.00E-06	5.00E-06	5.00E-06	5.00E-06		5.00E-06
Er	5.00E-06	5.00E-06	5.00E-06	5.00E-06		5.00E-06
U	5.00E-06	5.00E-06	6.00E-05	5.00E-06		5.00E-06

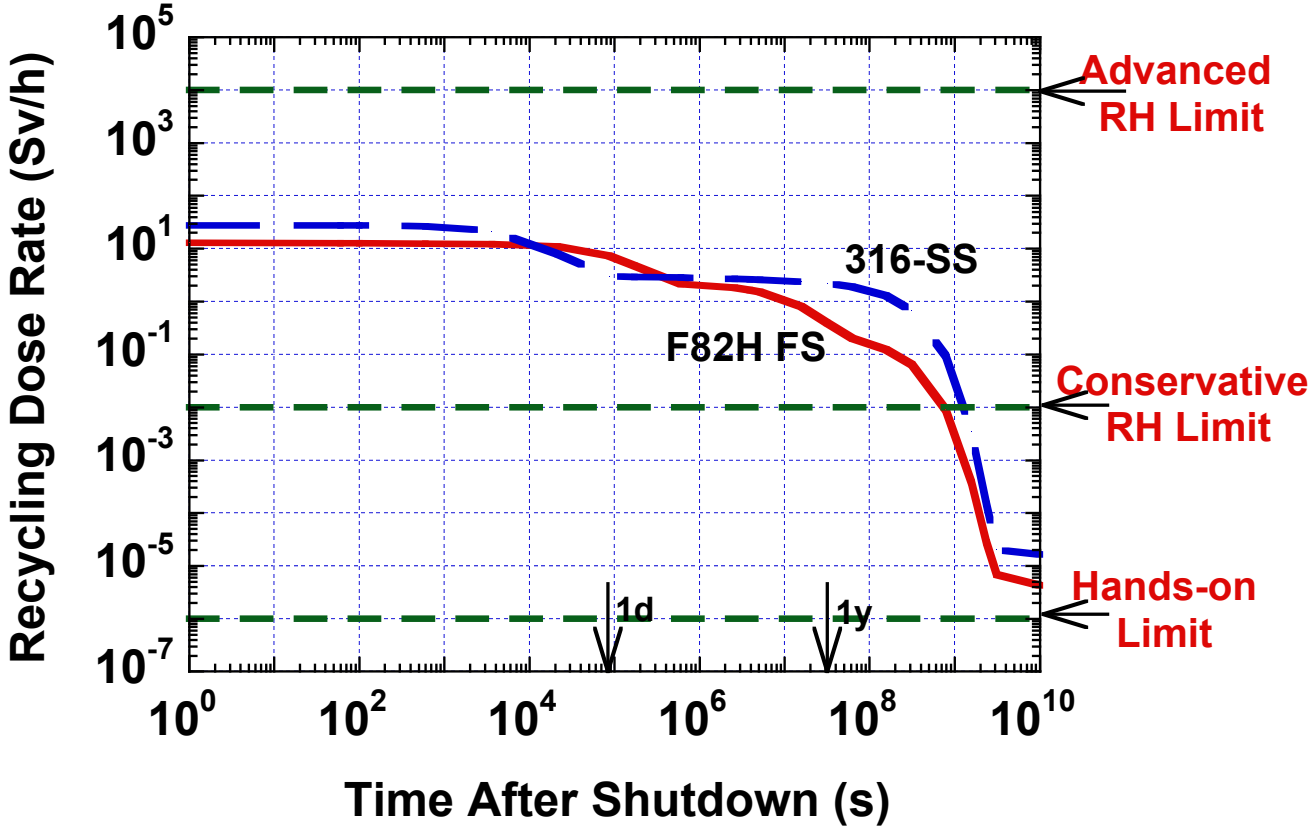
VV Activation Assessment

- Because ARIES-ACT design is still evolving, previous ARIES-CS design was considered for this activation comparison.
- Redoing analysis for ARIES-ACT will NOT alter conclusion.
- **ARIES-CS Key parameters**:
  - 2.6 MW/m^2 average NWL
  - 40 FPY VV lifetime
  - 85% availability.

