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ASSESSMENT OF ALKALI METAL COOLANTS FOR THE ITER BLANKET*

by

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June 1994

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Paper to be presented at the 3rd International Symposium on Fusion Nuclear Technology, Los Angeles, CA, June 27-July 1, 1994

*Work supported by the U.S. Department of Energy, Office of Fusion Energy, under Contract W-31-109-Eng-38.

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ASSESSMENT OF ALKALI METAL COOLANTS FOR THE ITER BLANKET*

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ABSTRACT

The blanket system is one of the most important components of a fusion reactor because it has a major impact on both the economics and safety of fusion energy. The primary functions of the blanket in a deuterium/tritium-fueled fusion reactor are to convert the fusion energy into sensible heat and to breed tritium for the fuel cycle. The Blanket Comparison and Selection Study, conducted earlier, described the overall comparative performance of different blanket concepts, including liquid metal, molten salt, water, and helium. This paper will discuss the ITER requirements for a self-cooled blanket concept with liquid lithium and for indirectly cooled concepts that use other alkali metals such as NaK.

The paper addresses the thermodynamics of interactions between the liquid metals (e.g., lithium and NaK) and structural materials (e.g., V-base alloys), together with associated corrosion/compatibility issues. Available experimental data are used to assess the long-term performance of the first wall in a liquid metal environment. Other key issues include development of electrical insulator coatings on the first-wall structural material to minimize MHD pressure drop, and tritium permeation/inventory in self-cooled and indirectly cooled concepts. Acceptable types of coatings (based on their chemical compatibility and physical properties) are identified, and surface-modification avenues to achieve these coatings on the first wall are discussed. The assessment examines the extent of our knowledge on structural materials performance in liquid metals and identifies needed research and development in several of the areas in order to establish performance envelopes for the first wall in a liquid-metal environment.

INTRODUCTION

Liquid metals are being considered as coolant/tritium-breeding blanket for International Thermonuclear Experimental Reactor (ITER). The liquid metals include lithium (Li), lead-0.7 wt.%lithium (Pb-Li), and sodium-78wt.% potassium alloy (NaK). The structural materials considered for the first wall application are Type 316 austenitic stainless steel and V-5 wt.%Cr-5 wt.% Ti alloy. In the fusion application, the structural material of the system must be compatible with the liquid metal and must also maintain structural integrity for long times while exposed to moderately elevated temperatures, thermal cycling, possibly intense irradiation, and, also be amenable to low MHD losses during the flow in the magnetic field.

*Work supported by the U.S. Department of Energy, Office of Fusion Energy, under Contract W-31-109-Eng-38.

Some of the key performance variables of importance in application of liquid metals in first wall/blankets are:

- (a) Liquid Metal Compatibility
 - Corrosion due to metallic element mass transfer
 - Non metallic element (O, C, and N) mass transfer
 - Influence of corrosion on mechanical properties
- (b) Minimization of MHD Pressure Drop
 - Electrical insulator candidates
 - Fabrication of coatings
 - Maintenance and repair of coatings
 - Degradation under irradiation
 - Coating effect on structural material properties
- (c) Tritium Inventory and Transport
 - Hydrogen/tritium solubility in liquid metal
 - Hydrogen/tritium distribution between liquid metal and structural material
 - Tritium recovery methods
 - Effects on structural materials
- (d) Safety Related Issues
 - Oxidation characteristics of structural materials
 - Liquid metal handling

LIQUID METAL COMPATIBILITY

Metallic Element Transfer: In general, structural materials can undergo a variety of interactions upon exposure to liquid metals. The extent of interaction depends upon the conditions of temperature, temperature gradient, liquid-metal velocity and purity, alloy composition, and the materials of construction of the containment system. In the case of ITER, the structural materials considered are Type 316 stainless steel and V-5 wt.%Cr-5 wt.%Ti alloy. The liquid metals of interest are NaK, Li, and Pb-Li eutectic mixture. A comparison of the physical properties of the three liquid metals is given in Table 1.

