Operator of computation of wear

Summarized:

This note presents three laws of attrition which make it possible to evaluate the volume used starting from the quantities resulting from a dynamic computation carried out with the operator DYNA_TRAN_MODAL [U4.54.03] and key word CHOC.

- The model of Archard,
- model KWU_EPRI,
- model EDF_MZ.

The coefficients of wear necessary for these computations are provided by the user or specified in a data base.

From worn volume and geometry of the contact, it is possible to calculate the depth of wear for the mobile or its obstacle.

An angular figure division of clearance authorizes the operator with calculating the quantities relating to wear by sectors.

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1 Introduction

the evaluating of the damage by wear during requires a thorough knowledge of the involved bodies the contact, loadings and kinematics. The investigations led to the Mechanical Department and Technology of the Components make it possible to provide coefficients for laws of attrition relative to configurations of wear affecting the components of the nuclear power plants. A transient computation by modal recombination, using operator DYNA_TRAN_MODAL [U4.54.03] makes it possible to know the kinematics and the dynamics of the contact for telegraphic structures such as the control rods and the tubes of steam generator which impact and slip against their guidance.

To compute: the power of wear, the modulus of postprocessing of the wear of *Code_Aster*®, (POST_USURE [U4.67.03]), uses, in a node of shock, result in generalized coordinates (tran_gene the) resulting one from DYNA_TRAN_MODAL. It and the combines the normal forces velocities of sliding according to the method definite with the following paragraph. From the knowledge of the power of wear, it is possible to go up with volumes used by means of one of the laws of attrition suggested in POST_USURE. The coefficients to be used are to be defined by the user or to search in a data base integrated into the operator.

In the second time, the knowledge of the geometry of internal structures of nuclear power plants makes it possible to calculate the depths of wear starting from worn volumes.

Operator POST_USURE allows to cut out the figure of clearance in sectors in order to assign several coefficients of wear to the same zone of shocks to take account of complex geometries. For example, the contact on edge leads to matter losses more important than the contact conformel in the case of the control rods.

The array generated by POST_USURE gives the value of the volumes used for several values of time. It can be used as starter of operator MODI_OBSTACLE to know the evolution of the figure of clearance due to the wear of the mobile and the obstacle. That gives the possibility of carrying out iterative computations which couple the evolution of the dynamics with the wear of the mechanisms.

2 Laws of attrition

In its initial form, the model of Archard [bib1] expresses, for a configuration of adhesive wear, in sliding, a relation between worn volume and of the characteristic quantities of the contact:

$$V=\frac{k.\|F_n\|.L}{H}$$

whe re	V	:	used volume
	k	:	coefficient of wear without dimension
	$\|F_n\|$	:	modulate normal force of contact, presumedly constant
	L	:	slipped length
	H	:	hardness.

The coefficient k is different for each involved body. It during depends on the geometrical and thermodynamic conditions the contact.

It was shown that the model of Archard can be wide with other mechanisms, in sliding dominating. With the help of a redefinition of certain parameters, the preceding equation can be written:

$$V=K.W$$

where K : is equal to $\frac{k}{H}$

W : is equal to $\|F_n\|.L$.

W the dimension of a work has. By convention, it is called "work of wear".

If the normal force of contact varies in the course of time (for example, in a situation of impact-slidings, $\|F_n\|$ present of very strong variations of short time during shocks), the definition of W becomes:

$$W=\int_{t_0}^{t_1}\|F_n\|\cdot\|V_t\|\cdot dt$$

where W : work of wear

$\|F_n\|$: modulate normal force during the contact

$\|V_t\|$: modulate velocity of sliding during the contact

t_0 : time of beginning of computation

t_1 : time of end of computation.

Consequently, by analogy with the usual models of the mechanics, it is possible to define a "power of wear" while posing:

$$P=\|F_n\|\cdot\|V_t\|$$

where P : power of wear.

If a steady mode is reached, the power of wear is supposed to be constant in the course of time. In order to make sure of this stationarity, the interval $[t_{0,}t_1]$ can be cut out in several blocks in operator POST_USURE [U4.67.03]. For each one of these blocks, it is advisable to check that the power of wear evolves little (in any rigor, the use of the laws of attrition below supposes that the power of wear is constant).

2.1 Law of attrition "ARCHARD"

model is of the linear type [bib1]: $V=K\cdot P\cdot t$

where V : volume of wear

K : coefficient of wear

P : power of wear

t : time interval.

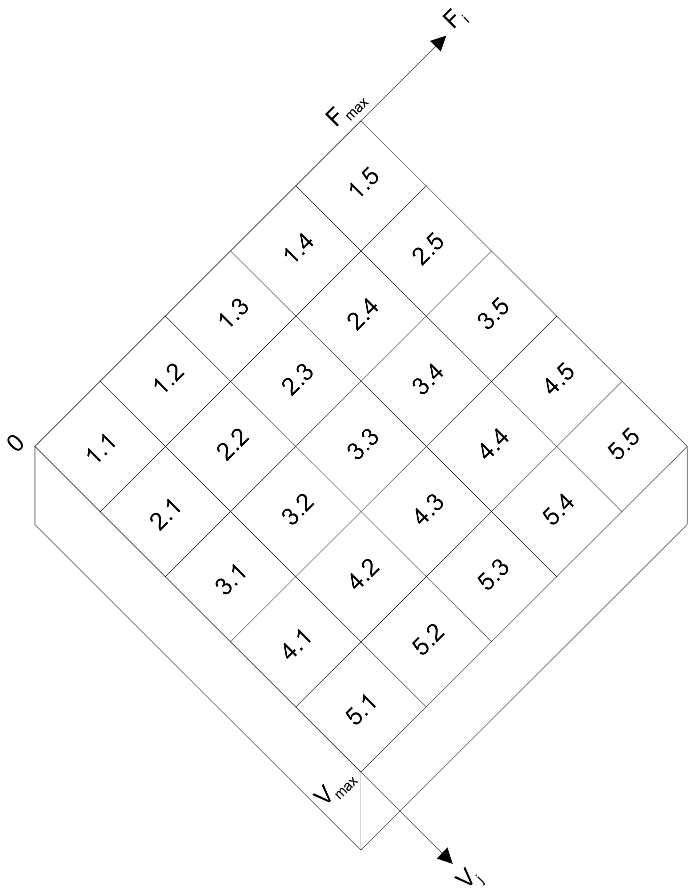
The coefficient K is provided by the user or is taken in a data base (see [§3]). It is different for the two involved bodies and depends on the geometrical and thermodynamic conditions in the contact. The time interval t used for the computation of wear does not correspond at the time of simulation manpower but to the time interval on which the user wishes to evaluate wear.

