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GONFLEMENT ET FLUAGE D'IRRADIATION DES ACIERS 316Ti ET 15-15Ti IRRADIES AUX NEUTRONS

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Résumé :

Nous comparons le comportement global, les résistances au gonflement et de fluage d'irradiation des aciers austénitiques écrouis 316Ti et 15-15Ti, utilisés comme matériaux de gaines et TH des réacteurs rapides français.

Le 15-15Ti conduit à une amélioration significative due à un accroissement de la dose d'incubation de gonflement.

On retrouve les mêmes phénomènes que pour le 316Ti. Toutes les structures sans combustible comme les échantillons, les TH ou les gaines vides fluent et gonflent moins que les gaines combustibles irradiées dans les mêmes conditions. Pour expliquer la différence de gonflement, comme pour le 316Ti, le gradient thermique est évoqué. La différence de comportement en fluage n'est pas encore clairement comprise. Pour prédire le comportement des gaines combustibles il est donc indispensable d'étudier les gaines elles-mêmes et d'utiliser des lois de comportement spécifiques.

Tous les résultats confirment le bon comportement du 15-15Ti, le meilleur comportement étant obtenu avec le 15-15Ti dopé au silicium (1%) irradié jusqu'à 115dpa.

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SWELLING AND IRRADIATION CREEP OF NEUTRON IRRADIATED 316Ti AND 15-15Ti STEELS

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ABSTRACT: The global behavior,the swelling and irradiation creep resistances of cold worked 316Ti and 15-15Ti, two variants of austenitic steels in use as core component materials of the French fast reactors, are compared.

The 15-15Ti leads to a significant improvement due to an increase in the incubation dose swelling.

The same phenomena observed on 316Ti are found on 15-15Ti. All species without fuel like samples, wrappers or empty clad swell and creep less than fuel pin cladding irradiated in the same conditions. To explain the swelling difference, as for 316Ti, thermal gradient is also invoked but the irradiation creep difference is not yet clearly understood. To predict the behavior of clads it is indispensable to study the species themselves and to use specific rules.

All results confirm the good behavior of 15-15Ti, the best behavior being obtained with the 1% Si doped version irradiated up to 115 dpa.

KEYWORDS: austenitic steels, 15-15Ti, Si-mod 15-15Ti, 316Ti, neutron irradiation, swelling, irradiation creep, fuel pin, wrapper, thermal gradient, fast breeder reactor, Phénix.

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The successful operation of fast breeder reactors is dependent, to a large extent, on the performance of the structural materials used in the construction of fuel and blanket assemblies. Limited dimensional changes and good mechanical behavior are the main properties required for the use of a material as fuel pin cladding or wrapper.

316Ti and 15-15Ti are the two variants of Titanium-stabilized austenitic steels in use as wrapper and cladding materials of the French fast breeder reactors. These materials are only used in the cold worked condition to minimize their dimensional changes during irradiation. These deformations are principally due to neutron void induced swelling and creep. As described in another paper [1], the swelling of these structures also control their mechanical properties. A substantial number of wrappers and fuel pins of both materials are or have been irradiated. To have better control of the different variables affecting swelling and irradiation creep, samples were also irradiated in capsules.

This document deals mainly with 15-15Ti, that is the present reference steel for the cladding of Phénix and Superphénix. A general presentation of the behavior of this material irradiated up to 90 dpa* have been already performed at the previous conference [2].

This report analyzes the main results for irradiation doses up to 115 dpa. After having compared the global behavior of 316Ti and 15-15Ti steels in fuel elements, we will examine in more details swelling and irradiation creep resistance of 15-15Ti clads and wrappers.

EXPERIMENTAL PROCEDURE

Materials

The main alloying elements of the various heats of 316Ti, 15-15Ti investigated are listed in table 1.

All these steels are in the cold-worked condition.

The 316Ti material considered here C2 W1 correspond to the clad and wrapper material described in [2] [3]. Several heats of 15-15Ti C4-C8, developed in collaboration with French and German people are used. Concerning this last material, a general overview of the developmental work achieved in the different countries has been already presented [4]. The first two C4, C6 and the next two C7, C8 heats belong to the 1.4970 and Phénix specifications respectively. The last C5 is a 1% Si doped version of the 15-15Ti [1] [2]. W7 represents the wrapper material manufactured from the same 15-15Ti heat clad material C7. The S4 material irradiated as samples corresponds exactly to the same heat C4 clad, same geometry, same fabrication route. W6 is a 1.4970 wrapper material used for comparison.

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* the dpa used herein are NRT dpa [2]

TABLE 1--Metallurgical Description of the Different Cladding, Wrapper and Sample materials

Alloy	Ref	Chemical composition (wt %)									cold.work
		Cr	Ni	Mo	Mn	Si	Ti	C	P	B	(%)
316 Ti	C2	17.1	14.1	2.75	1.5	0.49	0.34	0.049	0.015	0.0020	25
316 Ti	W1	16.9	14.0	2.53	1.7	0.50	0.49	0.055	0.020	...	29
15-15 Ti	C4/S4	14.7	14.7	1.15	1.6	0.43	0.43	0.096	0.007	0.0040	23
15-15 Ti	C6	15.2	14.7	1.14	1.8	0.46	0.40	0.100	0.005	0.0030	20
15-15 Ti	C7/W7	15.2	15.0	1.30	1.6	0.51	0.47	0.096	0.035	0.0065	17/23-30
15-15 Ti	C8	15.0	15.1	1.23	1.7	0.62	0.45	0.105	0.033	0.0060	20
15-15 Ti	W6	15.1	15.1	1.26	1.3	0.49	0.48	0.088	0.004	0.0048	20
Si-mod 15-15 Ti	C5	14.9	14.8	1.46	1.5	0.95	0.50	0.085	0.007	0.0040	23

C: Clad S: Sample W: Wrapper

Irradiation and Experimental Conditions

All the irradiations have been conducted in Phénix.

