



Design Challenges and Activation Concerns for ARIES Vacuum Vessel

L. El-Guebaly, T. Huhn (University of Wisconsin),

A. Rowcliffe (ORNL),

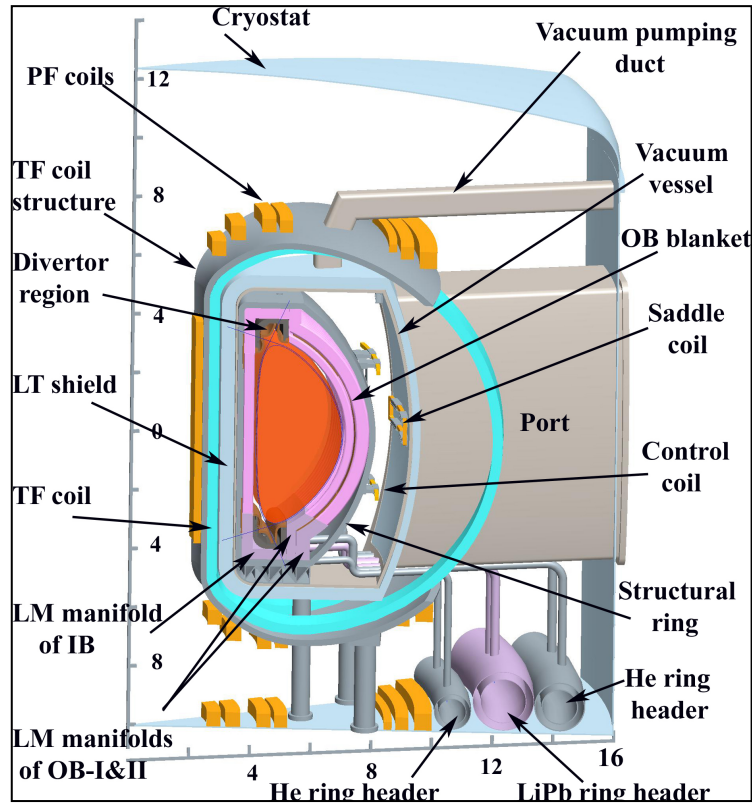
S. Malang (FNT Consulting, Germany)

and the ARIES-ACT Team

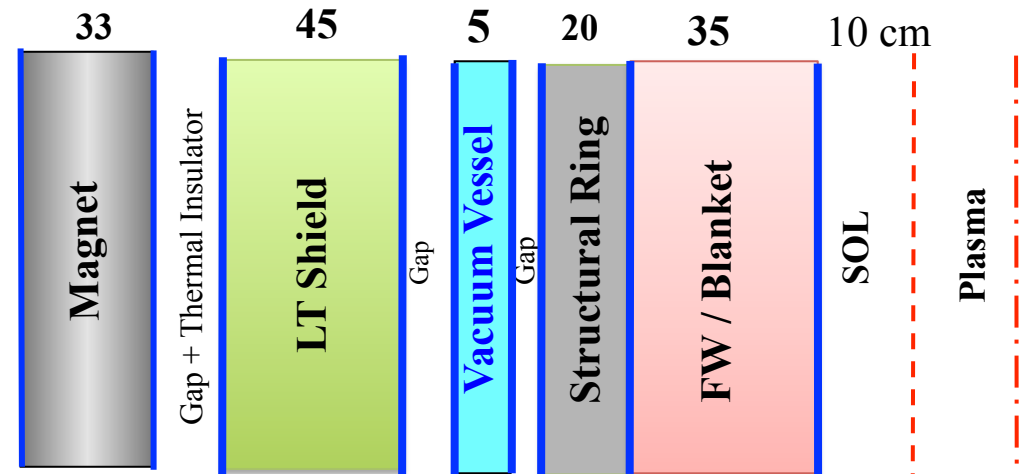
ANS 20th Topical Meeting on the Technology of Fusion Energy
August 27- 31, 2012
Nashville, TN, USA



ARIES-ACT Design



Inboard Radial Build



Water-cooled LT shield
~ 100 dpa peak dose
@ 40 FPY

He-cooled VV
~ 200 dpa peak dose
40 FPY



Vacuum Vessel Design Concerns

- Due to large size, it is impractical for VV to be heat treated following assembly and welding
- For this reason, F82H FS is unacceptable for VV due to complex heat treatment requirement
- Selection of austenitic stainless steel (such as 316-SS) eliminates need for welds to be tempered at 750°C. However, several materials issues would not support such choice:
 - Composition may not meet the activation requirements for maintenance dose, decay heat, and near-surface waste disposal
 - Possible swelling issues at doses > 20 dpa in sections operating at temperatures $> 350^{\circ}\text{C}$
 - Possible reductions in fracture toughness and loss of uniform strain for doses > 10 dpa at $\sim 200^{\circ}\text{C}$.
- These issues require careful evaluation from perspective of VV fabrication, materials properties under irradiation, and activation.



