DESIGN CHALLENGES AND ACTIVATION CONCERNS FOR ARIES VACUUM VESSEL

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Research has been conducted to find the optimal steel to use in the vacuum vessel (VV) of ARIES power plants. The VV should meet several design criteria, including activation and fabrication requirements. Seven different types of steel were examined in order to determine which steel would be the best candidate for the ARIES VV. The main concerns are related to activation, properties under irradiation, and fabrication of a sizable VV. Steels generating high-level waste (such as 316-SS) were excluded from possible material choices. As a VV material, there is the necessity for a carefully controlled the post-weld-heat-treatment at ~750°C after assembly, welding, and rewelding. For this particular reason, the F82H FS is not suitable for the ARIES VV. The newly developed 3Cr-3WV bainitic FS meets the activation requirements and has the potential to satisfy the fabrication requirements for the ARIES VV. It is recommended for further consideration because of several advantages over other candidate steels.

I. INTRODUCTION

The primary function of the vacuum vessel (VV) is to provide the high-level vacuum environment (necessary to achieve and maintain high-quality fusion plasma). It is a safety-class component that implements safety functions, such as confining the tritium and radioactivity and limiting the public/worker exposure to radiation during accidents. In past ARIES designs,[1] the 25-40 cm thick VV, along with the blanket and shield, provided a shielding function to protect the magnets against radiation.[2,3] Unlike the blanket and shield, the thick VV operated at lower temperature (150-200°C) and served as a heat sink during LOCA/LOFA events. The preferred coolant for the thick VV is water – a superior shielding material for the superconducting magnet.[2,3] The most recent ARIES-ACT design[4,5] calls for a thinner VV (5-10 cm thick) that is running hot (400-500°C) with helium coolant instead of water. Operating the VV at such high temperatures helps control the dust and tritium accumulation on the VV and avoids issues related to radiation hardening and loss of fracture toughness.

All previous ARIES designs employed the low-activation F82H ferritic steel[6] for the VV without paying much attention to the choice of material. This steel has the advantage of having a composition specifically tailored to facilitate the near-surface waste disposal and/or recycling after plant decommissioning. Given the 150-200°C operating temperatures for the thick VV, the Cr content of the F82H steel is satisfactory from the corrosion point of view, but the temperatures are in the regime of maximum radiation hardening. However, during assembly of either the thick or thin VV, it would normally require heat treatment at 700-750°C for 0.5 to 2 hours after welding to temper the martensitic structure and develop high toughness combined with a low ductile-to-brittle-transition-temperature (DBTT). Because of its large size, it is impractical for the VV to be heat-treated (tempered) following assembly and welding. Clearly, the necessity to temper the F82H FS at 700-750°C presents difficult issues. For this reason, the F82H FS is unacceptable for the VV due to the complex heat treatment requirement. Selection of an austenitic stainless steel would eliminate the DBTT issue and also eliminate the need for the welds to be tempered at 750°C. However, there are several materials issues that would not support such a choice:

- Selecting a composition that would meet the activation requirements for maintenance dose, decay heat, and near-surface waste disposal (e.g. excluding Mo)
- Possible reductions in fracture toughness and loss of uniform strain as a result of damage accumulation > 10 dpa at ~200°C
- Possible swelling issues at doses > 20 dpa in sections operating at temperatures > 350°C.

These issues and others require careful evaluation from the perspective of VV fabrication, materials properties under irradiation, and activation. A thorough evaluation of the various steel options should consider the following activation and fabrication requirements:

- Recyclability of structural and filler materials
- Only low-level waste, preferably Class A to reduce disposal cost

- Low decay heat to act as a heat sink during LOCA/LOFA events
- Operable at high temperature (400-500^{o}C) and compatible with water cooling at low temperature (150-200^{o}C)
- Develop a safe, fracture-resistant microstructure with adequate strength and toughness, including all welded regions
- No substantial embrittlement at low operating temperature
- Easily reweldable with no need for complex Post-Weld Heat Treatment (PWHT)
- Tolerable neutron-induced swelling, particularly behind assembly gaps and near penetrations (> 20 dpa).