Samples were irradiated as pressurized tubes fabricated from cladding segments of Phénix geometry (6.55 x 5.65, length 27 or 60 mm). They were welded or inserted end to end to form a pin, or individual to facilitate the personal reirradiation. They were irradiated in an experimental capsule placed in a special subassembly named DIMEP. The stresses ranged from 0 to 280 MPa. Argon was used as filling gas instead of helium, in order to get a greater weight loss in case of gas blow-out. Irradiation temperatures vary between 400 and 500°C, but at both ends the available dose rates are limited. Profilometry and density measurements allow us to separate the contributions of swelling and irradiation creep.

On some wrappers, full non-destructive tests have been performed (longitudinal and transverse directions) as well as density measurements at different levels to determine independently swelling deformation and irradiation creep under the effect of sodium pressure.

Most clads have been irradiated in standard or experimental subassemblies (217 pins). Sometimes to obtain higher level doses, pins were reirradiated in fissile capsule (19 pins). Tests performed on the fuel pins were generally profilometries. Density measurements have also been carried out on some defueled pins to determine plastic deformation at each dose increment. The accuracy of determining the density changes is 0.1% for the volume swelling. In this document often pin cladding swelling derived from profilometries after removal of the corresponding calculated plastic deformation. The results obtained by density measurements or from profilometries are in good agreement.

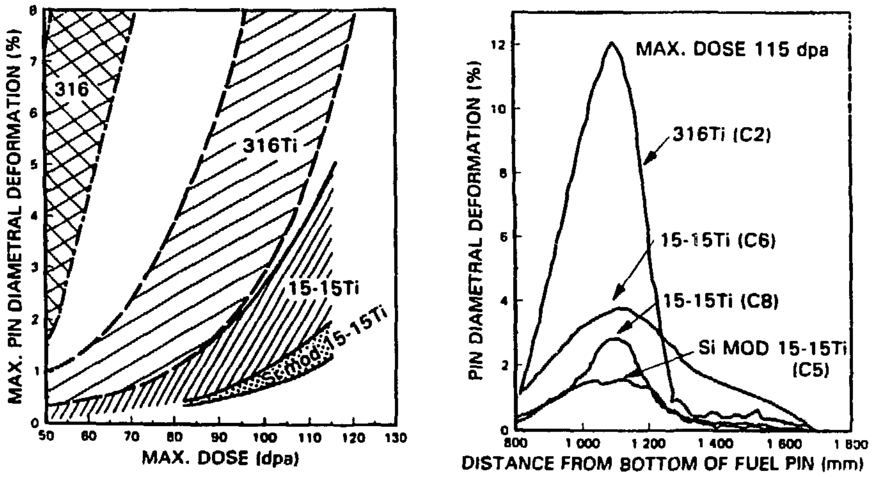
The temperatures were calculated and correspond at each level to an average during the lifetime of the thermal history of the mean fiber of each wrapper face and each clad sections.

GLOBAL BEHAVIOR OF CW 316Ti AND 15-15Ti

The Different Cladding Materials of the Fast Fuel Element

On the basis recent results obtained with higher doses on 15-15 Ti, the curves reflecting strains versus doses have been updated.

Figure 1a compares the performance of the different cladding materials used successively in Phénix in the cold worked condition. This treatment was found to have beneficial impact on the resistance to volume swelling of most austenites which have been tested in irradiation experiments [2 - 7]. This figure emphasizes the gain achieved on the diametral strain when moving from unstabilized 316 to 316Ti, 15-15Ti and a silicon modified version of this last steel (Si-mod 15-15Ti). The good behavior of 15-15Ti which can clearly go beyond the actual Phénix goal burn-up (100 dpa) is confirmed. Some fuel subassemblies have reached 115 dpa without excessive deformation, the record dose being at present of 147 dpa with fuel pins of heat C7 (subassembly still in pile). Most 15-15Ti subassemblies presented here were irradiated in core 1.



a) b)

FIG. 1--Comparison of the different cladding materials.
a) maximum pin diametral deformation versus dose.
b) pin diametral deformation versus distance from bottom of fuel pin at maximum dose around 115 dpa.

