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Sergei ZIMIN*, Hideyuki TAKATSU and Seiji MORI

日本原子力研究所
Japan Atomic Energy Research Institute

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Hydrogen Formation in Metals and Alloys During Fusion Reactor Operation

Sergei ZIMIN*, Hideyuki TAKATSU and Seiji MORI

Department of ITER Project
Naka Fusion Research Establishment
Japan Atomic Energy Research Institute
Naka-machi, Naka-gun, Ibaraki-ken

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The results of neutron transport calculations of the hydrogen formation based on the JENDL gas-production cross section file are discussed for some metals and alloys, namely ^{51}V, Cr, Fe, Ni, Mo, austenitic stainless steel (Ti modified 316SS : PCA), ferritic steel (Fe-8Cr-2W : F82H) and the vanadium-base alloy (V-5Cr-5Ti) . Impact of the steel fraction in steel／water homogeneous blanket／shield compositions on the hydrogen formation rate in above-mentioned metals and alloys is discussed both for the hydrogen formation in the first wall and the blanket／shield components. The results obtained for the first wall are compared with those for the helium formation obtained at JAERI by the same calculational conditions. Hydrogen formation rates at the first wall having ^{51}V, Cr, Fe, Ni and Mo are larger than those of helium by 3-8 times.

Keywords: Fusion Reactor, D-T Neutrons, Neutronics, Hydrogen Formation Rate, Helium Formation Rate, First Wall, Blanket, Shield, JENDL Gas-production Cross-section File, Neutron Transport Calculations.

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* Research Fellow

核融合炉の運転に伴う構造材料中の水素生成

日本原子力研究所那珂研究所ITER開発室
Sergei ZIMIN*・高津　英幸・森　　清治

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核データセットJENDLのガス生成断面積ファイルを用いて，核融合炉の運転に伴う構造材料中での水素生成量を評価した。対象とした構造材料及び構成元素は，V^{51}，Cr，Fe，Ni，Mo，Ti添加改良オーステナイト・ステンレス鋼（PCA），フェライト鋼（F82H）及びバナジウム合金（V－5Cr－5Ti）である。ステンレス鋼と水から構成される遮蔽ブランケットを対象として，上記構造材料を第一壁及びブランケット構造材料に用いた場合の水素生成量を調べた。得られた結果と従来の評価との比較検討も行った。V^{51}，Cr，Fe，Ni及びMoを有する第一壁においては，水素生成量がヘリウム生成量の3～8倍も大きいことが分かった。

那珂研究所：〒311－01　茨城県那珂郡那珂町大字向山801－1

*　リサーチフェロー

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1. Introduction

The list of about twenty neutronics responses to be accounted for the International Thermonuclear Experimental Reactor (ITER) Engineering Design Activity (EDA) design includes the helium and hydrogen formation in in-vessel components of a fusion reactor(1). The helium formation in the bulk of structural fusion materials by the fusion neutrons has been investigated recently(2) regarding the decrease with the distance from the first wall, where it reaches its maximum value. However, the problem of hydrogen formation in the bulk of structural fusion materials was not extensively investigated so far regarding the decrease of hydrogen formation behind the first wall of a fusion reactor.

The build ups of hydrogen and helium in representative alloys of a fast fission reactor have been obtained experimentally and by interpolation of nuclear systematics(3). The Ref. 3 shows larger hydrogen formation rates in most considered metals by 6-30 times than those of helium. However, it is believed that the hydrogen produced in the first wall, the blanket and the shield of a fusion reactor readily diffuses from the metal. This is due primarily to its high mobility in metals at high temperatures(4,5). Therefore the hydrogen formation has been predicted to be of less concern than that of helium formation and, correspondingly, less attention was paied to it.

On the other hand the hydrogen embrittlement is a widely studied field(4) and a large number of publications are appeared annually on this subject. The hydrogen embrittlement is indeed probably negligible at high temperatures because of the high diffusivities of hydrogen in candidate alloys to be used for the experimental fusion reactor design. However, some results show that irradiation-induced point defects and/or helium act as traps for hydrogen and, correspondingly, reduces its mobility(6). Thus, some researches show that the hydrogen embrittlement could be important even for a low temperature first wall of a fusion reactor(5) such as the NET whose first wall temperature foresees as low as 333K(7,8).

The JENDL gas-formation cross section file has been compiled recently(9) in Japan as one of the JENDL-3(10) special purpose files. Thus, it became possible to compile the gas formation cross sections as multigroup response function libraries(11) and to carry out an investigation of both the helium(2) and hydrogen formation in candidate alloys for a fusion reactor design.

The purpose of this article is to extend the results obtained in Ref. 2 for the helium formation to the hydrogen formation to give the fusion reactor designer an idea how much hydrogen can be produced at the first wall and different locations behind the first wall of a fusion reactor assuming 14-MeV neutrons interact in different elements and alloys of blanket/shield compositions.

2. Calculational Method

The same methodology is used in this study as that in Ref. 2. The ANISN(12) neutron transport code with the FUSION-40(13) library of multigroup constants (42 neutron + 21 photon) are used in this study. The neutron transport calculations in one-dimensional cylinder geometry were performed using the discrete ordinate method with an S_8 symmetric angular quadrature set and a P_5 Legendre expansion for the scattering cross section.

