HYDROGEN BEHAVIOUR IN THE AGED LOW ACTIVATION MARTENSITIC STEEL F82H FOR FUSION REACTOR APPLICATIONS

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ABSTRACT
A time dependent permeation method is used to measure the permeability, diffusivity and solubility of hydrogen in the low activation martensitic steel F82H aged for 2000 h under vacuum at 773 K. The measurements cover the temperature range from 373 to 723 K which includes the onset of hydrogen trapping effects on diffusivity and solubility. The results are interpreted using a trapping model. The number of trap sites and their average energies for hydrogen in the aged F82H steel are determined. These data are compared with those obtained for deuterium in F82H steel.

HYDROGEN PERMEATION, F82H MARTENSITIC STEEL, TRAPPING.

RIASSUNTO
In questo lavoro si sono misurate la permeabilità, la diffusività e la solubilità dell'idrogeno nell'acciaio martensitico a bassa attivazione F82H, invecchiato per 2000 h sotto vuoto a 773 K. Le misure coprono un range di temperature dai 373 ai 723 K, che permette di osservare l'effetto del trapping dell'idrogeno su diffusività e solubilità. I risultati sono stati interpretati usando un modello che tiene conto del fenomeno del trapping. È stato determinato il numero di siti di trapping e le loro energie medie per l'idrogeno nell'acciaio F82H invecchiato. Questi dati sono stati comparati a quelli ottenuti per il deuterio nell'acciaio F82H.
1. INTRODUCTION

The martensitic steel DIN 1.4914 (MArtensitic for NET, MANET) is a Nb bearing steel which has better swelling resistance, lower sensitivity to helium embrittlement and more suitable thermophysical properties than the austenitic stainless steel AISI 316L. The martensitic steel F82H (Japanese) belongs to the 7-10% Cr martensitic steel class that have undergone some modification in order to achieve better low-activation characteristics compared with those of MANET. The Reduced Activation Martensitic (RAM) F82H steel is a candidate material for the first wall and structure for the demonstration fusion reactor DEMO and it is still undergoing development and characterization from the point of view of its mechanical and physical properties.

In considering materials for fusion reactors a detailed understanding of the permeability, diffusivity and solubility of hydrogen and its isotopes through these materials is of crucial importance. The trapping of hydrogen isotopes in iron and steels (hydrogen may be trapped at particular defect sites such as inclusions, precipitates, grain boundaries or dislocations), has been invoked to explain differences in measured diffusivities in these materials during hydrogen isotopes absorption and desorption experiments at temperatures below 550 K. Furthermore, the retention of tritium in the structural materials of a fusion reactor will be affected by trapping and the consequent increase in the tritium inventory could affect adversely the prospects for breeding. The knowledge of the trapping parameters is required in fusion reactors in order to evaluate and control tritium retention in walls and structures when operated with deuterium/tritium plasmas. Numerical codes have been developed for the calculation of inventory, permeation and recycling of deuterium and tritium in fusion reactor design concepts in non steady state conditions; two of the essential input data for these codes are the trapping parameters such as the number of trap sites and their average energies.

There has also been a continuing interest by many authors in the hydrogen trapping behaviour in metal, because its relation with the resistance or susceptibility to hydrogen embrittlement of steels. The specific causes of this phenomenon remain controversial, but there seems to be general agreement that hydrogen transport within the steel is a controlling factor and that modification of the transport rate by trapping is one of the most promising routes to improve hydrogen compatibility.

Although the governing deuterium transport and inventory parameters (permeability, diffusivity and solubility) in F82H were studied in no data are yet available for hydrogen in F82H steel. In addition, in this work, a sample of F82H was aged for 2000 h under vacuum at 773 K to see if the hydrogen permeation is influenced by ageing.
Measurements of permeation rates of hydrogen in F82H specimens were performed using a gas permeation technique. Measurements were conducted over the temperature range 373-723 K with hydrogen driving pressures in the range 1-100 kPa (10 to 1000 mbar).