II. CANDIDATE STEELS FOR VV FABRICATION

With the preceding requirements as a guideline, a set of potential candidate steels was selected for a detailed analysis of their activation properties. Some steels are currently used in the industry while others are still in the developmental stage. Table I provides a brief assessment of the known and unknown properties and fabrication aspects of the following six steels as well as F82H:

- 3Cr-3WV bainitic steel
- 8-9%Cr reduced activation ferritic-martensitic steel (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).

Of particular interest is the 3Cr-3WV steel. This is a relatively new, reduced-activation steel originally developed at Oak Ridge National Laboratory (ORNL). In the 1990s, Klueh[7] investigated a series of 2-3 Cr ferritic steels based on the well-known 2 1/4 -1Mo steel widely used for water/steam piping applications. To ensure favorable long-term waste disposal characteristics, Mo, Ni, Nb and Cu were restricted to low levels and W and V were introduced for hardening/strengthening purposes. Several of these experimental alloys had good strength properties and for some alloys, the as-welded microstructure had very good toughness properties that would not require a post-weld heat treatment. The 3Cr-WV alloys subsequently attracted interest from the petroleum and chemical industries for reactor vessels and heat recovery systems. Compared to the widely used 2 1/4 Cr-Mo steels, these new alloys offer a combination of higher strength, reduced fabrication costs, a lower DBTT, a higher upper-shelf energy, ease of heat treating and a strong potential for not requiring a PWHT.[8] Under a joint ORNL-industry partnership, several of these steels have been successfully scaled up to 50-ton heats and significant progress has been made towards full commercialization. An ASME Code Case has been granted based on the extensive database developed for one of the alloy grades.

TABLE I. Comparison of Fabrication Parameters of Candidate Steels

Steel	MF82H	3Cr-3WV	ORNL 8-9% Cr	16-18% Cr	316-SS	DIN-4970	AMCR-0033
Type	**FS**	**Bainitic FS**	**RA F/MS**	**430-FS**	**AS**	**RAAS**	**AS**
Requires complex PWHT?	Y	N	Y	N	N	N	N
Corrosion resistant in 200^{o}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^{o}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^{o}C	TBD	TBD	TBD	TBD	High	High	High
Thermal expansion	Low	Low	Low	Low	High	High	High
Relatively expensive?						Y	N

\# No DBTT, but reductions in uniform strain and fracture toughness.

Ferritic steels containing 14%-18% Cr (e.g., Type 430) remain ferritic throughout their operating range and therefore a PWHT is not required to temper a martensitic structure as for the 8-9% Cr steel. While the ferritic steels have good corrosion resistance in aqueous environments, it may not escape the necessity of having some measure of water chemistry control particularly in a radiation environment. There are a couple of issues with these steels that need more consideration. Firstly, welding thick sections can be a problem because of rapid growth of the ferrite grains that can lead to reduced fracture toughness and increased susceptibility to intergranular corrosion. Secondly, ferritic steels operating at 150-250^{o}C will be more susceptible to radiation hardening and shifts in DBTT than the 8-9% Cr reduced-activation FS.

It was to avoid these kinds of issues that ITER[9] selected austenitic steel 316LN-IG for its VV since there is no DBTT in such materials. However, austenitic steels are not free from radiation damage and activation issues. Neutron-induced swelling is a concern in VV sections behind assembly gaps and close to penetrations and ports where the atomic displacement could exceed 20 dpa in ARIES designs. There is also the issue of radiation-induced loss of uniform strain and fracture toughness that occurs for 316-SS in a dose-temperature regime above ~5 dpa and temperatures of 250-350°C. For lower temperatures the strain-to-necking values remain > 5% for doses at least up to 10 dpa. The low-temperature radiation effects in 316-SS have been mapped out and ITER has a good database. As discussed later, the 2.5 wt% Mo of 316-SS causes activation problems and generates high-level waste. Rieth[10] proposed replacing Mo with W and made other modifications compared to 316-SS, aiming at producing a reduced-activation austenitic steel (RAAS). Even with a composition tailored to meet the activation requirement the use of RAAS does not solve the VV problems entirely. Depending on the operating condition, it may be necessary to assess the feasibility of radiation damage annealing treatment for RAAS to maintain uniform strain and fracture toughness at levels that would provide satisfactorily safe margins.