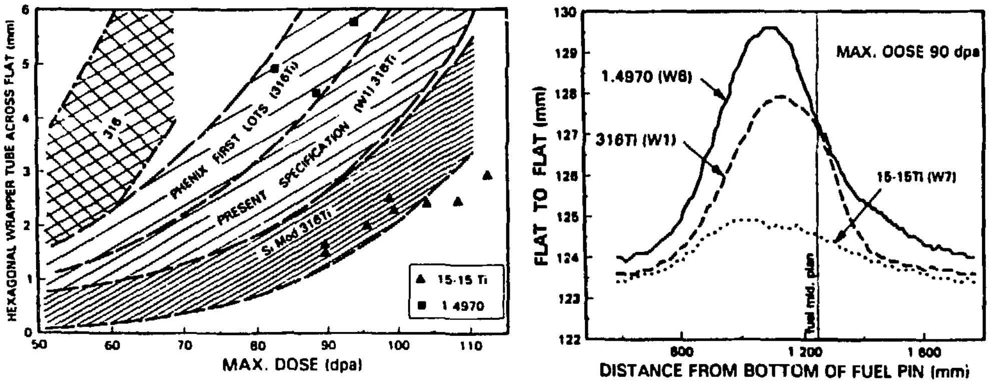
Figure 1b illustrates the difference in behavior between 316Ti (C2), 15-15Ti (C6) (C8) and Si-Mod 15-15Ti (C5) irradiated as fuel pin clad in similar conditions up to approximately 115 dpa. The high temperature swelling which penalized the unstabilized 316 is suppressed in the titanium modified steels.

It exists a factor 3 and 4 between maximal deformation of 316Ti and 15-15Ti (C6) and (C8) respectively. With the Si-mod 15-15Ti batch, the maximum pin deformation is divided by a factor of 10 or 2.4 when compared tc 316Ti or 15-15Ti (C8) respectively. The benefit gained with this steel previously observed at lower doses on samples irradiated in PFR [8] and on fuel pins irradiated in Phénix [3] is evident.

The Wrapper Materials: 316Ti and 15-15Ti

Wrapper swelling and irradiation creep associated with the sodium pressure induce flat to flat and cause handling problems.

As cladding materials, figure 2a compares the performance of the different wrapper tube materials used successively in Phénix, as austenitic steels in the cold worked condition.



a) b)

FIG.2--Performance of the different cold worked austenitic wrapper materials irradiated in Phénix.
a) across flat versus maximum dose
b) Flat to flat variation along three Phénix wrappers irradiated to ~90 dpa.

316Ti wrapper materials were already presented in [2]. Data concerning different 15-15Ti batchs manufactured from a same specification was added. Most of them correspond to the W7 heat. The 15-15Ti behaves as well as the best Si-mod 316Ti in the range 90-112 dpa.

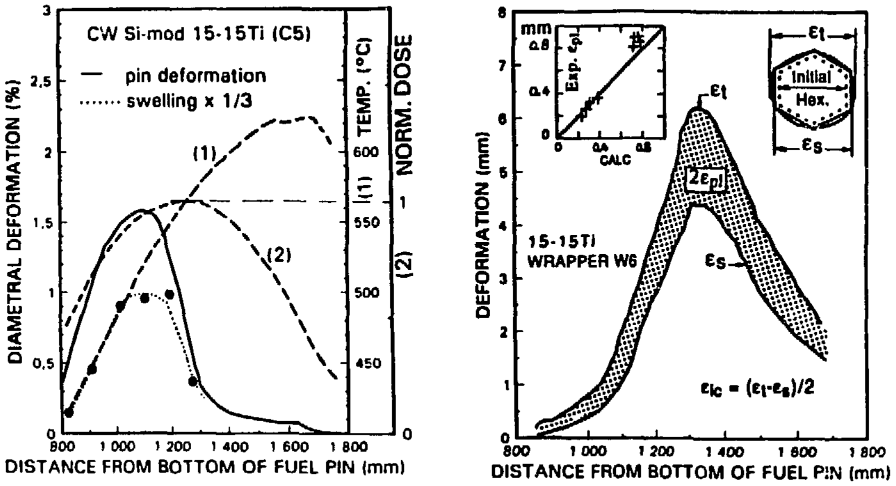
Three wrappers in 1.4970 steel (W6) are also irradiated in Phénix. They correspond to industrial manufactures and have classical Si, Ti, P contents. They behave like bad 316Ti batch (Fig. 2a).

Compared to an average behavior 316Ti and a 1.4970 steel, across flat measurements indicate that the austenitic 15-15Ti wrappers continue to show good dimensionnal stability up to 90 dpa (Fig. 2b) and even up to 112 dpa (Fig. 2a).

Clad and Wrapper Swelling of Fissile Subassemblies

It is important to analyze the deformation curves in terms of two components: swelling and irradiation creep.

The swelling is measured along the fuel pin clad by immersion density. The irradiation creep component is classically obtained from the difference between the total deformation given by profilometry and on third of the volume swelling. Before, it is necessary to ensure if in the irradiation conditions the part of thermal creep is negligible. Figure 3a compares the deformation and the experimental swelling profile (1/3 of the density changes) along the fuel pin for Si-mod 15-15Ti C5 heat. The swelling deformation represents about 70% of the total deformation. The results give further confirmation of the low swelling behavior of this material with the beneficial effect of silicon. Its swelling deformation is inferior to 1% for a maximum dose of 115 dpa.



a) b)

FIG.3--Deformation and swelling profile

a) along a fuel pin of Si-mod 15-15Ti (C5). Normalized dose is defined as the actual dose divided by the maximum dose (~115 dpa).

b) along a W6 wrapper (max. dose = 94 dpa).

As regard to the wrapper, from non destructive tests performed, as longitudinal profilometries, we determine for a faces couple total deformation εt (Fig.3b) which is the sum of swelling εs and irradiation creep εic deformations. From transverse profilometries, the plastic deformation due to irradiation creep can be defined, always for faces couples. As $\varepsilon ic = (\varepsilon t - \varepsilon s)/2$, swelling contribution, the difference between total and plastic deformation, can be determined. Figure 3b presents an example of average behavior of one of three faces couple of a wrapper manufactured from W6 heat. Here also, the contribution of swelling deformation is about 70%.