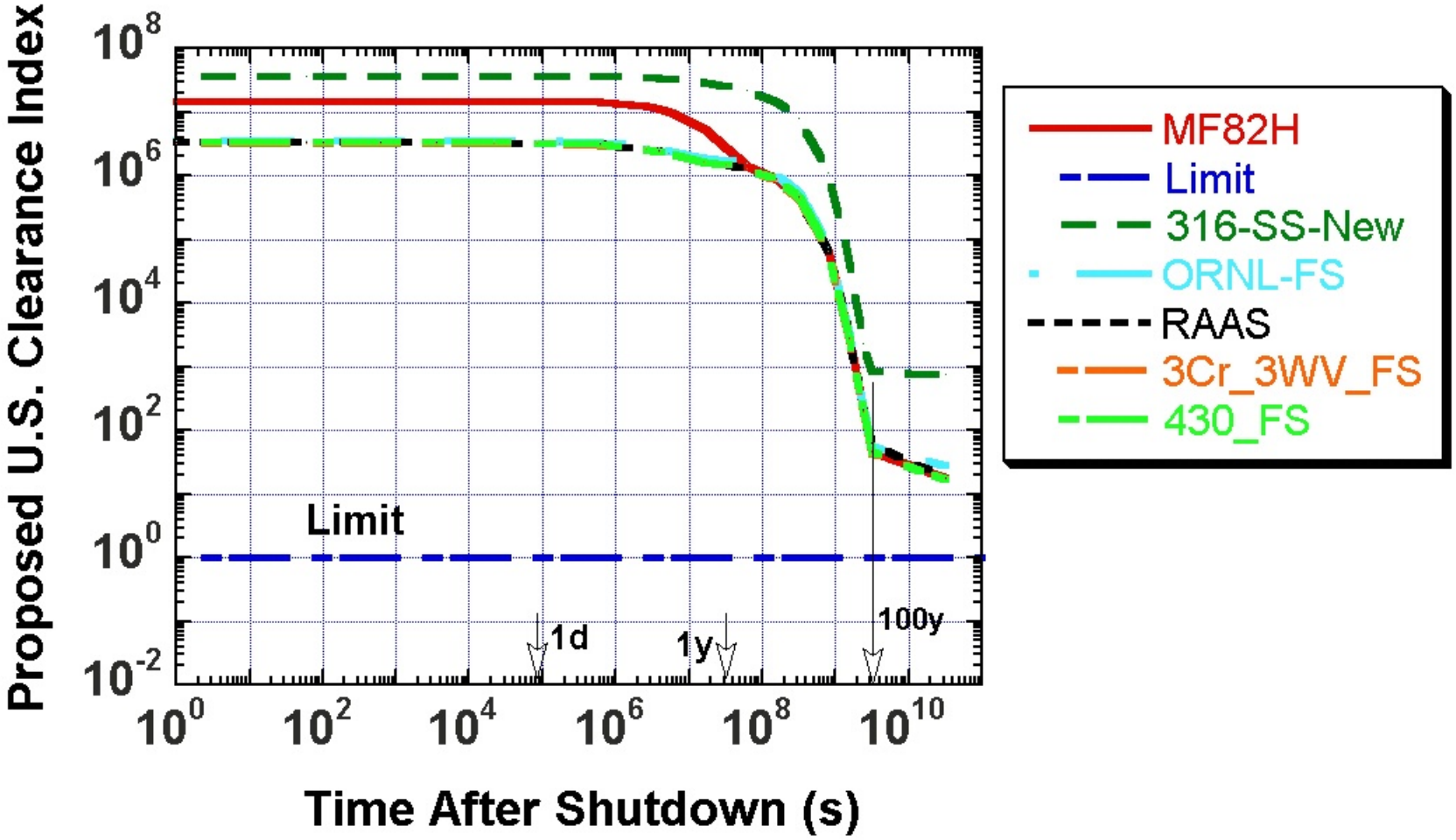


All Candidate VV Materials are Recyclable with Advanced RH Equipment

