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# Carburization Behavior of Steels in High Temperature Sodium

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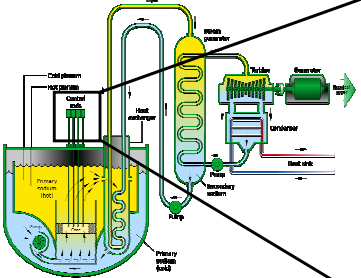
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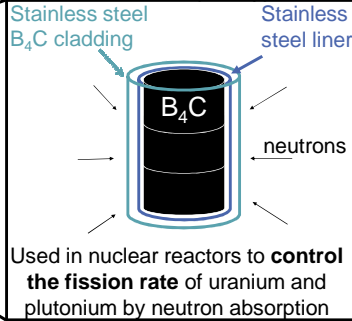


## Scope and Issue

### Sodium-cooled fast reactor (SFR)



### Control rod concept in next French SFR prototype



### Feedbacks from former SFR: Mechanical rupture



Conservative lifetime models based on the carburization kinetics of stainless steels have been proposed in countries having developed SFRs. All these previous studies proposed that the mechanical properties were highly degraded over a critical carbon concentration lying between 0.2 and 0.4 wt.% [1-3]. In order to optimize the control rod lifetime in the reactor, the carburization mechanisms and kinetics have to be described accurately.

[1] J.L. Krankota. *Journal of Engineering Materials and Technology*, 98(1), 9 (1976).

[2] A. W. Thorley and M. R. Hobdell. *Carbon in sodium: A review of work in the UK* (UKAEA Harwell 1984).

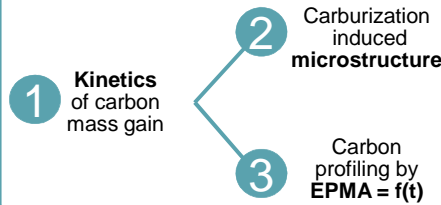
[3] L. Brunel. *Proposition d'une loi enveloppe de carburation* (CEA 1984).

## Experimental procedure

### Carburization experiment in Na

- $a_c = 1$  to maximize carburization
- $T = 600\text{ °C}$  near service temperature
- $t = 0$  to 5000 h
- Sample thickness = 1 mm
- Steels tested:  $\gamma$  17Cr10Ni – 316L  
 $\gamma$  14Cr14Ni0.4Ti – AIM1  
 $\alpha$  9Cr – EM10

## Collected data



## Objectives

Determination of an apparent carbon diffusion coefficient ( $D_{app}$ ) for technological use from:

**A**  $C(X, t) = \text{erfc}\left(\frac{X}{2\sqrt{D_{app}t}}\right) (C^S - C_0) + C_0$

Determination of a carburization model for extrapolation purpose on other steel grades from:

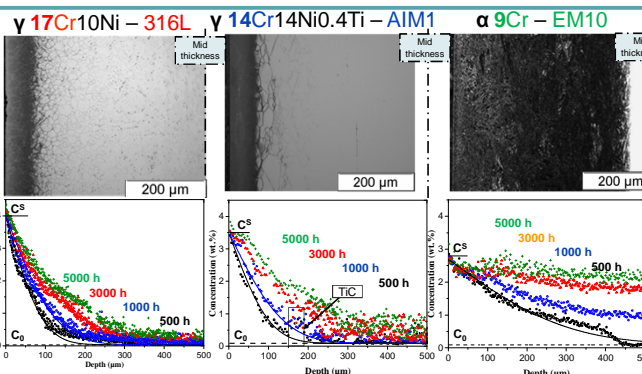
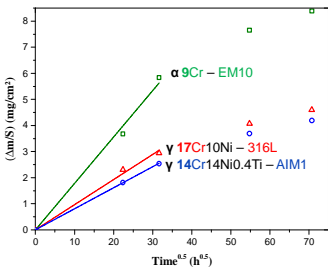
**B** Wagner's carburization model [4]  
Young *et al.*'s carburization model [5]

[4] C. Wagner. *Z. Elektrochem*, 63, 772.782 (1959).

[5] D. Young, P. Huczukowski, T. Olszewski, T. Hüttel, L. Singheiser, W.J. Quaddakers. *Corrosion Science*, 88, 161 (2014).