2.2 Law of attrition "KWU_EPRI"

the approach of the model consists in determining a coefficient of wear K , within the meaning of the model of Archard, in taking into account the particular conditions of the contact studied [bib2].

The normal forces $F_i(N)$ are divided into 5 classes, as well as the velocities of sliding $V_j(m/s)$.

One obtains 25 classes whose location is indicated as follows:



For a given computation, one determines the percentages obtained for each of the 25 classes.

The processing is done by applying suitable factor loadings for each class, which give an account of its particular contribution in the total process of wear.

In the case of the pure impacts (classes 1.1 with 1.5), the contribution of these classes is modelled by calling on a factor loading $m_{h_{ij}}$ defined by:

$$m_{h_{ij}} = k_1 \cdot k \cdot \left(\frac{F_i}{c} \right)^3$$

whe re	$m_{h_{ij}}$	:	adimensional factor of intensity of impact-hardening
	k_1	:	dimensional coefficient of correction
	k	:	experimental adimensional constant
	c	:	experimental adimensional constant
	F_i	:	mean value of the normal force for the class ij

In the case of the sliding (class 1.1 and classes 2.1 to 5.5), the contribution of these classes is modelled by calling on a factor loading $m_{w_{ij}}$ defined by:

$$m_{w_{ij}} = k_2 \cdot F_i \cdot \left(V_j\right)^2$$

where $m_{w_{ij}}$: adimensional factor of intensity of wear by sliding
k_2 : dimensional coefficient of correction
F_i : mean value of the normal force for the class ij
V_j : mean value velocity of sliding for the class ij

It is then necessary to calculate the percentages balanced for each class of the two categories impacts - hardening and wear by sliding:

$$P_{h_{ij}} = m_{h_{ij}} \cdot p_{ij}$$
$$P_{w_{ij}} = m_{w_{ij}} \cdot p_{ij}$$

where p_{ij} is the percentage of elements of the class ij .

What leads to a total factor of intensity of wear

$$w = \frac{\left(\sum P_{w_{ij}}\right)^2}{\sum P_{h_{ij}} + \sum P_{w_{ij}}}$$

the total factor of intensitéest w used like factor of correction of the coefficient of wear within the meaning of the model of ARCHARD according to the statement:

$$K_{KWU} = k_r \cdot w / w_r$$

$$V = K_{KWU} \cdot P \cdot t$$

where k_r : is the coefficient of wear of reference obtained in experiments for conventional conditions of test in oscillating sliding,
and w_r is the total factor of intensity evaluated for this same test.

2.3 Law of attrition "EDF_MZ"

It is currently developed for the only case of the control rods.

Feedback the watch which the kinetics of wear slows down with time t ; a way take account of the observations is to express the volume used in the form:

$$V = \left(\frac{S_0 - S}{n}\right) \cdot \left(1 - e^{-nt}\right) + S \cdot t$$

where S_0 is the initial velocity and S the velocity of wear asymptotic (see Ci - below),
n is a parameter of the model.

The values of n and of S are deduced from feedback.

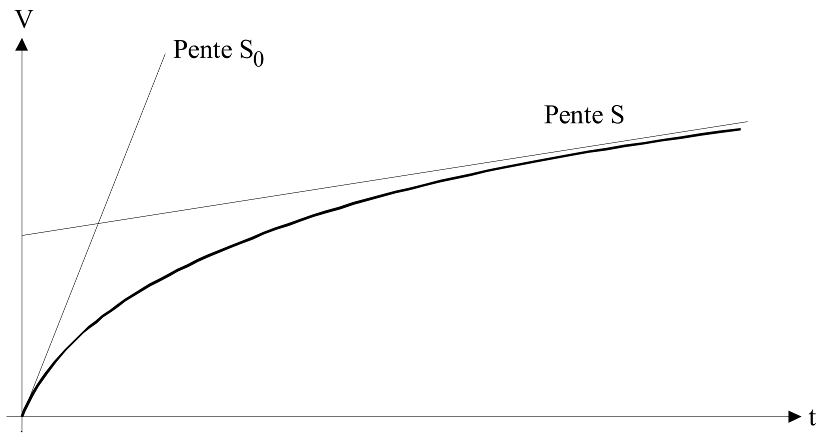
Tests on simulators, of short time compared to that of a cycle of operation of an engine, show that the velocity of initial wear S_0 follows a model of the type:

$$S_0 = A \cdot \left(P_0\right)^b$$

where P_0 is the power of initial wear
A and b are coefficients determined by tests on simulators [bib4]

feedback the watch that the velocity of wear reaches an asymptotic value S. The preceding relation, observed on simulator is supposed to be valid for all times of the phenomenon of wear. That supposes a power of wear P which makes it possible to reach $S = A \cdot \left(P\right)^b$, for the high values of time t (typically, one or more cycles of operation).

The corresponding evolution of the volume used according to time is form:



The worn volume V calculated with the assistance operator POST_USURE is written:

$$V = \left(\frac{A \cdot \left(P_0\right)^b - S}{n}\right) \cdot \left(1 - e^{nt}\right) + S \cdot t$$

where V : volume of wear
P_0 : power of wear calculated by *Code_Aster*®
A, b, S, n : coefficients of the model defined above.

This model is described in detail by the reference [bib4].

3 Data base

the materials are located by a followed letter by alphanumerics. The codes are indicated below with a usual name and between brackets, norm AFNOR.

