Operator of calculation of wear

Summary:

This note presents three laws of wear which make it possible to evaluate the volume used starting from the quantities resulting from a dynamic calculation carried out with the operator DYNA_TRAN_MODAL [U4.54.03] and the keyword SHOCK.

- The law of Archard,
- Law KWU_EPRI,
- Law EDF_MZ.

The coefficients of wear necessary for these calculations are provided by the user or specified in a database.

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 game authorizes the operator to calculate the sizes relating to wear by sectors.

Contents

1 Introduction

The evaluation of the damage by wear requires a thorough knowledge of the bodies in presence at the time of the contact, the loadings and kinematics. The investigations led to the Mechanical Department and Technology of the Components make it possible to provide coefficients for laws of wear relative to configurations of wear affecting the components of the nuclear power plants. A transitory calculation by modal recombination, using the operator DYNA_TRAN_MODAL [U4.54.03] allows 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 calculate the power of wear, the module of postprocessing of the wear of *Code_Aster*, (POST_USURE [U4.67.03]), uses, in a node of shock, the result in generalized coordinates (tran_gene) resulting from DYNA_TRAN_MODAL. It combines the normal forces and speeds of slip according to the method definite with the following paragraph. From the knowledge of the power of wear, it is possible to go back to the volumes used by using one of the laws of wear suggested in POST_USURE. The coefficients to be used are to be defined by the user or to search in a database integrated into the operator.

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

The operator POST_USURE allows to cut out the figure of game 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 table generated by POST_USURE give the value of the volumes used for several values of time.

2 Laws of wear

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

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

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

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

It was shown that the law of Archard can be wide with other mechanisms, in slip 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-slips, $\|F_n\|$ present very strong variations of short time at the time of the shocks), the definition of W becomes:

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

where
W : work of wear,
$\|F_n\|$: module of the normal force during the contact,
$\|V_t\|$: module the speed of slip during the contact,
t_0 : moment of beginning of calculation,
t_1 : moment of end of calculation.

Consequently, by analogy with the usual laws of 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 stationary mode is reached, the power of wear is supposed to be constant in the course of time. In order to make sure of this stationnarity, the interval $[t_{0,} t_1]$ can be cut out in several blocks in the 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 rigour, the use of the laws of wear below supposes that the power of wear is constant).

2.1 Law of wear **`ARCHARD'**

Law 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.

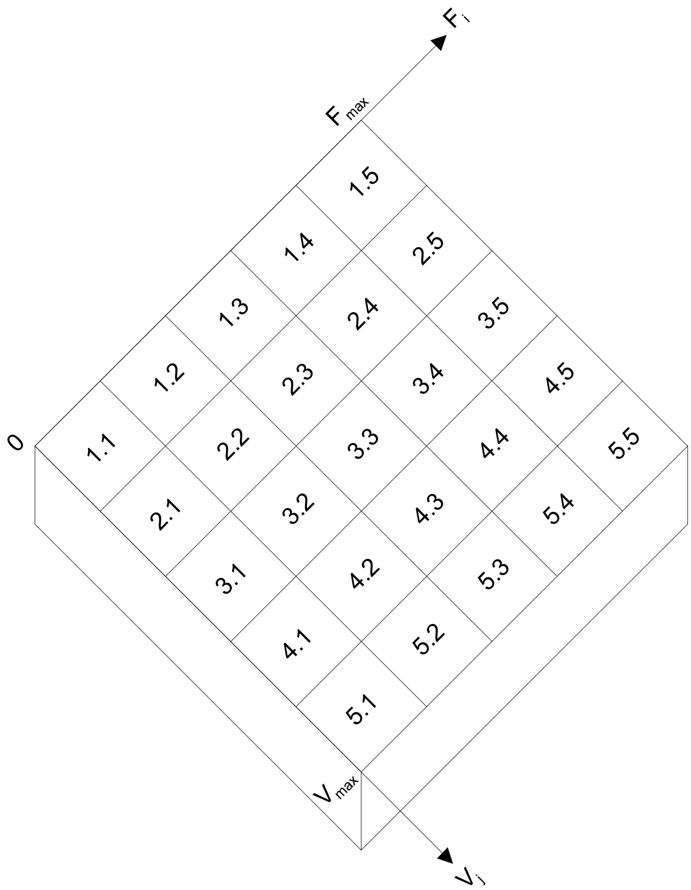
The coefficient K is provided by the user or is taken in a database (see [§3]). It is different for the two involved bodies and depends on the geometrical and thermodynamic conditions in the contact. The time interval t used for the calculation of wear does not correspond at the time of simulation manpower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

2.2 Law of wear **‘KWU_EPRI‘**

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

Normal forces $F_i(N)$ are divided into 5 classes, as well as speeds of slip $V_j(m/s)$.

