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Abstract

The general objectives of WP1 of the HTR-E program are to determine the critical issues, to assess and demonstrate the potential of success for the design of the helium turbine. This note is devoted to numerical calculations concerning turbine disk creep resistance at 650°C and 750°C.
From experimental data of creep, tensile, cyclic and relaxation tests, the identification of the mechanical behaviour for UDIMET 720 CG at 650°C and 750°C has been made. With these data, creep numerical calculations, with the help of finite element code Cast3m, have been realised to test the creep evolution of HTR-turbine disk. The validity of the results is discussed.

Keywords

HTR, Creep, Turbine disk, Finite Element simulation, Udimet 720

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1 Introduction

The general objectives of WP1 of the HTR-E program are to determine the critical issues, to assess and demonstrate the potential of success for the design of the helium turbine, mainly based on two concepts: power turbine (GT-MHR type reactor), high pressure compressor turbine (PBMR type reactor).
The in service temperature of the turbine disk is not completely fixed. Without cooling, the temperature can reach 850°C. Even using superalloys developed recently such as Udimet 720, it is clear that no metallic material can sustain the foreseen in service condition (850°C and 60000 hours) for such large disk rotating at 3000 rnd./min. This point has been discussed both in HTR-M and HTR-E programs. Consequently a disk cooling is necessary.
This note is devoted to numerical calculation concerning the turbine disk creep resistance at 650°C and 750°C. These two temperatures correspond respectively to actual temperature used in industry and to foreseen maximum temperature for a cooled disk in U720. The mesh and loading used to simulate creep in the turbine will be first presented, followed by the mechanical law used. The results of creep simulations are presented for 650°C and 750°C.

1.1 Turbine disk

The sketch of the welded turbine rotor disk is shown in fig. 2, p8. This sketch comes from Report for ISTC Project # 1313-2001 [Alek 01].

1.2 Definition of an envelope cycle

For structural and creep-fatigue computations an envelope cycle of the loading is needed. Framatome ANP has defined such a cycle, based on maximum shocks occurring for incidental conditions. The number of cycles is retained at a conservative value of 1350 for the total turbine life of 60 years. The hot parts of the turbine should be changed at overhaul periods every 7 years, these computations are to be performed by steps of 60000 hours (≈ 7 years), i.e. approximately 157 cycles [Gerb 02].
These proposed cycles are hypothetic cycles and do not correspond to reality. They are only defined for creating conservative situations in term of shocks in transient conditions and of temperature or pressure differences in steady states. The thermal cycle for first stage is presented in fig. 1. The initial heating rate is 240°C/hours.

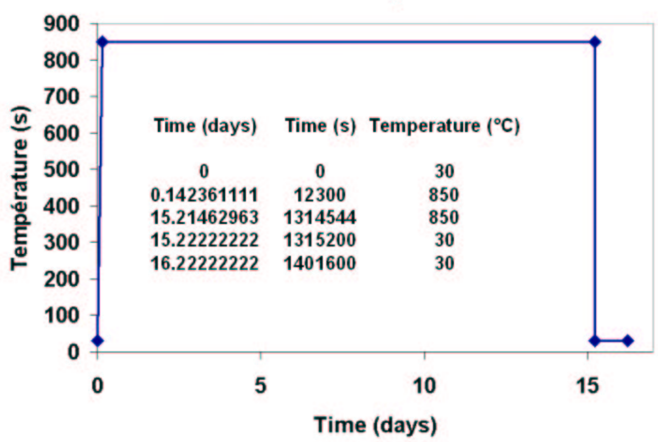

fig. 1 : Thermal envelope cycle

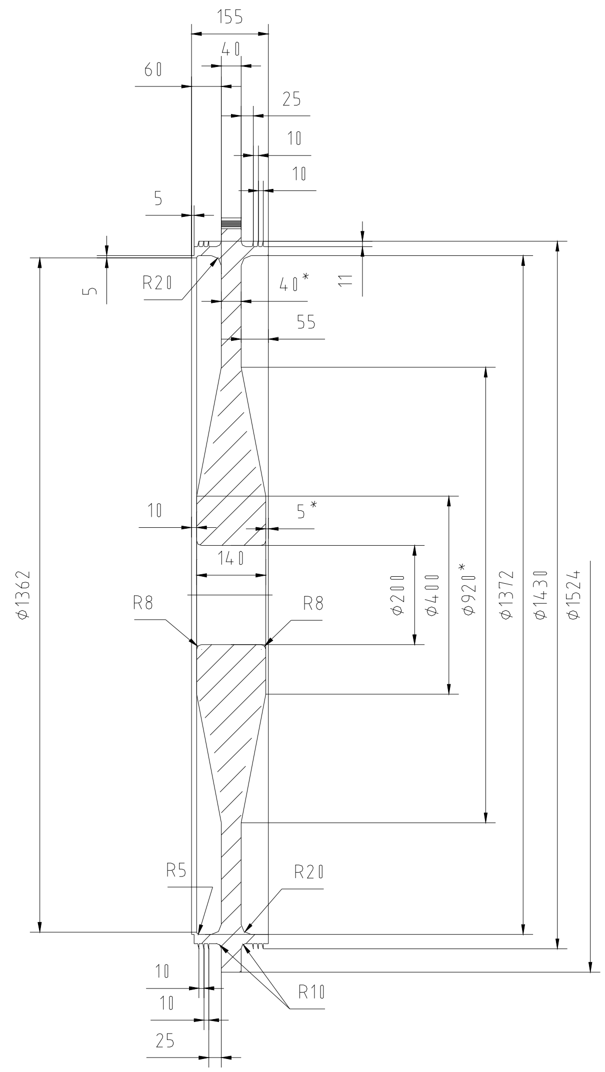

fig. 2: Sketch of welded turbine rotor disk [Alek 02]

2 Mesh and loading

Agrupado Empressario (A.E.) has performed elastic calculations and has evaluated the power needed to cool the turbine disk [D9 to be done]. As no turbine manufacturer is present in the project, no design is fixed for the blade feet and He design proposed by OKLS for the disk must be used..

The mesh used comes from A.E and has been adapted to Cast3M. To perform plastic calculation, the turbine disk has been modelled in two dimensions with an axisymetric hypothesis. To evaluate the effects of centrifugal stresses with a good approximation, the volume density of the blades has been adapted from 3D geometry in order to obtain an equivalent mass: a coefficient κ, calculated has shown in eq. 1, has been applied (fig. 3) to volume density of blade.

$$\kappa = \frac{real\ blade\ volume\ (3D)}{Equivalent\ blade\ volume\ with\ axisymetric\ hypothesis} \qquad (1)$$

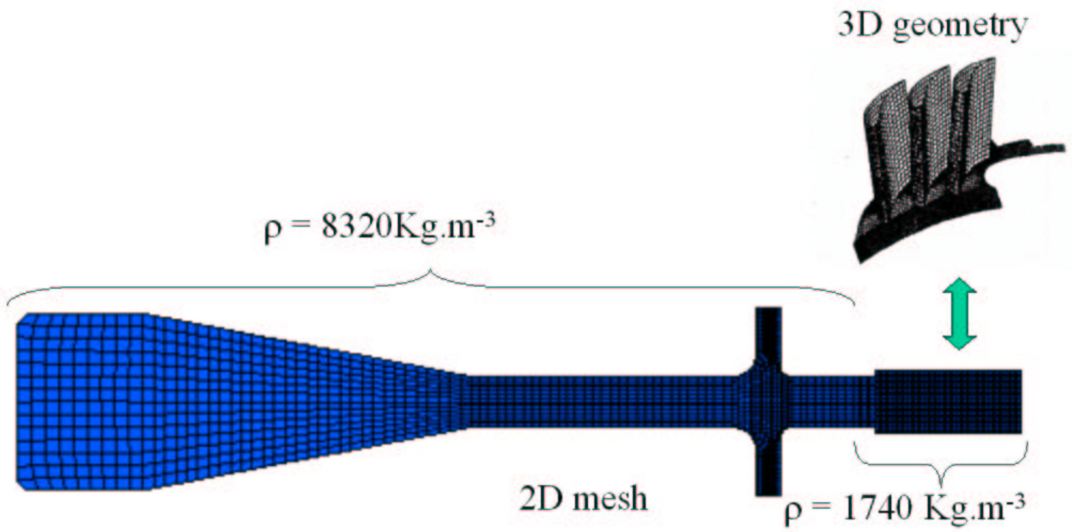

fig. 3 : mesh used for 2D calculations

The mesh is composed by 2592 axisymetric linear elements. The boundary conditions are presented in fig. 4, the fixed points correspond to the weld between the first and the second stage. No cooling channel (likely to exist in the real design but not yet defined) has been introduced in the mesh, consequently calculation do not take into account the associated stress concentration.

Only the first stage of the turbine is modelled because this is the hot part of the turbine.