A304L : Steel 304L (Z2 CN 18-9),
A304LNI : Steel 304L nitrided,
A304LCR : Chrome steel 304L,
A304LLC1C : Steel 304L covered with carbide of chromium,
A316L : Steel 316L (Z2 NDT 17-12),
A347 : Steel 347 (Z6 CNNb 18-11),

A405	:	Steel 405 (Z6 CA 13),
A42	:	Steel A42 (A 42),
Z10C13	:	Z10C13 (Z10 C13),
Z6C13	:	Z6C13 (Z6 C13),
I600	:	Inconel 600 (NC 15 Fe),
I600CR	:	Chrome Inconel 600,
I600TT	:	Inconel 600 treaty thermically,
I690	:	Inconel 690 (NC 30 Fe),
I690TT	:	Inconel 690 treaty thermically,
I800	:	INCOLOY 800 (Z5 NC 35-20),
I800CR	:	INCOLOY 800 chrome,

the tables below and the give the coefficients of wear for the mobiles obstacles for several couples of materials (mat1 is the material of the variable component and mat2 that of the obstacle). The empty boxes correspond to null coefficients. A certain number of situations is currently envisaged without all the coefficients being available because this data base could be supplemented with the results of the tests carried out at Department MTC.

Tables of the coefficients for the control rods for the model of ARCHARD:

CONTACT : “GRAPPE_ALESAGE” (cf [§4.1])

mat1	mat2	Coef_mobile	Coef_obst	References
A304L	A304L	2.6E-15	3.7E-15	[bib5]
A316L	A304L	4.2E-15	4.1E-15	[bib5]
A304LNI	A304L	0.1E-15	4.1E-15	[bib5]
A304LCR	A304L	0.1E-15	5.5E-15	[bib5]
A304LLC1C	A304L	0.1E-15	5.5E-15	[bib5]

CONTACT : “GRAPPE_1_ENCO” and “GRAPPE_2_ENCO” (cf [§4.2] and [§4.3])

mat1	mat2	Coef_mobile	Coef_obst	References
A304L	A304L	30.E-15	17.E-15	[bib5]
A316L	A304L	40.E-15	29.E-15	[bib5]
A304LNI	A304L	1.E-15	124.E-15	[bib5]
A304LCR	A304L	1.E-15	43.E-15	[bib5]
A304LLC1C	A304L	1.E-15	34.E-15	[bib5]

Tables of the coefficients for the control rods for the model EDF-MZ:

CONTACT : “GRAPPE_ALESAGE” (cf [§4.1])

mat1	mat2	Coef_mobile	Coef_obst	References
A304L	A304L	A = 2.6E-15 B = 1. N = 2.44E-8 S = 1.14E-16	A = 3.7E-15 B = 1. N = 2.44E-8 S = 1.14E-16	[bib5] [bib6]
A316L	A304L	A = 11.E-15 B = 1.61 N = 2.44E-8 S = 1.14E-16	A = 4.1E-15 B = 1. N = 2.44E-8 S = 1.14E-16	[bib5] [bib6]

CONTACT : “GRAPPE_1_ENCO” and “GRAPPE_2_ENCO” (cf [§4.2] and [§4.3])

mat1	mat2	Coef_mobile	Coef_obst	References
A304L	A304L	A = 20.E-15 B = 1.05 N = 2.44E-8 S = 1.14E-16	A = 23.E-15 B = 1.19 N = 2.44E-8 S = 1.14E-16	[bib5] [bib6]
A316L	A304L	A = 500.E-15 B = 1.78 N = 2.44E-8 S = 1.14E-16	A = 490.E-15 B = 1.91 N = 2.44E-8 S = 1.14E-16	[bib5] [bib6]

Tables of the coefficients for the steam generators for the model of ARCHARD:

CONTACT : "TUBE_BAV" (cf [§4.4])

mat1	mat2	Coef_mobile	Coef_obst	References
I600	I600	1.2E-13		[bib6]
I600TT	I600	4.5E-14		[bib6]
I600TT	I600TT	1.4E-15		[bib6]
I600	I600CR	7.2E-14		[bib6]
I600TT	I600CR	9.1E-16		[bib6]
I690TT	I600CR	1.2E-15		[bib6]
I600	Z10C13	9.9E-14		[bib6]
I600	A405	6.2E-14		[bib6]
I690	A405	4.1E-16		[bib6]
I600TT	Z6C13	9.2E-15		[bib6]
I600	Z6C13	7.1E-15		[bib6]
I690TT	Z6C13	7.7E-15		[bib6]
I600	A347	1.0E-13		[bib6]

CONTACT : "TUBE_ALESAGE" (cf [§4.5])

mat1	mat2	Coef_mobile	Coef_obst	References
I690	Z10C13	6.0E-17		[bib6]
I600	I600	1.6E-13		[bib6]
I690	I600	5.2E-14		[bib6]
I600	I600CR	2.2E-15		[bib6]
I690	I600CR	4.4E-15		[bib6]
I600	A42	2.2E-15		[bib6]

CONTACT : "TUBE_3_ENCO" (cf [§4.6])

mat1	mat2	Coef_mobile	Coef_obst	References
I600	Z10C13	2.5E-16		[bib6]
I690	Z10C13	2.4E-16		[bib6]

CONTACT : "TUBE_4_ENCO" (cf [§4.7])

mat1	mat2	Coef_mobile	Coef_obst	References
I600	Z10C13	2.4E-16		[bib6]
I690	Z10C13	8.2E-17		[bib6]
I600	A405	6.5E-14		[bib6]
I600TT	A405	1.4E-15		[bib6]
I690	A405	7.8E-15		[bib6]
I600	I800	1.3E-15		[bib6]
I600TT	I800	3.6E-16		[bib6]
I690TT	Z10C13	1.2E-15		[bib6]
I600	I800CR	2.2E-15		[bib6]
I600	A347	2.6E-16		[bib6]

CONTACT : "TUBE_TUBE" (cf [§4.8])

mat1	mat2	Coef_mobile	Coef_obst	References
I600	I600	1.8E-13		[bib6]
I690	I690	1.0E-12		[bib6]

the values indicated above correspond to averages of the values recorded in the references for temperatures as close as possible to the conditions REFERENCE MARK. It should be noted that the reference [bib6] does not give a value of coefficient of wear for the antagonists.

4 Relation between worn volume and the depth of wear

From the power of wear, operator POST_USURE calculates worn volumes then the depths of wear. The geometrical relations between volumes used and the worn depths depend on the type of contact.

