Magnet Near End Failure Analyses

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Introduction

It has been the objective of CDG to capture the structural/thermal behavior of the magnet under all conditions including assembly and operation. To fully meet the objective requires a 3-D analysis which is not yet complete. A 2-D analysis has been completed. Recent tests of the long magnet showed that excessive training was required, and the origin of these quenches was attributed to the ends of the coils, particularly the early quenches. In order to shed light on the conditions of the coil as a result of assembly loads with an uncertainty in dimensional control of end components, a 2-D representation has been attempted. As there are no definitive design criteria being met at the ends of the coil, the 2-D calculation described below sets out to establish coil capability to withstand radial assembly pressure that can help to formulate structural design criteria in the future magnets.

Model

The 2-D approximation near the tangent point of the coil consists of G-10 the wedges and replacement of the sections of the collar with G-10 material (see Fig. 1). A radial pressure p is applied to the outside surface of the outer coil and G-10; this differs from previous calculations where circumferential pressure or displacement was applied at the equatorial plane. The radial pressure p, is increased linearly. Slide lines separate the coil, wedges, and collar of the type that permits sliding with friction and separation. Friction values of .ϕ (perfect sliding plus separation), .3, and .3 everywhere except between the wedges and the coil which are bonded, differentiated the 3 sets of calculations reported herein. Using the post-processor (Orion) on the structural (NIKE)

results, principal stress, effective stress (von Mises' stress), maximum shearing stress and their respective strains, and displacements were obtained as a function of radial pressure for each set of conditions. It is assumed that the bond strength in the last set of calculations is as strong as that of the parent material. The bond is in fact most likely weaker than the interLaminar shear strength.

The mechanical properties of each material used were established. This included G-10 and the specific components used to make up the coil: niobium titanium wire, copper, kapton, and epoxy woven fiberglass. The structural failure criteria contained in the System Requirements were then applied to the material properties to quantitatively determine the failure levels. Once the failure criterion is obtained, the maximum radial pressure that can be sustained can be directly determined from the graphical results (given in the Appendix). The radial pressure is then the common denominator for which the maximum stress in the various components can be determined.

Results

The results are the maximum stress allowable without exceeding the System Requirements. The following describe basic terms used.

Failure Criterion: Failure criterion is the mode of failure by which inelastic or permanent deformation begins.

Principal Stress: There are two Principal Stresses — a max. and a min. usually designated σ_1 and σ_2 where $\sigma_1 > \sigma_2$. These are stresses one obtains on a plane which has been rotated such that there is no shear stress. Generally one obtains normal and shearing stresses and using Mohr's Circle or equivalent equations, obtains σ_1 and σ_2. The principal stress for the coil are σ_θ and σ_r, circumferential (hoop) and radial since this plane $\tau_{r\theta} = 0$. The hoop stress σ_θ is the min. principal stress since it is negative and greater then σ_r σ_r is max. principal stress and σ_θ is min. principal stress since a less negative value is greater — convention adopted by author of codes. σ_θ is the stress we wish to maximize to avoid separation due to energization. However, in all graphs it will appear as Minimum Principle Stress.

Principal stress criterion of failure: The principal stress reaches the yield of a material regardless of the normal or shearing stress that occurs on other planes.

$$\sigma_1(|\sigma_1| > |\sigma_2|) < \frac{2}{3}\sigma_e$$

where σ_e is the yield strength of a material and a material property and 2/3 is the System Requirement.

The Max. Shearing Stress Criterion says inelastic action begins only after the max. shearing stress reaches a value equal to max. shearing stress in a tension specimen when yielding starts.

$$\tau_{max} = \frac{1}{2}\left(\frac{\sigma_e}{N}\right) = \frac{1}{2}\frac{(\sigma_1 - \sigma_2)}{N}$$ (if $\frac{(\sigma_1 - \sigma_2)}{2}$ is shear strength , then for System Requirement N = 2).

The Max. Strain Criterion states that inelastic action begins when max. strain is equal to a value which occurs when inelastic action begins in a material in a tension test.

$$\varepsilon_{max} = \frac{\sigma_1}{E} - \frac{\mu\sigma_2}{E} - \frac{\mu\sigma_3}{E} \leq \frac{\sigma_e}{EN}$$

where μ Poisson Ratio and E modulus of elasticity.

The Energy of Distortion (also called the von Mises' or Effective Stress Criterion) says that inelastic action begins under any combination of stress only when the strain energy of distortion is equal to strain energy of distortion in a simple tensile test.

$$\bar{\sigma} = \frac{\sigma_e}{N} = [\sigma_1^2 + \sigma_2^2 - \sigma_1\sigma_2]^{1/2} = \frac{2}{3}\sigma_e$$

where $\frac{2}{3}$ is the System Requirement.

The weakest link and the controlling failure is the G-10 material based on low interLaminar shear stress capability or bond strength between components. Using the Maximum Shearing Stress Theory, the max. radial pressure that can be applied is 2500 psi. However, the data indicates that slippage first begins at 2000 psi radial pressure and can be observed under magnification on either the fringe plot for minimum principal stress (Fig. 2) or maximum displacement. What is in fact observed is the coil sliding past the G-10 wedge in the outer coil (see

Fig. 2). The maximum circumferential stress allowable under this condition is 1 kpsi in both Inner Coil (I.C.) and Outer Coil (O.C.) in the elements adjacent to the G-10 at the pole to counteract the affect of the Lorentz forces which means that the coil can be unloaded at very low values of current.

The Lorentz stress for 6.6 Tesla is approximately 15% lower at the tangent point (1.6 kpsi I.C. and 1.4 kpsi O.C. at the pole) then that of coil with Cu wedges and steel collar. This indicates that the system requirements for preload cannot be met . In the main body of the coil (Cu wedges, steel collar), the Kapton is the critical material and it allows –7 kpsi for the hoop stress for O.C. element at pole and 4 kpsi for I.C. element at pole which then presents no problems, since both exceed the Lorentz stress for 6.6 Tesla (–1.9, –1.7 kpsi for elements respectively). The effect of the longitudinal force was not being considered, and the uncertainty needs to be clarified and will be with a 3-D analysis. The results are summarized in Table I and Table II, with the more critical results in Table I.

Calculations were run as stated previously for f = .ϕ, f = .3, and f = .3 with bonded wedges. The critical case was for either f = .ϕ or f = .3 which produced the lowest failure criterion. The stresses for f = .ϕ and f = .3 for p < 4000 psi were indistinguishable. For p > 4000 psi with no friction, the output was smoother because of the absence of stick slip. For the case f = .3 bonded wedges, the stresses were slightly higher. The displacements were considerably higher for no friction than friction, since the absence of friction left the components free to slide.

Evaluating the graphical data, it appears that if a bond exists, the bond will most likely fail under a radial pressure of 4000 psi. However, if the bond strength is limited to strength of parent material, then it, more likely will fail at 2800 psi, since the Max. Shearing Stress with $\bar{\tau}$ = 3.5 results in a radial pressure of 2800 psi. If one considers failure in Kapton (using Max. Principal Stress) a pressure of 6000 psi is obtained (for the case where the wedges were bonded and friction elsewhere is .3). Therefore 2800 psi radial pressure is the critical failure and is the basis for the values in the chart in Table II. The results in Table I are more severe than the results in Table II.

TABLE I. SUMMARY OF FAILURE RESULTS
f = .3

M. Zaslawsky 9/15/87

R.T. f=.3 Material Kpsi	Material Properties R.T.	Failure Criterion	Radial Pressure Allowable	Criterion	I.C.	O.C.	G10	Element σ_θ 129	Element σ_θ 143
Kapton	$\sigma_u = 25$ $\sigma_y = 10$	σ_θ, Principal Stress Theory $\sigma_{\theta max} \leq \frac{2}{3}\sigma_e$ ≤ 6.8*	p = 3500 psi	Prin. Stress Eff. Stress Shear Stress	$\sigma_\theta = -3.5$ $\bar{\sigma} = 3$ $\bar{\tau} = 1.5$	$\sigma_\theta = -6.8$* $\bar{\sigma} = 4$ $\bar{\tau} = 2.5$	$\sigma_\theta = -6$ $\bar{\sigma} = 10$ $\bar{\tau} = 5.8$	$\sigma_\theta = -2.5$	$\sigma_\theta = -5.5$
				Strain	.1% – .3%	Def. < 7 mils			
Ni/Ti	$\sigma_u = 145$ $\sigma_y = 123$ 3% at Ut	Max. Strain Theory $\epsilon_{max} \leq 1.5\%$	p - 10,000 psi min. value ϵ_θ outer coil	*Not a critical strength material*				$\sigma_\theta = -9$	$\sigma_\theta = -19$
G-10	InterLaminar Shear Stress 6.1 – 8.7 $\sigma_u = 60.8$ comp. $E = 4.1 \times 10^6$ psi $\mu = .15$	Max Shearing Stress Theory $\bar{\tau} = \frac{1}{2}\tau$ = 3.5*	p = 2500 psi note: slip first occurs at 2000 psi	Prin. Stress Eff. Stress Shear Stress Strain	$\sigma_\theta = -1.5$ $\bar{\sigma} = 1.0$ $\tau = .500$ ~ .2%	$\sigma_\theta = -3.0$ $\bar{\sigma} = 2.0$ $\tau = 1.0$ Displ. ~ 3 mils	$\sigma_\theta = -4.0$ $\bar{\sigma} = 4.0$ $\bar{\tau} = 3.5$* p =	$\sigma_\theta = -1.0$ First slip occurs at 2000 psi	$\sigma_\theta = -2.5$
Epoxy/Fiberglass	InterLaminar Shear 24.6 ϵ 1.5 – 1.8%	Max. S. S. $\bar{\tau} = \frac{1}{2}\tau$ = 12.3 $\epsilon \leq .8\%$	$\tau \rightarrow p = 14{,}000$ psi $\epsilon \rightarrow p = 5500$ psi	⇐ *more critical than* $\tau \rightarrow$ *not a critical strength material*				$\sigma_\theta = -6$	$\sigma_\theta = -11.5$
Copper	$\sigma_u = 32$ $\sigma_y = 10$	σ_θ, Principal Stress Theory $\sigma_\theta \leq \frac{2}{3}$ 10 = 6.8	p = 3500 psi	⇐ *same as Kapton*				$\sigma_\theta = -2.5$	$\sigma_\theta = -5.5$
* G-10		First Major Slippage Based on obser-vation of data	p = 2000 psi	σ_θ $\bar{\sigma}$ $\bar{\tau}$	-1.0 .3 .2	-1.0 1.0 .3	-1.5 .9 .5	$\sigma_\theta = -1.0$	$\sigma_\theta = -1.0$
Coil (composite without wedge)	$E = .65 \times 10^6$ psi for $\sigma \leq 5000$ psi $E = 1.06 \times 10^6$ psi for $\sigma > 5000$ psi. $\mu = .3$								

In Table II, the value of hoop stress, σ_θ, for I.C. at the pole (–1.5 kpsi) is slightly below 1.6 kpsi. The bond improves the assembly behavior response. However, no hard evidence exists as to the quality of the bond or that, more importantly, the coil and wedges stay bonded. Therefore, if the bond does not exist, Table I represents the critical failure capability.

Table II

Summary of Failure Results, Kpsi, f = .3 "Wedges Bonded"

Theory	I.C.	D.C.	G-10	Element 129/143
Prin. Stress	$\sigma_\theta = -1.7$	$\sigma_\theta = -4$	$\sigma_\theta = 5$	$\sigma_\theta = -1.5 / \sigma_\theta = -4.0$
Effective Stress	$\bar{\sigma} = 1$	$\bar{\sigma} = 3$	$\bar{\sigma} = 5$	
Shear Stress	$\bar{\tau} = 0.5$	$\bar{\tau} = 2.8$	$\bar{\tau} = 3.5$*	
Strain	<0.2%			
Displ.	<4 mils.			

Conclusion

Maximum radial stress that the end assembly is capable to withstand is in the neighborhood of 2000 psi. This end configuration and composition of components are inadequate to compensate for the Lorentz stress. In practice, we do not know what loads are being applied at the ends (at BNL). Therefore if care is not taken during collaring operational failure of components of the end may result. Three-D analysis currently being performed will aid in evaluating more realistically the end behavior under multi-directional loading.

References

1. Seely and Smith, Advanced Mechanics of Materials, John Wiley, 1952.2. System Requirements Issues No. 2, June 16, 1987. Table 11-2 and as discussed with VNK.

3. SSC-126, Non-Linear Finite Element analysis of SSC Magnet, April 1987.

Appendix

Fig. 1 Boundary conditions.

Fig. 2 Radial pressure = 2000 psi. First slip magnified 200.

Fig. 3–5 Element, Nodes.

Fig. 6–26 Results Near End Section Friction 0.3.

Fig. 27–49 Results Near End Section Friction ϕ

Fig. 50–51 Results Center Section, Steel Wedges, Cu. Wedges Friction 0.3.

Fig. 52–73 Results Wedges Bonded to Coil, Friction Elsewhere 0.3.

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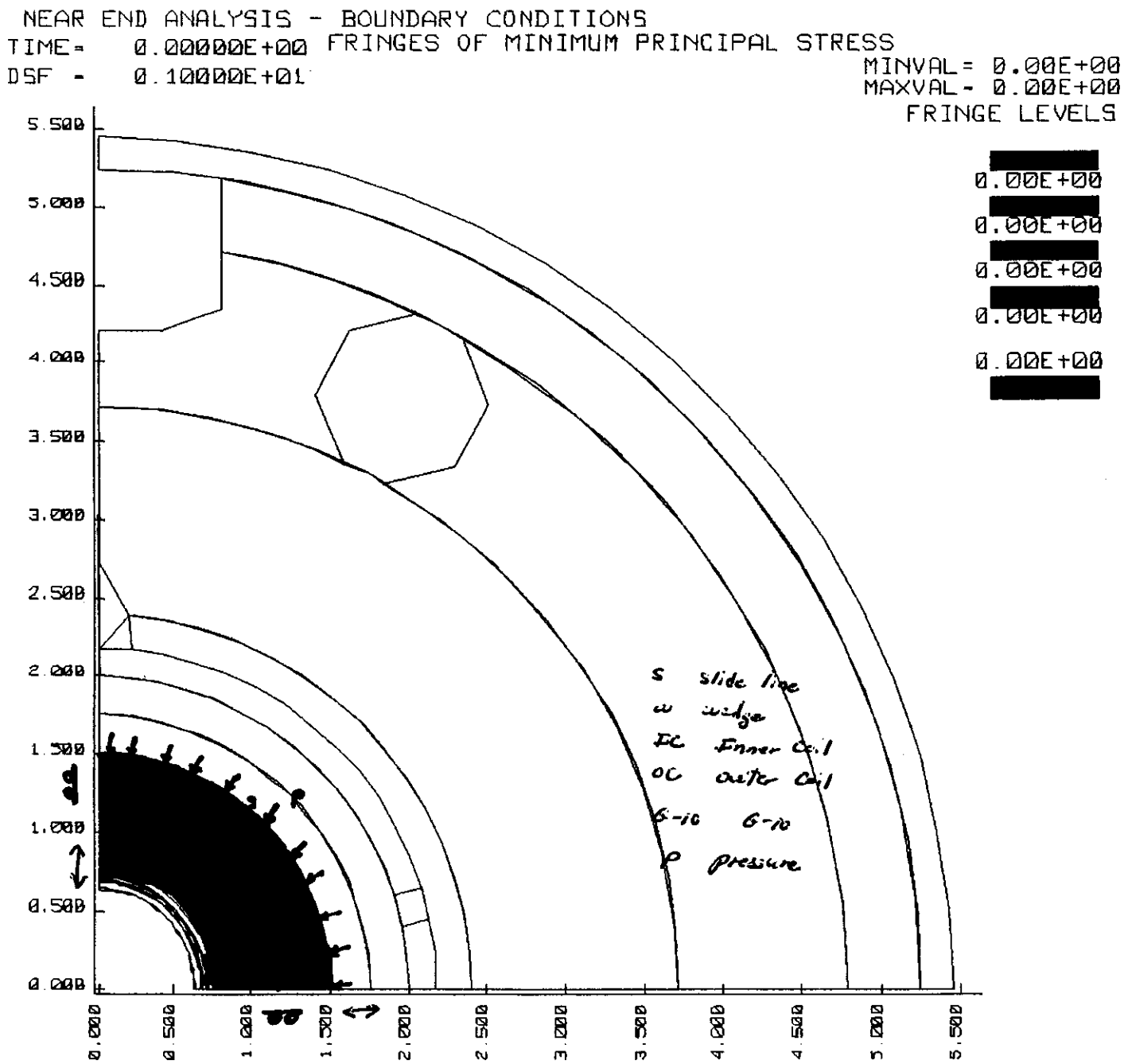
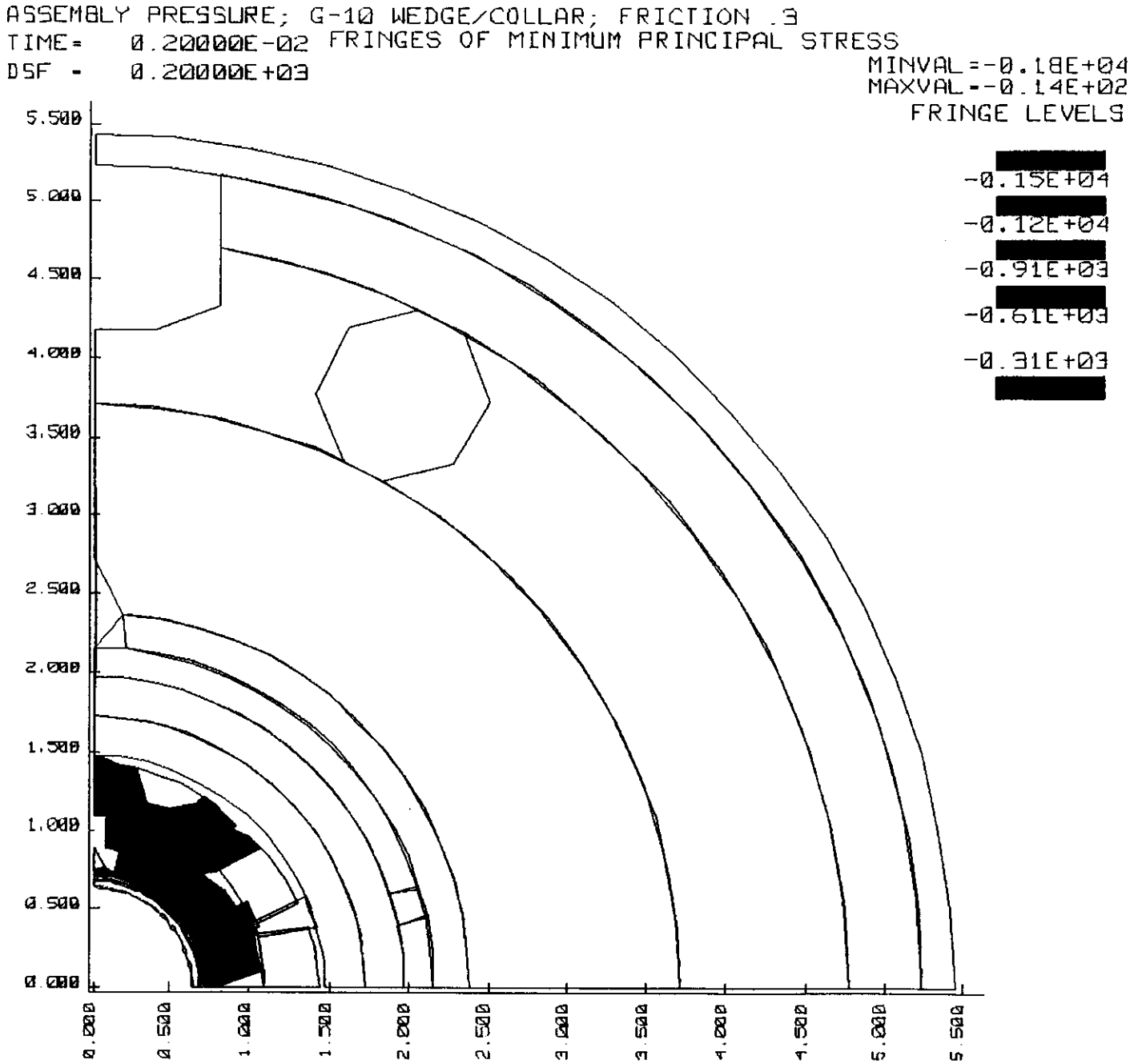

NEAR END ANALYSIS - BOUNDARY CONDITIONS
TIME= 0.00000E+00 FRINGES OF MINIMUM PRINCIPAL STRESS
DSF - 0.10000E+01
MINVAL= 0.00E+00
MAXVAL- 0.00E+00
FRINGE LEVELS
0.00E+00
0.00E+00
0.00E+00
0.00E+00
0.00E+00
5.500
5.000
4.500
4.000
3.500
3.000
2.500
2.000
1.500
1.000
0.500
0.000
0.000
0.500
1.000
1.500
2.000
2.500
3.000
3.500
4.000
4.500
5.000
5.500
S slide line
W wedge
IC Inner Coil
OC outer Coil
G-10 G-10
P pressure

Fig. 1


ASSEMBLY PRESSURE; G-10 WEDGE/COLLAR; FRICTION .3
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DSF = 0.20000E+03
MINVAL=-0.18E+04
MAXVAL=-0.14E+02
FRINGE LEVELS
-0.15E+04
-0.12E+04
-0.91E+03
-0.61E+03
-0.31E+03
5.500
5.000
4.500
4.000
3.500
3.000
2.500
2.000
1.500
1.000
0.500
0.000
0.000
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5.000
5.500