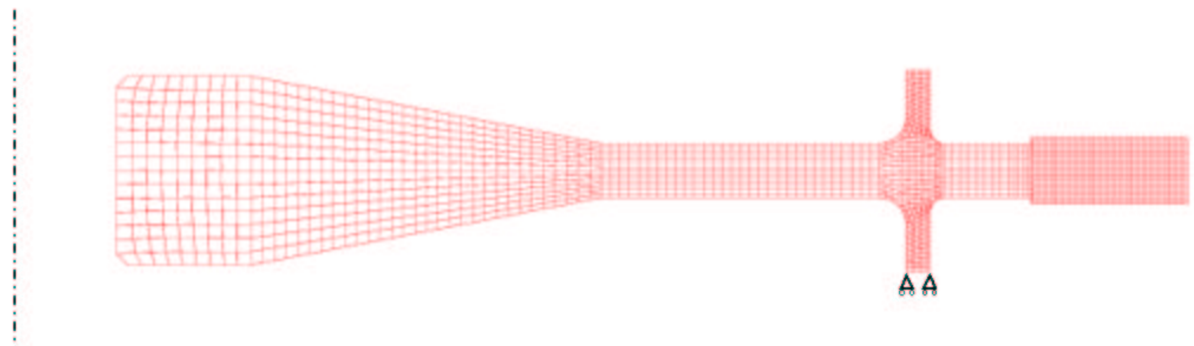

fig. 4: Boundary conditions (loop on the rim of the desk)

3 Mechanical behaviour

3.1 Viscoplastic law

The non-linear law used in this calculation is a viscoplastic Chaboche type law [Lema 88]:
The plasticity criterion is defined as follows:

$$F = J_2(\overline{\sigma} - \overline{X}) - KK - R_0 \tag{2}$$

With J_2 the second tensorial invariant,
R_0 the limit of elasticity and
KK the isotropic hardening
$\overline{X}$ the kinematic hardening

The evolution law is given by

$$\bar{\dot{\varepsilon}}_p = \frac{3}{2}\,\dot{p}\,\frac{\left\langle \overline{\sigma} - \overline{X} \right\rangle}{J_2\left\langle \overline{\sigma} - \overline{X} \right\rangle} \text{ and } \dot{p} = \left\langle \frac{F}{K_0} \right\rangle^n \tag{3}$$

With K_0 and n material parameters
The model that has been used contains one isotropic hardening and one non-linear kinematic hardening such as:

$$KK = Q(1-e^{(-bp)}) \tag{4}$$

$$\overline{X} = \frac{2}{3} C \overline{A} \tag{5}$$

$$\dot{\overline{A}} = \bar{\dot{\varepsilon}}_p - D\,\overline{A}\,\dot{p} - \frac{3}{2}\left[\frac{J_2(\overline{X})}{M}\right]^m \frac{\overline{X}}{J_2(\overline{X})} \tag{6}$$

In wich Q, b, C, D, M and m are material parameters.
The third term of left part of (6) can model recovery phenomena.

3.2 Identification of the parameters

The material proposed to manufacture the turbine disk is UDIMET 720 Coarse Grain. This material has been optimised to exhibit good creep properties. It is well known that the heat treatment strongly influences the mechanical properties of the material. Consequently, the validity of parameters presented here is limited by heat treatment variations (mainly cooling rate after the γ' dissolution) due to temperature gradient within the thickness of part, or material changes (microstructure, anisotropy, …) due, by example, to elaboration route.

3.2.1 650°C

From in-house experimental data (represented by points in fig. 5, fig. 6 and fig. 7) realised previously (three creep tests, one tensile test and one cyclic test on the cast and wrought material), a first set of parameters have been identified (set n°1):

E [GPa]	ν	R_0 [MPa]	n	K_0 [MPa^{-n}]	Q [MPa]	b	C [MPa]	D	m	M [MPa]
180	0.35	527	16	52	420	42.4	247128	1142	6.6	4841

tab. 1: parameters set n°1 at 650°C

Comparison between experimental data and simulation are given in fig. 5, fig. 6 and fig. 7.

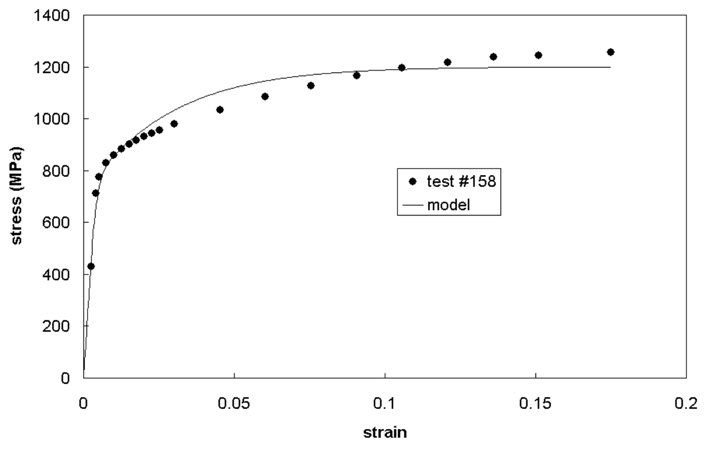

fig. 5: Tensile test at 5.10^{-3} s^{-1} (set n°1). Experiments: points; Model: line.

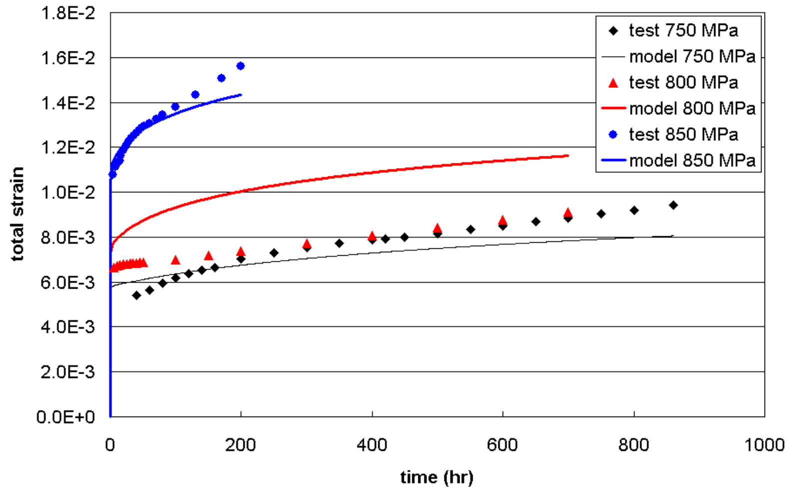

fig. 6: Creep tests at 750MPa, 800MPa and 850Mpa. Experiments: points; Model: line.

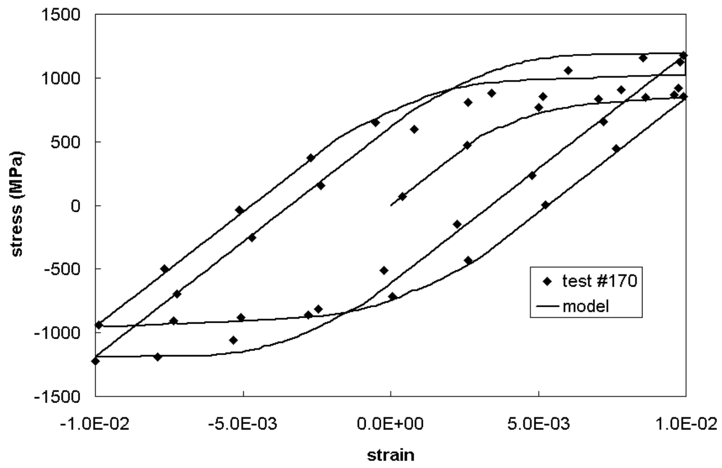

fig. 7: Fatigue test: first cycle and ½ life cycle. Experiments: points; Model: line.

As the value of R_0 is high, no viscoplasticity will be predicted for an equivalent stress lower than 527 MPa with such parameters. An elastic calculation on turbine disk gives a maximal value of 215 MPa for the Von Mises stress. Empressario Agrupado has found a maximal value of 241 MPa. The difference probably comes from calculation of centrifugal stresses or elastic parameters.
As new experimental data (with a material with a slightly different heat treatment) coming from the HTRM program [Cout 03] and CEA in-house database have been collected, a new optimisation has been realised with the help of the simulation module of ZEBULON, with a Levenberg-Marquardt algorithm [Leve 44] [Moré 77]. The best set of parameters obtained by optimisation on creep, tensile and fatigue tests (line on fig. 8, fig. 9, fig. 10,fig. 11, fig. 12) is reported in tab. 2.

E [GPa]	ν	R_0 [MPa]	n	K_0 [MPa^{-n}]	Q [MPa]	b	C [MPa]	D	m	M [MPa]
180	0.35	15.6	48	707	855	3.2	402000	841	6.2	10000

tab. 2: parameters set n°2 at 650°C

Compared to set n°1, we obtain a higher n value but this value is associated to a higher K_0 value. The limit of elasticity is lower in set n°2. This leads to visco-plasticity, but with very small strain rate for stress lower than 500MPa (by example, in this case, the strain rate is equal to $3.10^{-8}s^{-1}$). The viscous response of the material is higher with set n°2 than in set n°1. The saturation of isotropic hardening will occur at higher deformation since b is lower. Difference between set n°1 and set n°2 will be explored later.
Comparison between experimental data and numerical calculations (using parameters set n°2) are presented below. The fig. 8, fig. 9 and fig. 10 present creep data at different stress values. As the experimental strain values obtained are very small, the correlation between experimental data and simulation may be considered as satisfactory. Only the primary and secondary creep is selected in experimental data because the viscoplastic law used does not consider the damage or microstructure evolution governing the tertiary creep. Moreover, only relatively short duration have been experimentally tested. This may lead to an underestimation of strain for long time test. The fig. 11 presents results for tensile test: numerical calculation is in good agreement with experimental test for strain up to 10% but differences exist for the limit of elasticity. The fig. 12 presents a cyclic test: 1300 cycles with ε_{min} = 0.0006 and ε_{max} = 0.012. The correlation for the first cycle (fig. 12 a) and ½ life cycle (fig. 12 b) between experimental data and the model is correct.