VV Property Requirements

- Operable at high temperature (400-500°C) at high doses (up to 200 dpa).
- Adequate oxidation resistance in helium at 400-500°C
- Tolerable neutron-induced swelling, particularly behind assembly gaps and near penetrations.
- Easily weldable and reweldable after irradiation with no need for complex post-weld-heat-treatment (PWHT) at 700-750°C for 0.5-2 hrs.
- Develop safe, fracture-resistant microstructure with adequate strength and toughness, including all welded regions.



LT Shield Property Requirements

- Operable at relatively low-temperature (150-200°C) at ~100 dpa dose.
- Compatible with water cooling at 150-200°C.
- No substantial embrittlement at low operating temperature .
- Low decay heat to act as heat sink during LOCA/LOFA events.
- Tolerable neutron-induced swelling, particularly behind assembly gaps and near penetrations.
- Easily reweldable with no need for complex PWHT.



Activation Requirements

- 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 (least preferred option):
 - Only low-level waste:
 - Class A (such as magnet and bioshield) – lowest disposal cost
 - Class C (such as blanket, VV, shield) – more expensive to dispose of.
- ARIES project requires all materials to be recyclable and disposable as low-level waste until technical and political issues associated with both approaches are resolved in future by US regulators and governmental agencies.
 - ⇒ All materials should be recyclable **and** qualify as low-level waste.
- Low decay heat (⇒ no Mn-based steel).



Seven Steels Selected for Further Analysis

The seven steels:

- F82H ferritic steel (having composition specifically tailored for LLW)
 - 3Cr-3WV bainitic steels
 - 8-9%Cr reduced activation ferritic-martensitic steels (ORNL-FS)
 - 430 ferritic steel (430-FS)
 - 316 SS austenitic steel (316-SS)
 - Modified DIN-4970 austenitic stainless steel (RAAS)
 - AMCR-0033 Mn-stabilized austenitic stainless steel (Mn-AS).
-
- Some steels are currently used in industry while others are still at developmental stage.
 - All seven steels (including F82H) examined for detailed **activation** analysis.



Known and Unknown Properties and Fabrication Aspects of Seven Steels

Steel 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*	AMCR AS
Require complex PWHT? (for welding and rewelding)	Y	N	Y	N	N	N	N
Corrosion resistant in 200°C water?	Y	Y	Y	Y	Y	Y	Y
Need water chemistry control to inhibit IASCC?	TBD	TBD	TBD	TBD	Y	Y	Y
Radiation hardening and DBTT shift @150-200°C, 100 dpa	High	TBD	High	TBD	#	#	#
Welding issues for 2 cm thick plates	TBD	N	TBD	TBD	N	N	N
Thermal conductivity	High	High	High	High	Low	Low	Low
Swelling @ 200 dpa and 400-500°C	TBD	TBD	TBD	TBD	High	High	High
Thermal expansion	Low	Low	Low	Low	High	High	High
Relatively expensive?						Y	

• 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.



3Cr-3WV Reduced Activation Steel

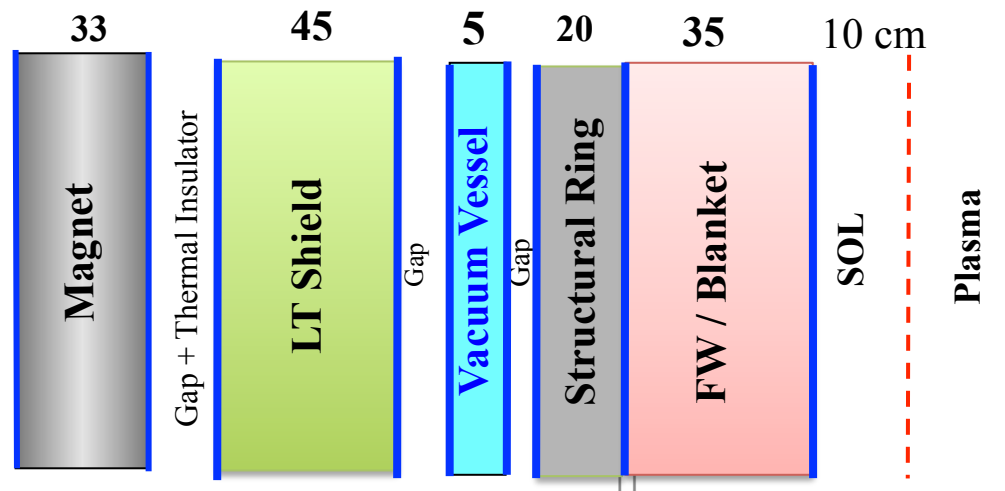
- Relatively **new** reduced activation steel: 3.0Cr, 3.0W, 0.25V, 0.5Mn, 0.14Si, 0.1C, Fe bal.
- Developed at **ORNL** over past 10 years.
- Currently undergoing scale-up to **50 ton heats** by joint ORNL-industry team.
- **ASME Code Case awarded for new Grades 315 and 315T** for tubing and piping for 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 water
 - Limited irradiation data.