III. COMPOSITION OF CANDIDATE STEELS

Alloying elements and impurities will definitely impact the activation level of steel-based components. For fusion, all materials are carefully chosen to minimize long-lived radioactive products such as C-14, Ni-59, Nb-94, Mo-99, Re-186m, etc. Manufacturing companies for fusion materials made a serious effort to use highly pure raw materials, strove to exclude Mo and Re, and minimize Nb impurities in particular. Reference 11 lists the alloying elements and impurities found in the six candidate steels as well as in F82H.[6] The F82H 18 impurity list (that includes 3.3 wppm Nb and 21 wppm Mo) is measured from the 5 ton heat produced in Japan for JAERI by the NKK corporation. For 3Cr-3WV, RAAS, and 430-FS where the steel is relatively new or the impurity list and/or density are missing, the F82H impurities and/or density are used since doing physical property measurements on new steels may be too far into the future. The impurities in this table are labeled "nominal" impurities.

In an effort to reduce the long-term radioactivity, Klueh[6] provided a list of the 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. They are not specific to any particular steel composition and should be achievable at present with a relatively modest effort and cost. This means such a list of controlled impurities would be achievable for any of the candidate steels for the VV (austenitic, ferritic, bainitic, or ferritic/martensitic). To quantify the impact on the activation, we examined the "nominal" and "present" impurities for all seven steels, including F82H. Reference 11 documents in more detail the complete list of both "nominal" and "present" impurities as well as the procedures of the activation analysis, codes, and methodology.

IV. ACTIVATION OF VV STEELS

There is a growing international effort to avoid the geological disposal of radioactive materials. Instead, recycling (reuse within the nuclear industry) and clearance (release to the commercial market if materials contain traces of radioactivity) offer an alternate, more environmentally attractive means for dealing with the radwaste stream.[12] Here, all three scenarios (recycling, clearance, and geological disposal) were first investigated for a VV made out of the seven candidate steels with "nominal" impurities. Then, the VV steels were reexamined with the list of "present" impurities.

The VV is not clearable but can potentially be handled and eventually recycled using advanced remote handling equipment. For all steels, ^{54}Mn (from Fe) is the main contributor to the recycling dose for up to 10 y. Storing the VV temporarily for several years helps drop the dose by a few orders of magnitude before recycling.

The geological disposal is the least preferred option for any fusion component. Nevertheless, the ARIES project requires all materials to be recyclable and disposable as low-level waste until the technical and political issues associated with both approaches are resolved in the future by US regulators and governmental agencies. Thus, we classified the VV for disposal based on its waste disposal rating (WDR – ratio of specific activity to allowable limit summed over all radioisotopes) to essentially exclude materials that generate high-level waste (HLW). The US has defined two main categories for low-level waste (LLW): Class A and Class C. The former is the least hazardous type of waste.

IV.A. Activation of ARIES-CS Thick VV

The ARIES-CS radial build[3] was considered in this analysis as representative of a design with a thick VV. All ARIES power plants deliver 1000 MW of net electric power. The radial build with uniform blanket[3] is shown in Fig. 1. The key activation-related parameters relevant to the ARIES-CS VV are the 2.6 MW/m^2 average neutron wall loading (NWL), 40 full power year plant lifetime, and 85% overall system availability. Within the 28 cm thick VV, 28% by volume consists of the primary steel structure, 23% borated version of the primary steel (typically containing 3 wt% boron), and the remainder is the water coolant.

We first examined the Class C waste shown in Fig. 2. The 316-SS steel must be excluded for generating HLW. All other steels fall well within the Class C LLW classification (WDR < 1). A reduction in the WDR of all steels, except 316-SS and RAAS, was notable when using "present" impurities. The main isotopic contributors to the WDRs can be found in Reference 11 for both "nominal" and "present" impurities.

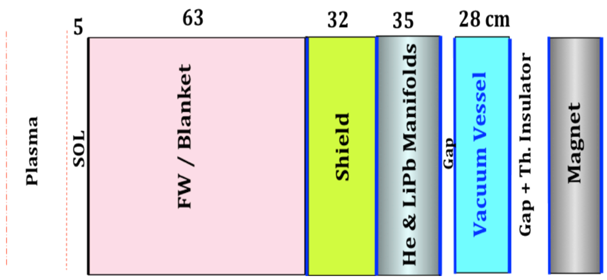

Fig. 1. Simplified ARIES-CS 1-D model showing the thick VV between blanket/shield and magnet.

