LOW CYCLE FATIGUE OF STEELS FOR NUCLEAR PRESSURE VESSELS IN HOT WATER

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1. Introduction

The fatigue behavior of mechanical structures in the construction of nuclear reactors is extremely important from both the safety and the reliability standpoints. It is in connection with nuclear reactors that fatigue analysis methods were introduced into the analysis of pressure vessels /1/. The provisions of the Decree of 26 February 1974 /2/,/3/,/4/ regulate the construction of the pressure components of nuclear reactors in France. A number of provisions relative to deterioration due to time, loads applied and the environment are examined. An estimation of fatigue behavior is required by Article 10 of the Decree of 26 February 1974, while Article 19 calls for the effect of the environment to be taken into account.

The computation procedure is related to the existence of test results on test specimens, which are moreover transposed for this use. It is then necessary to possess satisfactory test results to assess the proposed method.

Routine practice in estimating fatigue behavior is described in Section III of the ASME Code /5/, which refers to design curves giving the number of allowable cycles as a function of alternating stress intensity. This method is described in detail in the publications of B.F. Langer /6/,/7/ and in the comments /8/ relative to /5/. The design curves are plotted from test results on test specimens. On examination of the conditions of these tests, it appears that most of them have been performed in environmental conditions which are different from those surrounding the materials of a nuclear reactor. This remark is consistent with the general policy of /5/, of which the rules "Do not cover deterioration which may occur in service as a result of radiation effects, corrosion, erosion, or instability of the Material".

In order to assess the deterioration of the material under the combined effect of cyclic load variations (fatigue) and the presence of pressurized hot water, it is therefore necessary to secure fatigue test results obtained in a medium which suitably represents the water in the circuit of a pressurized water reactor. This program is under way at Saclay, and the results already obtained have been confined to previous publications on this matter /9/,/10/, /11/,/12/,/13/ for :

a) French pressure vessel steel similar to ASTM Specification;

b) A.508 Class 3;

c) Ni Cr Fe alloys 800 and 600 similar to ASTM Specification SB.409;

d) Stainless steel AISI 316.

2. Test Principle

The tests are performed on bending test specimens, and the variation in deflection is known and imposed during each test.

The test specimens consist of metal strips of rectangular cross-section placed between four studs, two of them fixed and the remaining two mobile. The movement of the mobile studs is imposed by the fatigue machine as shown in Plate 1.

The portion of the test specimen placed between the mobile studs is subjected to bending with a uniform moment and hence uniform deformation.

The test consists essentially of counting the number of bending variation cycles after which fracture occurs.

3. Test Installation

The Primeau rig test is used and the testing machines are connected to it. The Primeau bench is built of type 304 stainless steel, and its scheme is given in figure 2. The testing machines are connected directly to the bench by means of a pipe and a set of RTJ flanges. The hot water flows through the testing machine from one end to the other. The mechanical system designed to cause the deformation of the test specimens is placed inside the machine.

4. Test Specimens

The materials mentioned above were employed. Their mechanical and chemical properties are checked and published in the test reports. The test specimens are rectangular in form, L = 60 (in the rolling direction), l = 10, e = 2 mm.

The correspondence between the imposed deflection and the deformation is established by calibration. The form of the cycle selected is shown in Plate 3, and the frequency is 0.1 cycle per minute.

5. Operating Conditions

5.1 Water Quality Check

Tests are performed with deionized water deaerated by boiling. The pressure of 150 bars and the temperature of 320°C are recorded.

5.2 Water Resistivity

The resistivity of the water is checked once per week during each test period. This check is performed with the use of a resistivity meter, in which cooled, depressurized water flows through the measurement electrode. Accuracy of measurement is ± 1 % of full scale, and measurement reproducibility is ± 0.3 %. We use a cell with constant K = 1.84 and calibration of 100 kohm.

The Primeau resistivity measurement ranges from 30 to 100 kohm at 20°C.

