

# Material selection for spallation neutron source windows Application to PDS-XADS and XT-ADS prototypes

F. Sordo, A. Abánades, A. Lafuente, J.M. Martínez-Val, M. Perlado

*ETSII/Universidad Politécnica de Madrid, J. Gutiérrez Abascal, 2-28006 Madrid, Spain*

*Instituto de Fusión Nuclear (DENIM)/ETSII/Universidad Politécnica, Madrid, J. Gutiérrez Abascal, 2-28006 Madrid, Spain*

## ARTICLE INFO

## ABSTRACT

High performance neutron sources are being proposed for many scientific and industrial applications, ranging from material studies, hybrid reactors and transmutation of nuclear wastes. In the case of transmutation of nuclear wastes, accelerator driven systems (ADS) are considered as one of the main technical options for such purpose. In ADS a high performance spallation neutron source becomes an essential element for its operation and control. This spallation source must fulfil very challenging nuclear and thermo-mechanical requirements, because of the high neutron rates needed in ADS. The material selection for this key component becomes of paramount importance, particularly the source window that separates the vacuum accelerator tube from the spallation material where the accelerated protons impinge. In this paper, an integral analysis of spallation sources is done, taking as a reference the projects in this field proposed in the framework of European projects. Our analysis and calculations show that titanium and vanadium alloys are more suitable than steel as structural material for an industrial ADS beam window, mostly due to its irradiation damage resistance.

## 1. Introduction

Accelerator driven systems (ADS) are advanced nuclear concepts which could be used for the elimination of nuclear wastes by the so-called transmutation process with a surplus of energy generation. Such concepts were proposed in the 90's (Rubbia et al., 1995; Bowman et al., 1992) and are under development by many national and international programs (US-DOE, 1999; Park et al., 2002; Sasa et al., 2004; Abderrahim et al., 2001; EU Framework Program, in press). Most of the concepts under consideration are based on fast neutron cores, due to their most favourable fission to capture cross-section ratio at its application to the elimination of transuranics. Note that the aim of transmutation is the minimization of nuclear wastes by fissioning minor actinides (MA) as Np, Am and Cm. Therefore, those devices should be loaded with fuel highly enriched in MA. Those non-conventional fuels have a main drawback: its delayed neutron fraction ( $\beta$ ) is very low, what implies fast and large power variations from small reactivity variations. As a consequence, the reactivity control system has to be more complex. This fact can be overcome with subcritical cores, much less sensitive to reactivity transients especially, which need an external neutron source to operate (Schikorr, 2001).

In the framework of EURATOM research and development programs, the PDS-XADS (Cinotti et al., 2001) and the XT-ADS (Operational Office, 2006) prototypes are proposed as pre-industrial accelerator driven systems with high power neutron sources. The former has a window neutron source, the latter being windowless due to the heavy structural requirements that are expected. The main parameters of both ADS designs are given in Table 1. Nevertheless, a windowed alternative must also be studied for the XT-ADS as a back-up solution.

The state-of-the-art of ADS design proposes subcritical cores with multiplication factors ( $k_{\text{eff}}$ ) in the range from 0.95 to 0.98. With such subcriticality level, the nuclear core neutron population will be zero unless a high power neutron source delivers the needed neutrons that could stabilise neutron multiplication and population. One of the most efficient options is a spallation source based on a heavy material, as lead or lead-bismuth eutectic, bombarded by protons with energies in the 600–1000 MeV range.

The source neutron production determines the thermal power of a subcritical reactor depending of its criticality level. During fuel burn-up, a  $k_{\text{eff}}$  reduction must be compensated to keep the subcritical core power, which can be achieved by means of an increase in the neutron source strength. Such increase of the neutron production implies higher proton beam intensity, inducing a more severe thermo-mechanical stress in the neutron source structural materials and target. The neutron source design must assure the structural integrity of the target operating under the foreseen worst conditions and along the full operation cycle.

**Table 1**  
Reference configuration of the subcritical devices XT-ADS and PDS-XADS.

	XT-ADS (windowless)	PDS-XADS (windowed)
Core power (MWth)	50–100	80
Proton beam energy (MeV)	600	600
Max. beam intensity (mA)	2.5	6
Beam spot radius (cm)	3.7	8
Beam current density ( $\mu\text{A}/\text{cm}^2$ )	58.1	29.8
Core coolant	Lead–bismuth eutectic	Lead–bismuth eutectic
Neutron source target	Lead–bismuth eutectic	Lead–bismuth eutectic
Criticality ( $k_{\text{eff}}$ )	$\sim 0.95$	$\sim 0.95$

Current projects in the field of subcritical devices for transmutation of nuclear wastes and power generation are envisaging thermal power cores of the order of 50–100 MW, as will be seen later, what requires neutron sources with an associated thermal power of the order of a few MW. Neutron sources based on solid target materials are suitable for low power facilities (TRADE (Nifenecker and David, 2001; Rubbia et al., 2004), ISIS (Bauer, 2001)), but their performance is limited by thermo-mechanical constraints, that makes them unpractical for such industrial prototypes, therefore, molten metal targets are the technical option that has been chosen for spallation neutron sources for powerful ADS.

Molten metal neutron sources are classified into two main categories: windowed and windowless sources. The windowed sources are characterised for the physical separation between the vacuum accelerator tube and the spallation target. Such separation barrier is called window, and it must withstand very demanding mechanical stresses under high particle irradiation damage, what limits its expected operation lifetime. Several studies has been carried out by us (Sordo et al., 2007) and other authors (Song and Tak, 2003; Mantha et al., 2007; Prakash et al., 2006) taking into account thermal-hydraulic constraints and irradiation effects (Vladimirov and Möslang, 2006). In this paper, a multi-physics approach is presented for the analysis of the operation conditions of spallation source windows for ADS prototypes (PDS-XADS and XT-ADS under study in 6th and 7th European Framework Program).

