Radiation effects on the mechanical properties and long term ageing of spent fuel storage containers

Brissonneau, Laurent ; Barbu, Alain *; Bocquet, Jean-Louis*

DEN/DTEC/S2EC, CEA Valrhô, 30207 Bagnols/Cèze, France
* DEN/DMN/SRMP, CEA Saclay, 91191 Gif/Yvette, France

Introduction

The CEA is presently studying a spent fuel container which has to insure the insulation of the radio-nucleides and the retrieval of the spent fuel during a storage period covering several centuries. The container is a 50 mm thick low carbon steel cylinder with a welded lid (by TIG or electron beam). An alternative solution is a ferritic ductile cast iron container. Each container contains seven 4 mm stainless steel 304L individual fuel holders. The temperatures at the beginning of the storage are about 250°C at the fuel holder and 150°C at the container. As the duration of the storage can exceed those that are generally accepted for industrial containers, investigations must be carried out to insure that the materials performance will be kept sufficiently high during the whole storage period. A ten years experimental program has been undertaken by the CEA in order to predict the behaviour of the container and of the fuel holder in storage conditions [1]. In order to model the long term behaviour of the materials, the radiation-induced damages in the materials must also be evaluated.
In this paper, the damage flux from neutron and gamma radiation on the low carbon steel container are estimated. The influence of the irradiation on the container's ageing is estimated by a Cluster-Dynamics Model, developed for the reactor vessel. This model takes into account the hardening due to point defects clustering (vacancies and self interstitial atoms (SIA) created by irradiation develop cavities and loops which harden the materials) and copper precipitation : the copper mobility is enhanced by DP in excess and then precipitates. The increase of the shear stress is calculated for different storage conditions. The influence of some parameters is discussed. Conclusions are drawn on the effects of the irradiation and the Cu content on the mechanical properties of the container.

Irradiation damage flux

We consider the gamma and neutron activities over 300 years for two kinds of PWR spent fuels, named UOX G1 and UOX G4 (burn-up of 33 and 60 GW.d/t_U, respectively) [2]. The neutron activity with E_n>0,5 MeV is mainly due to the spontaneous fission of ^{244}Cm. The gamma activity with E_γ>0,5 MeV is mainly due to the decomposition of the ^{137}Cs (E_γ = 0.661 MeV), but ^{106}Ru and ^{144}Ce have also a contribution in the very first years of storage.
The flux on the fuel holders and the container is calculated using basic geometrical assumptions : uniform flux on the container, no neutron absorption by assemblies, gamma absorptions by neighbouring assemblies. The gamma absorption by the fuel holder and the container is taken into account. The gamma flux ϕ_x results from the absorption by x cm of steel of the initial flux ϕ_0 according :

$$\Phi_x = \Phi_0 \cdot \exp(-\Sigma_t \cdot x) \quad (1)$$

with Σ_t (E_γ = 0.661 MeV) ≈ 0.462 cm^{-1} [3]. As a consequence 17% of the gamma flux is absorbed by the stainless steel (SS) fuel holder and 90% of the remaining flux by the 50 mm steel container.
The neutron flux is very low, the maximum value is 3.5.10^3 n.cm^{-2}.s^{-1} at the beginning of the storage. The gamma flux is very high and decreases from 30 GBq/cm^2 at the beginning of the storage to 10^{-2} GBq/cm^2 after 300 years.
The damage flux expressed in 'displacements per atom' (dpa) for the different materials is calculated from the modified Kinchin-Pease formula :

$$< n_{dpa} >= 0{,}8 \cdot \left(\phi \cdot E_D \cdot \sigma(E_D) \Big/ 2 \cdot E_A \right) \quad (2)$$

where ϕ is the incident particle flux, σ is the damage cross section, E_D the energy of the incident particle and E_A is the formation energy of a Frenkel pair (E_A = 40 eV for α iron). For sake of comparison, the same neutron damage cross section as used for the SKB disposal canister by Guinan [4] from SPECTER [5] has been chosen. These values are about ten percent lower than those usually used by the CEA [6]. The damage cross section for the gamma

rays have also been calculated by Guinan [4]. The damage cross sections used in damage flux calculations by Eq.(2) are given in Table I.