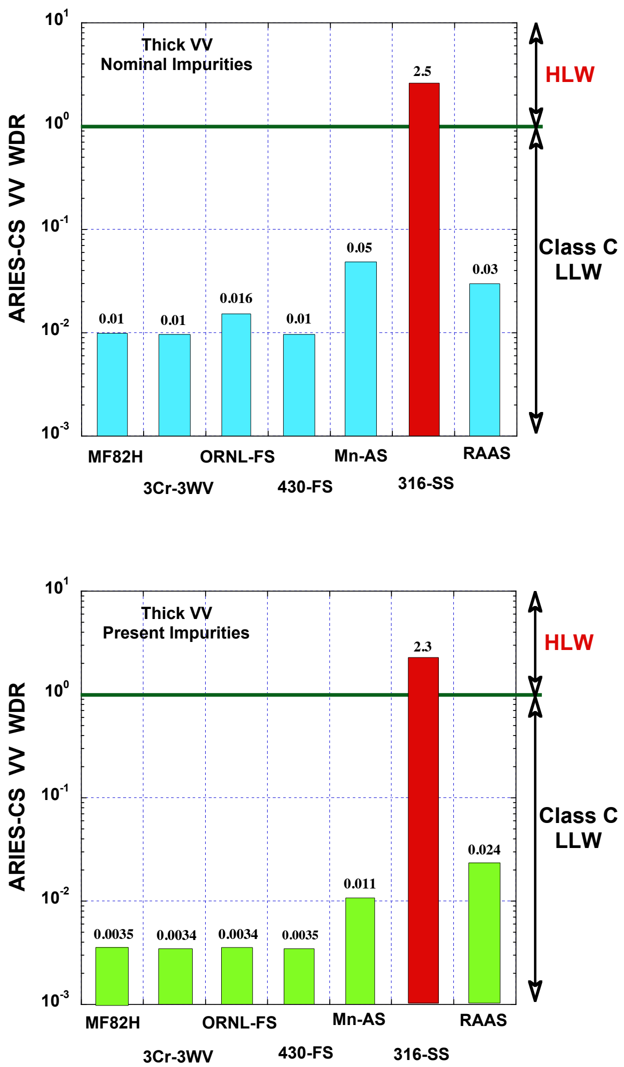

Fig. 2. Class C WDR for the seven candidate steels for ARIES-CS thick VV with "nominal" and "present" impurities.

Next, for the six steels with Class C WDR < 0.1, we identified which steel qualifies as Class A LLW; this designation is sought due to the cost savings encountered when disposing of materials in repositories. Figure 3 presents the Class A WDR. From this figure, the RAAS disqualifies while all remaining steels qualify as Class A LLW. The 15 wt% Ni contributes to ~98% of the Class A WDR for RAAS. If less than 5 wt% Ni could be tolerated, RAAS can meet the Class A disposal requirement.