Fig. 2

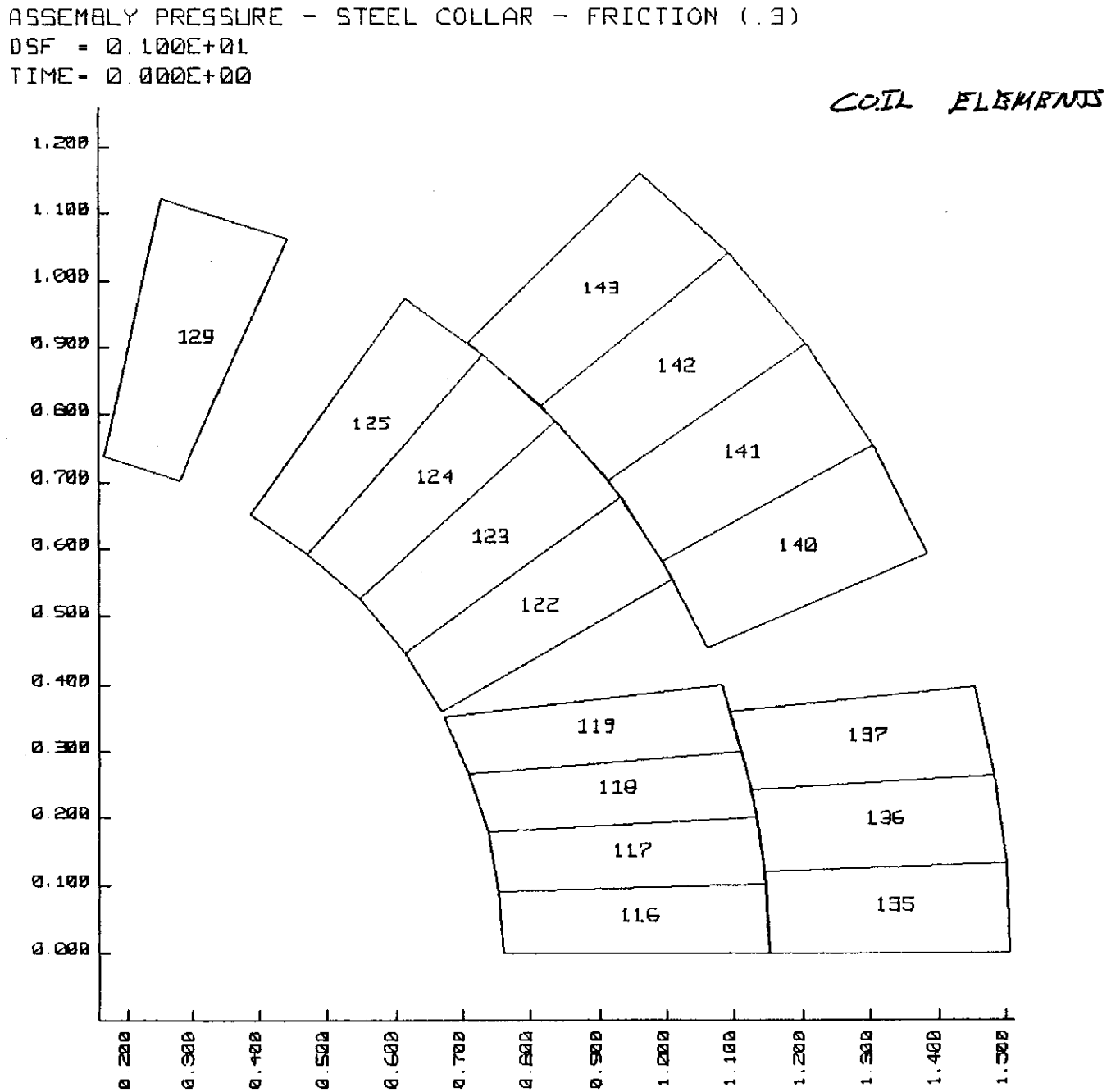

ASSEMBLY PRESSURE - STEEL COLLAR - FRICTION (.3)
DSF = 0.100E+01
TIME- 0.000E+00
COIL ELEMENTS
1.200
1.100
1.000
0.900
0.800
0.700
0.600
0.500
0.400
0.300
0.200
0.100
0.000
0.200
0.300
0.400
0.500
0.600
0.700
0.800
0.900
1.000
1.100
1.200
1.300
1.400
1.500
129
125
124
123
122
143
142
141
140
119
118
117
116
137
136
135

Fig. 3

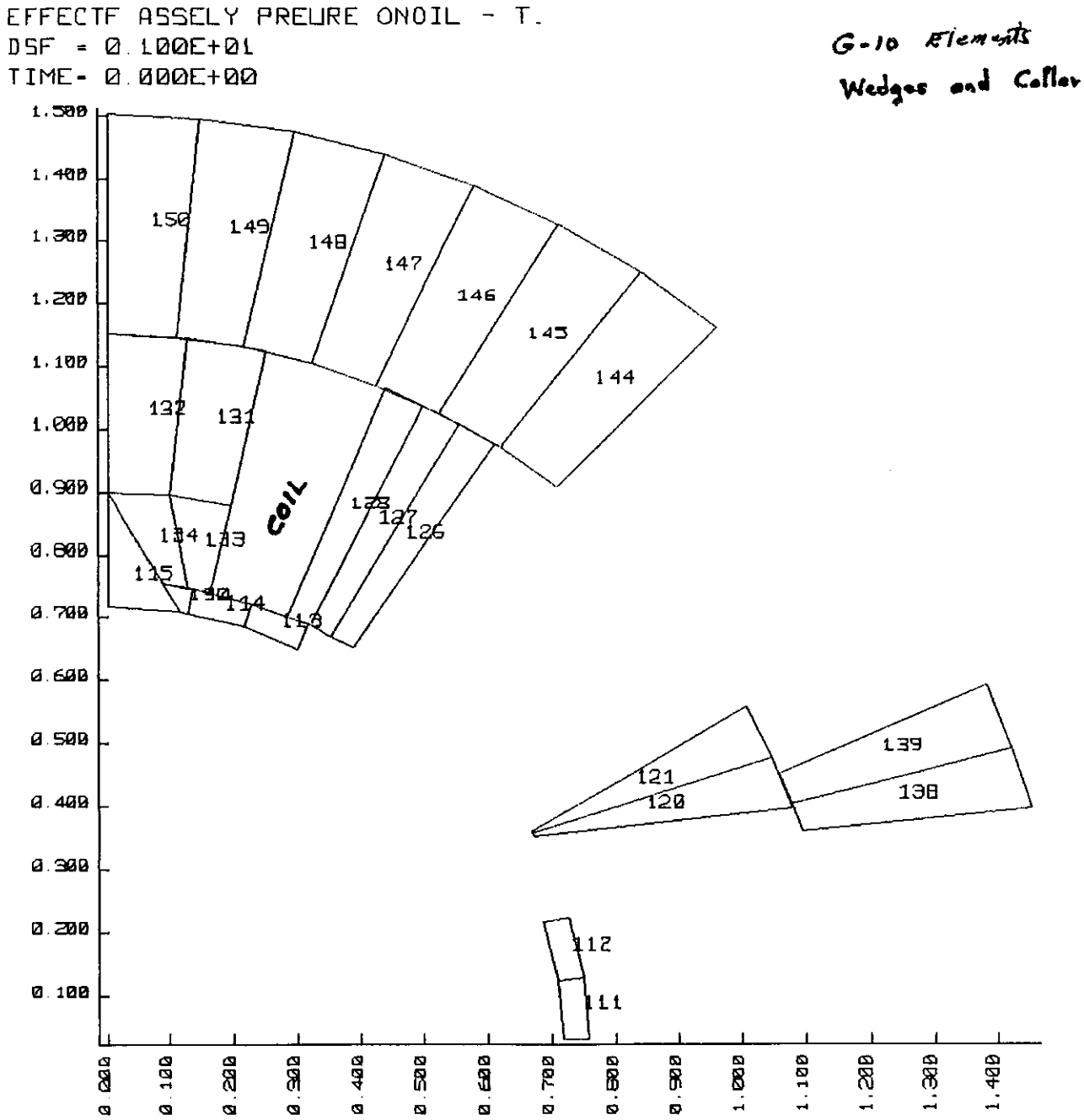

EFFECTF ASSELY PREURE ONOIL - T.
DSF = 0.100E+01
TIME- 0.000E+00
G-10 Elements
Wedges and Collar
150
149
148
147
146
145
144
132
131
COIL
134
133
115
114
113
123
127
126
121
120
139
138
112
111

Fig. 4

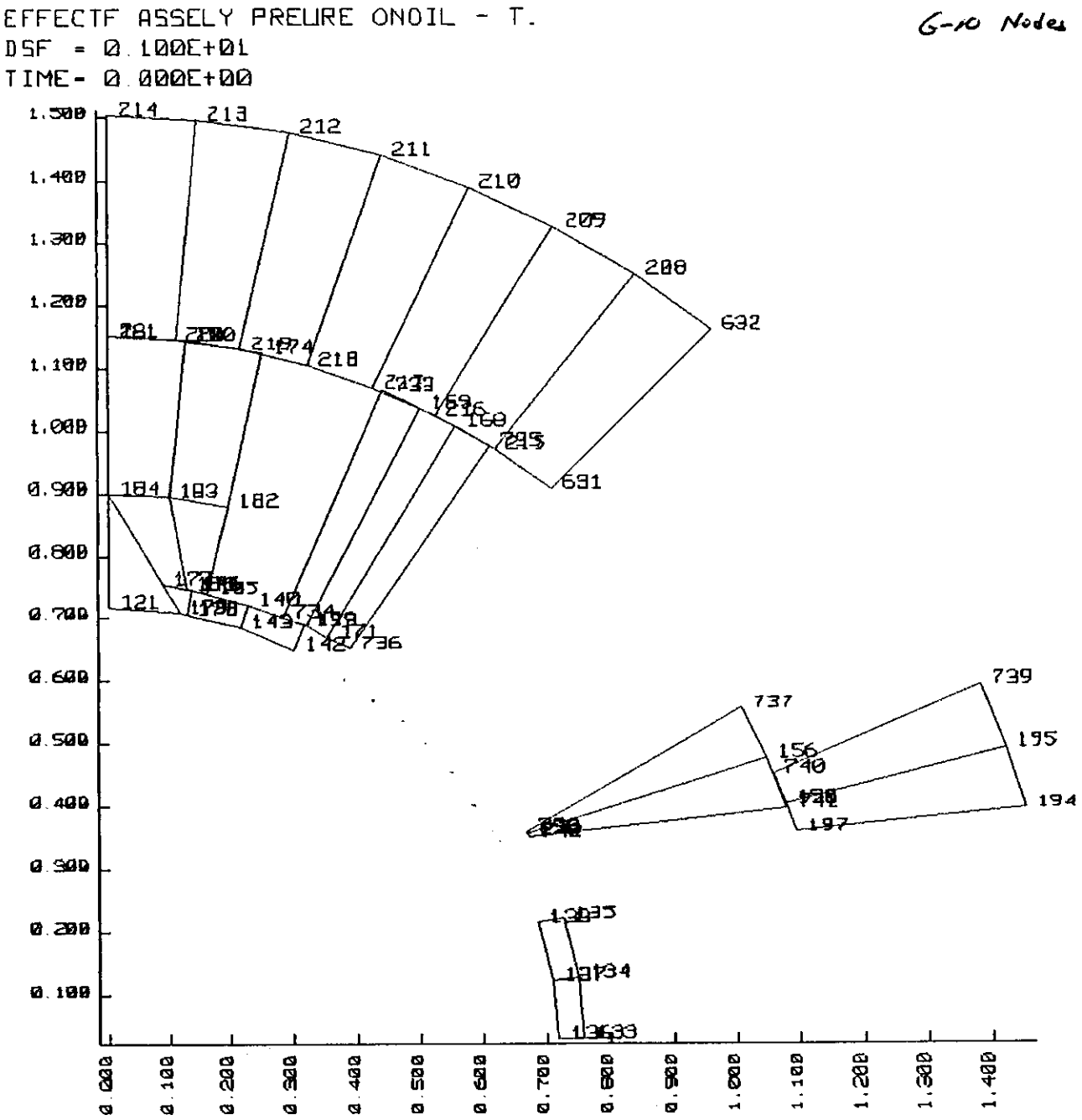

EFFECTF ASSELY PRELIRE ONOIL - T.
DSF = 0.100E+01
TIME- 0.000E+00
6-10 Nodes
214
213
212
211
210
209
208
632
631
184
183
182
121
737
739
156
740
195
194
197
1.500
1.400
1.300
1.200
1.100
1.000
0.900
0.800
0.700
0.600
0.500
0.400
0.300
0.200
0.100
0.000
0.100
0.200
0.300
0.400
0.500
0.600
0.700
0.800
0.900
1.000
1.100
1.200
1.300
1.400

Fig. 5

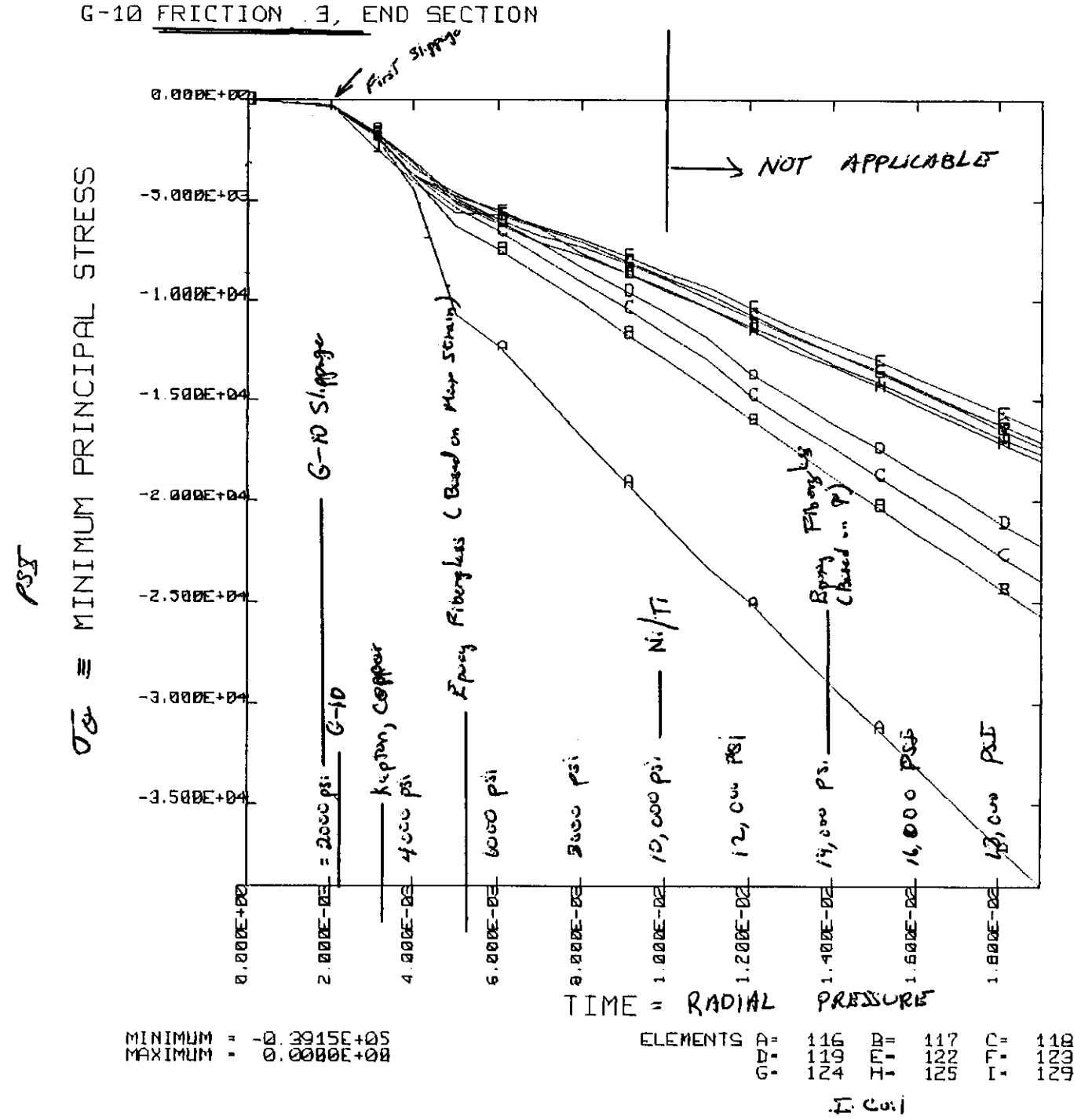

G-10 FRICTION .3, END SECTION
First Slippage
NOT APPLICABLE
0.000E+00
-5.000E+03
-1.000E+04
-1.500E+04
-2.000E+04
-2.500E+04
-3.000E+04
-3.500E+04
σz ≡ MINIMUM PRINCIPAL STRESS
psi
G-10 Slippage
= 2000 psi — G-10
Kapton, Copper
4000 psi
Epoxy Fiberglass (Based on Max Strain)
6000 psi
8000 psi
10,000 psi — Ni/Ti
12,000 psi
Phenolic
Epoxy Fiberglass (Based on P)
14,000 psi
16,000 psi
18,000 psi
0.000E+00
2.000E-02
4.000E-02
6.000E-02
8.000E-02
1.000E-02
1.200E-02
1.400E-02
1.600E-02
1.800E-02
TIME = RADIAL PRESSURE
MINIMUM = -0.3915E+05
MAXIMUM = 0.0000E+00
ELEMENTS A= 116 B= 117 C= 118
D= 119 E= 122 F= 123
G= 124 H= 125 I= 129
Ti Coil