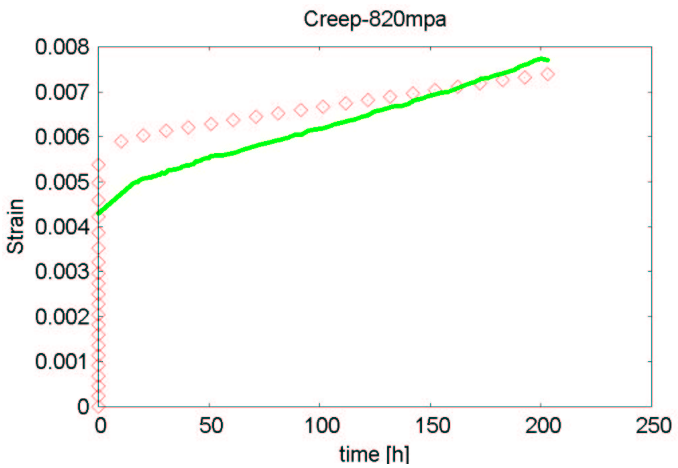

fig. 8: Creep test at 820 MPa. Line: experimental data, points: numerical test.

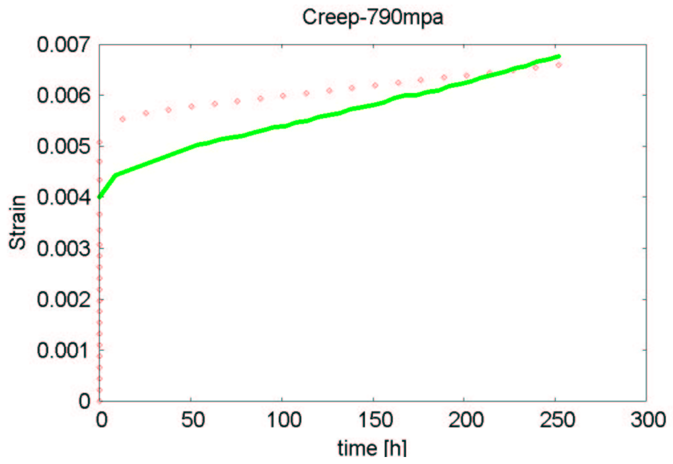

fig. 9: Creep test at 790 MPa. Line: experimental data, points: numerical test.

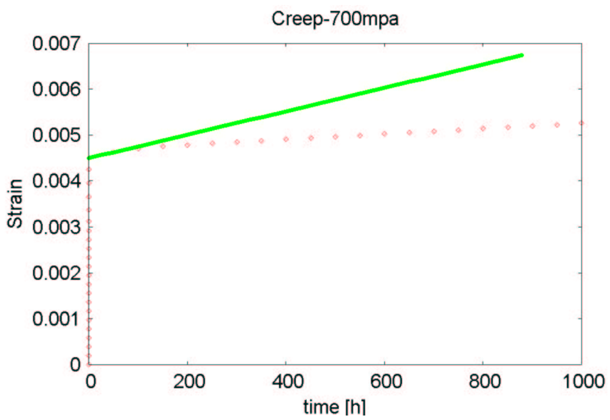

fig. 10: Creep test at 700 MPa. Line: experimental data, points: numerical test.

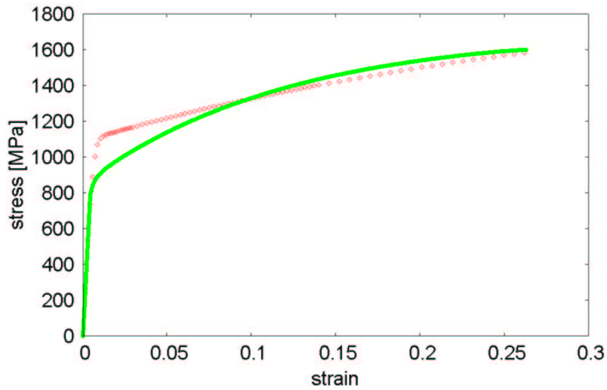

fig. 11: Tensile test at $10^{-3}s^{-1}$. Line: experimental data, points: numerical test.

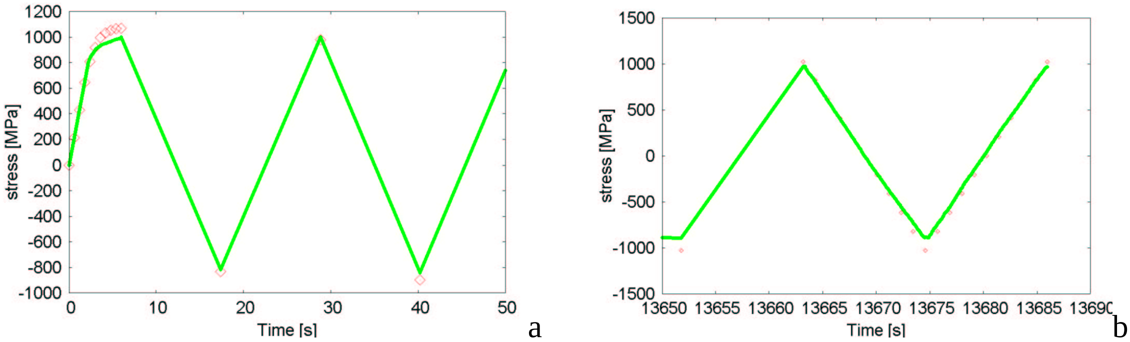

fig. 12: Low cycle fatigue test (ε_{min} = 0.0006; ε_{max} = 0.012)
a) initial loading b) cyclic response at half-life (650 cycles)
Line: experimental data, points: numerical test.

The experimental scattering on each test condition has not been tested (only one test by condition). Thus simulations obtained with set n°2 are considered satisfactory.
To check the influence of the parameters, creep tests up to 60000 hours have been simulated with the 2 sets at different stress values (fig. 13, fig. 14, fig. 15, fig. 16). It is noticeable that the numerical results are identical for short durations (≈ 1000hours), or low stresses (fig. 13), but significantly different for 60000 hours for σ = 600, 700 or 800MPa: the predicted strain may be more than 3 times higher with set n°2 (fig. 16) than set n°1. However the maximal strain reached is small in the two cases for a loading of 600MPa (fig. 14), a value higher than the stresses present in the component.
Although based on not very different material, the two models may present the same behaviour for a load of several hundred hours but may give a very different response for many thousand hours. This shows the need to have more experimental data to give a predictive model of the material. Relaxation tests allow measuring the viscous response of material depending on strain rate. Moreover long time tests are necessary to select the good model, particularly because, for short times, the strains at 650°C are very low.

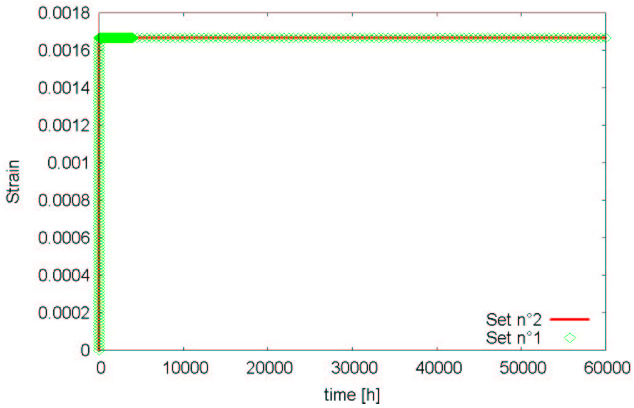

fig. 13: Creep simulations at 300MPa with set n°1 (points) and set n°2 (line)

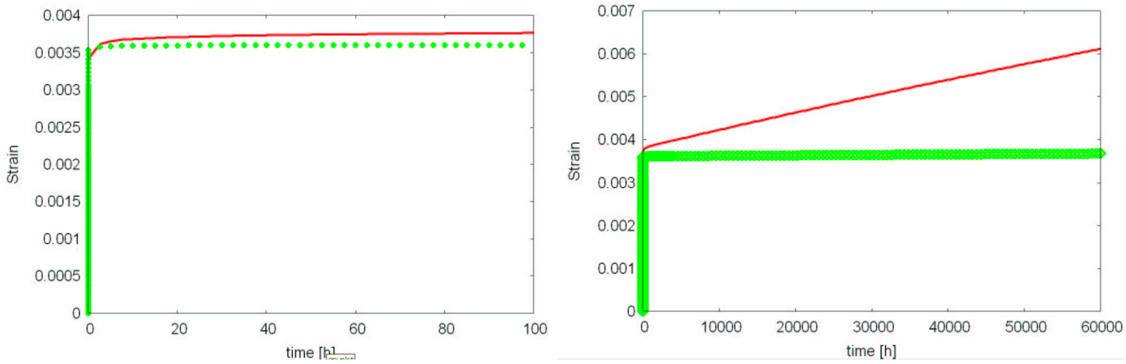

fig. 14: Creep simulations at 600MPa with set n°1 (points) and set n°2 (line)