The simplified geometrical model of an experimental thermonuclear reactor build-up is shown in Fig. 1. A uniform volume source of 14-MeV monoenergetic neutrons in the first energy group (15.00-13.72 MeV) was assumed to exist at zone 1. A neutron wall load of 1 MW/m^2 was assumed to exist on the first wall of employed calculational model. The zone 3 is assumed to be a 200-cm-thick homogeneous mixture of water and stainless steel of different fractions so that the results obtained could provide useful design-independent information on the hydrogen formation in metals of a fusion reactor.

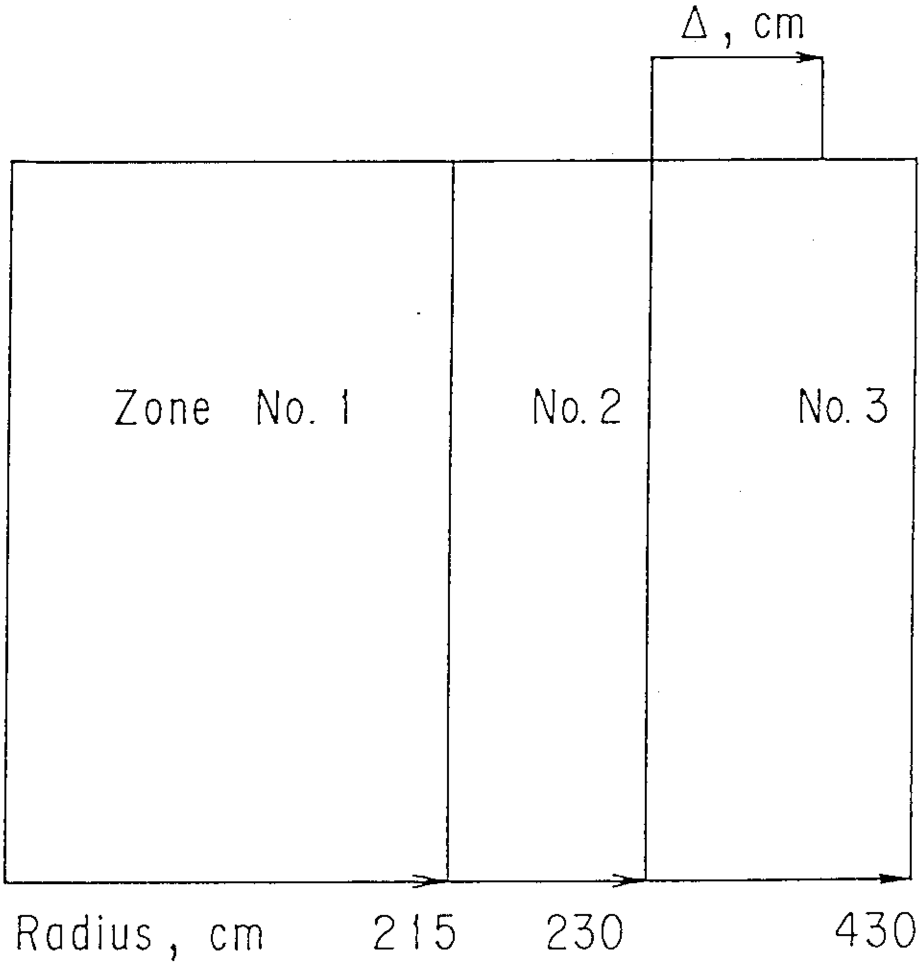

Fig. 1 One-dimensional cylinder calculational model.

3. Calculation Results and Discussion

The cross-sections used to calculate the hydrogen formation in metals are taken from Ref. 9 and shown in Fig. 2. The hydrogen formation cross-sections are largest for the high energy neutrons and have no contribution from photons. This is due to the exothermic character of (n,p) reaction, the process which generates hydrogen in metals.

The results of transport calculations of neutron/photon fluxes in steel/water homogeneous medias have been discussed in numerous studies indeed and are not shown here. The results of hydrogen formation calculations obtained for some metals and alloys of 80% stainless steel/20% water composition, most often used in the design of a fusion reactor, and of 80% water/20% stainless steel composition, as an extreme case of water-rich blanket, are shown in Figs. 3, 4 and Figs. 5, 6, respectively.

The results obtained in this study are compared in Table 1 and Table 2 for the first wall and at the 50 cm and 100 cm distance behind the first wall, respectively. The concentrations of hydrogen produced in the first wall of a fusion reactor are largest as those for helium. The hydrogen concentrations are larger than those of helium for all considered metals and alloys. For instance, as shown in Table 1, the hydrogen concentrations in the first wall are larger than those of helium by 3-8 times. It is primarily due to larger gas formation cross sections for the hydrogen, as shown in Fig. 2, than for the helium, as shown in Ref. 2.

The highest and smallest hydrogen formation rates at the first wall containing metals were observed for the nickel and the vanadium, respectively, namely 2014 H appm/1 MW·a/m^2 (for the 20% steel/80% water composition behind the first wall) and 116 H appm/1 MW·a/m^2 (for the 100% steel composition behind the first wall), respectively. The highest and smallest hydrogen formation rates at the first wall containing alloys were observed for the PCA and the V-5Cr-5Ti alloy, respectively, namely 816 H appm/1 MW·a/m^2 (for the 20% steel/80% water composition behind the first wall) and 144 H appm/1 MW·a/m^2 (for the 100% steel composition behind the first wall), respectively.