Particle Energy	σ neutrons (average)	σ gamma
0,5 - 0,821 MeV	44 barn-keV	$2.91.10^{-4}$ barn-keV
0,8 - 1,5 MeV		$7.96.10^{-3}$ barn-keV
2 – 2.5 MeV		$5.17.10^{-2}$ barn-keV

Table I : Damage cross-section *vs* particle energy for neutron and gamma on iron.

The damage rates *vs* storage time are plotted in Figure 1 for the two types of fuels, UOX G1 and UOX G4. The damage fluences are easily derived from integrated damage flux. Flux at different storage times are reported in Table II for UOX G1 and UOX G4 spent fuels and compared to the results of Guinan for Swedish PWR spent fuels.

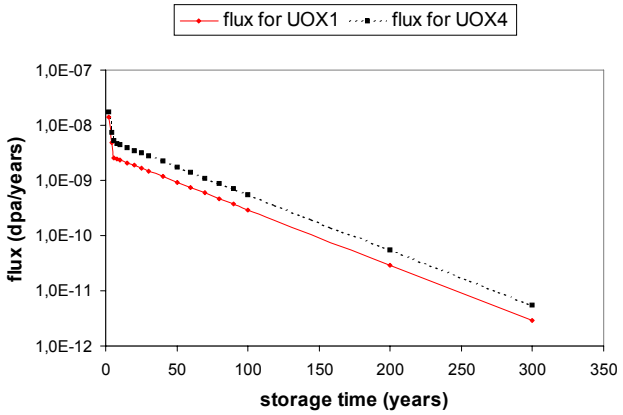


Figure 1 : Damage flux on the container *vs* storage time for spent fuels UOX G1 and G4.

	Damage flux (dpa/year)					
Storage time	Neutron (UOX G1)	Gamma (UOX G1)	Neutron (UOX G4)	Gamma (UOX G4)	Neutron (Guinan)	Gamma (Guinan)
t = 2 years	$4.5x10^{-11}$	$1.4x10^{-8}$	$2.8x10^{-10}$	$1.8x10^{-8}$	-	-
t = 30 years	$1.6x10^{-11}$	$1.5x10^{-9}$	$9.6x10^{-11}$	$2.8x10^{-9}$	$9.2x10^{-10}$	$4.0x10^{-9}$
t = 300 years	$1.1x10^{-12}$	$3.0x10^{-12}$	$3.1x10^{-15}$	$5.6x10^{-12}$	-	-

Table II : Damage flux for different storage times and spent fuels.

The gamma rays are the main contributors to the damage flux during the whole storage period. The damage flux by gamma is decreasing from 3.10^{-8} dpa/year after two years storage to 5.10^{-12} dpa/year after 300 years (UOX G4 case). The contribution of neutrons becomes closer to the gamma contribution at the end of the storage, but is still at least three times lower. Our results are similar to Guinan for the SKB's canister [4], which is not surprising since the fuels and the considered geometries are very similar. It should be noticed that the dose rates are only approximate as heavy assumptions are made. The uncertainty on the results is roughly 50%.

The damage flux on the container is about 10^6 times lower than for a core vessel steel. The total damage fluence after a 30 years storage is about 2.10^{-7} dpa and for 300 years storage is about 3.10^{-7} dpa for a UOX G4 spent fuel. It is several orders of magnitude lower than currently observed in PWR reactor vessels, where such damages are reached within a few hours. Such damages appear to be very low, but it is to be considered that the temperature is much lower than in a reactor and that the storage time is very long. The damage by gamma rays have already been considered by Farell et al. [7] to explain accelerated embrittlement in a test reactor. Their work proves that the gamma contribution must not be neglected compared to the neutron one when the gamma flux is high and the neutron flux is low. But in the case of storage, the effects of irradiation are often neglected. In his discussion [4], Guinan proposed that the vacancy mobility is too high to produce supersaturation and then enhance diffusion. In an AIEA report [8], it is concluded that damage irradiation under storage conditions are "few and far between" and only gamma radiation effects on corrosion are considered. However, in a recent paper, Lee et al. [9] calculated the

stress intensity on the container after a drop, assuming a change of a container mechanical properties due to irradiation during storage.
We use a model to describe the effect of the calculated damage flux on the container in the storage conditions. In order to take into account the variation of the damage flux in the model, it was described by the equation :

$$G = a \cdot \exp(x \cdot t) + b \cdot \exp(y \cdot t) + f \quad (3)$$

where the coefficients a, x, b, y and f for the spent fuels UOX G1 and UOX G4 are given in Table III.

	a	x	b	y	f
UOX G1 (33 MWd/t_U)	2.218×10^{-15}	-2.852×10^{-8}	8.968×10^{-17}	-7.127×10^{-10}	-9.5×10^{-21}
UOX G4 (60 MWd/t_U)	2.27×10^{-15}	-2.850×10^{-8}	1.8×10^{-16}	-7.4×10^{-10}	2×10^{-20}

Table III : Coefficients of equation 3 for the UOX G1 and UOX G4 spent fuels.