The main tests performed to characterize the dimensional stability are generally profilometries. Density measurements have also been carried out on some defueled pins to determine, from the total deformation, the swelling and plastic deformations. In a first time, let us focus ~~we~~ on the latters, more exactly on the irradiation creep.

IRRADIATION CREEP OF 15-15TI

Irradiation creep contributes to the dimensional changes occuring in 15-15Ti irradiated under stress.

Before going into the analysis of wrappers and clads of fissile subassemblies, we analyze the results obtained on samples.

Irradiation Creep of Samples

From pressurized tubes irradiated in capsules, irradiation creep deformation data were obtained by substracting the strains due to swelling from the total deformations. For the temperature range considered here (400-500°C) the part of thermal creep is nil.

The remaining irradiation creep strains may be explained as the sum of three deformation processes well known [9] [10]. The first one is proportional to stress and irradiation dose and corresponds to a SIPA type creep. The second ~~one~~ contribution presents a quadratic variation with stress and corresponds to a GAP type creep. The third one is proportional to stress and volume swelling and is comparable to the I creep proposed by Gittus [10].

In our experiments the irradiation creep strains measured on pressurized tubes of heat S4, for stresses up to 280 MPa exhibit a negligible contribution of the term GAP at least up to 180 MPa (Fig.4).

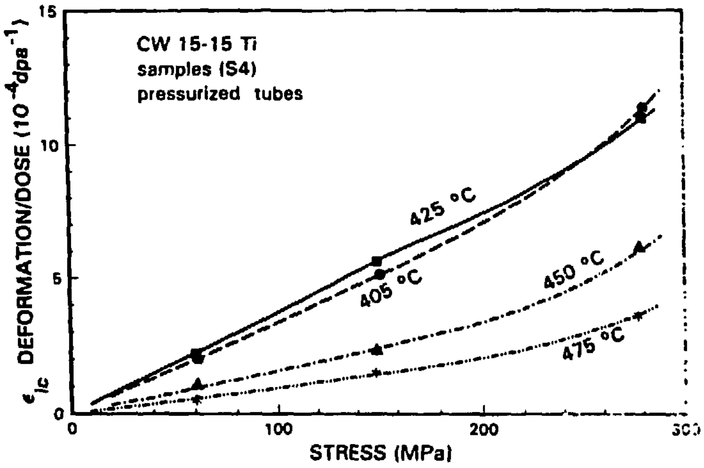
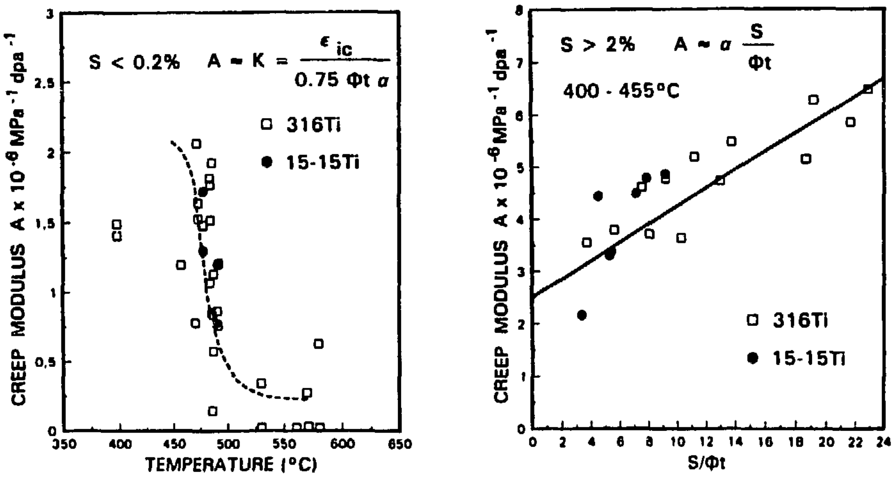


FIG.4--Irradiation creep strains/Dose versus stress for pressurized tubes 15-15Ti (S4).



a) b)

FIG.5-- Characterization of the irradiation creep obtained with the pressurized tube data.

From the analysis of 316Ti pressurized tubes explained in [3] [11], the figure 5a represents the results obtained on this material when selecting only the low swelling points (S < 0.2%) whose the stress is inferior to 180 MPa. In this case, the irradiation creep deformation $\varepsilon ic \sim \frac{3}{4} K \phi t \sigma$ where K is the APIC parameter, ϕt the dose and σ the hoop stress. When we plot 15-15Ti results, they coincide with 316Ti points. If using only the results of the high swelling specimens (S > 2%), figure 5b, here also 15-15Ti points are in the range of 316Ti results.

So we deduce that K and α coefficients of 316Ti and 15-15Ti samples are similar. The 15-15Ti behaves like 316Ti pressurized tubes.

Irradiation Creep of Wrappers

We found for 316Ti [3] that the irradiation creep parameters derived from pressurized tubes results allowed a good prediction of the plastic deformation measured on wrappers due to the sodium pressure. So, from the analysis of CW 316Ti pressurized tubes explained in [3], we verified effectively that the K and α irradiation creep coefficients derived from this last material allows a good prediction of the plastic deformations measured on wrappers of heat W6 (1.4970) Fig.3b. The chemical compositions of S4 and W6 heats are similar.

Accordingly, samples and wrappers of 316Ti and 15-15Ti creep in the same way.