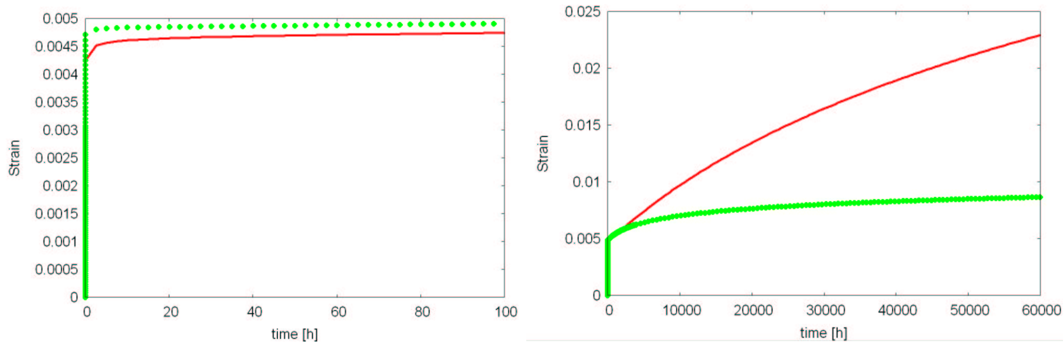

fig. 15: Creep simulations at 700MPa with set n°1 (points) and set n°2 (line)

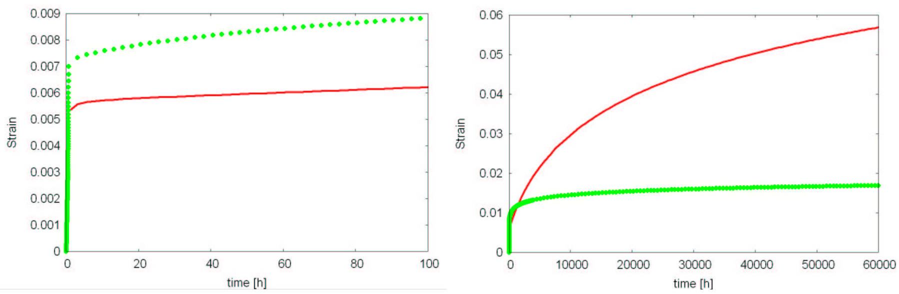

fig. 16: Creep simulations at 800MPa with set n°1 (points) and set n°2 (line)

3.2.2 750°C

For 750°C no cyclic data are available, consequently the kinematic hardening cannot be evaluated. The behaviour chosen has only a non linear isotropic hardening. The optimisation (realised with the same FE code than for 650°C) has been made only for the fifth parameters: R_0, n, K_0, Q, and b. The tab. 3 presents the best set of parameters obtained with the following set of test.

E [GPa]	ν	R_0 [MPa]	n	K_0 [MPa^{-n}]	Q [MPa]	b
166	0.35	10	12.3	1967	75.7	10.37

tab. 3: Parameters set at 750°C.

Five creep tests at different stress levels have been carried out and simulated (fig. 17). A very good agreement is obtained for the primary and secondary creep regime for the different stress values (but compared to 650°C simulations, the strains reached are higher). A tensile test (fig. 18) and a relaxation test (fig. 19) have also been used too to evaluate the law parameters. As at 650°C, the yield stress predicted by the simulation is a bit higher than experimental value (fig. 18). The simulation of the relaxation test is close to experimental data. This test is interesting since it allows to explore several decades in strain rate (10^{-4} initially to 10^{-9} at the end of the test) within the same test. However, long time effects (recovery) are not present.

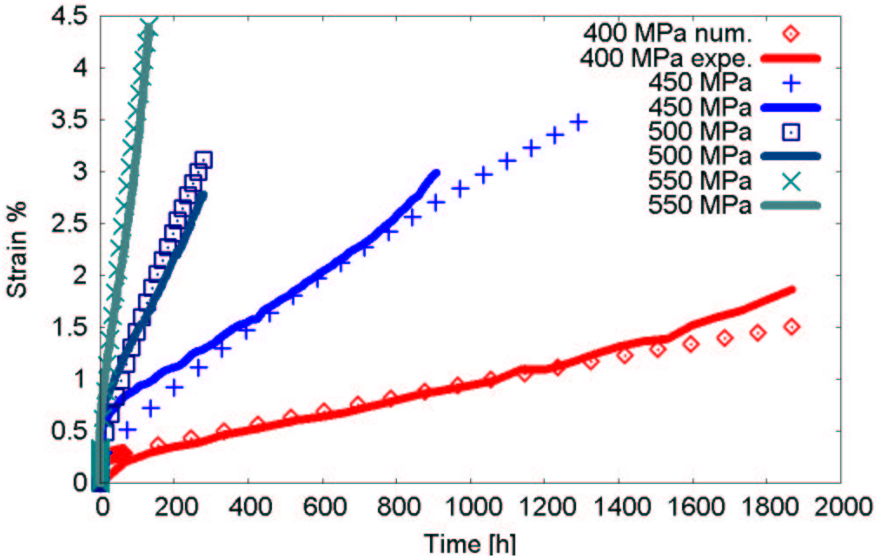

fig. 17: Creep test at different stress state. Line: experimental data, points: numerical test.

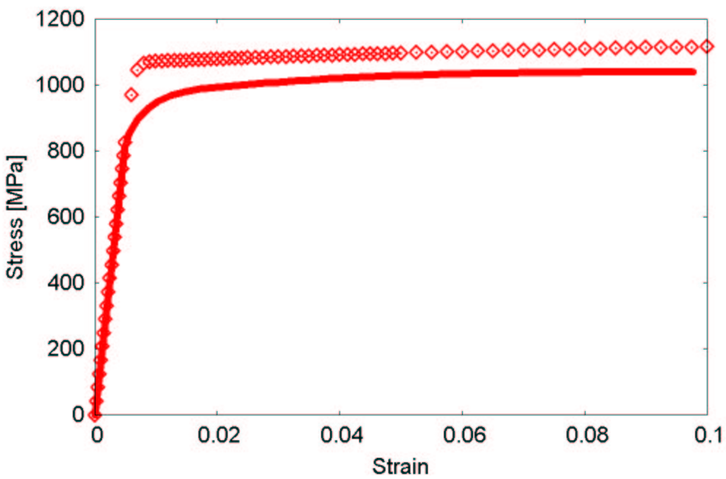

fig. 18: Tensile test. Line: experimental data, points: numerical test.

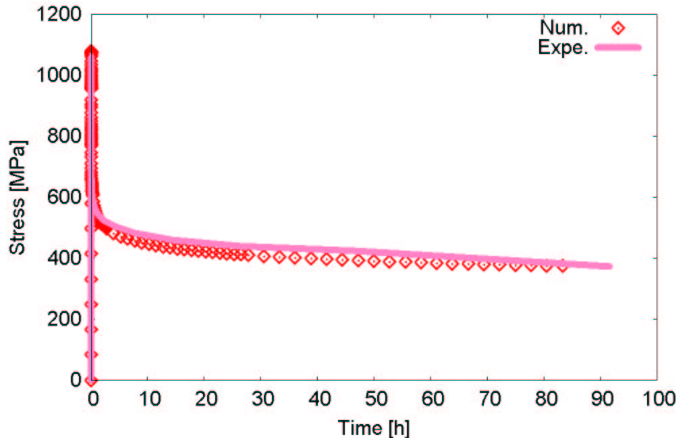

fig. 19: Relaxation test. Line: experimental data, points: numerical test.

4 Simulation

For each temperature, a first calculation of the turbine disk has been performed up to 60000 hours under a rotation speed of 3000 rnd/min. Then, several calculations have been made to evaluate the impact of cyclic loading or helium pressure.

4.1 Pure Creep loading: 60 000h at 650°C

The parameters set n°1 has been first used to calculate the turbine stress state under a constant temperature of 650°C and a rotation speed of 3000 rnd/min. The Von Mises stress (fig. 20) is maximal at the hub of the disk and presents a quite low value (maximal value = 215 MPa). The fig. 21 displays the maximal principal stress σ^I. The maximal value of σ^I is located at the minimum section of the disk. It is notable that no plasticity is predicted, and that the loading level is far below the limit of plasticity (527 MPa).

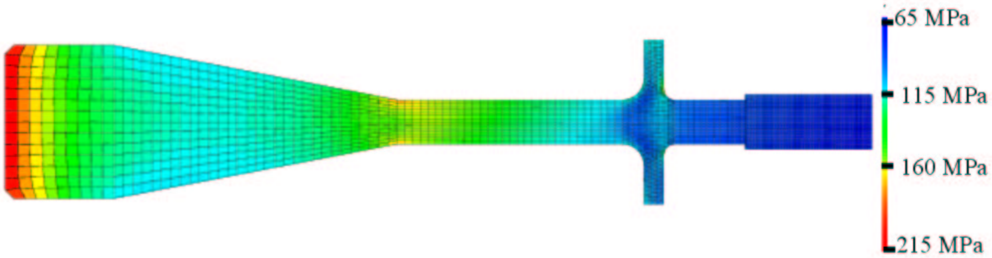

fig. 20: Von Mises stress after 60000h at 3000 rnd/min and 650°C. Parameters set n°1.