The peak temperature for the liquid metal in ITER is expected to be $\sim 400^{\circ}\text{C}$ with a maximum temperature gradient of $\sim 100^{\circ}\text{C}$ around the loop. Under these conditions the metallic element mass transfer between the structural materials and the liquid metal is predominantly determined by the kinetics of leaching of the alloy constituents of the materials, dictated by the solubility of the alloy constituents in the liquid metal and the temperature dependence of the solubility values. In some instances, the substrate constituents can react with nonmetallic elements such as oxygen, carbon, and nitrogen to form stable compounds which can alter the corrosion degradation of the materials. Table 2 lists the available data on the solubility values at 400°C for several substrate elements in NaK, lithium and Pb-0.7 wt.% Li. Also shown are the values for constant B in the solubility expression which determines the temperature dependence of the solubility. The information in Table 2 shows that the solubility values are small for the primary constituents (Fe, Cr, and Ni) of stainless steel in NaK. Further, the constituents of V-5Cr-5Ti alloy will have a tendency to develop oxide scales in NaK, that is purified by a cold-trapping technique. In lithium, the solubilities of Fe and Cr are small but that

of nickel is somewhat higher. As a result, the extent of corrosion of stainless steel in lithium involves loss of nickel from the steel and development of Fe-Cr ferritic layer in the surface regions of the lithium-exposed steel. Elements such as V and Ti tend to form respective nitrides in cold-trapped lithium. In Pb-0.7 wt.%Li, the solubility values for Fe, Cr, and Ni are higher with nickel exhibiting a substantial increase when compared to that in lithium. The data also show that the dependence of solubility values is less sensitive to temperature in Pb-Li (when compared with those in Li) indicating a potential for higher corrosion rates even at lower temperatures. An assessment of corrosion loss rates for austenitic stainless steel and V alloy in several liquid metal environments is shown in Fig. 1 as a function of reciprocal temperature.¹⁻⁷ The data show that at a service temperature of 400°C, corrosion losses for stainless steel are ~0.07, 2, and 20 $\mu\text{m}/\text{yr}$ in NaK, Li, and Pb-Li environments, respectively. At 400°C, the values for V alloy are 0.3 and 5 $\mu\text{m}/\text{yr}$ in NaK and Li environments, respectively. At present data are not available for V alloy exposed to Pb-Li environments.

Nonmetallic Element Transfer: Nonmetallic elements, such as oxygen, carbon, and nitrogen are known to migrate in structural-material/liquid-metal systems as a result of chemical activity differences. A detailed analysis has been published earlier on the thermodynamics of nonmetallic impurity elements in liquid metals with emphasis on purification of the liquid metals and chemical compatibility of candidate structural materials.^{8,9} Cold trapping, hot (getter) trapping, and molten-salt extraction are the three purification methods presently available to achieve the desired low concentrations of nonmetallic elements in liquid alkali metals and maintain them at low levels for extended periods of time in dynamic loop systems. The effectiveness of each method in achieving the desired purification varies for different nonmetallic elements present in the liquid and also differs for the same nonmetallic element in different liquid alkali metals. In general, the complexity of the purification system and the relative cost of purification increases as one goes from cold trapping to the molten-salt extraction method. Table 3 shows impurity concentrations (wpm) in sodium (also applicable to AK) and lithium after treatment with various purification methods.

Figure 2 shows a plot of solubility values excerpted from literature for nonmetallic elements in liquid Na, Li and Pb-0.7 wt.%Li as a function of temperature. The values for Na can be used in the assessment of NaK. The primary impurity of concern in NaK is oxygen whose level can be controlled by the cold-trap method. Carbon and nitrogen concentrations in NaK are too low to be of concern, especially in the temperature range of interest for ITER. The solubility curves for nonmetallic elements in liquid lithium indicate that concentrations of ~30, 800, and 3800 ppm for oxygen, carbon, and nitrogen can be achieved at a cold-trap temperature of ~200°C. The high concentrations of carbon and nitrogen have been of concern in the compatibility of structural materials in liquid lithium environment, especially at temperatures in excess of 450°C.

Figures 3 and 4 show the temperature dependence of the minimum oxygen concentration in sodium/NaK and lithium, respectively, for oxide formation on several metals of interest for ITER; Fig. 5 depicts the thermodynamic stability of nitrides of several structural metals with respect to nitrogen concentration in a lithium environment. From a knowledge of the distribution coefficients and the initial concentrations of nonmetallic elements in the solid and the liquid, one can assess the tendency for nonmetallic element transfer, i.e., solid to liquid or liquid to solid. One can then evaluate the types of nonmetallic element interaction that are likely to occur and their consequences for material behavior. Figure 6 shows the temperature dependence of the nitrogen concentration in lithium that will result in formation of metal nitrides in a lithium environment.