The Cluster-Dynamics Model

We use the Cluster dynamics model described in references [10,11]. It describes the nucleation, growth and coarsening of interstitial, vacancy or solute clusters, following the master equation :

$$\frac{\partial C_n}{\partial t} = \beta_{n-1} \cdot C_{n-1} + \alpha_{n+1} \cdot C_{n+1} - (\beta_n + \alpha_n \cdot) C_n \quad (4)$$

where n is the size of the clusters; C_n is the concentration of cluster n (of type, I for interstitial, v for vacancy or p for copper precipitates) ; β_n and α_n are respectively the absorption and emission rates of an element for a cluster of size n (depending on the nature of the cluster : I, v or p). β_n et α_n contain the whole physics of the model and are described following the classical theory of nucleation and growth. The model must solve the coupled differential equations for each n, taking also into account the points defects generated by the irradiation at rate G, and their annihilation by mutual recombination or by diffusion towards the sinks (dislocations, grain boundaries, point defect clusters…), which is currently written for the variation of the point defect concentration (C_d) :

$$\left(\frac{\partial C_d}{\partial t}\right) = G - B \cdot C_i \cdot C_v - \sum_s k_{sd}^2 \cdot D_d \cdot \left(C_d - C_{sde}\right) \quad (5)$$

B is the recombination rate (proportional to D_i+D_v, respectively diffusion coefficients for interstitials and vacancies), where C_d is the concentration of point defects of type d (d= I or v) far from the sink, C_{sde} the concentration of point defects of type d at sink of type s, k_{sd}^2 the sink strength of the sink of type s for the point defects of type d and D_d is the coefficient of diffusion of the defect d [12]. The expression of α_n, β_n, k_{sd}^2 , are given in references [12,13,14].
We use the values of the parameters reported in references [10,11], that have been fitted by comparison with experimental results. The dislocations are the sinks to be considered, with a density of 10^8 cm^{-2}. The clusters formed by interstitials are loops (2D), whereas those formed by vacancies are cavities (3D) and by copper are spherical precipitates. Following these considerations, the hardening $\Delta\sigma_y$ (the increase in the shear stress) induced by the interstitial loops is estimated by using the Orowan equation (Eq. 6), while the hardening induced by vacancy cavities or copper precipitates is modelled by using the Russell Brown model (Eq. 7) [15].

$$\Delta\tau = \alpha_l \cdot b \cdot \mu \cdot \left(\sum_n 2 C_{\ln} R_{\ln}\right)^{1/2} \quad (6)$$

$$\Delta\tau = \alpha_p b \cdot \mu \cdot \left(\sum_n 2 C_{pn} R_{pn} \left(1 - \frac{E_{pn}^2}{E_m^2}\right)^q\right)^{1/2} \quad (7)$$

where $\Delta\tau$ is the increase in the shear strength on the dislocation glide plan at 0 K, μ is the shear modulus, b is the Burger's vector of the dislocation, α_l a coefficient taken equal to 0.23, C_{ln} is the number density of interstitial loops of radius R_{ln} ; E_m and E_{pn} are the energies of the dislocation line in the matrix and the precipitates (voids) of radius

R_{pn} and number density C_{pn} respectively, α_p and q are coefficients equal to 0.8 and 1 respectively for $\sin^{-1}(E_{pn}/E_m) \leq 50°$ and 1 and 3/2 for $\sin^{-1}(E_{pn}/E_m) \geq 50°$. The final shear stress increase is the square root of the sum of the square contributions of the insterstial loops, the vacancy cavities and the copper precipitates. The effect of temperature on $\Delta\tau$ is estimated by using Kocks' model [16].
The Taylor factor allows us to convert the shear stress variation in a change of the uniaxial yield stress following :

$$\Delta\sigma_y = 3.06 \times \Delta\tau \quad (8)$$

According to William [17], the yield stress change induced a change in the brittle-ductile transition for ferritic steels :

