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Selection of properties and models for the HTR coated particle

HTR-F WP3

Deliverable Nb 12

A collaboration of work performed by
BNFL, CEA, FRAMATOME-ANP and FZJ

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Summary

The following Report represents the Deliverable Nb12 of the Work Package 3 (Fuel modelling) in the HTR-F created by the European Community.

It concerns the selection of properties and models for the materials, kernel and coatings which constitute the TRISO coated particle.

This review and this evaluation of the existing data was performed by the four organisations involved in the WP3 : BNFL, CEA, FRAMATOME-ANP and FZJ.

This report is a compilation of three documents relating to the following items:

Fuel properties and models,

Diffusion data,

Coatings properties.

List of documents

1. Fuel properties and models

"HTR-F Project : Selection of properties and models for the coated particle – Fuel kernel"
by M. Pelletier (CEA) and D. Martin (BNFL Consultant)
Report CEA SESC/LSC/03-029 ind. 0 August 2003

2. Diffusion data

"Choice of Data for HTR Fission Products Behaviour - FRAMATOME-ANP Contribution to HTR-F WP3"
by P. Guillermier
Report FRAMATOME-ANP FF DC 0556 May 2003

3. Coatings properties

"HTR-F Project : Selection of properties and models for the coated particle – PyC and SiC"
by M. Pelletier (CEA), H. Nabielek (FZJ), T. Abram (BNFL) and D. Martin (BNFL Consultant)
Report CEA SESC/LSC/03-028 ind. 0 gust 2003

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HTR-F PROJECT : SELECTION OF PROPERTIES AND MODELS FOR COATED PARTICLE : FUEL KERNEL

DE M. PELLETIER AND D. MARTIN (BNFL CONSULTANT)

Note Technique SESC/LSC 03-029 **Indice 0** **de août 2003**

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Titre : HTR-F PROJECT: SELECTION OF PROPERTIES AND MODELS FOR COATED PARTICLE: FUEL KERNEL

Auteur(s) : M. PELLETIER AND D. MARTIN (BNFL CONSULTANT)

Summary :

:
The Work Package 3 of the HTR-F program (WP3) is dedicated to the modelling of the different phenomena which occur into the fuel particle during irradiation and to develop at the European level a common code. This tool has to main mission to predict the time-to-failure taking into account several mechanisms such pressure vessel, SiC layer corrosion, coating debonding or kernel migration.

A first task of the WP3, has consisted to gather the knowledge on particle component properties and fundamental models for describing the behaviour of the coated particle under irradiation in order to reach the best accuracy. This collection of the current knowledge was the object of the Deliverable Nb11 of the WP3 published in December 2002.

The present document, part of the Deliverable Nb12, proposes a selection of properties and models of behaviour under irradiation for the fuel kernel. Furthermore, It supplies well-tried methods for the calculation of the internal pressure of gases (FP and CO/CO_2) produced by the kernel.

Mots Clés	HTR, FUEL, KERNEL, UO2, (U, PU)O2, PHYSICAL PROPERTIES, MODELS, MODELLING

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SOMMAIRE

1. INTRODUCTION

In order to develop HTR reactor in Europe, a program devoted to fuel technology development (HTR-F) was launched in 2000 in the framework of the European network HTR-TN. Around the world, the HTR fuel is based on spherical coated particles inserted in graphite blocks or pebble type elements. Their kernel generally consists of enriched uranium dioxide and the coatings are made of ceramic layers ensuring leak tightness to the fission products during normal and accidental situations.

One of the four Work Package of the HTR-F program (WP3) is dedicated to the modelling of the different phenomena which occur into the fuel particle during irradiation and to develop at the European level a common code. This tool has to main mission to predict the time-to-failure taking into account several mechanisms such pressure vessel, SiC layer corrosion, coating debonding or kernel migration.

Among the tasks of the WP3, the first one has consisted to gather the knowledge on particle component properties and fundamental models for describing the behaviour of the coated particle under irradiation in order to reach the best accuracy. This work is concretised in a document which constitutes the Deliverable No 11.

In the present document, which is a part of the Deliverable Nb12, we propose a selection of properties and models of irradiation behaviour for UO_2 and (U, Pu)O_2 fuels. We also recommend in the last chapter some methods concerning the calculation of the internal pressure of gases (FP and CO/CO_2) produced by the kernel.

2. PHYSICAL AND MECHANICAL PROPERTIES FOR UO_2 AND (U, PU)O_2 FUELS

Most of the properties of UO_2 and (U, Pu)O_2 fuels proposed below result from recommendations for sintered fuels fabrication of the fields PWR and FBR. In our knowledge, there are no laws so complete for oxide fuels made according to the Sol Gel process. In the future, for the new kernel fabrications, measurements of certain properties would be necessary to verify the merits of the present recommendations.

2.1. DENSITY

	UO_2 *[1]*	$(U_{1-y}, Pu_y)O_{2-x}$ *[2]*
ρ (kg / m^3), P (/) N_A: 6.0221 10^{23} a (m) U_i: isotopic composition : U_i / U Pu_j: isotopic composition: Pu_j / Pu τ (at% FIMA)	ρ = 10950 (1 - P)	$\rho = \frac{4}{N_A}\left(\frac{M_{UPu} + 16(2-x)}{a^3}\right)(1-P)$ with a = [5.47 - 0.074 y + (0.301 + 0.11 y) x - 0.00039 τ]10^{-10} and M_{UPu} = (1-y) [235 U_5 + 236 U_6 + 238 U_8] +y [238 Pu_8 + 239 Pu_9 + 240 Pu_0 + 241 Pu_1 + 242 Pu_2]

2.2. LINEAR THERMAL EXPANSION

	UO_2 *[3]*	$(U_{1-y}, Pu_y)O_{2-x}$
α (K^{-1}) T_K (K)	**For T_K < 923 K:** $\frac{l_{T_K}}{l_{273}} = 9.9734\ 10^{-1} + 9.802\ 10^{-6} T_K - 2.705\ 10^{-10} T_K^2 + 4.391\ 10^{-13} T_K^3$ **For T_K ³ 923 K:** $\frac{l_{T_K}}{l_{273}} = 9.9672\ 10^{-1} + 1.179\ 10^{-5} T_K - 2.429\ 10^{-9} T_K^2 + 1.219\ 10^{-12} T_K^3$ $\alpha_{(273-T_K)} = \frac{1}{(T_K - 273)}\left(\frac{l_{T_K}}{l_{273}} - 1\right)$ Correction for substoichiometric mixed oxide fuels (O / M < 2): $\alpha(MO_{2-x}) = (1 + 3.9\,x)\,\alpha(MO_2)$ with $x = 2 - (O / M)$	

2.3. HEAT CAPACITY

	UO_2	$(U_{1-y}, Pu_y)O_{2-x}$ ***[4]***
c_p (J/(mole K)) T (K)	$c_p\left[(U_{1-y}Pu_y)O_{2+x}\right] = c_p\left[(U_{1-y}Pu_y)O_2\right] + \frac{x}{2}c_p(O_2)$ If (O/M) > 2 : x > 0, else: x < 0 $c_p\left[(U_{1-y}Pu_y)O_2\right] = (1-y)\ c_p(UO_2) + y\ c_p(PuO_2)$ with: $c_p\ (UO_{2.00}) = 46.776 + 10.015\ 10^{-2}\ T - 10.045\ 10^{-5}\ T^2 + 4.2386\ 10^{-8}\ T^3 - 5.0145\ 10^{-12}\ T_K^4$ $c_p\ (PuO_{2.00}) = 91.526 + 3.184\ 10^{-6}\ T^2 - 2.269\ 10^{6}\ T^{-2}$ $c_p\ (O_2) = 27.849 + 8.530\ 10^{-3}\ T - 2.0454\ 10^{-6}\ T^2 + 1.932\ 10^{-10}\ T^3$	

2.4. THERMAL CONDUCTIVITY

	UO_2 ***[5]***
λ, λ_0 (W/(m.K)) T_K (K) τ (at% FIMA) P (/)	$\lambda = K_{1d}\ K_{1p}\ K_{2p}\ K_{3x}\ K_{4r}\ \lambda_0$ With: $\lambda_0(T_K) = \frac{1}{0.0375 + 2.165\ 10^{-4} T_K} + \frac{4.715\ 10^9}{T_K^2}\exp\left(-\frac{16{,}361}{T_K}\right)$ $K_{1d} = \left(\frac{1.09}{\tau^{3.265}} + \frac{0.0643}{\sqrt{\tau}}\sqrt{T_K}\right)\arctan\left[\frac{1}{\left(\frac{1.09}{\tau^{3.265}} + \frac{0.0643}{\sqrt{\tau}}\sqrt{T_K}\right)}\right]$ $K_{1p} = 1 + \frac{0.019\ \tau}{3 - 0.019\ \tau}\frac{1}{\left(1+\exp\left(-\frac{(T_K - 1200}{100}\right)\right)}$ $K_{2p} = \frac{1-P}{1+2\ P}$ $K_{3x} = 1$ $K_{4r} = 1 - \frac{0.2}{\left(1+\exp\left(\frac{(T_K - 900}{80}\right)\right)}(1-\exp(-\tau))$

	$(U_{1-y}, Pu_y)O_{2-x}$ *[2]*
λ, λ_0 (W/(m K)) T_K (K) τ (/ FIMA) P (/) x_s: (2 - O/M) (/)	$\lambda_0 = \frac{1}{A + B\,T_K} + C\,T_K^3$ with: $A = 1.32\sqrt{x_s + 0.00931} - 0.0911 + 0.38\,\tau$ $B = 2.493\,10^{-4}$ $C = 88.4\,10^{-12}$ The correction relating to porosity is as follows: $\lambda = \left(\frac{1-P}{1+2P}\right)\lambda_0$

2.5. EMISSIVITY

	UO_2 *[6]*	$(U_{1-y}, Pu_y)O_{2-x}$
ε (/)	$\varepsilon = 0.87$	

2.6. ELASTIC CONSTANTS

2.6.1. Young's Modulus

	UO_2 *[7]*	$(U_{1-y}, Pu_y)O_{2-x}$
E, E_0 (GPa) T_K (K) P (/)	**For 273 £ T_K £ 2610 K:** $E_0 = 2.2693\,10^2 - 1.5399\,10^{-2}\,T_K - 9.597\,10^{-6}\,T_K^2$ **For T_K > 2610 K:** $E_0 = -1.33445\,10^3 + 1.18106\,T_K - 2.38803\,10^{-4}\,T_K^2$ The correction due to porosity is as follows: **If P £ 0.3:** $E = (1 - 2.5\,P)\,E_0$ **If P > 0.3:** $E = \frac{1-P}{1+6P}\,E_0$	

2.6.2. Poisson's Ratio and shear modulus

The Poisson's ratio is given by the following equation:

$$\upsilon = \frac{E}{2G} - 1$$

where E is the Young's modulus and G the shear modulus.

Data concerning the shear modulus are given in the following table:

	UO_2 *[7]*	$(U_{1-y}, Pu_y)O_{2-x}$
G, G_0 (GPa) T_K (K) P (/)	**For 273 £ T_K £ 2610 K:** $G_0 = 85.83 - 5.157\,10^{-3}\,T_K - 3.747\,10^{-6}\,T_K^2$ **For T_K > 2610 K:** $G_0 = -5.7625\,10^2 + 5.02189\,10^{-1}\,T_K - 1.00939\,10^{-4}\,T_K^2$ The correction due to porosity is as follows: **If P £ 0.3:** $G = (1 - 2.25\,P)\,G_0$ **If P > 0.3:** $G = \frac{1-P}{1+3.85P} G_0$	

2.7. IRRADIATION INDUCED THERMAL CREEP

2.7.1. UO_2

The equation of the stationary creep law is as follow *[8]*:

$$\dot{\varepsilon}_{st} = k_\phi \min\left[\max\left(\dot{\varepsilon}_{st1}; \dot{\varepsilon}_{st2}\right); \dot{\varepsilon}_{st\,lim}\right] + \dot{\varepsilon}_{irr}$$

with:

$\dot{\varepsilon}_{st}$	:	equivalent creep rate	(%/h)
$\dot{\varepsilon}_{st1}$	:	equivalent creep rate (1st mechanism)	(%/h)
$\dot{\varepsilon}_{st2}$	:	equivalent creep rate (2nd mechanism)	(%/h)
$\dot{\varepsilon}_{st\,lim}$	:	equivalent creep rate (limit law)	(%/h)
$\dot{\varepsilon}_{irr}$	:	irradiation induced equivalent creep rate	(%/h)
k_ϕ	:	multiplicative factor of the thermal creep under irradiation	

The 5 terms of the stationary creep law spell in the following way:

$$\dot{\varepsilon}_{st1} = 3.16\,10^{7}\,\exp(0.32\,P)\,D^{-1.87}\,\sigma^{3.06}\,\exp\left(-\frac{401{,}700}{R\,T}\right)$$

$$\dot{\varepsilon}_{st2} = 5.33\,10^{-2}\,\exp(0.37\,P)\,D^{2.01}\,\sigma^{8.4}\,\exp\left(-\frac{534{,}700}{R\,T}\right)$$

$$\dot{\varepsilon}_{st\,lim} = 7.13\,10^{6}\,\exp(0.15\,P_m)\,\sigma^{4.03}\,\exp\left(-\frac{461{,}300}{R\,T}\right)$$

$$\dot{\varepsilon}_{irr} = 1.87\,10^{-18}\,\sigma\;\Phi\,\exp\left(-\frac{8{,}100}{R\,T}\right)$$

$$k_{\Phi} = 1 + 2.44\,10^{-13}\,\Phi$$

with:

σ	:	equivalent stress	(MPa)
Φ	:	fission rate	(fiss / (cm^3.s))
P	:	porosity	(%)
P_m	:	maximum of porosity for the limit law (P_m = 7%)	
D	:	grain diameter	(µm)
T	:	temperature	(K)
R	:	8.314	(J / (mole.K))

2.7.2. (U, Pu)O_2

The equation of the stationary creep law is as follow ***[9]***:

$$\dot{e}_{éq} = \exp(25\,P)\left[A\,s_{éq}\exp\left(-\frac{48{,}000}{T_K}\right) + B\,s_{éq}^{4,5}\exp\left(-\frac{75{,}000}{T_K}\right) + C\,s_{éq}\right]$$

in which:

$$A = \frac{3.84\;10^{-7}}{D^{2}}$$

$$B = 3.13\,10^{4}$$

$$C = 2.69\,10^{-30}\;\dot{F}$$

where:

$\dot{\varepsilon}_{eq}$	:	equivalent creep rate	(1 / s)
D	:	grain diameter	(m)
T_K	:	temperature	(K)
σ_{eq}	:	equivalent stress (MPa)	limited to 100 MPa
P	:	pore fraction	(/)
$\dot{F}$	:	fission rate	(fission / (m^3.s))

3. OXIDE FUEL MODELS

The main models which should be taken into account for the behaviour under irradiation of the oxide fuel kernels are:

- In pile densification,
- Fuel swelling due to fission products,
- Fission gas release
- CO / CO_2's production

For the three ones, the proposed models come from the experiences on PWR and FBR oxide fuels. Most are used in CEA fuel codes for several years and were validated on numerous experiences.