2. EXPERIMENTAL

The F82H samples consisted of discs 48 mm in diameter and 4 \times 10^{-4} \text{ m} in thickness. In table 1 the composition of this steel is given. The membranes were machined from a slab of material and underwent the following heat treatment in order to produce a fully martensitic phase: austenising at 1313 K for 38 min, quenching to room temperature, tempering at 1023 K for 1 hour, slow cooling to room temperature. A sample of F82H was aged for 2000 h under vacuum at 773 K.

The method chosen for the permeation measurements during the current investigation was a gas-phase technique where, after evacuating the apparatus to a Ultra High Vacuum, so that both sides of a sample are initially in contact with vacuum, one side of the sample (the "high pressure side") is instantaneously exposed to hydrogen gas at a known, fixed pressure. Gas permeates through the sample and is released at the other side (the "low pressure side"), where it causes a pressure rise in an initially evacuated, calibrated volume. The pressure rise is measured using a Baratron capacitance manometer with a full scale reading of 1300 Pa (13 mbar). Since the volume is calibrated, either the pressure rise could be converted into an amount of gas in moles permeating through unit area of the sample \(Q(t)\) or the rate of pressure rise could be converted into an amount of gas in moles permeating through unit area of the sample per second \(J(t)\). The permeation apparatus is constructed from standard stainless steel UHV components (see fig. 1). Bakeout of the entire system is possible using heating tapes. Residual pressures lower than \(10^{-6} \text{ Pa} (10^{-8} \text{ mbar})\) prior to system bakeout at 573 K and less than \(10^{-7} \text{ Pa}\) afterwards are obtained before any experiment. High pressure hydrogen gas, with an impurity content less than 1 ppm of \(\text{H}_2\text{O}\) or \(\text{O}_2\), is produced by a hydrogen generator (mod. HG 200-CLAI\text{ND/RIVOIRA}) jointed to a hydrogen purifier. The sample is heated by a resistance furnace and the temperature may be set at values up to 773 K by a temperature controller with a thermocouple held in a well drilled into one of the flanges holding the sample, allowing a temperature stability of ±0.5 K. An analysis of the high pressure gas and the permeated gas are made with a quadrupole mass spectrometer. Thus it is possible to check for possible contaminants and to distinguish permeation from outgassing. The volume of the low pressure side of the sample is measured by a gas expansion method (Sieverts' method) using a calibrated volume \(9.5 \times 10^{-5} \text{ m}^3\) which is permanently attached to the apparatus. A personal computer interfaced to the equipment via a digital voltmeter is used for data storage and later processing.
Before the membranes were inserted into the permeation measuring equipment, both sides were mechanically polished. Thus, only oxide layers resulting from exposure to air at room temperature should be present.

3. THEORY

It is possible to obtain an expression for the permeation flux \( J \) (moles of gas m\(^{-2}\) s\(^{-1}\)) of hydrogen atoms through a membrane of uniform thickness \( d \) (m), in the case where the driving hydrogen pressure is increased instantaneously from zero to \( p \) (Pa) (always very much higher than the pressure on the low pressure side), and where the initial concentration throughout the solid is zero (i.e. the experimental conditions used for the present work). Here \( J(t) \) is given by the one-dimensional solution of Fick's law and can be expressed as:

\[
J(t) = \frac{D \cdot K_s \cdot p^{1/2}}{d} \left[ 1 + 2 \sum_{n=1}^{\infty} (-1)^n \exp \left( -D \frac{n^2 \pi^2}{d^2} t \right) \right]
\]  