Fig. 6

G-10 FRICTION .3, END SECTION

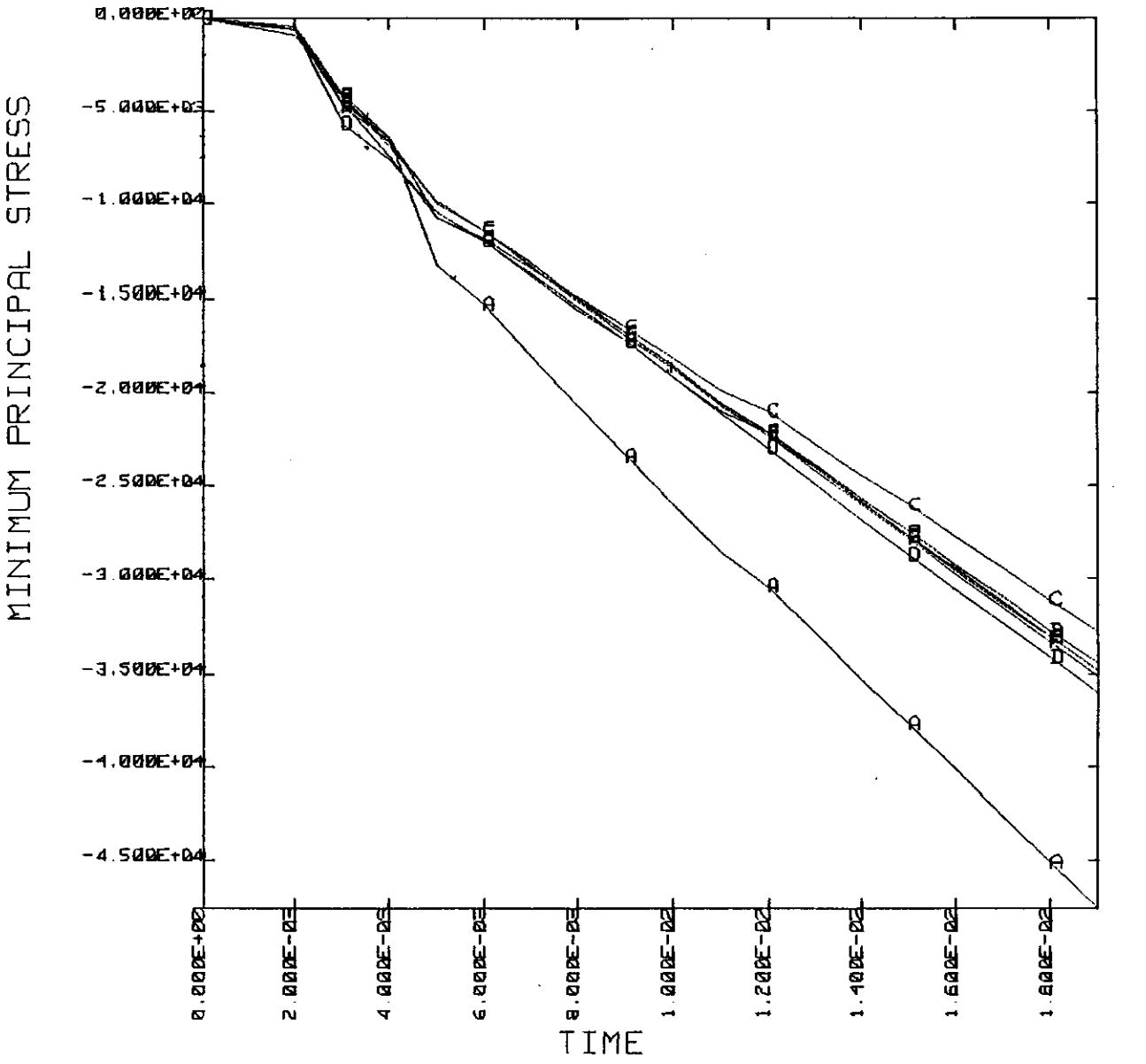


Fig. 7

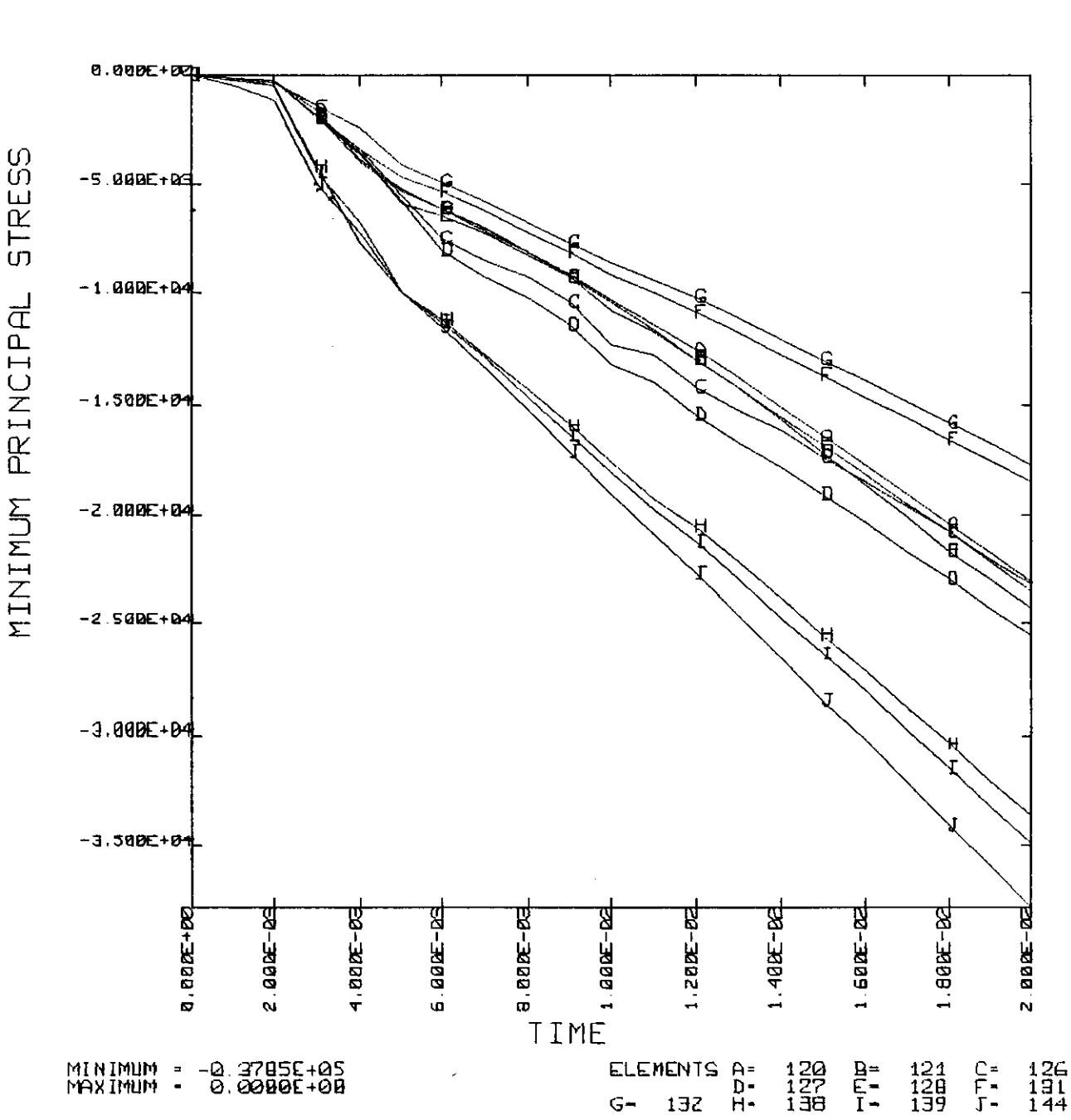
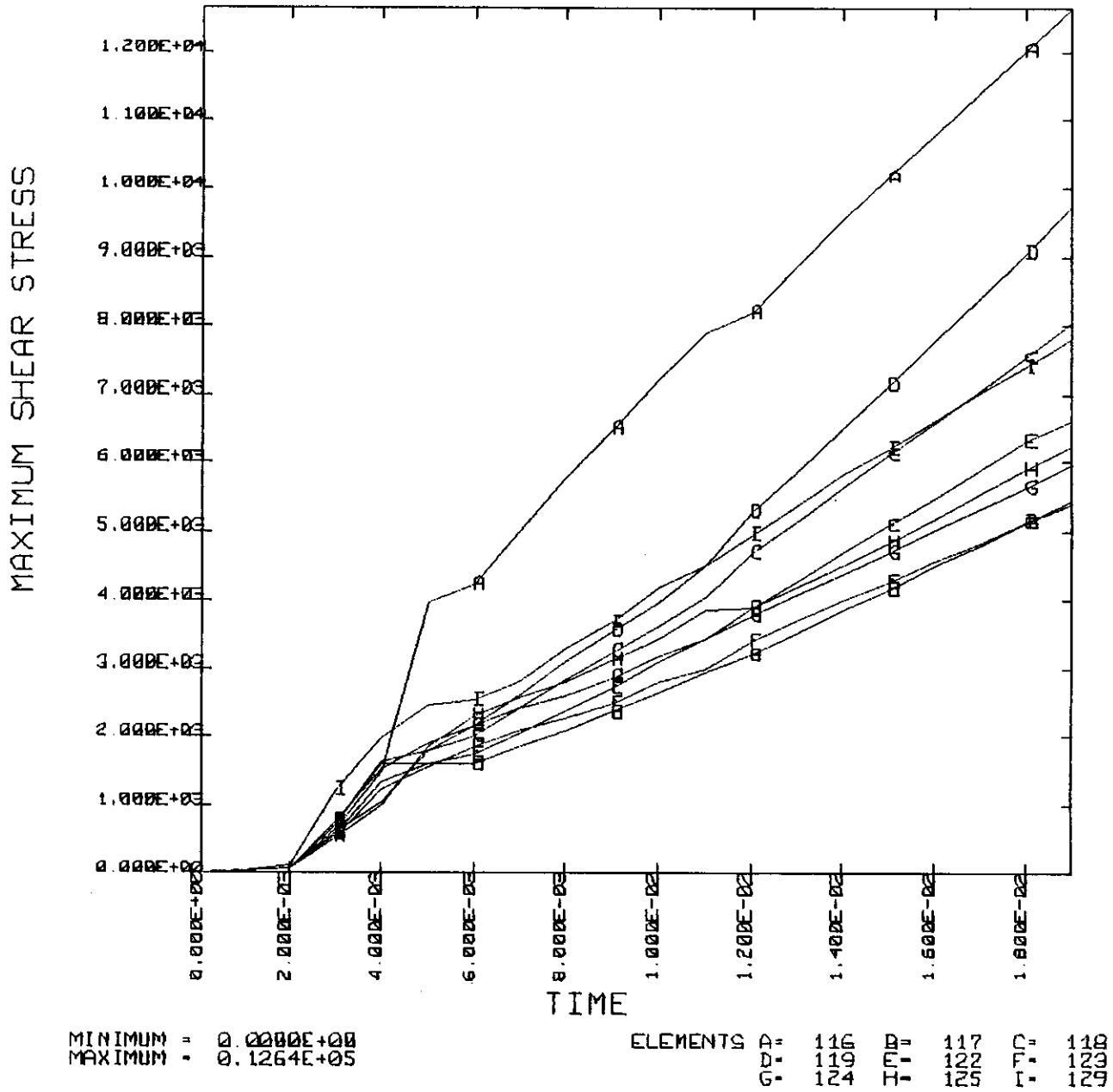


Fig. 8

Wedges, Collar


G-10 FRICTION .3, END SECTION
MAXIMUM SHEAR STRESS
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1.100E+04
1.000E+04
9.000E+03
8.000E+03
7.000E+03
6.000E+03
5.000E+03
4.000E+03
3.000E+03
2.000E+03
1.000E+03
0.000E+00
0.000E+00
2.000E-03
4.000E-03
6.000E-03
8.000E-03
1.000E-02
1.200E-02
1.400E-02
1.600E-02
1.800E-02
TIME
MINIMUM = 0.0000E+00
MAXIMUM = 0.1264E+05
ELEMENTS A= 116 B= 117 C= 118
D= 119 E= 122 F= 123
G= 124 H= 125 I= 129

Fig. 9

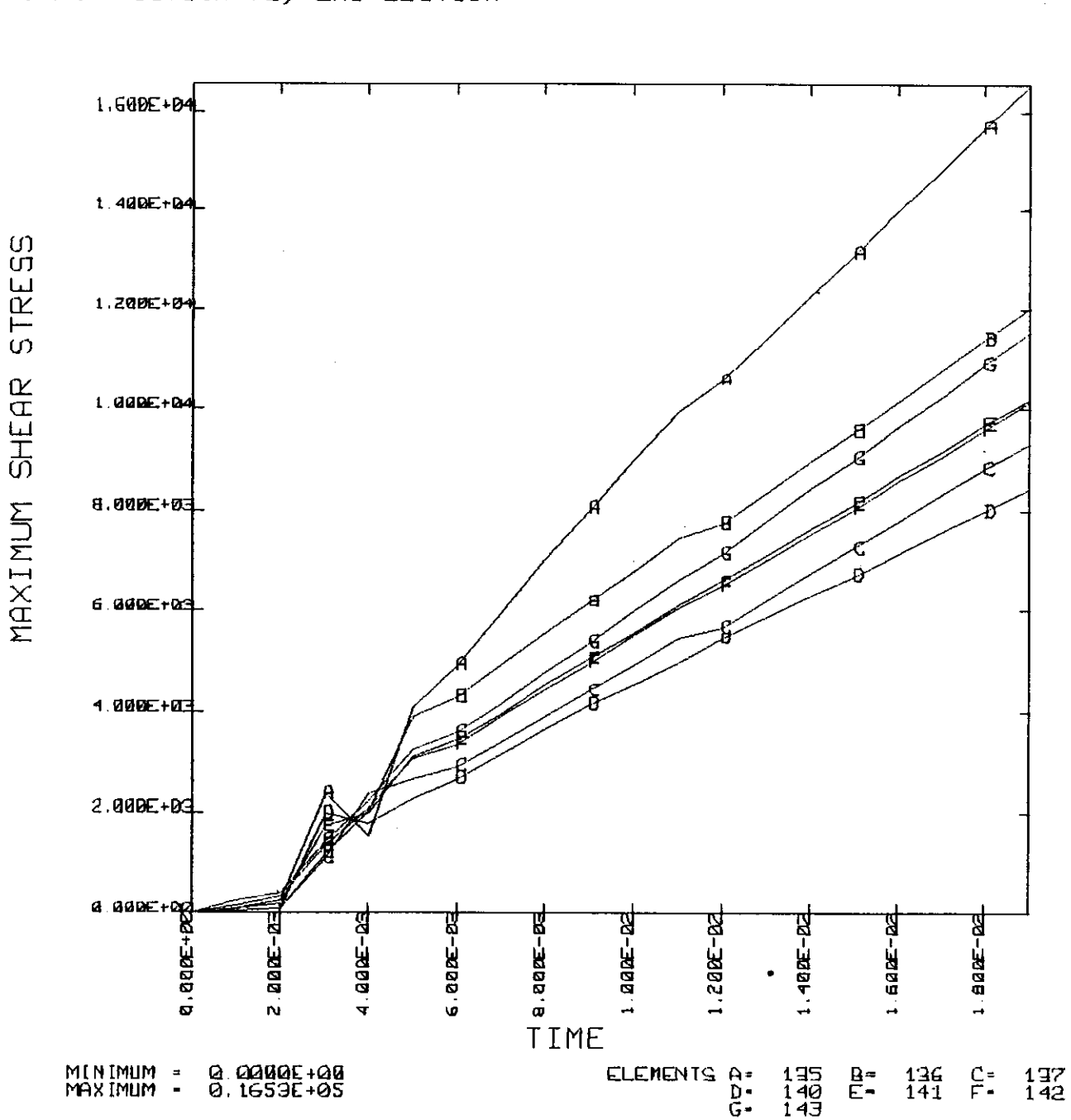
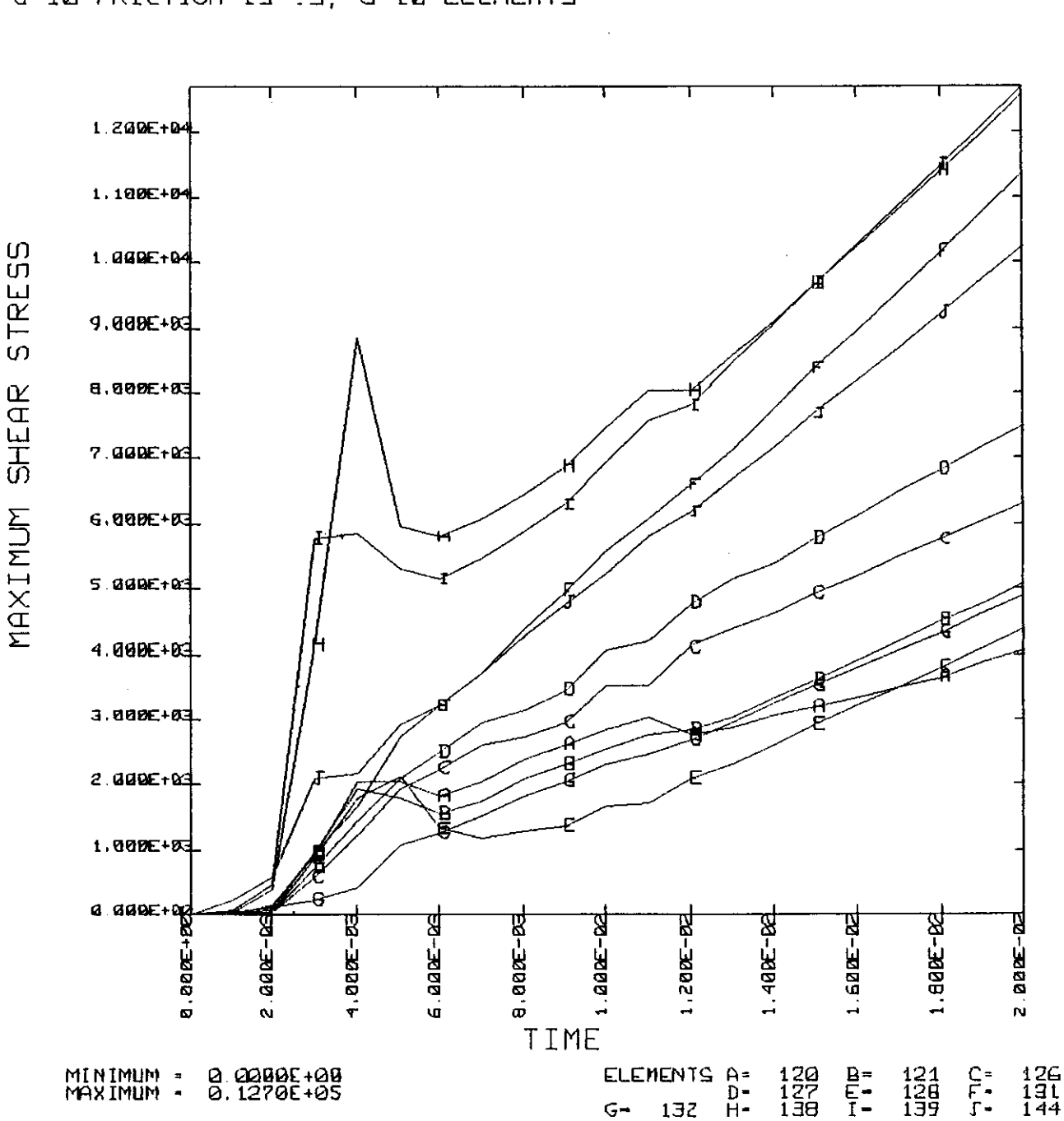

G-10 FRICTION .3, END SECTION
MAXIMUM SHEAR STRESS
1.600E+04
1.400E+04
1.200E+04
1.000E+04
8.000E+03
6.000E+03
4.000E+03
2.000E+03
0.000E+00
0.000E+00
2.000E-03
4.000E-03
6.000E-03
8.000E-03
1.000E-02
1.200E-02
1.400E-02
1.600E-02
1.800E-02
TIME
MINIMUM = 0.0000E+00
MAXIMUM = 0.1653E+05
ELEMENTS A= 135 B= 136 C= 137
D= 140 E= 141 F= 142
G= 143

Fig. 10


G-10 FRICTION IS .3; G-10 ELEMENTS
MAXIMUM SHEAR STRESS
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1.100E+04
1.000E+04
9.000E+03
8.000E+03
7.000E+03
6.000E+03
5.000E+03
4.000E+03
3.000E+03
2.000E+03
1.000E+03
0.000E+00
0.000E+00
2.000E-03
4.000E-03
6.000E-03
8.000E-03
1.000E-02
1.200E-02
1.400E-02
1.600E-02
1.800E-02
2.000E-02
TIME
MINIMUM = 0.0000E+00
MAXIMUM = 0.1270E+05
ELEMENTS A= 120 B= 121 C= 126
D= 127 E= 128 F= 131
G= 132 H= 138 I= 139 J= 144

Fig. 11

G-10 FRICTION .3, END SECTION

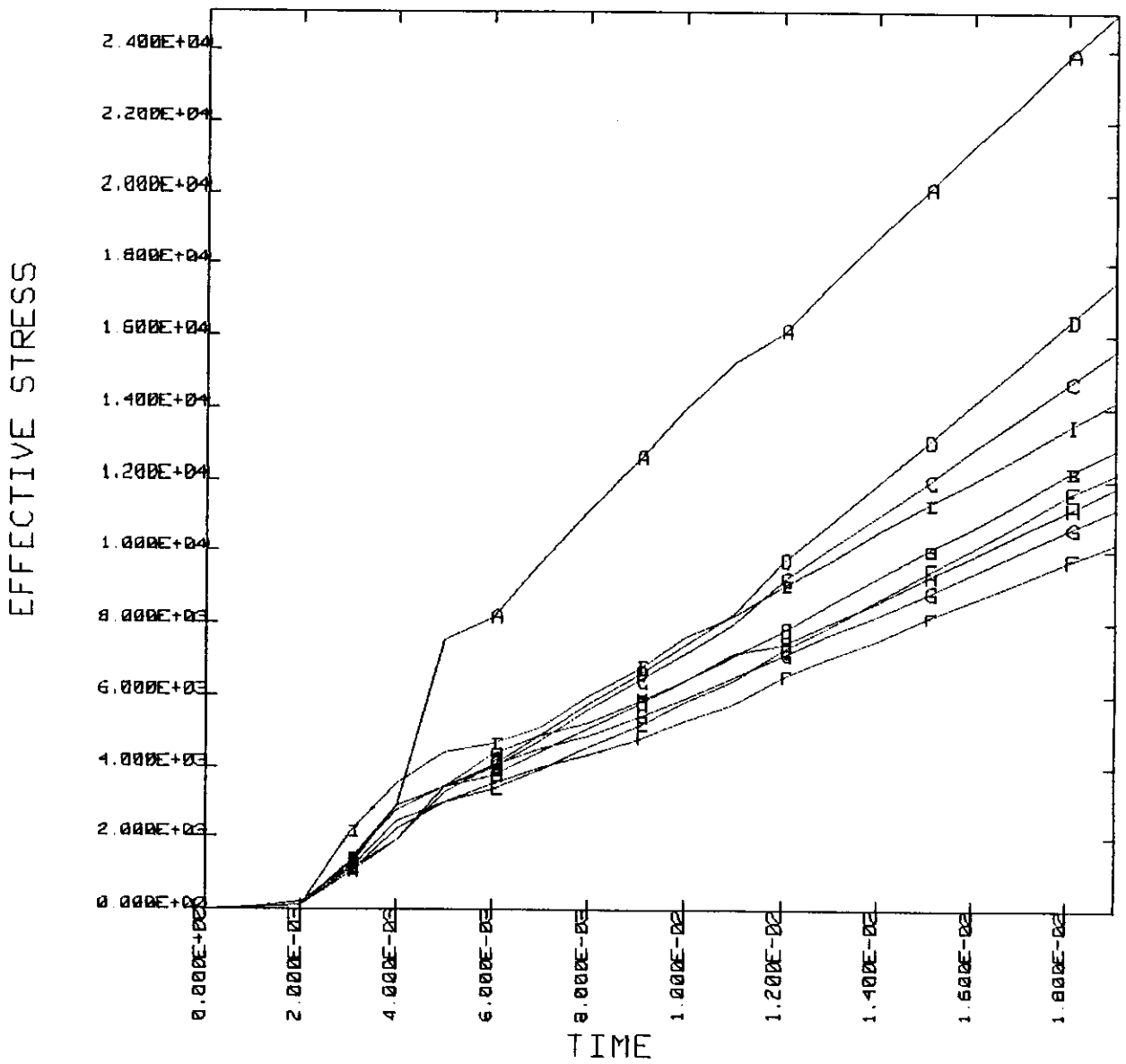


Fig. 12

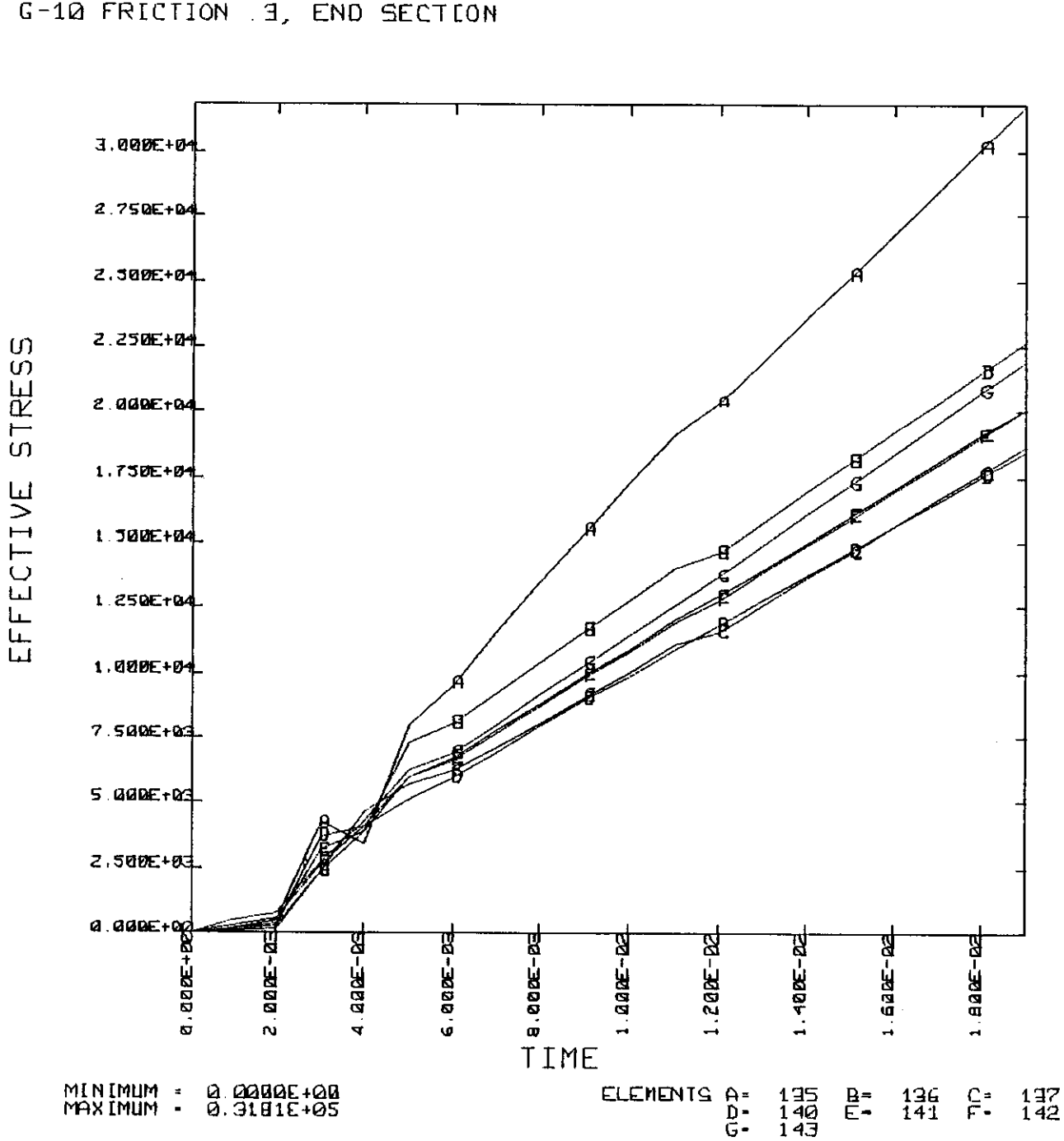

G-10 FRICTION .3, END SECTION
EFFECTIVE STRESS
3.000E+04
2.750E+04
2.500E+04
2.250E+04
2.000E+04
1.750E+04
1.500E+04
1.250E+04
1.000E+04
7.500E+03
5.000E+03
2.500E+03
0.000E+00
0.000E+00
2.000E-05
4.000E-05
6.000E-05
8.000E-05
1.000E-02
1.200E-02
1.400E-02
1.600E-02
1.800E-02
TIME
MINIMUM = 0.0000E+00
MAXIMUM = 0.3181E+05
ELEMENTS A= 135 B= 136 C= 137
D= 140 E= 141 F= 142
G= 143