Concerning CO's production, we chose in the open literature empirical models built on experimental data and which were already used in the past in other applications.

3.1. DENSIFICATION

The fuel densification, at the beginning of the irradiation, results from a sintering under both the temperature and the fission spikes. It is the fine porosity population (Φ < 1.5 µm), which is the natural residue of the sintering, which is mainly removed.

Densification models are generally more or less empirical.

In the case of present HTR fuels, the manufactured kernel density is required to be ≥ 95%TD. Consequently, we recommend to apply the following semi-empirical CEA model newly developed for PWR UO_2 and MOX fuels in 2001 ***[10]***.

Nevertheless, the different mode of manufacture from both types of fuels: sintering for the PWR pellets, Sol gel process for the HTR kernels can lead to a size and a distribution in size of the porosity which could probably be different.

1- The volume variation due to the reduction of the porosity is expressed by:

$$\frac{\Delta V}{V} = A\left[1 - \exp\left[-\frac{3\,q\,t}{86{,}400\;\rho\,\tau_0}\left(1+\exp\left(-\frac{Q}{T}\right)\right)\right]\right] \quad (/)$$

with:

A:	function of maximum amplitude densification,	
q :	power density	(W/mm^3)
t :	irradiation time	(s)
ρ :	initial fuel density	(g/mm^3)
τ_0:	end of densification burn up	(MWd/t_{HM})
Q :	activation thermal constant	(K)
T :	fuel temperature	(K)

The equation takes into account the key roles of the fission spikes and local temperature to the removal of the small porosity.

Q and τ_0 are empirical constants which depend of the initial microstructure of the fabricated fuel and are set up from experimental data: Q = 750 K and τ_0 = 10,000 MWd / t_{HM}.

The function "A" was also determined from the experience. We provide the subsequent equation of which the coefficients are fitted from the characteristics of the French PWR fuel.

$$A = \alpha \max(5\ 10^{-3} ; 1.8\ 10^{-5}\ T - 1.26\ 10^{-2})$$

with:

α : ajustment parameter: 1 for the French PWR UO_2 fuel

2- Evolution of the porosity:

The initial porosity is given by:

$$P_0 = 100\frac{\rho_{th} - \rho_0}{\rho_{th}} \qquad (\%)$$

with:

ρ_{th} : theoretical fuel density (kg / m^3)
ρ_0 : fabricated fuel density (kg / m^3)

The variation of porosity by in pile densification during a time increment Δt is given by:

$$\Delta P = -\left(\frac{\Delta V}{V}(t) - \frac{\Delta V}{V}(t - \Delta t)\right)$$

3.2. SWELLING

3.2.1. Solid FP swelling

The fuel is considered as an isotropic material. The swelling rate which is determined in UO_2 and $(U,Pu)O_2$ fuels from density measurements reflects the "solid swelling". The density measurements carried out on post-irradiated PWR and FR fuels clearly display a linear behaviour in relation with the burn-up.

This solid swelling includes not only the contribution of solid FP, but also that of the fission gas in super saturation in the fuel or partly precipitated as nanometric bubbles.

For both UO_2 and $(U, Pu)O_2$ fuels the solid swelling rate, $\dot{S}_S$ is given by the equation ***[11]***:

$$\dot{S}_s = \frac{dS_s}{d\tau} = \frac{d\left(\frac{\Delta V}{V_0}\right)}{d\tau} = 0.06$$

with:

$\dot{S}_s$: solid swelling rate (% / GWd / t_{HM})

The volume variation from solid swelling during a burn-up increment $\Delta\tau$ is given by:

$$\Delta S_s = \dot{S}_s \, \Delta\tau$$

Input data : $S_s\,(t - \Delta t)$

Output data : $S_s(t) = S_s(t - \Delta t) + \Delta S_s$

Validity domain : $0 < \tau < 150\ GWd/t_M$

3.2.2. Gaseous swelling

The fuel swelling due to gaseous fission products (Xe, Kr) mainly results to the increase of the bubble population and the bubble size in the matrix and in the grain boundaries. The mechanisms which lead to this swelling are generally complex. It is the reason for which gaseous swelling models are often empirical correlations which depend only from some parameters of which the principals are temperature and burn-up.

Some models are available in open literature, and for the HTR application, we propose to use the "MATPRO" model ***[12]***.

This empirical model simulates the gaseous steady state free swelling between 1000 and 2000 K. It was correlated on the volumic variations related from CHUBB ***[13]*** and TURNBULL ***[14]***.

The gaseous swelling rate in relation with local temperature is as follow:

$$\dot{S}_g = \frac{dS_g}{d\tau} = 2.19912\,10^{-28}\,(2800 - T_K)^{11.73}\,\exp\left[-0.0162(2800 - T_K)\right]$$

with:

$\dot{S}_g$: gaseous swelling rate (% / GWd / t_{HM})

T_K : temperature (K)

Taking into account the gas production, the volume variation from gaseous swelling during a burn-up increment is given by :

$$\Delta S_g = \dot{S}_g \exp\left(-0.19992\ \tau\right)\Delta\tau$$

with:

$\dot{S}g$: gaseous swelling rate (% / GWd / t_{HM})

τ : burn-up at time t (GWd / t_{HM})

$\Delta\tau$: burn –up increment (GWd / t_{HM})

Input data : $S_g\,(t - \Delta t)$

$\Delta\tau$

τ

T_K

Output data : $S_g(t) = S_g(t - \Delta t) + \Delta S_g$

Validity domain : $0 < \tau < 150\ GWd / t_{HM}$

3.2.2.1. Calculation of the gaseous porosity

The gaseous swelling leads to an increase of the porosity (new gaseous porosity):

Input data : $P_g\ (t - \Delta t)$

ΔS_g

Output data : $P_g\ (t)$

3.3. FISSION GAS RELEASE UNDER STEADY STATE CONDITIONS

A certain number of fission gas release models are available for steady state conditions.

For its simplicity, the "equivalent sphere" diffusion model (Booth model) is the first selected. This model assumes that the fission gas is released by a diffusion mechanism within the fuel grains and escapes when it reaches the boundary of an equivalent sphere.

More sophisticated models are always based on the original Booth model but take into account other contributions such the trapping of gas atoms by defects and the resolution by fission spikes or in the case of high burn-up the principle of a saturation threshold which leads to an increase of the kinetic release in the range of low temperatures. It is this type of model (§ 3.3.3) that we recommend.

3.3.1. Fission gas release by direct recoil

In a fuel particle, the radial variation of temperature in the UO_2 kernel is not enough to generate thermal stresses which can lead to its fragmentation. Consequently, it is mainly the outer surface of the spherical kernel which contributes to the direct recoil of fission products (FP).

The diameter of the kernel plays a key role on the quantity of FP which can be emitted by recoil. For a kernel of diameter **d** and for an average distance of FP recoil in oxide **l**, the fraction of FP ejected (F_{eject}) is given by the following relation:

$$F_{eject} = \frac{3}{4}\frac{2\lambda}{d} - \frac{1}{16}\left(\frac{2\lambda}{d}\right)^3$$

The ejected atoms result essentially from the cortical zone of the kernel, and its thickness is equal to the average distance of FP recoil. Consequently, this zone becomes depleted in FP independently of any process of diffusion ; in addition, this depletion is important all the more as the kernel is of small size. The expression below gives the fraction of fission products which is emitted by this area:

$$F'_{eject} = \frac{F_{ejec}}{\left[1 - \left(1 - \left(\frac{2\lambda}{d}\right)\right)^3\right]}$$

For values of diameter usually used for HTR fuel kernels, i.e: **200** to **600** µm and for an average distance of FP recoil in UO_2: λ = **8** µm, F_{ejec} is comprised between **6 and 2%** of the production.

3.3.2. Equivalent sphere model

For the long-lived fission gases, the fractional gas release (FGR) was first described by Booth. It is given by the classical formulation for diffusive release from a sphere:

$$F_B = 1 - \frac{6}{D't}\sum_{n=1}^{\infty}\frac{1-\exp\left(-n^2\pi^2 D't\right)}{n^4\pi^4}$$

with:

t :	irradiation time	(s)
D':	reduced gas diffusion coefficient	(s^{-1})

The reduced gas diffusion coefficient is related to the diffusion coefficient as $D' = D/a^2$ where "a" is the radius of the "equivalent sphere".

An attempt was made to fit this model to the results obtained from coated particles. Generally, if the reduced gas diffusion coefficient is chosen to fit the high release data, most of the lower values are overestimated. HORSLEY and all ***[15]*** have proposed an evolution of the Booth model to improve the correlation between measured and calculated gas release. At low BU, the equivalent sphere radius is assumed to be the mean grain radius. Intergranular bubbles build up gradually in the grain boundaries and the degree of retention decreases when the quantity of gas present at the boundary increases.

As a consequence, it is assumed that the actual release F is simply a fraction of the release calculated from the Booth model : F_B. The fraction α is a function of the gas atoms reaching the boundary and is, thus, proportional to the burn-up.

$$F = \alpha F_B$$

Below a threshold value of gas atoms arriving at the grain boundary, a negligible amount of gas is released and thus:

for $F_B\,\tau < 0.5$ $\qquad \alpha = 0$

Above a saturation level there is no further retention and the release follows the Booth model:

for $F_B\,\tau > 5$ $\qquad \alpha = 1$

One assumes a linear transition between these two extremes:

for $0.5 < F_B\,\tau < 5$ $\qquad \alpha = \dfrac{F_B\tau - 0.5}{4.5}$

with:

τ:	burn up	(%FIMA)

The reduced fission gas coefficient is given by a classical Arrhenius expression:

$$D' = 5\,10^{-3}\exp\left(-\frac{155{,}000}{R\,T}\right) \qquad (s^{-1})$$

with:

T :	fuel temperature	(K)
R = 8.314		(J / (mole.K))

Input data : $F(t - \Delta t)$
T
Δt
τ

Output data : $F(t)$

3.3.3. CEA model

This model was developed for the Fast Breeder Reactor mixed oxide fuel by CEA; it takes into account the fact that the fission gas release evolves with the burn-up increase ***[16]***. If a "BOOTH" model is suitable for low burn-up, it does not allow to correctly assess the FGR when the fuel structure changes at high burn-up particularly in the temperature range : 600 – 1200°C. Consequently, this model seems well adapted for describing LEU UO_2 and $(U, Pu)O_2$ fuels for high burn-up (> 10% FIMA).

The model takes into account an athermal diffusion of the fission gas atoms which is prevailing below 1000°C and a gas saturation threshold function of the temperature. For the calculation of the saturation threshold, the model adopts the SPEIGHT theory ***[17]*** which considers that the phenomena is controlled by the resolution into the matrix of the gas atoms from the bubbles as a result of fission spikes. The main consequence is the formation of an intra and inter granular gaseous porosity which interconnects and favours the fission gas release.

We provide, hereafter, the outlines of the modelling.

A Saturation threshold model

The saturation threshold is reached when the value of the output flux of fission gas atoms from the fuel is equal to the value of the resolution flux from the bubbles in the fuel grain.

From the equality of the two fluxes, we can estimate the fission gas concentration in the fuel at the saturation threshold:

$$Q_{sat} = \frac{bd\dot{F}N_S}{2D} \qquad (at./m^3)$$

with:

b :	probability of resolution	(m^3 / fiss.)
d :	resolution distance	(m)
$\dot{F}$:	fission density	(fiss. / m^3.s)
N_S :	surface density of gas in the bubbles	(at. / m^2)
D :	fission gas diffusion coefficient	(m^2 / s)

the coefficients "b" and "d" are adjustable ; their respective values are get from the open literature ***[18] [19] [20]***:

$b = 5\ 10^{-24}\ m^3 / fiss.$

$d = 10^{-8}\ m$

the fission gas diffusion coefficient is from the LAWRENCE review ***[21]***:

$D = 7.6\ 10^{-10} \exp[-35{,}225 / T] + 1.2\ 10^{-39} F$

the surface density of gas in the bubbles is given by the following established equation for the lenticular bubbles :

$$N_S = 0.3839 \frac{r_b}{kT}\left(\frac{1.6}{r_b} + P_{ext.}\right) \qquad (at./m^2)$$

with:

r_b :	bubble radius	(m)
k :	Boltzmann's constant	$1.38066\ 10^{-23}\ J/K$
$P_{ext.}$:	plenum pressure	(Pa)

Experimental results on various PHENIX fuel allowed to determine a rough estimate for the bubble radius ***[16]***:

$r_b = 5\ 10^{-8}\ m$

B Limit of gas retention

Experimental measurements (EPMA and fuel sublimations) indicate a limit of gas retention in the oxide fuel at high burn up independent from the fuel temperature below 1000 °C. This value is assessed to ***[16]*** :

$N_l = 0.8\ cm^3\ NTP / g_{oxide}$

At high burn up and in this range of fuel temperature, the kinetic of fission gas release tends towards a regime characterized by the following equation:

$$\frac{dN}{dt} = \beta - h'N$$

with:

N :	fission gas retention in the fuel	(cm^3/g)
β :	fission gas production	$(cm^3/(g.s))$
$h' = \frac{15\ D}{a'^2}$	time diffusion constant	(s^{-1})
D :	fission gas diffusion coefficient	(m^2/s)
a'² :	radius of the equivalent sphere	(m)

For a limit of fission gas retention of $0.8\ cm^3\ NTP/g_{oxide}$, the value of the radius of the equivalent sphere is equal to: $4\ \mu m$ ***[16]***.

C Transition towards the high burn up regime

The transition towards the equilibrium regime for high burn up supposes that we accurately describe the development of the gas porosity and the kinetic of gas release. This type of description is very complex and we have preferred to adopt a advantageous simplification which consists to add at the diffusion

equation a transient term indicating that the gas release is proportional to the excess of fission gas retained versus the equilibrium state:

$$\frac{dN}{dt} = \beta - h'N - k(N - N_1)$$

with:

k : time constant (s^{-1})

N_1 : limit of fission gas retention at high BU (cm^3 / g_{oxide})

The time constant "k" compatible with the fission gas retention measurements performed on irradiated fuels is taken to: $2\ 10^{-7}\ s^{-1}$ ***[16]***.

3.4. CO PRODUCTION

Among the different gas which contribute to the inner pressure build-up, the CO production from the reaction between the free oxygen liberated by fissions and the carbon of the inner coatings may become a significant part.

In a large measure, the production of free oxygen depends on the nature of the fuel. It is proved that fuels containing carbon do not produce free oxygen unlike UO_2 and $(U, Pu)O_2$. A lot of data exists for UO_2 fuels but it is not the case for mixed oxide or pure PuO_2 fuels.

3.4.1. « PROKSCH » model

The empirical expression proposed by PROKSCH and coll ***[22]***, based on a large number of mass-spectrometric CO measurements seems to be the best at present to describe this phenomenon. It takes into account both the role of plutonium fissions on the oxygen production and the irradiation time.

