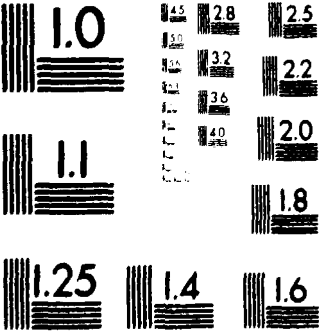

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ENEA
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A THERMO-MECHANICAL BENCHMARK CALCULATION OF AN HEXAGONAL CAN IN THE BTI ACCIDENT WITH INCA CODE

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RT/TIB/88/4

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Progetto Enea: Sistema progettazione nocciolo (VW)

This work has been performed in the frame of the international agreement AGT4 (W.P.3) and the results are published both as "Note Technique CEA" and as "Rapporto Tecnico ENEA".

Summary : The thermomechanical behaviour of an hexagonal can in a benchmark problem (simulating the conditions of a BTI accident in a fuel assembly) is examined by means of the INCA code and the results systematically compared with those of ADINA.

INDEX

1. INTRODUCTION

The safety analysis of a fuel assembly, undergoing a BTI accident in a RNR, requires the knowledge of the mechanical behaviour of its hexagonal can under internal temperature and pressure gradients.

The problem is quite complicated because beside the plastic deformation due to thermal and pressure loads we have to face the partial melting of the can itself.

In the frame of these studies a mechanical benchmark problem has been created, starting from realistic SPX1 data, with two main goals :

- to qualify different available codes by reciprocal comparison ;
- to get some preliminary indications about the mechanical behaviour of the structure.

The present work is an analysis of this benchmark performed by means of the structural code INCA and a comparison of the results with those of the ADINA code.

2. BENCHMARK

The geometry of the problem is shown in Figure 2 : 1/12 of the cross section of an hexagonal pipe is discretized by 3 x 15 quadrilateral isoparametric parabolic elements. The loads are :

- a non-uniform temperature distribution across the section ;

- a pressure applied on the inner face.

The temperature distribution is given by a thermal analysis of the same structure with DELFINE in the conditions specified by a previous thermal benchmark [1].

The pressure load varies with time according to Figure 1.

The material properties are :

- Young's modulus (GPa) : $E = 194 - 0.0814*T$ $T \leq 700°C$
  $E = 277.02 - 0.2*T$ $T \geq 700°C$

- Poisson's coefficient : $\nu = 0.3$

- Yield stress (MPa) : $\sigma_e = 702 - 0.545*T$

- Hardening modulus : (M in Table 1)

- Thermal expansion $(°C)^{-1}$: $\alpha = (16750 + 2.76*T)\ 10^{-9}$

- Ultimate yield stress (MPa) : $\sigma_u = 879 - 0.628*T$

- Ultimate yield strain (plastic) :

$$\varepsilon_u = \exp\left|-5.36 + \frac{933}{T+273}\right| + \exp\left|7.87 - \frac{15559}{T+273}\right|$$

Beside the benchmark assumes the following hypothesis :

- plane strain
- Von Mise's yield criteria
- isotropic hardening

TABLE 1

Material properties

T (°C)	E (GPa)	σ_e (MPa)	M (MPa)	α $(10^{6}\,°C)^{-1}$
400	161.44	484.0	7301	17.85
500	153.30	429.5	8160	18.13
600	145.16	375.0	8706	18.41
700	137.02	320.5	8855	18.68
800	117.02	266.0	8207	18.96
900	97.02	211.5	6394	19.23
1000	77.02	157.0	3941	19.51
1100	57.02	102.5	2037	19.79
1200	37.02	48.0	986	20.06
1300	17.02	0	477	20.34
≥ 1385 (*)	0	0	0	20.57

(*) melting temperature

TABLE 2

INCA assumptions

T (°C)	E (GPa)	σ_e (MPa)	M (MPa)	α $(10^{6}\,°C)^{-1}$
≥ 1250°C	27.02	24.5	731.5	20.20

TABLE 3

ADINA assumptions

T (°C)	E (GPa)	σ_e (MPa)	M (MPa)	α $(10^{6}\,°C)^{-1}$
1300	17.02	1.0	477	20.34
13[illegible]0	7.02	1.0	330	20.48
13[illegible]5	0.02	1.0	19	20.57
> 1385	0.02	1.0	19	0

3. CALCULATIONS

Several tests have been performed with the INCA code, but with the material properties described in the previous paragraph (elastic modulus and yield stress going to zero for temperatures approaching the melting point) the benchmark calculation does not converge any more at $t = 21 + 21.1$ s for numerical problems, still far from can failure. This happens indipendently of :

1) pressure application
2) number of Gauss points (2/3)
3) time step (0.01/1.0 s)
4) convergence criteria ($10^{-2}/10^{-3}$)
5) displacement hypothesis (small/large)

We can remark also that previous parameters have no effect also on the displacements up to $t = 21$ s. A different mesh of 12 x 15 triangular linear elements (TRI3) for 112 nodes (Figure 3) has been used in an other calculation, but again it does not converge at $t = 21$ s.

In this case we get slight smaller displacement (- 6 % at $t = 21$ s) of the center of the face (points A and B in Figure 2) : this reduction can be explained with the greater stiffness of the structure due to the reduced number (16 instead of 31) of nodes in the x-direction.

In order to continue the calculation with INCA after 21 s up to a physical non-convergence (collapse of the structure) an approximation had to be introduced :

- material properties above 1250°C (even above melting point) are assumed not to change any more (see Table 2).

This has been easily carried out modifying the nodal temperatures on the input file from DELFINE : any temperature above 1250° has been set to 1250°C.

It is obvious that in this way we assume a material stiffness greater than the actual one and we can therefore expect a slight under estimation of displacements and strains.

The above assumption has been justified "a posteriori" by the very good agreement with the results obtained in the same benchmark by he ADINA code [2] and can be explained as follow :

- The approximation of the material properties is carried out only in the region at highest temperature whose importance for the structural stiffness is any way small due to the low yield limit.

The ADINA assumptions for material properties near melting point are shown in Table 3 [2].

The reference INCA calculation (Fig.18) has been executed in the following conditions :

. 2 x 2 gaussian integration points
. small displacement hypothesis
. time step : 1.0 s up to 21 s, 0.2 s after.

In the last time step the convergence is very slow and the calculation stops after 80 iterations when the convergence parameter (~ 3 %) is still above the desired value (1 %).

Therefore the last INCA point (t = 24.6 s) in the time graphs, which will be presented in the next paragraph, is not completely reliable.

4. RESULTS

The results of the INCA calculation in the center and in the corner (points A through D in Fig. 2) are presented as time plots of the required variables (Figure 4-16) and they are systematically compared with those of the ADINA code [2]. Sometimes the behaviour of the point E has been added because of its importance in failure, but corresponding ADINA results were not available in [2].

The input nodal temperature distributions for INCA and ADINA are in apparent perfect agreement (Figure 4-5), with the exception of the region above 1250°C, where the INCA value has been kept constant according to the assumption described in the previous paragraph.

The most important result in this benchmark is the nodal displacement in the y-direction : the application of the internal pressure after 21 s determines a large non linear displacement at the center of the section (Figure 6-8) which drives the structure to failure.

The equivalent stress, after having reached the elastic limit, decrease due to the reduction of the yield limit with the increasing temperature (Figure 9-10) : on the inner face, as the material approaches the melting point, the equivalent stress should go to zero.

We can remark here that the ADINA equivalent stresses and plastic strains have some anomalous behaviour just before structure collapse : the former at 25 s are above the yield stress corresponding to the plastic strain and temperature in the corner (Figure 10) while the latter at 23 s shows an unusual decrease on the inner face (Figure 11).

The largest plastic strain (Figures 11-12) is reached in the inner face of the corner (~ 10 %), when the material is already molten.

Because the main question in the physical problem behind this benchmark concerns the point where structure could fail with rising internal pressure, it is of great interest to compare actual equivalent strains and stresses with their ultimate values at rupture in tensile tests (Figures 13-16).