5.3 Water pH

pH measurement calls for the same precautions as those observed for resistivity measurements, in relation to pressure and temperature.

The pH meter measurement range covers 0 to 14 pH, and calibration at pH 7 can be carried out with an accuracy better than ± 0.01 pH. Stability is better than 0.002 per day.

The Primeau pH measurement varies from pH 7.8 to 8.5.

5.4 Water Analyses

The determination of oxygen and chloride ions is performed with samplings taken from special pots under helium blanket. The following table provides one example of the results obtained.

Reference	Cl (ppb)	Fe (ppb)	O_2 (ppb)	Li (ppm)	B (ppm)	Cd (ppb)
PII of 17 Aug. 1978	78	136	$\lesssim$ 50	4	1420	-
PII of 21 Sep. 1978	38	18	140	2.3	1070	0.1
PI of 13 Oct. 1978	50	$\lesssim$ 5	$\lesssim$ 100	-	-	-

6. Performance of Tests

Performance of the test is described in CEA Publications /9/ and /10/. Note that the force is permanently recorded, and that the test stops when the value of the recorded force decreases significantly and falls to 75 % of its initial value.

7. Test Results

For each test, we know the deformation amplitude and the number of cycles necessary for fracture, as well as the duration of immersion in hot water at the end of which fracture occurs. Photographs of broken test specimens are given in Plate 4 for NiCrFe alloy 800. It may be noted that outside the fracture zone the test specimen exhibits considerable cracking in the central zone, showing that fatigue has spread over a broad zone.

The number of cycles to fracture as a function of deformation amplitude εa(1/2 range) is shown in figures 5 to 8.

are very close to the curve $\varepsilon a = 5.6^{N-0.3}$.

Alloys 800 and 600 are shown respectively on curves $\varepsilon a = 13.77^{N-0.485}$ and $\varepsilon a = 9.52^{N-0.34}$ for tests performed in hot water, and tests performed in air at ambient temperature are placed on the curves $\varepsilon a = 17.5^{N-0.39}$ and $\varepsilon a = 11.26^{N-0.35}$.

Plotted on Plates 5, 6, 7 and 8 is the Best Fit Curve relative to A.302 steel for figure 5, for 18.8 stainless stell alloy for Plates 6, 7 and 8 as they are given in /8/.

8. Comparison with ASME Code Fatigue Curves

The alternating stress intensity is obtained from the amplitude of deformation εa by multiplying the latter by $E/1 - \mu^2$.

The results obtained for pressure vessel steel and the two NiCrFe alloys are plotted on figures 9, 10, 11 and 12.

9. Conclusions

9.1 Pressure Vessel Steel A.508 Class 3

In the tests which we performed, no significant effects due to the presence of hot water at 265°C were noted. Results both in air at ambient temperature and in water at 265°C were similar to those on which the design curve of Section III of the ASME Code for low alloy steels was based.

9.2 NiCrFe alloy 800

The results of tests performed on this alloy in water at 265°C show that the effect of the environment reduced its fatigue strength in comparison with tests conducted in air at ambient temperature.

9.3 NiCrFe alloy 600

This alloy behaved substantially like alloy 800. We observed a drop in the properties for tests conducted in hot water, as compared with those conducted in air at ambient temperature.

9.4 Stainless Steel 316^L

This discussion contains test results which are very recent and incomplete. Tests are continuing and a separate report will be prepared (see figures 8 and 12).

References

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/3/ Arrêté et circulaire du 26 février 1974. Journal Officiel de la République Française 1974 (N°74-63).

/4/ DE TORQUAT, C. and ROCHE, R.L., SMIRT 3, (paper G)

/5/ ASME, Boiler and pressure vessel code. Section III nuclear components Div.1 - ASME 1977.

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/7/ LANGER, B.F., "Pressure vessel engineering technology" (ed. R.W. NICHOLS). Applied science pub. Ed. London 1971.