One obtains 25 classes whose location is indicated as follows:



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

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

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

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

In the case of the slip (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 slip
k_2 : dimensional coefficient of correction
F_i : median value of the normal force for the class ij
V_j : median value the speed of slip for the class ij

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

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

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 intensity w is used as factor of correction of the coefficient of wear within the meaning of the law of ARCHARD according to the expression:

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

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

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

2.3 Law of wear '`EDF_MZ`'

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

The experience feedback shows that the kinetics of wear slows down with time t ; a manner of taking 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 initial speed and S the speed of wear asymptotic (see Ci - below),
n is a parameter of the model.

Values of n and of S are deduced from the experience feedback.

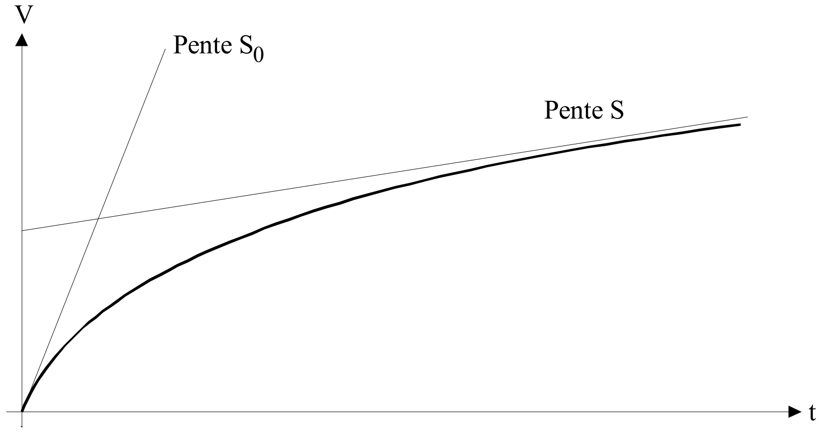
Tests on simulators, of short time compared to that of a cycle of operation of an engine, show that the speed of initial wear S_0 a law of the type follows:

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

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

The experience feedback shows that the speed of wear reaches an asymptotic value S. The preceding relation, observed on simulator is supposed to be valid for every moment of the phenomenon of wear. That supposes a power of wear P who allows to reach $S = A \cdot (P)^b$, 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:



Worn volume V calculated with the assistance the operator `POST_USURE` is written:

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

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 Database

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

A304L	:	Steel 304L (Z2 CN 18-9),
A304LNI	:	Steel 304L nitrided,
A304LCR	:	Chrome steel 304L,
A304LLC1C	:	Steel 304L covered with chromium carbide,
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 give the coefficients of wear for the mobiles and the obstacles for several material couples (mat1 is the material of the variable component and mat2 that of the obstacle). The empty boxes correspond to worthless coefficients. A certain number of situations is currently envisaged without all the coefficients being available because this database 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 model EDF-MZ:

`CONTACT : 'GRAPPE_ALESAGE'` (cf [§4.1])

mat1	mat2	Coef_mobile	Coef_obst	References
A304L	A304L	With = 2.6E-15 B = 1. NR = 2.44E-8 S = 1.14E-16	With = 3.7E-15 B = 1. NR = 2.44E-8 S = 1.14E-16	[bib5] [bib6]
A316L	A304L	With = 11.E-15 B = 1.61 NR = 2.44E-8 S = 1.14E-16	With = 4.1E-15 B = 1. NR = 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	With = 20.E-15 B = 1.05 NR = 2.44E-8 S = 1.14E-16	With = 23.E-15 B = 1.19 NR = 2.44E-8 S = 1.14E-16	[bib5] [bib6]
A316L	A304L	With = 500.E-15 B = 1.78 NR = 2.44E-8 S = 1.14E-16	With = 490.E-15 B = 1.91 NR = 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, the operator POST_USURE calculate worn volumes then the depths of wear. The geometrical relations between worn volumes 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 : ray external of the mobile tube,
R_o : interior ray 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.