$$\Delta DBT_{0.5}(°C) = 0.65 \times \Delta\sigma_y(MPa) \quad (9)$$

In the case of the storage, some change appears compared to usual calculations concerning time-independent neutron flux. It is to be noticed that the equation (4) becomes explicitly dependent of the time since G varies with the time (following Eq. 3). It must be considered when equations (4) and (5) are solved. As the damage are produced by gamma rays (in fact by photo-electrons produced by the gamma rays), the incident particle does not produce any cascade but removes only one atom from its equilibrium position (only one Frenkel pair is produced by one incident particle).
The calculations are performed for storage times between 1 and 10^{10} s (317 years). The code performs 30 calculations but in some cases, the last time cannot be reached probably because the concentration of one specy is too close to its stationary value and results for only the first 143 first years of storage are obtained.
We study the influence of three parameters : the temperature, the damage rate and the copper concentration. Four temperatures are studied 100°C, 150°C, 200°C typical for the storage and 300°C (typical of thermal ageing). Three copper concentrations are studied 0.05%, 0.12% and 0.25%. They correspond respectively to typical copper concentrations in cast iron, in low carbon steel (for example our mock-ups) and in some welds (for example in RPV steels [17]). Five different damage rates are investigated : 0 (only thermal ageing) $G_1/3$, G_1, G_4 and $2*G_4$, where G_1 and G_4 correspond respectively to the damage rates with the coefficients for UOX G1 and UOX G4 given in Table III. $G_1/3$ corresponds to the damage rate produced by the spent fuel G1 at the mid-thickness of the container (see equation 1) ; $2*G_4$ is considered to take into account uncertainties on the flux calculations. Some calculations are also performed at constant damage flux : $G = G_4$ (0). It should be kept in mind that : $G_{4*2} = 2xG_4 \approx 3.8\ G_1 = 11.4\ G_{1/3}$, except in the six first years of the storage when G_1 and G_4 are closer.

Results and Discusion

The shear stress increases very quickly under irradiation, whereas it does not change under thermal ageing, at any temperature. In Table IV, we report the change in the shear stress at 143 or 317 years of storage, for different conditions. The final shear stress depends mainly on the copper concentration, the variation τ *vs* %Cu is almost linear. It is about 23 Mpa for C_{Cu}=0.05%, 36 Mpa for C_{Cu}=0.12%, 50 Mpa for C_{Cu}=0.25%. For low irradiation rate the shear stress is little higher at 200°C, whereas at upper irradiation rate, the shear stress is higher at 100°C. In some cases the calculations stopped, due to the fact that the copper concentration in the matrix is very close to the equilibrium concentration.

Damage Flux	Temperature (°C)	C_{Cu} = 0.05%	C_{Cu} = 0.12%	C_{Cu} = 0.25%
G_1 /3	100	22.8	35.1	51.6
	150	23.3	35.9	51.6
	200	x	36.3	51.0
G_1	100	23.4	36.2	52.0
	150	23.2*	36.4 *	52.4*
	200	x	36.3*	52.3*
G_4	100	23.6	36.4	52.3
	150	23	36.1	51.9
	200	x	35.9	51.6
G_4 x2	100	**	36.5	52.5
	150	22.6	35.3	50.8
	200	**	**	49.9

* calculated at 143 years ; ** not calculated ; x calculation stopped.

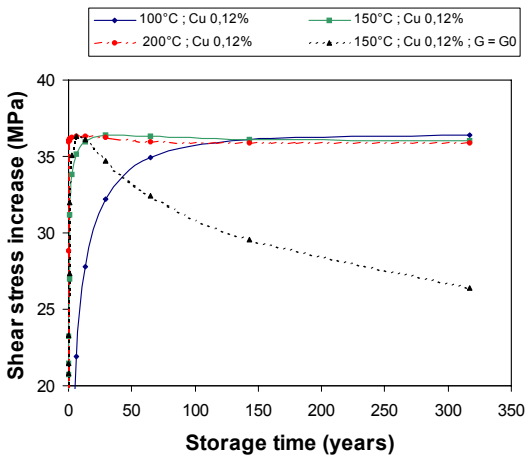
Table IV : Shear stress increase (in Mpa) calculated at 143 or 317 years.