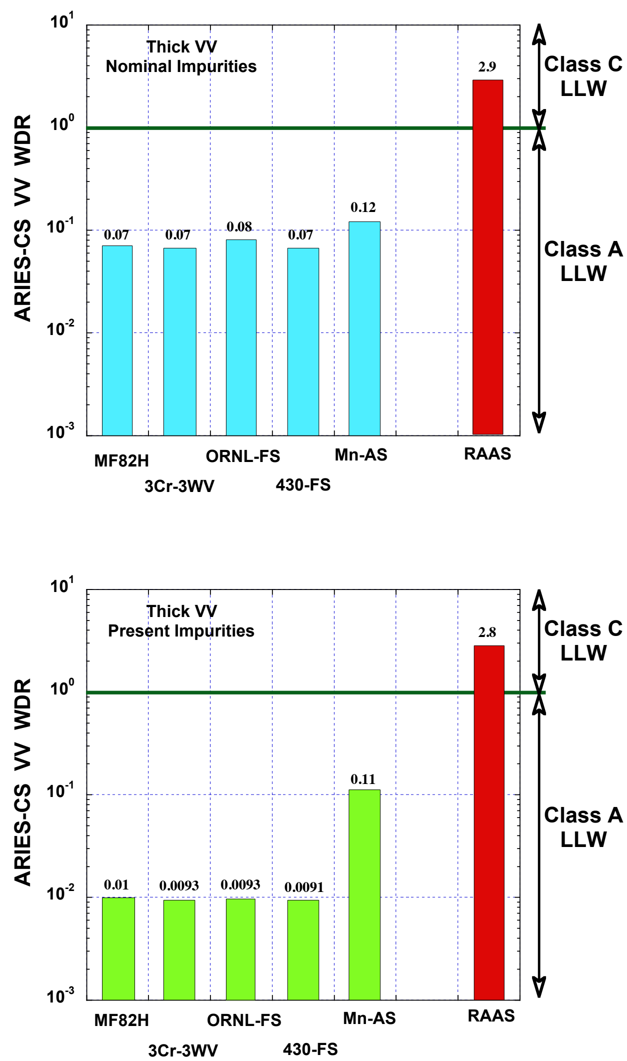

Fig. 3. Class A WDR for the six candidate VV steels that passed the Class C qualification with "nominal" and "present" impurities.

IV.B. Activation of ARIES-ACT Thin VV

The ARIES-ACT[4,5] IB radial build is shown in Fig. 4. It is somewhat similar to the ARIES-AT configuration,[2] but with a thin VV operating at 400-500^{o}C. The primary water-cooled low-temperature (LT) shielding component is located outside the VV.

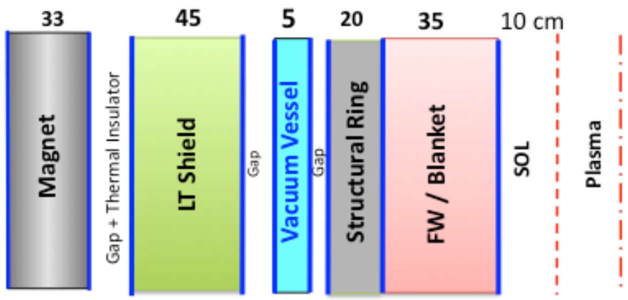

Fig. 4. IB radial build of ARIES-ACT-1.

We assessed the WDR of the thin VV using the seven candidate steels listed in Section II. The VV has a 40 FPY lifetime and the NWL averages at 2.3 MW/m^2 over the IB FW. For the case of "nominal" impurities present in all seven steels, the IB VV generates HLW (see Fig. 5), which is unacceptable. On the other hand, the "present" impurity levels allow the thin VV to barely achieve the desired Class-C LLW classification for only four steels including 3Cr-3WV. The Mn-AS, 316-SS, and RAAS steels should be excluded from further consideration for generating HLW even with "present" impurities. The higher WDR of the thin VV is attributed to the higher neutron flux averaged over the thin VV and the less shielding provided by only 55 cm thick IB blanket and Structural Ring. This analysis stresses the need for a strict control of impurities (particularly Nb and Mo) for the thin VV to avoid the generation of HLW.