Fig. 13

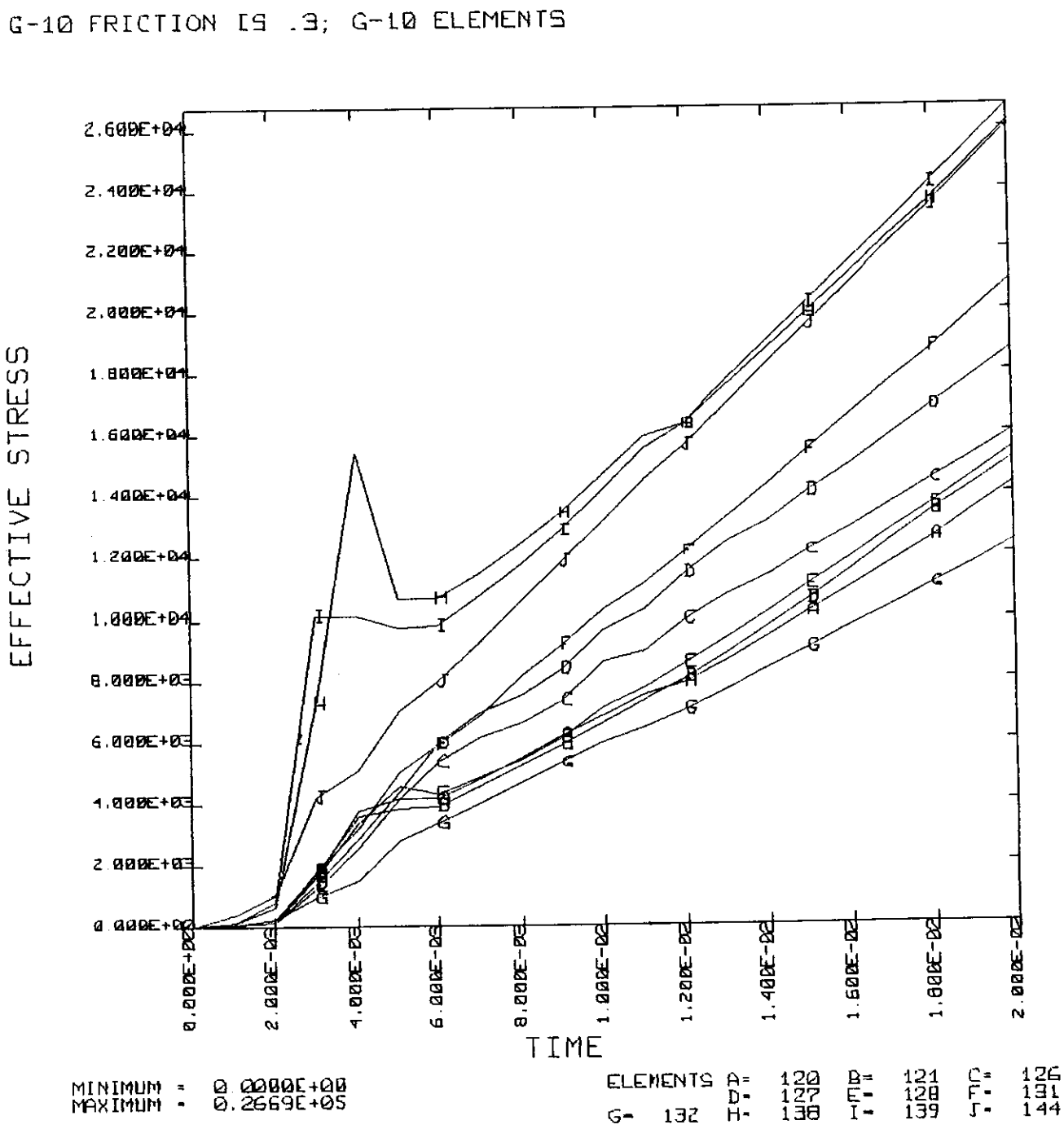

G-10 FRICTION IS .3; G-10 ELEMENTS
EFFECTIVE STRESS
2.600E+04
2.400E+04
2.200E+04
2.000E+04
1.800E+04
1.600E+04
1.400E+04
1.200E+04
1.000E+04
8.000E+03
6.000E+03
4.000E+03
2.000E+03
0.000E+00
0.000E+00
2.000E-03
4.000E-03
6.000E-03
8.000E-03
1.000E-02
1.200E-02
1.400E-02
1.600E-02
1.800E-02
2.000E-02
TIME
MINIMUM = 0.0000E+00
MAXIMUM = 0.2669E+05
ELEMENTS A= 120 B= 121 C= 126
D= 127 E= 128 F= 131
G= 132 H= 138 I= 139 J= 144

Fig. 14

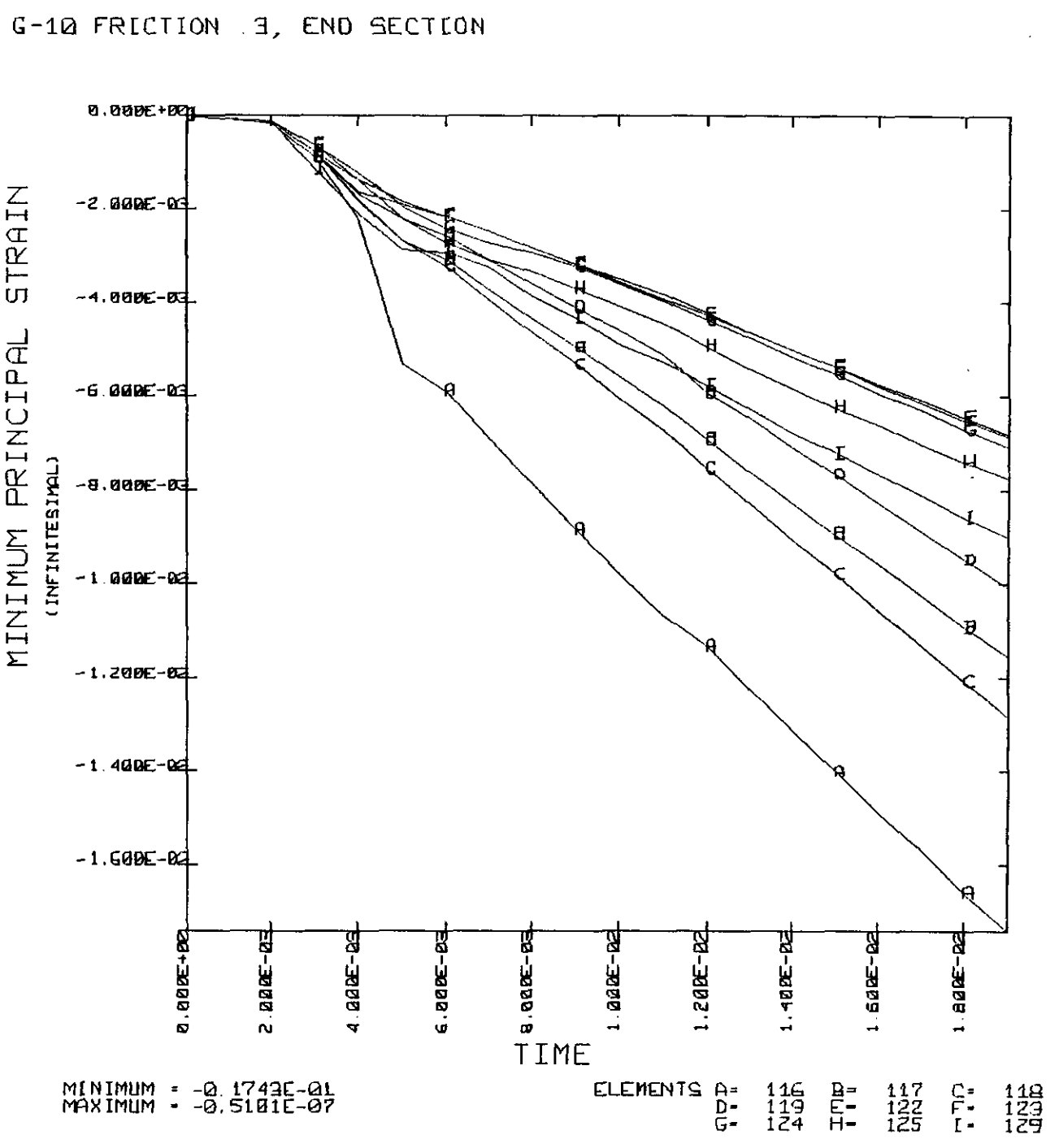

G-10 FRICTION .3, END SECTION
MINIMUM PRINCIPAL STRAIN
(INFINITESIMAL)
0.000E+00
-2.000E-03
-4.000E-03
-6.000E-03
-8.000E-03
-1.000E-02
-1.200E-02
-1.400E-02
-1.600E-02
0.000E+00
2.000E-03
4.000E-03
6.000E-03
8.000E-03
1.000E-02
1.200E-02
1.400E-02
1.600E-02
1.800E-02
TIME
MINIMUM = -0.1743E-01
MAXIMUM = -0.5101E-07
ELEMENTS A= 116 B= 117 C= 118
D= 119 E= 122 F= 123
G= 124 H= 125 I= 129

Fig. 15

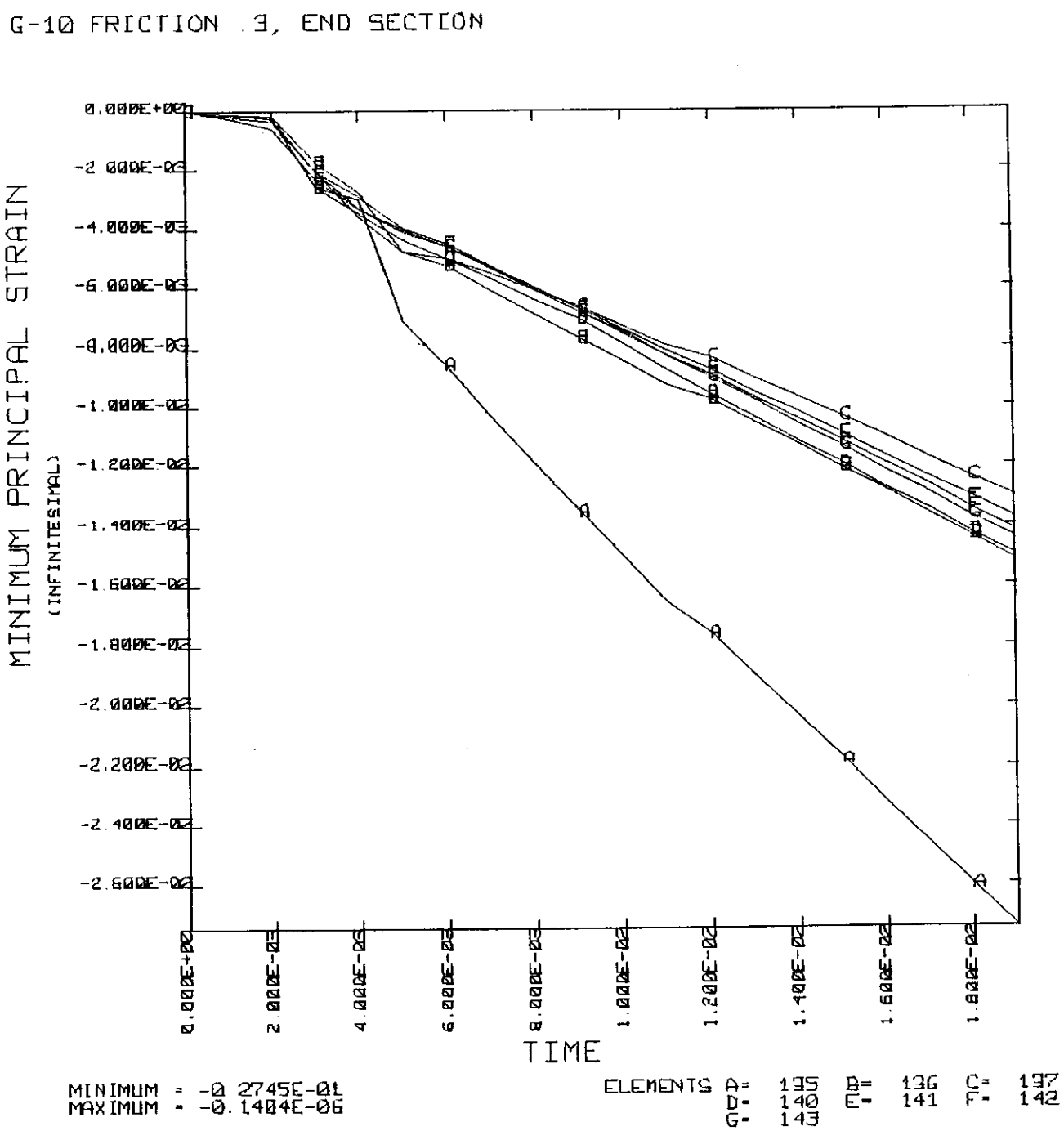
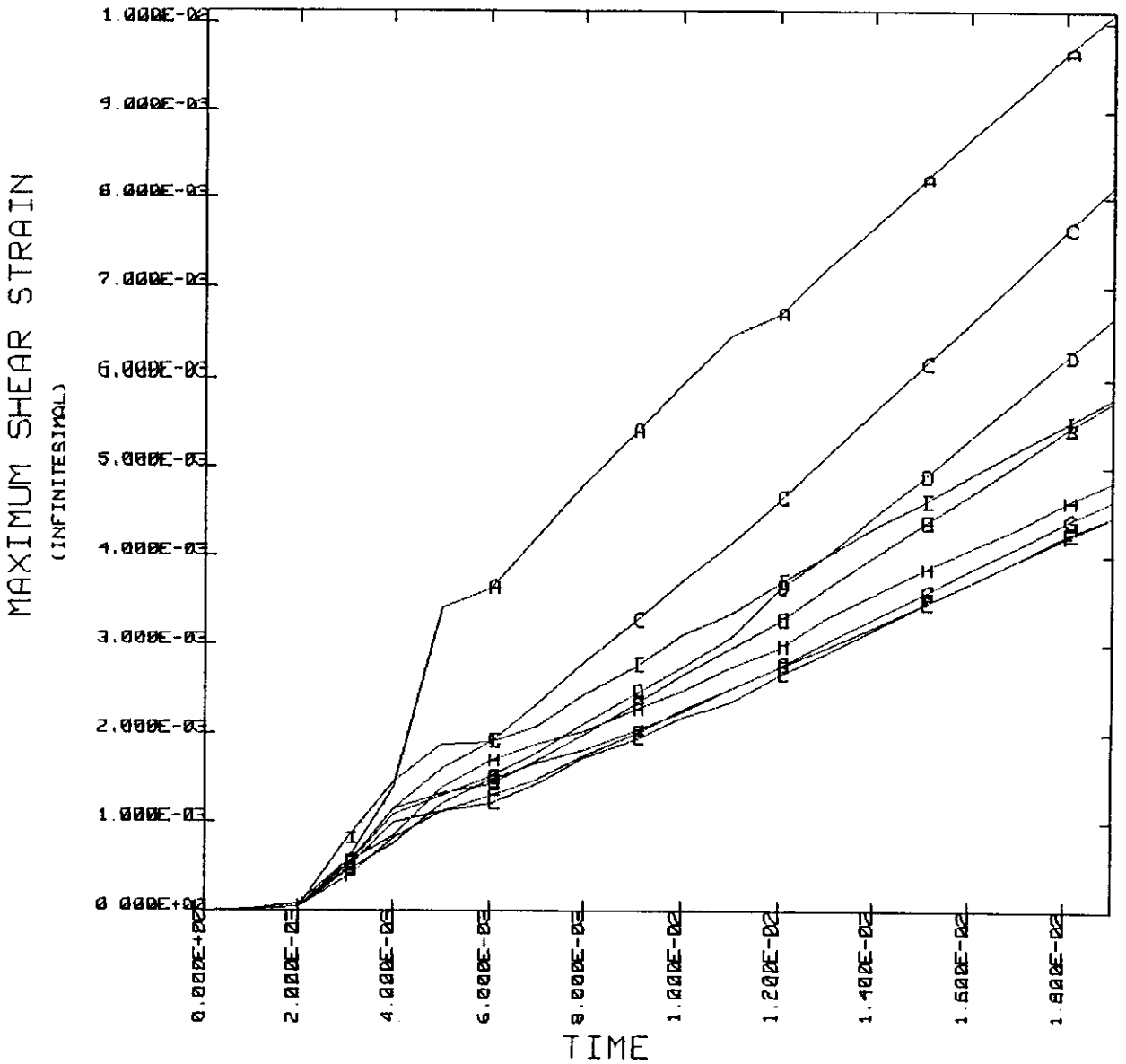

G-10 FRICTION .3, END SECTION
MINIMUM PRINCIPAL STRAIN
(INFINITESIMAL)
0.000E+00
-2.000E-03
-4.000E-03
-6.000E-03
-8.000E-03
-1.000E-02
-1.200E-02
-1.400E-02
-1.600E-02
-1.800E-02
-2.000E-02
-2.200E-02
-2.400E-02
-2.600E-02
0.000E+00
2.000E-03
4.000E-03
6.000E-03
8.000E-03
1.000E-02
1.200E-02
1.400E-02
1.600E-02
1.800E-02
TIME
MINIMUM = -0.2745E-01
MAXIMUM = -0.1404E-06
ELEMENTS A= 135 B= 136 C= 137
D= 140 E= 141 F= 142
G= 143