Windowless sources overcome structural problems eliminating the window, but some drawbacks are highlighted as the uncertainties regarding liquid target surface instabilities, or target material boiling in contact with the vacuum of the accelerator tube, what requires the development of trapping systems of the boiled-off gas. Besides that, there would be the very severe problem of radioactive products confinement. This is why the window option is mainly considered for ADS prototypes.

The main objective of this paper is to analyse the feasibility of windowed target designs in both ADS prototypes, equipped with windows of high irradiation materials that have been developed as structural materials for the first wall of fusion reactors. For our purpose, we will apply some modification on their reference designs in order to broaden our parameter design limits for a better optimised design with different materials and operating conditions, but keeping the expected neutronic performance of both neutron generation targets. Note that XT-ADS has been proposed with a windowless neutron source due to the technological uncertainties to assess its structural integrity for a reasonable operation lifetime. In our analysis, a windowed neutron source for such prototype will be analysed, made of the above-mentioned fusion first wall materials in order to explore their performance as structural material for ADS beam windows.

In Section 2, the analysis methodology is presented and discussed. In Section 3, the thermo-mechanical stress estimates of both targets are calculated. Section 4 presents the discussion about the effect of irradiation damage on material properties and their integrity along the fuel cycle of an ADS. Finally, our conclusions are summarized in Section 5.

## 2. Methodology

The design of a spallation neutron source is a multidisciplinary process that must address all physical phenomena that take place in the target and their inter-relation. A brief description of the physical processes to be considered in the analysis of a neutron source is depicted in Fig. 1.

This analysis should include nuclear, thermo-mechanical and material aspects. The radiological aspect is less critical due to the small volume of the window and the small amount of material to manage. Concerning material issues, it must be noted that the required window lifetime will be, at best, of the order of a time span between fuel loads, what implies that the corrosion effects can likely be neglected in comparison with the phenomena related to thermo-mechanical stresses and irradiation damage. Corrosion effects in iron-based steels has been extensively studied and reported with lead and lead–bismuth coolants in the temperature operational range of the considered designs (Sapundjiev et al., 2006b). In the case of the vanadium alloy (V–Cr–Ti), corrosion in molten lead has been reported less aggressive than in iron-based steels when oxygen impurities are limited (Smith et al., 2000; Karatushina and Beznosov, 1995). In the case of titanium alloys, corrosion could be an inconvenience, though the amount of experimental data is scarce. Titanium solubility in lead–bismuth is higher than for steels (Rosenblatt and Wilson, 1970).

The window design of spallation targets for ADS must be mainly focused in the analysis of nuclear and thermo-mechanical aspects, and the study of the material behaviour and its properties evolution under irradiation. For such purpose, we have developed a simulation tool based on the coupling of reference codes for every of these aspects, as shown in Fig. 2. The nuclear variables are estimated by the Monte Carlo code MCNPX (Waters, 2002), extensively used and validated for the analysis of medium and low energy physics involved in the design of ADS and neutron sources. Its output provides relevant information related to the neutron yield and neutron flux obtained by the spallation process and the hadronic interaction within the target. Other relevant data given by this code are the radiation damage and the energy deposition in the target and the window, that are the input required for the thermal-hydraulic analysis done with the multipurpose computational fluid dynamics (CFD) code FLUENT (Operational Office, 2006) to obtain the temperature field in the window. This temperature field is analysed by the mechanical code ANSYS (FLUENT, 2005) to estimate the mechanical stresses in the window. An MCNPX module, HTAPE3X, is used to determine the spallation products and the proton damage cross-section that is used to obtain the basic damage parameters from proton damage.

The results of the FLUENT and ANSYS codes depend on the MCNPX results. The MCNPX results have some sensitivity on the choice of the nuclear data library (JEFF, ENDF, JENDL), on the temperature selected to determine nuclear data with the NJOY code processed nuclear data, on the intranuclear cascade model (BERTINI, ISABEL, CEM), and on the inclusion of material impuri-

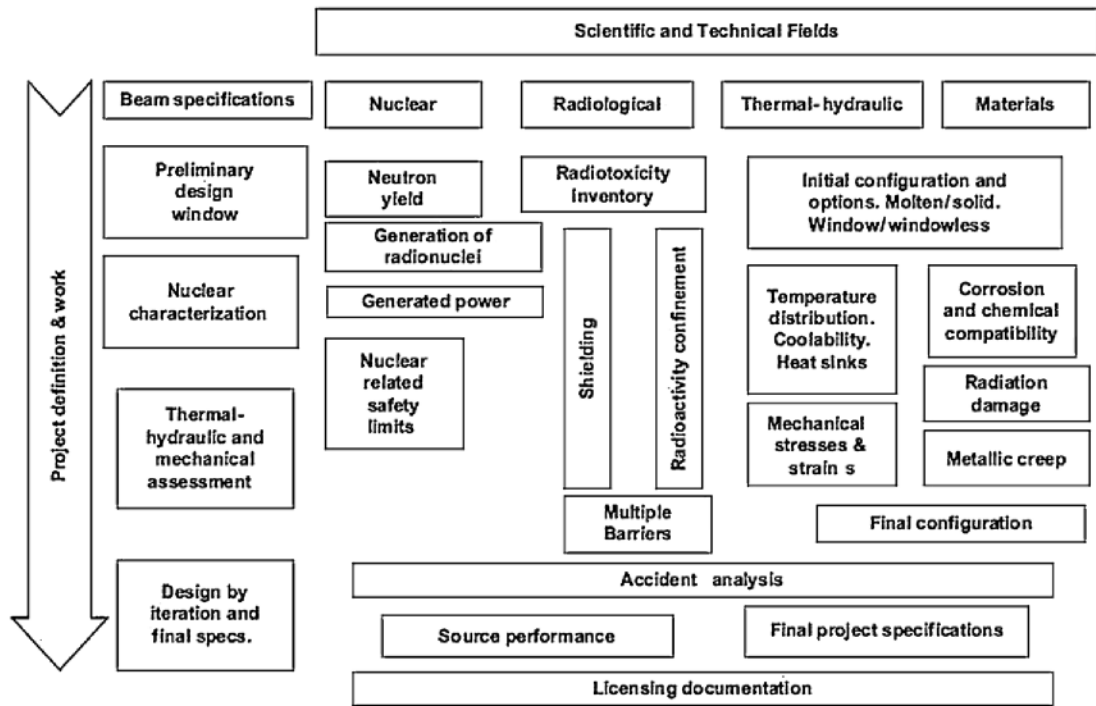


Fig. 1. Aspects in the design of a neutron source and their relation.