The major effects that are likely to occur in solid-metal/liquid-metal systems with large distribution coefficients are (a) embrittlement of the solid metal as result of increased interstitial-element concentration and (b) compound formation, i.e., oxide, nitride, or carbide formation, in the surface region of the solid metal. Based on the information developed on distribution coefficients, embrittlement and compound formation are expected with groups IIIB, IVB, and VB metals with regard to oxygen and carbon in liquid sodium or NaK. The analysis suggests that structural metals such as V, Nb, Ti, and Y and their alloys are prone to absorb oxygen and carbon upon exposure to liquid sodium or NaK. Since nonmetallic elements influence the ductile-brittle transition in many metals, the transfer of significant quantities of these interstitial elements to solid metals can have substantial effects on their mechanical integrity. The effect on ductility is particularly critical when thermal cycling and cyclic stresses are considered.

Unlike in sodium and NaK, the distribution coefficients for oxygen in a lithium environment are much less than unity for most metals, except for Y. Two detrimental effects that can occur with low distribution coefficients are (a) reduction of mechanical strength of the metals as a result of loss of interstitial elements to the liquid metal and (b) the grain-boundary penetration of solid metals that contain critical amounts of nonmetallic impurities. In the liquid sodium and NaK environments, austenitic stainless steels will not develop iron or chromium oxides, especially at oxygen levels that correspond to cold-trapped liquid. Under such conditions, the corrosion rates of the materials are fairly small and specific allowances based on temperature, oxygen level in the liquid metal, and time can be made to account for thickness loss. At temperatures of interest for ITER, these rates will be essentially negligible. On the other hand, refractory metals such as V, Ti, and Y will form their respective oxides upon exposure to liquid sodium and NaK at oxygen levels corresponding to cold-trapped liquid. A nonadherent vanadium suboxide and Ti oxide can form on the surface of the V-alloy accompanied by diffusion of oxygen into the substrate. However, at the temperatures of 200-400°C of interest for ITER, the rate of formation of corrosion product as well as diffusion rate for oxygen in the alloy will be small enough to be of concern.

Unlike the behavior of refractory metals in sodium and NaK, the oxides of constituents of both stainless steel and V-Cr-Ti alloys are not stable in lithium at oxygen levels corresponding to a cold-trapped condition. The results also show that, in general, the oxygen transfer will be from the structural metal to lithium and the lack of oxide scale on the metal surface enables other interstitials, nitrogen and carbon, to play a larger role in the corrosion process. The high solubility of nitrogen in lithium coupled with the absence of oxide barriers on metal surfaces exposed to a lithium environment, can result in significant nitridation of materials in lithium. However, at the ITER temperatures the nitridation rates will be low and the hardened nitride layers will be confined to surface regions of the material.

HYDROGEN/TRITIUM EFFECTS

Hydrogen gas dissolves in atomic form in metals, and for dilute solutions of hydrogen in a metal the relationship between the concentration and the partial pressure of hydrogen follows Sieverts' law in which the concentration is directly proportional to square root of the hydrogen partial pressure. The equations relating the Sieverts' constant and temperature for various metal-hydrogen systems and coefficients describing the distribution of hydrogen among various structural metals and lithium

are presented elsewhere.^{9,10} The hydrogen concentrations required for the formation of hydrides of selected metals are large and calculations for hydride formation similar to those for other nonmetallic elements are generally not useful; however, calculations of hydrogen concentrations in various structural and alkali metals for specific hydrogen partial pressures are useful. Figures 7 and 8 show the results of calculations for hydrogen partial pressures of 10^{-3} and 10^{-6} Torr, which are representative of liquid-metal systems. The calculations indicate that the hydrogen distribution ratio between lithium and vanadium is >1000 and that hydrogen concentrations in V-alloy exposed to lithium containing up to 100 wppm hydrogen are considerably smaller than those corresponding to ductile-brittle transition in the alloy.^{11,12} Even though the distribution of hydrogen/tritium between V alloy and liquid metal and its impact on the mechanical properties of the structural metal are known, the effects of insulator coating on the structural alloy on hydrogen/tritium distribution and transport are not known.