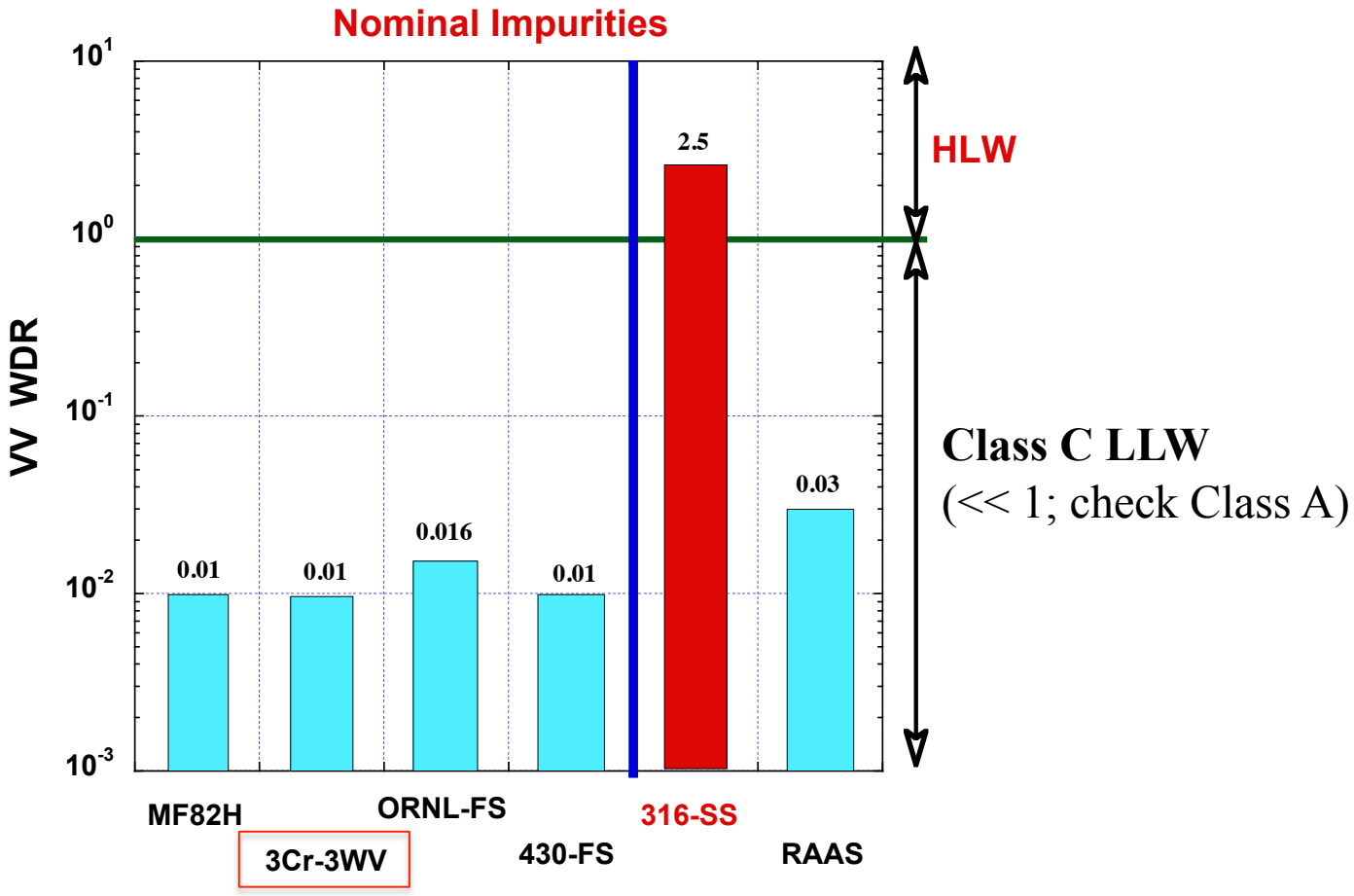
Examples of ferritic and austenitic steels