The impact of steel fraction in the steel/water shielding blanket on the hydrogen formation rate at the first wall having different metals is shown in Fig. 7. The impact seems to be very small even when the steel fraction changes from 100% to 20%, namely about 3% for all considered metals. Therefore, we concluded that the hydrogen formation rate depends primarily on the 14-MeV neutron fluence and almost does not depend on the neutron spectra. It is due to the sharp decrease of hydrogen formation cross sections for the neutron energy less than 4-8 MeV, as shown in Fig. 2.

According Figs. 3-6 and Table 2, the hydrogen formation rates decrease sharp with the distance from the first wall in an approximately exponential fashion, as those for the helium(2). The largest and smallest decreases are observed for the 100% stainless steel and the 20% steel/80% water, respectively, as those for the 14-MeV neutron flux in the steel/water media(14).

The relation between the gas formation rate and the displacement damage rate often described as the Gas/dpa ratio is the important neutronics characteristics of a fusion reactor(15). Therefore, we calculated the H/dpa ratios for the two shielding compositions considered in this study and shown obtained results in Fig. 8 together with those obtained in Ref. 2 for He.

As shown in Fig. 8, the Gas/dpa ratio is very sensitive to the steel fraction in the blanket/shield composition. The larger steel fraction in the blanket/shield, the larger reduction in the Gas/dpa ratio we obtained. This is primary due to the difference in the gas formation and the displacement damage cross sections(2), such that the gas formation increases larger than the displacement damage, when the neutron spectrum became harder.

Table 1. Hydrogen formation rate at the first wall having ^{51}V, Cr, Fe, Ni and Mo metals.

Metal type Blanket/shield contents	H formation rate , H appm/ 1 $MW{\cdot}a/m^2$				
	Ni	Fe	Cr	Mo	^{51}V
20% steel 80% water	2014 (266*)	612 (119)	497 (97)	282 (35)	120 (42)
50% steel 50% water	1992	605	493	280	119
80% steel 20% water	1972 (273)	598 (116)	488 (95)	277 (34)	117 (41)
100% steel	1957	591	483	274	116

* Helium formation rate(2).

Table 2. Hydrogen formation rate in the blanket/shield having ^{51}V, Cr, Fe, Ni and Mo metals at 50 cm and 100 cm distance behind the first wall.

Metal type Blanket/shield contents	H formation rate , H appm/ 1 MW·a/m^2				
	Ni	Fe	Cr	Mo	^{51}V
20% steel 80% water	8.64* 5.65-2**	1.96 1.19-2	1.39 8.05-3	8.10-1 4.72-3	3.81-1 2.30-3
50% steel 50% water	2.71 6.07-3	6.33-1 1.33-3	4.59-1 9.27-4	2.67-1 5.43-4	1.23-1 2.59-4
80% steel 20% water	1.05 9.52-4	2.47-1 2.12-4	1.83-1 1.52-4	1.06-1 8.86-5	4.77-2 4.11-5
100% steel	4.46-1 2.13-4	9.71-2 3.41-5	7.31-2 2.49-5	4.21-2 1.44-5	1.85-2 6.48-6

* 50 cm behind the first wall;

* 100 cm behind the first wall;