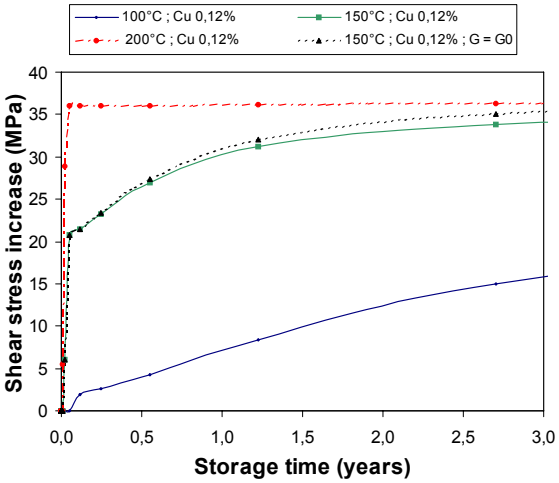
By using equations (8) and (9) we can convert the shear stress increase in yield stress and ductile brittle transition change. The results are given in Table V for average values of τ at different Cu contents. The yield stress increase due to the copper precipitation (between 70 and 150 Mpa) is to be compared with the difference between the yield stress and upper tensile stress before ageing : about 200 MPa for the low carbon steel and the ductile cast iron choosen for the experimental program [1]. The container becomes far less ductile after ageing. The ductile britte transition ($DBT_{0,5}$) for the low carbon steel tested in the program is about –50°C. For the closure weld, the $DBT_{0,5}$ varies from –110°C for TIG welding to –30°C for electron beam welding. Thus, the hardening caused by Cu content of 0.12% or 0.25 % may be a serious problem, as the ductile plateau would be above the room temperature after ageing. A Cu content of 0.05% should be an upper limit for the low carbon steel container. It must be noticed that the shear stress increase at long storage times does not depend sharply on irradiation rate : although the irradiation rate is greatly decreased through the container thickness (Eq. 1), its mechanical properties will remain homogeneous. A calculation under reactor vessel conditions was also performed (T=300°C, $G=10^{-10}$ dpa.s^{-1}, C_{Cu}=0.25%). It is interesting to notice that the same maximum value for the shear stress is obtained that for the storage conditions and C_{Cu} 0.25% : 50 Mpa (maximum reached after 10 years and a rapid decrease after 20 years).

Cu content	C_{Cu} = 0.05%	C_{Cu} = 0.12%	C_{Cu} = 0.25%
Av. Shear stress increase	22.5 MPa	35.5 MPa	50.5 MPa
Av. Yield stress increase	69 MPa	108 MPa	154 MPa
Av. $\Delta T_{0,5}$ increase	45°C	70°C	100°C

Table V : Average shear stress, yield stress and ductile-brittle transition increase after interim storage for different Cu contents in the container.

The maximum value of the shear stress is reached in the very first times of the storage, depending mainly of the irradiation rate and the temperature. Figure 2 shows the increase of the shear stress *vs* storage time for the condition (G4, C_{Cu} 0.12%) at different temperatures.





a) b)

Figure 2 : Shear stress variation for a UOX G4 container with Ccu = 0.12% at 100°C ♦, 150°C ■ and 200°C ● during a) 300 years storage and b) the two first years of storage. A constant damage rate G=G_4(0) at 150°C is also reported ▲.

The increase of the shear stress is very fast at 200°C (two days to reach the maximum value). At 150°C more than half of the increase is reached in 18 days, and the value $\Delta\tau$ =35 Mpa is reached in 6 years. At 100°C the kinetic is much slower and the value $\Delta\tau$ =35 Mpa is reached only after 65 years of storage, though a significant increase occurs in the first years.
After the maximum value is reached, the shear stress slightly decreases during about 100 years at 150°C and 200°C before it attains a plateau. At the contrary, the shear stress still increases at 100°C after 300 years of storage and becomes higher than the values obtained at 150°C and 200°C.
When the damage rate is kept constant at G_4(0), the behavior is unchanged during the first year of storage compared to G_4(t).Then the shear stress increase is little faster but once the maximum value is reached, it decreases much faster and the final value after 317 years of storage is quite lower : 27 MPa instead of 36 Mpa under G_4 .