Irradiation Creep of Fuel Pin Clads

From K and α parameters derived from pressurized tubes, it was attempting to use them to predict the behavior of fuel pin clads.

Figure 6 gathers the plastic deformation of a clad (C4), same heat as samples (S4), experimental and predicted values. The latter deformations were obtained with the same method used for W6 wrapper. Here, predictions are bad. The experimental values are larger than those expected from the stress due only to fission gas pressure.

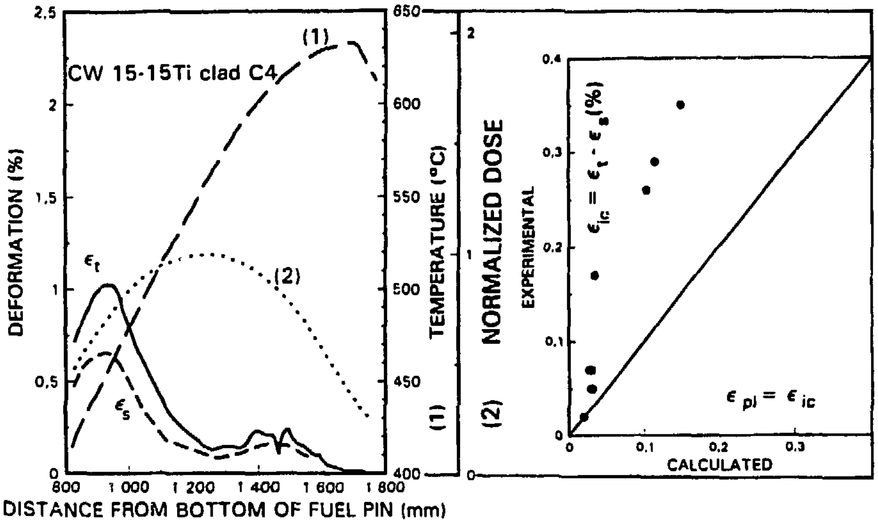


FIG.6--Characterization of the plastic deformation observed on C4 fuel pin.

As for 316Ti, the behavior of pressurized tubes describe very well the behavior of wrapper but not that of fuel pin cladding. So, we have to study irradiation creep of clads on species themselves.

From 9 pins of different 15-15Ti heats ~~whose~~ out of which 2 of Si-mod 15-15Ti, an analysis based on SIPA, PAG and I creep mechanisms was done, using a progressive stress. The coefficients K and α are supposed not depending on different heats of 15-15Ti. This has been shown in [11] for two steels of the same material class, the 316Ti on the one hand and the 316 TiP on the other hand.

In Phénix reactor, since the observed plastic deformations are quite small for 15-15Ti, it is difficult to surround the coefficient α. Conversely, in Rapsolie reactor the stress due to fission gaz was high and the plastic deformations were important. We used early results of 15-15Ti fuel pins irradiated in that reactor. They show that α parameter is constant in a large range of temperature (Fig.7). Its value, around 2 10^{-3} MPa^{-1} is close~~d~~ to ~~this~~ the one got from 316Ti and 15-15Ti pressurized tubes.

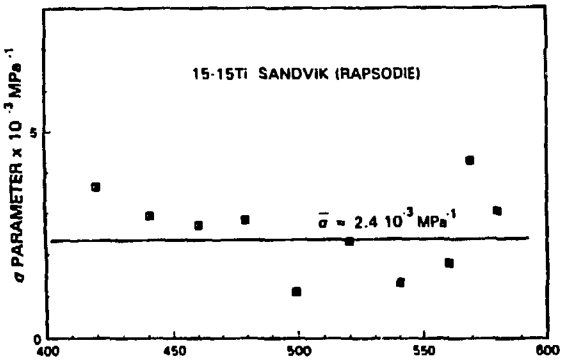


FIG.7-- Variation of α parameter versus temperature for CW 15-15Ti fuel pins (Sandvik heat) irradiated in Rapsodie.

The plastic deformations obtained *on* Si-mod 15-15Ti, the more resistant swelling steel, allows, at low dose level (max dose 86 dpa), to determine the dependence in temperature of the coefficient K (Fig.8). For this material, at low dose level we can assume that I creep contribution is nil.

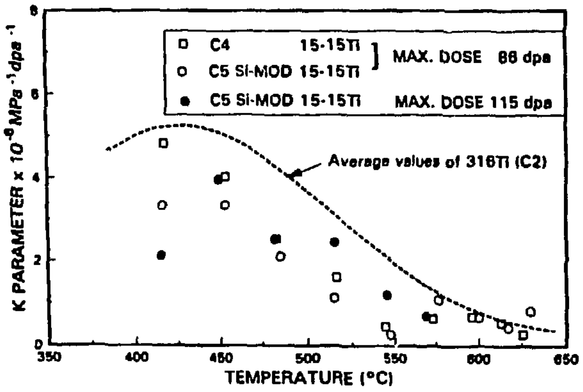


FIG.8-- Variation of K parameter versus temperature for 3 CW 15-15Ti fuel pins irradiated in Phénix (α parameter around 2 10^{-3} MPa^{-1}).

K can be considered almost constant in the range 400 to 455°C, decreasing with temperature up to about 550°C and nearly constant after this last temperature. Knowing experimental irradiation creep deformations, α parameter and the temperature dependence of the K parameter, it is possible to fit this last coefficient using an exponential equation. Compared to the average values of the parameter K obtained on CW 316Ti fuel pin C2 (Fig.8), for 15-15Ti K is rather slower and significantly higher than the values measured on pressurized tubes.