We recall that in the INCA calculation the actual temperature distribution T has been modified as follows :

$$T^* = \min \{T, T_{max}\}, \quad T_{max} = 1250°C$$

and that the limit values are function of the nodal temperature.

T* has then been chosen for the evaluation of the ultimate stress, while T has been prefered for the strain.

The limit ratios has not been calculated any way for T above the melting point (1385°C).

According to the strain ratio (Figures 13-14) the critical points, that is nodes where we can expect the material to fail being its equivalent strain near the ultimate value, are the nodes A and E of the structure, the first in the center of the side, the other near the corner, both on the outer face of the can. That is confirmed also by the stress ratios (Figures 15-16).

The ADINA results for the point D (Figure 16) is not reliable : as we already remarked above, the stress in that node is not consistent with the yield stress, and in the same way the stress ratio is inconsistent with the strain ratio (Figure 14).

The main difference between the behaviour of nodes A and E concerns the stress in the x-direction : the center is always in traction, while the area near the corner initially in traction becomes compressed later. At failure all normal stresses are of traction in A, of compression in E.

The sensitivity of the results to the approximation introduced in the INCA calculation has been checked by performing a new calculation where the maximum temperature allowed (T_{max}) is 1260°C instead of 1250°C. That means basically a reduction of about 20 % (from 24.5 to 19.8 MPa) of the yield stress in the region near melting point ($T > T_{max}$).

The calculation stops for numerical non-convergence at 22.4 s : it show's only a slightly steeper behaviour of the non linear part of the central displacement (Figure 17), due, as obvious, to the more plastic material.

On the contrary a more general calculation, where the large displacements are correctly taken into account, has the opposite result to stiffen the structure, without effecting the convergence (Figure 17). Due to the rapidly increasing pressure the main effect is anyway just to delay the collapse of few tenths of second.

5. CONCLUSIONS

The INCA calculations has been made possible, overcoming the convergence problems, only with a restrictive hypothesis on the materials properties above 1250°C.

The resulting nodal displacements of the hexagonal cross-section are linear up to the application of the pressure (t = 21 s), when they start growing very rapidly in the center of the faces, carrying the structure to collapse at about 24.6 s.

The material reaches its failure limit in two points on the outside : in the middle of the face, where the main stress is a longitudinal traction, and near the corner due to a longitudinal compression.

The INCA results are in very good agreement with those of the ADINA code [2], specially as far as the nodal displacements are concerned.

This justifies "a posteriori" the above approximation in the benchmark problem : the extrapolation of this result to different condition would require any way a deeper sensitivity, which could be obtained for example with a parametric study of the problem.

As far as rupture of the can is concerned, it would be necessary at this stage some significant experimental support before it could be possible to draw any reasonable conclusion.

FIGURES

FIG. 1

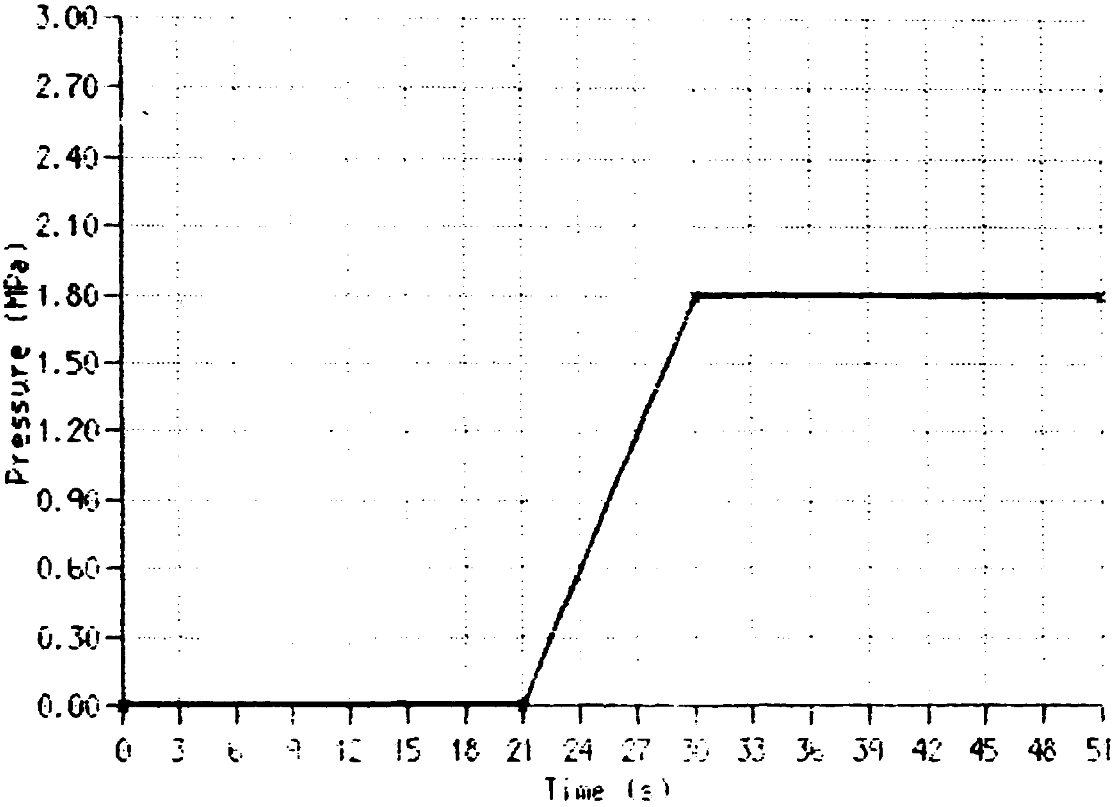

3.00
2.70
2.40
2.10
1.80
1.50
1.20
0.90
0.60
0.30
0.00
Pressure (MPa)
0
3
6
9
12
15
18
21
24
27
30
33
36
39
42
45
48
51
Time (s)