/8/ Criteria of the ASME Boiler and pressure vessel Code for design by analysis in sections III and VIII Division 2 - ASME 1969.

/9/ GARNIER C. et al., Note CEA-N-1973 - CEN Saclay, Juillet 1977.

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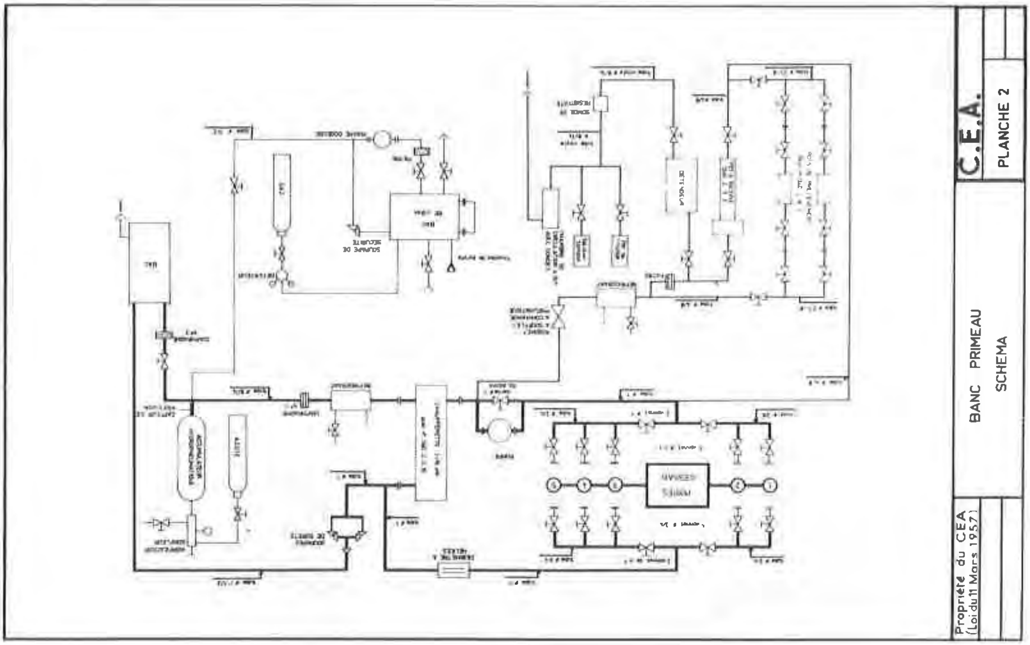
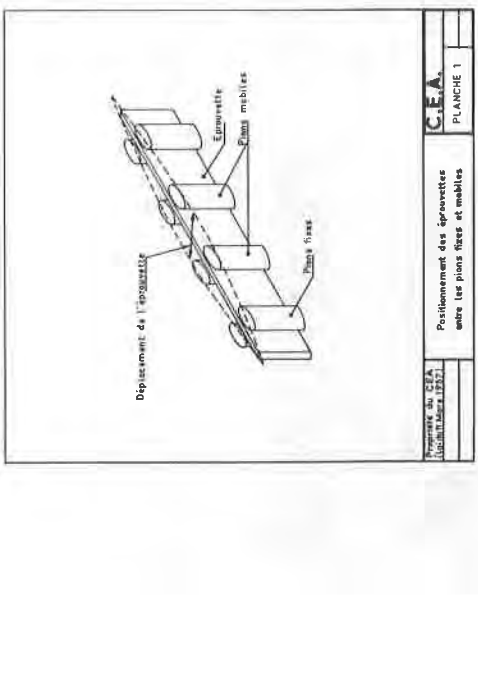
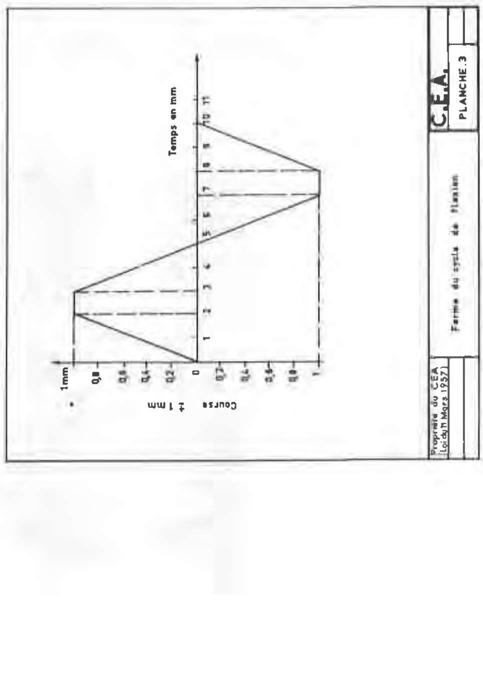
/11/ GARNIER C. et al., L8/8 SMIRT 4 (ed. T.A. JAEGER and B.A. BOLE North Holland Pub Cy Amsterdam 1977.