(1)

where \( D \) (m\(^2\) s\(^{-1}\)) is the diffusion coefficient of the membrane and \( K_s \) (mol m\(^{-3}\) Pa\(^{-1/2}\)) its Sieverts' constant. It is also assumed that the diffusion coefficient \( D \) is independent of concentration within the experimental range and no surface effects are present, i.e. the rate limiting process is diffusion through the material rather than surface reactions. At steady-state (i.e., \( t \to \infty \)) eq. (1) becomes:

\[
J = \frac{P}{d} \left( \frac{1}{p^{1/2}} \right)
\]

where \( P = D K_s \) (mol m\(^{-1}\) s\(^{-1}\) Pa\(^{-1/2}\)) is defined as the permeability of the material. The total amount of gas, \( Q(t) \) moles of gas, which has permeated after time \( t \), is given by:

\[
Q(t) = \int_0^t J(t') dt' = \frac{P}{d} \left[ \frac{p^{1/2}}{6D} t - \frac{2P^{1/2}d}{\pi^2 D} \sum_{n=1}^{\infty} (-1)^n \exp \left( -D \frac{n^2 \pi^2}{d^2} t \right) \right]
\]  

(2)

\( Q(t) \) is obtained experimentally from the pressure rise data, using the ideal gas law (\( Q(t) = p(t)V_{eff}R^{-1}T^{-1} \)).

As shown in fig. 2, the values of \( P \) and \( D \) can be obtained by least squares fitting to the experimental data for each permeation run using eq. (2) above. It is possible also to obtain \( P \) from the steady state behaviour, and \( D \) from the so-called time lag \( t = d^2/6D \), the time at which a line fitted to the asymptotic region of the pressure rise curve intersects the time axis. Then, having obtained the permeability \( P \) and the diffusivity \( D \), the Sieverts' constant is determined directly from the relationship \( K_s = P/D \).

Internal trapping is a process that delays the flow of hydrogen in a solid via the capture and release of hydrogen atoms by sites other than the ordinary solution ones. For a single type of trapping site
uniformly distributed throughout the solid, it is assumed that the hydrogen atoms in the solid are distributed either in the ordinary or lattice sites characterized by the normal enthalpy of solution $E_s$ (J mol$^{-1}$), or in the extraordinary or trapping sites with an energetically favoured environment for occupancy by the hydrogen, with respect to an atmosphere of gaseous hydrogen with which the metal may be brought into contact. As shown in fig. 3:

$$E_t = E_s + \Delta E \quad (3)$$

represents the energy difference between a normal and a trapping site. $E$ represents the energy change between a gas-phase and a trapped hydrogen atom. Generally the majority of sites are lattice sites. It should be noted that, contrary to the convention adopted by Oriani $^8$, here the energy $E_t$ has been defined as positive to avoid possible confusion.

Exchange between these two states occurs through a reversible reaction with rate constants $k_A$ (s$^{-1}$) for trapping and $k_B$ (s$^{-1}$) for detrapping $^9$. The trapping rate, $k_A$, is defined as to $\exp[(-E'-E_d)/RT]$, whereas the detrapping rate $k_B$ is equal to $\exp[(-E_t - E_d - E')/RT]$ $^{10}$. The term $E_d$ is the energy barrier between normal lattice sites, while that between a normal site and a trapping site is taken to be increased by a further energy $E'$. (s$^{-1}$) is the vibrational frequency for trapped hydrogen and $R$ is the molar gas constant (8.314 J K$^{-1}$ mol$^{-1}$). These rate constants are assumed to vary with temperature, but not with the concentrations $c_l$ (mol m$^{-3}$) and $c_t$ (mol m$^{-3}$) of hydrogen atoms in the lattice and in the trapping sites, respectively. If $C_l = c_l 2N_A/N_l$ and $C_t = c_t 2N_A/N_t$ are the fractions of available sites occupied in the lattice and in traps, respectively, $(N_l$ and $N_t$ are the number of lattice and trapping sites per unit volume, respectively, and $N_A$ is Avogadro's number), the variation in time of $C_t$ is the difference between a trapping and a detrapping term. The former is proportional, through $k_A$, to $C_l$ and to the fraction of unoccupied trapping sites $1-C_t$. The latter is similarly proportional to $C_t$ multiplied by a correction factor representing the fraction of available solution sites, $1-C_s/C_s$, where $C_s$ is the saturation concentration. The rate equation is:

$$\frac{\partial C_l}{\partial t} = k_A C_l (1-C_t) - k_B C_t \left(1 - \frac{C_t}{C_s}\right) \quad (4)$$