In figure 3, we report the shear stress increase for a container with C_{Cu}=0.12% at 150°C for different damage rates. The higher the damage rate, the fastest the shear stress increase in the first times of the storage. However, the kinetics observed for G_1 and G_4 are almost similar when it is much lower for G_1/3, which for the maximum value for the shear stress increase seems not to be reached even after 143 years ageing. For the damage rate G_4x2, the value $\Delta\tau$=35 Mpa is reached in 2,7 years, but it begins to slightly decrease after 25 years. Thus the damage rate has a role similar to the temperature for the kinetic of the shear stress variation. It is to be noticed that calculations carried out with G=0 show no hardening under thermal ageing, even at 300°C.

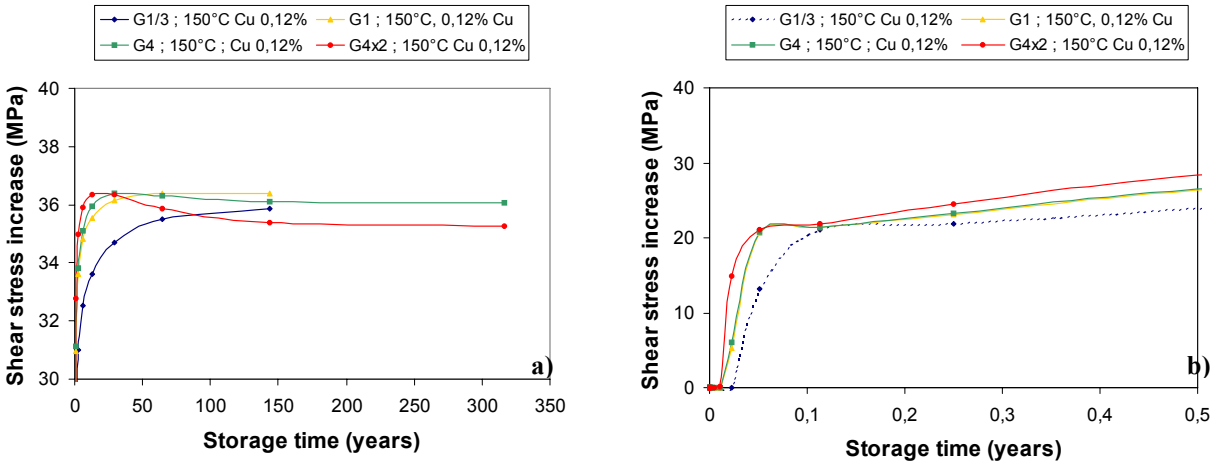
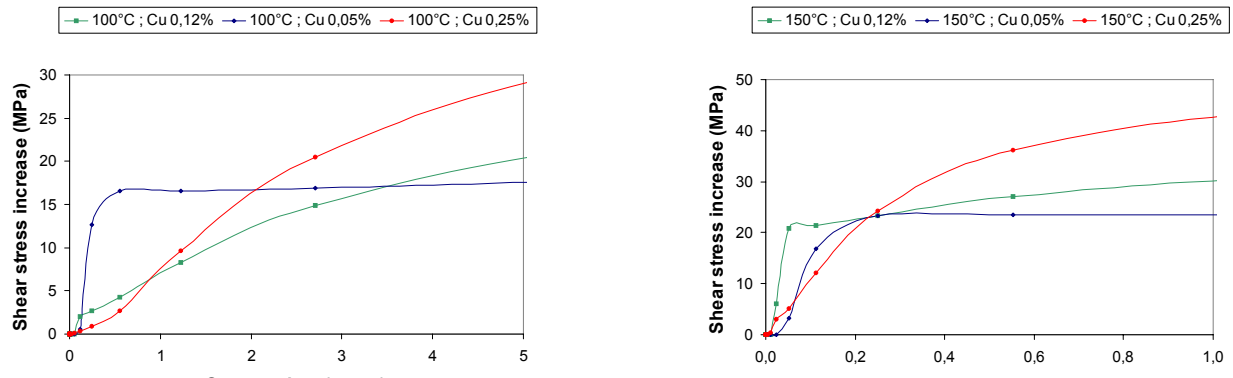


Figure 3 : Shear stress variation vs storage time for a container with C_{Cu} = 0.12% at T=150°C for different irradiation rates : a) during 300 years ; b) during six months of storage.

The considerations on damage rate influence are also true for the other storage temperatures 100°C and 200°C and for the other copper concentrations. However, it must be noticed that the kinetic behavior versus copper concentration is complex at small ageing times. In figure 4, we report the increase of the shear stress during the first years of storage for container at 100 and 150°C for different copper concentrations and an irradiation rate G_4. At 100°C, the kinetic is very fast at low copper content, whereas it is faster for C_{Cu}=0.12% at 150°C.



a) b)

Figure 4 : Shear stress increase during the first times of storage (irradiation rate G_4) for a container with different copper contents at : a) 100°C ; b) 150°C.