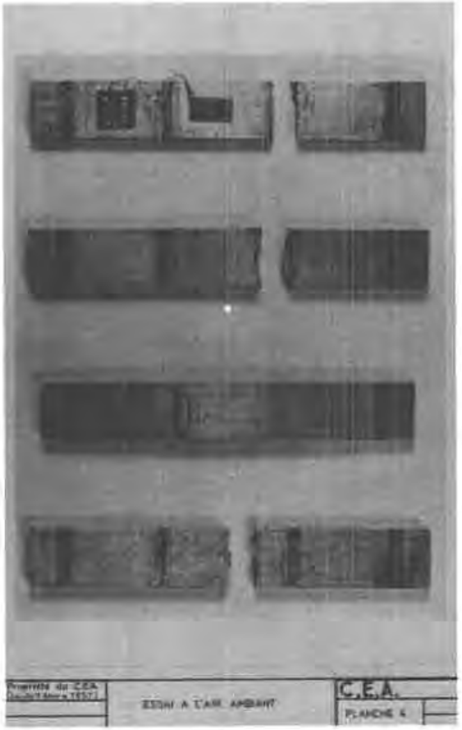
/12/ LEBEY, J. et al., "Reliability problems of reactor pressure components", Vol. 1, Int. Atm. Energ. Ag. Vienna 1978.

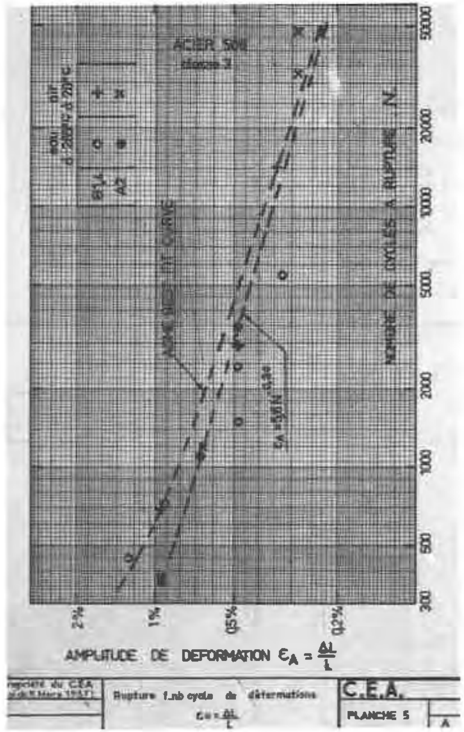
/13/ Experimental tests on low cycle fatigue of metals in hot water. Innsbruck, Austria 20-21 Nov. 1978.