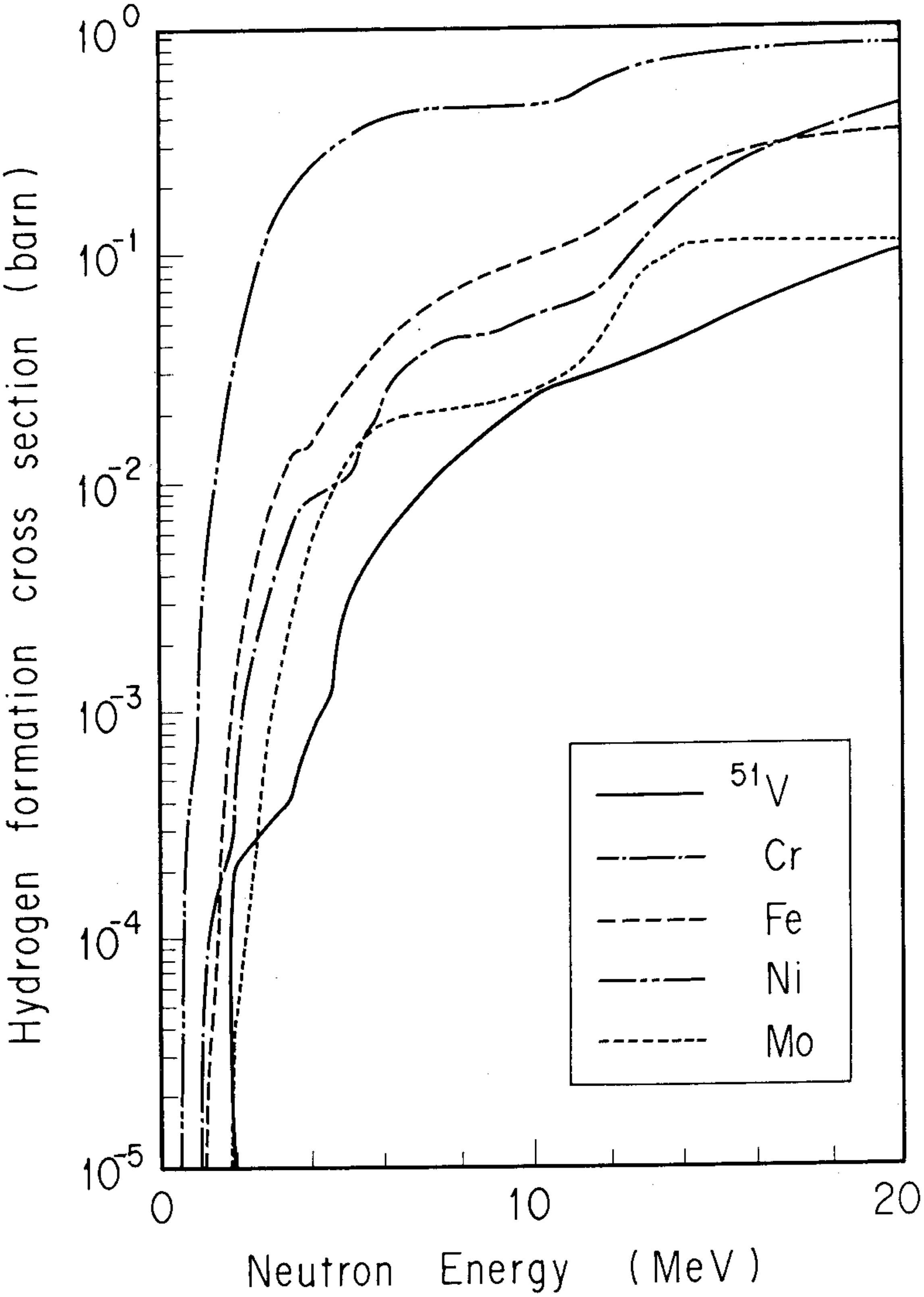

Fig. 2 Hydrogen formation cross sections of ^{51}V, Cr, Fe, Ni and Mo.

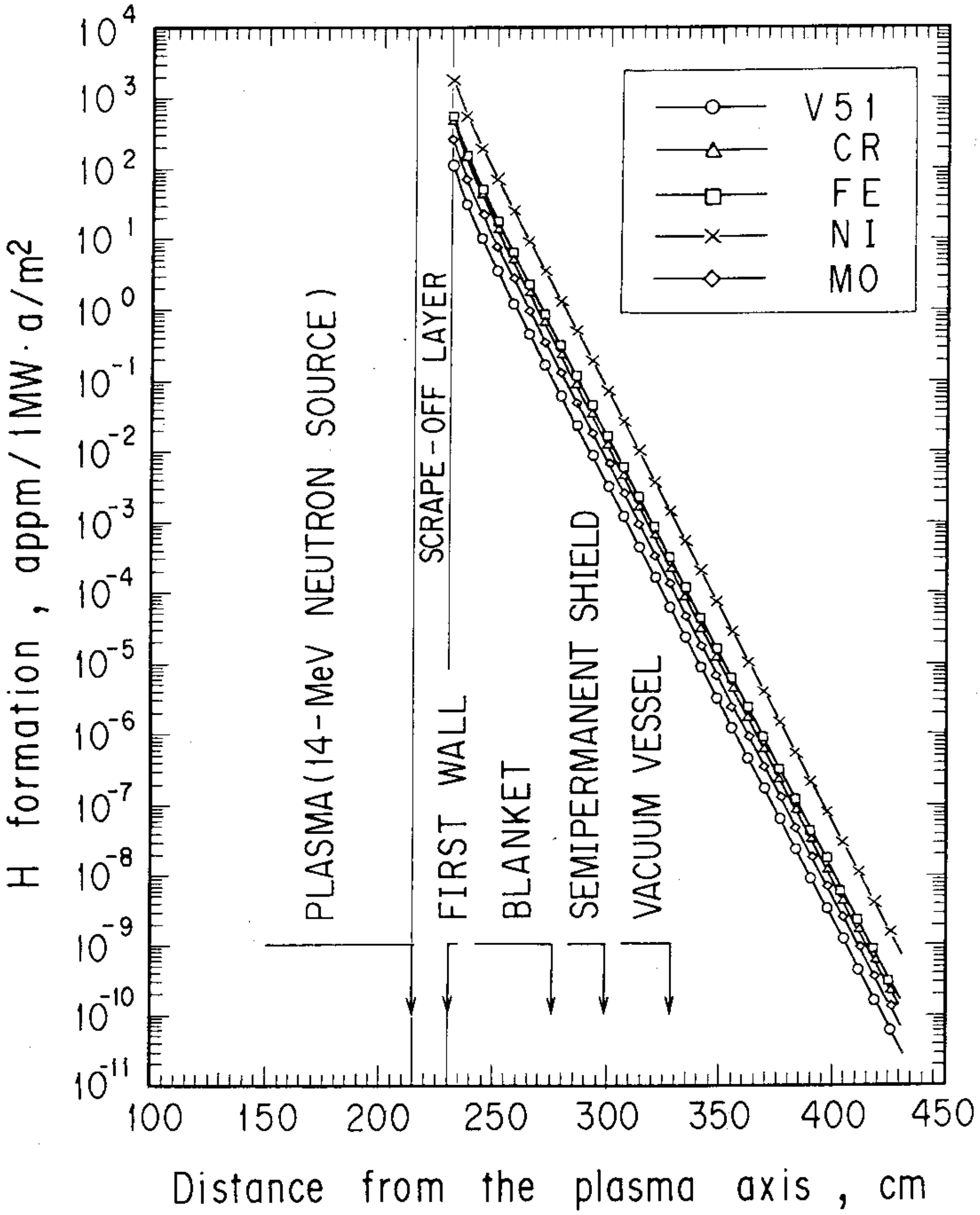

Fig. 3 Hydrogen formation rate in ^{51}V, Cr, Fe, Ni and Mo of 80% steel/20% water homogeneous blanket/shield composition versus the distance from the plasma axis.