He proposes the following equations for the oxygen atoms per fission, neglecting any possible contribution:

$$\log_{10}[(O / f) / t^2] = -0.21 + (-8500 / T)$$

and

$$O / f_{max} = 0.4\ f_U + 0.85\ f_{Pu} \text{ with a upper limit of } 0.625$$

with:

O / f : atomic oxygen release per fission (/)

t : irradiation time (days)

T : particle surface temperature (K)

f_U : U fission rate (/)

f_{Pu} : Pu fission rate (/)

In principle, the validity of the equation is strictly held only in the region covered by experiments:

$950 < \theta < 1525°C$

$66 < t < 550$ days

3.4.2. « STRESS 3 » model

This model proposed by D.G. MARTIN assumes that the number of oxygen atoms released during irradiation is proportional to the number of fissions occurring via plutonium ***[15]***. The temperature dependence is given by:

$$O / f_{Pu} = 1.641 \exp\left(-\frac{3311}{T}\right)$$

For a LEU UO_2 fuel, the ratio between Plutonium fissions and total fissions depends both on the ^{235}U enrichment of the fuel and on the burn up. This function is available in the section 4.1.

3.4.3. Gas pressure: contribution due to CO and CO_2

During irradiation, free oxygen is liberated by UO_2 fuel. In practice, this oxygen will react virtually completely with carbon to produce equilibrium concentrations of CO and CO_2 in accordance with the classical BOUDOUARD reaction:

$$C + CO_2 \Leftrightarrow 2\,CO$$

With the equilibrium constant K_p defined as

$$K_p = \frac{[p(CO)]^2}{p(CO_2)} = \exp\left(18.36 - \frac{19970}{T}\right) \qquad \text{(MPa)}$$

This equation shows that CO is the dominating compound of carbon oxides with high temperature.

If $f = \frac{p(CO)}{p(O)}$ is the fraction of oxygen atoms that react to form CO, the total pressure due to CO and CO_2 is given by:

$$p = p(CO) + p(CO_2) = 0.5\,(1 + f)\,p(O)$$

To calculate the composition of the mixture, if we consider that n_O moles of oxygen are created by irradiation, the number of moles of CO (n_{CO}) and CO_2 (n_{CO_2}) are given by:

$$f = \frac{p(CO)}{p(O)} = \frac{n_{CO}}{n_O} = \frac{\left(K_p^2 + 8\,K_p\,p(O)\right)^{1/2} - K_p}{4\,p(O)}$$

and

$$\frac{p(CO_2)}{p(O)} = \frac{n_{CO_2}}{n_O} = \frac{1}{2}(1 - f).$$

4. OTHER MODELS

4.1. NEUTRONICS

Numerous properties and models depend on irradiation parameters such the fission rate, the burn up … Therefore, it needs to accurately calculate these parameters all along the fuel irradiation.

4.1.1. Burn up

The burn up is the energy released during the life of fuel per unit of mass. Generally the burn up is expressed either by taking the oxide mass or the mass of heavy metal (HM).

The local increment of burn up is given by the following equation:

$$\Delta\tau = \frac{q\,\Delta t}{\rho} \qquad MWd / t_{HM}$$

with:

q :	local power density	(W / cm^3)
Δt :	time increment	(d)
ρ :	HM fuel density	(g_{HM} / cm^3)

The total burn up at time t is:

$$\tau(t) = \tau(t-\Delta t) + \Delta\tau \qquad MWd / t_{HM}$$

4.1.2. Fission rate

Many properties of fuel are affected by the fission rate and by the cumulative number of fissions (fission density).

If the power density is given as an input data by an external neutronics analysis, it is achievable to calculate the fission rate from the power density by the subsequent equation:

$$\dot{F} = \frac{q}{E_f} \qquad fissions / (cm^3.s)$$

with:

q :	local power density	(W / cm^3)
E_f :	averaged fission energy	(J)

A recommended data for E_f is **200 MeV**, that is : **$3.204\ 10^{-11}$ J**

The fission density at time t is:

$$F(t) = F(t-\Delta t) + \dot{F}\Delta t \qquad fissions / cm^3$$

with:

Δt :	time increment	(s)

4.1.3. Fuel burn-up

The fractional fuel burn-up (% FIMA) may be deduced from the fission density with the following equation:

$$\tau = 100 \frac{F}{HM_0} \qquad \% \text{ FIMA}$$

with:

F : fission density (fissions / cm^3)
HM_0 : initial density of heavy-metal atoms (atHM / cm^3)

This initial density of heavy-metal atoms is obtained from the relation:

$$HM_0 = N_A \frac{\rho_{HM}}{M_{HM}} \qquad \text{atHM / cm}^3$$

with:

N_A : Avogadro's number: $6.0221\ 10^{23}$
ρ_{HM}: HM fuel density (gHM / cm^3)
M_{HM}: HM molar mass (g)

The HM fuel density and the HM molar mass depend on the nature of the fuel (UO_2, $(U,Pu_y)O_{2-x}$).

4.1.4. U and Pu fissions

To calculate the amount of oxygen coming from U and Pu fissions, It is necessary to know the evolution of the distribution between U and Pu fissions for different initial ^{235}U enrichments and according to the fuel burn up.

The following table supplies f_U values. Neglecting MA fissions, $f_{Pu} = (1 - f_U)$ ***[23]***.

Burn up (% FIMA)	^{235}U enrichment					
	7.6	10.1	12.6	15.2	17.7	20.2
0	1	1	1	1	1	1
0.5	0.959	0.967	0.973	0.978	0.982	0.985
1	0.92	0.937	0.949	0.958	0.964	0.97
1.5	0.884	0.909	0.925	0.938	0.948	0.956
2	0.851	0.882	0.904	0.92	0.933	0.942
2.5	0.82	0.858	0.883	0.903	0.918	0.929
3	0.792	0.835	0.864	0.887	0.904	0.917
3.5	0.765	0.813	0.846	0.872	0.891	0.906
4	0.74	0.793	0.829	0.857	0.878	0.894
4.5	0.717	0.774	0.814	0.843	0.866	0.884
5	0.696	0.757	0.799	0.83	0.854	0.874
5.5	0.676	0.74	0.785	0.818	0.843	0.864
6	0.657	0.725	0.771	0.806	0.833	0.854
6.5	0.64	0.71	0.759	0.795	0.823	0.845
7	0.624	0.696	0.747	0.784	0.813	0.836
7.5	0.608	0.683	0.735	0.774	0.804	0.828
8	0.594	0.67	0.724	0.764	0.794	0.82
8.5	0.58	0.659	0.713	0.754	0.786	0.812
9	0.567	0.647	0.703	0.745	0.777	0.804
9.5	0.554	0.636	0.693	0.736	0.769	0.796
10	0.542	0.625	0.684	0.727	0.761	0.789
10.5	0.53	0.615	0.674	0.718	0.753	0.782
11	0.519	0.605	0.665	0.71	0.745	0.775
11.5	0.508	0.595	0.656	0.702	0.738	0.768
12	0.497	0.585	0.647	0.694	0.73	0.761
12.5	0.487	0.575	0.638	0.686	0.723	0.754
13	0.476	0.566	0.629	0.678	0.716	0.747
13.5	0.466	0.556	0.621	0.67	0.709	0.741
14	0.455	0.547	0.612	0.662	0.702	0.734
14.5	0.445	0.537	0.603	0.654	0.695	0.728
15	0.435	0.528	0.595	0.647	0.688	0.722
15.5	0.425	0.519	0.586	0.639	0.681	0.715
16	0.415	0.509	0.578	0.632	0.674	0.709
16.5	0.405	0.5	0.569	0.624	0.667	0.703
17	0.395	0.49	0.561	0.617	0.661	0.697
17.5	0.385	0.481	0.553	0.61	0.654	0.691
18	0.375	0.471	0.545	0.602	0.648	0.685
18.5	0.365	0.462	0.537	0.595	0.641	0.679
19	0.355	0.453	0.529	0.588	0.635	0.673
19.5	0.346	0.443	0.521	0.581	0.628	0.667
20	0.337	0.434	0.513	0.574	0.622	0.661
20.5	0.328	0.425	0.506	0.568	0.616	0.656
21	0.319	0.417	0.499	0.561	0.61	0.65
21.5	0.311	0.408	0.492	0.555	0.604	0.645
22	0.303	0.4	0.486	0.549	0.599	0.639
22.5	0.296	0.392	0.48	0.543	0.593	0.634
23	0.29	0.385	0.475	0.538	0.588	0.629
23.5	0.284	0.378	0.47	0.533	0.583	0.624
24	0.28	0.372	0.466	0.528	0.579	0.619
24.5	0.276	0.366	0.463	0.524	0.574	0.615
25	0.273	0.361	0.46	0.52	0.57	0.61

4.2. THERMAL CONDUCTIVITY OF GASES IN THE COATED PARTICLE

Following the MATPRO recommendation **[12]**, the thermal conductivities (λ_i) of pure gases as a function of temperature may be described as follows:

$$\lambda_i = A_i \, T^{s}i \qquad (W/(m\,K))$$

Constants A_i, S_i and the molecular weight M_i for gases classically produced in a coated particle are given in the table below:

gas	A_i	S_i	M_i (kg/mol)
CO	$1.403\ 10^{-4}$	0.9090	0.028
CO_2	$9.46\ 10^{-6}$	1.312	0.044
Kr	$8.247\ 10^{-5}$	0.8363	0.0838
Xe	$4.351\ 10^{-5}$	0.8616	0.1313

Thermal conductivity values of gas mixtures may be calculated using the "Mason-Saxena" relation **[24]**:

$$\lambda_{mixture} = \sum_{i=1}^{n} \frac{x_i \, \lambda_i}{x_i + \sum_{j=1(j\neq i)}^{n} x_j \Phi_{ij}} \qquad (W/(m\,K))$$

where:

$$\Phi_{ij} = 0.3765 \left[1 + \frac{M_i}{M_j}\right]^{-0.5} \left[1 + \left(\frac{\lambda_i}{\lambda_j}\right)^{0.5} \left(\frac{M_i}{M_j}\right)^{0.25}\right]^2$$

with:

M_i:	molecular weight of gas i	(kg/mol)
λ_i:	thermal conductivity of gas i	(W/(m K))
x_i:	mole fraction of gas i	/

4.3. CALCULATION OF GAS PRESSURE

The classical perfect gas law is inadequate to calculate the inner pressure of the coated particle. Because of the particular conditions which prevail inside the particle : low volume, low to high temperature and pressure, it neglects the volume that gas atoms and molecules occupy. As a consequence, it is necessary to use a more appropriate equation of state.

Among the numerous equations of state for gases, the relation proposed by Redlich and Kwong **[25]** seems, according the analysis performed by D.G. MARTIN **[26]**, the best adapted for calculating gas pressure within coated particles. It combines a simple formula with a high level of accuracy.

The Redlich-Kwong equation of state is:

$$\left[P + \frac{a}{T^{1/2}\, V\, (V+b)}\right](V-b) = RT$$

where:

P:	pressure	Pa
V:	volume per mole	m^3/mol
T:	temperature	K
R:	gas constant	8.31441 J/(K mol)

"a" and "b" are gas constants whose values are obtained by noting that at critical point:

$$\left(\frac{\partial P}{\partial V}\right)_T = \left(\frac{\partial^2 P}{\partial V^2}\right)_T = 0$$

implying for each gas that:

$$a = \frac{R^2 T_c^{2.5}}{9\,\xi\, P_c} \quad \text{and} \quad b = \frac{\xi\, R\, T_c}{3\, P_c}$$

Values of the critical temperatures and pressures, together with the derived "a" and "b" values for the four gases of interest (CO, CO_2, Xe, Kr) are given in the table below:

gas	T_c (K)	P_c (MPa)	a ($N\,m^4\,K^{0.5}/mol^2$)	b (m^3/mol)
CO	132.91	3.5	1.72	$2.736\ 10^{-5}$
CO_2	304.14	7.38	6.46	$2.969\ 10^{-5}$
Kr	209.45	5.5	3.411	$2.743\ 10^{-5}$
Xe	289.75	5.9	7.158	$3.538\ 10^{-5}$

The coefficient "ξ" in the equations of "a" and "b" is equal to $(2^{1/3} - 1) \cong 0.259921$.

In the case of gas mixture, mean values of "a" and "b" are required. They are given by:

$$\bar{a} = \left[\sum_{i=1}^{n} x_i\, a_i^{1/2}\right]^2$$

$$\bar{b} = \sum_{i=1}^{n} x_i\, b_i$$

where:

n:	number of gas species
x_i:	fraction of gas specie i

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SUMMARY

In the Work Package 3 (Modelling) in HTR-F (Fuel Technology) funded by the European Community, the participants intend, in order to understand and to predict the irradiation behaviour of HTR fuels, to model the different phenomenon occurring in the fuel in reactor.
This document is the contribution of FRAMATOME-ANP to the Work Package 3. It deals with fission products behaviour.
The fission products diffusion is described.
The diffusion coefficients data, used in different countries, are given, extracted from literature, especially from IAEA-TECDOC-978, Fuel performance and fission product behaviour in gas cooled reactors for:

1. Fuel kernel
2. Buffer layer
3. Pyrocarbon layer
4. Graphite

Conceptual models for particle failure are also described.
Evaluation of fission products release has been carried out in order to compare available diffusion coefficients coming from different countries (USA, Germany, Japan).
Regarding the model used, FRAMATOME-ANP recommends to use the German coefficients with the associated model described in this document.
These data will be integrated in the common code taking into account relevant existing models that will be developed at the European level.

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1. CONTEXT AND OBJECTIVES

HTR Fuel Coated particles designed in the 1960s and 1970s have been perfected for steam cycle applications in the 1980s and early 1990s enabling the design of small inherently safe modular HTRs with self-limiting temperatures of less than 1600°C.
Now, new applications are of interest:

- gas turbine directly in primary circuit (direct cycle),
- burning of civil and weapons grade plutonium,
- higher in-reactor burnup for ecological and economical reasons.

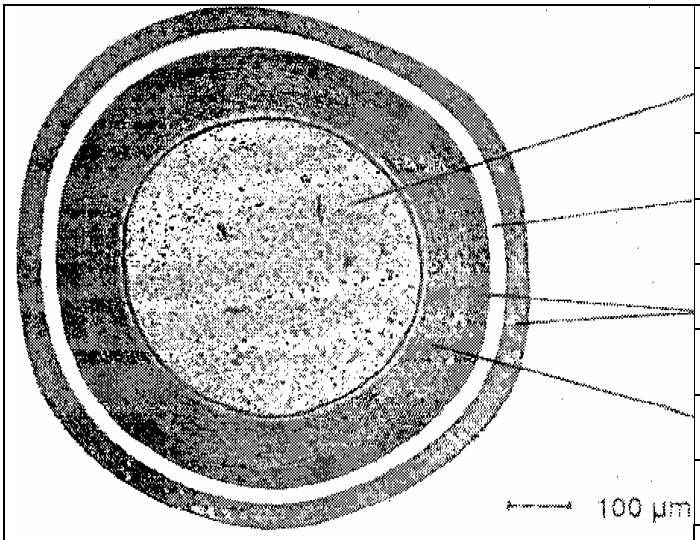
On one hand, to make the coated particle equally convincing for these applications, available results should be re-analyzed and re-investigated in the light of these applications.
On the other hand, new results and new computing tools have been developed and have to be used in these tasks regarding :

- Re-evaluation of ^{110m}Ag release data during normal operations for better source term data base in direct cycle applications.
- Determination of the influence of burnup greater than 10% FIMA on irradiation performance.
- Accident condition performance analysis at temperature greater than 1600°C for an improved coated particle model.