Are:
- d_m : worn depth of the mobile tube
- d_o : worn depth of the obstacle
- R_m : radius external of the mobile tube
- R_o : interior radius of the obstacle
- l : width of the obstacle
- θ : mobile angle/obstacle
- V_m : worn volume of the mobile tube
- V_o : worn volume of the obstacle.

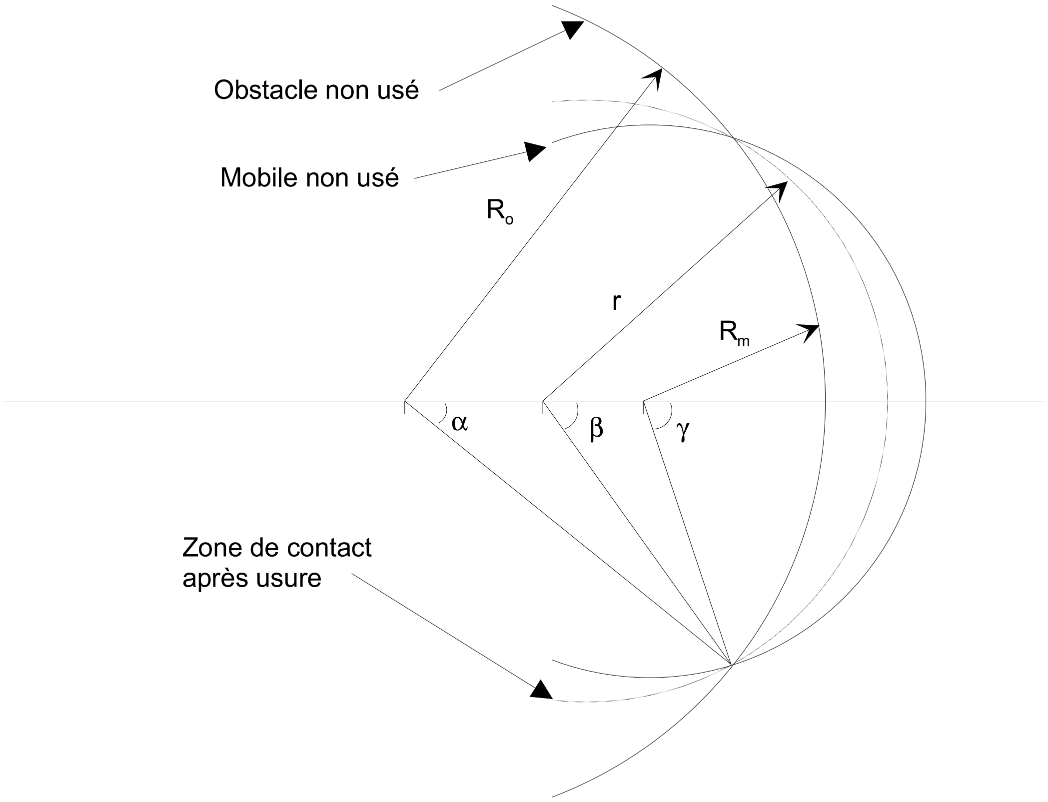
4.1 Situation “GRAPPE - BORING”

the key word used is “GRAPPE_ALESAGE”. The cluster is centered in a boring. The trace of wear has a section in the shape of lunule [bib6]. Worn volume is brought back to an area used in a section, multiplied by the worn height l

worn volumes are written [bib3]:

$$\frac{V_m}{l} = r^2(\beta - \sin(2\beta)) - R_m^2(\alpha - \sin(2\alpha))$$
$$\frac{V_o}{l} = R_o^2(\gamma - \sin(2\gamma)) - r^2(\beta - \sin(2\beta))$$
$$R_m \sin(\alpha) = r \sin(\alpha)$$
$$r \sin(\beta) = R_o \sin(\gamma)$$

The variables r, α, β and γ are intermediate variables of computation defined on figure Ci - below:



A numerical solver integrated into *Code_Aster*® allows to pass to solve this system of equations coupled to 4 unknowns r, α, β, γ . The depths of wear are then given by the following relations:

$$d_o = r - R_t - \left(r\cos(\beta) - R_t\cos(\alpha)\right)$$
$$d_m = R_o - r - \left(R_o\cos(\gamma) - r\cos(\beta)\right)$$

4.2 Situation "GRAPPE - NOTCH the SIMPLE"

key word used is "`GRAPPE_1_ENCO`".
The card of guidance comprises only one notch. Worn volume is brought back to an area used in a section, multiplied by the worn height l.

Worn volumes are written [bib7]: $\begin{cases} \dfrac{V_m}{l} = A_m d_m^3 + B_m d_m^2 + C_m d_m + D_m \\ V_o = 0{,}47 \cdot h \cdot R_o \cdot d_o \cdot \pi \end{cases}$

with [bib7]: $\begin{cases} A_m = -2{,}76 \\ B_m = 10{,}30 \\ C_m = 0{,}83 \\ D_m = 0 \end{cases}$

These coefficients are founded feedback. They apply only to the control rods whose characteristics are:

- diameter external of the pencil of cluster: 9,7 mm
- internal diameter of the card of guidance: 10,5 mm

a solver integrated into POST_USURE make it possible to determine d_m according to V_m

4.3 Situation "GRAPPE - NOTCH DOUBLES"

the key word used is "GRAPPE_2_ENCO".
The card of guidance is made of 2 notches diametrically opposite. Worn volume is brought back to an area used in a section, multiplied by a worn height l .

Worn volumes are written [bib7]: $\begin{cases} \frac{V_m}{l} = A_m d_{m^3} + B_m d_{m^2} + C_m d_m + D_m \\ V_o = 0{,}94 \cdot h \cdot R_o \cdot d_o \cdot \pi \end{cases}$

with [bib7]: $\begin{cases} A_m = -5{,}52 \\ B_m = 20{,}60 \\ C_m = 1{,}66 \\ D_m = 0 \end{cases}$

These coefficients are founded feedback. They apply only to the control rods whose characteristics are:

- diameter of the pencil: 9,7 mm
- diameter of the card: 10,5 mm

a solver integrated into POST_USURE make it possible to determine d_m according to V_m

4.4 Situation "Tubes of steam generator - antivibratory Bar"

the key word used is "TUBE_BAV".

Case 1:

The tube is presented vertically, the bar impacts perpendicular to the tube, one supposes that the bar does not wear.