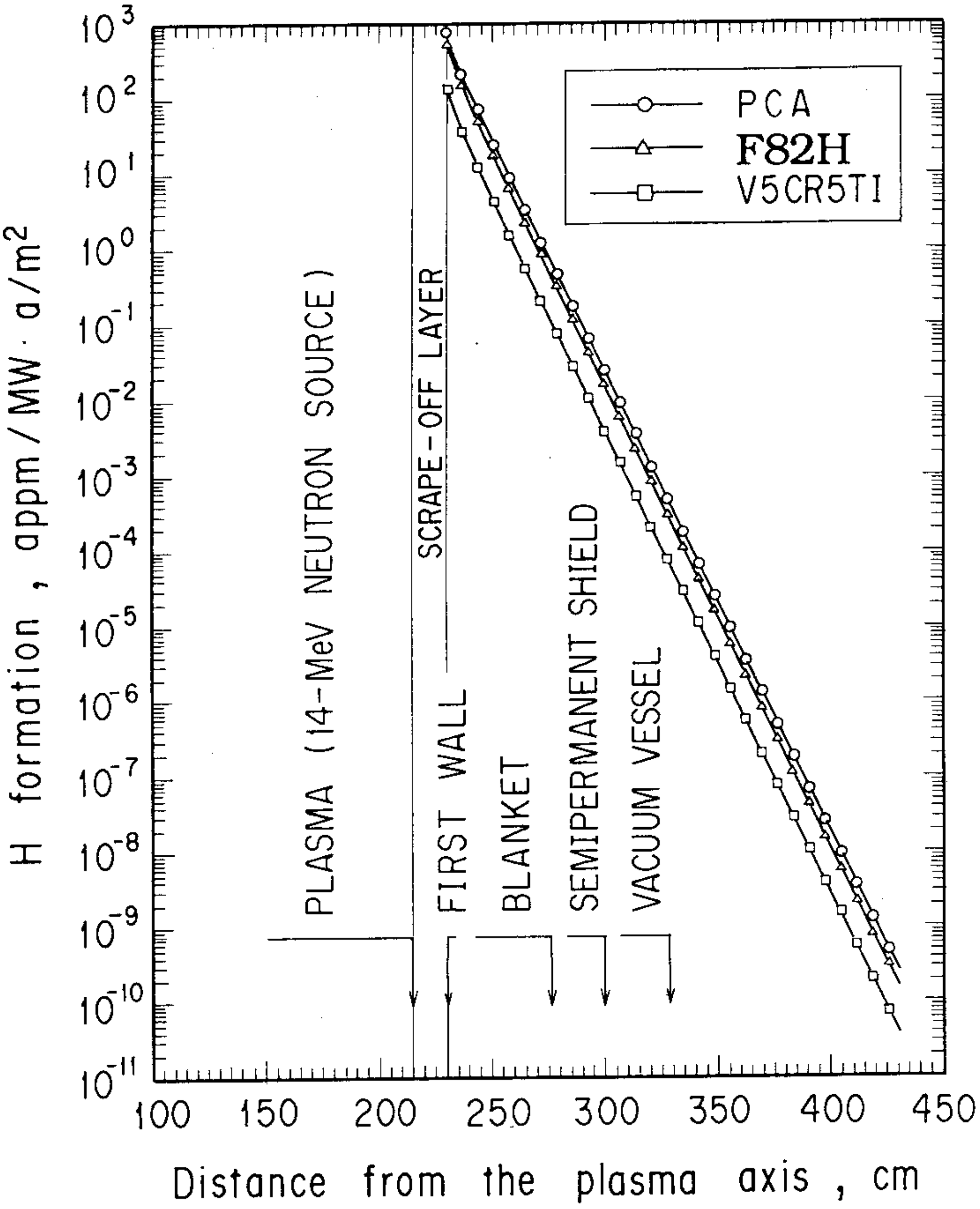

Fig. 4 Hydrogen formation rate in PCA, F82H and V5Cr5Ti alloy of 80% steel/20% water homogeneous blanket/shield composition versus the distance from the plasma axis.