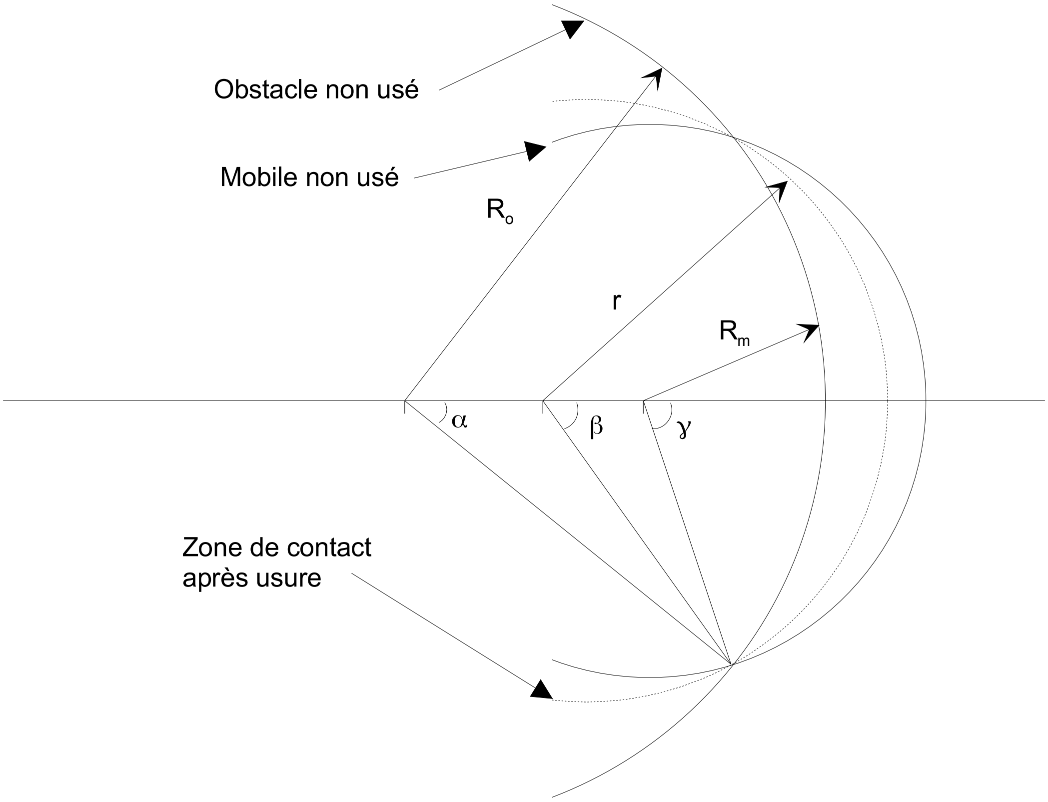
4.1 Situation 'BUNCH - BORING'

The keyword used is "GRAPPE_ALESAGE". The bunch is centered in a boring. The trace of wear has a section in the shape of lunule [bib6]. Worn volume is brought back to a surface used in a section, multiplied by the worn height l

Worn volumes are written [bib3]:

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

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



A digital solvor integrated into *Code_Aster*® allows to pass to solve this system of equations coupled to 4 unknown factors, 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 'BUNCH - NOTCH SIMPLE'

The keyword used is "`GRAPPE_1_ENCO`".
The map of guidance comprises only one notches. Worn volume is brought back to a surface 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 the experience feedback. They apply only to the control rods whose characteristics are:

- diameter external of the pencil of bunch: 9.7 mm
- internal diameter of the map of guidance: 10.5 mm

A solvor integrated into `POST_USURE` allows to determine d_m according to V_m

4.3 Situation 'BUNCH - NOTCH DOUBLES'

The keyword used is "`GRAPPE_2_ENCO`".
The map of guidance is made of 2 notches diametrically opposite. Worn volume is brought back to a surface 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 the experience feedback. They apply only to the control rods whose characteristics are:

- diameter of the pencil: 9.7 mm
- diameter of the map: 10.5 mm

A solvor integrated into `POST_USURE` allows to determine d_m according to V_m

4.4 Situation 'Tubes of steam generator - Bar antivibratory'

The keyword 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]: $\begin{cases} d_m = \left(\dfrac{1}{2R_m}\right)^{1/3} \cdot \left(\dfrac{3V_m}{41}\right)^{2/3} \\ d_o = 0 \end{cases}$

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]: $\begin{cases} d_m = \left(\dfrac{1}{2R_m}\right)^{1/5} \cdot \left(\dfrac{15\cdot\theta\cdot V_m}{8}\right)^{2/5} \\ d_o = 0 \end{cases}$

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

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

$$\begin{cases} V_m = \dfrac{8\sqrt{2R_m}}{15\,\theta} \cdot \left[d_m^{5/2} - \left(d_m - \theta l\right)^{5/2} \right] \\ d_o = 0 \end{cases}$$

A solvor 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 factor to be determined.