In order to achieve these goals, in the Work Package 3 (Modelling) in HTR-F (Fuel Technology) funded by the European Community, the participants intend, in order to understand and to predict the irradiation behaviour of HTR fuels, to model the different phenomenon occurring in the fuel in reactor.
A common code taking into account relevant existing models will be developed at the European level.
This document deals with fission products behaviour.

2. HTR FUEL DESCRIPTION

Generally, the TRISO HTR Fuel particles have a 500 µm diameter UO_2 kernel and a 200 µm thick coating, consisting of a porous buffer layer and two dense layers of pyrocarbon with a silicon carbide layer in between, named IPyC and OPyC for inner and outer pyrocarbon. While all these layers have important mechanical and chemical functions, it is the SiC that guarantees the highest degree of fission product retention.
In normal and transient operation, and in accidents not exceeding 1600-1700°C, it was demonstrated that all radiologically relevant fission products (iodine, caesium, strontium) are completely retained inside the silicon carbide layer of intact fuel particles. The dominant source term of fission product release will, therefore, be the small number of particles with defective coatings [2, 3].



UO_2 fuel kernel

Silicon carbide layer

Inner and outer pyrocarbon layers

Buffer layer

Cross-section through an LEU TRISO coated particle

3. FISSION PRODUCTS DIFFUSION

The equation that governs the fission products diffusion is the second Fickian equation using average diffusion coefficients for the fission product species in the different barriers of reactor materials. All the transport mechanisms are summarised in this simplified single transport law for the HTR fuel particle materials. The diffusion model is generally regarded to be valid both for normal operation and for accident conditions.

The equation is used, with a transient system and a spherical symmetry. The source term and radioactive disintegration must be added to complete the balance sheet :

$$\frac{\partial c^{(i)}}{\partial t} = \frac{1}{r^2}\frac{\partial}{\partial r}\left(r^2 D^{(i)}\frac{\partial c^{(i)}}{\partial r}\right) - \lambda c^{(i)} + \dot{s}$$

Where

- λ is the radioactive disintegration constant (s^{-1});
- $\dot{s}$ is the source term ($kg.m^{-3}.s^{-1}$),
- $D^{(i)}$ is the diffusion coefficient in the layer number i ($m^2.s^{-1}$): the 1st is the kernel, the 2nd is the buffer, the 3rd is the IPyC, the 4th is the SiC and the 5th is the OPyC,
- $c^{(i)}$ is the fission products concentration in the i^{th} layer ($kg.m^{-3}$),

Thus, the variation in fission product concentration is due to three terms:

- The Fickian diffusion, by the term $\frac{1}{r^2}\frac{\partial}{\partial r}\left(r^2 D^{(i)}\frac{\partial c^{(i)}}{\partial r}\right)$.
- The radioactive disappearance, by the term $-\lambda c^{(i)}$.
- The creation by fission reaction, by the term $\dot{s}$.

4. SOURCE TERM INPUT DATA

The source term is the expression in the Fickian law that gives the creation of a fission product during the irradiation.
This input data term is noted $\dot{s}$ in the equation of diffusion.
The concentration of 90-Strontium, 137-caesium and 110m-Silver are concerned.

5. DIFFUSION COEFFICIENTS DATA

The diffusion coefficients are usually given as an Arrhenius type equation as a function of temperature. Empirically found deviations from this behaviour could be overcome by assuming additional dependencies, for instance on fast neutron fluence or fission product concentration or burnup, or by combining diffusion processes with different activation energies in different temperature ranges:

$$D(T,\Gamma,c,...) = \sum_i D_{0,i}(\Gamma,c,...)\exp\left(-\frac{Q_i}{RT}\right)$$

where:

- $D_{0,i}$ is the pre-exponential term, in $m^2.s^{-1}$,
- Q_i is the activation energy, in J/mole,
- T is the temperature, in K,
- R=8.314 in mol/J/K,
- Γ is the fast fluence in 10^{25} m^{-2}, E>16fJ (different cut-off limit for the neutron energy E>0.1 MeV (16fJ), E>0.18 MeV (29 fJ), or EDN are found in the literature. The correct unit is explicitly mentioned wherever necessary.
- c is the fission product concentration in m^{-3}.

Diffusion coefficients have been adopted from the evaluation of numerous irradiation and heating experiments with complete spherical fuel elements, fuel compacts, single fuel particles, or graphite samples.
Recommendations of transport data have been collected over many years and were continuously revised. In a joint effort of KFA and German industries within the project "Hochtemperaturreactor-Brennstoffkreislauf" (HBK), a set of data to be used for predicting fission product transport during HTGR normal operation has been established [4]. Its purpose was to summarise the data base for HTGR design calculations for licensing procedure. A comprehensive data collection was created in the 1970s by UKAEA/AERE Harwell. Transport data as applied to US HTGR designs have been published as part of the Fuel Design Data Manual by General Atomics.
A common assumption in most diffusion models is the neglect of any effects of sorption or trapping within a coating layer or of any preferential retention in a specific layer. The ratio of fission product concentrations at the surfaces of contiguous materials (partition coefficient) is assumed to be one. Consequently, the concentrations are equal at contiguous surfaces. Measurements of this ratio range from about 0.3 to 3 and may change with temperature and fast fluence. For lack of adequate measurements of the ratio under a sufficiently large range of conditions, the error associated with the assumed value of 1.0 has been accepted. The few experimental studies related to desorption from coating materials indicate some kind of discontinuity in concentration profiles at coating interfaces, for instance for caesium between buffer and inner pyrocarbon (IPyC) layer or the significant palladium peaks at the inner surface of the SiC layer [5] in microprobe profiles.
Experiments at KFA have been proposed in 1989 for investigation of the thermal chemical partition coefficients at material boundaries to better estimate the magnitude of this effect. The development of

an alternative calculation model has even been proposed at KFA which considered the fission product transport to be dependent on the gradient of the chemical potential rather than of the concentration. This alternative is described in [6].

5.1 Fuel Kernel

Diffusion coefficients in UO_2 fissile particle kernels which were used in recent German safety analysis have been derived from irradiation and heating experiments with designed to fail UO_2 particles (kernel and buffer layer). According to an evaluation of the German irradiation and heating experiment FRJ2-P28, caesium and iodine release under accident conditions is considered at KFA to be best approximated by a two branch diffusion coefficient while those for strontium and silver were lowered by a factor of 20 and 10, respectively, compared to the recommendation of the last HBK data set. A different recommendation is given for iodine at lower temperatures(< 1000°C) which was derived from irradiation experiments in the R2 reactor at Studsvik.
In the US, most data were derivated from ThO_2, fertile kernels. A significant dependence of the reduced diffusion coefficient on temperature and burnup but no dependence on fast fluence was found. The diffusion data for metallic fission products [7] are also used for UO_2, with a separate set of constants used for UCO kernels which are slightly higher than those for UO_2. UC_2 fuel is assumed to retain no metallic fission products. However, for safety analysis calculations, the use of KFA data for the metallic fission products is recommended [8].

5.2 Buffer Layer

The carbonaceous buffer layer is assumed in the diffusion model to have no significant retention capability for fission products. In FRG calculations, a value of the diffusion coefficient of 10^{-8} $m^2.s^{-1}$ with no temperature dependence (activation energy equal to zero) is used. The US recommendation for the corresponding diffusion coefficient is 10^{-10} m^2/s. The difference is negligible since either one is significantly larger than the diffusion coefficient for the other coating materials.

5.3 Pyrocarbon Layers

Diffusion coefficients in pyrocarbon were mostly derived from early experimental data with LTI and HTI-PyC from BISO particles. Due to its comparably smaller retention capability, diffusion in PyC has not been investigated in that detail as it has been for the main barrier silicon carbide. At temperatures beyond 1900°C, it is recommended to assume rapid diffusive transport (similar to the buffer layer) for metallic fission products in LTI-PyC. For HTI-PyC, this critical temperature has been assumed in German safety analysis calculations for the THTR-300 to be as low as 1200°C, except caesium for which experimental evidence suggests much better retention than strontium or silver. The diffusion coefficient of krypton in PyC is based on an evaluation of GA heating data at 2050°C and ramp tests and of KFA 1600 °C tests [9]. No modification of KFA transport data is considered to take into account possible irradiation damage in PyC due to a high probability of irradiation damage annealing [9]. No change of KFA data has been made compared to the status report.
US recommendations for strontium and silver as well as for iodine and fission gases are identical to those at KFA. The data for caesium and strontium represent an average of the measurements of many authors. Early US studies [10] have also found the caesium transport data through isotropic pyrocarbon to be orders of magnitude lower than those for strontium, both being in the range of the later reported data.
In Japan, several studies have been made on caesium in different temperature ranges [8]
Diffusion data given by other authors ([10], [11]) are fairly close to each other despite their strong dependence on the pyrocarbon deposition conditions during manufacture and material characteristics. This dependence was reported to be the reason for the relatively large difference in JAERI and KFA activation energies for caesium [12].

5.4 Silicon Carbide Layer

The transport properties of fission products in silicon carbide, as the most efficient barrier of the coated particle, were the subject of many detailed studies in the past years. The experimental data gave impetus to either confirm and/or refine existing models or even to develop new ones.

The original way to describe the permeability of the SiC coating for fission products was a diffusion coefficient derived from numerous heating tests at KFA with single coated fuel particles. The radio nuclide caesium was investigated more than any other relevant metallic fission product species. The Arrhenius relation for caesium proposed by Allelein entered the HBK data set as recommended data for use in HTGR core release predictions under normal operating conditions.

For irradiation experiments with modem HTGR fuel, the Allelein diffusion coefficient was found to overestimate in some cases the caesium release fraction from fuel particles. An evaluation of the experimental data by Christ has taken the fast neutron fluence as a parameter for the Arrhenius relation, thus influencing the amount of caesium penetrating the SiC layer during irradiation and the delay of the diffusive break-through at elevated temperatures. This new recommendation for the low-temperature branch of KFA data is -for zero fast fluence- lower compared to the Allelein data but will come close to it with increasing fast fluences.

A theoretical evaluation of several researchers' experimental caesium release data from coated particles was made by Myers in the early 1980s. The result was a diffusion coefficient subdivided into, a low temperature branch and a high temperature branch dominant at greater than 1600°C.

A evaluation of data from all heating experiments conducted in the KüFA furnace -a total of 44 tests with respect to caesium- using the diffusion code FRESCO-II has led to a new KFA recommendation for a diffusion coefficient in silicon carbide.

An analogous evaluation has been made for strontium on the basis of 11 KüFA heating tests with modern HTGR fuel in the temperature range between 1600 and 1800°C. The new diffusion coefficient has a higher activation energy resulting in a diffusion coefficient lower by a factor of about 20 at 1600°C compared to the old recommendation. Unfortunately, the combination of this new high-temperature Arrhenius relation with the old HBK relation for normal operation temperatures into a single two branch diffusion coefficient significantly underestimates the experimental retention quality of SiC for strontium at 1600°C.

KFA silver transport data have been taken from the HBK data set. No evaluation of available silver release data from KüFA heating tests has been made because no consistent release behaviour was observed and is in many cases not reproducible by any existing model. A possible explanation as proposed by Myers could be the silver to be trapped at neutron induced defects in the silicon carbide structure at normal operation temperatures resulting in a burst release of the trapped silver at elevated temperatures.

According, to the definition of the "Integrated Failure and Release Mode for Standard Particles" which represents the US reference model, no diffusion of caesium and strontium through silicon carbide is assumed to occur. There are, however, US diffusion data available which were published before the statistical model was created. Ongoing work by Martin, [13], suggests that a fast fluence dependent diffusion coefficient similar to that of Christ represents an improvement over the reference model.

No big difference between Japanese and KFA data was found for caesium and silver. For strontium, the same data as KFA for the low-temperature branch are used.

The uncertainty range for transport data in silicon carbide is a result of the very low release level for high quality fuel at temperatures less than 1600°C which sometimes only allows the indication of an upper limit. When considering heating tests with complete fuel elements, other parameters such as heavy metal contamination fraction in the graphite grain are of importance.

The approach in the JAERI code FORNAX uses a third type of particle with a degraded SiC layer simulated by larger values for the diffusion coefficient. No specific transport data have been published.

Röllig has provided an interesting analysis of the Cs137 release data for FRG sphere R2-K13/1 heated to 1600°C for 1000 hours [14]. Nearly 2000 particles were gamma counted, and 7% had released over 10% of their Cs137 inventory, with a small number of particles releasing 50 to 90%. Röllig applied a diffusion model to the release data, but rather than a single diffusion coefficient lie assumed a log-normal distribution of values around the average diffusion coefficient. He obtained reasonable agreement with the data for particle release as a function of position within the sphere. This method of

assuming a distribution of diffusion coefficients is a promising approach to account for the inherent microstructural variation in SiC and its effect on particle-to-particle release comparisons.

5.5 Graphite

The uncertainty for the given transport data in graphitic materials is considered to be fairly high. The metallic radionuclide transport in graphite is strongly dependent on graphite type and nature, structure, temperature, fission product concentration, state of oxidation, irradiation damage, coolant gas pressure, and interference with other fission product species.
The trapping mechanism is not considered, which is known to better approximate the real transport process in graphite. The overall uncertainty range is estimated to be at least one order of magnitude, for silver as high as three orders of magnitude. For safety analysis purposes, however, transport data for the oversimplifying Fickian diffusion model in graphite can be used to obtain realistic, or at least conservative radionuclide release data.