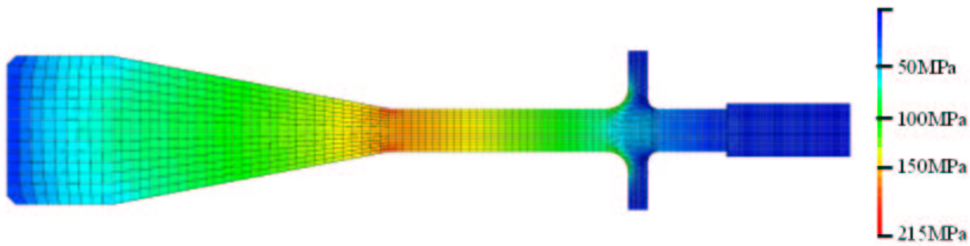

fig. 21: Maximal principal stress after 60000 h at 3000 rnd /min and 650°C. Parameters set n°1.

A second simulation has been made with the parameters set n°2. No plasticity is detectable although the yield stress is very low. In fact, the stress level lead to strain rate so small (< 10^{-25}) that plasticity is considered equal to zero by the calculation code. Consequently, the stresses map are identical with parameters set n°1 and n°2. Earlier simulations realised on one gauss point with Zebulon (fig. 13) confirm that no ***detectable*** plasticity is present for these low stresses.

Theses results confirm that it is possible to use UDIMET 720 for the turbine disk at 650°C. Moreover microstructural evolutions are quite reduced at this temperature. However, it is important to evaluate the influence of cyclic loading on the structure response.

4.2 Thermo-mechanical loading of the disk (20°C to 650°C)

As no viscoplasticity is predicted under a stationary loading, transient thermo-mechanical loading has been introduced in the calculations.
The real cyclic loading may be simulated by 157 equivalent cycles (see §1.2). Tensile tests and thermal data are available between 20°C and 650°C for UDIMET 720 CG (annexe A). Consequently, the plastic (time independent) behaviour with an isotropic hardening (based on a Von Mises criterion) has been used. The calculation was limited to the first heating/loading step since the cyclic behaviour of the material was not known.
The thermo-mechanical loading introduced in the calculations is given in tab. 4. Two cases have been considered: a first one with a temperature imposed along the turbine disk boundary, and a second one, with an imposed gas temperature, the temperature of the desk being calculated from heat transfers.

Time [s]	Round per min.	Temperature [°C]
0	0	30
12300	3000	650

tab. 4: Thermo-mechanical loading

A reference case, corresponding to tab. 5, is given in Annexe B.

Time [s]	Round per min.	Temperature [°C]
0	0	650
12300	3000	650

tab. 5: Load of the reference case (given in Annexe B)

As no clear data is available on the thermal boundary condition, thermal loading (imposed temperature or convection) will be imposed in the whole turbine disk boundary (fig. 22).

fig. 22: Thermal conditions are imposed on the whole boundary

4.2.1 *Thermo-mechanical calculation with imposed temperature*

A thermo-mechanical calculation has been performed with the following assumption: the helium temperature is instantaneously transmitted to turbine disk boundary. Heat conduction is then modelled: no radiation being considered. The fig. 23 presents the temperature field in the disk: the maximum temperature gradient is around 25°C. These gradients lead to a slight increase in maximal values for Von Mises (fig. 24) and maximal principal stresses (fig. 25): respectively. + 8 MPa and +6 MPa. These increases are not able to change plasticity results obtained in 4.1: even for a cyclic loading, the loading remains purely elastic.

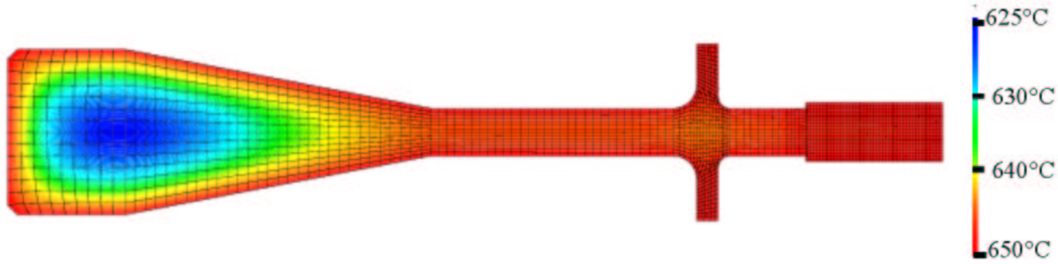

fig. 23: Temperature map at time = 12 300s (see fig. 1) with imposed T on boundary (T_{0s} = 30°C T_{12300s} = 650°C)

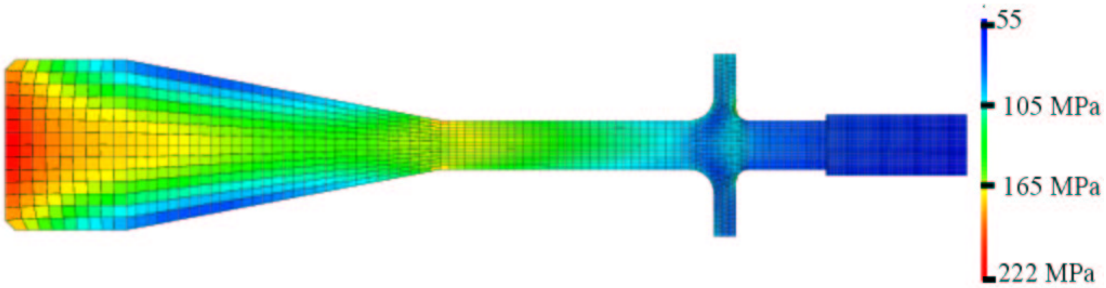

fig. 24: Von Mises stresses at time = 12300s with imposed T on boundary (T_{0s}= 30°C and T_{12300s}= 650°C)

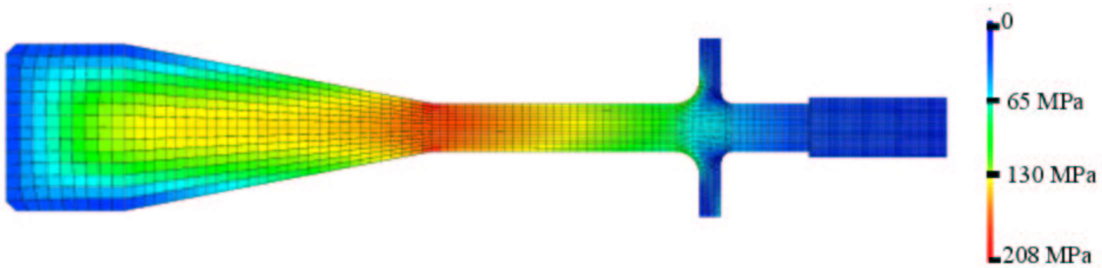

fig. 25: Maximal principal stress at time = 12300 s with imposed T on boundary (T_{0s}= 30°C and T_{12300s}= 650°C)

4.2.2 *Thermo-mechanical calculation with convection*

Instead of fixing the boundary temperature, heat exchanges are now simulated by convection between helium gas and turbine disk boundary. In a natural external convection hypothesis, the transfer coefficient h may be evaluated at about 2000W/m² [Annexe C]. However this value may present large variation according to the hypothesis chosen: values lower than 100W/m² may be proposed [Bejan 95]. To obtain the most conservative stress state, a value of

100W/m² has been chosen. Consequently, the heat of the part is slower than the previous case: after 12300 s the minimum value of temperature is about 513°C (fig. 26), leading to important temperature gradients. The maximal Von Mises stresses are 40% higher than without temperature gradients (fig. 27 and fig. 20). Differences are notable too on the maximal principal stress (fig. 28 and fig. 21). However, these gradients will not lead to plasticity in the disk turbine.