The analysis of the different contributions to the shear stress increase shows that interstitial loops and vacancy cavities play no role in the hardening. For example, under damage rate G_1 the maximum concentration for vacancy cavities is 10^7 cm^{-3} after 317 years of storage (cavity diameter is 0.3 nm, about 10 vacancies), that is 10^7 times lower than the copper precipitates concentration (see Fig. 6). The whole hardening is due to copper precipitation enhanced by vacancy supersaturation.

We report the vacancy concentration *vs* storage time in figure 5. It increases very quickly, reaches a maximum value and then decreases. In the first times, few vacancies are annihilated on dislocations as their mobility is very low because of the low temperature (which is not the case of interstitials that remain very mobile even at 100°C : their concentration remains always very low). As the vacancy concentration increases, more vacancies are annihiled on the dislocations. As the damage flux decreases with time, their concentration also decreases.

The vacancy build-up kinetic is much faster at 200°C than at 100°C : the max value is reached after 0.1 year and 30 years, respectively, for damage rate G_4. The lower the temperature, the higher the vacancy concentration. Even, the kinetic of vacancy concentration decrease have the same log slope at 150°C and 200°C, when at 100°C it is much lower.

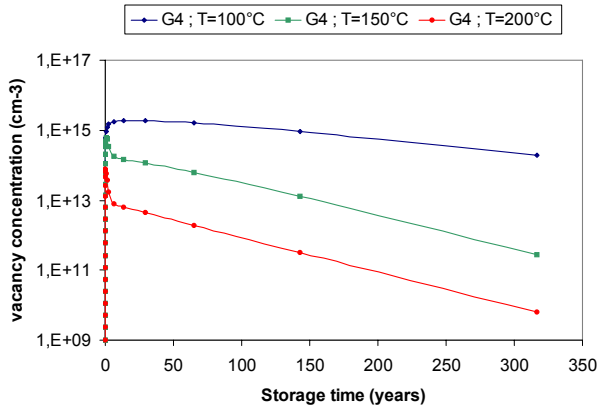


Figure 5 : Vacancy concentration *vs* storage time under damage rate G_4 at 100°C, 150°C and 200°C.

Figure 6 illustrates the copper precipitates distribution :

- at three storage times 0.11 year, 6 years and 317 years for a container with C_{Cu} = 0.12 % at 150°C under damage rates $G_1/3$, G_4 and $G_4(0)$
- at 6 years for a container with C_{Cu} = 0.25% at 200°C under damage rates $G_1/3$, G_1, G_4 and G_4x2.

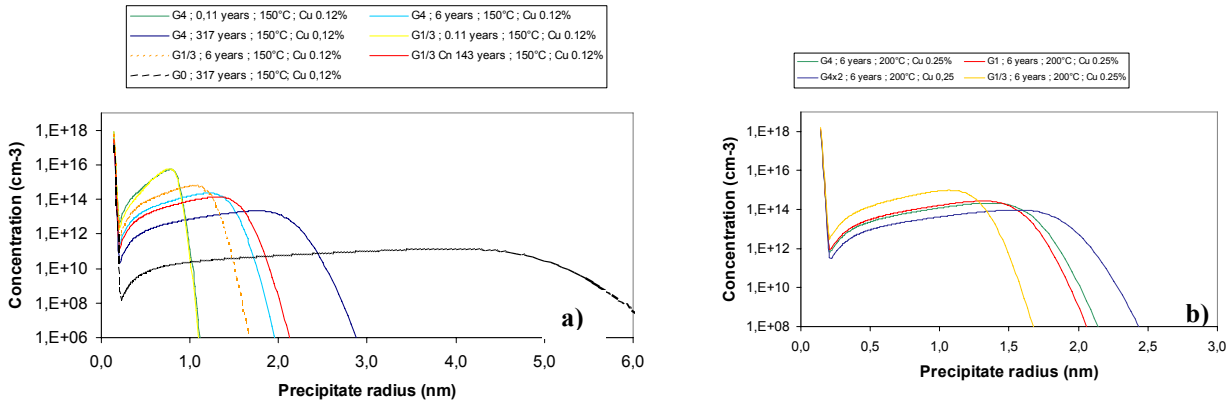


Figure 6 : Copper precipitate concentration *vs* radius for : a) T=150°C, Ccu=0.12%, G = $G_1/3$, G_4 and $G_4(0)$; b) T=200°C, Ccu=0.25%, G = $G_1/3$, G_1, G_4 and G_4x2.