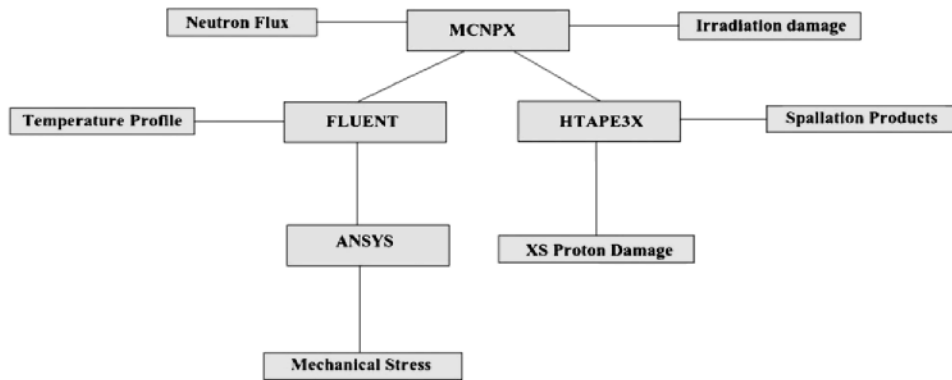


Fig. 2. Code system used in our integral simulation.

ties. Furthermore, Monte Carlo results are associated with statistical errors.

In our estimates, we have analysed carefully all the mentioned effects. In the case of using different intranuclear

cascade model, one of the most critical issues when spallation reactions are calculated, we have found less than 3 °C discrepancies in the maximum temperature in the window material between the three mentioned models, what implies less than

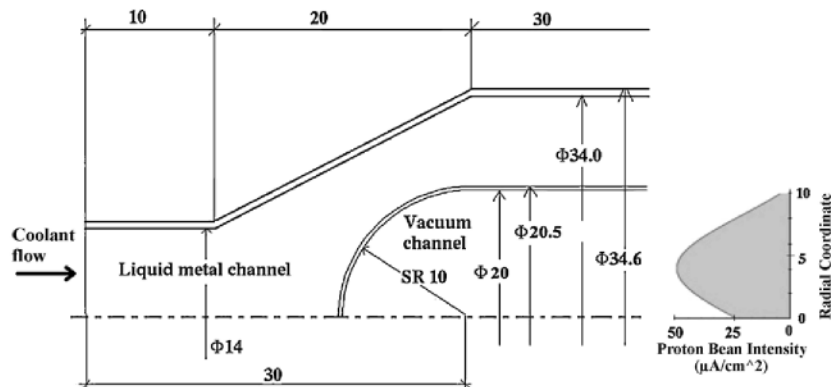


Fig. 3. Design of the PDS-ADS spallation target.

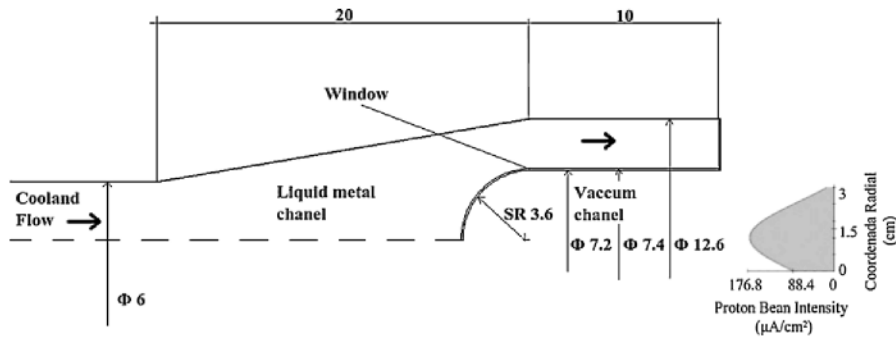


Fig. 4. Design of the XT-ADS neutron source in the windowed alternative.

2% error taking into account the thermal magnitudes of our design.

The main criterion that should be fulfilled in the design of the window of any spallation target is its structural integrity during a whole burn-up cycle of the ADS. During burn-up, a decrease in the neutron multiplication coefficient ( $k_{eff}$ ) is produced. The thermal power in the subcritical core is then kept at nominal level by an increase in the proton beam intensity. Therefore, the design analysis should be done under the most unfavourable conditions, i.e., with the maximum proton beam intensity at the end of the burn-up cycle. That operating conditions will be the most demanding at the end of the burn-up cycle, when the proton beam intensity and the integrated radiation damage are maximum, what implies maximum thermo-mechanical stresses and material weakness.

The spallation target for the PDS-XADS project is depicted in Fig. 3. The target window has a thickness of 2.5 mm with a static pressure of 10 bar. Such hydrostatic pressure has been introduced to take into account the molten metal coolant column height.

In the case of the XT-ADS at the IP-EUROTRANS project, its original concept has a windowless target as reference design. Nevertheless, for our analysis we have analysed a window case, adapted to the requirements for such source with the configuration shown in Fig. 4, with a 7.2 cm diameter for the beam tube of 1 mm thickness, with a total outer diameter of 12.6 cm to fit into the XT-ADS core and a hydrostatic pressure of 10 bar as well. The window thickness has been calculated in this case to fulfil design criteria limitation, mainly thermo-mechanical stress. The proton beam density in this case is three times higher than the case of the PDS-XADS, mainly because the beam spot is smaller. This increase in proton beam intensity involves a higher energy deposition and the reduction of the window thickness becomes a must to reduce temperature gradients and hence thermo-mechanical stresses.