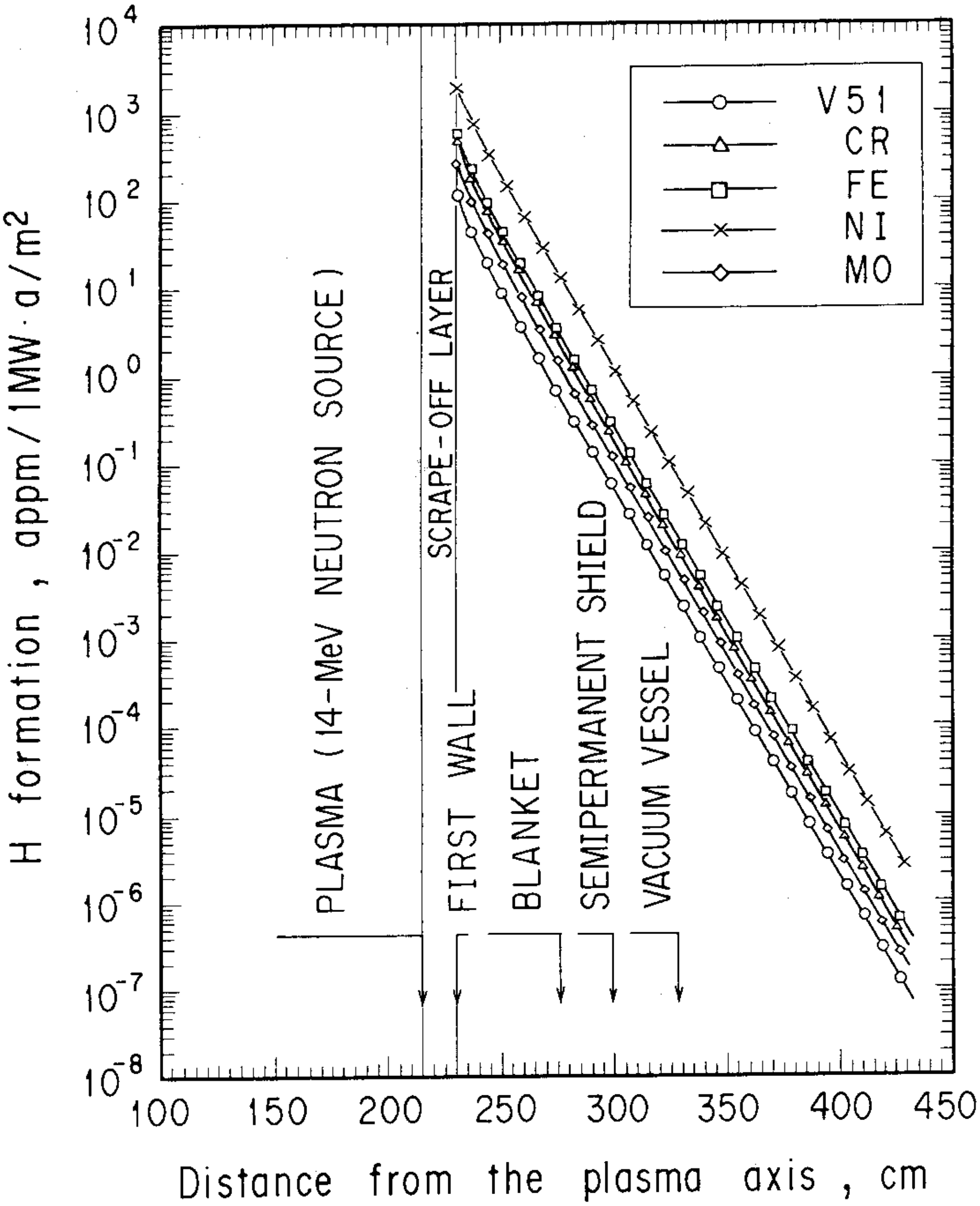

Fig. 5 Hydrogen formation rate in ^{51}V, Cr, Fe, Ni and Mo of 20% steel/80% water homogeneous blanket/shield composition versus the distance from the plasma axis.