ELECTRICAL INSULATOR COATINGS

Extensive thermodynamic calculations have been made to evaluate potential electrical insulator candidates that are (a) chemically compatible in liquid metals and (b) possess adequate insulating characteristics for use as a coating on the first-wall and blanket structural material. A review of available information on the electrical resistivity values for several oxides, nitrides, and oxynitrides showed that a number of oxides (e.g., CaO, MgO, SiO₂, Al₂O₃, MgAl₂O₄) and nitrides (e.g., AlN, Si₃N₄) have resistivities $>10^5$ Ohm-m at temperatures below $\sim 600^\circ\text{C}$. The requirement is that the product of insulator coating electrical resistivity and thickness should exceed a nominal value of 0.01 Ohm m² under operating conditions. This translates to a minimum resistivity value of 10^4 Ohm-m for a coating thickness of 1 μm or a resistivity of 10^3 Ohm-m for a coating thickness of 10 μm . Based on the resistivity values of materials listed above, a coating layer <1 μm in thickness of any of these materials would be adequate from the insulating standpoint, provided the resistivity is not reduced during operation, i.e., by irradiation. Figures 9 and 10 show a comparison of resistance of several oxide and nitride materials, respectively, along with the requirements for ITER application.

Based on chemical compatibility in a liquid sodium-potassium (NaK) alloy and adequate electrical resistivity, materials such as Al₂O₃, CaO, MgO, and Y₂O₃, and nitrides such as AlN and Si₃N₄ will be acceptable. On the other hand, Al₂O₃ is not stable in liquid Li and other candidate oxides and nitrides need to be considered. While the bulk oxides mentioned above are potential candidates, it is difficult to apply them with sufficient bonding onto the first-wall structural material such as Type 316 stainless steel, martensitic steel such as MANET, and V-5wt.%Cr-5wt.%Ti alloy so that the coating will be intact for long times under thermal cycling conditions.

The primary candidate for application in Li is AlN. The thermodynamic stability of several of the nitrides as a function of temperature is shown in Figure 2. Superimposed in this diagram are the lines corresponding to different concentrations of N in Li. It is evident that AlN will be stable in Li with a wide range of N concentrations, whereas Si₃N₄ will be stable up to $\sim 400^\circ\text{C}$ in Li containing >300 ppm N. The calculations show that Ti in the V-alloy can also form a nitride in the same Li but TiN is not viable as an electrical insulator. As a result, it is desirable to aluminize the surface regions of the first-wall alloy and nitride the surface Al to form the insulating layer. Further, Al is favored because a reservoir of Al can be built into the alloy surface by different

techniques and if the coating layer cracks/spalls, the Al-enriched surface could be renitrided by N in Li.

Several possible approaches are being examined to develop an AlN coating on the structural material. Some of these are: (a) prealuminize the surface of the material by a (pack) diffusion process and subsequently convert it to nitride in an external gas atmosphere; (b) a physical vapor deposition process with and without bond coats; (c) chemical vapor deposition process at temperatures between 600 and 900°C; (d) a low temperature method involving sequential reactions; (e) prealuminize the surface of the alloy and convert it to nitride in high-N Li environment; (f) preexpose the material to liquid Al and convert it to nitride in Li; (g) in-situ formation of coating in Li with high thermodynamic activities for Al and N; and (h) prealuminize specimens of structural material and nitride it using N₂ cover gas during Li exposure.

Fabrication of Coatings. The pack process is a well established approach to cover stainless steels and Ni-base alloys with layers of an intermediate phase.¹³ The substrate materials are contacted and heated for 4-12 h at temperatures of ~900°C with a pack of powders. The composition of such powders (e.g., 65 wt.% Al₂O₃, 33 wt.% Al, 2 wt.% NH₄Cl) provides the packing with metallic Al, alumina as filler material, and NH₄Cl as activator. The amount of Al can be reduced by partly replacing with Ni. The Al deposited on the substrate surface diffuses into the subsurface regions of the material, where it forms intermetallic phases as aluminides of Fe or Ni. Since the substrate materials are heated to temperatures close to the annealing range for times sufficient to cause solution processes in the matrix, the materials need a final treatment in order to optimize the structure. The aluminide layers reach thicknesses of 0.025-0.20 mm, depending on the composition of the substrate materials. Figure 11 shows the elemental concentration profiles for Al, V, Cr, and Ti in a V-5Cr-5Ti alloy sample after an aluminizing treatment.¹⁴ The diffusion processes lead to layers of very good adhesion to the substrate. The high temperature of the formation process creates layers that develop compressive stresses at lower temperatures; thus the layers do not contain cracks after the completion of the preparation.