Inboard VV Activation Analysis



IB VV Activation Analysis

- **Key parameters:**
 - 2.3 MW/m² average inboard NWL
 - 40 FPY VV lifetime
 - 85% availability.
- All materials are recyclable, but not clearable.
- Evaluate waste disposal rating:
 - WDR < 1 means low-level waste (LLW)
 - WDR > 1 means high-level waste (HLW).



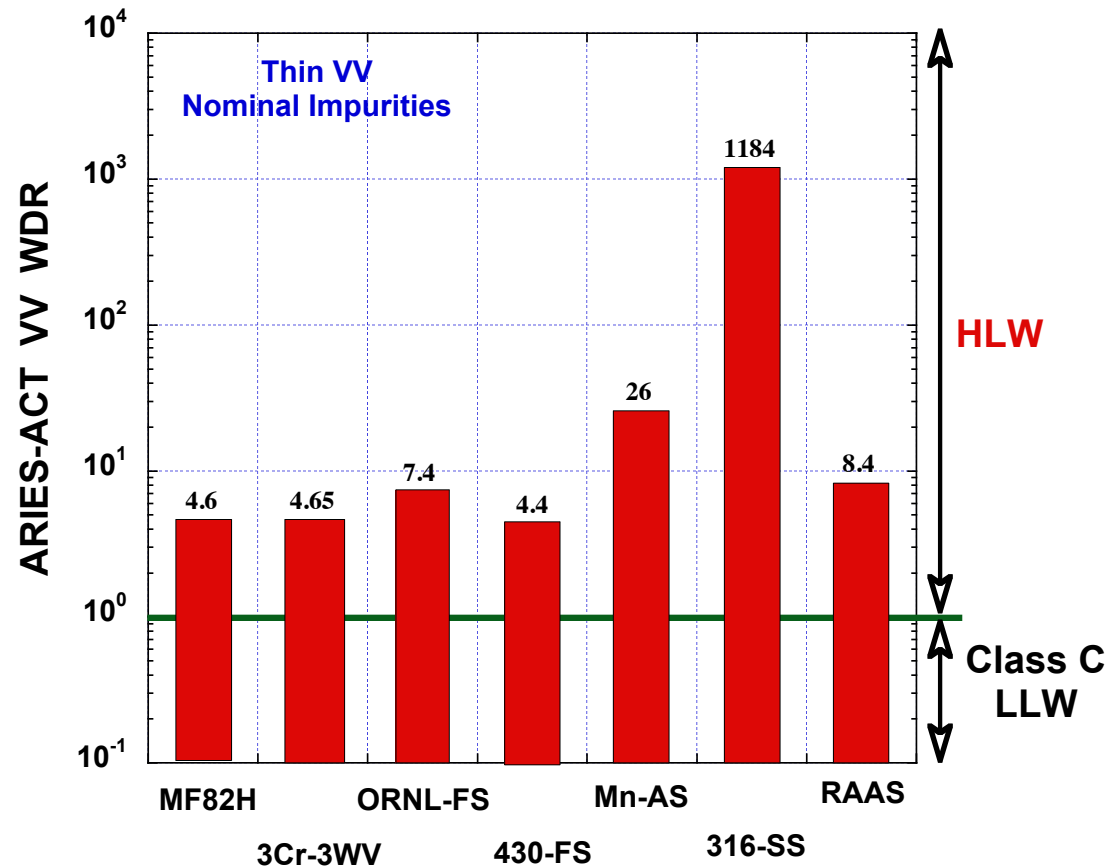


Nominal Impurities (from steel suppliers)

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



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



- All steels generate High-Level Waste.
- Reevaluate WDR using "Present" impurities.