Here, the irreversible trapping sites, which are described by setting $k_{B,t}=0$, are not considered, because $T=373$ K during the present investigation. Irreversible means that the traps are so deep that the time constants for release are too long to be measured during an experiments. Irreversible traps
have been defined by Oriani as traps where $E_t > 67 \text{ kJ/mol}$, and thus, $k_{B,i} \neq 0$ at room temperature. The continuity equation becomes:

$$\frac{\partial (c_i + c_t)}{\partial t} + \frac{\partial J}{\partial x} = 0$$  \hspace{1cm} (5)

It is evident that the effect of trapping is to increase the hydrogen uptake by providing additional sites to accommodate hydrogen and to increase the time necessary for hydrogen to move into the solid, therefore creating an apparent decrease of the diffusivity. In other words, the effective diffusion coefficient $D_{\text{eff}}$ measured when trapping is present is smaller than $D_l$, where $D_l$ is the diffusivity of hydrogen in the lattice (see fig. 2). On the other hand, trapping does not affect the steady state permeation through the membrane. The steady state permeation flux $J$ across the membrane is always given by eq. (1) and does not depend on the trapping parameters $N_t$, $k_A$ and $k_B$. Then we can write Fick's first law for the flux $J$ in terms of the occupied lattice sites exclusively:

$$J = -D_l \frac{\partial c_i}{\partial x}$$  \hspace{1cm} (6)

The diffusion equation for a system exhibiting trapping can be written as:

$$\frac{\partial c_i}{\partial t} = D_l \frac{\partial^2 c_i}{\partial x^2} - \frac{\partial c_i}{\partial t}$$  \hspace{1cm} (7)

The system of equations (4) and (7) is nonlinear owing to the product $C_i C_t$ and can only be solved numerically.

At equilibrium ($\partial/\partial t = 0$), the effect of trapping on the solubility can be found by eq. (4):

$$C_{t,eq} = \frac{k_A C_{t,eq}}{k_B + \left( \frac{k_A - k_B}{C_t} \right) C_{t,eq}}$$  \hspace{1cm} (8)

For low mobile concentration and low trap occupation, i.e. if $C_t << 1$ and $C_t << 1$, at equilibrium, equation (4) becomes:

$$C_{t,eq} = \frac{k_A}{k_B} C_{i,eq}$$  \hspace{1cm} (9)

and the total concentration $c_{eq}$ is then:

$$c_{eq} = c_{i,eq} + c_{t,eq} = c_{i,eq} \left( 1 + \frac{N_i k_A}{N_i k_B} \right)$$  \hspace{1cm} (10)

or using the definition of $k_A$ and $k_B$: 9
If an effective Sieverts' constant is defined as \( K_{seff} = c_{eq} \sqrt{p} \), since the permeability is not affected by trapping, \( P = D_i \cdot K_s, l = D_{eff} \cdot K_{seff} \) and \( K_s, l = c_{eq} \sqrt{p} \), the effective diffusivity is:

\[
D_{eff} = D_i \frac{K_{s,l}}{K_{seff}} = D_i \frac{c_{eq}}{1 + \frac{N_i}{N_0} \cdot \exp \left( \frac{E_i}{RT} \right)}
\]  

Eqs. (11) and (12) are the relations for the effective concentration and diffusivity arrived at in Oriani's work \(^9\). It can be seen from eq. (12) that at high enough temperatures \( D_{eff} \cdot D_i \), but when the temperature is decreased, \( D_{eff} \) starts to fall below the value of \( D_i \). Note that the temperature at which this occurs depends on both \( E_i \) and \( N_i/N_0 \). Eventually the exponential dependence starts to dominate the denominator and again an Arrhenius behaviour is obtained, but with an activation energy increased by \( E_i \). Eqs. (11) and (12) describe correctly the transition region and the region where, although most of the hydrogen is in the traps, only a small fraction of the traps are filled. Here, it should be noted that if all traps have been filled, i.e. \( C_I l \), the total concentration gradient again becomes identical to the gradient of \( c_I \) and the effective diffusion coefficient approaches \( D_i \).