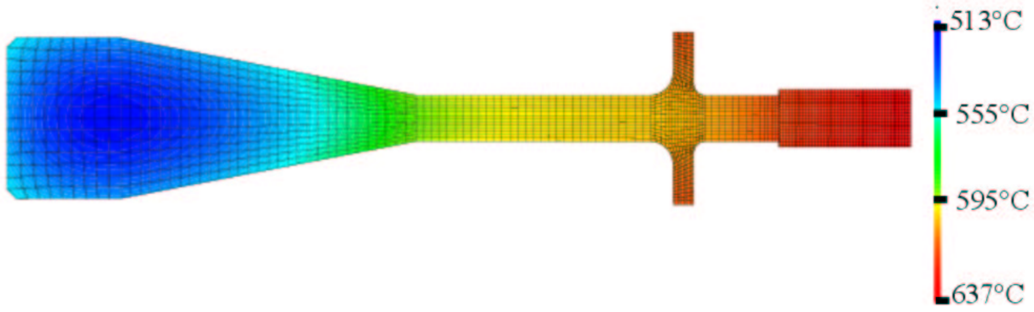

fig. 26: Temperature map at time = 12 300 s (see fig. 1) with convection

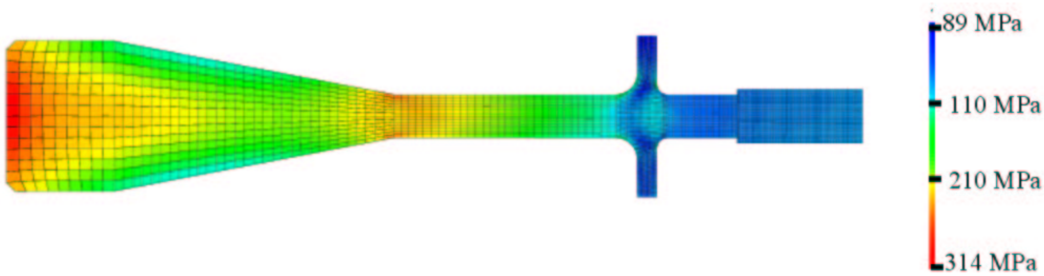

fig. 27: Von Mises stresses at time = 12300 s with convection

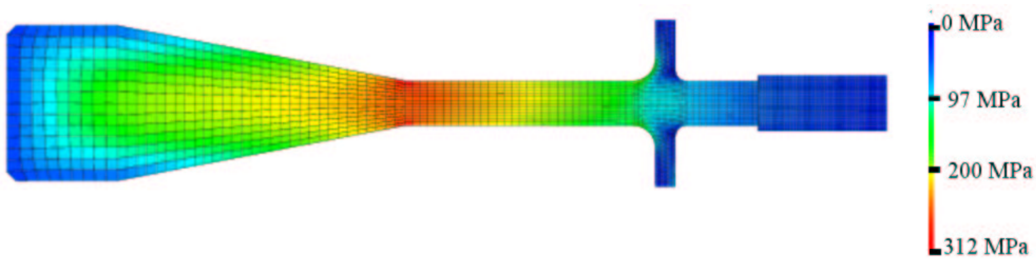

fig. 28: Maximal principal stress at time = 12300s with convection

The thermal stabilisation of the disk is reached after 16000 s (fig. 29). The maximal Von Mises stresses are reached at 12 300s, when the temperature gradients are the highest.

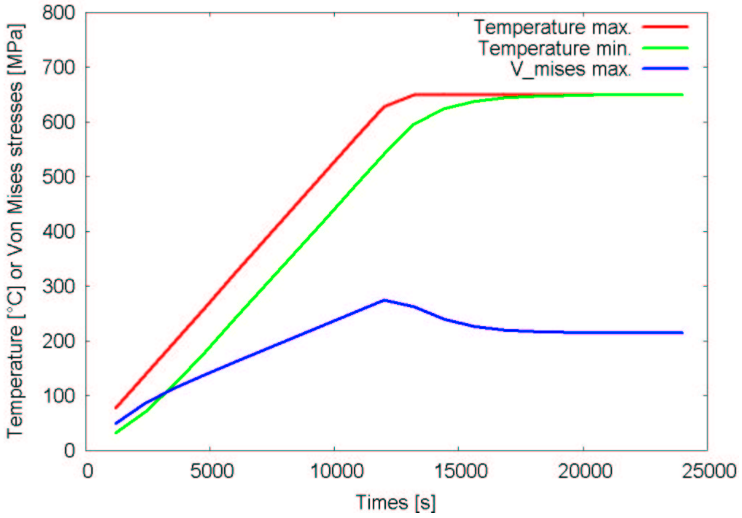

fig. 29: Evolution of the maximal temperature (imposed temperature), minimal temperature and maximal Von mises stress in the turbine disk

These calculations confirm that there is no plasticity or visco-plasticity at 650°C even for 60000 hours.

4.3 Creep of the turbine disk at 750 °C

With the parameters set obtained in §3.2.2, a first calculation has been realised. The loading is given in tab. 6.

Time [h]	Round per min.	Temperature [°C]
0	0	750
4	3000	750
60000	3000	750

tab. 6: Description of the loading

The resulting map of Von Mises stresses is presented in fig. 30. The simulation predicts the presence of some visco-plastic strain (fig. 31). However, the predicted maximal cumulated plastic strain is about 0.01%, wich is a quite low value. This maximum appears at the hub of disk, where Von Mises stresses are maximal.

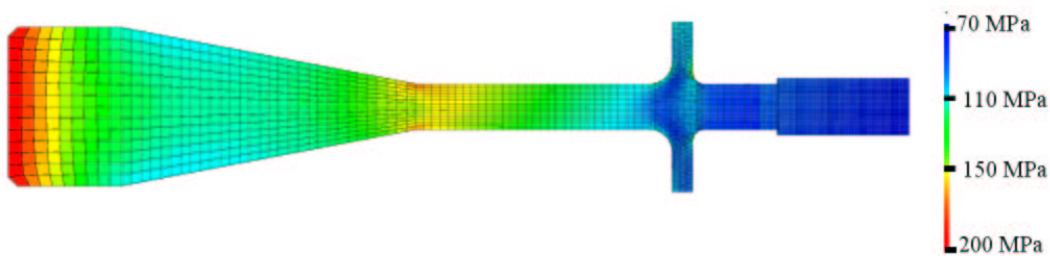

fig. 30: Von Mises stresses after 60000 h at 750°C

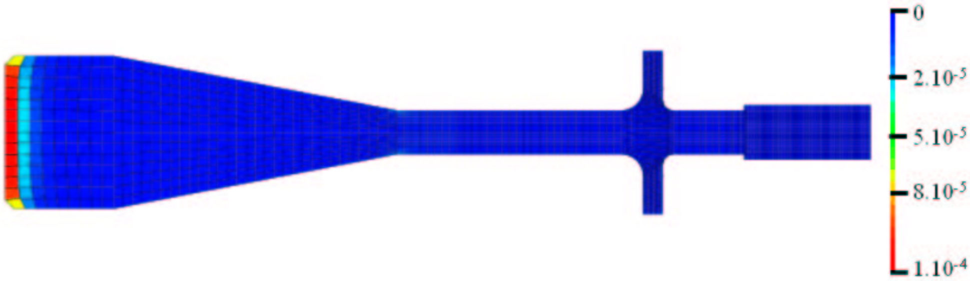

fig. 31: Cumulated plastic strain after 60000 h at 750°C.

The evolution of the cumulated plastic strain is presented in fig. 32. This value increases quickly at the beginning of the load (5000 h), and the evolution is still important after 60000 h of creep.

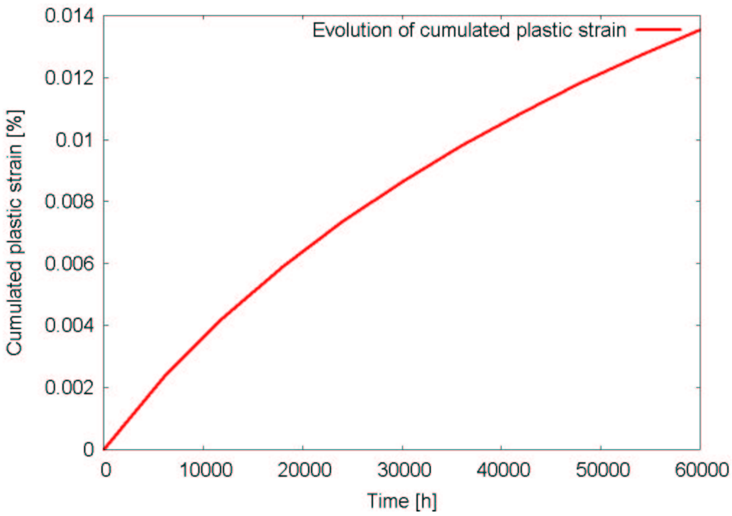

fig. 32: Evolution of cumulated plastic strain

The simulation indicates that the turbine might resist to creep phenomena at 750°C. However, other loadings must be considered to evaluate the disk response: pressure of helium, and thermal loading.

4.3.1 Impact of he gas pressure

The helium pressure produces loads on the blade surface, and the distribution of resulting stresses have been studied by Empressario Agrupado [Empr 05]. As this distribution is fundamentally connected to 3D geometry, our calculation cannot be used to predict effect of this pressure on visco-plasticity. The elastic calculation made by EA has shown that the maximal stresses are present in a very specific area of the foot of the blade -the place where the disk and foot are joined- because of the bending of the blade due to the unequal pressure on its faces. On the rest of the blade, the predicted stress values vary from 200 MPa to 250 MPa. These values may lead to creep of the blade.

For the disk, our previous calculations have shown that creep strains are present at the bottom of the disk (inside radius, see fig. 31) and stresses due to pressure are almost zero in this area (fig. B-6 of [Empr 05]).

4.3.2 Thermo-mechanical calculations

The mechanical response of the turbine disk may be influenced by thermo-mechanical stresses due to the increase of temperature from 30°C to 750°C. Calculations have been performed with the same elasto-plastic behaviour, the same boundary conditions and loading than in §4.2 (with 750°C instead of 650°C). With a heat transfer coefficient h = 100W/m², a thermal gradient is present in the piece (fig. 33). At t = 12300 s, this gradient leads to maximum Von Mises stresses equal at 331 MPa (fig. 34). With the elasto-plastic model, no plasticity is predicted. On the opposite, the Chaboche visco-plastic model defined in this rapport shows that plasticity occurs for this Von Mises stresses levels. Consequently, cyclic loading may lead to additional deformations due to thermo-mechanical stresses.
A complete cyclic calculation cannot be done because the visco-plastic model has been determined only with an isotropic behaviour (3.2.2).