The aluminizing of V and its alloys by means of the "HOT-DIP" process covers the substrate materials at about 800°C in 1-2 minutes with a layer of solid solutions of the substrate metals in Al or of aluminides of the alloying elements.¹⁵ The process requires clean surfaces of the structural materials in order to get a good wetting and well adherent layers. The adherence can be improved by a thermal treatment of the couples at 500 to 600°C. The thermal treatment may result in pores or cavities in the outer part of the aluminide layer. The aluminide layer consists of two parts, the inner one being in contact with the substrate by means of diffusion bonding. The outer one contains pores and cavities due to diffusion effects similar to the Kirkendall effect. The complete layers have a thickness of ~0.2 mm and the inner ones of ~0.12 mm. The aluminide layers have to be oxidized in order to get an insulating surface layer. Specimens of V-alloy are being aluminized by this process at KfK in Germany.

Aluminum nitride coatings were also made by reaction sputtering in low-pressure N₂ atmosphere at temperatures of 350, 400, and 450°C. The coating thicknesses after 1 h of deposition were in a range 0.8-1.4 µm. The coating covered the entire surface of the V-alloy specimen and the layer was found to be of very high resistance indicating adequate insulating properties. The coatings developed at 350 and 450°C tended to crack, but the one developed at 400°C was fairly adherent and mechanically hard. Additional specimens are being prepared using this approach with emphasis on optimization of coating parameters to achieve 5-10 µm thick coatings without defects.

Testing of Coatings in Liquid Metal: Aluminized layers have been found to be stable in Li at 400°C in a recirculating Li loop.¹⁶ However, the kinetics of layer growth and chemical/mechanical integrity of the layer needs to be determined, especially at temperatures of 250-400°C of interest in this application. Bulk samples of AlN have been exposed to liquid Li at 350°C and were found to lose weight after ~750 h.¹⁷ On the other hand, Al transport/deposition to a specimen surface was achieved by additions of 2-5% Al to liquid Li, which may be an approach to maintain the coating for long periods of exposure.¹⁸ This indicates that if the externally performed AlN layer cracks or spalls in flowing Li, in-situ repair or self healing of the layer is possible by control of the activities of Al and N in Li. At present, experiments are underway to develop coatings by different methods and to evaluate their performance in a lithium environment. Additional experiments are needed to determine the repair procedures for reformation of layers in-situ via control of thermodynamic activities of N and Al in Li, N₂ in the cover gas, and exposure temperature.

SAFETY RELATED ISSUES

One of the safety related issues is the handling of the liquid metal and in the event of a leak, the reactions between the liquid and air/water environments leading to generation of hydrogen and heat. Extensive work has been done with liquid sodium in the areas of system design, control/maintenance of purity of liquid metal, air/water reactions with the liquid at elevated temperatures, and sodium cleaning procedures in support of liquid-metal fast-breeder reactor. In general, liquid Li and Pb-Li are less reactive than sodium and can be handled with the procedures developed for handling of sodium.

Another safety issue is the elevated temperature oxidation of the first wall material, especially the V alloy, in the event of a loss of vacuum in the system. Prolonged exposures to the oxidation process can lead to embrittlement of the material and may degrade the structural integrity of the first wall. Oxidation experiments have been conducted with V-5Cr-5Ti alloy at several temperatures in a range 300-575°C in an air environment.¹⁹ Figure 14 shows the temperature dependence of the parabolic rate constant for oxidation of the alloy with and without aluminizing treatment. The results indicate that even at 500°C the oxidation rates for the bare and aluminized alloy are 20 and 5 $\mu\text{m}/\text{yr}$, which are acceptable for application of the alloy in fusion device. Further, tensile tests were conducted on specimens of V-5Cr-5Ti preoxidized in air for time periods between 24 and 1000 h at 500°C.¹⁹ Figure 15 shows the engineering stress-engineering strain data for different preoxidized specimens tested at a strain rate of $1.75 \times 10^{-4} \text{ s}^{-1}$. An exposure of 1000 h at 500°C in an air environment leads to surface scaling and diffusion of oxygen into the substrate alloy; but, the impact of such diffusional transport is to reduce the tensile ductility from 23 to 13% and no catastrophic embrittlement of the alloy was observed.

SUMMARY

A detailed assessment is made of the requirements of liquid metals such as NaK, Li, and Pb-Li for application in ITER. The assessment includes corrosion performance of first-wall candidate materials in the liquid metals with regard to metallic and nonmetallic element mass transfer in the temperature range of interest for ITER, hydrogen effects in liquid Li systems, requirements/development of electrically insulating coatings that are compatible with the first wall material and liquid coolant/breeding blanket, and safety-related issues. The paper discusses the current

state of knowledge in the above areas and identifies areas of further research/development for reliable application of liquid metals in fusion devices.