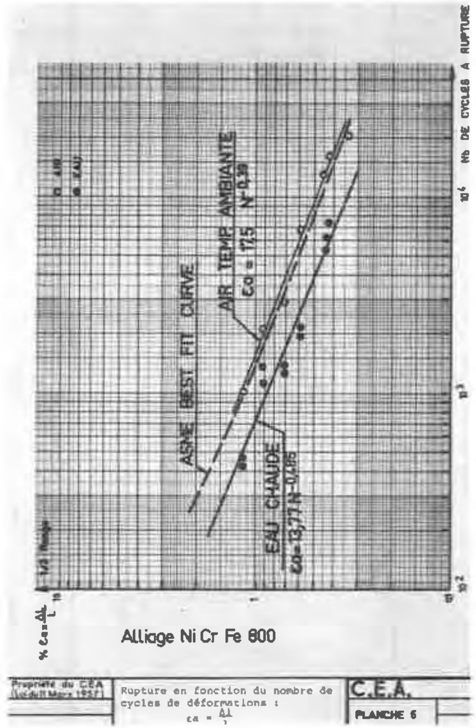

BANC PRIMEAU
SCHEMA
C.E.A.
PLANCHE 2
Propriété du CEA
(Loi du 11 Mars 1957)

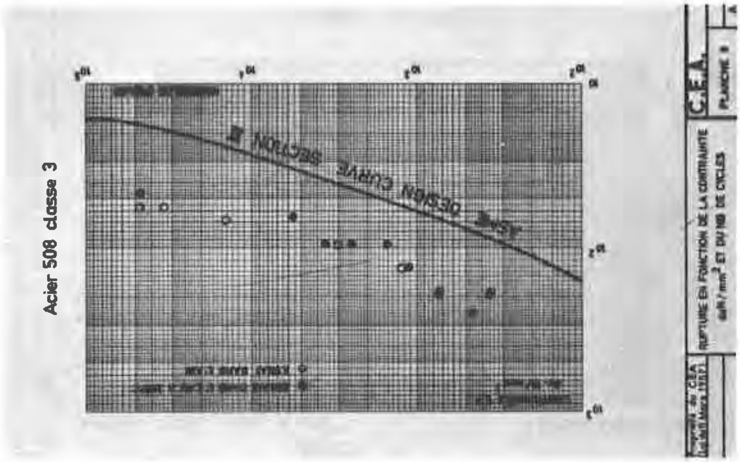

Déplacement de l'éprouvette
Eprouvette
Pions mobiles
Pions fixes
Positionnement des éprouvettes
entre les pions fixes et mobiles
C.E.A.
PLANCHE 1
Propriété du CEA
(Loi du 11 Mars 1957)

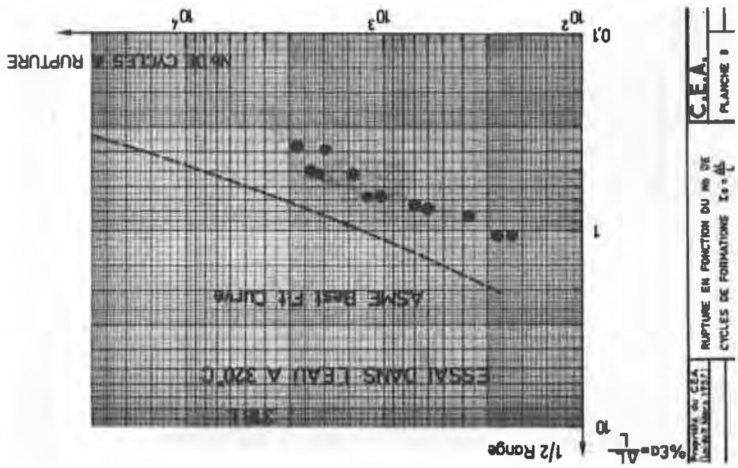

Temps en mm
Course ± 1 mm
1mm
Forme du cycle de flexion
C.E.A.
PLANCHE 3
Propriété du CEA
(Loi du 11 Mars 1957)