FIG. 2

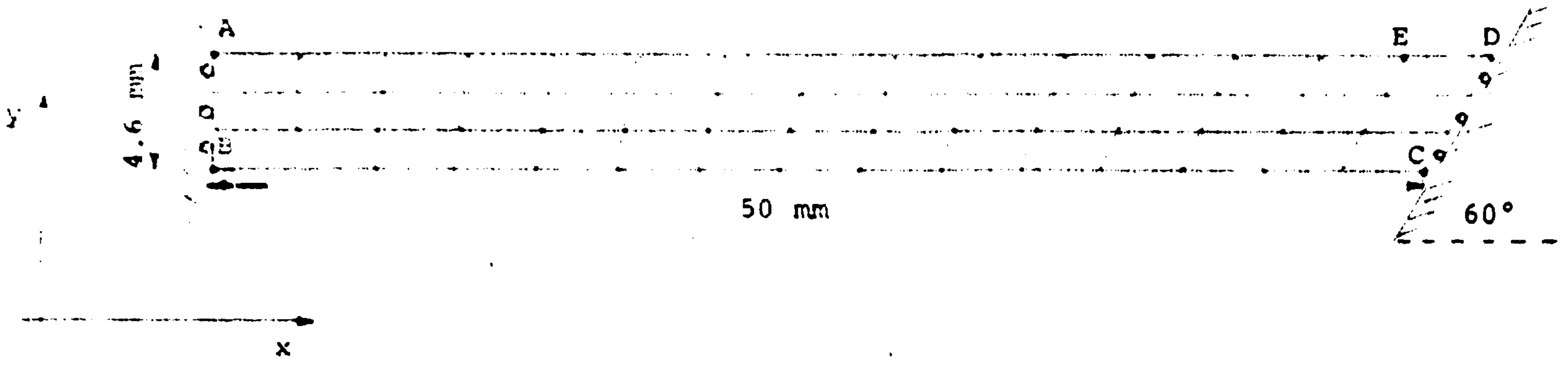


FIG. 3

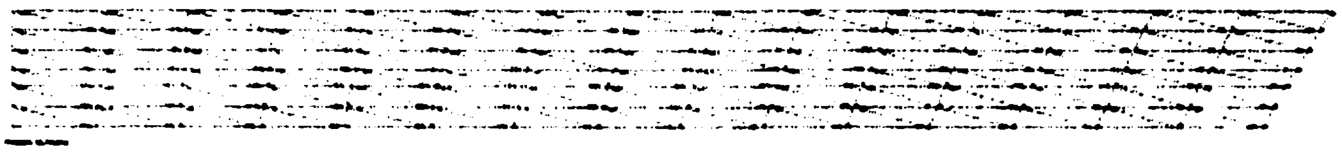


FIG. 4

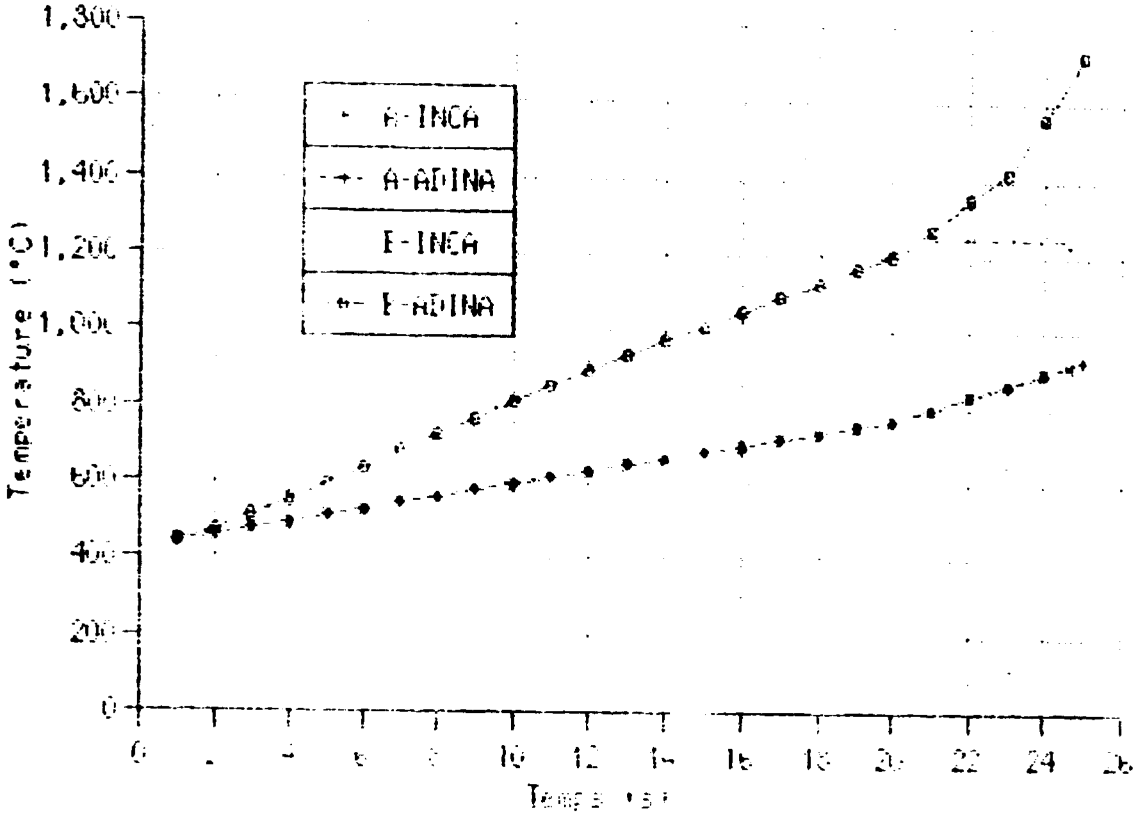

1,800
1,600
1,400
1,200
1,000
800
600
400
200
0
Temperature (°C)
A-INCA
A-ADINA
B-INCA
B-ADINA
0
2
4
6
8
10
12
14
16
18
20
22
24
26
Temps (s)

FIG. 5

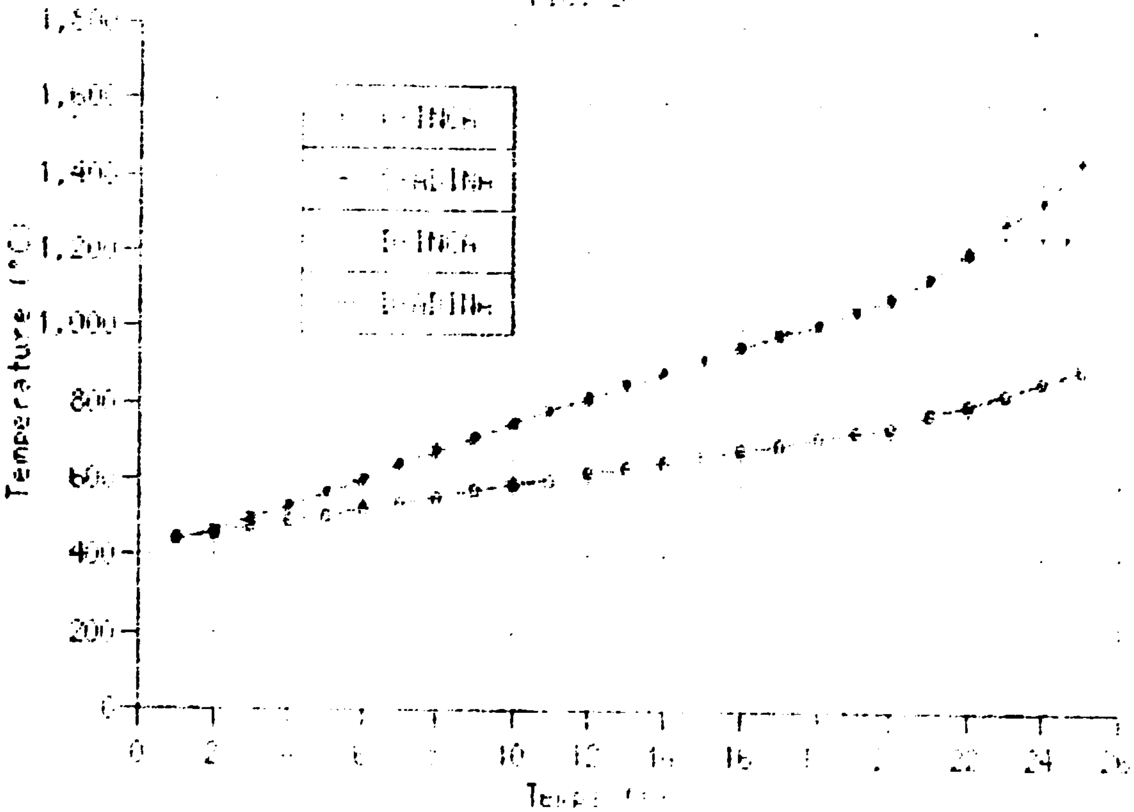

1,800
1,600
1,400
1,200
1,000
800
600
400
200
0
Temperature (°C)
A-INCA
A-ADINA
B-INCA
B-ADINA
0
2
4
6
8
10
12
14
16
18
20
22
24
26
Temps (s)