## Kinetic study

Parabolic kinetics until 1000 h (semi-infinite media only valid for exposure times of 500 h and 1000 h)



Cross section images by optical microscopy showing: Intragranular carburization zone with or without Intergranular carburization zone

$C^S$  constant with time

**A**  $D_{app} = 1.4 \cdot 10^{-11} \text{ cm}^2 \cdot \text{s}^{-1}$

$D_{app} = 3.2 \cdot 10^{-11} \text{ cm}^2 \cdot \text{s}^{-1}$

$D_{app} = 1.7 \cdot 10^{-10} \text{ cm}^2 \cdot \text{s}^{-1}$

## Carburization model

### Wagner's diffusion model:

All Cr precipitate to form carbides

Only carbon diffuses which implies:  $C^S_M \times D_c(\gamma) \gg C^S_C \times D_c(\alpha)$

$D_c(\gamma \text{ or } \alpha) = \frac{k_p^C v C_{Cr}^0}{C_M^S}$

For  $\gamma$  14Cr14Ni0.4Ti – AIM1  
 $C^S_M \times D_c(\gamma) \gg C^S_C \times D_c(\alpha)$   
 $v$ : Carbide  $CrC_x$  with  $v = 3/7$   
 $C^S_C$ : Chromium content in the steel  
 $C^S_M$ : Carbon content in the matrix calculated with ThermoCalc (TCFE8)

- $D_c(\gamma) = 1.8 \cdot 10^{-8} \text{ cm}^2 \cdot \text{s}^{-1}$
- $D_c(\alpha) = 2.9 \cdot 10^{-9} \text{ cm}^2 \cdot \text{s}^{-1}$
- $D_c(\alpha) = 6.7 \cdot 10^{-7} \text{ cm}^2 \cdot \text{s}^{-1}$

From Wagner's model of carburization,  $D_c(\gamma, \alpha)$  should be overestimated compared to literature values in order to fit the experimental carburization kinetics

The fact that not all Cr form carbides may explain this discrepancy

[6] J. Agren. *Scripta Metallurgica*, 20, 1507 (1986).  
[7] A. W. Bowen, G. M. Leak. *Metallurgical Transactions*, 1, 1695 (1970).

### Young *et al.*'s carburization model:

Not all Cr precipitate

Normal diffusion of solute carbon within the metal phase coupled with rapid carbide precipitation and equilibrium partitioning of carbon between the metal and the precipitates phases

$\frac{\partial C_M}{\partial t} = D_C \frac{\partial^2 C_M}{\partial x^2} - \frac{\partial C^P}{\partial t}$   
 $C^P \approx C^{TOT} - \beta C_M \approx \beta C_M$   
 $\frac{\partial C^{TOT}}{\partial t} = \frac{D_C}{1 + \beta} \frac{\partial^2 C^{TOT}}{\partial x^2}$

$C^P$ : Carbon content in carbide precipitates determined with ThermoCalc (TCFE8)  
 $C_M$ : Carbon content in the matrix calculated with ThermoCalc (TCFE8) neglected  
 $\beta$ : Partitioning coefficient supposed constant considering only one carbide  $M_3C_2$   
 $C^{TOT}$ : Total carbon content in the steel from [3]  
 $\frac{D_C}{1 + \beta} = D_{app}$ : Apparent carbon diffusion coefficient

- $D_c(\gamma) = 5.6 \cdot 10^{-10} \text{ cm}^2 \cdot \text{s}^{-1}$
- $D_c(\alpha) = 1.2 \cdot 10^{-9} \text{ cm}^2 \cdot \text{s}^{-1}$
- $D_c(\alpha) = 2.7 \cdot 10^{-7} \text{ cm}^2 \cdot \text{s}^{-1}$

Young *et al.*'s carburization model well described the observed kinetics

Slight discrepancy for AIM1: effect of strong carbide former TiC on  $\beta$ ?

## Conclusions

- $C^S$  at equilibrium with  $a_c = 1$  can be estimated from EPMA profiles
- Parabolic carburization kinetics in strong carburizing Na ( $a_c = 1$ )
- Faster carbon diffusion in ferritic and low Cr steel (but lower carbon absorption power)
- Carburization well described using Young *et al.* diffusion model

## Prospects

- The apparent diffusion coefficient,  $D_{app}$ , which has technological interest, can be predicted whatever steel grades by the expression:  $D_{app} = \frac{D_C}{1 + \beta}$
- Characterization of carbides within the steels
- Experiments in reactor's conditions ( $B_4C$ )