None of Candidate Materials is Clearable even after 100 y Following Shutdown

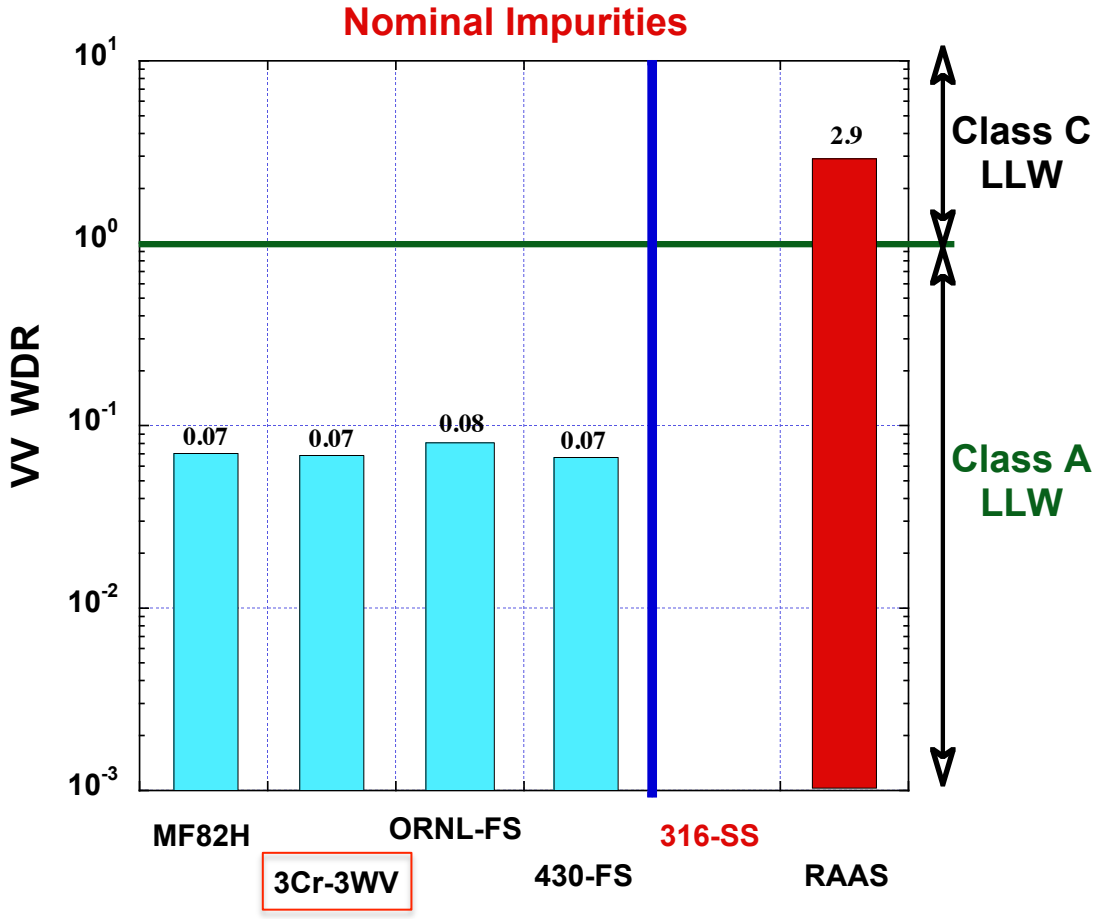


Waste Disposal Rating @ 100 y after shutdown (Class C Classification)



- Exclude 316-SS for generating High-Level Waste.
- Which steels qualify as Class A LLW (cheaper to dispose of)?

Waste Disposal Rating @ 100 y after shutdown (Class A Classification)



- Exclude RAAS for disqualifying as Class A LLW.
- Remaining steels qualify as Class A LLW (MF82H, 3Cr-3WV, ORNL-FS, 430-FS).

"Present" Impurities

- A. Rowcliffe suggested using list of "Present" impurities for **all** candidate steels.