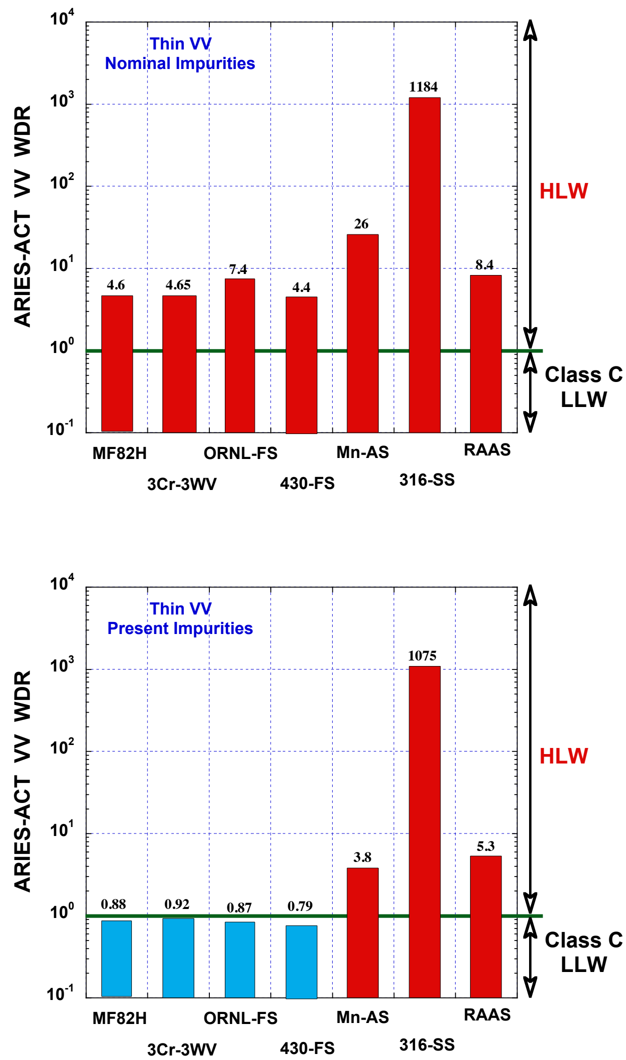

Fig. 5. WDR of the seven candidate steels for ARIES-ACT-1 thin VV with "nominal" and "present" impurities.

V. RECOMMENDED STEEL FOR ARIES VV

The main features of the 3Cr-3WV steel include superior weldability, radiation damage tolerance for temperatures in the 400-500^{o}C range (for ARIES-ACT thin VV), adequate corrosion behavior in water in the 150-200^{o}C range (for ARIES-CS thick VV and ARIES-ACT LT shield), and high toughness microstructure that develop during continuous cooling (tempering probably not necessary). For the high-temperature VV application, this steel probably possesses adequate oxidation resistance in helium at 400-500^{o}C, but this remains to be confirmed. In the case of a low-temperature VV (and LT shield) operating at 150-200^{o}C, radiation hardening and the resulting DBTT shifts could present a fracture toughness management issue similar to that with the 8-9% Cr martensitic steels (F82H, Eurofer, etc.). However, the bainitic steels appear to offer the potential to develop nano-scale microstructures with enhanced resistance to both the initiation and propagation of brittle cleavage cracks during operation in the radiation hardening regime.

There is a current worldwide interest in developing the 3Cr-WV super-bainitic steels for advanced fossil fuel power generation applications, not only because of their high creep strength and good toughness properties, but also because of major savings in assembly costs that could result from not requiring a PWHT.

VI. CONCLUSIONS

Seven different types of steel were examined in order to determine which steel would be the best candidate for the ARIES vacuum vessel. The main concerns are related to activation (recyclability, clearability, low-level or high-level waste), properties under irradiation (DBTT shift, corrosion resistance, swelling, etc.) and fabrication of a sizable VV (welding, PWHT, etc.). Although none of the candidate steels were clearable under ARIES operating conditions, all steels are recyclable. They qualify as Class A LLW with either "nominal" or "present" impurities for the thick VV option, except 316-SS and RAAS. They only qualify as Class C LLW with "present" impurities for the thin VV option, except Mn-AS, 316-SS and RAAS. This means, for ARIES-ACT with thin VV, Mn-AS, 316-SS and RAAS disqualify from further consideration for generating HLW. Note that Mn-AS should also be disqualified because of the expected high level of decay heat resulting from the 17.5 wt.% Mn alloying element.

The most popular F82H FS was initially envisaged as a FW/blanket structural material operating above 350^{o}C. As a material for the thick VV, it would be operating at 150-200^{o}C and subject to shifts in the DBTT. In addition, there is also the necessity for a carefully controlled PWHT at ~750^{o}C after the assembly of either thin or thick VV, welding, and rewelding. For these reasons, the F82H FS is not suitable for the ARIES VV. It appears from this study the newly developed 3Cr-3WV bainitic FS mitigates most of the identified F82H problems. Besides meeting the activation requirements, this steel has the potential to satisfy the fabrication requirements for the ARIES VV. It is recommended for further consideration because of several advantages over other candidate steels:

- Classifies as low-level waste
- Generates low decay heat
- Could satisfy fabrication requirements
- 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.

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