Fig. 16

G-10 FRICTION .3, END SECTION



MINIMUM = 0.4264E-07
MAXIMUM = 0.1013E-01

ELEMENTS A= 116 B= 117 C= 118
D= 119 E= 122 F= 123
G= 124 H= 125 I= 129

Fig. 17

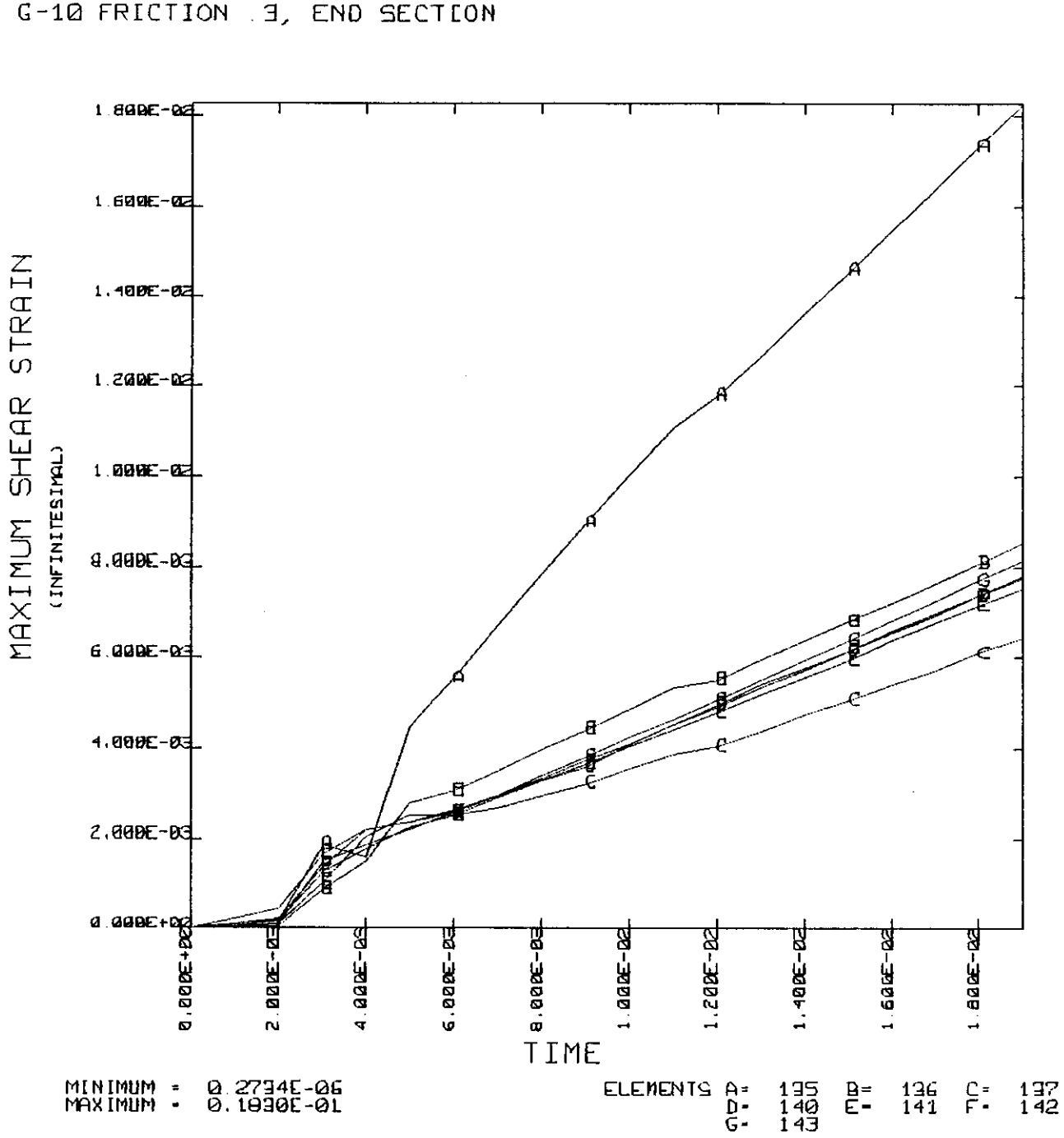

G-10 FRICTION .3, END SECTION
MAXIMUM SHEAR STRAIN
(INFINITESIMAL)
1.800E-02
1.600E-02
1.400E-02
1.200E-02
1.000E-02
8.000E-03
6.000E-03
4.000E-03
2.000E-03
0.000E+00
0.000E+00
2.000E-05
4.000E-03
6.000E-03
8.000E-03
1.000E-02
1.200E-02
1.400E-02
1.600E-02
1.800E-02
TIME
MINIMUM = 0.2734E-06
MAXIMUM = 0.1030E-01
ELEMENTS A= 135 B= 136 C= 137
D= 140 E= 141 F= 142
G= 143

Fig. 18

G-10 FRICTION .3, END SECTION

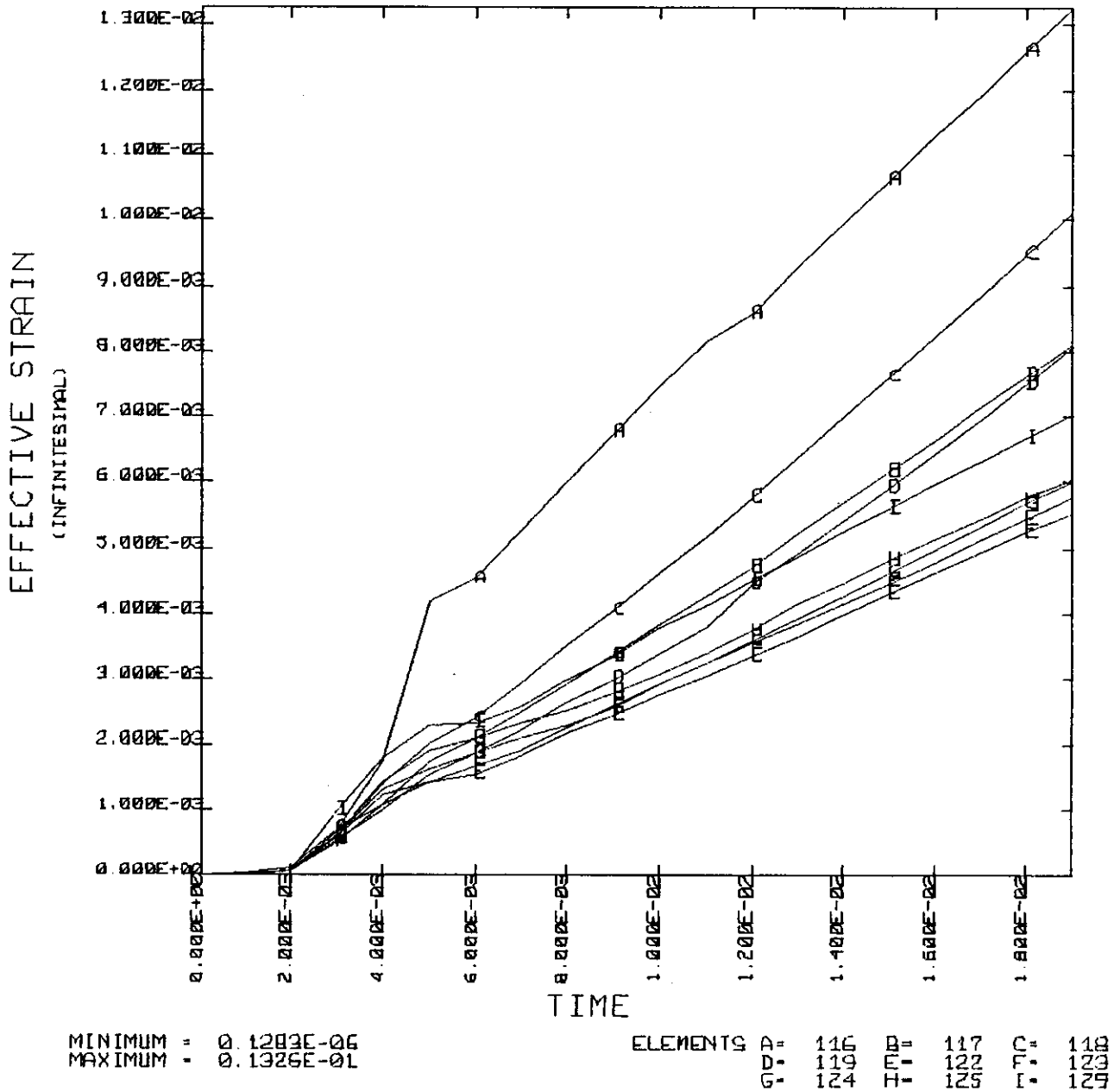
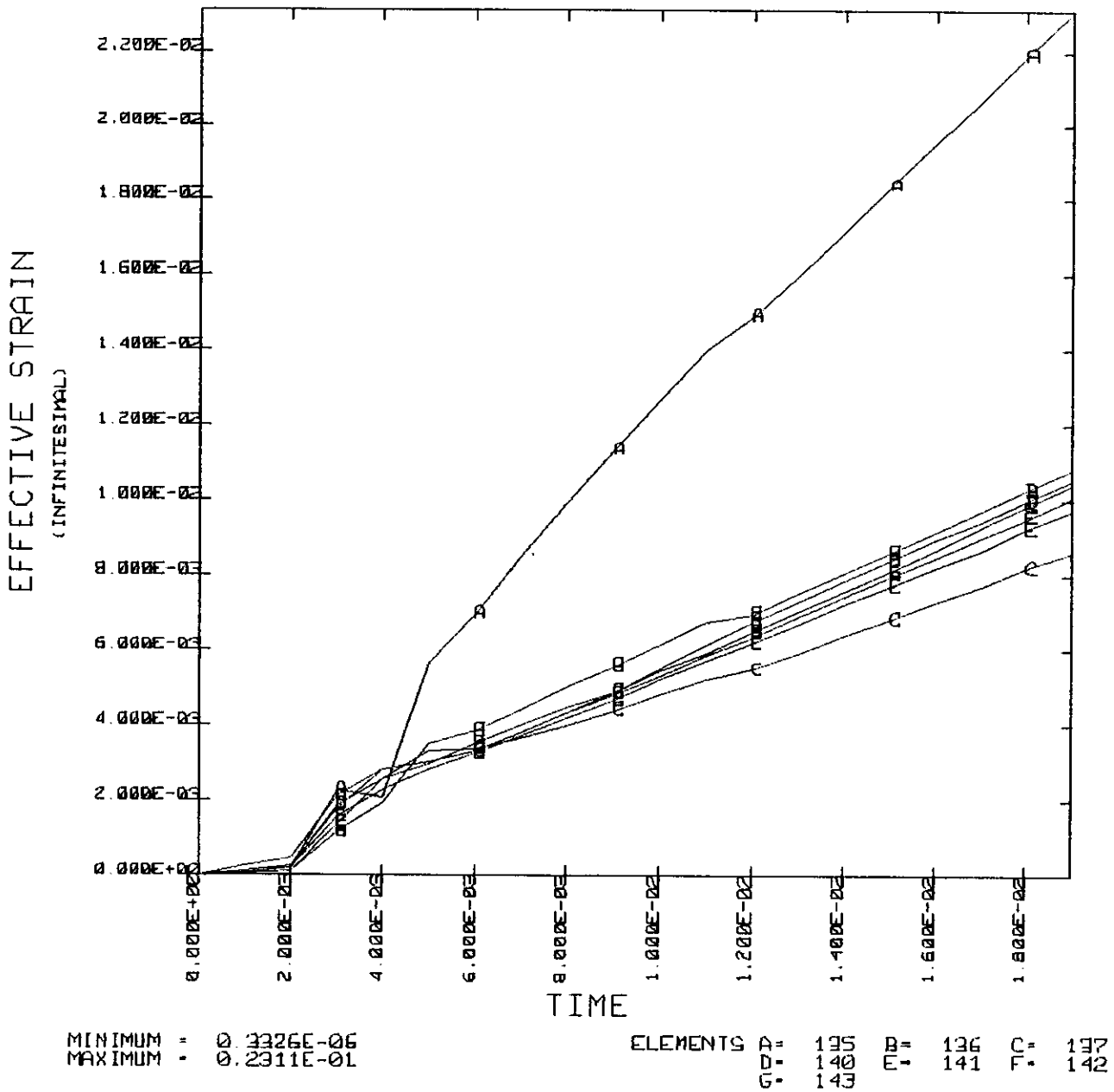


Fig. 19

G-10 FRICTION .3, END SECTION



MINIMUM = 0.3326E-06
MAXIMUM = 0.2311E-01

ELEMENTS A= 135 B= 136 C= 137
D= 140 E= 141 F= 142
G= 143

Fig. 20

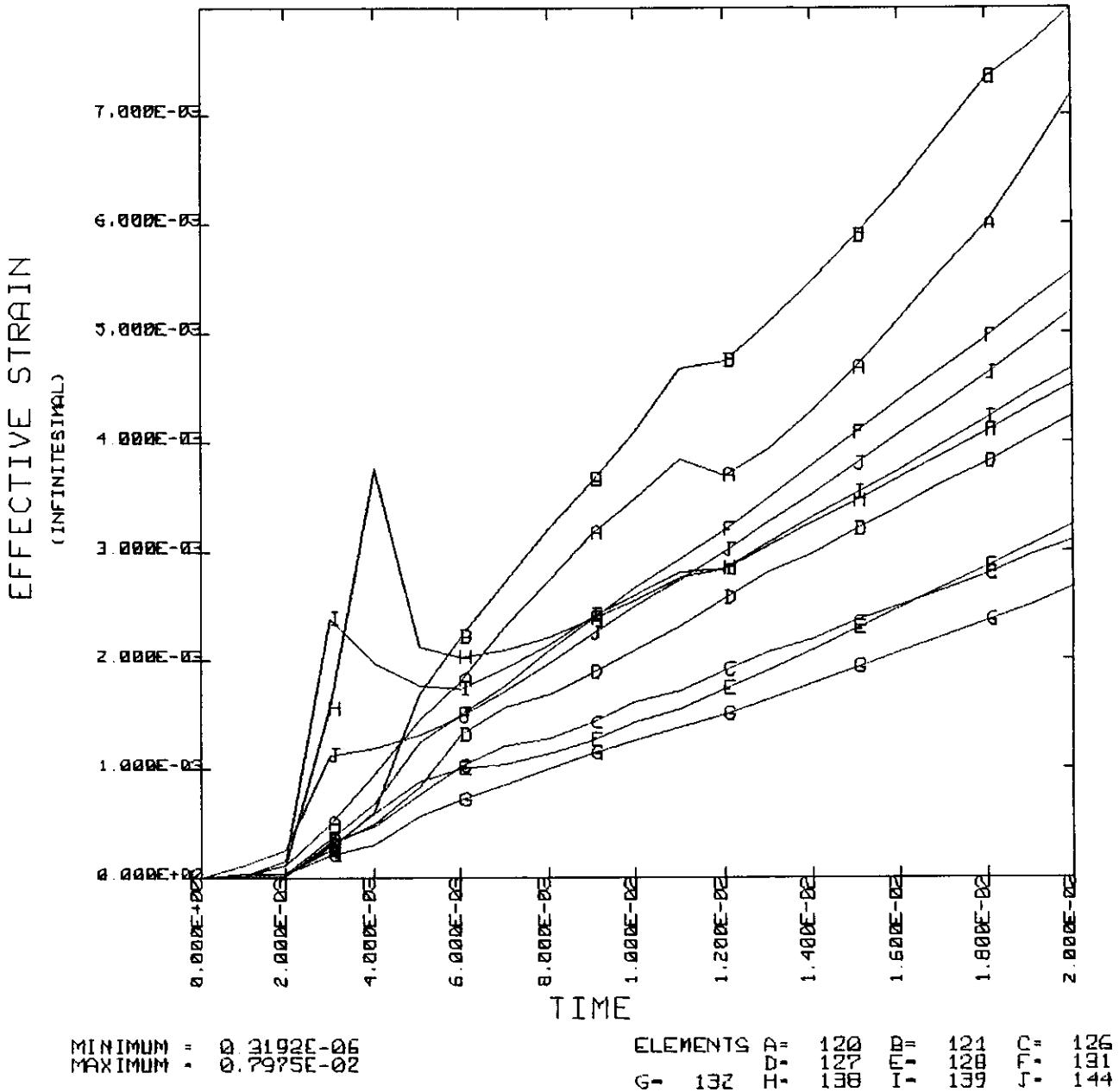

G-10 ELEMENTS; FRICTION = .3; ENDF SECTION
EFFECTIVE STRAIN
(INFINITESIMAL)
7.000E-03
6.000E-03
5.000E-03
4.000E-03
3.000E-03
2.000E-03
1.000E-03
0.000E+00
0.000E+00
2.000E-03
4.000E-03
6.000E-03
8.000E-03
1.000E-02
1.200E-02
1.400E-02
1.600E-02
1.800E-02
2.000E-02
TIME
MINIMUM = 0.3192E-06
MAXIMUM = 0.7975E-02
ELEMENTS A= 120 B= 121 C= 126
D= 127 E= 128 F= 131
G= 132 H= 138 I= 139 J= 144

Fig. 21

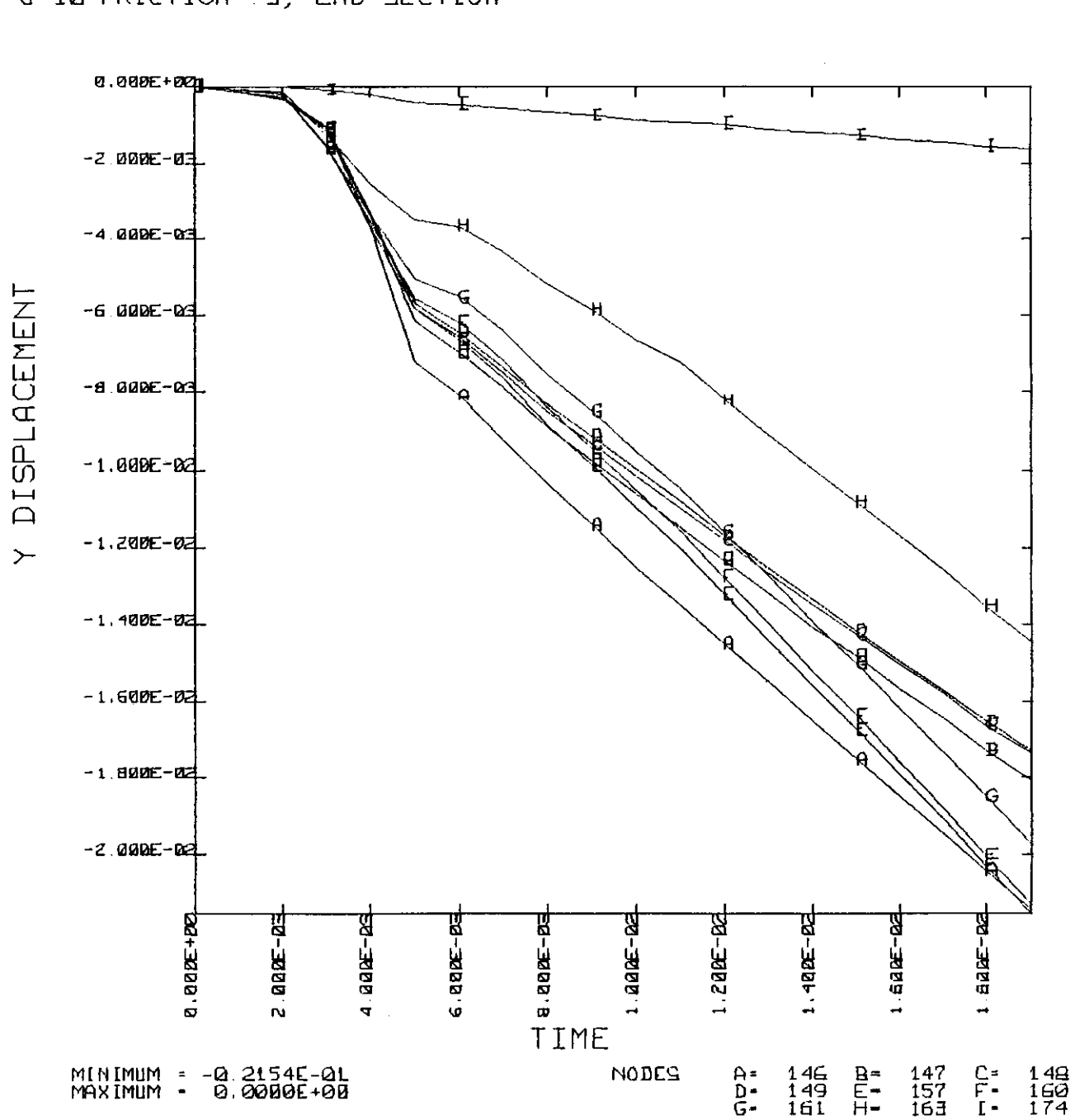
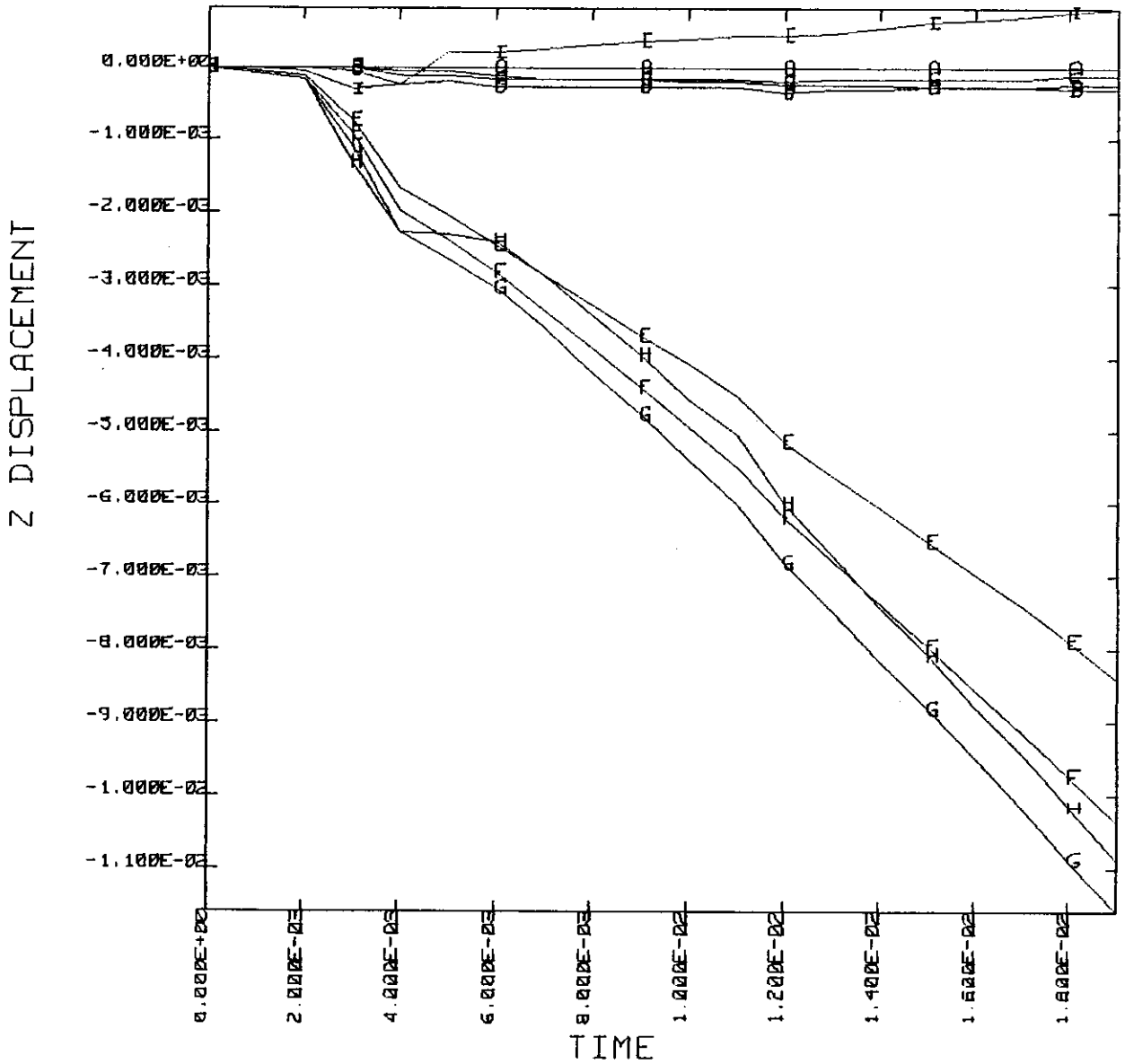