The rationale for the choice of the spallation target material is imposed by several criteria and performance results, as neutron yield, lead-bismuth eutectic being the state-of-the-art concepts, especially if integrated in accelerator driven systems. The material choice for the window has a negligible effect in the neutron target yield, what opens the possibility to make its material selection taken into account thermo-mechanical criteria. In Table 2, a

summary is given of the most relevant thermal and mechanical properties for our window material.

### 3. Thermo-mechanical analysis

There are two additive causes of mechanical stress during the operation in the window of a neutron source in an ADS, namely the hydrostatic pressure due to the coolant flow and coolant column height, and the thermal-gradient-induced stress that will depend on the thermal expansion coefficient of each material and the temperature difference between the inner and outer faces.

The hydrostatic pressure can be taken as constant during the whole burn-up cycle of the ADS as the operational parameters as the coolant flow and levels will be rather stable. In our estimates we have fixed 10 bar for that pressure. The thermo-mechanical stress depends on the energy deposited in the window structure by the proton beam, directly dependant on the beam intensity density. The integral mechanical stress will be more demanding at the end of the burn-up cycle when beam will reach its upper intensity to keep the subcritical system power.

We have calculated the temperature profile in the internal and external surface of the window at the maximum design beam intensity reported for PDS-XADS and XT-ADS (Table 1). The results for both cases are depicted in Figs. 5 and 6 for each window material considered in our analysis. The window is cooled by lead bismuth eutectic, where the neutrons are generated, acting as coolant and target material. The CFD window model assumes the internal surface to be adiabatic and convection heat transfer at the external surface, and includes the energy deposition in the window and the target material provided by the neutronic model. The molten metal flow has a strong influence in the window temperature and its temperature gradients between the internal and external surface. For our window material comparison, we have estimated a pressure loss in the spallation source of 0.1 bar to accomplished with design criteria that can fit in the design of the spallation target loop, what gives a mass flow of 314 and 70 kg/s for the PDS-XADS and XT-ADS target, respectively. The temperatures reached under our reference coolant flow at each case are well below fusion temperatures of each material and compatible with the nominal design of both projects.

**Table 2**  
Properties of the window material options.

Base material	Ti-Al-V	V-Cr-Ti	T-91
Composition	Ti-92.5, Al-5, V-2.5	V-92, Cr-4, Ti-4	Fe-90, Cr-8.32, Mo-0.86, Mn-0.48, V-0.2
Density (kg/m <sup>3</sup> )	4500	6072	7800
Conductivity (W/m °C)	7.9	28.1	28.8
Fusion temperature (°C)	1668	1910	
Thermal expansion coefficient (μm/m °C)	8.8	9.8	13
Young modulus (Gpa)	118	123	175
Yield strenght (Mpa)	700	250	175
Atom displacement threshold energy (eV)	40	40	40
Maximum radiation damage (dpa)	34	10	37

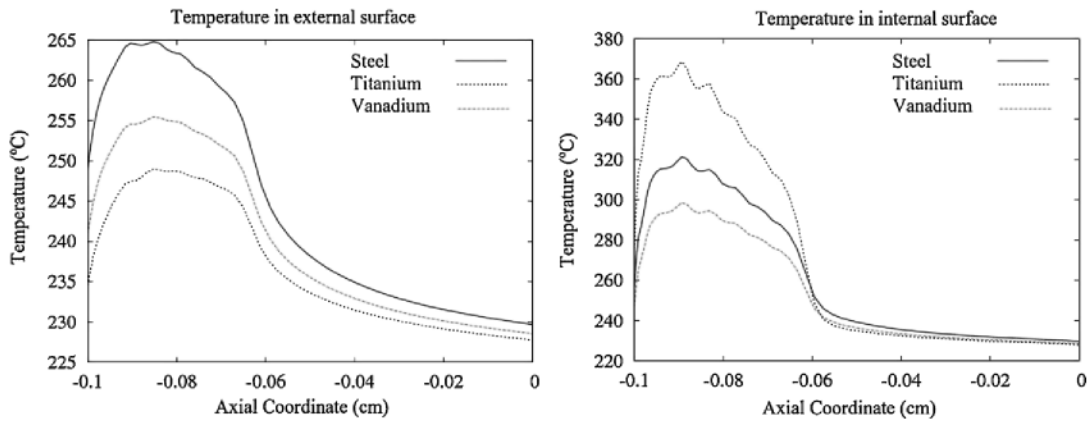


Fig. 5. Influence of the material in the temperature profile at the external and internal surfaces of the PDS-XADS design window. (Origin in the centre of the hemispherical window, proton beam with negative axial direction).

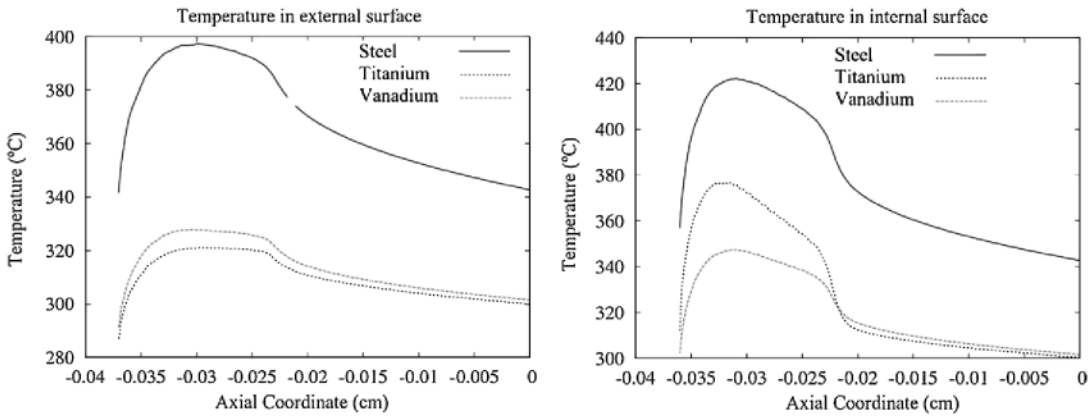


Fig. 6. Influence of the material in the temperature profile at the external and internal surfaces of the XT-ADS design window. (Origin in the centre of the hemispherical window, proton beam with negative axial direction).