FIG. 6

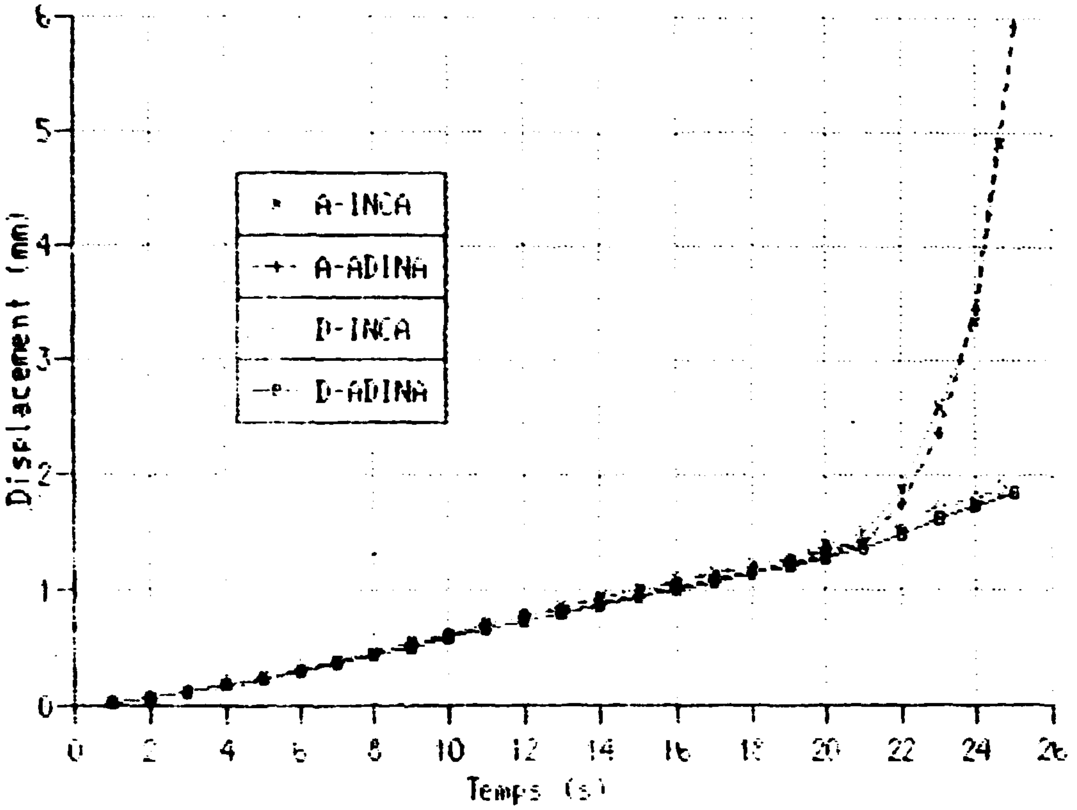

A-INCA
A-ADINA
D-INCA
D-ADINA
Displacement (mm)
Temps (s)
0
1
2
3
4
5
6
0
2
4
6
8
10
12
14
16
18
20
22
24
26

FIG. 7

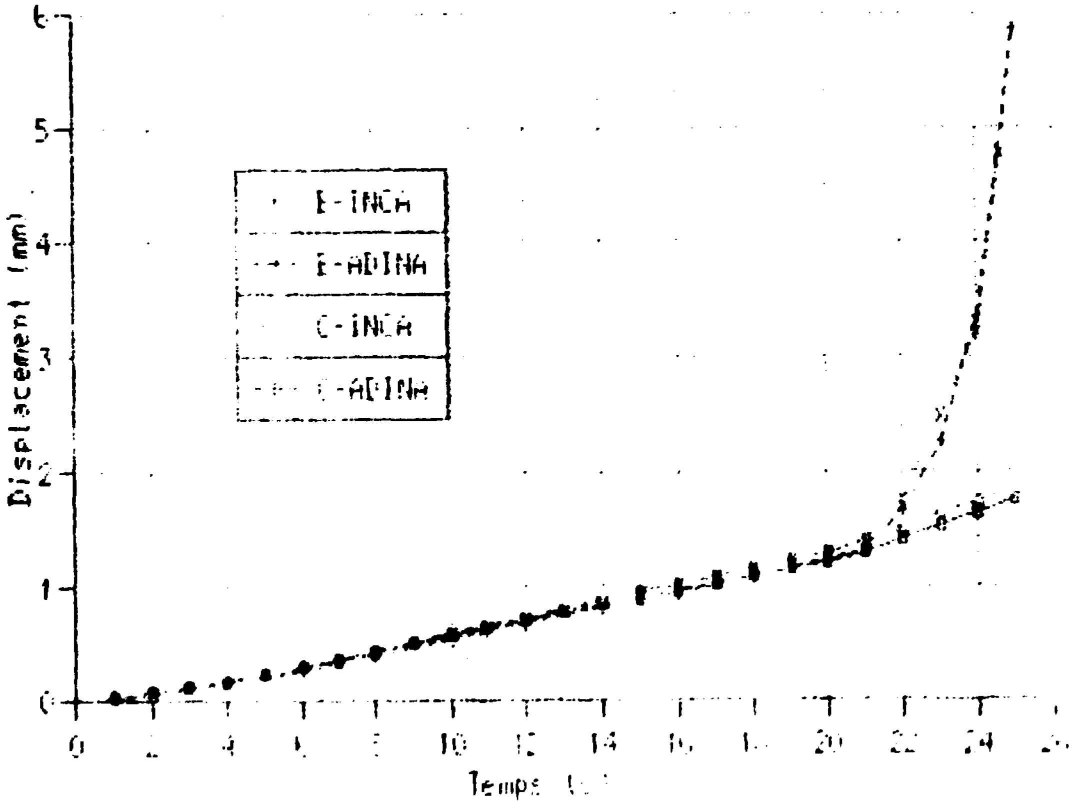
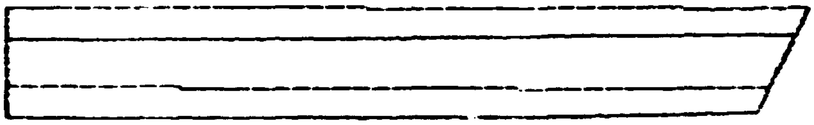
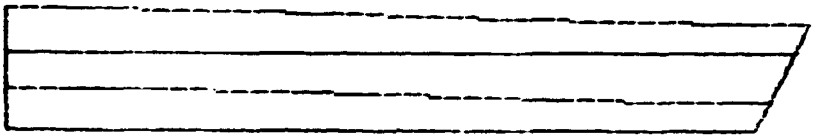

E-INCA
E-ADINA
C-INCA
C-ADINA
Displacement (mm)
Temps
0
1
2
3
4
5
6
0
2
4
6
8
10
12
14
16
18
20
22
24
26