5.5.1 Matrix Graphite

Effective diffusion data are relatively well known for caesium and silver [15] and strontium [16] in German A3-3 matrix graphite in the Henrian concentration regime as well as the influence of irradiation and corrosion on the diffusive process. The matrix graphite type A3-3 was used for the THTR-300 spherical fuel elements and was chosen to be the reference fuel element graphite for future German HTGRs. In contrast, all of the last German fuel elements which were used in irradiation and post irradiation experiments consisted of the matrix graphite type A3-27. Comparative measurements of Hoinkis showed diffusion coefficients for caesium and silver in as-received A3-27 lower by a factor of 20 and 7, respectively, at 1000°C compared to as-received A3-3 [15]. A Hoinkis report presents the diffusion coefficients of silver in as-received A3-3, as-received A3-27, and irradiated A3-3 in the temperature range of 800 - 1300°C [17] confirming, the above single measurement.
According to the experience from measurements, caesium and strontium diffusion through graphite has been assumed in German safety analyses to proceed rapidly at temperatures beyond 2000°C, for silver already at temperatures less than 1000°C.
The evaluation of caesium inventory measurements in the matrix of heated fuel elements with the KFA code FRESCO-II have also demonstrated the diffusion coefficient in A3-27 to be at least one order of magnitude lower compared to A3-3 in the accident temperature range of 1600 to 1800°C. But the fitted diffusion coefficients for A3-27 cannot consistently be described in a new Arrhenius relation on a lower level [18]. The choice of heavy metal contamination fraction in the matrix which is used as input data for the model calculations has a major effect on the release level from the fuel element, especially at lower heating temperatures less than 1600°C (when the release from the coated particles is comparably small) and especially for strontium which is more strongly bound in graphite than is caesium. An adequate recommendation for caesium and strontium transport in A3-27 matrix graphite may be the reduction of the Hoinkis diffusion coefficient curves (for A3-3) by one order of magnitude which would still envelope the calculated results [18].
US diffusion data on fuel compact matrix material are not given due to the assumption of a rapid transport of the metallic and gaseous fission products through this porous material zone.
Japanese data have been published for strontium in graphite matrix for the VHTR design [19] which is one to two orders of magnitude above German reference data. The Japanese data are, however, somewhat smaller compared to early KFA measurements conducted for strontium and caesium in irradiated A3 matrix of AVR fuel elements.
Fission gases released from the coated particles are assumed in US modeling to be transported through the fuel compact matrix material without any time delay both under normal operating and accident conditions. This assumption has the same result as the German approach which uses a large diffusion coefficient for xenon in helium to simulate fission as and iodine transport in the graphite pores (= grain boundaries). The US modeling of radionuclide transport in graphite has been recently refined by introducing the effect of graphite oxidation into the diffusion coefficient by making the pre-exponential factor a function of weight percent burnoff.

The transport behaviour of iodine in graphite under accident conditions is considered in German model calculations to be similar to that of the noble gases krypton and xenon. Rather than simulating an effective, one-phase diffusion, the iodine transport is conservatively treated in the KFA reference modeling to consist of a slow diffusion phase out of the graphite grain proposed by Müller at temperatures less than 1250°C and of rapid diffusion phase via the pores and the graphite grain boundaries. The iodine from the heavy metal contamination is assumed to be buried deep inside the grains. In contrast, iodine released from defective particles into the graphite is assumed to be immediately transported in the graphite pores. The quick phase transport is independent of temperature and corresponds to the diffusive behaviour for Xenon in helium, and does not allow for any realistic retention in the graphite.

The transport of iodine and fission gases in graphite has been recently the subject of a special series of KFA experiments [20]. Spherical fuel elements with low burnup were heated to investigate the release behaviour of short-lived isotopes originating from the heavy metal contamination. Iodine release curves were found to be akin to those for xenon, with both supporting the interpretation of a release from traps in the matrix graphite. Diffusion coefficients derived from these experimental data using the FRESCO model [18] revealed that the reference diffusion coefficient as explained in the above paragraph was too small at lower temperatures and too large at higher temperatures less than 1250°C. But from the arrangement of the fitted data, an activation energy could be recognised which is similar to that for an effective diffusion coefficient for xenon transport in irradiated AUF graphite which was impregnated with uranium carbide. This Canadian investigation had shown that relatively high fractions of xenon were retained in the graphite even at temperatures up to 2000°C.

The above mentioned evaluation of the KFA heating experiments with the FRESCO-II code was repeated, but now using for the contamination fraction in the spheres a single value (1.10^{-7}) rather than the release value measured at the end of each series. The last calculation results shown are up to two orders of magnitude lower than the earlier results, and the low temperature data fall close to the Müller slow phase diffusion coefficient. However, all things considered, these calculation results do not seem to represent a good basis for recommending a new diffusivity. The old one remains sufficiently conservative for safety analyses, although an approach using a trapping mechanism will be the more accurate one.

The objectives of tests conducted in the Russian Federation on iodine and fission gas release from HTGR fuel element graphite were to obtain the temperature dependence of the release and to study the correlation of gaseous and aerosol fission product release. The objects used for the investigations were standard spherical fuel elements, fuel element "failure" imitators, i.e., graphite spheres containing uncoated kernels instead of coated particles, coated particles with a different number of protective coatings, a mix of coated particles with kernels (in bulk), as well as "contamination" imitators, i.e., either 35 mm diameter spheres manufactured from a mix of graphite with uranium or 60 mm diameter spherical graphite models without fuel particles.

The investigations were conducted using the technique of "weak" irradiation. The fractional release of the iodine isotopes during isothermal heating was determined on the basis of a measurement of the activities of the daughter isotopes (Xe135, Xe133) built-in in the facility test section after its cooling down. The temperature dependence of the iodine release was obtained by cyclic heating of the investigated samples. The experimental results were analysed by means of the activation model.

The temperature dependence of the iodine and xenon isotopes has been obtained within the temperature range 200 - 1100°C. It has been observed that an increase of the graphite quantity in the sample results in a relative reduction of the iodine release, an effect which is apparently connected with iodine absorption especially at low concentrations. It has also been shown that a heat treatment of the imitator samples leads to an enhanced radionuclide release and also changes the character of the temperature dependence; this influence can be explained by a probable uranium carbidization at high temperatures and, consequently, a decrease of the kernels' retention capability. It should be noted that an estimation of the primary circuit activity using Xenon135 benchmark nuclide release data can lead to overestimated values of iodine release (for release values < 10^{-2}).

5.5.2 Structural Graphite

No diffusion data are available for the German reference reflector graphite ASR-1RS. The US data for H-451 graphite grade have been used instead in model calculations. The transport of iodine and fission gases in structural graphite is only considered via the rapid diffusive phase since they have penetrated the graphite from the coolant side, thus being transported using the pores rather than entering the grains.

The silver transport in H-451 measured at temperatures up to 800°C was supposed in [21] to consist of a slow phase with high concentrations near the surface and of a fast phase with low concentrations away from the surface.

JAERI studies of IG-110 structural graphite in in-pile experiments have revealed significant differences in caesium and silver diffusion data relative to German and US data [22]. In particular. silver released from the fuel compact was found to be effectively retained in the graphite sleeve for low burnups < 2% FIMA. Diffusion coefficients for caesium obtained from experiments with Cs impregnated IG-110 graphite specimens were found to be larger by 3-4 orders of magnitude and with a lower activation energy compared to those data obtained from the in-pile experiments. An explanation is proposed by assuming an additional trapping effect by irradiation induced surface defects with stronger binding energies than those of existing traps [23].

5.5.3 Concentration Dependence of the Diffusion Coefficient

Experimental data on the concentration dependence of transport data have been collected by several authors. A significant effect was found for strontium where a tremendous increase of diffusivity by several orders of magnitude occurred as soon as a certain concentration was exceeded. Only small effects were found for silver and caesium. The concentration dependence of strontium diffusion is expressed in the empirical equation

$$\log D(T, c_{gr}) = 4.51 - 2.58 \log c_{gr} - (29300 - 7000 \log c_{gr})/T$$

Where c_{gr} is the concentration in the range of 60- 2000 µg Sr/g of C

The following, empirical strontium diffusion coefficient dependent on temperature and concentration was found to be in good agreement with experimental data and recommended for US safety studies :

$$D(T, c_{gr}) = 3.47 * 10^{-13} {c_{gr}}^2 \exp\left[-\frac{64000\chi}{R} \left(\frac{1}{T} - \frac{1}{1273} \right) \right]$$

Where:

$$\chi = 0.422 + \frac{0.5805}{1 + {c_{gr}}^3 / 80}$$

and c_{gr} is the concentration in the range of 0.7- 50 µg Sr/g of C

A modeling refinement for diffusive transport of caesium and strontium in graphite which simulates this effect uses the British experimental data obtained for strontium [24]. In the FRESCO model, corresponding sorption data for strontium and caesium are taken to introduce a factor consisting of the ratio of the partition coefficient based on Freundlich sorption isotherms over that based on Henry sorption isotherms.

The partition coefficient $\alpha = \alpha(T)$ is defined by the equation:

$$c_{gas} = \alpha . c_{gr}$$

where c_{gas} is the concentration in coolant (atoms.m^{-3})

c_{gr} is the concentration in graphite surface layer (atoms.m^{-3})

The concentration dependence is given by modifying the pre exponential term of the diffusion coefficient in graphite by a factor ,which is equal to 1 for the Henrian concentration regime and greater than 1 for the Freundlich concentration regime:

$$D_0^x(c_{gr}) = D_0 \frac{\alpha_{Freundlich}}{\alpha_{Henry}}$$

with the above definition of α.

This type of concentration dependence reproduces the results of [24]. This procedure is also applied to the structural graphite of the reflectors in the 'core' version of FRESCO [25].
Another approach has been proposed in [26] which is employed in the SPTRAN code. The pre-exponential factor of the diffusion coefficient is additionally dependent on temperature

$$D_0^x(T, c_{gr}) = D_0\left[1 + \left(\frac{c_{gr}}{c_t}\right)^{\tau E_F / T}\right]$$

where :

c_t is the transition concentration between Henry and Freundlich regime,
τ is an empirical parameter,
E_F is a parameter of the Freundlich sorption isotherm.

A value of 0.25 for the parameter τ was fitted to best approximate caesium experimental data [26.

6. TEMPERATURE

The temperature is naturally used in the formulation of the Arrhenius' law and this input data has a highly important impact on results.
Temperature gradients have to be calculated in the particle and in the core.

7. CONCEPTUAL MODELS FOR PARTICLE FAILURE

The principal potential mechanisms of coating failure at high temperatures are :
Pressure vessel failure whereby the internal gas pressure induces a stress in the SiC layer in excess of the SiC tensile strength. In addition to basic design and material properties, critical data are required about a possible decrease of SiC strength during irradiation and annealing.
Kernel migration –or amoeba effect– at high temperatures and under temperature gradients. It can lead to destruction of coating layers.
Interactions of fission products with silicon carbide that can lead to a thinning and weakening of the SiC layer (corrosion), thereby reducing strength and impermeability to fission products.
Finally, at very high temperatures, silicon carbide thermal decomposition that leaves only a disordered carbon structure in the place of the SiC layer.

Corrosion of the SiC Layer

Some corrosion or thinning of the SiC can lead to the fracture of this layer, or can create some micro-fissures that release the fission products.
At less temperatures than 2000°C, the interaction of fission products with the silicon carbide (corrosion) is the dominant failure mechanism. A linear dependence of the corrosion rate on the time has been determined with an activation energy of 252kJ/mol.
Some tests have shown that this corrosion rate, k, depends on irradiation parameters and fuel type: $k=k_0.\exp(-Q_i/RT)$ where :

R is the gas constant 8.3143 $J.mol^{-1}.K^{-1}$
T is the heating temperature
Q_i is the activation energy
$\log(k_0)=-36{,}53+3.\log(T_{irradiation})+\log(f_{SiC})$ (k_0 in s^{-1})
$T_{irradiation}$ irradiation temperature (K),
f_{SiC} density of fission (m^{-3}).

Qi are given for different countries in reference [1].
Some TRISO particles with a UO_2 kernel and containing palladium have shown 3 different possible interactions that are :

- Localised attacks characterised by the penetration of the palladium in the silicon carbide layer, constructions of palladium at the IPyC/SiC interface, and anisotropy of the environment.
- Emergence of little bright grains of palladium in the silicon carbide thickness.

- Metallic impacts distributed on the inner surface of the silicon carbide.

Decomposition of the SiC Layer

Thermal decomposition of SiC was confirmed to be the main failure mechanism at higher temperatures than 2000°C. The 137-caesium release indicates the weight loss.

The decomposition rate is given by : $k=k_0.\exp(-Q_j/RT)$ where :

R is the gas constant 8.3143 $J.mol^{-1}.K^{-1}$

T is the heating temperature

Q_j is the activation enegy

$\log(k_0)=-1,58+2,67.\log(T_{irradiation})+0,61.\log(\Gamma)$ (k_0 in s^{-1}) where Γ is the fast fluence ($10^{25}m^{-2}$).

Qj are given for different countries in reference [1].

The chemical reaction involved in the thermal decomposition is: $SiC_{(s)} \rightarrow Si_{(g)}+C_{(s)}$.

The different countries working on the HTR field have determined some specifications from experiences and evaluations, which are given in the following table [1] :

	FRG	**USA**	**JAPAN**	**USSR**	**CHINA**
As-manufactured free uranium					
Heavy metal contamination	10^{-7}	10^{-5}	10^{-5}	4.10^{-6}	4.10^{-6}
Defective coating (exposed kernel)	3.10^{-5}	-	10^{-5}	$<5.10^{-5}$	
Failed-SiC	-	5.10^{-5}	5.10^{-4}	$<10^{-4}$	
TOTAL (expected value)	3.10^{-5}	6.10^{-5}	5.10^{-4}		
TOTAL (design value)	6.10^{-5}	$1,2.10^{-4}$	2.10^{-3}	10^{-4}	$\leq 3.10^{-4}$
Irradiation-induced failures					
Expected value	2.10^{-5}	5.10^{-5}	0		
Design value	2.10^{-4}	2.10^{-4}	8.10^{-3}	$<10^{-4}$	5.10^{-4}

The assumption of a defective or failed particle in the diffusion code FRESCO-II is equivalent to simulating, an exposed particle kernel. This means that fission products released from the particle kernel by diffusive transport are immediately released to the surrounding graphite structure. The failure of a particle coating, however, is not necessarily equivalent to a non-existing coating ; such an assumption is a conservative approach. There is experimental evidence for a better retention of fission products in particles with a broken coating compared to exposed kernels. The simulation of a partly existing coating as a kind of a third type of particle (besides intact particles and exposed kernels) has been proposed by JAERI [28]. Another possibility of modeling a broken but still existent coating is the choice of a smaller diffusion coefficient in the kernel as an simulative diffusion coefficient for this 3rd type of particle as has been done in the FRESCO-II code [29]. A post calculation of the 1800 °C isothermal heating, test HFR-K3/3 has shown that the reduction of the kernel diffusion coefficient by two orders of magnitude simulates a failed but still existing coating, and reproduces the high release peak of the observed IMGA bimodal distribution of single particle inventories [30].

To be modelled, the particles have to be separated in three categories such as described in the international experience:

1°) Intact Coated Particles

Intact particles will be modelled in one dimension. The important parameters are the diffusion coefficients of the fission products in the different layers. All those layers are intact and the retention of the fission products is high.

The Figure 1 gives the structure of an intact particle built and proposed.