Temperature gradients produce thermo-mechanical stress in the window according with the results depicted in Fig. 7, where the temperature differences between the internal and external surface are represented for each material. The corresponding Von Misses (ANSYS, 2003) stress profiles are shown in Figs. 8 and 9. Such profiles depend on aspects as the material thickness and the thermal expansion coefficient. In our comparison, the higher thickness of the PDS-XADS window implies higher mechanical stress than for the XT-ADS case. The different thermal expansion coefficient for each material produces different mechanic behaviours versus the

temperature gradients shown below, what gives that steel is the material that is working closer to its yield strength. Those yield strengths are summarised in Tables 3 and 4 for our material selection based on titanium, vanadium alloys and T91 steel.

The mass flow at each case corresponds to a maximum molten metal speed (note that the flow cross-section is variable) of 1.5 m/s for the fix pressure losses. This flow velocity is compatible with a recommended 2 m/s to avoid excessive corrosion effects (Allen, 2007). In any case, the window must be replaced a few times during the burn-up cycle due to the severe particle irradiation damage, as

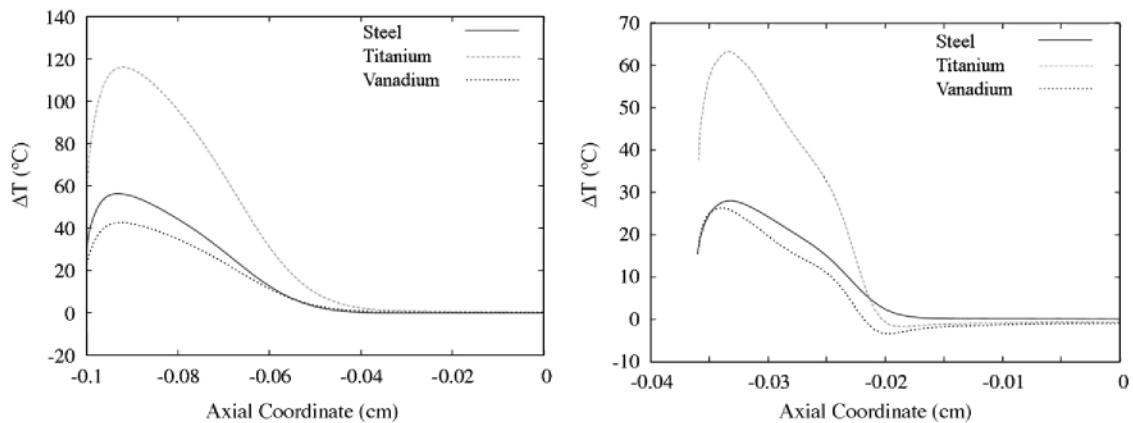


Fig. 7. Temperature differences between the internal en external surface of the window target for the PDS-XADS and XT-ADS with our different materials. (Origin in the centre of the hemispherical window, proton beam with negative axial direction).

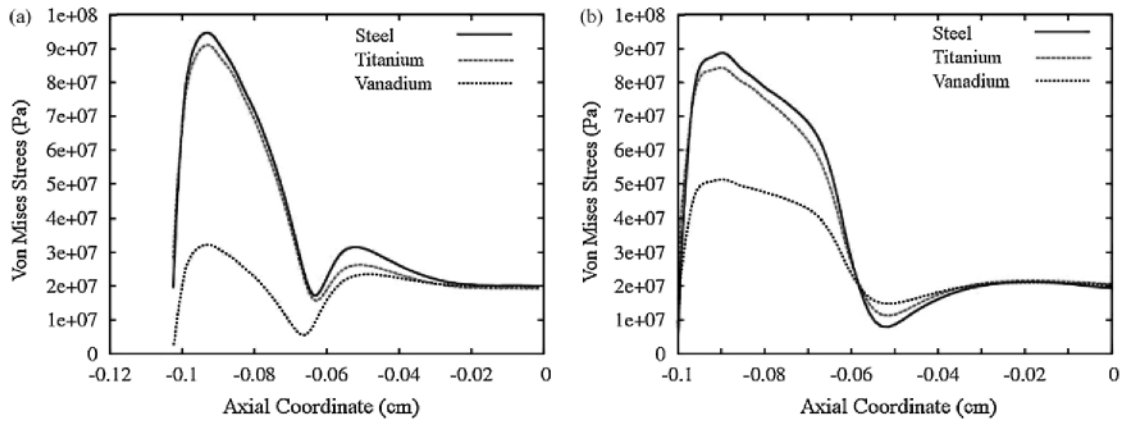


Fig. 8. Von Misses stress profile at the external (a) and internal (b) surface of the PDS-XADS window for the selected materials.

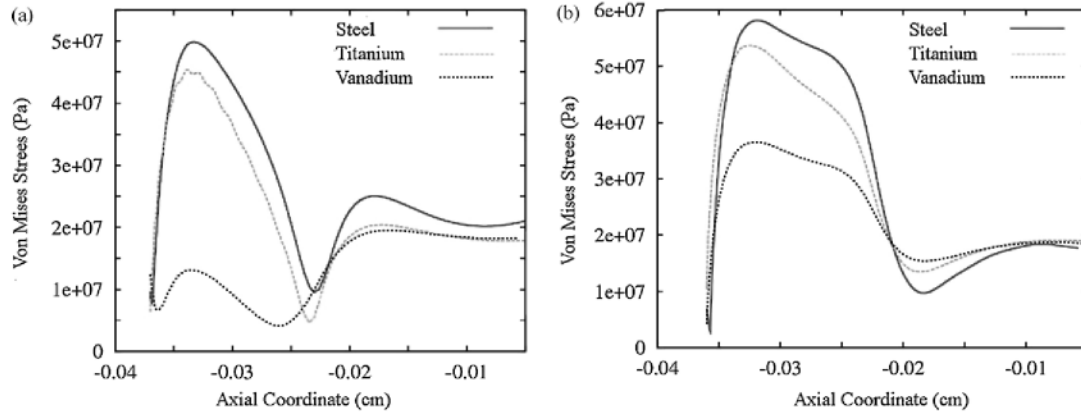


Fig. 9. Von Misses stress profile at the external (a) and internal surface (b) of the XT-ADS window for the selected materials.