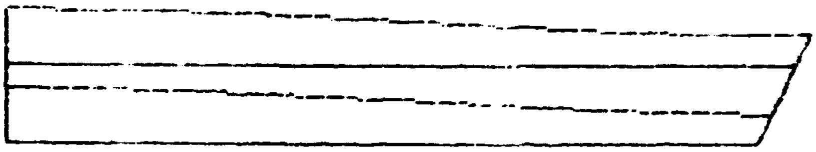
FIG. 8



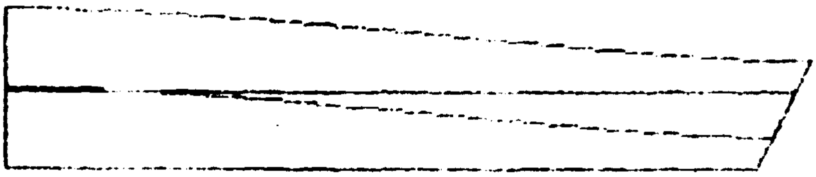
t=22s



t=23s



t=24s



t=24.6s

FIG. 9

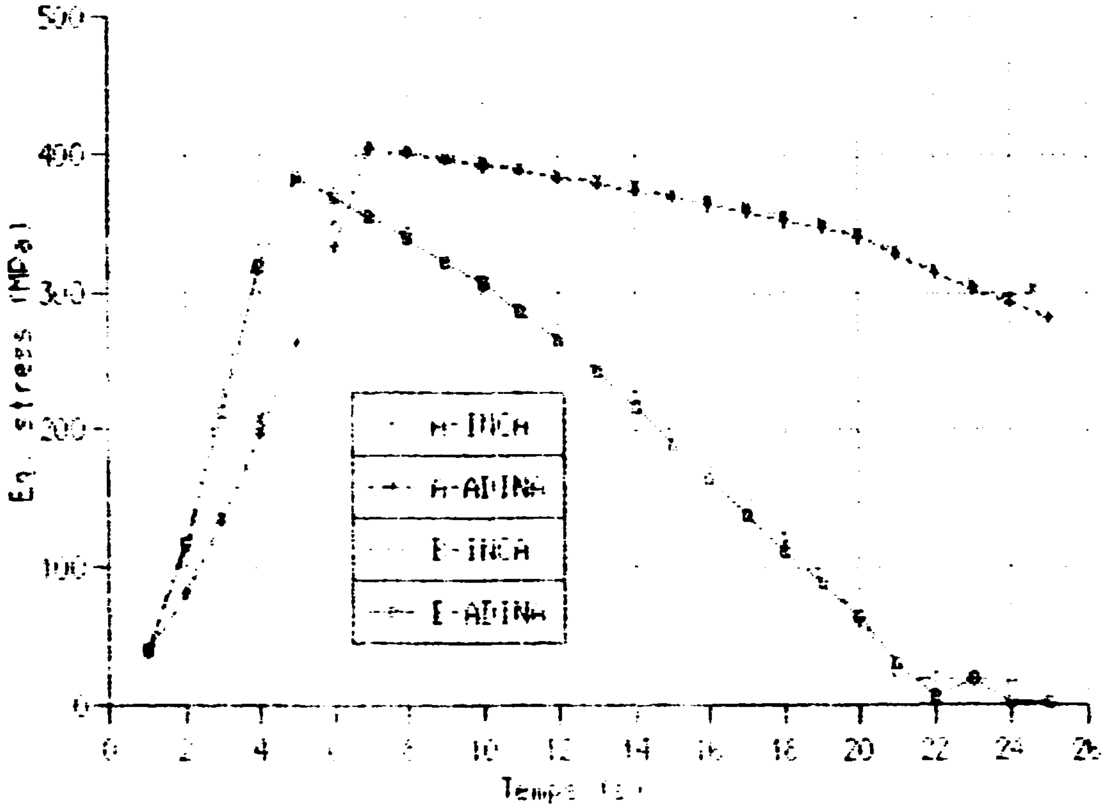

500
400
300
200
100
0
Eq. stress (MPa)
0
2
4
6
8
10
12
14
16
18
20
22
24
26
Temp. (°C)
A-INCA
A-ADINA
B-INCA
B-ADINA

FIG. 10

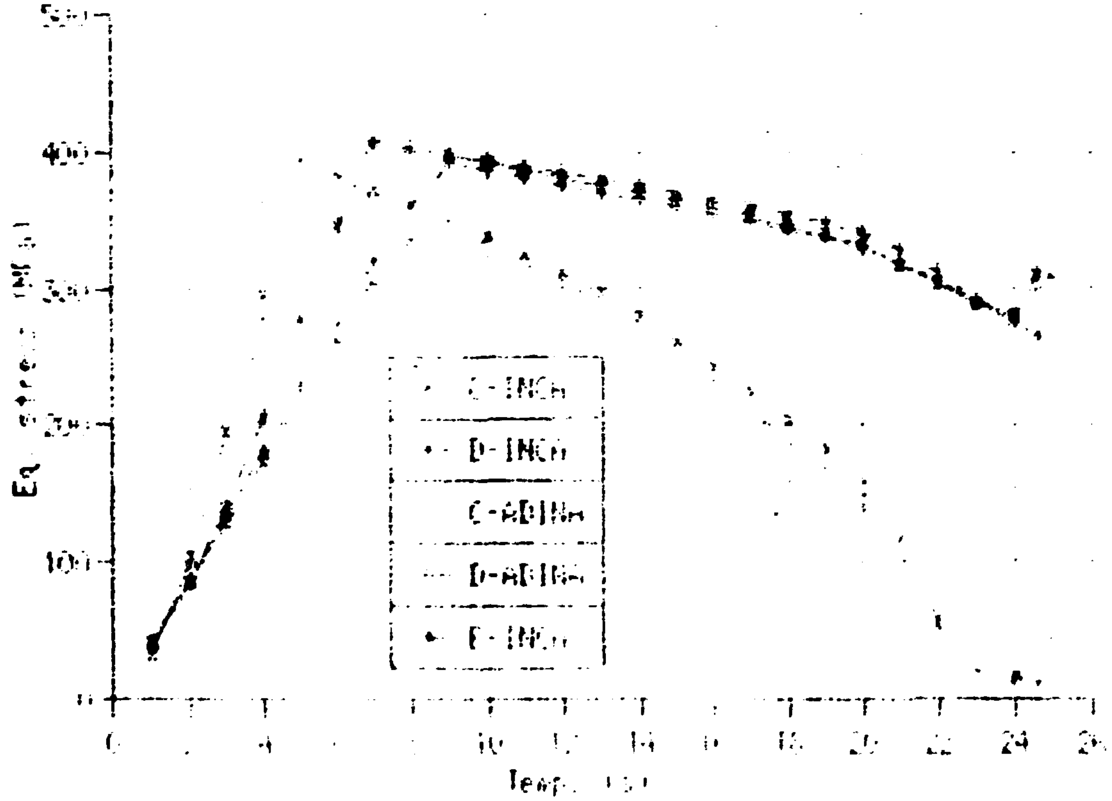

500
400
300
200
100
0
Eq. stress (MPa)
0
2
4
6
8
10
12
14
16
18
20
22
24
26
Temp. (°C)
C-INCA
D-INCA
C-ADINA
D-ADINA
E-INCA

FIG.11

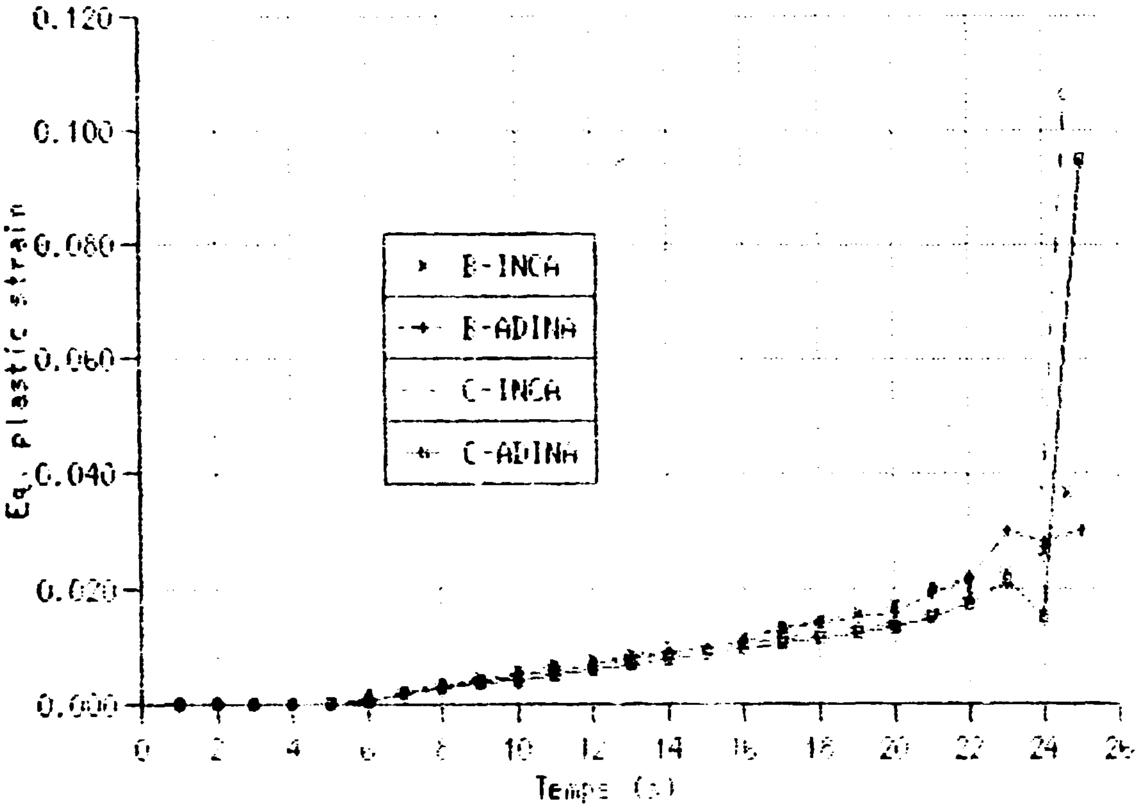

0.120
0.100
0.080
0.060
0.040
0.020
0.000
Eq. plastic strain
B-INCA
B-ADINA
C-INCA
C-ADINA
0
2
4
6
8
10
12
14
16
18
20
22
24
26
Temps (s)