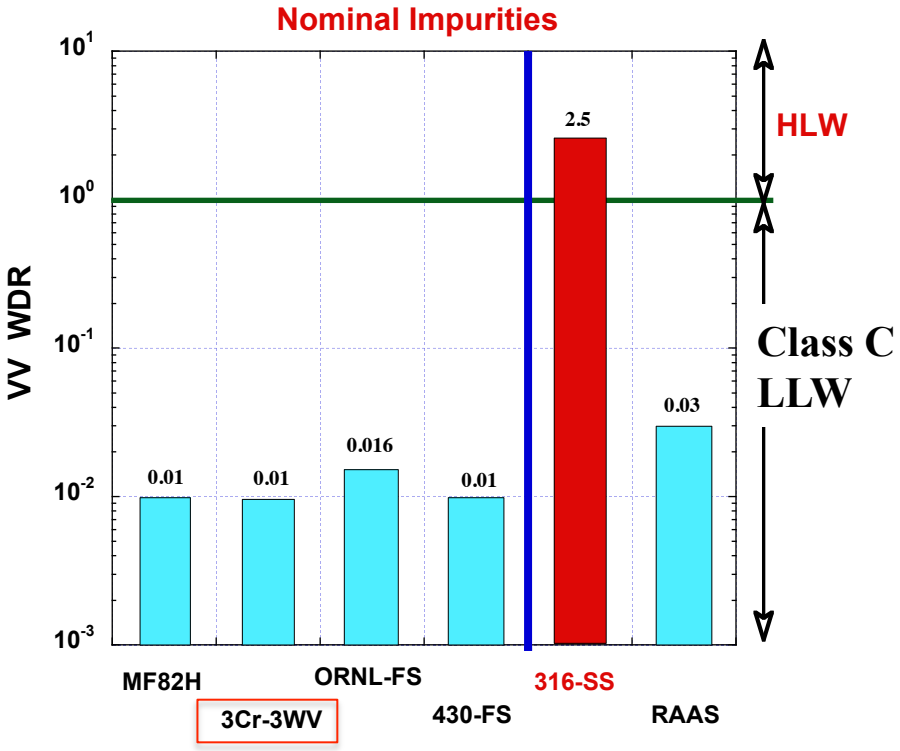
- "Present" impurities represent:
  - Lowest values measured in **different** steels
  - Best achievable at *present* **with relatively modest effort.**

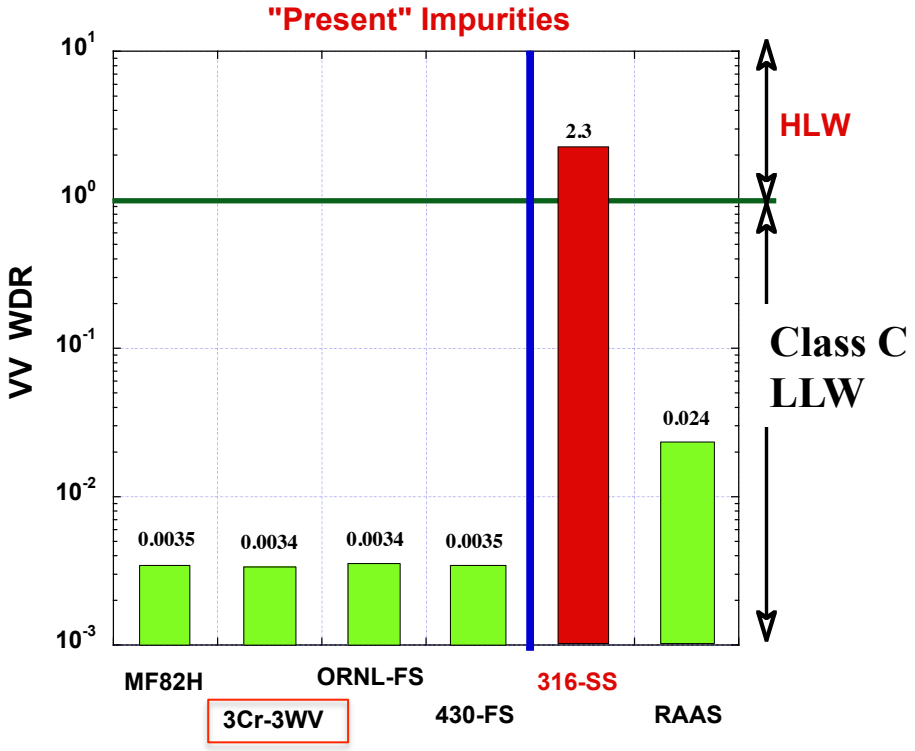
- **Reference** for "Present" impurities:
  R. Klueh et al., Impurity effects on reduced-activation ferritic steels developed for fusion applications, Journal of Nuclear Materials 280 (2000) 353-359. Table 4, Page 357.