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Table 1. Selected physical properties for liquid metals of interest for ITER

Liquid metal	Melting point (°C)	Density at 400°C (Kg/m ³)	Viscosity at 400°C (Kg /m s)	Volume expansion at melting (%)	Thermal conductivity at 400°C (W/m K)	Specific heat at 400°C (KJ/Kg K)	Electrical Resistivity (Ohm m)
NaK	-12.3	775	2.1×10^{-4}	2.5	24.1	0.76	6.0×10^{-7}
Li	181	518	6.7×10^{-5}	1.5	53.1	4.2	3.2×10^{-7}
Pb-Li	235	9600	1.5×10^{-3}	3.5	15.2	0.19	1.3×10^{-6}

Table 2. Solubility data for several elements of interest in different liquid metals

Element	Liquid Metal					
	NaK		Lithium		Lead-lithium	
	Solubility at 400°C (wppm)	Constant B*	Solubility at 400°C (wppm)	Constant B*	Solubility at 400°C (wppm)	Constant B*
Fe	0.04	4116	0.94	3084	35	665
Cr	9×10^{-5}	9010	0.90	3219	5	500
Ni	0.55	1570	56.8	3304	2366	981
V	†	-	††	-	**	-
Ti	†	-	††	-	**	-
Al	24.2	440	4×10^5	-	2000	1680

* The solubility is expressed by an expression: $\log S(\text{wppm}) = A - B/T(K)$.

† Solubility values are low and form V_2O_3 or Ti_2O_3 compound in cold-trapped NaK.

†† Solubility values are low and form V_2N or TiN compound in cold-trapped lithium.

** Data not available.

Table 3. Nonmetallic impurity concentrations (wppm) in Na/NaK and Li after treatment with various purification methods

Nonmetallic Impurity	Purification Method		
	Cold trapping	Getter trapping	Salt extraction
<i>Sodium/NaK</i>			
Oxygen	~1	<0.01	-
Carbon	minimal effect	<0.1	-
Nitrogen	a	-	-
Hydrogen	~0.1	<0.01	-
<i>Lithium</i>			
Oxygen	~40	~40	-
Carbon	~800	<100	<10
Nitrogen	>1000	<100	<10
Hydrogen	>1000	<100	<1
Halogens	Not applicable	Not applicable	>300

^aThe solubility of nitrogen in sodium is too low to be of concern.

Figure 1. Corrosion loss versus reciprocal temperature for stainless steel and V alloy in several liquid metals

Figure 2. Solubility as a function of reciprocal temperature for oxygen, carbon, and nitrogen in liquid metals

Figure 3. Temperature dependence of minimum oxygen concentration in Na/NaK for oxide formation on several metals

Figure 4. Temperature dependence of minimum oxygen concentration in Li for oxide formation on several metals

Figure 5. Thermodynamic stability of nitrides of several structural metals in a lithium environment

Figure 6. Temperature dependence of minimum nitrogen concentration in Li for nitride formation on several metals

Figure 7. Hydrogen concentration as a function of temperature in selected structural and alkali metals for hydrogen partial pressure of 10^{-3} Torr

Figure 8. Hydrogen concentration as a function of temperature in selected structural and alkali metals for hydrogen partial pressure of 10^{-6} Torr

Figure 9. Resistance of several oxides as a function of coating thickness; requirements for ITER application shown for reference

Figure 10. Resistance of several nitrides as a function of coating thickness; requirements for ITER application shown for reference

Figure 13. EDX elemental profiles for V, Cr, Ti, and Al for a V-alloy specimen after 900 h exposure at 500°C in contact with bulk AlN in vacuum

Figure 14. Temperature dependence of the parabolic oxidation rates for bare and aluminized V-5Cr-5Ti alloy specimens in air.

Figure 15. Effect of preoxidation on the stress-strain behavior of V-5C-5Ti alloy tested at 500°C in air at a strain rate of $1.75 \times 10^{-4} \text{ s}^{-1}$.

Figure 11. Depth profiles for Al, V, Cr, and Ti for an aluminized specimen of V-5Cr-5Ti alloy

Figure 12. Weight change data for bare and aluminized alloys and bulk AlN exposed to lithium at 350°C

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