G-10 FRICTION .3, END SECTION
Y DISPLACEMENT
TIME
MINIMUM = -0.2154E-01
MAXIMUM = 0.0000E+00
NODES A= 146 B= 147 C= 148
D= 149 E= 157 F= 160
G= 161 H= 163 I= 174

Fig. 22

G-10 FRICTION .3, END SECTION



MINIMUM = -0.1161E-01
MAXIMUM = 0.8069E-03

NODES A= 146 B= 147 C= 148
D= 149 E= 157 F= 160
G= 161 H= 163 I= 174

Fig. 23

G-10 FRICTION .3, END SECTION

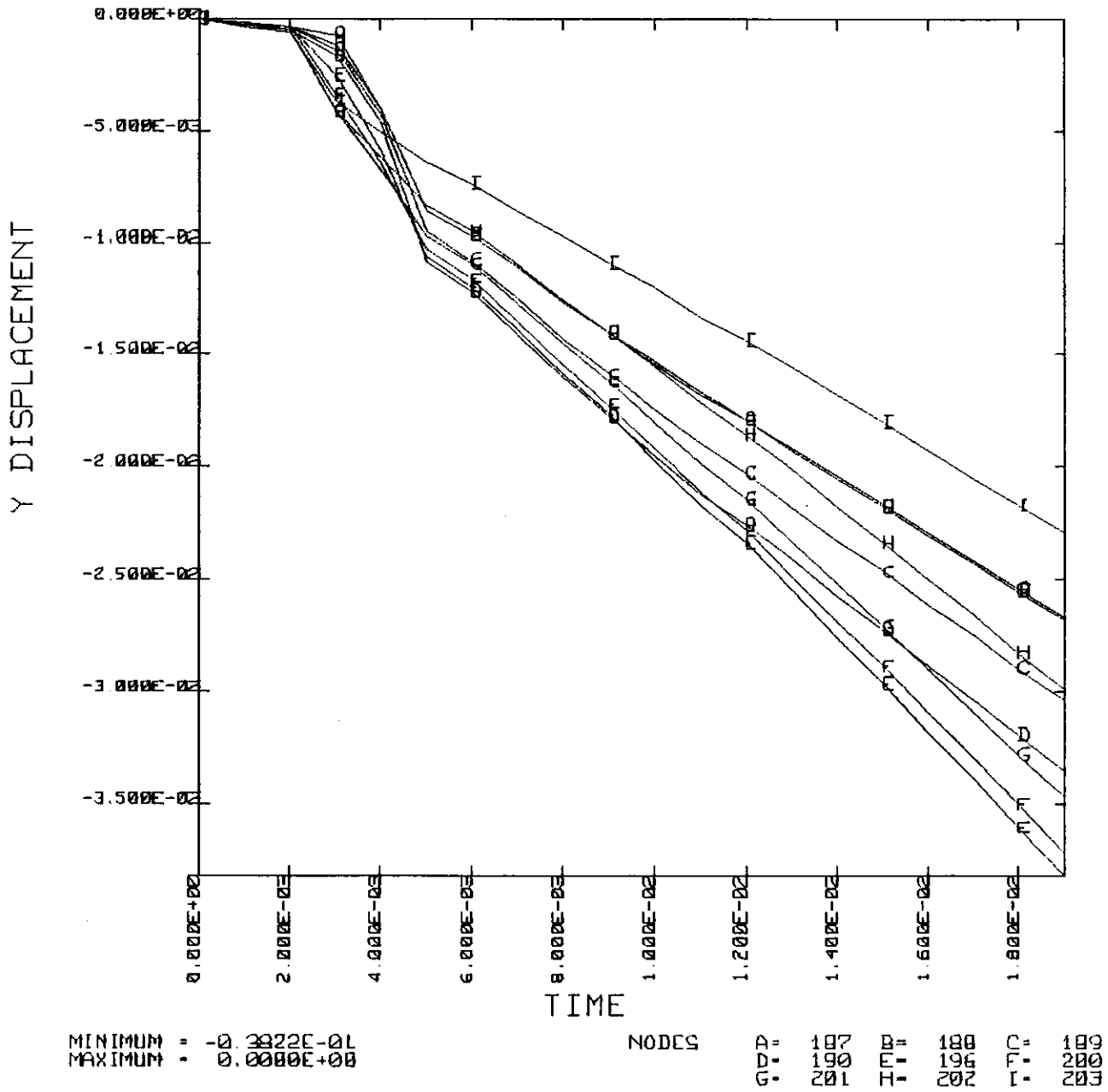


Fig. 24

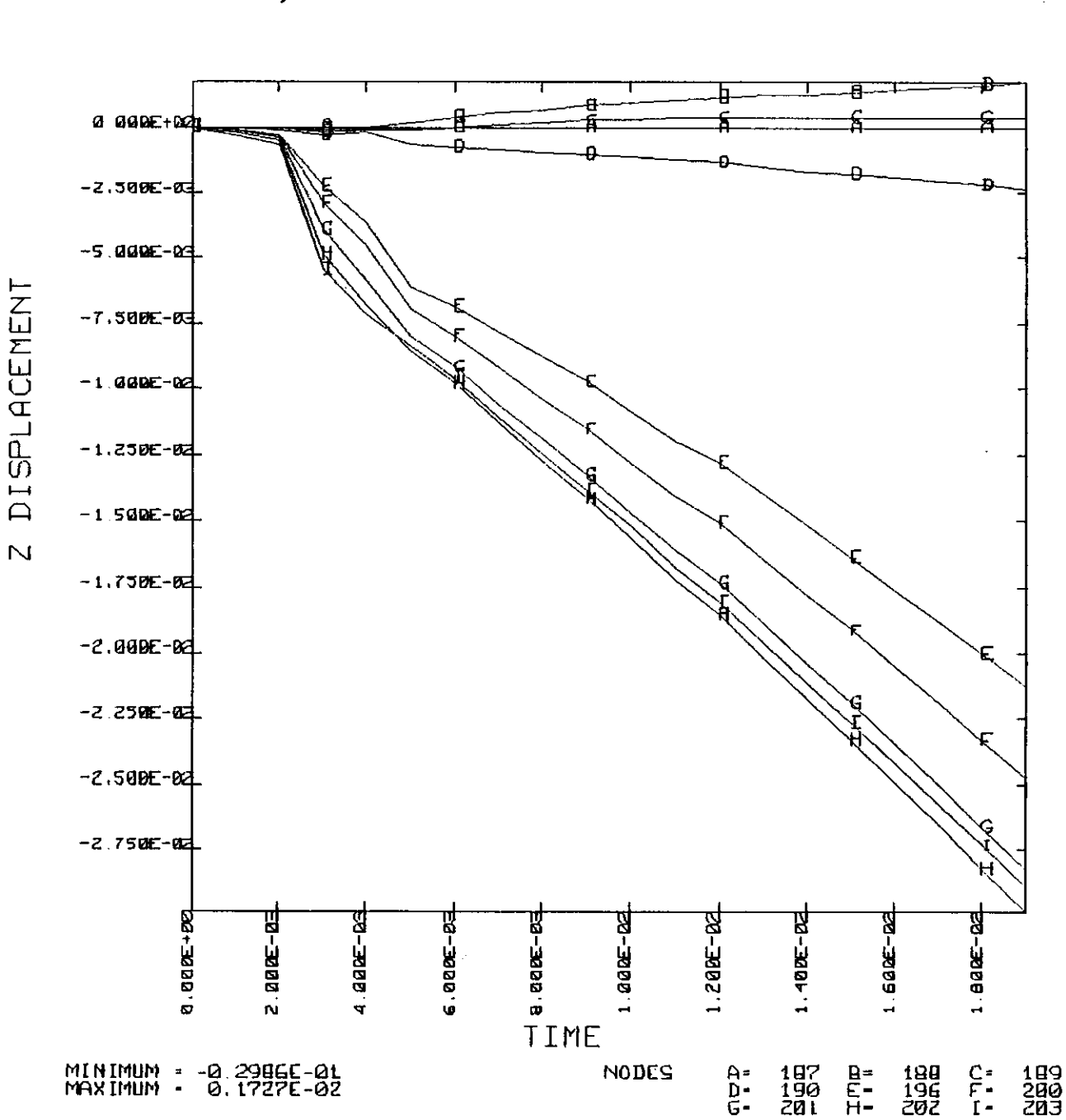

G-10 FRICTION .3, END SECTION
Z DISPLACEMENT
TIME
MINIMUM = -0.2986E-01
MAXIMUM = 0.1727E-02
NODES A= 187 B= 188 C= 189
D= 190 E= 196 F= 200
G= 201 H= 202 I= 203

Fig. 25

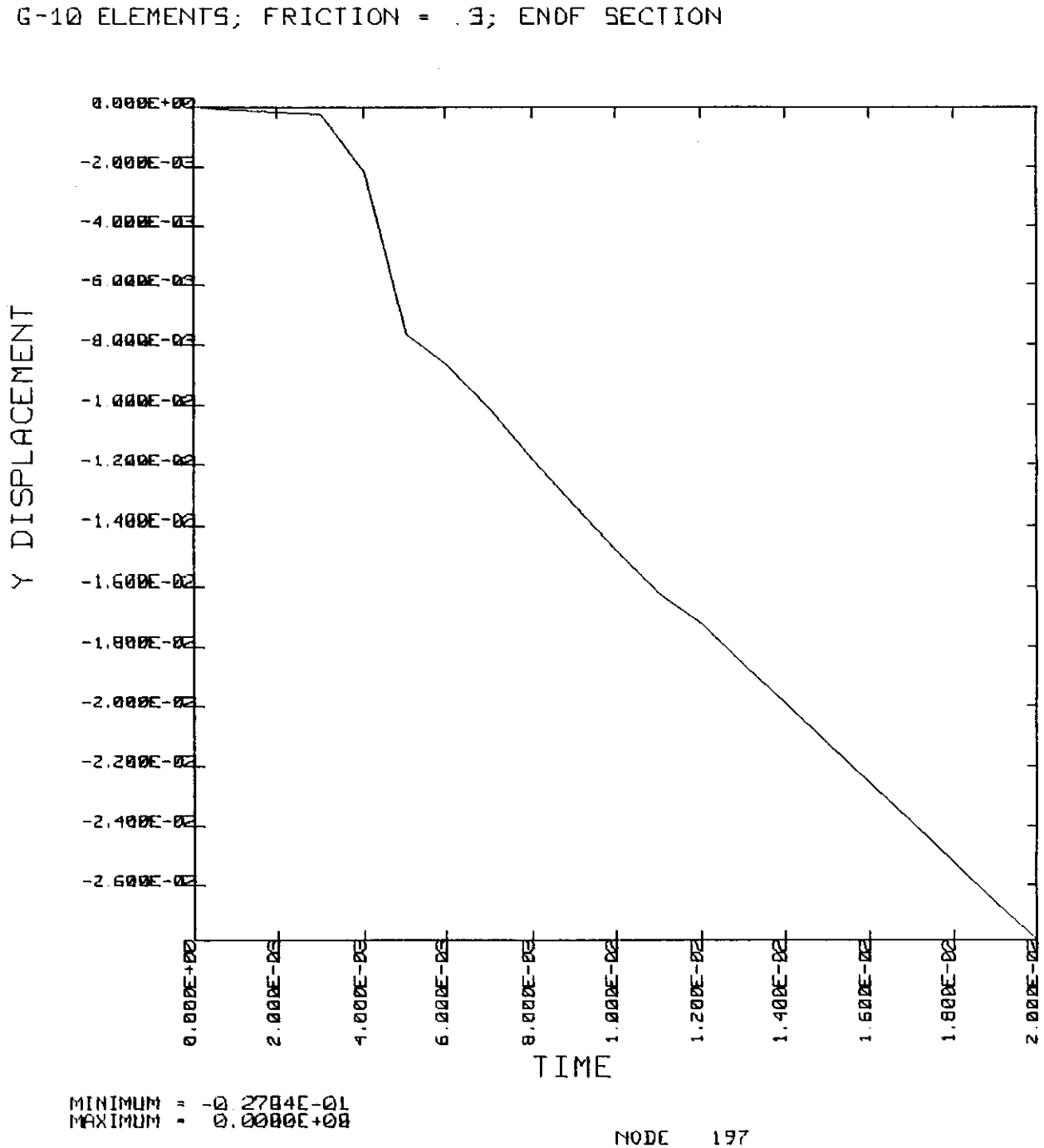

G-10 ELEMENTS; FRICTION = .3; ENDF SECTION
Y DISPLACEMENT
0.000E+00
-2.000E-03
-4.000E-03
-6.000E-03
-8.000E-03
-1.000E-02
-1.200E-02
-1.400E-02
-1.600E-02
-1.800E-02
-2.000E-02
-2.200E-02
-2.400E-02
-2.600E-02
0.000E+00
2.000E-03
4.000E-03
6.000E-03
8.000E-03
1.000E-02
1.200E-02
1.400E-02
1.600E-02
1.800E-02
2.000E-02
TIME
MINIMUM = -0.2784E-01
MAXIMUM = 0.0000E+00
NODE 197