“Present” Impurities

- To reduce long-term radioactivity, Klueh (ORNL) provided list of lowest 17 impurities (including 0.5 wppm Nb and 5 wppm Mo) that have ever been achieved in large-scale melting and fabrication practices of various steels.
- “Present” impurities are not specific to any particular steel composition and should be achievable at present with relatively modest effort and cost.

Reference: 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.

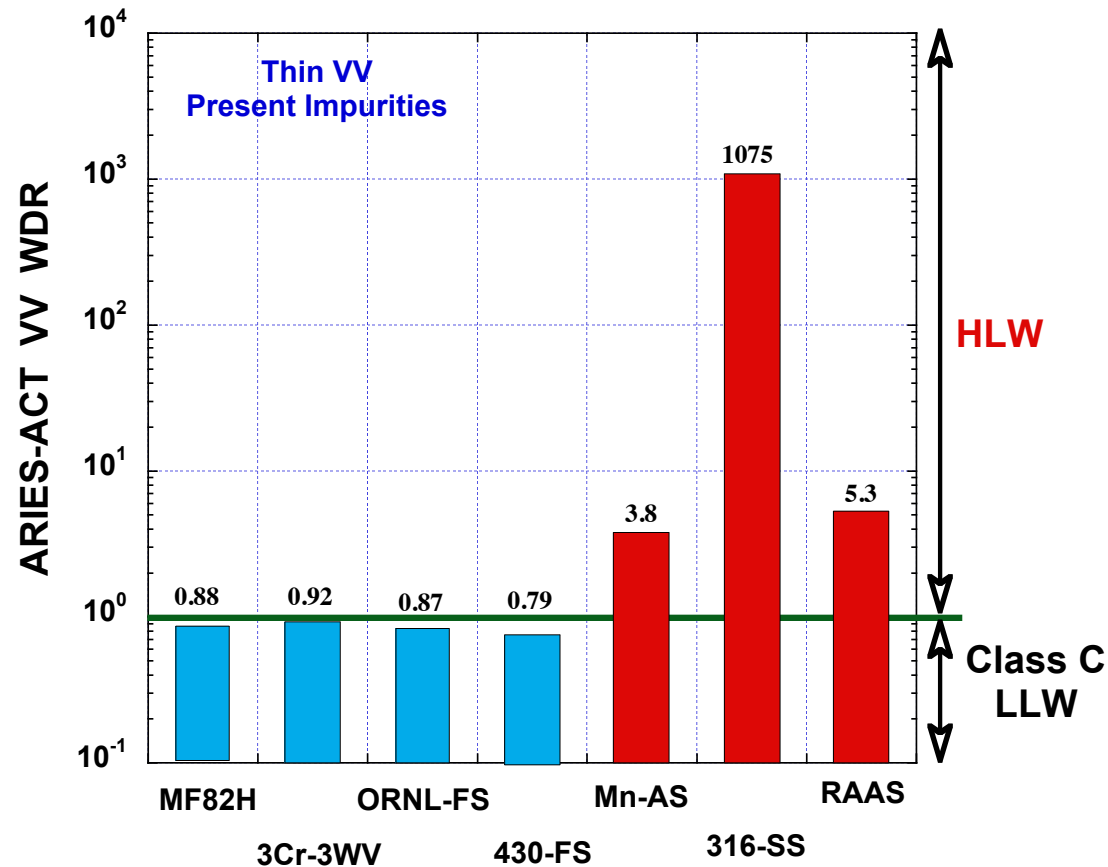


Candidate VV Steels with “Present” Impurities

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 Classification of VV



Four steels achieve LLW classification with “Present” impurities



Recommended Steel for ARIES VV (and LT Shield)

- Newly developed 3Cr-3WV bainitic FS mitigates most of identified F82H problems.
- It has potential to satisfy fabrication requirements for ARIES VV (and LT shield).
- Other features include:
 - Classifies as Class C LLW with “Present” impurities
 - Superior weldability with the potential for eliminating the need for a PWHT
 - Potential for the development of bainitic microstructures with improved resistance to low-temperature radiation embrittlement.
- Worldwide interest in developing the 3Cr-WV super-bainitic steels for advanced fossil fuel power generation applications because of major savings in assembly costs that could result from not requiring a PWHT.
- 3Cr-3WV bainitic FS is recommended for further consideration because of several advantages over other candidate steels.