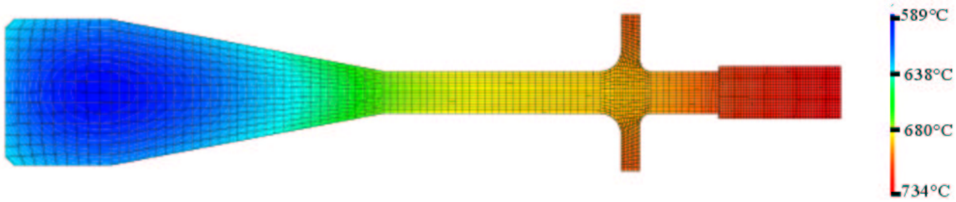

fig. 33: Temperature map at time = 12 300 s (see fig. 1) with convection

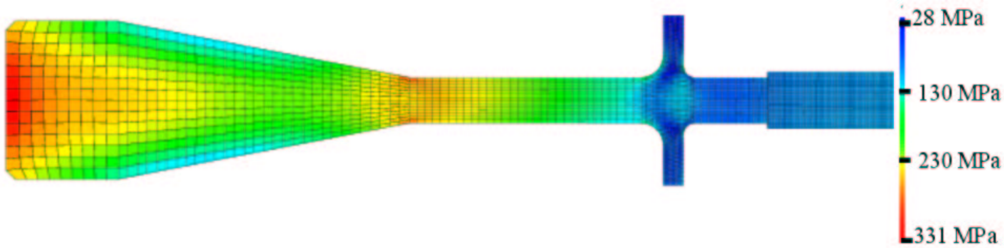

fig. 34: Von Mises stresses at time = 12 300 s (see fig. 1) with convection

The thermal stabilisation of the disk is reached after 20000 s (fig. 35). The maximal Von Mises stresses are reached at 12 300s, when the temperature gradients are the highest.

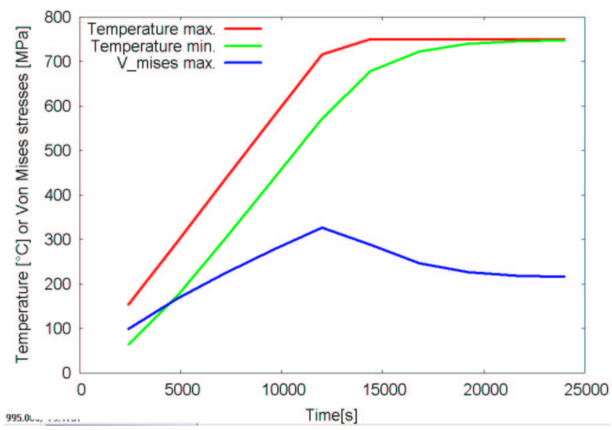

fig. 35: Evolution of extremum temperatures and maximum Von Mises stresses

5 Limits of calculations and Conclusions

Simulations presented here indicate that the U720 CG turbine disk will resist to creep phenomena at 650°C. At 750°C, calculation predicts very small strains after 60 000 h of creep. However, this study must be considered only as a pre-work for the following reasons.

Material laws have been determined with the help of actual database. Real material used in the turbine may present important differences with material of used database. In fact the realisation of large piece always introduced several changes concerning microstructure, anisotropy, etc.

All calculations have been realised with an "equivalent" geometry and it is not possible to know the impact of this fact. Particularly, three-dimensional effects, or impact of the cooling channel may be important in a mechanical point of view.

The material law used are based on data concerning about 1000 hours of creep when the turbine must work 60000 hours. Recovery phenomena or micro-structural changes may occurs and completely change the mechanical response, especially at 750°C.

Cyclic loadings have not been modelled, and it seems that thermo-mechanical stresses lead to supplementary strains.

To conclude, an important mechanical campaign test must be realised to obtain reliable material database allowing more predictive simulations (see rapport HTRE deliverable n°10 [Briottet 05]) , but first results are encouraging to develop turbine with UDIMET 720 CG.

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ANNEXE A
Thermal and mechanical data for elasto-plastic calculation