**Table 3**  
Summary of thermo-mechanical material analysis for the PDS-XADS window.

	T91	Ti-Al-V	V-Cr-Ti
Coolant mass flow (kg/s)	314	314	314
Coolant max. speed (m/s)	<1.5	<1.5	<1.5
Inlet coolant temperature (°C)	167	167	167
Maximum temperature (°C)	321	368	298
Temperature differences (°C)	56	119	43
Maximum Von Misses stress (Mpa)	95	91	52
Yield strength (Mpa)	175	700	200
Stress ratio	0.55	0.13	0.261

we will show later, what minimise the contribution foreseen for corrosion phenomena to the structural integrity of the window. The relevant cooling and mechanical data are shown in Tables 3 and 4 for both systems. The maximum mechanical stresses are well below the yield strength in all cases.

For the PDS-XADS window, the steel window based on T91, the mechanical stress reach more than 50% of the yield strength. This

**Table 4**  
Summary of thermo-mechanical material analysis for the XT-ADS window.

	T91	Ti-Al-V	V-Cr-Ti
Coolant mass flow (kg/s)	70	70	70
Coolant max. speed (m/s)	<1.2	1.2	1.2
Inlet coolant temperature (°C)	167	167	167
Maximum temperature (°C)	422	376	347
Temperature differences (°C)	24	55	19
Maximum Von Misses stress (Mpa)	58	53	36
Yield strength (Mpa)	175	700	200
Stress ratio	0.33	0.08	0.18

stress, the high operation temperature and the foreseen irradiation damage during burn-up can produce risk of mechanical fluence. To avoid this fact, a reduction in the thickness of the window is recommended, what will reduce the thermal stress, because of smaller temperature differences. For the titanium and vanadium windows, mechanical stresses are below one third of the yield strength, what means that mechanical fluence is not expected and the structural integrity of the window can be taken for granted at nominal conditions.

Table 4 shows the main results for the XT-ADS window with the selected materials. In every case, the maximum temperature is well below the fusion point. The coolant velocity is limited to 1.2 m/s (Sapundjiev et al., 2006a), what will be good for mitigating erosion and corrosion phenomena will not be critical for the window lifetime. In the case of the steel window, mechanical fluence could appear as the expected stress is slightly higher than one third of its yield strength. titanium and vanadium windows show low stress ratio and its structural integrity can be taken for granted

#### 4. Irradiation damage

The maximum stress found in our calculations is safely far from the yield strength for the window of the spallation targets we have studied, even at the maximum proton beam intensity. Nevertheless, the irradiation damage during operation will affect the material mechanical properties. Irradiation, both by protons and neutrons, induces cascades of defects that after their diffusion generate a progressive accumulation of defects of different types and concentrations that finally will produce embrittlement and swelling

**Table 5**  
Irradiation damage in the PDS-XADS window for a 2-year 4.05 mA beam cycle.

	T91	Ti-Al-V	V-Cr-Ti
Hydrogen production (ATM/2-y)	5456	4699	4775
Helium production (TM/2-y)	3595	3120	2930
Neutron damage (dpa/2-y)	38	32	40
Proton damage (dpa/2-y)	25	18	18
Total irradiation damage (dpa/2-y)	64	51	60
Ratio neutron/proton damage	1.52	1.77	2.22
Allowable radiation damage (dpa)	10	37	34
Window removals per burn-up cycle	7	2	2

that can cause the window breakage. Energy of particles, flux and fluence are key parameters.

The estimate of the irradiation damage in the beam window is one of the key aspects to be taken into account for the design of the operation and maintenance procedure for any ADS. The evaluation of the irradiation damage has several uncertainties, from the main microscopic magnitudes to be extrapolated to the macroscopic consequences, and it certainly will depend on the window material and the burn-up cycle evolution.

The irradiation damage of the beam window can be subdivided into three main components: (I) source induced proton damage, (II) induced neutron damage, and (III) intranuclear reactions damage (fission and spallation). In our calculations, we have estimated separately the proton damage (Lu, 2006), including spallation reactions, and induced neutron damage.

Irradiation damage in the window depends on the beam intensity density during burn-up. In the case of the PDS-XADS, power cycles are 2-years long with a  $k_{eff}$  of 0.96 at start-up, and 0.932 at the end of the cycle (Cinotti et al., 2001) due to the transmutation of fissile material and the generation of fission products. The nominal proton beam current evolves from 2.6 mA at start-up to 5.5 mA at the end of the cycle to keep the core power. Assuming a linear beam intensity evolution, the average beam intensity is 4.05 mA, what has been adopted as reference value for our full cycle irradiation damage estimate of the window. The results are depicted in Table 5. The particle irradiation damage makes compulsory the replacement of the beam tube/window 7 times per cycle (approx. every 3 months) in the case of steel and 2 times per cycle (approx. every year) for a titanium and vanadium window. The window material becomes an important issue for the maintenance strategy in the operation of any ADS. Moreover, the maximum irradiation damage for titanium and vanadium is based on actual experimental data with probes that keep excellent mechanical properties, what makes our removal ratio conservative.