The depths of wear are written [bib3]: $$\begin{cases} d_m=\left(\frac{1}{2R_m}\right)^{1/3}\cdot\left(\frac{3V_m}{41}\right)^{2/3} \\ d_o=0 \end{cases}$$

Case 2:

The bar is presented tilted (angle θ) compared to the tube, the bar impacts perpendicular to the tube, one supposes that the bar does not wear.

- if $d_m<l\theta$

  the depths of wear are written [bib3]: $$\begin{cases} d_m=\left(\frac{1}{2R_m}\right)^{1/5}\cdot\left(\frac{15\cdot\theta\cdot V_m}{8}\right)^{2/5} \\ d_o=0 \end{cases}$$

- if $d_m\geqslant l\theta$

  the relations between worn volume and depths of wear are written [bib3]:
  $$\begin{cases} V_m=\frac{8\sqrt{2R_m}}{15\theta}\cdot\left[d_m^{5/2}-\left(d_m-\theta l\right)^{5/2}\right] \\ d_o=0 \end{cases}$$

A solver integrated into POST_USURE allows to determine d_m according to V_m

Case 3:

The tube is presented vertically, the bar impacts perpendicular to the tube, one takes into account the wear of the bar. α is an unknown to be determined.

The relations between worn volume and depths of wear are written [bib3]:

$$\begin{cases} d_m=\left(\frac{V_m}{V_m+V_o}\right)\left(\frac{1}{2R_m}\right)^{1/3}\left(\frac{3\cdot\left(V_m+V_o\right)}{4\cdot l}\right)^{2/3} \\ \frac{V_m+V_o}{l}=\alpha\cdot R_m^2-R_m^2\sin\left(\alpha\right)\cos\left(\alpha\right) \\ d_o=R_t\left(1-\cos\left(\alpha\right)\right)-d_m \end{cases}$$

A solver integrated into POST_USURE allows to determine α

Case 4:

The bar is presented tilted (angle θ) compared to the tube, the bar impacts perpendicular to the tube, one takes into account the wear of the bar. α is an unknown to be determined.

- if $(d_m+d_o)<l\theta$

  the relations between worn volume and depths of wear are written [bib3]:

$$\begin{cases} d_m=\left(\dfrac{V_m}{V_m+V_o}\right)\left(\dfrac{1}{2R_m}\right)^{1/5}\left(\dfrac{15\cdot\theta\cdot(V_m+V_o)}{8}\right)^{2/5} \\ \dfrac{V_m+V_o}{l}=\alpha\cdot R_m^2-R_m^2\sin(\alpha)\cos(\alpha) \\ d_o=R_m(1-\cos(\alpha))-d_m+\dfrac{l}{2}\sin(\theta) \end{cases}$$

A solver integrated into POST_USURE allows to determine α

- if $(d_m+d_o)\geqslant l\theta$

  the relations between worn volume and depths of wear are written [bib3]:

$$\begin{cases} V_m=\dfrac{8\cdot\sqrt{2R_m}}{15\cdot\theta\cdot(1+k)}\cdot\left[\left((d_m+d_o)\cdot(1+k)\right)^{5/2}-\left((d_m+d_o)\cdot(1+k)-l\theta\right)^{5/2}\right] \\ \dfrac{V_m+V_o}{l}=\alpha\cdot R_m^2-R_m^2\sin(\alpha)\cos(\alpha) \\ d_o=R_m\cdot(1-\cos(\alpha))-d_m+\dfrac{l}{2}\sin(\theta) \end{cases}$$

  where k is the relationship between worn volumes of the bar and of the tube ($k=\dfrac{V_o}{V_m}$)

a solver integrated into POST_USURE allows to determine d_m according to V_m . In the same way, a solver allows to determine α .

4.5 Situation "Tubes of steam generator - Boring"

the key word used is "TUBE_ALESAGE".

Case 1:

The tube is centered perfectly in an animated boring of a pure orbital motion which wears in a uniform way on all the periphery in contact with the obstacle.

The worn depths are written [bib3]: $$\begin{cases} d_m = \dfrac{V_m}{2\cdot\pi\cdot l\cdot R_m} \\ d_o = \dfrac{V_o}{2\cdot\pi\cdot l\cdot R_o} \end{cases}$$

Case 2:

The tube is centered in an animated boring of a motion of impact-slidings of the elliptic type which leads to the training of traces of wear of the cylindrical type diametrically opposite on the tube and having a section in the shape of lunule.

Worn volumes are written [bib3]:

$$\begin{aligned} \frac{V_m}{l} &= r^2(\beta-\sin(2\beta))-R_m^2(\alpha-\sin(2\alpha)) \\ \frac{V_o}{l} &= R_o^2(\gamma-\sin(2\gamma))-r^2(\beta-\sin(2\beta)) \\ R_m\sin(\alpha) &= r\sin(\beta) \\ r\sin(\beta) &= R_o\sin(\gamma) \end{aligned}$$

system of equations coupled to four unknowns to determine: r, α, β, γ

$$\begin{aligned} d_o &= r-R_m-(r\cos(\beta)-R_m\cos(\alpha)) \\ d_m &= R_o-r-(R_o\cos(\gamma)-r\cos(\beta)) \end{aligned}$$

These formulas have the same origin as those of the paragraph [§4.1].

Case 3:

The tube, animated of a motion of impact-slidings, presents this time a slope compared to the support. One obtains two symmetric traces of wear on the tube.