2°) 'Failed-SiC' Coated Particles
For this second kind of particles is the 'failed-SiC', the FORNAX code considers that the diffusion coefficient in the silicon carbide is the same as in the pyrocarbon, but the results do not suit the experience. To solve this problem, this code adapts the diffusion coefficient to the experimental results and considers that the coefficient in silicon carbide is 100 times higher than the normal one.
A fissure, all around the particle, going through the SiC layer, will model this kind of defective layer. The parameter will be the thickness of the fissure.
The Figure 2 gives the structure of a failed-SiC particle built and proposed.
3°) Exposed Kernels
The three layers, IPyC, SiC and OPyC, of this last kind of particles are cracked. The kernel is directly exposed to the outside.
The Figure 3 gives the structure of an exposed kernel built and proposed.

8. PRELIMINARY RESULTS

8.1 Hypothesis

The following average thicknesses coming from a Japanese reference publication referenced in [31] have been adopted for the different ceramic layers:

UO_2		Buffer	I-PyC	SiC	O-PyC
Radius = 250	Thickness (μm)	115	30	35	40

The Fickian law, described in Chapter 3 has been chosen in this preliminary study to describe the global diffusion through the whole core. The source term in the kernel and the radiaoactive decrease must be added to complete the balance sheet: :

$$\frac{\partial c}{\partial t} = D.\Delta c - \lambda.c + \dot{s}$$

c: fission product concentration in at.cm^{-3} of UO_2
λ: constant decay of the fission product in s^{-1}

D: equivalent diffusion coefficient of the considered layer= $D_0.e^{\frac{Q_0}{R.T}}$

D_0: pre exponential term in m^2.s^{-1}
Q_0: activation energy in J.mol^{-1}
R=8.314 mol.J^{-1}.K^{-1}
T: temperature in K

The values of D_0 and Q_0 for each layer are given herewith for ^{137}Cs:

	UO2	Buffer	I-PyC	SiC	O-PyC	Matrix	Graphite
Do (m²/s)	5.6 E-8	1 E-8	6.6 E-8	5.5E-14*exp(Γ/5)	6.6E-8	3.6 E-4	1.7 E-6
Qo (J/mol)	209 000	0	222 000	125 000	222 000	189 000	149 000

Γ is the fast fluence in 10^{25} n/m^2

Three types of particle have been considered:

- Failed particle which have a fissured SiC layer
  The diffusion coefficient of the defective layer is replaced by the PyC value and the ratio of coated particle with this defect is taken equal to 5.10^{-4}.
- Exposed kernels
  These particles have all their coatings completely failed, then fission products migrate directly and rapidly outside the particle. The ratio of this type of particle is taken equal to 2.10^{-5}.
- Intact particles
  All the coatings of these particles are unbroken.

8.2 Models used

The models used are described in Chapters 3 and 7.

8.3 Preliminary Results

For ^{137}Cs taken as example, the following tables summarises the results obtained with FRAMATOME ANP evaluation in comparison with results obtained for different HTR design:

- **HTGR-GT :**

	FRAMATOME ANP result	**JAERI result Ref. [31]**
FPs released into coolant He from a 600 MW_{th} HTGR-GT core per 450 days of activity	11.25 TBq	15.84 TBq

- **PBMR**

	FRA ANP result	**JAERI result Ref. [31]**	**PBMR SA result. Ref. [32]**
FPs released into coolant He from a 300 MW_{th} PBMR core per 960 days of activity	0.44 TBq	0.55 TBq	0.22 TBq

- **GT-MHR**

	FRAMATOME ANP result	**Kurtchatov Institute result Ref. [33]**
FPs released into coolant He from a 600 MW_{th} GT-MHR core per seven operating years	11.47 TBq	14.09 TBq

9. CONCLUSION

This document describes the methodology and the currently data used for fission products behaviour in order to predict and to understand the irradiation behaviour of HTR Fuels and to model the different phenomenon occurring in the fuel in reactor.

It supplements and makes choice regarding the data listed in Reference [34].
Evaluation of fission products release has been carried out in order to compare available diffusion coefficients coming from different countries (USA, Germany and Japan).
Regarding the model used, FRAMATOME-ANP recommends to use the German coefficients with the associated model described in this document.
This document is the FRAMATOME-ANP contribution in the Work Package 3 (Modelling) in HTR-F (Fuel Technology) funded by the European Community.

Figure 1

Structure of an intact particle built and proposed

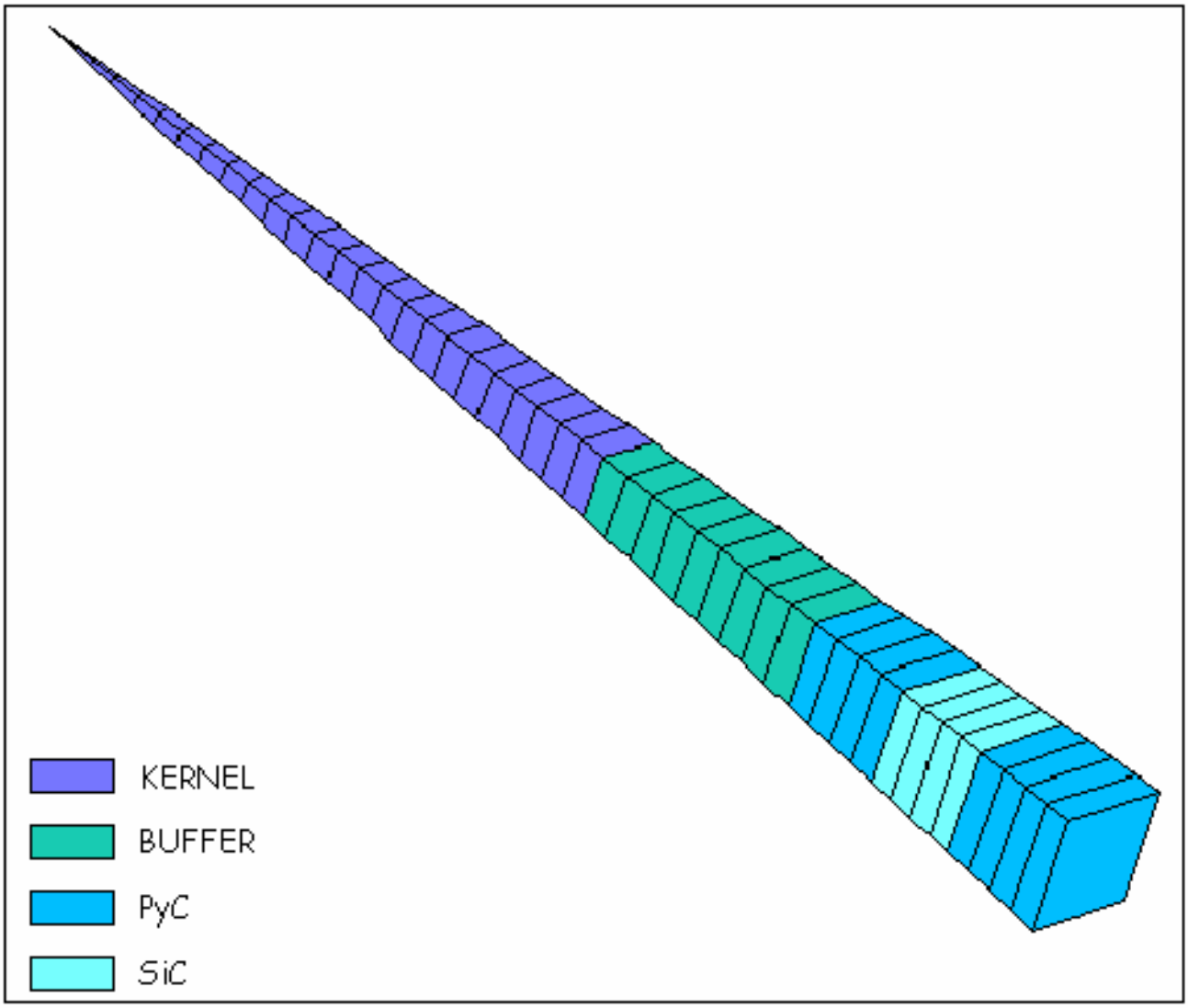
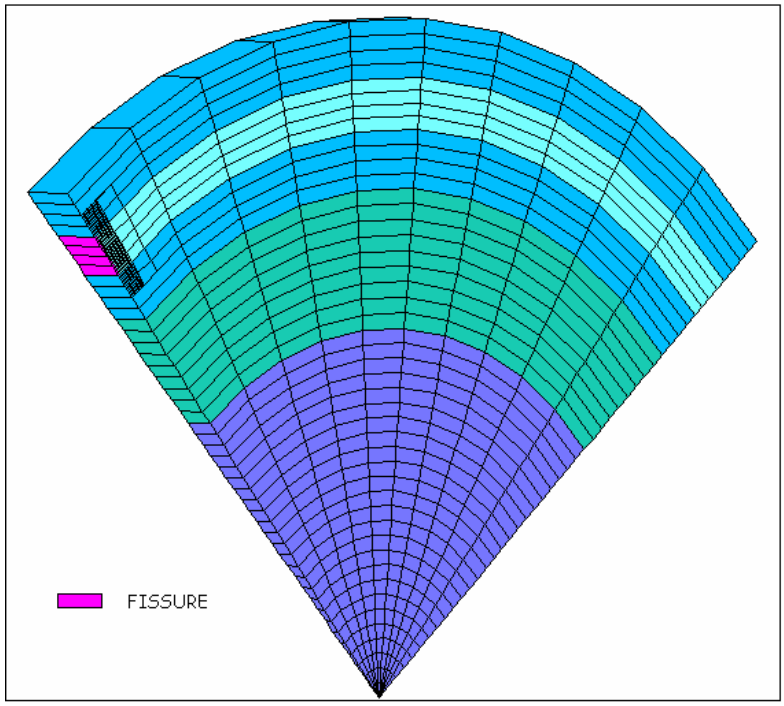


Figure 2

Structure of a failed-SiC particle built and proposed



Zoom near the fissure

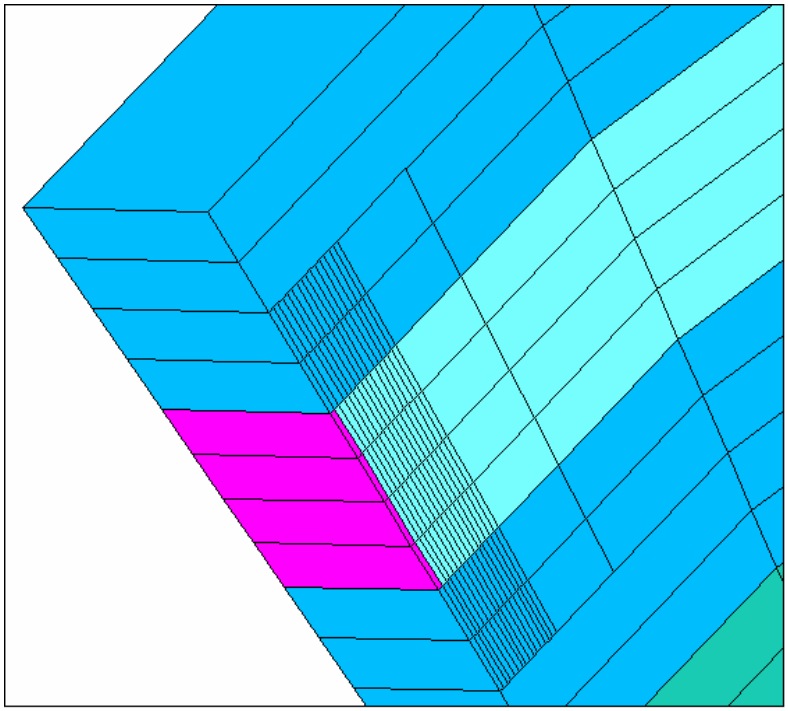
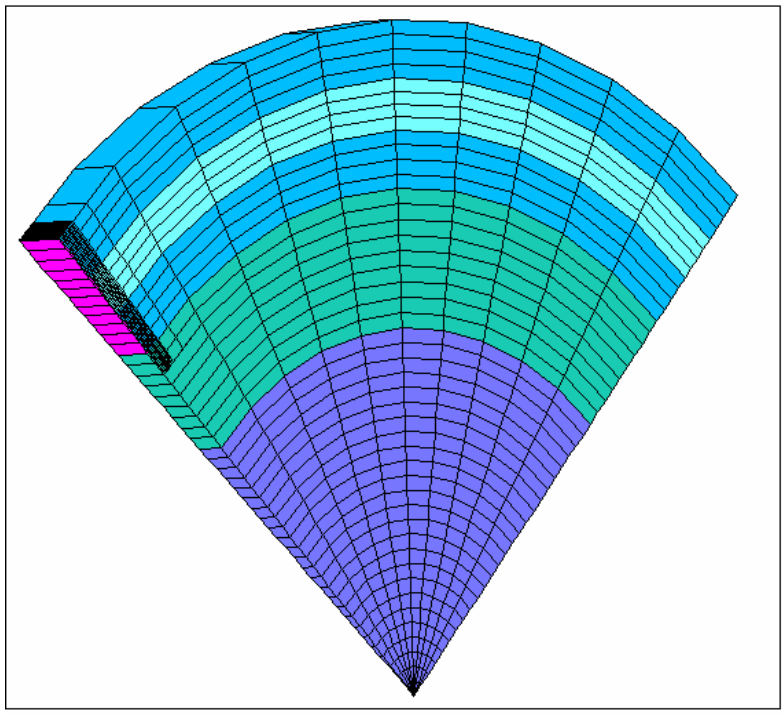
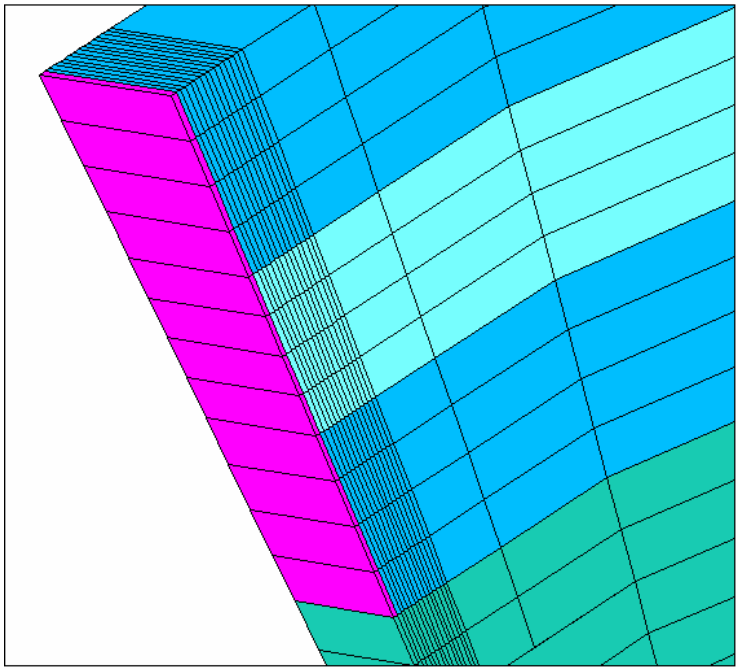


Figure 3

Structure of an exposed kernel particle built and proposed



Zoom near the fissure



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HTR-F PROJECT: SELECTION OF PROPERTIES AND MODELS FOR THE COATED PARTICLE - PYC AND SIC

DE M. PELLETIER, H. NABIELEK (FZJ), T. ABRAM (BNFL) AND D. MARTIN (BNFL CONSULTANT)

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Titre : HTR-F PROJECT: SELECTION OF PROPERTIES AND MODELS FOR THE COATED PARTICLE - PYC AND SIC

Auteur(s) : M. PELLETIER, H. NABIELEK (FZJ), T. ABRAM (BNFL) AND D. MARTIN (BNFL CONSULTANT)

Summary :

The Work Package 3 of the HTR-F program is dedicated to the modelling of the different phenomena which occur into the fuel particle during irradiation and to develop at the European level a common code. This tool has to main mission to predict the time-to-failure taking into account several mechanisms such pressure vessel, SiC layer corrosion, coating debonding or kernel migration.