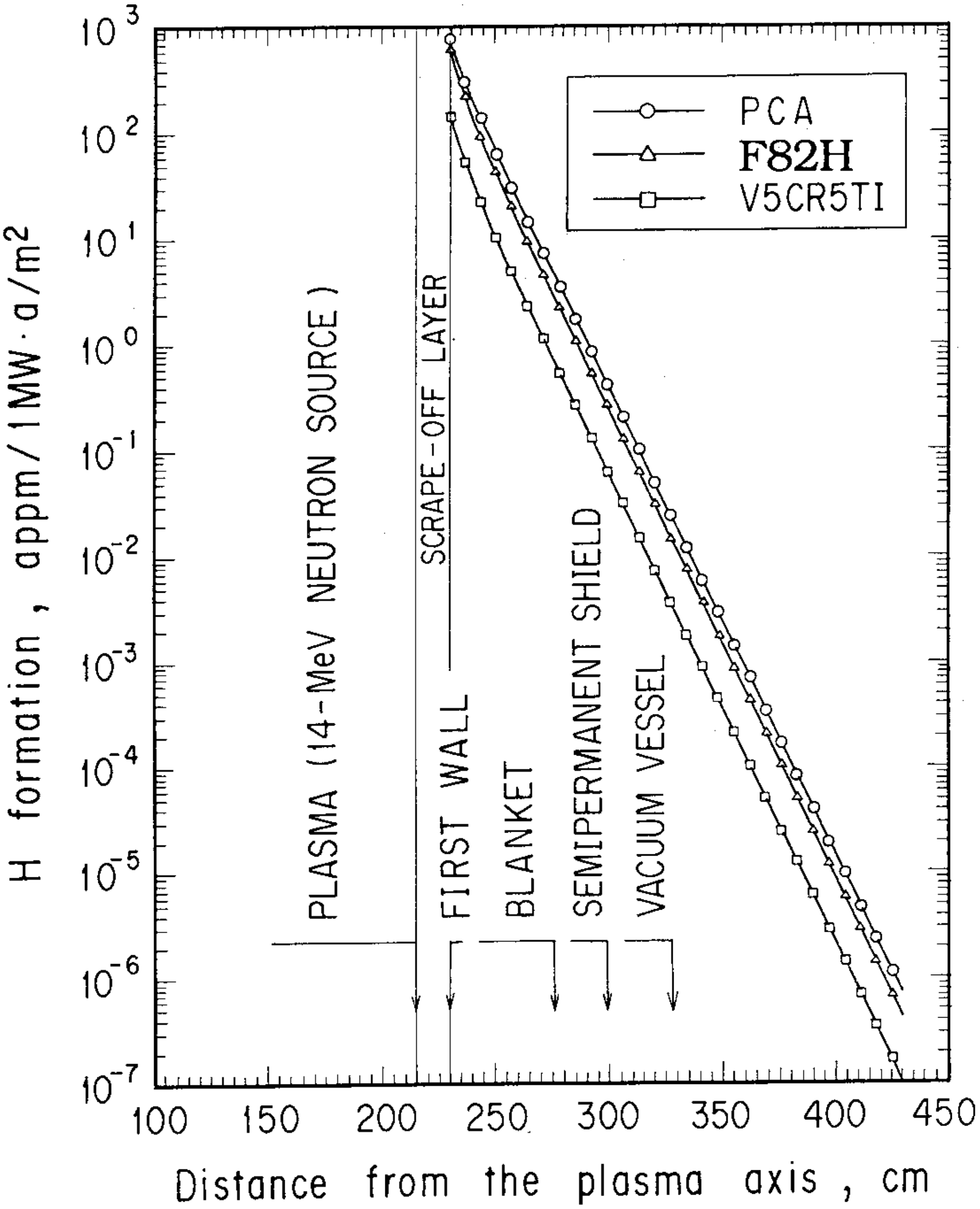

Fig. 6 Hydrogen formation rate in PCA, F82H and V5Cr5Ti alloy of 20% steel/80% water homogeneous blanket/shield composition versus the distance from the plasma axis.

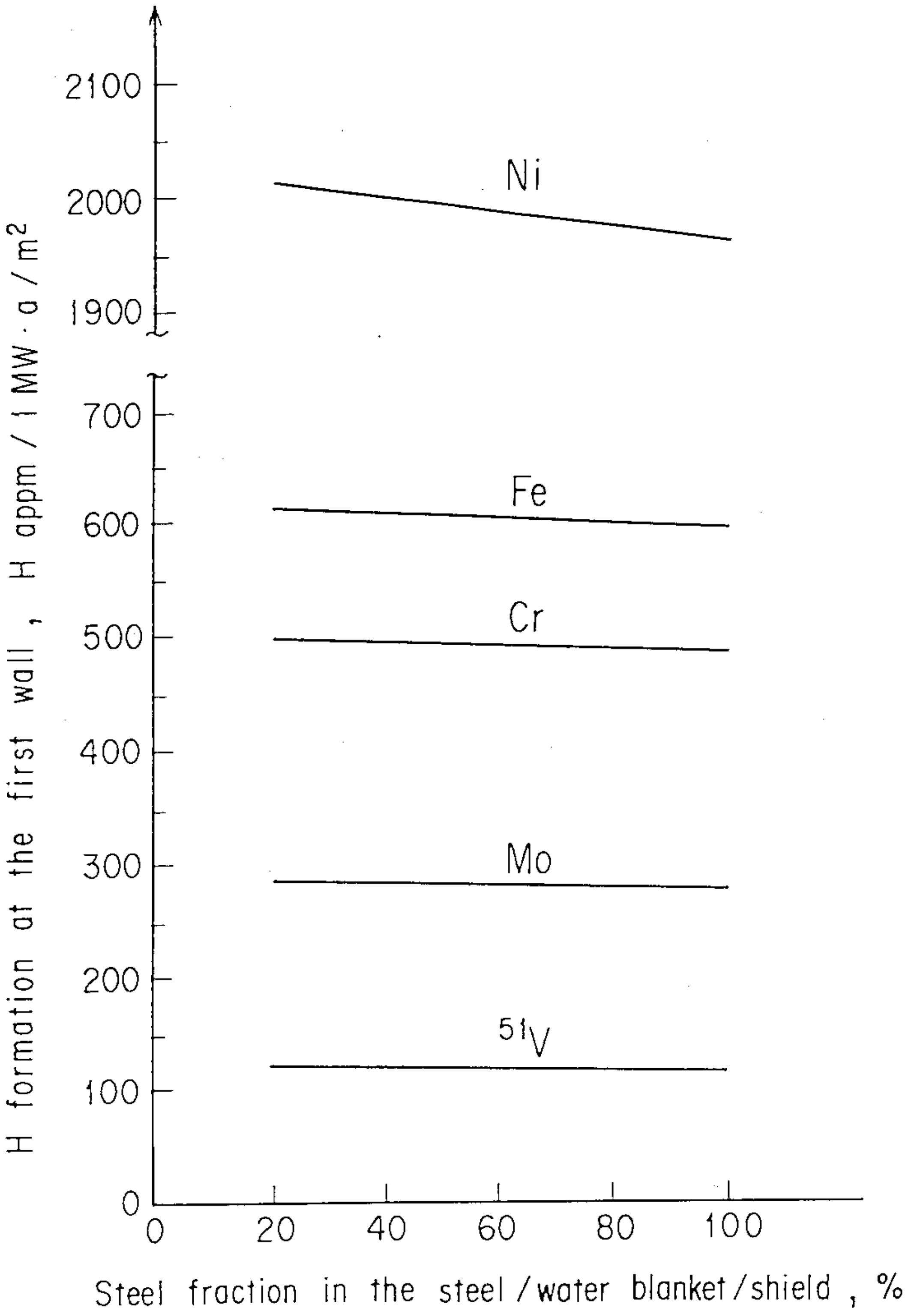

Fig. 7 Hydrogen formation rate at the first wall having ^{51}V, Cr, Fe, Ni and Mo metals.