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

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

A solvor 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 factor to be determined.

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

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

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

A solvor integrated into `POST_USURE` allows to determine α

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

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

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

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

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

4.5 Situation 'Tubes of steam generator - Boring'

The keyword used is "TUBE_ALESAGE".

Case 1:

The tube is centered perfectly in an animated boring of a pure orbital movement 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 movement of impact-slips of the elliptic type which leads to the formation 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]:

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

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

$$d_o = r - R_m - (r\cos(\beta) - R_m\cos(\alpha))$$
$$d_m = R_o - r - (R_o\cos(\gamma) - r\cos(\beta))$$

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

Case 3:

The tube, animated of a movement of impact-slips, presents this time a slope compared to the support. One obtains two symmetrical traces of wear on the tube.

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

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

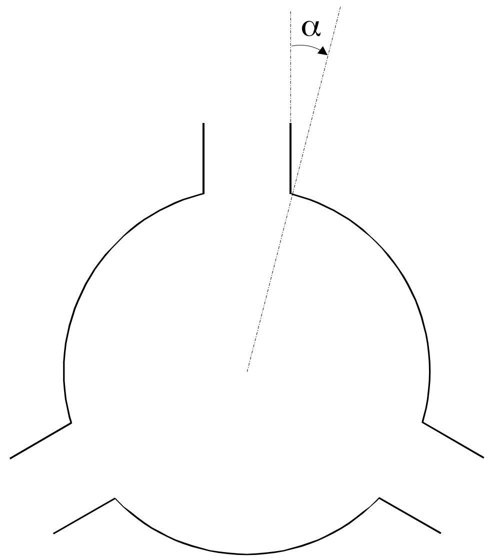
$$d_o = r - R_m - \left(r\cos(\beta) - R_m\cos(\alpha)\right) + \frac{l}{2}\sin(\theta)$$

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

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

4.6 Situation 'Tubes of steam generator - Trifoliate'

The keyword 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 solvor 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 solvor 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 solvor 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 solvor integrated into `POST_USURE` allows to determine d_m according to V_m.

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

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

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

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

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

A solvor integrated into `POST_USURE` allows to determine d_m according to V_m

4.7 Situation 'Tubes of steam generator - Quadrifoliate'

The keyword used is "`TUBE_4_ENCO`".
That is to say an angle α characteristic of the isthmus of quadrifoliate, definite boring in the same manner 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]:

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

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 solvor 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 by report 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]:

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

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

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

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

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

A solvor 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]:

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

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

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]:

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

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

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

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

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

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

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

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

4.8 Situation 'Tubes of steam generator - Tube of steam generator'

The keyword used is "TUBE_TUBE". Following the rupture 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 Figure division of game in sectors

The user has the possibility of defining a figure division of game in angular sectors for which it gives a kind of contact (GRAPPE_1_ENCO...), a coefficient of wear and 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 moments, cut out beforehand in blocks, of the product of the standards of the normal force of shock and the speed of slip 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 defect does not exceed that of the sector where it is detected.

It is the keyword SECTOR who allows to define the whole of these modifications.

It is not envisaged to check the total coherence of calculations carried out. In particular, a wear can be distributed on several sectors and in this case, the calculation depth of wear does not have any more a direction. It is up to the operator to make sure a posteriori of the validity of its results. A new calculation 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. Interest to carry out these calculations in CONTINUATION is obvious, taking into account what precedes.

6 Actualization of the table

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

It restores a table which contains worn volumes and the depths of wear for all the sectors and every moment defined by the user by cumulating them since the initial moment of simulation.

It is possible to give a table to be reactualized by using the keyword ETAT_INIT. That makes it possible to hold of the evolution of the geometries related to wear:

- From a figure of game, the user carries out a dynamic calculation.
- It obtains volumes and depths of wear at exit of POST_USURE.
- It carries out a new dynamic calculation with the figure of game modified.
- It from of deduced from new sizes related to wear and cumulates them in the table result of 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	*D. HARROWING, L. VIVAN (EDF/RNE/MTC, CISI)*	Initial text