FIG.12

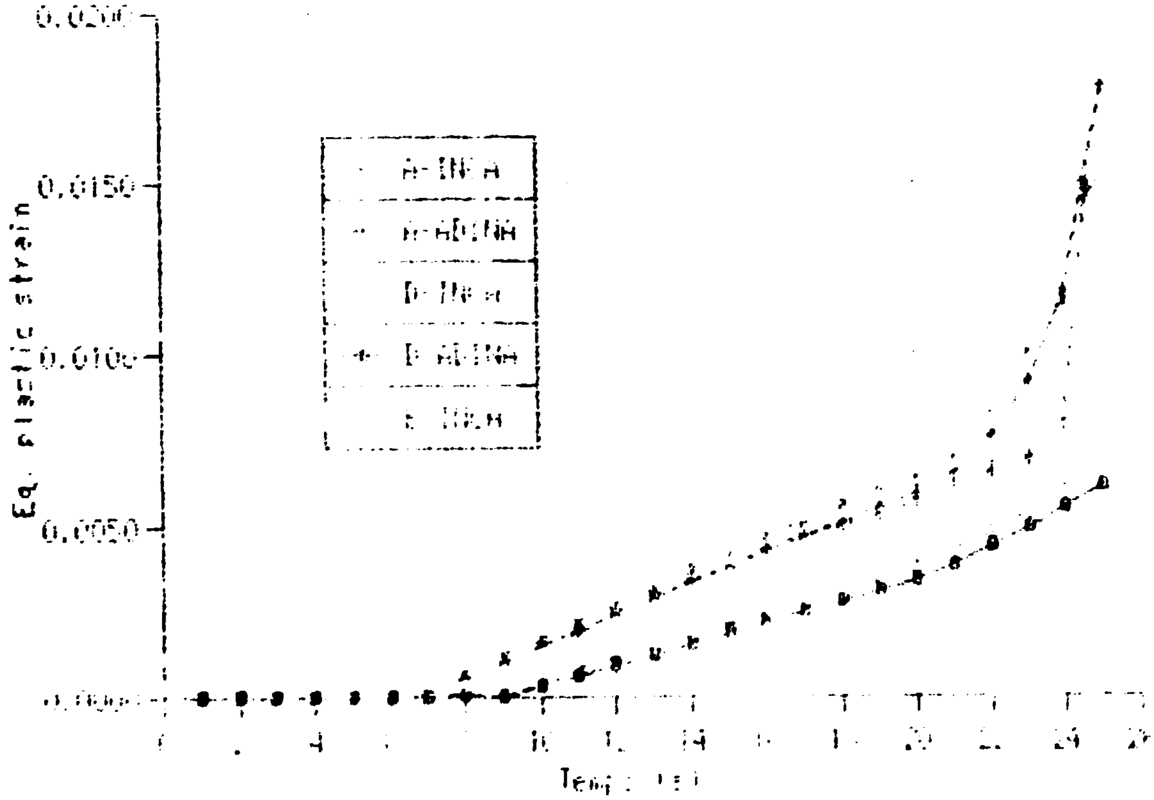

0.0200
0.0150
0.0100
0.0050
0.0000
Eq. plastic strain
A-INCA
A-ADINA
D-INCA
D-ADINA
E-INCA
0
2
4
6
10
12
14
16
18
20
22
24
26
Temps (s)

FIG.13

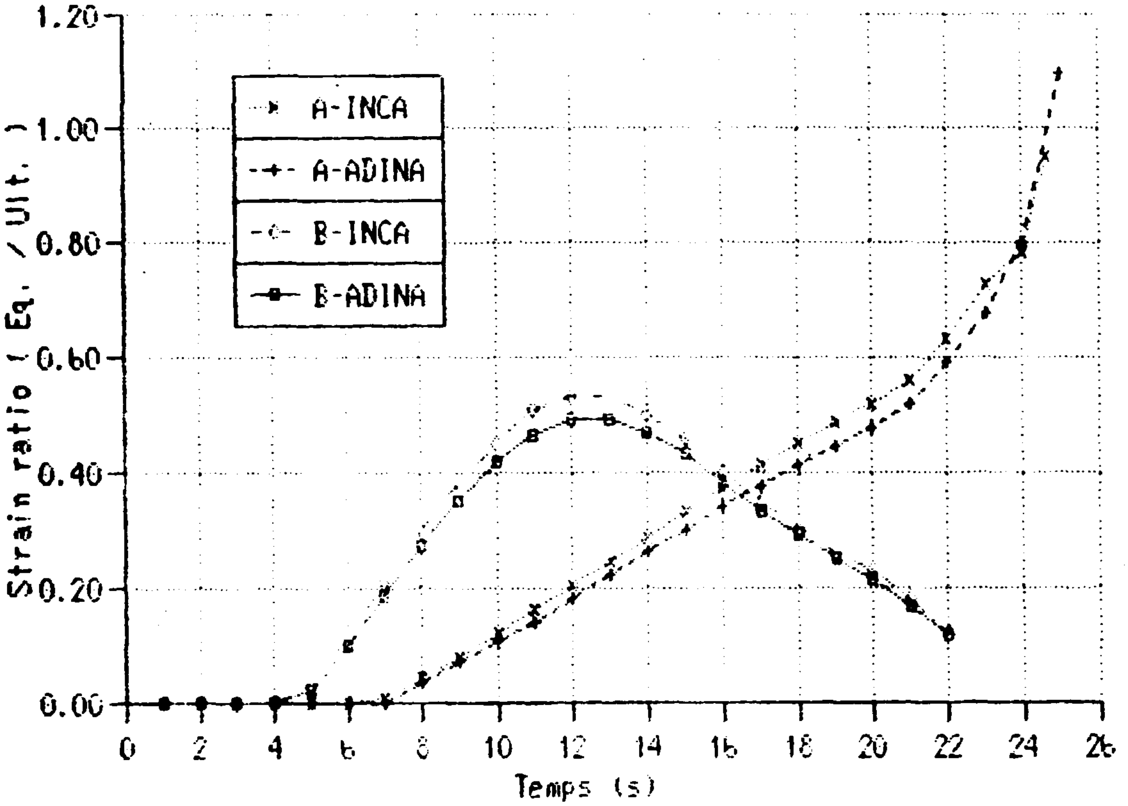

1.20
1.00
0.80
0.60
0.40
0.20
0.00
Strain ratio (Eq. / Ult.)
A-INCA
A-ADINA
B-INCA
B-ADINA
0
2
4
6
8
10
12
14
16
18
20
22
24
26
Temps (s)