Regarding the XT-ADS spallation source, its preliminary design is based on the MYRRHA project (Abderrahim et al., 2001), and its burn-up cycle should be the same as the proposed for MYRRHA, 90 days, with a 30 days fuel recharge period that could be used to remove the beam window. The  $k_{eff}$  will shift from 0.96 to 0.945 (Abderrahim et al., 2001), with a nominal beam intensity ranged

**Table 6**  
Irradiation damage in the XT-ADS-like window for a 90 days 2.16 mA fuel cycle.

	T91	Ti-Al-V	V-Cr-Ti
Hydrogen production (appm/90-d)	2712	2376	2438
Helium production (appm/90-d)	1793	1589	1501
Neutron damage (dpa/90-d)	6.7	5.7	6.7
Proton damage (dpa/90-d)	13.6	10	10.8
Total irradiation damage (dpa/90-d)	20.4	15.7	17.6
Ratio neutron/proton damage	0.49	0.57	0.62
Allowable radiation damage (dpa)	10 (Dai et al., 2003)	37 (Sapundjiev et al., 2006c; Dai et al., 2003)	34 (Grosse et al., 2006; Sapundjiev et al., 2006c; Dai et al., 2003; Duncan et al., 1981)
Window removals per burn-up cycle	0.5	>2	2

from 1.82 to 2.5 mA. We have assumed in our integral analysis a beam current of 2.16 mA. Our simulation results are summarised in Table 6.

It is worth explaining that the ratio between neutron and proton damage is significantly different between both cases due to the different beam spot radius given in the specifications of the PDS-XADS and XT-ADS prototypes. The higher beam current density (28.9 vs. 58.1 mA/cm<sup>2</sup>) makes proton irradiation a critical issue in the latter, what has boosted the windowless option in the actual XT-ADS project, though the application of fusion first-wall alloys, as the proposed in this paper, could be an alternative for such design under the present operation requirements.

The results presented in the following are those of primary damage such as displacement per atom (dpa) and production of He and H gases in the materials. These are the basic input values to correlate with the mechanical properties of the material under irradiation. We certainly understand that not in all cases such correlation is completely well explained from a combination of simulation and experimental evaluations, and it is simply a good starting point to qualitatively get some general conclusions, appreciated from the macroscopic effects. Steel is more sensitive to proton damage, as can be realised from the lower neutron/proton damage ratio. A very important fraction of the irradiation effect is produced by protons, especially in the case of XT-ADS, what implies a higher integrated irradiation damage in the steel window that is even more appreciated in that case. This fact, and the lower radiation damage strength, suggests that the steel window is unlikely to withstand a full burn-up cycle in ADS. Titanium and vanadium windows undergo irradiation damage lower than their irradiation damage strength and they would withstand a full power fuel cycle without removal, even under our conservative assumptions.

## 5. Conclusion

Spallation neutron sources are a very challenging component of many scientific and technological facilities, either for material testing under irradiation, or for their application as neutron provider for subcritical accelerator driven system. For the latter, there are international research programs in progress that show how one of their main show-stoppers is focused on the reliability of the window that serves as separator between the void accelerator beam tube and the liquid spallation target material where neutrons are produced by the impinging accelerated protons. In this paper the problem of material selection has been addressed, following an integral scheme that takes into account nuclear, thermo-hydraulic and mechanical aspects. The material selection alternatives for such beam window based on fusion first-wall materials (vanadium and titanium alloys) has been applied to the concepts that has been proposed in the framework of the European Union Framework Program for Research and Development under the umbrella or EURATOM, namely the PDS-XADS (Cinotti et al., 2004; IP-EUROTRANS, in press) and the XT-ADS (Knebel et al., 2006).

We have shown how a beam window for both systems is feasible from the thermal point of view as their cooling capabilities keep their temperatures safely under their structural material fusion temperature, with reasonable pressure losses and coolant velocities that would produce low corrosion effects.

The temperature gradients that are produced by the energy deposition in the window, linearly depending on the beam intensity density, induce mechanical stress that in every case is well below the yield strength of each material. Nevertheless, maximum stress in the case of steel can be higher than 30% of the yield strength, what can produce material fluence at the relatively high operation temperature. Titanium and vanadium alloys are far from that case and their structural integrity can be taken for granted. As a result of our analysis, we would recommend to consider titanium and vanadium alloys as main choices for accelerator driven system (ADS) beam window design.

Last but not least, the irradiation damage analysis becomes the most important issue for the material selection in the beam window. According to our estimates, a steel window can be discarded due to the limited time (approx. 3 months) that can withstand the foreseen irradiation damage. Titanium and vanadium alloys have a better behaviour under irradiation, and seem more suitable as structural material for the beam window of an ADS. Concerning irradiation damage, we have based our assumptions in limiting values corresponding to neutron experimental data due to the lack of proton damage experimental data. We believe that experiments to evaluate such proton damage should be considered in the future to assess more accurately our estimations.