Fig. 26a

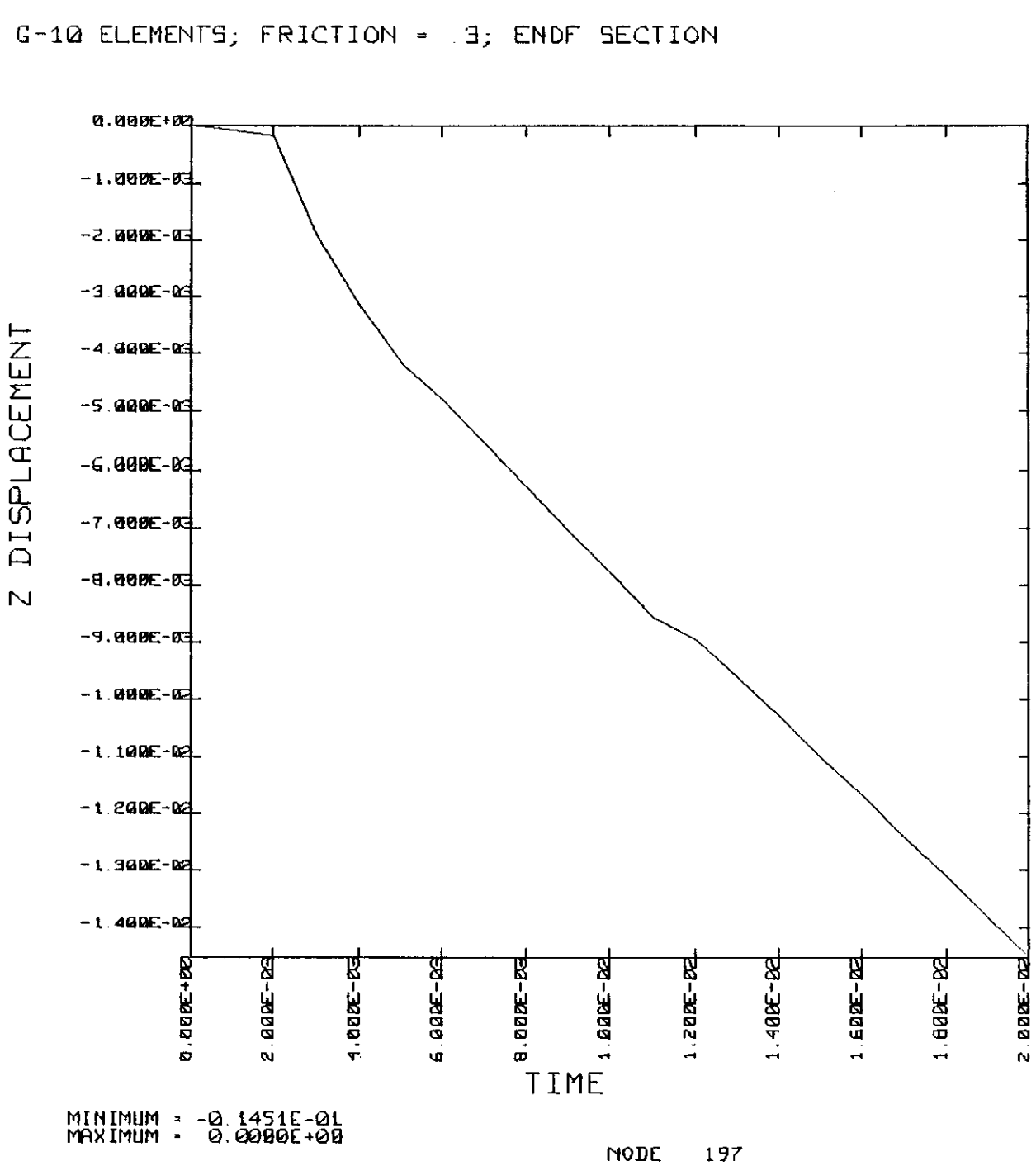

G-10 ELEMENTS; FRICTION = .3; ENDF SECTION
Z DISPLACEMENT
TIME
MINIMUM = -0.1451E-01
MAXIMUM = 0.0000E+00
NODE 197

Fig. 26b

G-10 NO FRICTION - END SECTION; ASSEMBLY PRESSURE

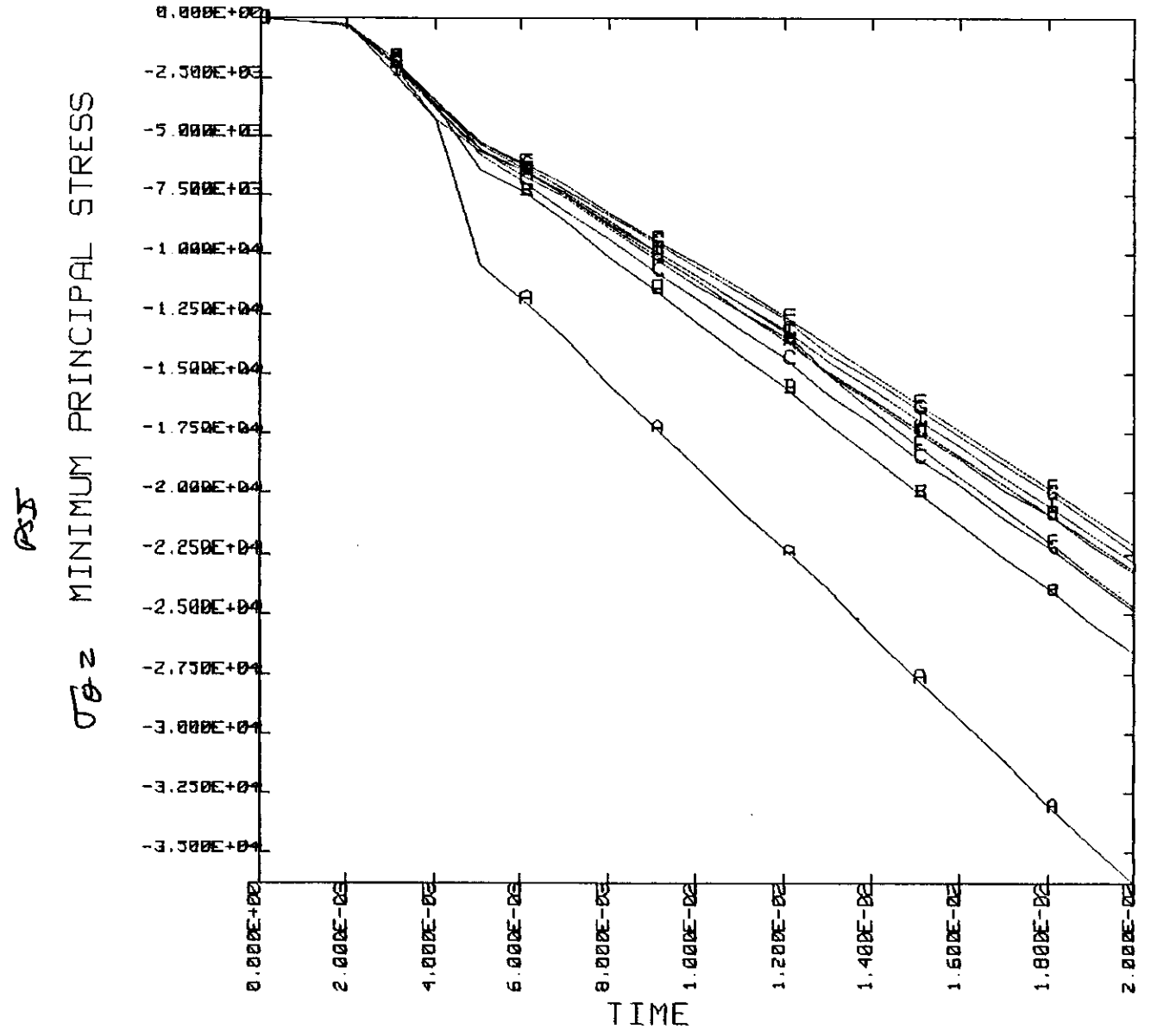


Fig. 27

G-10 NO FRICTION - END SECTION; ASSEMBLY PRESSURE

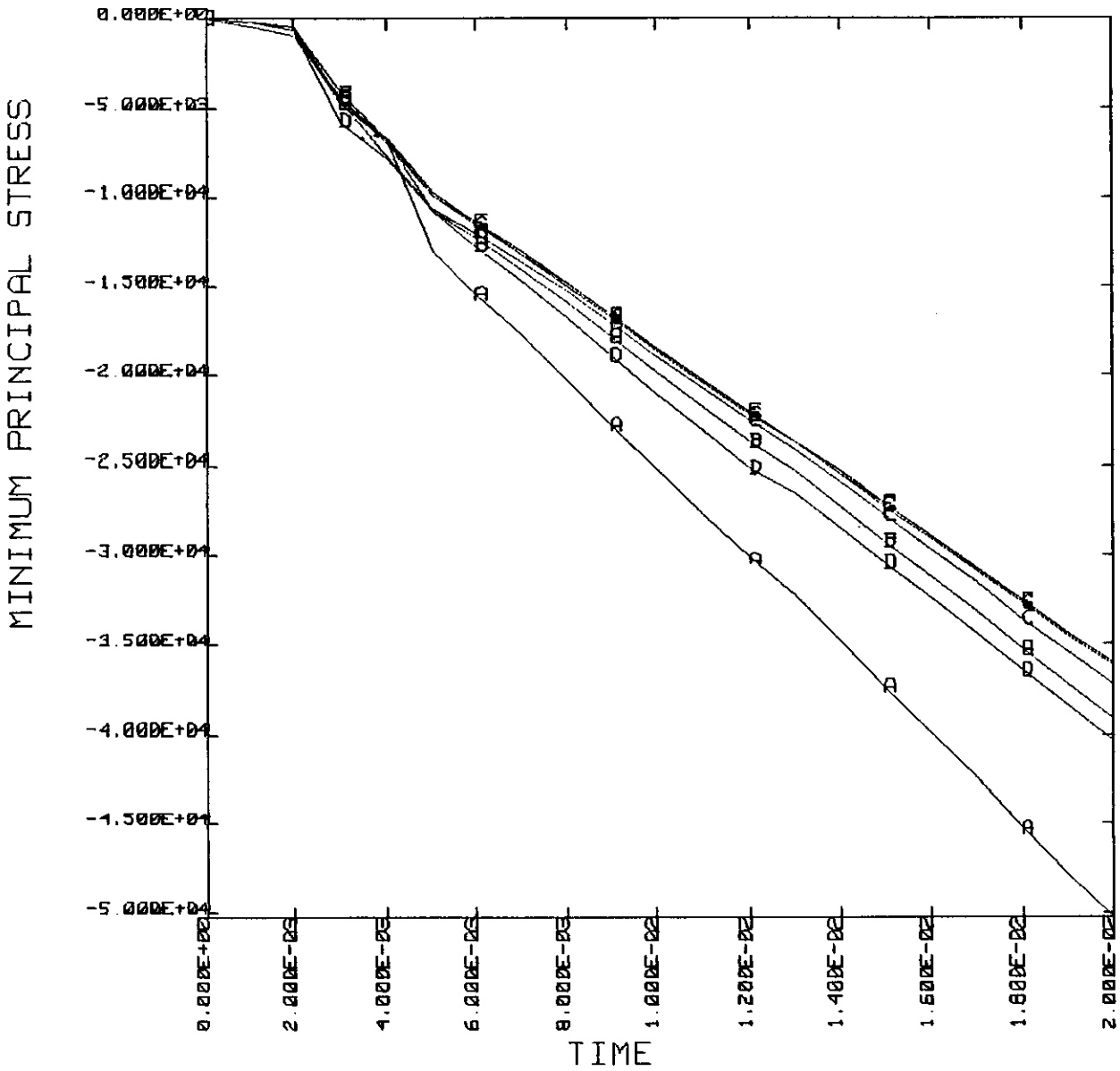


Fig. 28

G-10 NO FRICTION - END SECTION G-10 ELEMENTS

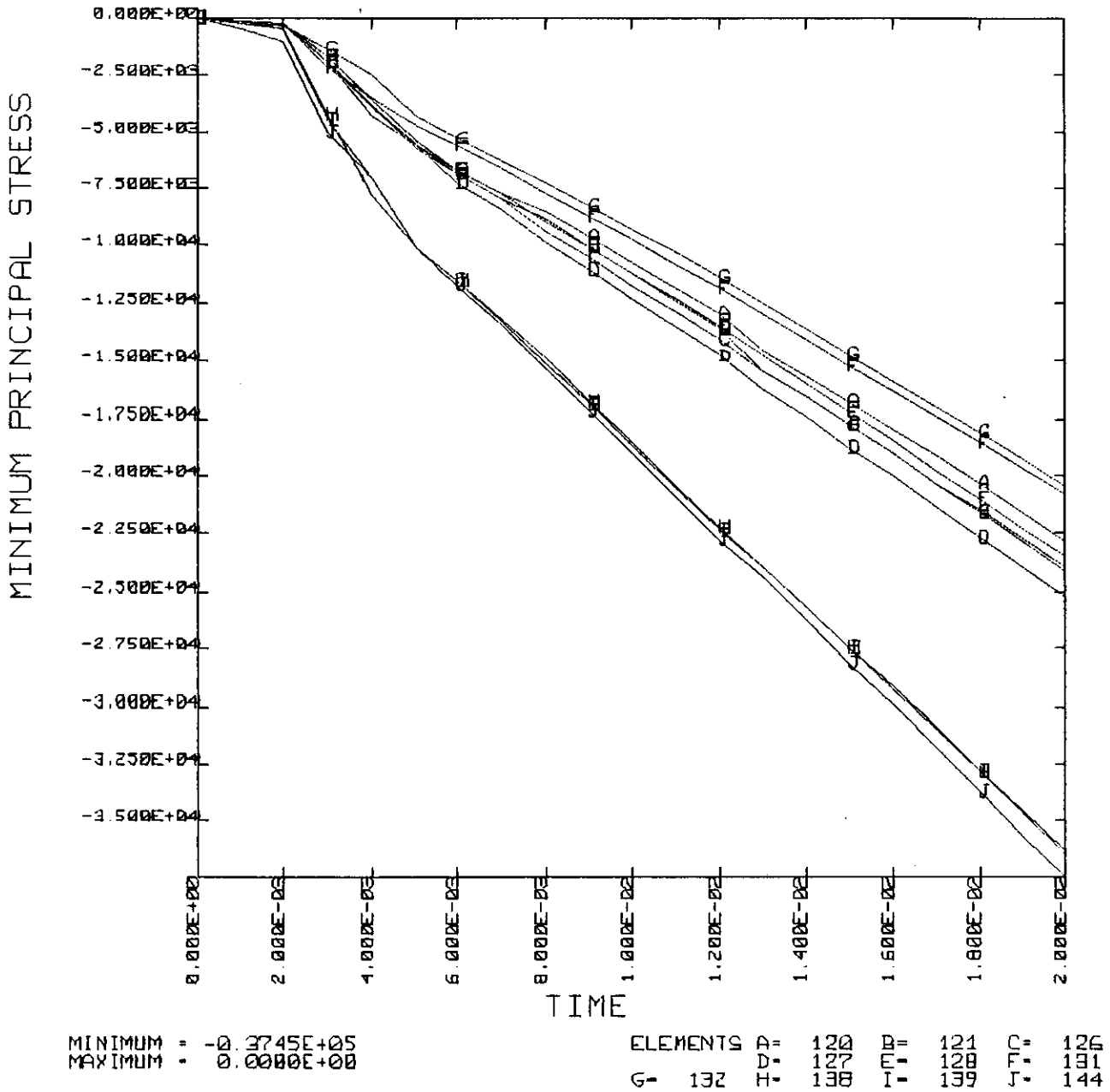


Fig. 29

G-10 NO FRICTION - END SECTION; ASSEMBLY PRESSURE

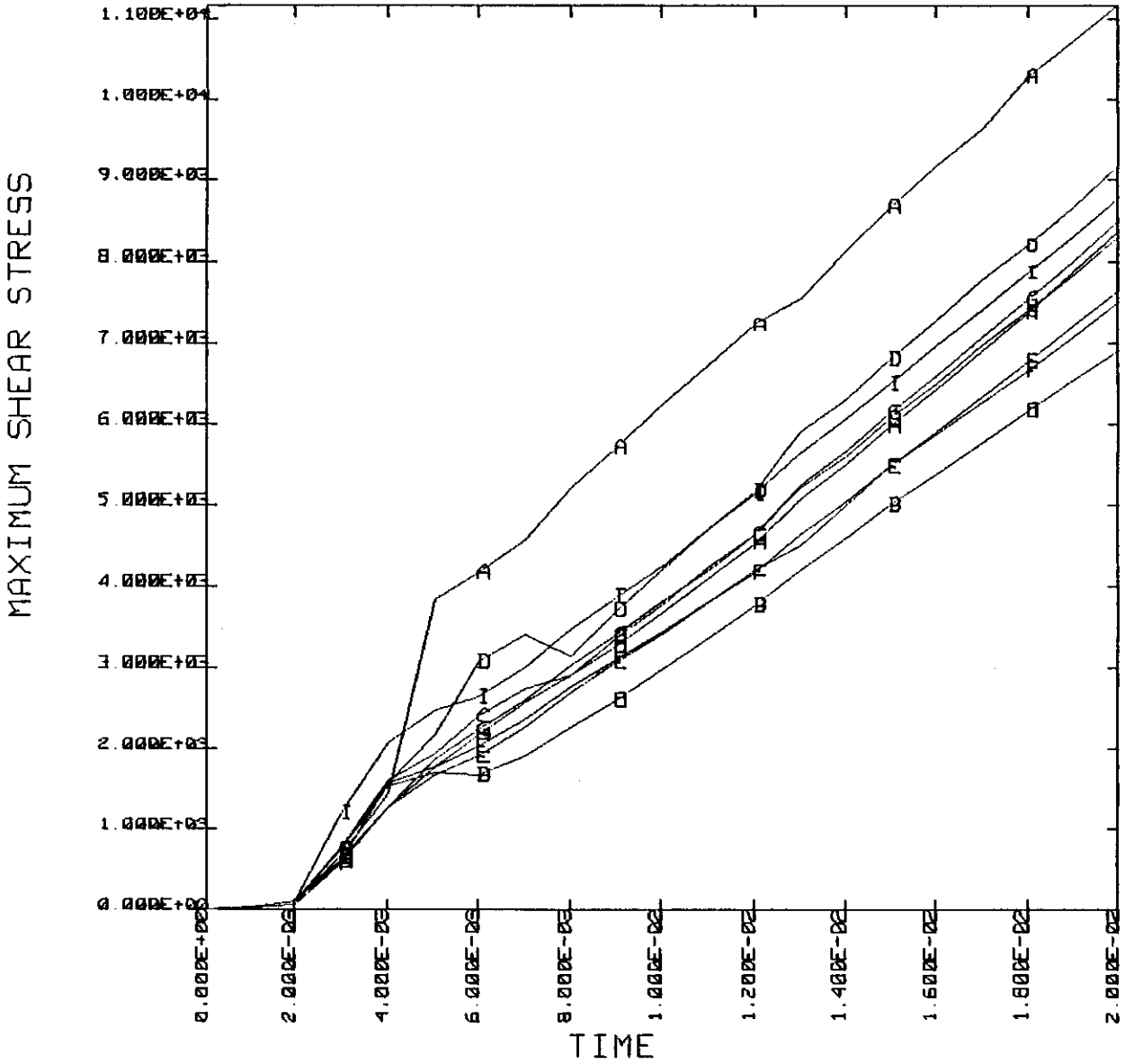


Fig. 30

G-10 NO FRICTION - END SECTION; ASSEMBLY PRESSURE

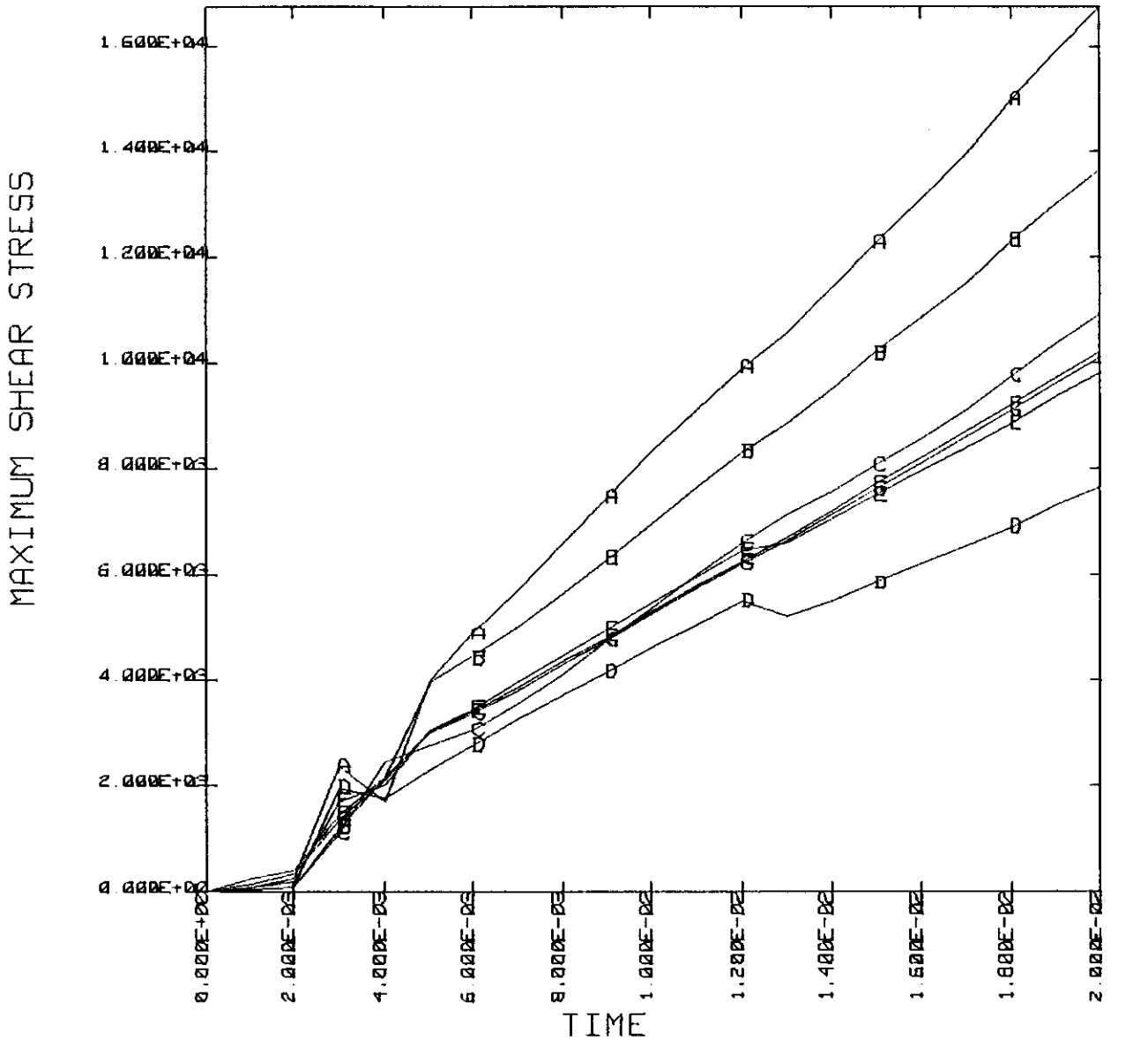


Fig. 31

G-10 NO FRICTION - END SECTION G-10 ELEMENTS

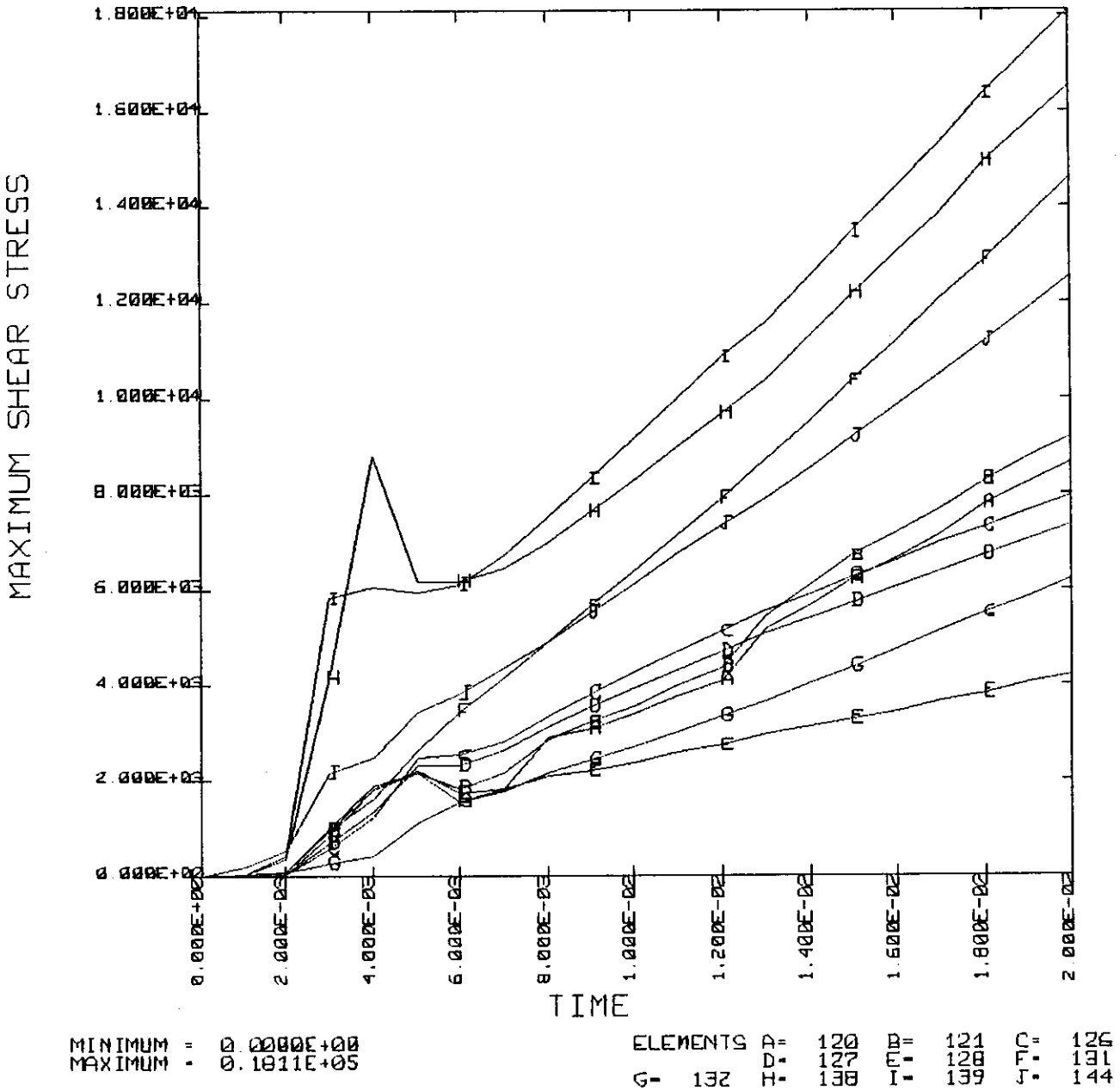


Fig. 32

G-10 NO FRICTION - END SECTION, ASSEMBLY PRESSURE

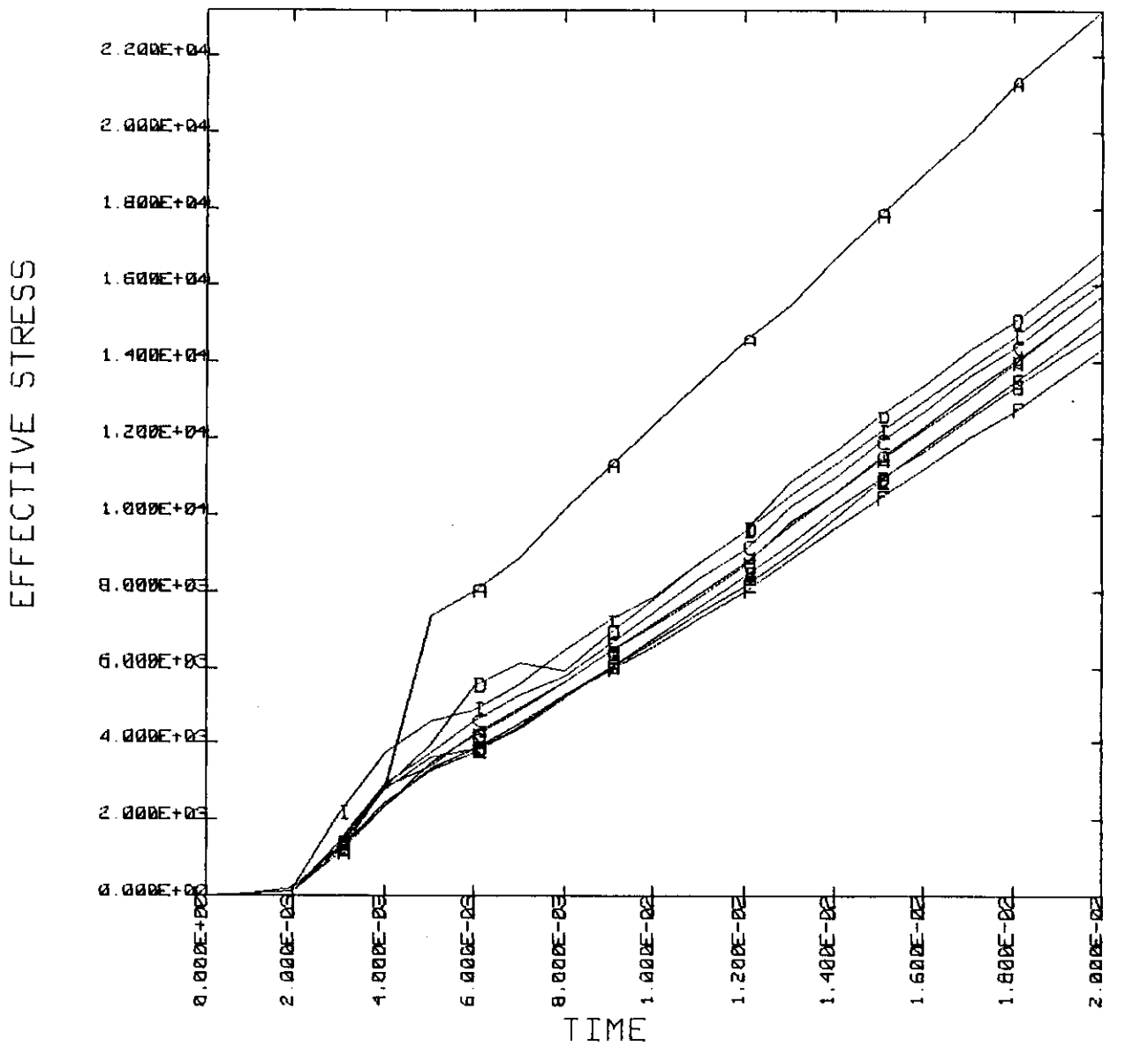


Fig. 33

G-10 NO FRICTION - END SECTION, ASSEMBLY PRESSURE