$$\begin{aligned} \frac{V_m}{l} &= r^2(\beta-\sin(2\beta))-R_m^2(\alpha-\sin(2\alpha)) \\ \frac{V_o}{l} &= R_o^2(\gamma-\sin(2\gamma))-r^2(\beta-\sin(2\beta)) \\ R_m\sin(\alpha) &= r\sin(\beta) \\ r\sin(\beta) &= R_o\sin(\gamma) \end{aligned}$$

system of equations coupled to four unknowns to determine: r, α, β, γ

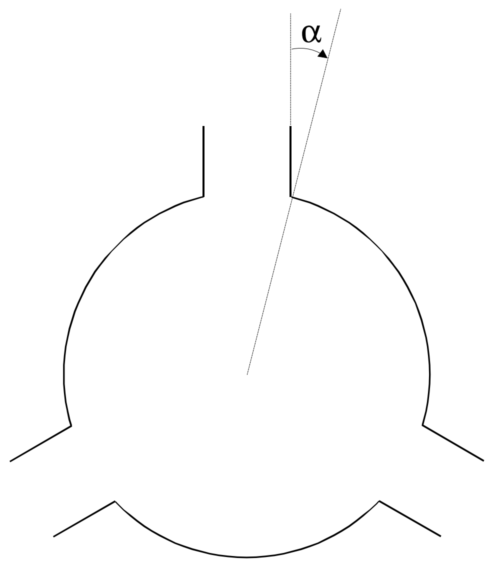
$$d_o = r - R_m - \left(r\cos(\beta) - R_m\cos(\alpha) \right) + \frac{l}{2}\sin(\theta)$$

$$d_m = R_o - r - \left(R_o\cos(\gamma) - r\cos(\beta) \right) + \frac{l}{2}\sin(\theta)$$

These formulas have the same origin as those of the paragraph [§4.1].

4.6 Situation "Tubes of steam generator - Trifoliate"

the key word used is "TUBE_3_ENCO".
That is to say an angle α characteristic of the isthmus of the trifoliate boring, defined by the figure below:



Case 1:

The initial contact is carried out against an edge of one of the isthmuses of trifoliate boring. One supposes the tube perfectly centered compared to his obstacle. The trace of wear does not extend to the entire isthmus. One does not take into account the wear of the obstacle.

The relations between worn volume and the depth of wear are written [bib3]:

$$\begin{cases} V_m = \frac{l}{2}\left[R_m^2 \sin^{-1}\left(\frac{x}{R_m}\right) - R_o^2 \sin^{-1}\left(\frac{x}{R_o}\right) + x\left(R_o - R_m + d_m\right) + d_m^2 tg\,\alpha \right] \\ d_o = 0 \end{cases}$$

with $x = \sqrt{R_m^2 - \frac{\left(R_o^2 - R_m^2 - \left(R_o - R_m + d_m\right)^2\right)^2}{4\left(R_o - R_m + d_m\right)^2}}$

a solver integrated into POST_USURE allows to determine d_m according to V_m

Case 2:

Same assumptions as for case 1 except the position of the tube compared to the obstacle. One supposes this time that the tube presents an angle of inclination θ .

- if $d_m < l\,\theta$

  the relations between worn volume and the depth of wear are written [bib3]:

$$\begin{cases} V_m = \dfrac{d_m}{6\theta}\left[R_m^2 \sin^{-1}\left(\dfrac{x}{R_m}\right) - R_o^2 \sin^{-1}\left(\dfrac{x}{R_o}\right) + x\left(R_o - R_m + d_m\right) + d_m^2 tg\,\alpha\right] \\ d_o = 0 \end{cases}$$

with $x = \sqrt{R_m^2 - \dfrac{\left(R_o^2 - R_m^2 - \left(R_o - R_m + d_m\right)^2\right)^2}{4\left(R_o - R_m + d_m\right)^2}}$

a solver integrated into POST_USURE allows to determine d_m according to V_m

- if $d_m \geqslant l\,\theta$

  the relations between worn volumes and depths of wear are written [bib3]:

$$\begin{cases} V_m = \dfrac{l}{6}\left(V1 + \sqrt{V1 \cdot V2} + V2\right) \\ d_o = 0 \end{cases}$$

with $x1 = \sqrt{R_m^2 - \dfrac{\left(R_o^2 - R_m^2 - \left(R_o - R_m + d_m\right)^2\right)^2}{4\left(R_o - R_m + d_m\right)^2}}$

$$V1 = R_m^2 \sin^{-1}\left(\frac{x1}{R_m}\right) - R_o^2 \sin^{-1}\left(\frac{x1}{R_o}\right) + x1\left(R_o - R_m + d_m\right) + d_m^2 tg\,\alpha$$

$$x2 = \sqrt{R_m^2 - \frac{\left(R_o^2 - R_m^2 - \left(R_o - R_m + d_m - l\cdot\theta\right)^2\right)^2}{4\left(R_o - R_m + d_m - l\cdot\theta\right)^2}}$$

$$V2 = R_m^2 \sin^{-1}\left(\frac{x2}{R_m}\right) - R_o^2 \sin^{-1}\left(\frac{x2}{R_o}\right) + x2\left(R_o - R_m + d_m - l\cdot\theta\right) + \left(d_m - l\cdot\theta\right)^2 \cdot \mathrm{tg}\,\alpha$$

a solver integrated into POST_USURE allows to determine d_m according to V_m .

Case 3:

The contact is carried out against an edge of one of the isthmuses of trifoliate boring. One supposes the tube perfectly centered compared to his obstacle. One takes into account the wear of the obstacle. α is an angle characteristic of the isthmus of trifoliate boring.

Worn volumes are written [bib3]:

$$\begin{cases} V_m+V_o=\frac{1}{2}\left[R_m^2\sin^{-1}\left(\frac{x}{R_m}\right)-R_o^2\sin^{-1}\left(\frac{x}{R_o}\right)+x\left(R_o-R_m+d_m+d_o\right)+\left(d_m+d_o\right)^2 tg\,\alpha\right] \\ V_o=1.41\cdot R_o\cdot d_o\cdot\pi \end{cases}$$

with $x=\sqrt{R_m^2-\frac{\left(R_o^2-R_m^2-\left(R_o-R_m+d_m+d_o\right)^2\right)^2}{4\left(R_o-R_m+d_m+d_o\right)^2}}$

Case 4:

The contact is carried out against an edge of one of the isthmuses of trifoliate boring. One supposes this time that the tube presents an angle of inclination θ compared to its obstacle. One takes into account the wear of the obstacle. α is an angle characteristic of the isthmus of trifoliate boring.

- if $\left(d_m+d_o\right)<l\theta$

  worn volumes are written [bib3]:

$$\begin{cases} V_m+V_o=\frac{d_m+d_o}{6\theta}\left[R_m^2\sin^{-1}\left(\frac{x}{R_m}\right)-R_o^2\sin^{-1}\left(\frac{x}{R_o}\right)+x\left(R_o-R_m+d_m+d_o\right)+\left(d_m+d_o\right)^2 tg\,\alpha\right] \\ V_o=1.41\cdot R_o\cdot d_o\cdot\pi \end{cases}$$

  with $x=\sqrt{R_m^2-\frac{\left(R_o^2-R_m^2-\left(R_o-R_m+d_m+d_o\right)^2\right)^2}{4\left(R_o-R_m+d_m+d_o\right)^2}}$

a solver integrated into POST_USURE allows to determine d_m according to V_m.