## References

- Abderrahim, H.Ait., et al., 2001. MYRRHA: a multipurpose accelerator driven system for research and development. *Nuclear Instruments and Methods A* 463, 487–494.
- Allen, T.R., 2007. Lead-Cooled Fast Reactor Systems and the Fuels and Materials Challenges. *Hindawi Publishing Corporation Science and Technology of Nuclear Installations*, vol. 2007, 11 pp. doi:10.1155/2007/97486 (review article).
- ANSYS User's Manual, 2003. Release 8.1. USA: ANSYS Inc.
- Bauer, 2001. The ISIS solid plate target.
- Bowman, C., Jameson, R., Lawrence, G., 1992. Accelerator driven transmutation technology for incinerating radioactive waste and for advanced application to power production. *Nuclear Instruments and Methods B* 68, 474.
- Cinotti, L., et al., 2001. XADS Pb-Bi Cooled Experimental Accelerator Driven System – Reference Configuration – Summary Report, ANSALDO ADS1SIFX0500, Rev 0, ANSALDO, Technical Report, Technical specification and target unit interfaces (LDE and gas cooled concepts, window and windowless options', 30.10.2001, ADS 43 THX 010, FIKW-CT-2001-00179.
- Cinotti, L., Giraud, B., Ait Abderrahim, H., 2004. The experimental accelerator driven system (XADS) designs in the EURATOM 5th framework programme. *Journal of Nuclear Materials* 335, 148–155.
- Dai, Y., Jia, X.J., Farrell, K., 2003. Mechanical properties of modified 9Cr-1Mo (T91) irradiated at <math>300\text{ }^\circ\text{C}</math> in SINQ Target-3. *Journal of Nuclear Materials* 318, 192–199.
- Duncan, D.R., Puigh, R.J., Opperman, E.K., 1981. Titanium alloy tensile properties after neutron irradiation. *Journal of Nuclear Materials* 104, 919–923.
- EU Framework Program, [http://cordis.europa.eu/fp7/euratom-fission/p-and-t\\_en.html](http://cordis.europa.eu/fp7/euratom-fission/p-and-t_en.html).
- FLUENT 6.2 User's Guide, January 2005.
- Grosse, M., Dai, Y., Van Petegen, S., 2006. Irradiation-induced structural changes in martensitic steel T91. *Journal of Nuclear Materials* 356, 112–117.
- IP-EUROTRANS project <http://cordis.europa.eu/fetch?CALLER=FP6.PROJ&ACTION=D&DOC=1&CAT=PROJ&QUERY=011f36d217c9:f7a5:5a168663&RCN=85226>.
- Karatushina, I.V., Beznosov, A.V., 1995. Experimental investigations for substantiation of the concept of a thermonuclear reactor cooled with Lead-based liquid metals. *Atomic Energy* 78, 4.
- Knebel, J.U., Ait Abderrahim, H., Cinotti, L., Mansani, L., Delage, F., Fazio, C., Giot, M., Giraud, B., González, E., Granget, G., Monti, S., Mueller, A.C., 2006. European research programme for the transmutation of high level nuclear waste in an accelerator driven system (EUROTRANS). In: *Proceedings of the Ninth International Exchange Meeting on Partitioning and Transmutation*, Nimes, France, September 25–29.
- Lu, W., 2006. The NCSU radiation damage database; proton-induced damage energy and application to radiation damage at SINQ. *Journal of Nuclear Materials* 356, 280–286.
- Mantha, V., et al., 2007. Thermal-hydraulic studies related to the design of LBE neutron spallation target for accelerator driven systems. *Nuclear Engineering and Design* 237, 607–617.
- Nifenecker, H., David, S., 2001. Basics of accelerator driven subcritical reactor. *Nuclear Instruments & Methods in physics research A* 463, 428–467.
- Operational Office, 2006. Boeretang 200, BE-2400 MOL – Scientific Report 2006, Neutronic design of the XT-ADS core.
- Park, W.S., Song, T.Y., Lee, B.O., Park, C.K., 2002. A preliminary design study for the HYPER system. *Nuclear Engineering and Design* 219, 2007–2223.
- Prakash, K.A., et al., 2006. Thermal-hydraulics of the spallation target module of an accelerator driven sub-critical system: a numerical study. *Heat and Mass Transfer* 49, 4633–4652.
- Rosenblatt, G., Wilson, J.R., 1970. The solubility of several transition metals in liquid lead-bismuth eutectic. In: *Draley, J.E. et al., Corrosion by Liquid Metals* Plenum, New York, pp. 469–477.
- Rubbia, C., et al., 1995. Conceptual Design of a Fast Neutron Operated High Power Energy Amplifier. CERN/AT/95-44 (ET).
- Rubbia, C., et al., 2004. Neutronic analyses of the TRADE demonstration facility. *Nuclear Science and Engineering* 148, 103–123.
- Sapundjiev, D., Van Dyck, S., Bogaerts, W., 2006a. Liquid metal corrosion of T91 and A316L materials on Pb-Bi eutectic at temperatures 400–600 °C. *Corrosion Science*, 577–594.
- Sapundjiev, D., Van Dyck, S., Bogaerts, W., 2006b. Liquid metal corrosion of T91 and A316L materials in Pb-Bi eutectic at temperatures 400–600 °C. *Corrosion Science* 48, 577–594.
- Sapundjiev, D., Al Mazouzi, A., Van Dyck, S., 2006c. A study of the neutron effects on the susceptibility to embrittlement of A316L and T91 steels in lead-bismuth eutectic. *Journal of Nuclear Materials* 356, 229–236.
- Sasa, T., et al., 2004. Research and development on accelerator-driven transmutation system at JAERI. *Nuclear Engineering and Design* 230, 209–222.
- Schikorr, W.M., 2001. Assessment of the kinetic and dynamic transient behaviour of sub-critical systems (ADS) in comparison to critical reactor systems. *Nuclear Engineering and Design* 210, 95–123.
- Smith, D.L., Billone, M.C., Natesan, K., 2000. Vanadium-base alloys for fusion first-wall/blanket applications. *International Journal of Refractory Metals and Hard Materials* 18, 213–224.
- Song, T.Y., Tak, N.L., 2003. Optimal design of HYPER target system based on the thermal and structural analysis of Pb-Bi spallation target and beam window. *Annals of Nuclear Energy* 30, 1297–1308.
- Sordo, F., Leon, P.T., Martínez-Val, J.M., 2007. Nuclear and thermal-hydraulics analysis of spallation window targets. *Nuclear Instruments and Methods for Physics Research A* 574, 232–243.
- US-DOE, 1999. A roadmap for developing Accelerator Transmutation of Wastes. A Report to Congress. DOE/RW-0519.
- Vladimirov, P., Möslang, A., 2006. Irradiation conditions of ADS beam window and implication for window material. *Journal of Nuclear Materials* 356, 287–299.
- Waters, L.S., 2002. MCNPX User's Manual, Version 2.3.0, Report LA-UR-02-2607, Los Alamos National Laboratory, Los Alamos, NM.