4. RESULTS AND DISCUSSION

The results for hydrogen in aged F82H in comparison with deuterium in F82H \(^1\) are presented by Arrhenius plots of effective diffusivity, permeability and, hence, values for Sieverts' constant in figures 4, 5 and 6, respectively. The measurements in these figures were determined using a driving pressure, i.e. the pressure on the high pressure side of the apparatus, of 70 kPa. Besides, other permeation measurements with hydrogen driving pressures in the range 30-10^5 Pa were performed, but no significant difference in \( D, P \) and \( K_s \) values, at any temperatures of the present temperature interval (373-723 K), were observed.

Occasionally during the permeation measurements, a small decrease of permeability and diffusivity values was noted, especially at high temperature (723 K). Every time this phenomenon has been observed, due to a build-up of an oxide on the surface during the permeation, the sample has been taken out of the rig and both its sides have been mechanically polished. In fact, the input and output surface conditions must be rigorously controlled to preclude surface impedance to permeation that can affect the determination of diffusivity and permeability values, especially at low temperatures.
It is evident from the results shown in fig. 4 that the measured diffusion coefficients for all the martensitic steels, in the lower part of the present temperature interval (373-523 K), drop sharply below the broken lines representing the data at higher temperatures (633-723 K). Therefore, it may be assumed that, in this high temperature range, the trapping effect becomes negligible and $D_{\text{eff}}$ becomes $D_l$. Thus, the increase in the activation energy of $D_{\text{eff}}$ at lower temperatures is most probably a result of trapping as predicted by eq. (12). It can be seen also that the values of permeability can be described by an Arrhenius straight lines in the present temperature interval. This result arises from the fact that the values of permeabilities have been estimated from the steady part of the time dependent increase of pressure on the low pressure side of the sample, i.e. when the trapped population has reached equilibrium and, thus, does not affect any further the flux of hydrogen through the sample. The contrasting behaviour of the independently measured values of $P$ and $D_{\text{eff}}$ provides remarkably convincing proof of the applicability of Oriani’s model to the present investigation.

According to the classical theory of diffusion, i.e. diffusivities $D_1, D_2$ (and therefore the permeation rates) of two different isotopes of hydrogen should be related to the masses $m_1, m_2$ by a relation of the form $D_1/D_2 = (m_2/m_1)^{1/2}$, the hydrogen diffusivity and permeability for aged F82H obtained in this work were about 2 higher than the deuterium diffusivity and permeability for F82H obtained in 1. This also means that the ageing of 2000 h at 773 K does not significantly affect the hydrogen transport parameters in F82H steel. The Arrhenius expressions for the hydrogen permeability obtained from a fitting to the whole temperature range, lattice diffusivity $D_l$ and lattice Sieverts’ constant values $K_{s,l}$ are as follows:

$$P = 4.9 \times 10^{-5} \exp\left(-\frac{39340}{RT}\right) \text{ (mol m}^{-1}\text{s}^{-1}\text{Pa}^{-\frac{1}{2}})$$

$$D_l = 1.8 \times 10^{-7} \exp\left(-\frac{14090}{RT}\right) \text{ (m}^2\text{s}^{-1})$$

$$K_{s,l} = 0.3 \exp\left(-\frac{25830}{RT}\right) \text{ (mol m}^{-3}\text{Pa}^{-\frac{1}{2}})$$

The values of $E_l$ and $N_l/N_l$ may be estimated, using eq. (13), by a non-linear least square fitting of the experimental data $D_{\text{eff}}$ onto the theoretical curve eq. (12). In fig. 4, the fit is the curve that links the data of both temperature regimes. For such evaluation the following hypotheses have been made:

- the concentration of lattice sites is $5.2 \times 10^{29}$ m$^{-3}$, this value is based on the assumption that, in bcc iron, there are 6 tetrahedral lattice sites per host atom $^{11,12}$,
• the diffusivity of the lattice has been taken to be equal to the diffusivity obtained using the data at high temperatures \( T > 573K \) where the trapping effects are negligible.