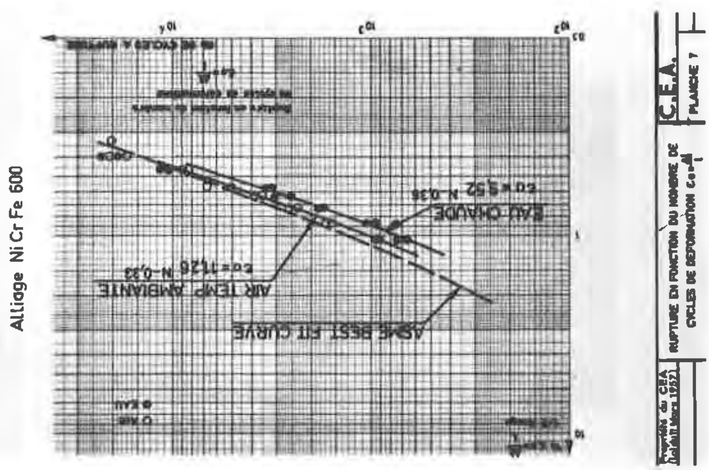

Propriété du C.E.A.
ESSAI A L'AIR AMBIANT
C.E.A.
PLANCHE 4

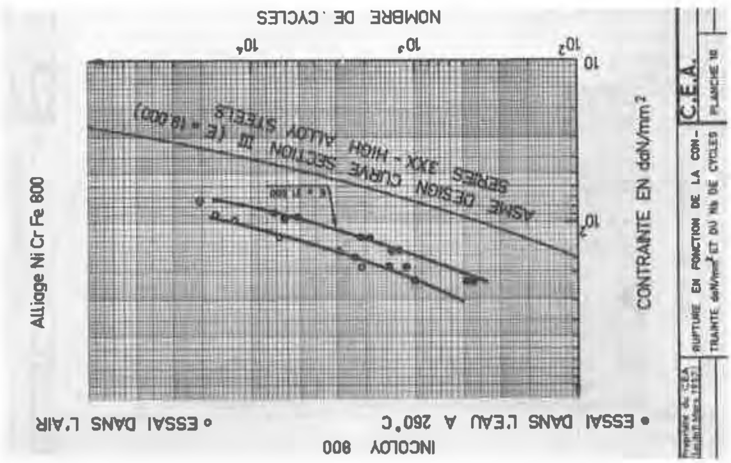

ACIER 50E
ASME BEST FIT CURVE
NOMBRE DE CYCLES A RUPTURE "N"
AMPLITUDE DE DEFORMATION $\varepsilon_A = \frac{\Delta l}{l}$
2%
1%
0,5%
0,2%
300
500
1000
2000
5000
10000
20000
50000
Propriété du C.E.A.
Rupture f. nb cycle de déformations
$\varepsilon a = \frac{\Delta l}{l}$
C.E.A.
PLANCHE 5
A

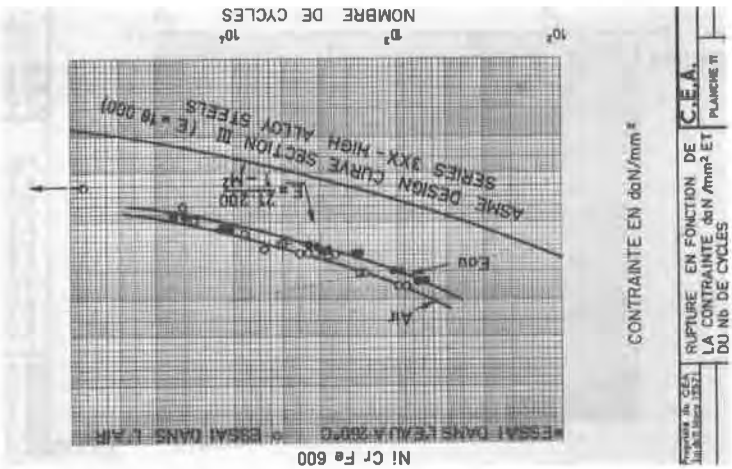

ASME BEST FIT CURVE
AIR TEMP. AMBIANTE
EAU CHAUDE
$\varepsilon o = 13,77\ N^{-0,685}$
o AIR
● EAU
Nb DE CYCLES A RUPTURE
10^2
10^3
10^4
Alliage Ni Cr Fe 800
Propriété du C.E.A.
Rupture en fonction du nombre de cycles de déformations :
C.E.A.
PLANCHE 6