A first task of the WP3 has consisted to gather the knowledge on particle component properties and fundamental models for describing the behaviour of the coated particle under irradiation in order to reach the best accuracy. This collection of the current knowledge was the object of the Deliverable Nb11 of the WP3 published in December 2002.

The present document, part of the Deliverable Nb12, proposes selections of properties for coating materials : pyrolitic carbons (PyC) and silicon carbide (SiC). For these two materials, 3 sets of data were constituted:

- for the PyC, they result of BNFL, FZJ and CEGA (USA) organisations,
- for the SiC from BNFL, FZJ and CEA.

Mots Clés	HTR, COATING, PYROCARBON, SILICON CARBIDE, PHYSICAL PROPERTIES, BEHAVIOUR, MODELLING

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RÉVISIONS

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SOMMAIRE

1. INTRODUCTION

In order to develop HTR reactor in Europe, a program devoted to fuel technology development (HTR-F) was launched in 2000 in the framework of the European Project HTR-TN. Around the world, the HTR fuel is based on spherical coated particles inserted in graphite blocks or pebble type elements. Their kernel generally consists of enriched uranium dioxide and the coatings are made of ceramic layers ensuring leak tightness to the fission products during normal and accidental situations.

One of the four Work Package of the HTR-F program (WP3) is dedicated to the modelling of the different phenomena which occur into the fuel particle during irradiation and to develop at the European level a common code. This tool has to main mission to predict the time-to-failure taking into account several mechanisms such pressure vessel, SiC layer corrosion, coating debonding or kernel migration.

Among the tasks of the WP3, the first one has consisted to gather the knowledge on particle component properties and fundamental models for describing the behaviour of the coated particle under irradiation in order to reach the best accuracy. This work is concretised in a document which constitutes the Deliverable Nb 11 *[1]*.

In the present document, which is a part of Deliverable Nb12, we propose a selection of properties for coating materials. In chapter 3, we provide a selection of 3 datasets for the PyC properties and behaviour under irradiation coming from BNFL, FZJ and CEGA corporation (USA). Concerning the SiC ones, we recommend in chapter 4 a selection 3 datasets coming from BNFL, FZJ and CEA.

2. FAST NEUTRON UNITS

In this document, a majority of properties depending of fast neutron flux ($\frac{d\Phi}{dt}$) or fluence (Φ) is given in units: n/m^2 for E > 0.1 MeV or 16 fJ unless otherwise specified. The conversion to other used units such as: Dido Nickel Equivalent (DNE) or E > 0.18 MeV or 29 fJ are as follows:

↱	n/m^2 (E > 0.1 MeV or 16 fJ)	n/m^2 (E > 0.18 MeV or 29 fJ)	n/m^2 (DNE)
n/m^2 (DNE)	1.67	1.52	1
n/m^2 (E > 0.18 MeV or 29 fJ)	1.1	1	0.66
n/m^2 (E > 0.1 MeV or 16 fJ)	1	0.91	0.6

3. PYROLYTIC CARBONS

Pyrolytic carbons (PyC) are key protective materials in the design of the classical HTR fuel coated particles (CP).

PyC are basically used for the constitution of the first very porous coating (50%) named "buffer" layer and for the two "dense" layers: the inner pyrolytic carbon (IPyC) and the outer pyrolytic carbon (OpyC) which enclose the usual silicon carbide layer (SiC) of the TRISO particle.

According to both the temperature of the pyrolysis process and the nature of the hydrocarbon, one commonly consider two classes of "dense" PyC materials: the high-temperature isotropic (HTI) PyC (θ > 1800 °C and CH_4 - Ar mixture) and the low-temperature isotropic (LTI) PyC (θ < 1500 °C and generally C_3H_6 - Ar mixture). Many available data come from the first class (HTI), because the greatest amount of tests was performed during the 60 and 70ties on this category of materials.

In this chapter, we provide the properties for the porous and dense PyC which are needed for the calculation of the behaviour and the prediction of failure during irradiation and heating of coated particles.

Physical and mechanical properties of PyC are greatly affected by the fabrication parameters, particularly the coating rate which influences the density of the coating, the degree of anisotropy and the crystallite size. The degree of anisotropy is generally quantified by the preferred orientation parameters, R_1 and R_3, in the directions parallel (1) and normal (3) to the deposition plane, respectively, or by the Bacon Anisotropy Factor (BAF). Relations between R_1, R_3 and the BAF are the following:

$$R_3 = \frac{2}{2+BAF}, \text{ and } R_1 = \frac{1+BAF}{2+BAF}$$

One may deduce $R_1 = 1 - R_3/2$ and $BAF = 2/R_3 - 2$ from these equations.

These properties come, on one hand, from proposals of BNFL *[2] [3] [4] [5]* and FZJ *[6]* organisations which provide the data in the framework of the WP3 of the HTR-F European programme and, on the other hand, of CEGA *[7]*.

Concerning these last, laws or constants for properties are generally given as a function of the following parameters: fast fluence, temperature, degree of anisotropy, density and eventually crystallite size. The scarcity of the data cannot establish a mutual coupling between these parameters and it is assumed that the combined effect is obtained by multiplying them together.

3.1. DENSITY

The theoretical density of graphite material is 2.27 g/cm^3. The value supplied by FZJ and BNFL for a 100 % dense PyC is a little lower than this value:

Theoretical density (g/cm^3)	2.2
Fabricated density of the porous PyC (buffer layer) and the "dense" PyC:	
"buffer" layer (g/cm^3)	$0.9 < \rho < 1.1$ *
dense PyC layers (g/cm^3)	$1.8 < \rho < 2$ *

- These ranges are the proposition for the current specification for HTR fuel particles

3.2. COEFFICIENT OF THERMAL EXPANSION

Very often, the data reported in the literature is not the true linear thermal expansion coefficient (α) but the mean value ($\overline{\alpha}$) given between two temperatures T_1 and T_2.

	FZJ	BNFL	CEGA [1]
"buffer" layer α (10^{-6} K^{-1})	$\alpha = 3.5$	$\alpha = 3.5$	*For BAF < 3 (R_1 < 0.8 and R_3 > 0.4)* *And in the range of temperature around 1100°C* $\alpha_1 = 40\,(R_1 - 1)^2 + 1.11$ $\alpha_3 = -41.67\,R_3 + 33.33$
dense isotropic PyC layers α (10^{-6} K^{-1})	$\alpha = 5.5$	$\alpha = 5.6$	

[1] The parallel and normal directions are respectively subscripted by the indications 1 and 3

3.3. SPECIFIC HEAT

	FZJ [1]
For graphite materials: c_p (J mol^{-1} K^{-1})	*For 298 < T < 1100 K:* $c_p = 0.109 + 3.897\,10^{-2}\,T - 1.482\,10^{5}\,T^{-2} - 1.7410^{-5}\,T^{2}$ *For 1100 < T < 4073 K:* $c_p = 24.46 + 4.354\,10^{-4}\,T - 3.165\,10^{6}\,T^{-2}$

[1] Data according to Ihsan Barin and Ottmar Knacke (1973)

No recommendation is proposed by both BNFL and CEGA corporation.

3.4. THERMAL CONDUCTIVITY

The thermal conductivity depends on the porosity and, consequently on the made-up density.

	FZJ	BNFL [1]
"buffer" layer λ (W m^{-1} K^{-1}) P (/)	$\lambda = 0.5$	$\lambda = 10.98222\left(\frac{1-P}{1+2P}\right)+0.00444$ For P = 0.5 $\lambda = 2.75$ For P = 0.2 $\lambda = 6.28$
dense isotropic PyC layers λ (W m^{-1} K^{-1})	$\lambda = 4$	

[1] According to the "Red book" (Unpublished U.K. data property handbook). Value obtained from that proposed for the dense PyC by applying it a correction of porosity given by the Maxwell-Eucken relationship (1 – P)/(1 + 2P)

No recommendation is proposed by CEGA corporation.

3.5. YOUNG'S MODULUS

	FZJ [1]	BNFL [2]
"buffer" layer E (MPa) Φ (10^{25} n/m^2 >0,1MeV)	*For* $0 < \Phi < 0.5$ $E = 7000 + 6000\ \Phi$ *For* $\Phi > 0.5$ $E = 10000$	$E = 12500\ (1 + 0.18\ \Phi)$
"dense" PyC layers E (MPa) Φ (10^{25} n/m^2 >0,1MeV)	$E = 29000$	$E = 25000\ (1 + 0.18\ \Phi)$

[1] Polynomial adjustment according to the FZJ contribution
[2] For the buffer, E = half the dense PyC value

	CEGA
"buffer" layer E (MPa) P (/)	*For 0.2 < P < 0.6* $E = 34500 \exp(-2.03\ P)$
"dense" PyC layers E (MPa) θ (°C) ρ (g/cm^3) Lc (nm) ** Φ (10^{25} n/m^2 >0,1MeV)	$E_1 = k_\rho\ k_{BAF01}\ k_{Lc}\ k_\phi\ k_T\ E_{01}$ and $E_3 = k_\rho\ k_{BAF03}\ k_{Lc}\ k_\phi\ k_T\ E_{03}$ *With:* $E_{01} = E_{03} = 25500$ $k_\rho = 0.384 + 0.324\ \rho$ $(1.8 < \rho < 2)$* $k_{Lc} = 2.985 - 0.662\ Lc$ $(2.5 < Lc < 3.5)$* $k_\Phi = 1 + 0.23\ \Phi$ $(< 4\ 10^{25})$* $k_T = 1 + 0.00015\ (\theta - 20)$ $(20 < \theta < 2000)$* $k_{BAF01} = 0.481 + 0.519\ BAF_0$ $k_{BAF03} = 1.463 - 0.463\ BAF_0$ $(1 < BAF_0 < 2)$*

* Recommended ranges of variation of the parameters
** Lc : crystallite size

3.6. POISSON'S RATIO

	FZJ	BNFL	CEGA [1]
"buffer" layer ν (/)	ν = 0.3	ν = 0.21	ν = 0.23
"dense" PyC layers ν (/)	ν = 0.3	ν = 0.21	$\nu_{12} = 0{,}766\ R_3 - 0{,}275$ $\nu_{13} = -0{,}884 R_3 + 0{,}825$ $\nu_{31} = \nu_{13}\ E_3/E_1$

[1] Preferred orientation parameter R_3 in the direction normal to the deposition plane (Cf. § 3)

3.7. ULTIMATE TENSILE STRENGTH

Pyrolytic carbons are generally treated as brittle materials. The scatter in the fracture strength (UTS) is often rather large because failure starts from the defects existing inside and at the surface of the material. The distribution density of failure "f" is given by a statistical distribution expressed in terms of a Weibull equation whose usual expressions are:

$$f = 1 - \exp\left\{-\ln 2\left(\frac{\sigma}{\sigma_{med}}\right)^m\right\} \qquad \text{or} \qquad f = 1 - \exp\left\{-\int_V \left(\frac{\sigma}{\sigma_{0V}}\right)^m dV\right\}$$

where σ_{med} or σ_0 and m are constants whose values are determined from experiments.

	BNFL [1]	CEGA
"buffer" layer σ_{med} (MPa)	σ_{med} = 50	No recommendation
"dense" PyC layers σ_{med} (MPa) σ_{0V} (MPa $m^{(3/m)}$) m (/)	σ_{med} = 190 m = 7	$\sigma_{0V} = 154.46\ BAF_0^2 - 141.1\ BAF_0$ m = 9.5

[1] Linear adjustments for σ_{med} and m versus the density according to the data from Bongartz *et al* (1976) on results obtained from propylene derived PyC with densities between 1.73 to 1.95 g/cm^3.

No recommendation is proposed by FZJ.

3.8. IRRADIATION INDUCED CREEP

The irradiation induced creep rate is given by the following expression:

$$\dot{\varepsilon}_1 = K\left[\sigma_1 - \nu_c(\sigma_2 + \sigma_3\right]\frac{d\Phi}{dt}$$

where

K:	creep constant
σ_1, σ_2 and σ_3	components of the stress tensor
ν_c	Poisson's coefficient for creep
$\frac{d\Phi}{dt}$	fast neutron flux

Like that was underlined in the Deliverable Nb11, values of the creep constant **K** present a wide scatter of magnitude according to the different sources.

The recommendations of FZJ, BNFL and CEGA corporation are the following:

	FZJ	BNFL [1]	CEGA
"buffer" layer K [MPa n m^{-2}(E> 0.1 MeV)]$^{-1}$ ν_c (/)	K = 9.6 10^{-30} ν_c = 0.5	K = 4.4 10^{-29} ν_c = 0.4	*For 1 < ρ < 2* K = K_0 [1 + 2,38 (1,9 - ρ)] *For 600 < θ < 1300* K_0 = 1.996 10^{-29} – 4.415 10^{-32} θ + 3.6544 10^{-35} θ^2 ν_c = 0.5
"dense" PyC layers K [MPa n m^{-2} (E > 0.1 MeV)]$^{-1}$ ρ (g/cm^3) θ (°C) ν_c (/)	K = 1.4 10^{-29} ν_c = 0.5	K = 4.4 10^{-29} ν_c = 0.4	

[1] data from Buckley et al (1975) used in STAPLE code

3.9. IRRADIATION INDUCED DIMENSIONAL CHANGE RATE

Under irradiation, the buffer and the dense PyC are submitted to a fast neutron flux which brings about an irradiation induced dimensional change. According to the density of fabrication and the initial anisotropy of the material, the dimensional change rate can vary considerably.

A considerable number of measurements of dimensional change in unrestrained PyC has been reported in the open literature.