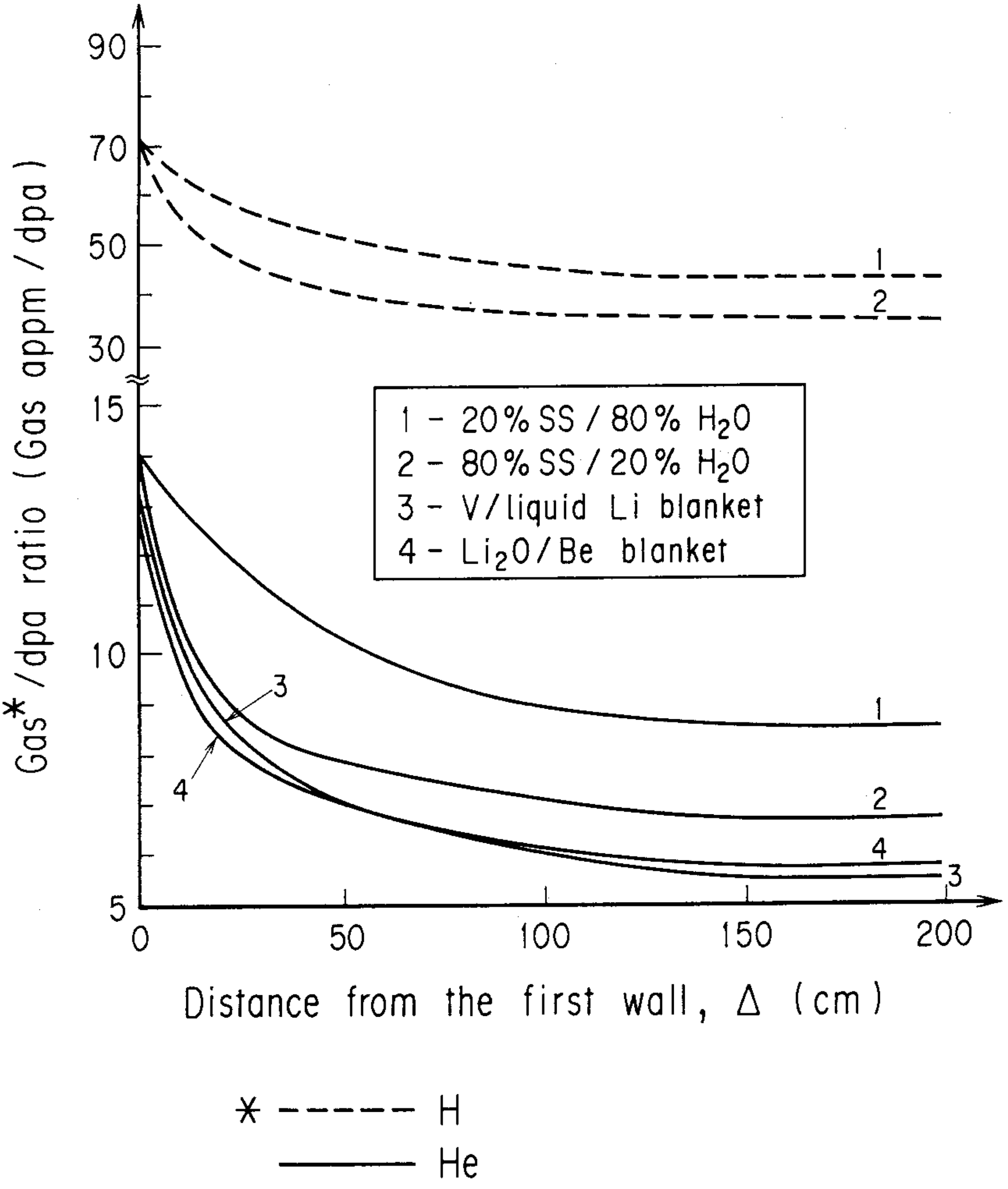

Fig. 8 H(---), He(——)/dpa ratios in stainless steel components of blanket/shield composition of a fusion reactor.

4. Conclusion

The hydrogen formation rates in metals and alloys of a fusion reactor during operation was found to be larger by 3-8 times than those of helium. The nickel has been found the most vulnerable metal, regarding the hydrogen formation during operation of a fusion reactor. The hydrogen formation rate at the first wall of a fusion reactor containing this metal is in the order of 2000 Happm/1 MW·a/m^2, subject to a fraction of steel in the steel/water homogeneous mixture behind the first wall.

The hydrogen formation in the first wall decreases by about 3% only when the steel fraction in the homogeneous steel/water composition behind the first wall increases from 20% to 100%. The hydrogen formation behind the first wall decreases in approximately exponential fashion. The largest and smallest shielding effect was found for the 100% steel composition and for the water-rich (20%steel/80% water) composition, respectively.

However it is steel unclear for which in-vessel components of a fusion reactor the hydrogen embrittlement could be important. It seems to be important at least for a low-temperature components, such as the vacuum vessel (or some parts of vacuum vessel, such as the back walls, etc.). Therefore it is seriously suggested to consider during the ITER EDA design taking into account the data base obtained in this study.

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