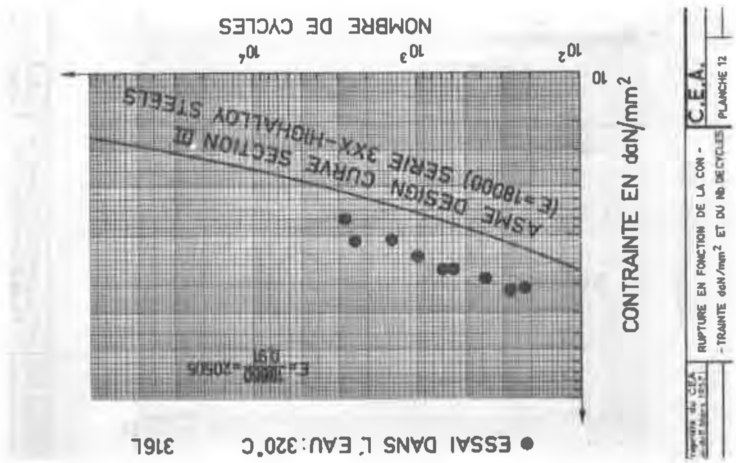

Acier 508 classe 3
ASME DESIGN CURVE SECTION III
Propriété du C.E.A. Loi du 11 Mars 1957
RUPTURE EN FONCTION DE LA CONTRAINTE daN/mm² ET DU NB DE CYCLES
C.E.A.
PLANCHE 9


NB DE CYCLES A RUPTURE
ASME Best Fit Curve
ESSAI DANS L'EAU A 320°C
1/2 Range
Propriété du C.E.A. Loi du 11 Mars 1957
RUPTURE EN FONCTION DU NB DE CYCLES DE DEFORMATIONS
C.E.A.
PLANCHE 8


Alliage Ni Cr Fe 600
EAU CHAUDE
AIR TEMP. AMBIANTE
ASME BEST FIT CURVE
Propriété du C.E.A. Loi du 11 Mars 1957
RUPTURE EN FONCTION DU NOMBRE DE CYCLES DE DEFORMATION
C.E.A.
PLANCHE 7


Alliage Ni Cr Fe 800
INCOLOY 800
• ESSAI DANS L'EAU A 260°C
∘ ESSAI DANS L'AIR
ASME DESIGN CURVE SECTION III SERIES 3XX - HIGH ALLOY STEELS (E = 18 000)
NOMBRE DE CYCLES
CONTRAINTE EN daN/mm²
C.E.A.
RUPTURE EN FONCTION DE LA CONTRAINTE daN/mm² ET DU Nb DE CYCLES
PLANCHE 10


Ni Cr Fe 600
• ESSAI DANS L'EAU A 260°C
∘ ESSAI DANS L'AIR
ASME DESIGN CURVE SECTION III SERIES 3XX - HIGH ALLOY STEELS (E = 18 000)
Eau
Air
NOMBRE DE CYCLES
CONTRAINTE EN daN/mm²
C.E.A.
RUPTURE EN FONCTION DE LA CONTRAINTE daN/mm² ET DU Nb DE CYCLES
PLANCHE 11


316L
• ESSAI DANS L'EAU : 320°C
ASME DESIGN CURVE SECTION III SERIE 3XX-HIGHALLOY STEELS (E=18000)
NOMBRE DE CYCLES
CONTRAINTE EN daN/mm²
C.E.A.
RUPTURE EN FONCTION DE LA CONTRAINTE daN/mm² ET DU Nb DE CYCLES
PLANCHE 12