Candidate VV Steels with "Present" Impurities

Alloy	MF82H_Present	3Cr_3WV_FS_Present	ORNL-FS_Present	430_FS_Present	316_SS_Present	RAAS_Present
Density (g/cm^3)	7.89	7.89	7.78	7.7	7.966	7.966
Composition in wt%						
B					0.001	
C	0.1	0.1	0.1	0.12	0.0225	0.1
N					0.07	
O					0.002	
Al	3.00E-03	3.00E-03	3.00E-03	3.00E-03	3.00E-03	3.00E-03
Si		0.14	0.25	1	0.5	0.5
P					0.025	
Ti					0.15	0.5
V	0.2	0.25	0.025		0.004	
Cr	7.5	3	9	17	17.5	15
Mn		0.5	0.5	1	1.8	1.7
Fe	90.173301	93.003301	88.118301	80.873301	65.060601	64.894601
Co	8.00E-04	8.00E-04	8.00E-04	8.00E-04	8.00E-04	8.00E-04
Ni	1.30E-03	1.30E-03	1.30E-03	1.30E-03	12.25	15
Cu	1.00E-03	1.00E-03	1.00E-03	1.00E-03	0.1	1.00E-03
Y						0.3
Zr						
Nb	5.00E-05	5.00E-05	5.00E-05	5.00E-05	5.00E-05	5.00E-05
Mo	5.00E-04	5.00E-04	5.00E-04	5.00E-04	2.5	5.00E-04
Pd	5.00E-06	5.00E-06	5.00E-06	5.00E-06	5.00E-06	5.00E-06
Ag	5.00E-06	5.00E-06	5.00E-06	5.00E-06	5.00E-06	5.00E-06
Cd	5.00E-06	5.00E-06	5.00E-06	5.00E-06	5.00E-06	5.00E-06
Ta	0.02				0.01	
W	2	3	2		0.001	2
Os	5.00E-06	5.00E-06	5.00E-06	5.00E-06	5.00E-06	5.00E-06
Ir	5.00E-06	5.00E-06	5.00E-06	5.00E-06	5.00E-06	5.00E-06
Bi	5.00E-06	5.00E-06	5.00E-06	5.00E-06	5.00E-06	5.00E-06
Eu	2.00E-06	2.00E-06	2.00E-06	2.00E-06	2.00E-06	2.00E-06
Tb	2.00E-06	2.00E-06	2.00E-06	2.00E-06	2.00E-06	2.00E-06
Dy	5.00E-06	5.00E-06	5.00E-06	5.00E-06	5.00E-06	5.00E-06
Ho	5.00E-06	5.00E-06	5.00E-06	5.00E-06	5.00E-06	5.00E-06
Er	5.00E-06	5.00E-06	5.00E-06	5.00E-06	5.00E-06	5.00E-06