- if $\left(d_m+d_o\right)\geq l\theta$

  worn volume is written [bib3]: $V_m=\frac{l}{6}\left(V1+\sqrt{V1\cdot V2}+V2\right)$

  $V_o=1.41\cdot R_o\cdot d_o\cdot\pi$

with $x1=\sqrt{R_m^2-\frac{\left(R_o^2-R_m^2-\left(R_o-R_m+d_m+d_o\right)^2\right)^2}{4\left(R_o-R_m+d_m+d_o\right)^2}}$

$$V1=R_m^2\sin^{-1}\left(\frac{x1}{R_m}\right)-R_o^2\sin^{-1}\left(\frac{x1}{R_o}\right)+x1\left(R_o-R_m+d_m+d_o\right)+\left(d_m+d_o\right)^2\operatorname{tg}\alpha$$

$$x2=\sqrt{R_m^2-\frac{\left(R_o^2-R_m^2-\left(R_o-R_m+d_m+d_o-l\cdot\theta\right)^2\right)^2}{4\left(R_o-R_m+d_m+d_o-l\cdot\theta\right)^2}}$$

$$V2=R_m^2\sin^{-1}\left(\frac{x2}{R_m}\right)-R_o^2\sin^{-1}\left(\frac{x2}{R_o}\right)+x2\left(R_o-R_m+d_m+d_o-l\cdot\theta\right)+\left(d_m+d_o-l\cdot\theta\right)^2\cdot\operatorname{tg}\alpha$$

a solver integrated into POST_USURE allows to determine d_m according to V_m

4.7 Situation "Tubes of steam generator - Quadrifoliate"

the key word used is "TUBE_4_ENCO".
That is to say an angle α characteristic of the isthmus of quadrifoliate, definite boring of the same way as in the paragraph [§4.6]:

Case 1:

The initial contact is carried out against an edge of one of the isthmuses of quadrifoliate boring. One supposes the tube perfectly centered compared to his obstacle. One does not take into account the wear of the obstacle.

Worn volume is written [bib3]:

$$V_m=\frac{l}{2}\left[R_m^2\sin^{-1}\left(\frac{x}{R_m}\right)-R_o^2\sin^{-1}\left(\frac{x}{R_o}\right)+x\left(R_o-R_m+d_m\right)+d_m^2\operatorname{tg}\alpha\right]$$
$$d_o=0$$

with $x=\sqrt{R_m^2-\frac{\left(R_o^2-R_m^2-\left(R_o-R_m+d_m\right)^2\right)^2}{4\left(R_o-R_m+d_m\right)^2}}$

a solver integrated into POST_USURE allows to determine d_m according to V_m

Case 2:

Same assumptions as for case 1 except the position of the tube compared has the obstacle. One supposes this time that the tube presents an angle of inclination q.

- if $d_m < l\,\theta$

  the relations between worn volumes and depths of wear are written [bib3]:

$$\begin{cases} V_m = \dfrac{d}{6\cdot\theta}\left[R_m^2 \sin^{-1}\left(\dfrac{x}{R_m}\right) - R_o^2 \sin^{-1}\left(\dfrac{x}{R_o}\right) + x\left(R_o - R_m + d_m\right) + d_m^2 \operatorname{tg}\alpha\right] \\ d_o = 0 \end{cases}$$

with $x = \sqrt{R_m^2 - \dfrac{\left(R_o^2 - R_m^2 - \left(R_o - R_m + d_m\right)^2\right)^2}{4\left(R_o - R_m + d_m\right)^2}}$

a solver integrated into POST_USURE allows to determine d_m according to V_m

- if $d_m \geq l\,\theta$

  the relations between worn volumes and depths of wear are written [bib3]:

$$\begin{cases} V_m = \dfrac{l}{6}\left(V1 + \sqrt{V1\cdot V2} + V2\right) \\ d_o = 0 \end{cases}$$

with $x1 = \sqrt{R_m^2 - \dfrac{\left(R_o^2 - R_m^2 - \left(R_o - R_m + d_m\right)^2\right)^2}{4\left(R_o - R_m + d_m\right)^2}}$

$$V1 = R_m^2 \sin^{-1}\left(\frac{x1}{R_m}\right) - R_o^2 \sin^{-1}\left(\frac{x1}{R_o}\right) + x1\left(R_o - R_m + d_m\right) + d_m^2 \operatorname{tg}\alpha$$

$$x2 = \sqrt{R_m^2 - \frac{\left(R_o^2 - R_m^2 - \left(R_o - R_m + d_m - l\cdot\theta\right)^2\right)^2}{4\left(R_o - R_t + d_m - l\cdot\theta\right)^2}}$$

$$V2 = R_m^2 \sin^{-1}\left(\frac{x2}{R_m}\right) - R_o^2 \sin^{-1}\left(\frac{x2}{R_o}\right) + x2\left(R_o - R_m + d_m - l\cdot\theta\right) + \left(d_m - l\cdot\theta\right)^2 \operatorname{tg}\alpha$$

a solver integrated into POST_USURE allows to determine d_m according to V_m

Case 3:

The contact is carried out against an edge of one of the isthmuses of quadifolié boring. One supposes the tube perfectly centered compared to his obstacle. One takes into account the wear of the obstacle.

Worn volumes are written [bib3]:

$$\begin{cases} V_m+V_o=\frac{1}{2}\left[R_m^2\sin^{-1}\left(\frac{x}{R_m}\right)-R_o^2\sin^{-1}\left(\frac{x}{R_o}\right)+x\left(R_o-R_m+d_m\right)+d_m^2\,\mathrm{tg}\,\alpha\right] \\ V_o=1.88\cdot R_o\cdot d_o\cdot\pi \end{cases}$$

with $x=\sqrt{R_m^2-\frac{\left(R_o^2-R_m^2-\left(R_o-R_m+d_m+d_o\right)^2\right)^2}{4\left(R_o-R_m+d_m+d_o\right)^2}}$

Case 4:

The contact is carried out against an edge of one of the isthmuses of quadrifoliate boring. One supposes this time that the tube presents an angle of inclination θ compared to its obstacle. One takes into account the wear of the obstacle.