The precipitate radius for the concentration peak is between 0.5 and 1.5 nm after 0.11 years, when it is between 1.5 and 2.2 nm after 317 years. These are typical sizes of precipitates encountered in the welds of reactor vessel steels [17, 18]. The precipitate coarsening is more obvious at higher temperatures and higher damage rates. When the damage rate is kept constant at $G_4(0)$, the copper precipitate distribution is much wider : the maximum concentration, for a precipitate diameter of about 4 nm, is more than 100 lower than under $G_4(t)$.
The diffusion coefficient under irradiation is proportionnal to the point defect supersaturation S ($D^{irr}=SxD^{eq}$). The vacancy supersaturation in the first years of storage is about $S=10^{13}$ at 100°C, $S=10^{10}$ at 150°C and $S=10^{7}$ at 200°C (by comparing vacancy concentration in the iron with and without irradiation).Thus the copper diffusion in iron is highly enhanced (this is taken into account in the model in coefficients β_n and α_n of equation 4), even if it remains slow as the vacancies themselves are slow. As the temperature is low, the copper supersaturation is very high and the nucleation of precipitates is favored when their growth is not (because of the “slow mobile” copper atoms). Thus in the first times of storage are produced a large amount of very small Cu precipitates. This large precipitate concentration of small clusters yields a high increase of the shear stress. It is related to the copper concentration.
At longer storage time, the vacancy supersaturation becomes much lower : about 10^{8} at 150°C and 10^{4} at 200°C.Then, the growth and the coarsening of the copper precipitates slow down. At a given storage time, an increase of the temperature or an increase of the damage rate have a similar effect : it increases the coarsening of the Cu precipitates that becomes larger and less numerous. In some cases, it leads to a decrease of the shear stress.
Further calculations show that if the vacancy supersaturation is lower (obtained by a lower irradiation rate or an higher dislocation concentration), the maximum value for the shear stress is not reached because the Cu precipitation is very slow and even stopped at long storage times when the damage rate becomes very low.
The validity of the results relies strongly on the modelling of the nucleation. Some uncertainty exists for the nucleation because the data used in the model are obtained at higher temperature. It concerns mainly the copper equilibrium concentration and the Cu diffusion coefficient that also play a major role in the nucleation rate [18].
A great question is also the influence of Mn at low temperature. Irradiation experiments conducted at 215°C and 300°C on FeCu and FeCuMn model alloys (C_{Mn} = 1.37%) shows that Mn sharply slows down the copper precipitation [19]. As the copper precipitates contain about 6-10% Mn, Mn may play a role in the precipitate nucleation or in the vacancy mobility [20]. In order to verify these results, irradiation experiments should be conducted on FeCu and FeCuMn model alloys at composition, low dose rates and low temperatures typical of spent fuel storage conditions.

Conclusion

The damage rate on a spent fuel container in interim storage conditions has been calculated. It is mainly caused by gamma rays and is very low compared to RPV steel irradiation. We use a cluster dynamic model to determine the influence of the copper precipitation and point defects clustering on the mechanical properties of the container. It is found that copper precipitation leads to high increases of the shear stress, between 23 and 50 MPa depending on the copper content. Most of the hardening occurs during the first years of the storage, before it reaches a plateau. The higher the irradiation and the temperature, the faster the precipitation kinetic.
This behaviour is attributed to the low temperature, the high enough initial damage rate and the rapid decrease of the damage rate. These conditions promote the nucleation of numerous small copper precipitates but not their growth nor their coarsening. If these results are backed by irradiation experiments, Cu content will have to be specified for the container composition : it will have to be at least lower than 0.05%.
These unexpected results lead us to conduct further works on the irradiation effects in storage conditions. First the results on Cu must be confirmed by irradiation experiments. Then, other similar calculations have to be conducted for the storage of vitrified wastes. Finally, some other phenomena should be carefully studied, as they could lead to serious embrittlement : phosphorus segregation in the carbon steel container and ferrite decomposition in the stainless steel welds of the fuel holder.

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