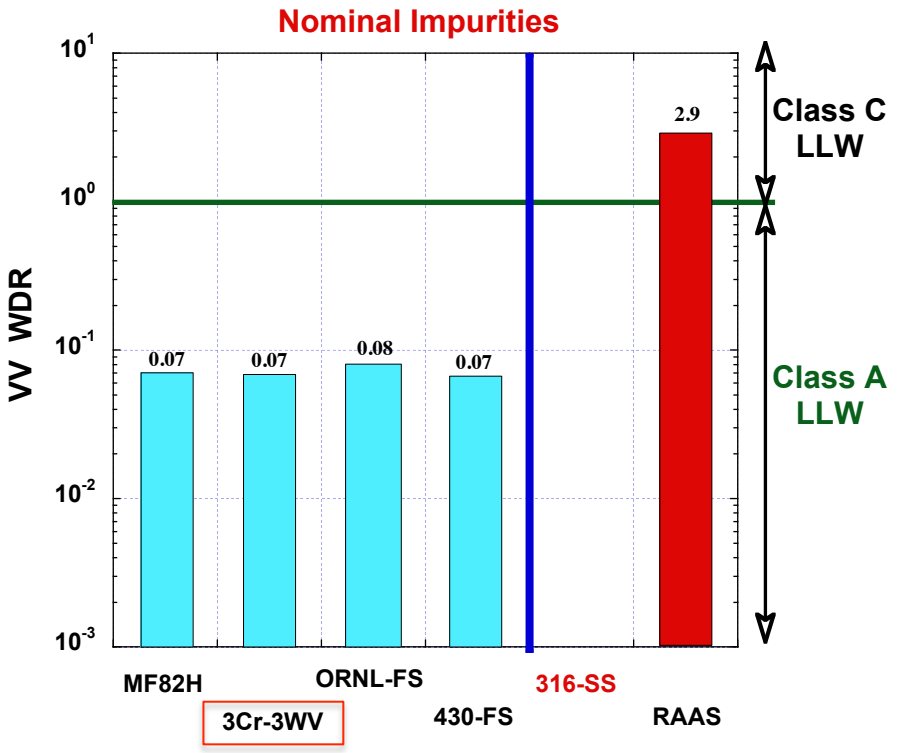
Class C Comparison

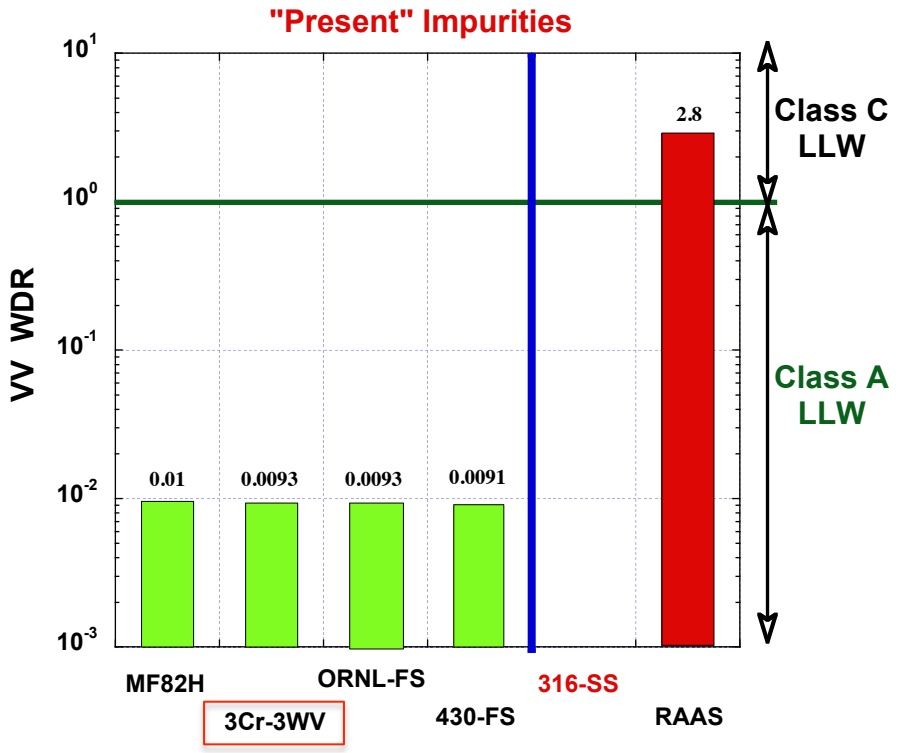




"Present" impurities result in lower Class C WDR

Class A Comparison





"Present" impurities result in lower Class A WDR

Recommended Steel for ARIES VV

- Newly developed 3Cr-3WV FS by ORNL:
  - R.L. Klueh, A.T. Nelson, J. Nuclear Materials 371 (2007) 37-52.
  - S.X. Muo, V.K. Sikka, ORNL/TM-2006/44 (2006).
- 3Cr-3WV steel:
  - Classifies as Class A LLW with either nominal or "Present" impurities
  - Could satisfy fabrication requirements
  - Probably satisfies strength, fracture toughness, ductility requirements
  - Needs low temperature irradiation data on hardening/shifts
  - Needs to assess IASCC, but is being developed for high temperature water/steam boiler applications.
- Loads on VV and ferromagnetic effects?