The comparison between samples, wrappers and cladding behaviors leads, in the 15-15Ti to the same conclusions than in the 316Ti [3]. The origin of the discrepancy between clads on the one hand, and samples or wrappers on the other hand, is not yet fully understood and obliges us to use a specific rule to predict the plastic deformations of the fuel pins. This relationship allows us to compute the swelling profile of a clad from their profilometry.

SWELLING OF 15-15 Ti

The influence of the different irradiation variables on the swelling of samples, wrappers and clads 316Ti and 15-15Ti has been already presented [2] [3]. This section deals mainly with the behavior of 15-15Ti. We will point out only the new results concerning the swelling of clads. Then we will present the behavior differences between species like samples, clads and wrappers.

Isothermal swelling versus dose curves can also be derived from swelling data and these are shown in figure 9a. Most austenitic steels exhibit the usual form of swelling behavior with dose. Analogous curves were already presented for 316 Ti [3] and standard 15-15Ti [2], they showed that the steady state swelling rate does not vary significantly at the different temperatures but the incubation dose increases with increasing temperature.

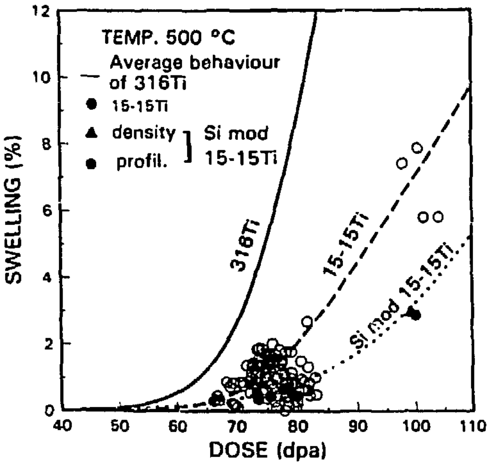


FIG.9a--Variation with dose of the swelling of 15-15Ti, Si-mod 15-15Ti and 316Ti.

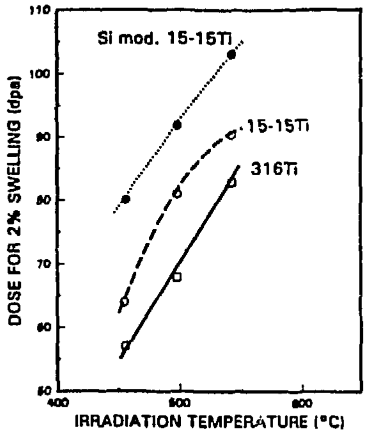


FIG.9b--Variation with temperature of the average dose to reach 2% swelling.

On figure 9a which compares at 500°C the swelling of different 15-15Ti, Si-mod 15-15Ti fuel pin cladding and the average trends for 316Ti, Si-mod 15-15Ti present always the best behavior. The largest part of the gain is achieved by an increase of the incubation dose (Fig.9b).

Behavior Differences between 15-15Ti Clads and Samples.

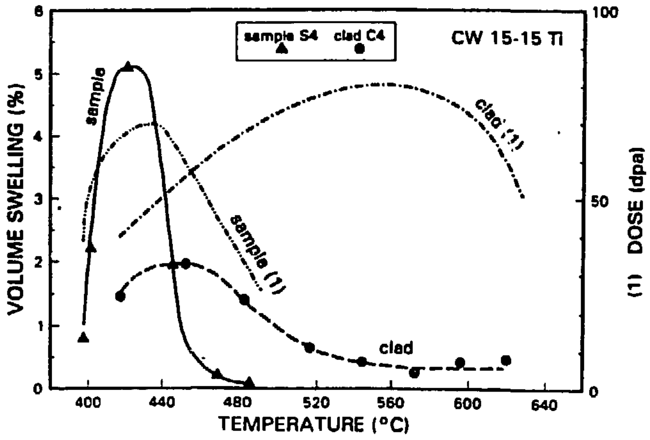


FIG.10--Behavior Differences between 15-15Ti clads and samples.

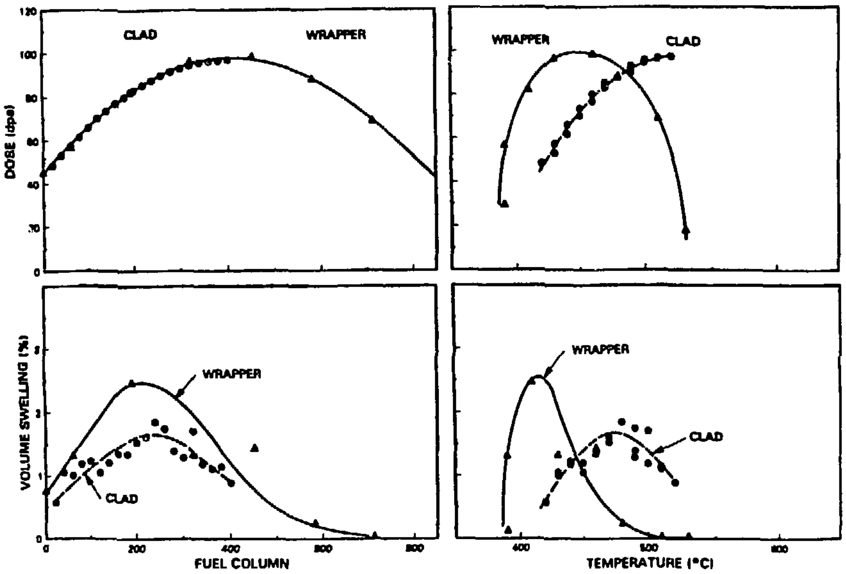
Samples and clads manufactured from the same heat, with the same fabrication route, were irradiated in Phénix. Figure 10 presents the comparison of swelling of the C4/S4 heat (density measurements). The irradiation conditions like temperature and dose distributions are different but times are similar. In each case~~s~~ it exists one specific level where irradiation conditions of samples are identical with one level of clads, here between 450-460°C. As observed previously with 316Ti [3], with identical irradiation conditions (temperature, dose, dose-rate) samples swell always less than clads.