The evaluation of the trapping sites and their binding energy was made using the diffusivity data. The values obtained for these two parameters are reported in table 2. An estimation of the trapping parameters was also done using the solubility data. However, this is less accurate because the solubility is not measured directly by the experimental procedure but is obtained by combining permeability and diffusivity data. Using eq. (8) with \( C_t \ll 1 \) there is an estimation of \( C_t \), \( C_I \) and \( c/c_t \) values based on data of fig. 4 in table 3. It is evident from the table that, at high temperatures \( T > 573K \), \( c_t \gg c_t \) and therefore, this supports the approximation made for \( D_I \), i.e. \( D_I \) is obtained from the high temperature range only.

Some published results \(^{13}\) for the trapping energy in various types of trap in ferritic steels are given in table 4. In the grain boundary category, the traps with an activation energy of 59 \( kJ/mol \) relate to high-angle grain boundaries, whereas the traps with an activation energy of 32 \( kJ/mol \) to low-angle grain boundaries \(^{10}\). The interfaces between the second phase particles and the matrix in which they have been precipitated have the highest trapping energy, whereas the second largest values are for grain boundaries and the least effective traps are interstitial N and C atoms or substitutional Cr, Mo, V and Mn atoms. It is worth noticing that, substitutional elements which are located to the right of iron in the periodic of the elements (Ni) should repel hydrogen when present in solid solution, while elements to the left of iron should trap hydrogen. This is confirmed by the literature \(^{16}\), which indicate that substitutional Ni atoms are repulsive trap in an iron lattice. Single vacancies should only exist in significant quantities in irradiated materials. A number of authors \(^{22,23}\) has suggested that lattice defects that have a coherent interface with the surrounding matrix such as dislocations and fine precipitates in the early stages of formation, have a lower trapping energy than, for example, fully coarsened second phase particles which have incoherent boundaries with the metal lattice. After the heat treatment was applied to the present samples, the main trapping places are probably grain boundaries, interstitial atoms and particle interfaces but since the calculated \( E_t \) value for F82H is less than any of the literature values in table 4 for high-angle grain boundaries or precipitates and higher than those for interstitial atoms and low-angle grain boundaries, it is difficult to indicate which trap is predominant. Here it is useful to compare the present measurements with the work of Benamati et al. \(^{24}\) on the hydrogen diffusivity of MANET II using Devanathan's electrochemical technique. These investigators calculated a trapping energy of 22.4 \( kJ/mol \).

However, these authors were not able to measure the trapping energies of traps such as fully coarsened particles since, in the low temperature region of their investigation (278-343 K), such traps were considered to be irreversible because of their depths, i.e. the detrapping rate was too low.
to allow equilibrium between the trapped and non-trapped populations to occur during a measurement. In the present work, such measurements are possible and they seem to suggest that in F82H the trapping is more likely to be associated with the lathe boundaries (martensitic laths), with fine coherent Fe$_3$C precipitates and with dislocations.

5. CONCLUSION

The hydrogen behaviour in F82H aged 2000 h at 773 K was investigated using a gas phase technique employing a step change in pressure. The ageing did not significantly affect the hydrogen transport parameters in F82H steel. In addition, the date obtained in this work well agree with the data obtained in 1 although they were obtained with two different permeation equipments. The data were fitted very well using Oriani's model and the trapping parameters such as the number of trap sites and their average energies were determined. The surfaces of samples were kept under control for the presence of oxide layers.

The trapping process in F82H is very pronounced in the low temperature range up to 523 K. The results obtained can be used as a reference for future evaluation of the effects of the presence of hydrogen in steels damaged by radiation.