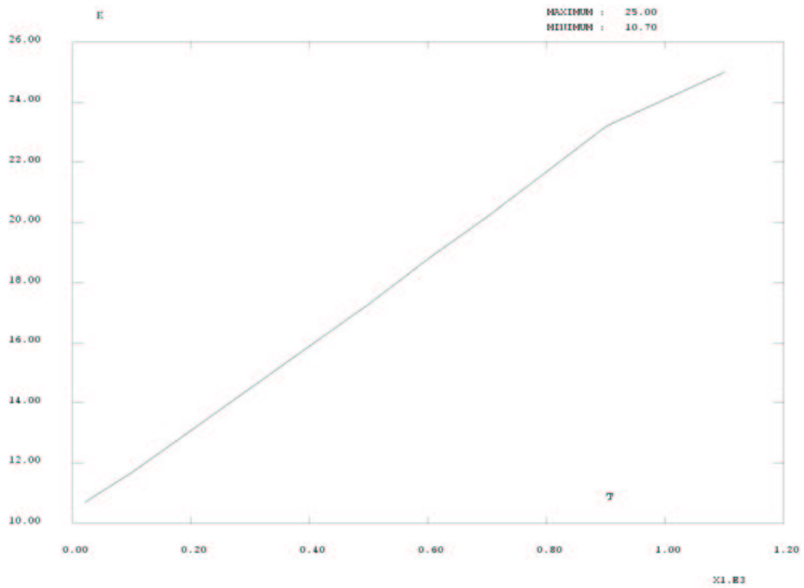


fig. 36: Evolution of thermal conductivity K with temperature

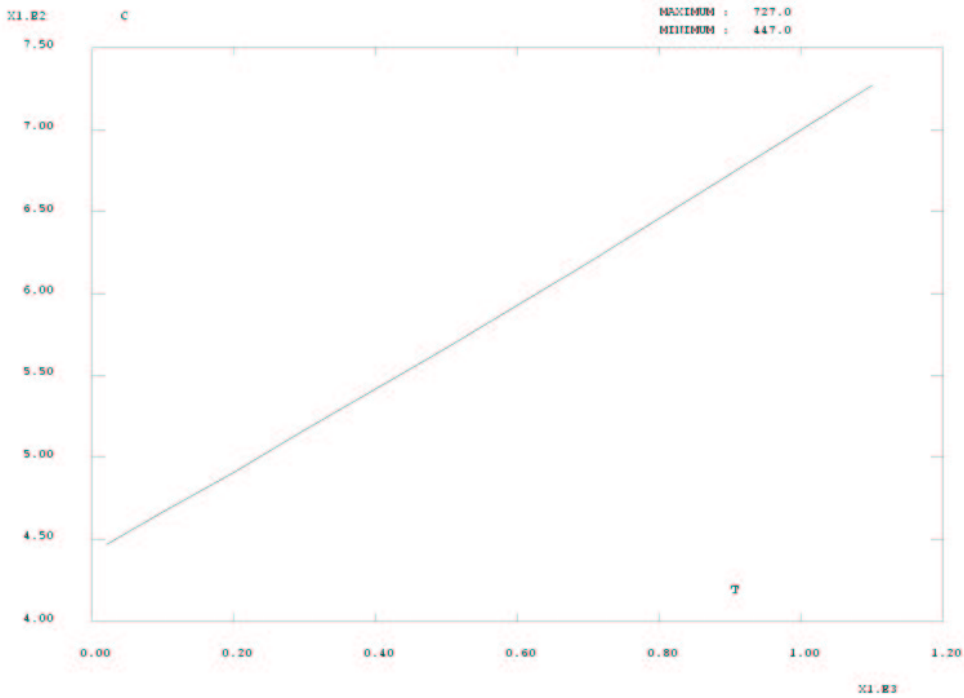


fig. 37: Evolution of heat capacity Cp with temperature

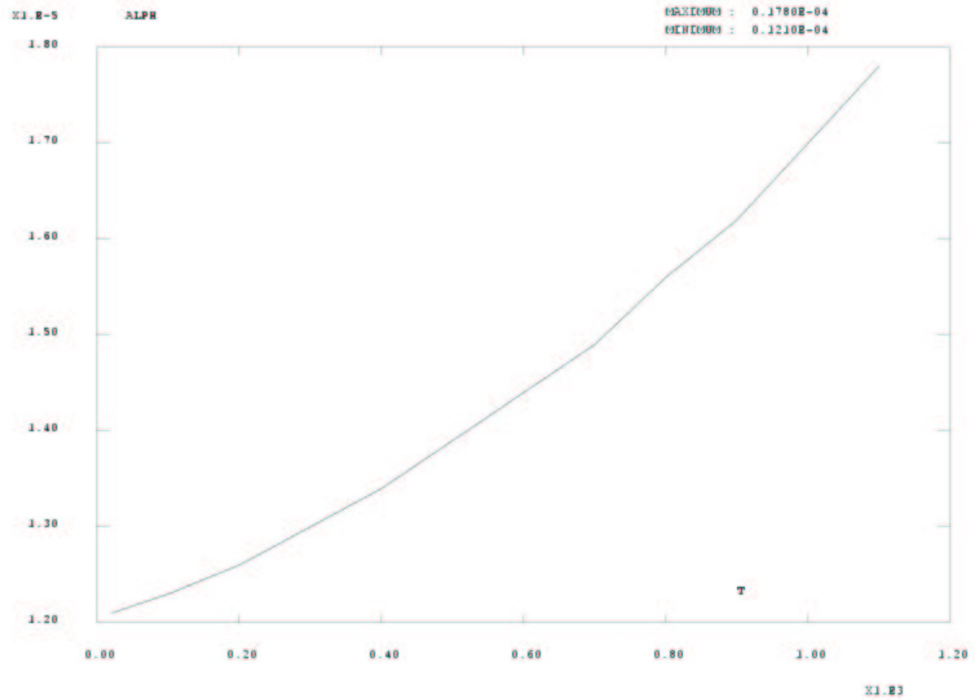


fig. 38: Evolution of thermal dilatation coefficient α with temperature

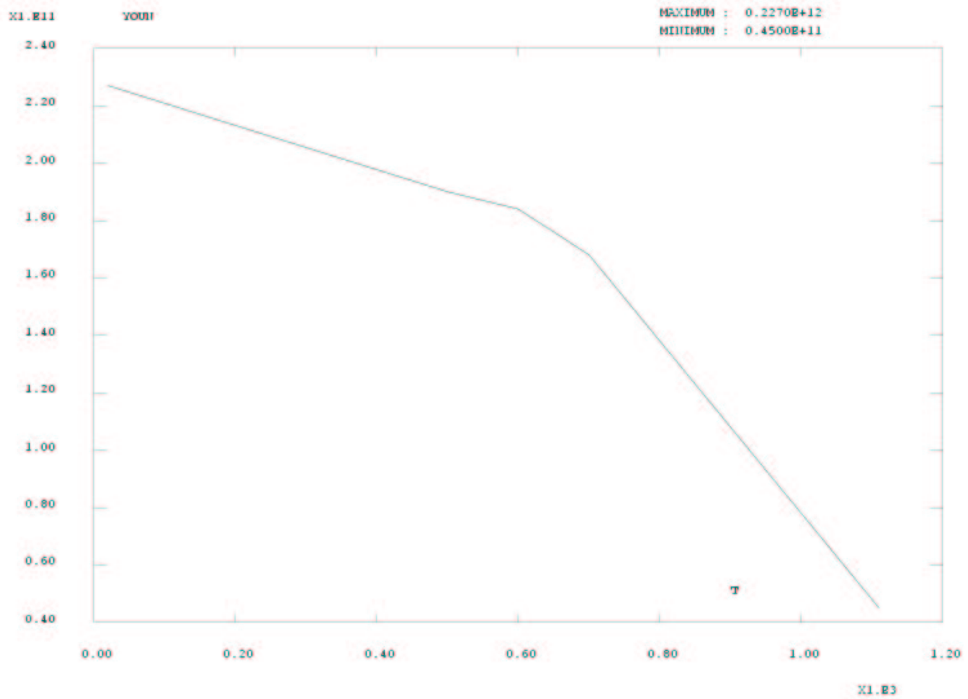


fig. 39: Young modulus evolution with temperature

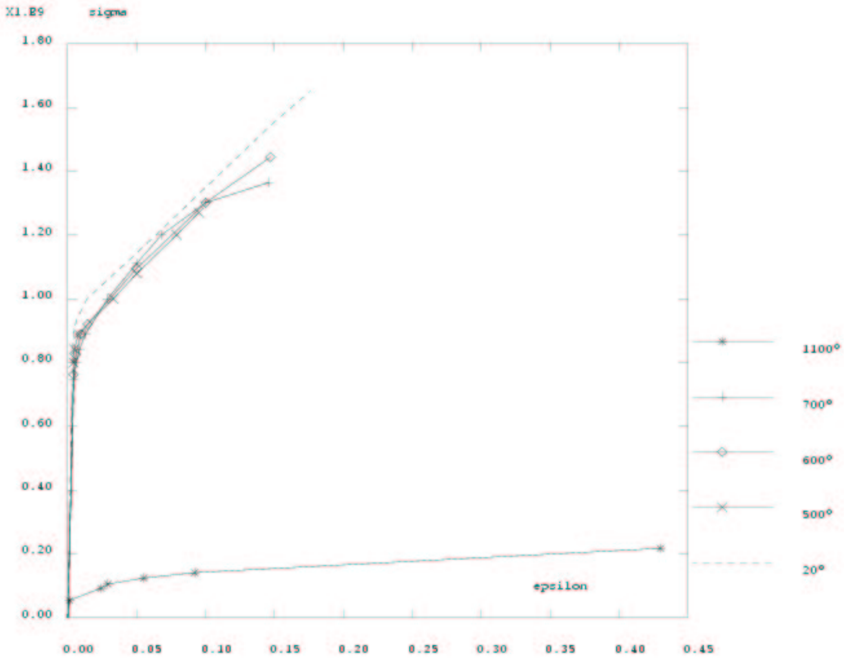


fig. 40: Tensile tests at different temperature used in the calculation

ANNEXE B

A reference case has been simulated to isolate gradient temperature effects: a constant temperature of 650°C is fixed in all elements from initial time to final time: resulting mechanical maps are presented in fig. 41 and fig. 42. No plasticity is present because stresses are inferior to the yield stress.

Time [s]	Round per min.	Temperature [°C]
0	0	650
12300	3000	650

Load of the reference case

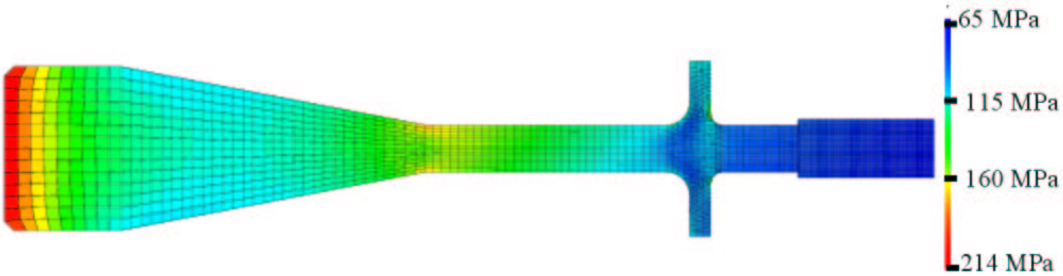


fig. 41: Von Mises stresses reference map at T= 12300s
(with $T_{0s} = T_{12300s}$ = 650°C i.e. with no temperature evolution)

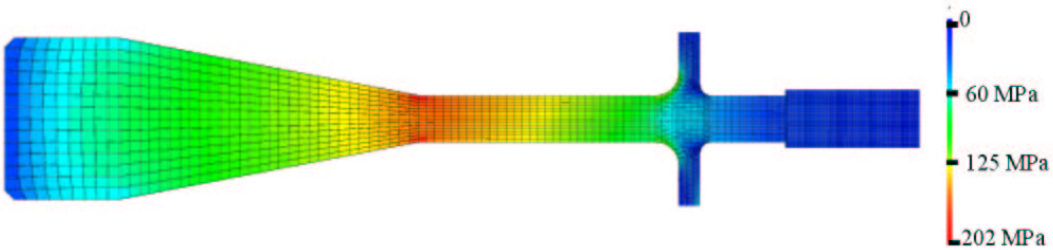
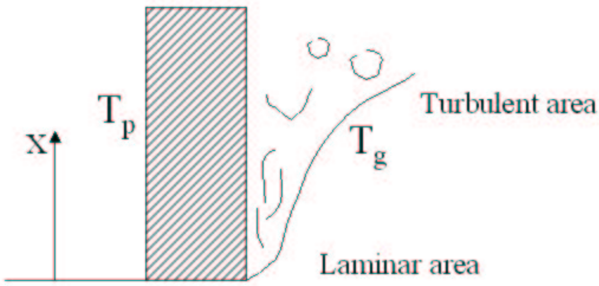


fig. 42: Maximal principal stress reference map at T= 12300s (with $T_{0s} = T_{12300s}$ = 650°C i.e. with no temperature evolution)

ANNEXE C

H evaluation



Hypothesis: External natural convection
Exchange coefficient h = N_{ul} x λ/L

Nusselt expression:

$$N_{ul} = 0.59\ R_{al}^{\ 1/4} \text{ si } 10^4 < R_{al} < 10^9$$
$$N_{ul} = 0.13\ R_{al}^{\ 1/3} \text{ si } 10^4 < R_{al} < 10^9$$

With $R_{al} = (g.\beta.\Delta T.x^3)/(\alpha.\nu)$ and $g = 9.81$m/s
$\beta = 1/T$ (perfect gaz)
$\Delta T = Tp - Tg$

Physical properties are evaluated at Tf (K) = (Tp+Tg)/2 = 623K

L	0.795
Tf	623
delta t	300
landa	14.5
rho	2
cp	517
nu	0.000013
alpha	0.014023211
Ral	1.30E+09
Nul	112.0740866
h	2044.118561

Parameters used in calculation (Units: SI)