Behavior Differences between 15-15Ti Clads and Wrappers.

Figure 11 compares the swelling of a wrapper and a clad issued from exactly the same heat (W7/C7) and irradiated in the same subassembly. The wrapper swelling data was obtained by immersion density measurements and clad swelling, in a first time, from profilometry corrected from computer irradiation creep strain. The figure 11a which presents the swelling of ~~the~~ both components versus core level shows that the maximal swelling deformations lie at neighboring core levels but wrapper swelling is slightly more important than clad swelling (factor 1.6).

In figure 11b swelling are reploted versus temperature. At 480°C, wrapper and clad have the same dose, it is clear that as samples, wrapper swells less than clad (factor 6). We found again the same phenomenon observed on 316Ti but here, furthermore, the wrapper and clad heat is rigorously identical. In those irradiation conditions, clad C7 behaves well, almost like Si-mod 15-15Ti.

From the average curves of the figure 9a a swelling rule can be computed but, as in the case of the irradiation creep, it cannot be applied to predict the swelling of samples or wrappers.



a) b)

FIG.11--Swelling differences between C7 clad and W7 wrapper, same heat, irradiated in the same subassembly.

<u>Behavior Differences between a Clad of a Fuel Pin and an Empty Clad.</u>

We compared the swelling of two clads of the same heat (standard CW 15-15Ti) irradiated in the same subassembly. One is a classical fuel pin cladding while the other one, called empty clad, is a pheripheral clad where fuel was exchanged with ferritic material pellets. So the repartitions of doses and temperatures are different for both but like for the above comparisons (clad/samples-clad/wrapper) it exists one temperature where irradiation conditions are identical (dose and dose rate). We observed that, irradiated in the same conditions, the empty clad swells less than the fuel pin cladding.

Samples of cladding segments of 15-15Ti (S4) and wrapper segments of 1.4970 heat have been irradiated in the same experiment. Their free-swelling (zero-stress) behaviors are similar. Samples and wrappers behaves in the same way.

Thus as for 316Ti, we confirm the fact that all species without fuel like samples, wrappers or empty clad swell less than fuel pin cladding.

DISCUSSION

The main purpose of this study was to compare the swelling and irradiation creep of neutron irradiated 316Ti and 15-15Ti steels. Our results will be summarized and discussed as follows.

The best behavior of 15-15Ti is clearly emphasized, Si-mod 15-15Ti being the best cladding material. The beneficial effect of silicon observed on samples [8] and on fuel pins [3] is confirmed. As regard to wrapper materials, 15-15Ti behaves like the best 316Ti. In any case the 15-15Ti is not selected as structure material of wrapper.

The analyses of irradiation creep deformations from pressurized tubes has shown that 15-15Ti and 316Ti present the same behavior. Moreover, as already seen for 316Ti, on 15-15Ti it is observed a marked difference between the irradiation creep of clad and wrapper, the behavior of latter is analogous to pressurized tubes. The origin of this discrepancy is not yet fully understood. We can think that the primary stress due to fission gaz, is perhaps not the only one to be considered. Another unidentified phenomenon might deliver a plastic deformation, in addition. Since there is a difference behavior between Samples-wrappers and clads it is indispensable for the design, to predict the clads behavior to study the species themselves and to use a specific rule. Compared to 316Ti clad material, the α parameter of 15-15Ti is slightly higher while the K is rather slightly slower.

Concerning swelling deformation, the average incubation dose of 15-15Ti is larger than the one observed in 316Ti. The beneficial effect of Silicon on the incubation dose of 15-15Ti is evidenced.

As in the case of the irradiation creep a swelling rule computed from clads results cannot be applied to predict the swelling of samples or wrappers. As for 316Ti, it is clearly shown that the clads swell more than wrappers because their swelling temperature domain is larger. In the 450-500°C where the doses received by both of the structures are similar, the wrapper exhibits a marked swelling cut-off whereas the clad reaches its maximum. This behavior difference cannot be explained by some differences in fabrication routes of tubes and hexagonal cans because we saw that specimens of empty Phénix tubes of the same cladding material swell as a wrapper and not as a fuel pin.

In fissile pins the hoop stress due to fission gases is low, less than 45 MPa at the end life for a maximum dose of 115 dpa. The influence of the primary stresses on swelling in this range of stress is weak and cannot used as an explanation for the difference between wrappers and fuel cladding.

The same arguments presented for 316Ti [3] are also used particularly the thermal gradient (ΔT) that exists through the thickness of the material. This last parameter differs within the different species and provide a new variable influencing the properties of irradiated materials.