Data recommended by both FZJ and BNFL are summarized in the following table:

	FZJ [1]	BNFL [2]
"buffer" layer $\dot{\varepsilon}_r$ $\dot{\varepsilon}_\theta$ [10^{25} n m^{-2} (>0,1MeV)]$^{-1}$	$\dot{\varepsilon}_r = \dot{\varepsilon}_\theta = -0.176 \exp(-1.75\,\Phi)$	$\dot{\varepsilon}_r = \dot{\varepsilon}_\theta = -0.241 \exp(-2.2\,\Phi)$
"dense" PyC layers $\dot{\varepsilon}_r$ $\dot{\varepsilon}_\theta$ [10^{25} n m^{-2} (>0,1MeV)]$^{-1}$	$\dot{\varepsilon}_r = -0.077 \exp(-\Phi) + 0.031$ $\dot{\varepsilon}_\theta = -0.036 \exp(-2.1\,\Phi) - 0.01$	$\dot{\varepsilon}_r = -0.1335 \exp(-1.5\,\Phi^{0.8}) - 1.12\,10^{-3}\Phi^2 + 1.85\,10^{-2}\Phi$ Approached formula for the radial deformation: If $\Phi < 4$ $\varepsilon_r = 0.164253\,\Phi^4 - 1.64495\,\Phi^3 + 6.6379\,\Phi^2 - 10.4153\,\Phi$ If $\Phi > 4$ $\varepsilon_r = 0.472672\,\Phi^2 + 2.29629\,\Phi - 15.6717$ $\dot{\varepsilon}_\theta = -0.0225 \exp(-0.7\,\Phi) - 2.1\,10^{-3}\Phi - 8\,10^{-3}$

[1] Adjustment from FZJ contribution

[2] Adjustment from the data used in the code STRESS 3 i.e. the Williams/Shipp correlation at 1200°C for a density range : 1.75 – 1.86)

	CEGA
"buffer" layer $\dot{\varepsilon}_r$ $\dot{\varepsilon}_\theta$ [10^{25} n m^{-2} (>0,18 MeV)]$^{-1}$	$\dot{\varepsilon}_r = \dot{\varepsilon}_\theta = -0.06352 + 0.0095\,\Phi$
"dense" PyC layers $\dot{\varepsilon}_r$ $\dot{\varepsilon}_\theta$ [%/(10^{25} n/m^2 E > 0,18 MeV)] θ (°C)	$\dot{\varepsilon}_r = CR1 + 2\,CR2\,\Phi$ For $\phi > 6\,10^{25}$ n/m^2, $\dot{\varepsilon}_r$ is assumed to remain constant and equal to $(\dot{\varepsilon}_r)_{\phi = 6\,10^{25}}$ Coefficients CR1 and CR2 can be obtained from the following equations: $CR1 = CR1T2\,\theta^2 + CR1T1\,\theta + CR1T0$ $CR2 = CR2T2\,\theta^2 + CR2T1\,\theta + CR2T0$ In which coefficients CRjTi are given by: For j = 1 $CR1Ti = a_{2i}\,BAF_0^2 + a_{1i}\,BAF_0 + a_{0i}$

CEGA

i =	a_{2i}	a_{1i}	a_{0i}
0	-1.547E+02	3.567E+02	-2.029E+02
1	4.115E-01	-9.353E-01	5.232E-01
2	-2.544E-04	5.776E-04	-3.232E-04

For j = 2

$CR2Ti = b_{2i}\, BAF_0^2 + b_{1i}\, BAF_0 + b_{0i}$

if $BAF_0 < 1.03$

i =	b_{2i}	b_{1i}	b_{0i}
0	4.01744E+02	-8.29844E+02	4.28088E+02
1	-0.943444	1.9484	-1.00457
2	4.89444E-04	-1.00876E-03	5.19147E-04

if $1.03 < BAF_0 < 1.05$

i =	b_{2i}	b_{1i}	b_{0i}
0	0	-2.25	1.8775
1	0	4.9E-03	-3.667E-03
2	0	-5.0E-07	-1.05E-07

if $1.05 < BAF_0 < 1.1$

i =	b_{2i}	b_{1i}	b_{0i}
0	0	-1.11524	0.686004
1	0	2.11896E-03	-7.46907E-04
2	0	0	-6.3E-07

$\dot{\varepsilon}_\theta = CT1 + 2\, CT2\, \Phi$

For $\phi > 4\,10^{25}$ n/m^2,

$\dot{\varepsilon}_\theta$ is assumed to remain constant and equal to $(\dot{\varepsilon}_\theta)_{\phi = 4\,10^{25}}$

Coefficients CT1 and CT2 can be obtained from the following equations:

$CT1 = CT1T2\, \theta^2 + CT1T1\, \theta + CT1T0$

$CT2 = CT2T2\, \theta^2 + CT2T1\, \theta + CT2T0$

In which coefficients CTjTi are given by:

For j = 1

$CT1Ti = c_{3i}\, BAF_0^3 + c_{2i}\, BAF_0^2 + c_{1i}\, BAF_0 + c_{0i}$

CEGA

i =	c_{3i}	c_{2i}	c_{1i}	c_{0i}
0	-2056.865	6492.003	-6837.18	2401.046
1	4.75697	-15.01806	15.82031	-5.559754
2	-2.174319E-03	6.850273E-03	-7.207533E-03	2.531618E-03

For j = 2

$CT2Ti = d_{3i}\ BAF_0^3 + d_{2i}\ BAF_0^2 + d_{1i}\ BAF_0 + d_{0i}$

i =	d_{3i}	d_{2i}	d_{1i}	d_{0i}
0	635.02826	-1992.5331	2084.7227	-727.22875
1	-1.4607633	4.5802947	-4.7891012	1.6699538
2	6.6869010E-04	-2.0855729E-03	2.1688388E-03	-7.5212054E-04

4. SILICON CARBIDE

As the PyC layers, the silicon carbide (SiC) layer of the CP is set down from a mix of gases ; the more often used is the methyltrichlorosilane (MTS) with argon. The microstructure of pyrolytic SiC depends on temperature and rate of deposition of MTS.

The β (cubic) structure dominates but α phase and free silicon may be present at low (<1250 °C) deposition temperature.

Material property considerations are generally less of a problem for the SiC compared with the PyC materials. However, this layer plays a fundamental role for the mechanical and diffusion resistance of the CP ; consequently, a good knowledge of the UTS of the SiC layer which can be enhanced by reducing the flaws, is very important for achieving high burn-up.

In this chapter, we provide the properties for pyrolytic SiC which are needed for the calculation of the behaviour and the prediction of failure during irradiation and heating of coated particles.

These properties are mainly from proposals of BNFL *[2] [3]*, FZJ *[6]* and CEA *[8]* organizations which provide the data in the framework of the WP3 of the HTR-F European programme.

With regard to the properties proposed by the CEA, they come from a recent critical review realized within the framework of the studies which are currently led for the GCFR fuel element design.

4.1. DENSITY

The β-SiC phase possesses a **fcc** crystal structure. At room temperature, the lattice parameter **a** is equal to 0.4349 nm.

Theoretical density (g/cm^3)	3.238
fabricated density (%TD)	> 99

4.2. COEFFICIENT OF THERMAL EXPANSION

Very often, the data reported in the literature is not the true linear thermal expansion coefficient (α) but the mean value ($\overline{\alpha}$) given between two temperatures T_1 and T_2.

	FZJ	BNFL	CEA [1]
$\overline{\alpha}(20°C, \theta)$ (10^{-6} K^{-1}) θ (°C)	5	5	$\alpha = 3.43846 + 1.19402\ 10^{-3}\ \theta - 2.05716\ 10^{-7}\ \theta^2$

[1] Uncertainty: 2%, Range of determination: 20 to 1300°C

4.3. SPECIFIC HEAT

	FZJ [1]	CEA
c_p (J mol^{-1} K^{-1}) T (K)	*For 298 < T < 3259 K:* $c_p = 50.824 + 1.951\ 10^{-3}\ T - 4.924\ 10^6\ T^{-2} + 8.21\ 10^8\ T^{-3}$	*For 273 < T < 2273 K:* $c_p = 34.537 + 0.01313\ T - 3.7428\ 10^{-7}\ T^2 - 1.1981\ 10^6/T^2$

[1] Data according to Ihsan Barin and Ottmar Knacke (1973)

No recommendation is proposed by BNFL.

4.4. THERMAL CONDUCTIVITY

	FZJ	BNFL	CEA
λ (W m^{-1} K^{-1}) T (K) P (/) θ (°C) ε (/)	$\lambda = 16$	*Unirradiated SiC* at room temperature : $\lambda_{ni} = 67$ *Irradiated SiC*: $\lambda_i = 8.24$	*Unirradiated SiC:* $\lambda_{ni} = 42.58 - \frac{1.5564\,10^4}{T} + \frac{1.2977\,10^7}{T^2} - \frac{1.8458\,10^9}{T^3}$ *Correction due to irradiation [1] :* $\frac{\lambda_{i.}}{\lambda_{ni.}} = (1-P)\frac{1}{(1+4.05\,10^3\varepsilon)^{0.7}}$ with ε : reversible swelling (for calculation see §4.9)

[1] The evolution of λ under irradiation depends on irradiation defects created in the material which also generate the reversible swelling (see 4.9). As a consequence, the proposed relation connects the evolution of the thermal conductivity to the reversible swelling.

4.5. YOUNG'S MODULUS

	FZJ [1]	BNFL [2]	CEA [3]
E (MPa) T (K) θ (°C)	*For 298 < T < 573 K:* E = 386000 *For 573 < T < 1873 K:* E (T)/E (298 K) = $-2.12\,10^{-7}\,T^2$ $+ 2.52\,10^{-4}\,T + 0{,}9252$	E = 421000	$E = a + b\,\theta + c\,\theta^2 + d\,\theta^3 + e\,\theta^4 + f\,\theta^5 + g\,\theta^6$ *With:* a = 432 000 b = -74.1 c = 0.1541 $d = -5.401\,10^{-4}$ $e = 8.142\,10^{-7}$ $f = -5.187\,10^{-10}$ $g = 1.043\,10^{-13}$

[1] The fractional variation of the Young's modulus : E(T)/E(298 K) with temperature is according to the of the FZJ contribution.

[2] The Young's modulus is deduced from the constants of compliance used in the code STRESS 3 by the relation: $E = 1/E_{11}$

[3] Range for use: 20 to 1400 °C

4.6. POISSON'S RATIO

	FZJ	BNFL [1]	CEA
ν (/)	0.3	0.33	0.18

[1] The Poisson's ratio is deduced from the constants of compliance currently used in the code STRESS 3 by the relation: $\nu = - E_{12}/E_{11}$

4.7. ULTIMATE TENSILE STRENGTH

The disparities of nature, size, geometry, localization and orientation of the defects, as well as the differences of state of surface of the nominally identical test samples explain the big variations of the ultimate tensile strength (UTS) frequently observed. The distribution density of failure "f" is given by a statistical distribution expressed in terms of a Weibull equation whose usual expressions are:

$$f = 1 - \exp\left\{-\ln 2\left(\frac{\sigma}{\sigma_{med}}\right)^m\right\} \qquad \text{or} \qquad f = 1 - \exp\left\{-\int_V \left(\frac{\sigma}{\sigma_{0V}}\right)^m dV\right\}$$

where σ_{med} , σ_{0V} and m are constants whose values are determined from experiments.

	FZJ [1]	BNFL	CEA
σ_{med} (MPa) σ_{0v} (MPa $m^{3/6}$) m (/) T (K) Φ (10^{25} n/m^2 E > 0.1 MeV)	$\sigma_{med} = \sigma_{med0}\left(1 - \frac{\Phi}{1.67\,\Phi_\sigma}\right)$ [2], $\sigma_{med\,min} = 196$ $\log \Phi_\sigma = 0.556 + \frac{650}{T}$ $\sigma_{med0} = 834$ $m = m_0\left(1 - \frac{\Phi}{1.67\,\Phi_m}\right)$ [2], $m_{min} = 2$ $\log \Phi_m = 0.394 + \frac{650}{T}$ $m_0 = 8.02$	$\sigma_{med} = 200$ m = 5	$\sigma_{0V} = 9.64$ m = 6

[1] The relationship of the UTS comes from Allelein (1983) who proposes a decreasing of σ_{med} and m under irradiation. Data for σ_{med0} and m_0 in the previous table come from measurements performed on German particle variety : EO 1607.

[2] A coefficient 1.67 is applied to transform DNE in E > 0.1 MeV (see table page 4)

4.8. IRRADIATION INDUCED CREEP

The irradiation induced creep rate for the SiC is given by the following expression:

$$\dot{\varepsilon}_{eq} = K\,\sigma_{eq}\,\frac{d\Phi}{dt}$$

where

K: creep constant

σ_{eq} equivalent stress

$\frac{d\Phi}{dt}$ fast neutron flux

	FZJ	BNFL	CEA
θ (°C) K [MPa n m-^{2}(E>0.1 MeV)]$^{-1}$	K = 8.4 10^{-32}	K = 1.68 10^{-31}	*For* $\theta < 1000°C$ K = 0.4 10^{-31} *For* $1000 < \theta < 1100°C$ $K = \left[0.4 + 1.42\,10^{-2}\,(\theta - 1000)\right]10^{-31}$ *For* $\theta > 1100°C$ K = 1.82 10^{-31}

4.9. IRRADIATION INDUCED DEFORMATION

	FZJ [1]	BNFL [2]
$\dot{\varepsilon}$ [10^{25} n m^{-2} (>0,1MeV)]$^{-1}$	$\dot{\varepsilon} = 3.65\,10^{-3}\,\exp(-14\,\Phi)$	$\dot{\varepsilon}_r = \dot{\varepsilon}_\theta = 6.6\,10^{-4}$

[1] Adjustment according to the FZJ contribution

[2] Adjustment from the data used in the code STRESS 3

	CEA
$\dot{\varepsilon}$ [10^{25} n m^{-2} (>0,1MeV)]$^{-1}$ θ (°C)	*For θ < 1000°C (Saturation swelling)** 25 < θ < 800°C $\quad \varepsilon_{sat} = 1.038\ 10^{-2} - 1.1094\ 10^{-5}\ \theta$ 800 < θ < 1000°C $\quad \varepsilon_{sat} = 5.1097\ 10^{-3} - 4.509\ 10^{-6}\ \theta$ $\dot{\varepsilon} = \frac{\varepsilon_{sat}}{\Phi_0} \exp\left(-\frac{\Phi}{\Phi_0}\right)$ with $\Phi_0 = 0.3396$ *For 1000 < θ < 1250°C* $\dot{\varepsilon} = \frac{6\ 10^{-4}}{\Phi_0} \exp\left(-\frac{\Phi}{\Phi_0}\right) + 4.3233\ 10^{-29} \frac{(\theta - 1000)}{250}$

* This low temperature swelling is reversible

4.10. CORROSION RATE

Corrosion of the SiC layer by diffusion of metallic fission products leads to strength loss which is assumed by a spread of the Weibull distribution as a function of time and temperature:

	FZJ
$\dot{\eta}$ (1/s) T (K) R = 4.186 m t (s)	grain boundary corrosion rate : $\dot{\eta} = 0.565 \exp\left(-\frac{1.874\ 10^5}{R\ T}\right)$ Evolution of Weibull modulus: $m = m_0\ [0.44 + 0.56 \exp(-\dot{\eta}\ t)]$

No recommendation is proposed by both BNFL and CEGA corporation.

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