FIG.14

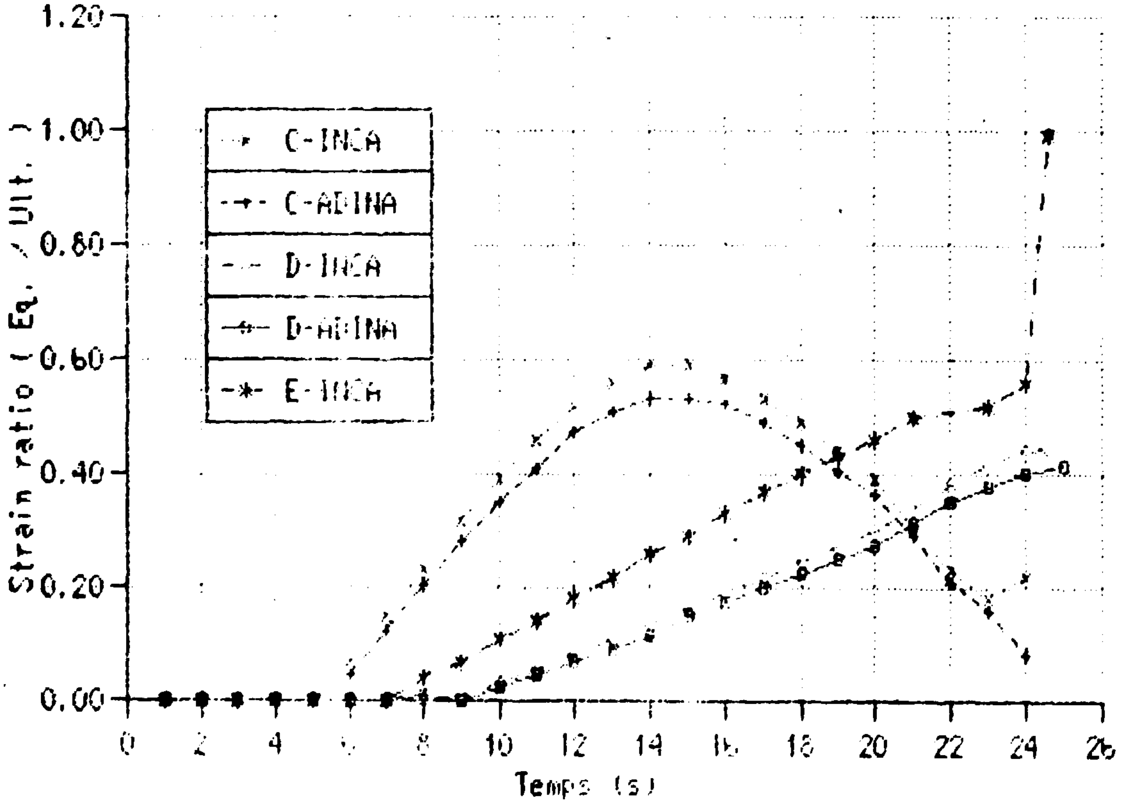

1.20
1.00
0.80
0.60
0.40
0.20
0.00
Strain ratio (Eq. / Ult.)
C-INCA
C-ADINA
D-INCA
D-ADINA
E-INCA
0
2
4
6
8
10
12
14
16
18
20
22
24
26
Temps (s)

FIG.15

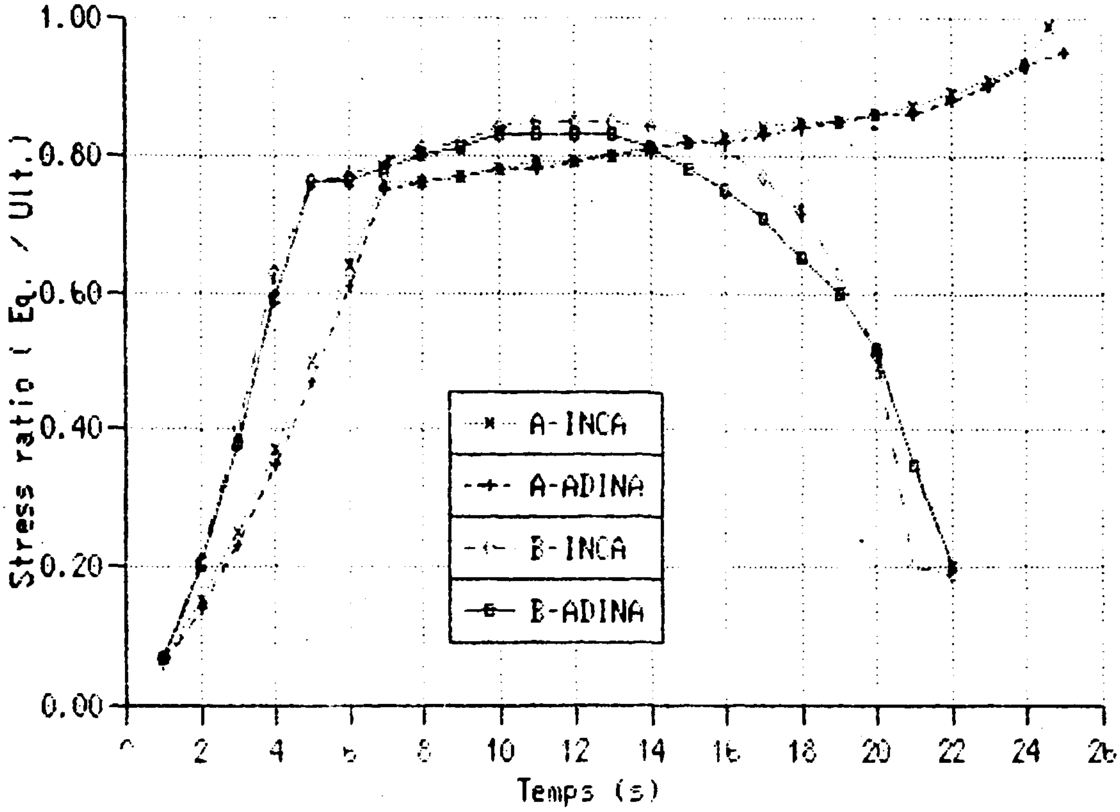

1.00
0.80
0.60
0.40
0.20
0.00
Stress ratio (Eq. / Ult.)
0
2
4
6
8
10
12
14
16
18
20
22
24
26
Temps (s)
A-INCA
A-ADINA
B-INCA
B-ADINA

FIG.16

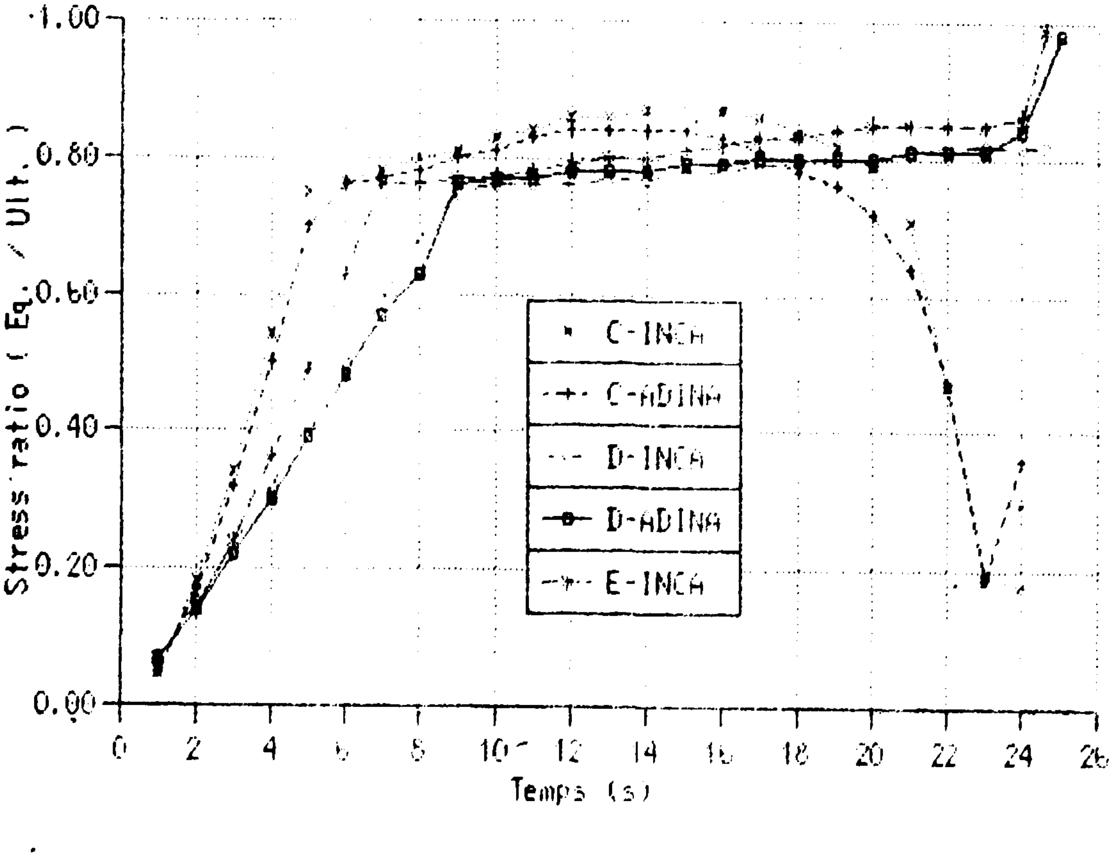

1.00
0.80
0.60
0.40
0.20
0.00
Stress ratio (Eq. / Ult.)
0
2
4
6
8
10
12
14
16
18
20
22
24
26
Temps (s)
C-INCA
C-ADINA
D-INCA
D-ADINA
E-INCA