ACKNOWLEDGEMENTS

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**Table Captions**

Table 1. Chemical composition of F82H (wt %).

Table 2. Trapping parameters for hydrogen in aged F82H and deuterium in F82H.

Table 3. Estimation of $C_t$, $C_l$ and $c_l/c_t$ values based on data of fig. 4. $C_l$ and $C_t$ are the fractions of available sites occupied in the lattice and in traps, respectively. $c_l/c_t$ is the ratio between the hydrogen atoms in the lattice and traps sites.

Table 4. Trapping energies for hydrogen in ferritic steels and iron alloys.
**FIGURE CAPTIONS**

Fig. 1 Schematic of the permeation apparatus.

Fig. 2. Rate of pressure rise in sealed volume due to hydrogen permeation through aged F82H steel at 423 K. The upstream hydrogen pressure side was about $7 \times 10^4$ Pa. The solid line represents the least squares fitting to the experimental data using eq. (2). The broken line represents an estimation of the pressure rise using eq. (2) and the lattice diffusivity $D_l$ (assuming no trapping). It is evident that, the trapping affects the diffusivity (longer time lag) and leaves the permeability unaffected (same slope). In the insertion, the first 50 sec are depicted.

Fig. 3. Energy model for trapping sites. The energies $E_s$ and $E_d$ are related to solution in the solid (enthalpy of solution) and lattice diffusion, respectively, whereas $E'$ and $E_t$ are related to trapping.

Fig. 4. Arrhenius plot of hydrogen diffusivities for aged F82H compared with deuterium diffusivities for F82H \(^1\).

Fig. 5. Arrhenius plot of hydrogen permeabilities for aged F82H compared with deuterium permeabilities for F82H \(^1\).

Fig. 6. Arrhenius plot of hydrogen Sieverts’ constants for aged F82H compared with deuterium Sieverts’ constants for F82H \(^1\).
Fig. 1

Fig. 2
\[ H(g) \]

\[ \frac{1}{2} H_2(g) \]

Distance

\[ 773 \ 673 \ 623 \ 523 \ 473 \ 423 \ 373 \ (K) \]

\[ 1000/T \ (K) \]

\[ D \ (m^2 \cdot s^{-1}) \]

- aged F82H H_2
- F82H D_2

Fig. 3

Fig. 4
Fig. 5

Fig. 6.
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Table 1
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Table 2

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<td>473 K</td>
<td>0.14</td>
<td>$1.7 \times 10^{-7}$</td>
<td>2.6</td>
</tr>
<tr>
<td>573 K</td>
<td>0.042</td>
<td>$5.2 \times 10^{-7}$</td>
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<tr>
<td>673 K</td>
<td>0.018</td>
<td>$1.2 \times 10^{-6}$</td>
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<tr>
<td>773 K</td>
<td>0.01</td>
<td>$2.1 \times 10^{-6}$</td>
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Table 3
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<th>Type of trap</th>
<th>Trapping energy, kJ/mol</th>
<th>Ref.</th>
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<tr>
<td>Single vacancy</td>
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<td>14</td>
</tr>
<tr>
<td></td>
<td>46.6 and 78.3</td>
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<tr>
<td>Atomic traps</td>
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<tr>
<td>Substitutional Cr atoms</td>
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<tr>
<td>Substitutional Mo atoms</td>
<td>27</td>
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</tr>
<tr>
<td>Substitutional V atoms</td>
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<td>16</td>
</tr>
<tr>
<td>Substitutional Mn atoms</td>
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<tr>
<td>Interstitial C atoms</td>
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<tr>
<td>Substitutional Ni atoms</td>
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<tr>
<td>Interstitial N atoms</td>
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<td>Grain boundaries</td>
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<td>Second phase particles (surfaces)</td>
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<td>AlN</td>
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<tr>
<td>carbide (Fe$_{2-3}$C)</td>
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<td>MnS</td>
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<td>Dislocation</td>
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Table 4