- if $\left(d_m+d_o\right)<l\theta$

  worn volumes are written [bib3]:

$$\begin{cases} V_m+V_o=\frac{d_m+d_o}{6\theta}\left[R_m^2\sin^{-1}\left(\frac{x}{R_m}\right)-R_o^2\sin^{-1}\left(\frac{x}{R_o}\right)+x\left(R_o-R_m+d_m+d_o\right)+\left(d_m+d_o\right)^2.\,\mathrm{tg}\,\alpha\right] \\ V_o=1.88\cdot R_o\cdot d_o\cdot\pi \end{cases}$$

  with $x=\sqrt{R_m^2-\frac{\left(R_o^2-R_m^2-\left(R_o-R_m+d_m+d_o\right)^2\right)^2}{4\left(R_o-R_m+d_m+d_o\right)^2}}$

- if $\left(d_m+d_o\right)\geq l\theta$

worn volumes are written [bib3]: $\begin{cases} V_m=\frac{l}{6}\left(V1+\sqrt{V1\cdot V2}+V2\right) \\ V_o=1.88\cdot R_o\cdot d_o\cdot\pi \end{cases}$

with $x1=\sqrt{R_m^2-\frac{\left(R_o^2-R_m^2-\left(R_o-R_m+d_m+d_o\right)^2\right)^2}{4\left(R_o-R_m+d_m+d_o\right)^2}}$

$$V1=R_m^2\sin^{-1}\left(\frac{x1}{R_m}\right)-R_o^2\sin^{-1}\left(\frac{x1}{R_o}\right)+x1\left(R_o-R_m+d_m\right)+\left(d_m+d_o\right)^2.\operatorname{tg}\alpha$$

$$x2=\sqrt{R_m^2-\frac{\left(R_o^2-R_m^2-\left(R_o-R_m+d_m+d_o-l\cdot\theta\right)^2\right)^2}{4\left(R_o-R_m+d_m+d_m-l\cdot\theta\right)^2}}$$

$$V2=R_m^2\sin^{-1}\left(\frac{x2}{R_m}\right)-R_o^2\sin^{-1}\left(\frac{x2}{R_o}\right)+x2\left(R_o-R_m+d_m+d_o-l\cdot\theta\right)+\left(d_m+d_o-l\cdot\theta\right)^2\cdot\operatorname{tg}\alpha$$

4.8 Situation “Tubes of steam generator - Tube of steam generator”

the key word used is “TUBE_TUBE”. Following the fracture of a stopped tube, there can be contact between this tube and one of its neighbors. The wear of the two tubes by accommodation of surfaces leads to the contact with the creation of two plane surfaces. This assertion is confirmed by tests carried out on machine of wear.

The worn depths are written [bib3]: $$\begin{cases} d_t=\left(\frac{1}{2\cdot R_m}\right)^{1/5}\left(\frac{15\cdot\theta\cdot V_m}{8}\right)^{2/5} \\ d_o=\left(\frac{1}{2\cdot R_o}\right)^{1/5}\left(\frac{15\cdot\theta\cdot V_o}{8}\right)^{2/5} \end{cases}$$

5 Division the figure of clearance in sectors

the user has the possibility of defining a figure division of clearance in angular sectors for which it gives a kind of contact (GRAPPE_1_ENCO…), a coefficient of wear and the angles of beginning and end of cutting (these angles must be increasing between -180° and +180°). The power of wear for each sector is then calculated like the arithmetic mean over the times, cut out beforehand in blocks, of the product of the norms of the normal force of shock and velocity of sliding by taking account only contacts which take place in the angular sector concerned. From this power, it is possible to define a volume used by multiplying the power of wear of the sector by the coefficient of wear of the sector and by an operating time given by the user. It is also possible to calculate the depth of wear for this sector, by supposing that the angular extension of the default does not exceed that of the sector where it is detected.

It is the key word SECTEUR which makes it possible to define the set of these modifications.

It is not envisaged to check the total coherence of computations carried out. In particular, a wear can be distributed on several sectors and in this case, the computation depth of wear does not have any more a meaning. It is up to the operator to make sure a posteriori of the validity of its results. A new computation with another cutting must possibly be carried out to obtain the value depth of wear. This choice is not constraining because of the speed of postprocessing considered. The interest to carry out these computations in POURSUITE is obvious, taking into account what precedes.

A typical case deserves a development. It is the case of the control rods for which the results of POST_USURE are used as starter of the command MODI_OBSTACLE. In this case, the number of sectors is fixed at 10, as he is explained in the reference [bib8]. Operator MODI_OBSTACLE feedback uses data resulting from to compute: wear which can extend on several sectors while setting out again from the worn volumes obtained using POST_USURE. In this case, the worn depths of POST_USURE do not have necessarily physical meaning.

6 Actualization of the array

operator POST_USURE extrapolates the worn volume obtained in a few seconds of simulation at periods defined by the user (typically a few months, even a few years).

It restores an array which contains volumes used and the depths of wear for all the sectors and all the times defined by the user by cumulating them since the initial time of simulation.

It is possible to give an array to reactualize key word ETAT_INIT by means of. That makes it possible to hold of the evolution of the geometries related to wear:

- From a figure of clearance, the user carries out a dynamic computation.
- He obtains volumes and depths of wear in output of POST_USURE.
- Using geometrical considerations, it evaluates the evolution of the figure of clearance connected to this wear thanks to operator MODI_OBSTACLE.
- It carries out a new dynamic computation with the figure of clearance modified.
- It of deduced from new quantities related to wear and the cumulates in the array result POST_USURE.

By reiterating the process a certain number of times [bib9], it are possible to take into account the evolution of the geometries according to wear and to deduce the impact from it from this phenomenon on the dynamics of the studied system.

7 Bibliography

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8 Description of the versions of the document

Version Aster	**Author (S) Organization (S)**	**Description of the modifications4**
4	*HARROWING D., L. VIVAN (EDF/RNE/MTC, CISI)*	initial Text