FIG.17

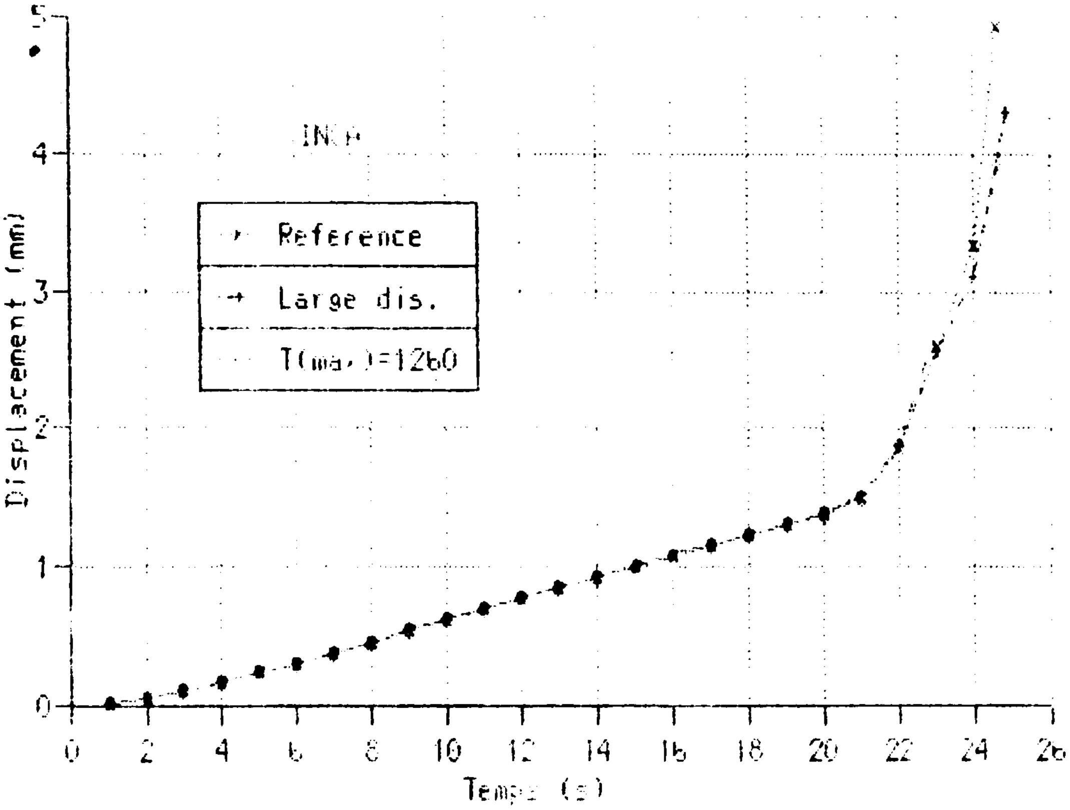

INCA
Reference
Large dis.
T(max)=1260
Displacement (mm)
0
1
2
3
4
5
Temps (s)
0
2
4
6
8
10
12
14
16
18
20
22
24
26

FIG. 18

```
* CONS 41  SUITE PAS 20
*  TAILLE EQUA 1600 MATRI 20000 DISQUE 1
*  PLAN DEFO
*  GEOMETRIE  POINTS 172  Q8 45
*  MATE 1 COEF YOUNG INTE 3 ALPHA 2 PLASTIQUE 1
*  ECRI DONN CONT 5 PAS 100 ITER 5 INCO 5
*  NONLINEAIRE  PLAS TABLE 2 5 COURBE RESEAU 12 5 THERMIQUE 4 VAYU
*  LONG 3400 ISOTROPE
*  FORCE TEMPERATURE
*  TRAC ALICE 10 EPSP TEMPE
*FIN
*  ACCIDENT D'ASSEMBLAGE BENCH3   :   TEST ZC
*  GEOMETRIE 30 ZONE 1 Q8 45
*  MATERIAU
*                 1 NU 0.3 VARIABLE  REFE 430.
*YOUNG INTE 3   0 19400   700 13702   1385 2
*                ALPHA 2 16.75E-6  2.76E-9
*                PLASTIQUE COURBE
*                TRACTI 1
*TEMP  0.40000E+03
*  0.4840E+02 0.300E-02 1.0310E+02 0.0780   157.9    0.1530
*TEMP  0.50000E+03
*  0.4295E+02 0.280E-02 1.0420E+02 0.0778   165.4    0.1528
*TEMP  0.60000E+03
*  0.3750E+02 0.258E-02 1.0280E+02 0.0776   168.1    0.1526
*TEMP  0.70000E+03
*  0.3205E+02 0.234E-02 0.9850E+02 0.0773   164.9    0.1523
*TEMP  0.80000E+03
*  0.2660E+02 0.227E-02 0.8820E+02 0.0773   149.7    0.1523
*TEMP  0.90000E+03
*  0.2115E+02 0.218E-02 0.6910E+02 0.0772   117.1    0.1522
*TEMP  0.10000E+04
*  0.1570E+02 0.204E-02 0.4520E+02 0.0770    74.8    0.1520
*TEMP  0.11000E+04
*  0.1025E+02 0.180E-02 0.2560E+02 0.0768    40.9    0.1518
*TEMP  0.12000E+04
*  0.4800E+01 0.130E-02 0.1220E+02 0.0763    19.6    0.1513
*TEMP  0.13000E+04
*  0.1000E+00 0.006E-02 0.0367E+02 0.0751     7.25   0.1501
*TEMP  0.13500E+04
*  0.1000E+00 0.014E-02 0.0257E+02 0.0751     5.05   0.1501
*TEMP  0.13850E+04
*  0.1000E+00 5.000E-02 0.0024E+02 0.1250     0.38   0.2000
*        TERM  LECT 1 PAS 1 45 TERM
* RELATION,    2  LECT 2 3 5 6 8 9 10  TERM EGAL
*        1.732  1  LECT 2 3 5 6 8 9 10  TERM
*  CHARGEMENT COMP 1 TEMP REFE 430. BANDE DELFINE 32  30
*                COMP 2 PRESS REPAR 1.E-2 1 LECT 1 PAS 1 15 TERM
*  RIGI
*  EDIT ELEM 1 16 31 INCO 149 171
*  DEPLACEMENT COMP 1
*                 0. 1  LECT  148 147 161 160 166 165 171 TERM
*   TABLE 1  1.       21.   1.      30   1.      TERM
*          2  0.      21.   0.      30   18      TERM
*   ITER MAXI 80 ACCE 15 TAUM 0.98 TEST 0.01
*   RESO TEMP  0  PAS  1.0 21  TERM  ECRI  -10 -20 TERM
*         TEMP 21  PAS  0.2 25  TERM  ECRI -5 PAS -5 -20 TERM
*FIN
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