The difference between clads on the one side and wrappers, samples and empty clad on the other can be partially due to the temperature gradient, since only fissile pins exhibit sufficiently high values of ΔT (≤ 40°C). The difference behavior of wrapper and clad manufactured from same heat presented figure 6 is due to a thermal gradient ~~slightly inferior to 40°C~~ for the fuel pin clad at considered level (mid-wall temperature = 480°C).

As for 316Ti, we can do the same assumptions. The temperature gradient induces differential thermal expansion which results in a stress gradient. Irradiation creep acts to reduce the stress gradient. The stress gradient induced by differential thermal expansion is positive on the clad wall outside, and thus results in positive irradiation creep strain on the clad wall outside. We saw now, with slightly higher level dose (Fig.1b) the 15-15Ti swelling begins to be sensitive to temperature. If ΔT is large enough, a swelling gradient creates inside the clad. In the previous example, the inside clad temperature is around 500°C while the outside clad temperature is around 460°C. In this temperature range swelling decreases with increasing temperature, then swelling strains are larger on the clad wall outside. Further, this discrepancy is enhanced by the stress gradient due to the differential thermal expansion. In its turn, differential swelling strain increases stress gradient. It is positive on the clad wall inside. ~~In this case,~~ the global swelling of the clad inevitably will be larger than a specimen at the same average temperature but with no ΔT present.

As compared to 316Ti, 15-15Ti is an important improvement because its swelling is lower and its incubation dose for swelling is beyond 100 dpa. Furthermore, as presented in another paper in this conference [1] an improvement of the stability of the mechanical properties and the microstructures under extended neutron irradiation confirms the best behavior of this material.

CONCLUSION

The present analysis of the post-irradiation properties of swelling and irradiation creep of the Ti-stabilized 316 and 15-15Ti austenitic steels used as cladding materials confirms that the choice of the 15-15Ti leads to a significant improvement as compared to the 316Ti. This progress is due to an increase in the incubation dose of swelling, the largest one being obtained on Si-mod 15-15Ti.

It has been demonstrated, as already shown on the 316Ti, that the swelling of the 15-15Ti fuel pins is significantly higher than the swelling of species irradiated without fuel like samples, wrappers or unfueled clad. The irradiation-induced plastic deformations observed on 316Ti and 15-15Ti are slightly different. If these deformations are due to irradiation creep occuring under fission gases pressure, they appear to be markedly higher than expected from pressurized tube data or from plastic deformation of wrappers. Specific rules have to be used to predict the swelling or the irradiation creep behavior of clads.

The 15-15Ti cladding is now statistically qualified up to the dose of 115 dpa and there is a good possibility that this performance could be increased to 140-150 dpa.

REFERENCES

[1] Fissolo, A., Lévy, V., Maillard, A., Séran, J.L., Rabouille O., in this conference.

[2] Séran, J.L., Lévy, V., Dubuisson, P., Gilbon, D., Maillard, A., Fissolo, A., Touron, H., Cauvin, R., Le Boulbin, E., Effects of Radiation on Materials: 15th Conference, ASTM STP 1125, American Society for Testing and Materials, Philadelphia, to be published.

[3] Séran, J.L., Touron, H., Maillard, A., Dubuisson, P., Hugot, J.P., Le Boulbin, E., Blanchard, P., Pelletier, M., Effects of Radiation on Materials : 14th International Symposium (Volume II), ASTM STP 1046, N.H. Packan, R.E. Stoller, and A.S. Kumar, Eds., American Society for Testing and Materials, Philadelphia, 1990, pp.739-752.

[4] Lévy, V., Séran, J.L., Maillard, A., Martella, T., Bergmann, H.J., Dietz, W., Erlich, K., Herschbah, K. Lippens, M., Vanderborck, Y., British Nuclear Energy Society, Conference on fast reactor core and fuel structural behaviour. 4-6 June 1990 Inverness.

[5] Azam, N., Delaplace, J., Le Naour, L., Irradiation Behaviour of metallic materials for fast reactor Core components, INTERNATIONAL CONFERENCE, J. Poirier and J.M. Dupouy Eds, AJACCIO, Corsica, 1979, pp 177.182.

[6] Brager, H.R., Garner, F.A., Effects of Radiation on Materials: 11th Conference, ASTM STP 782, H.R. Brager and J.S. Perrin Eds., American Society for Testing and Materials, Philadelphia, 1982, pp 152-165.

[7] Séran, J.L., and Dupouy, J.M., "Dimensional Stability and Mechanical Behaviour of Irradiated Metals and Alloys", Proceedings of the Conference Organized by the British Nuclear Energy Society (BNES), Vol.1.1983, British Nuclear Energy Society, pp 25-28.

[8] Herschbach, K., Schneider, W., and Bergmann, H.J., Effects of Radiation on Materials: 14th International Symposium (Volume II), ASTM STP 1046, N.H. Packan, R.E. Stoller, and A.S. Khumar, Eds., American Society for Testing and Materials, Philadelphia, 1990, pp. 739-752.

[9] Mansur, L.K., Philosophical Magazine A, Vol.39, N° 4, 1979, pp. 497-506.

[10] Gittus, J., Philosophical Magazine 25, 1972, pp. 345-354.

[11] Dubuisson, P., Maillard, A., Delalande, C., Gilbon, D., Séran, J.L.,Effects of Radiation on materials: 15th Conference ASTM STP 1125, American Society For Testing and Materials, Philadelphia,to be published