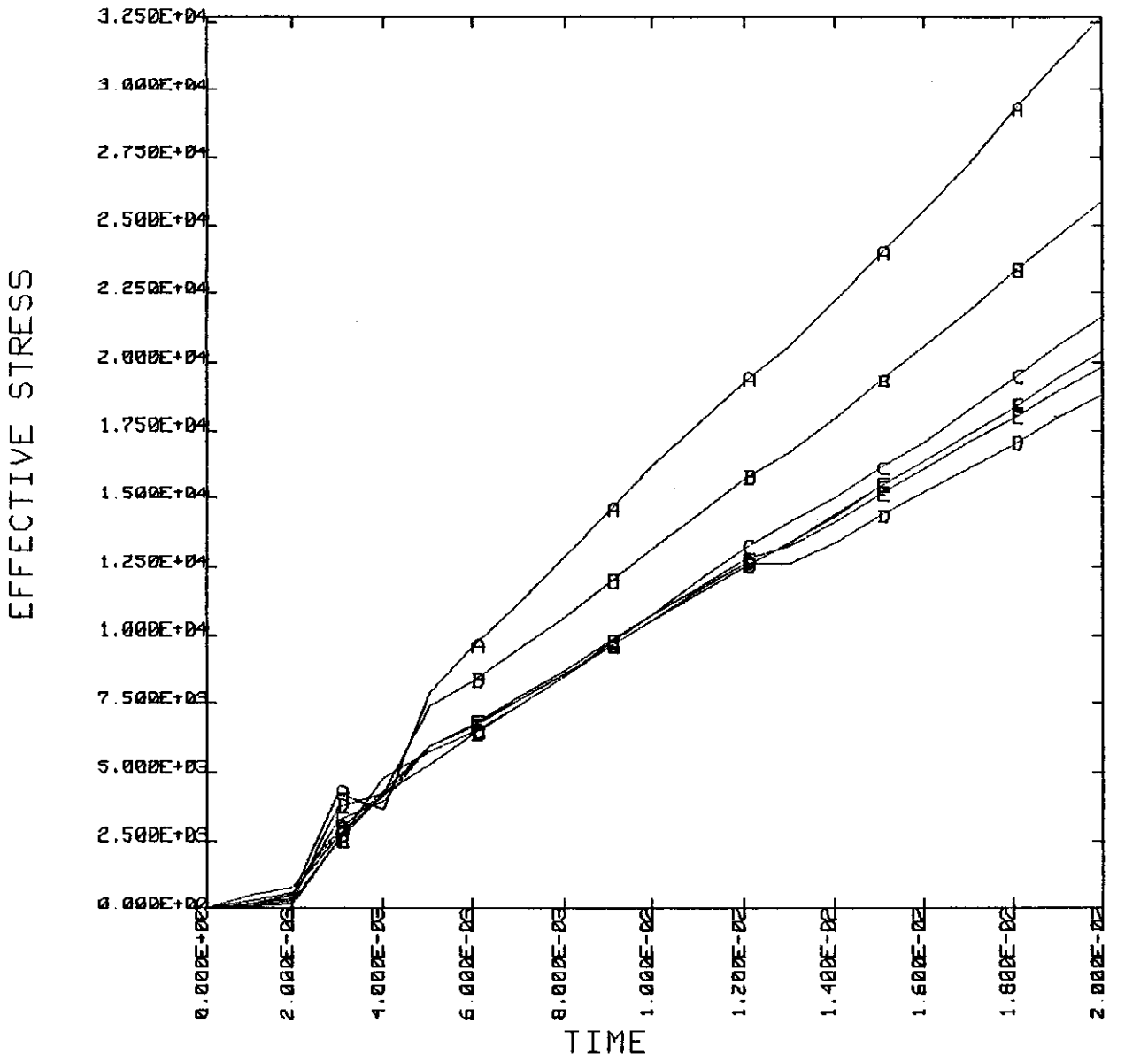


Fig. 34

G-10 NO FRICTION - END SECTION G-10 ELEMENTS

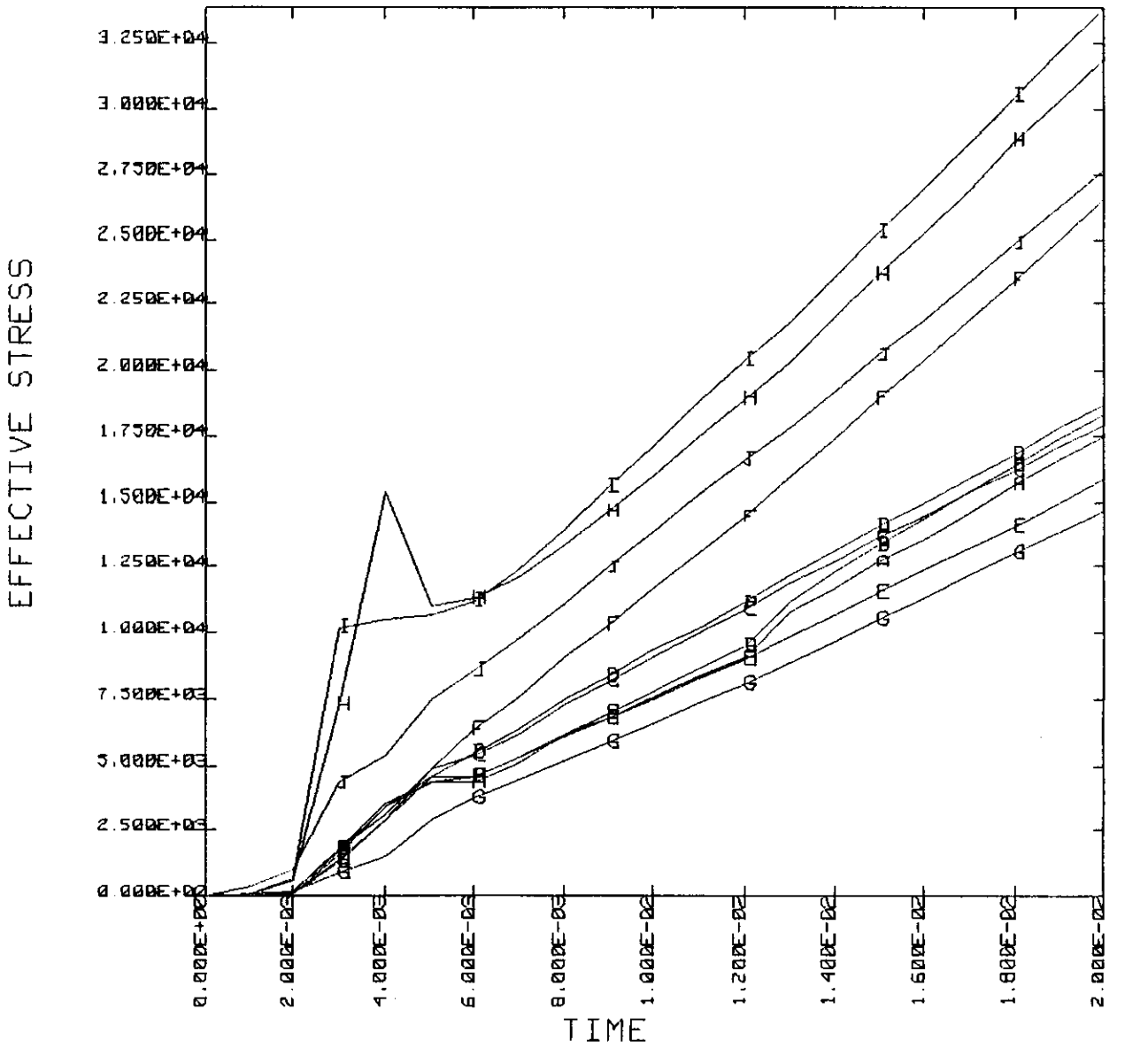


Fig. 35

G-10 NO FRICTION - END SECTION; ASSEMBLY PRESSURE

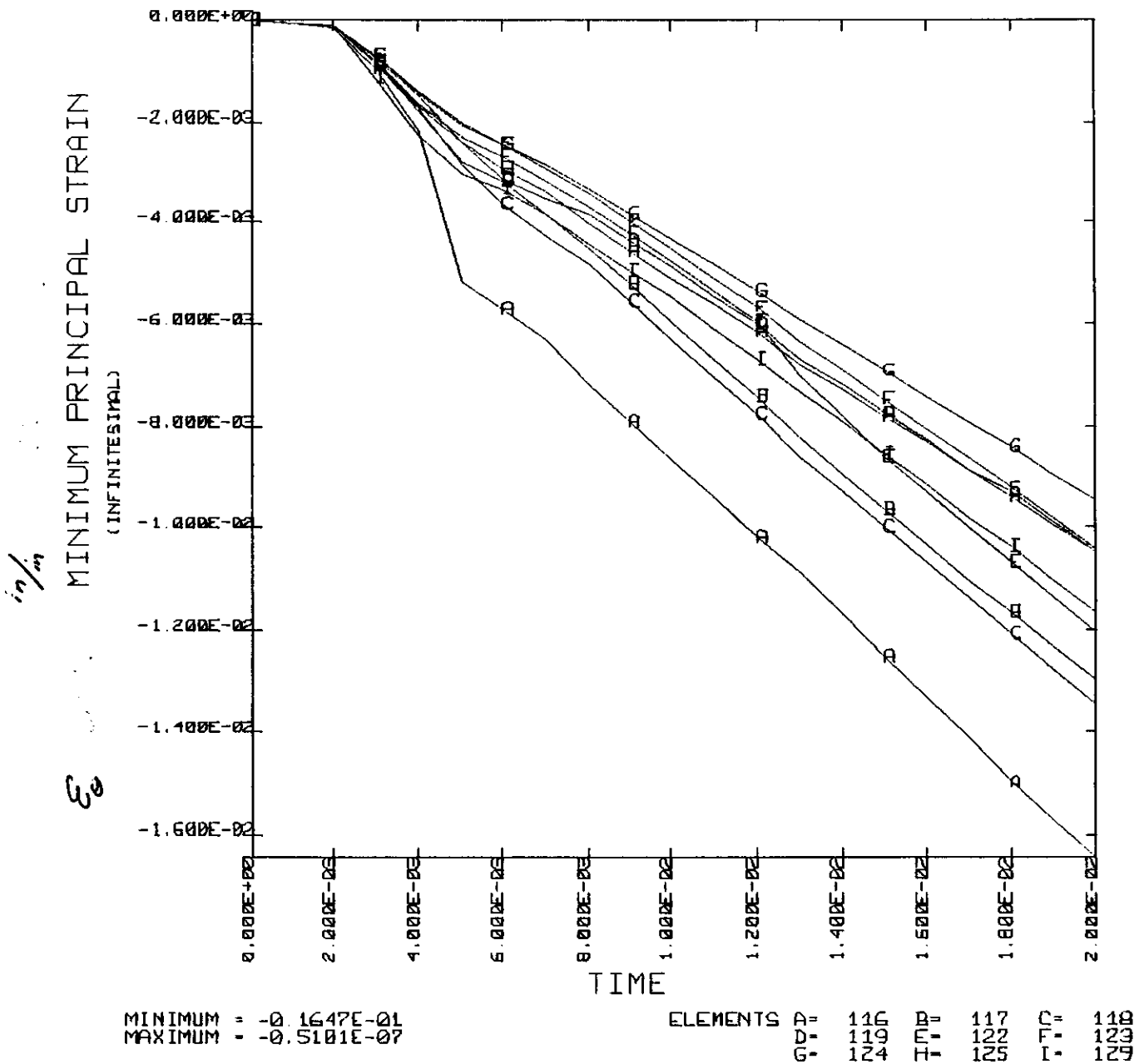


Fig. 36

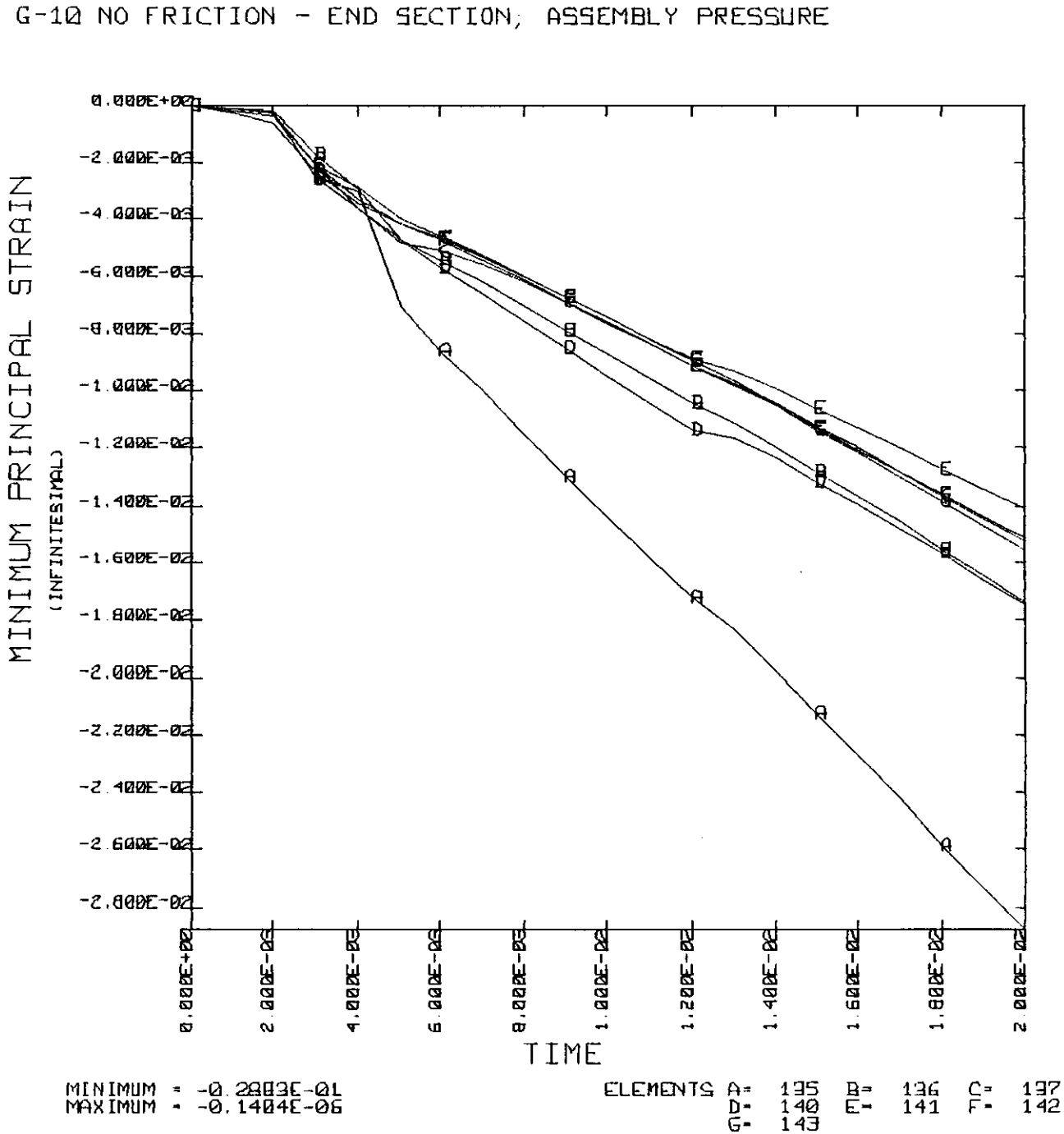

G-10 NO FRICTION - END SECTION; ASSEMBLY PRESSURE
MINIMUM PRINCIPAL STRAIN
(INFINITESIMAL)
0.000E+00
-2.000E-03
-4.000E-03
-6.000E-03
-8.000E-03
-1.000E-02
-1.200E-02
-1.400E-02
-1.600E-02
-1.800E-02
-2.000E-02
-2.200E-02
-2.400E-02
-2.600E-02
-2.800E-02
0.000E+00
2.000E-03
4.000E-03
6.000E-03
8.000E-03
1.000E-02
1.200E-02
1.400E-02
1.600E-02
1.800E-02
2.000E-02
TIME
MINIMUM = -0.2803E-01
MAXIMUM = -0.1404E-06
ELEMENTS A= 135 B= 136 C= 137
D= 140 E= 141 F= 142
G= 143

Fig. 37

G-10 NO FRICTION - END SECTION; ASSEMBLY PRESSURE

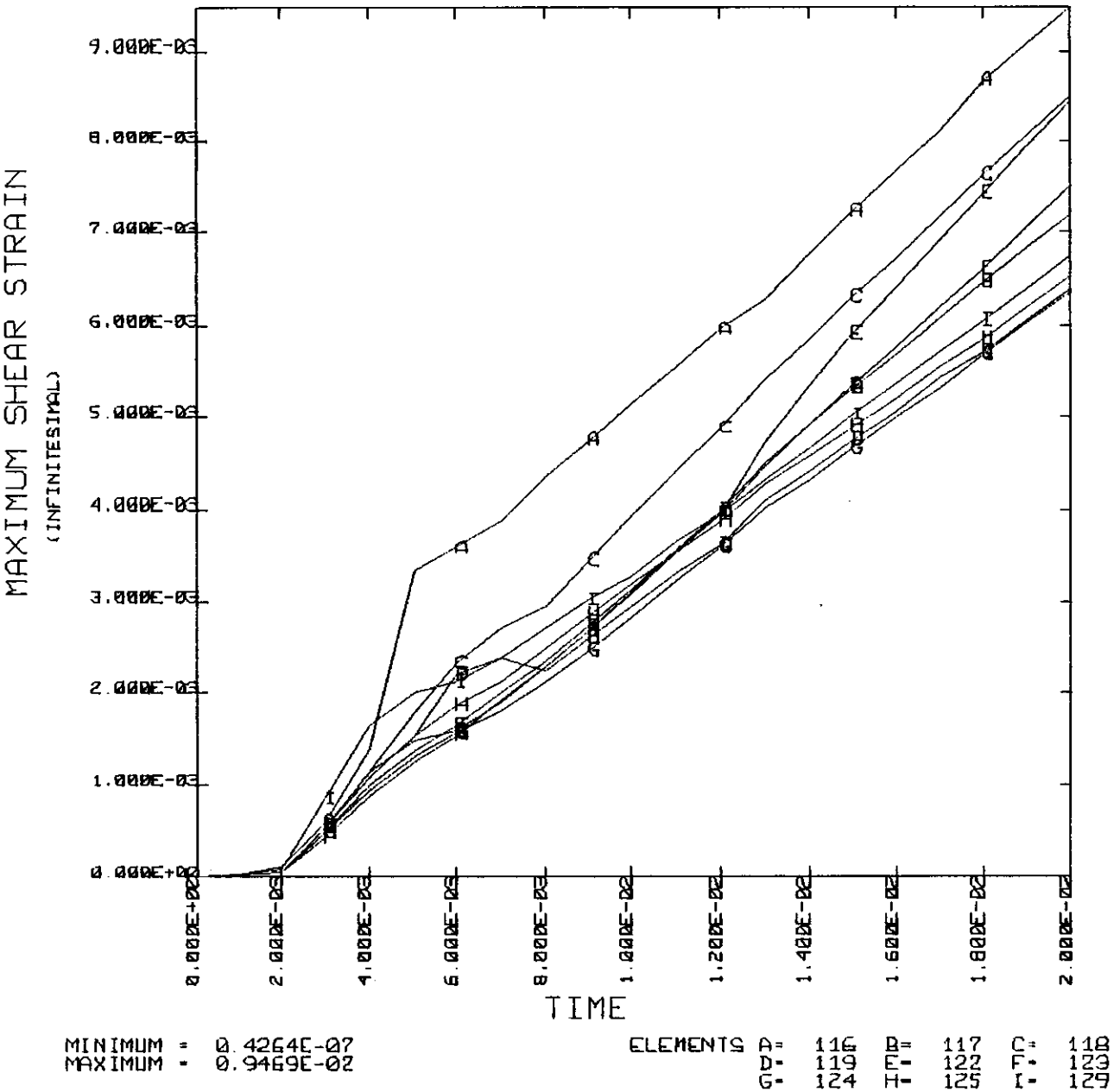


Fig. 38

G-10 NO FRICTION - END SECTION; ASSEMBLY PRESSURE

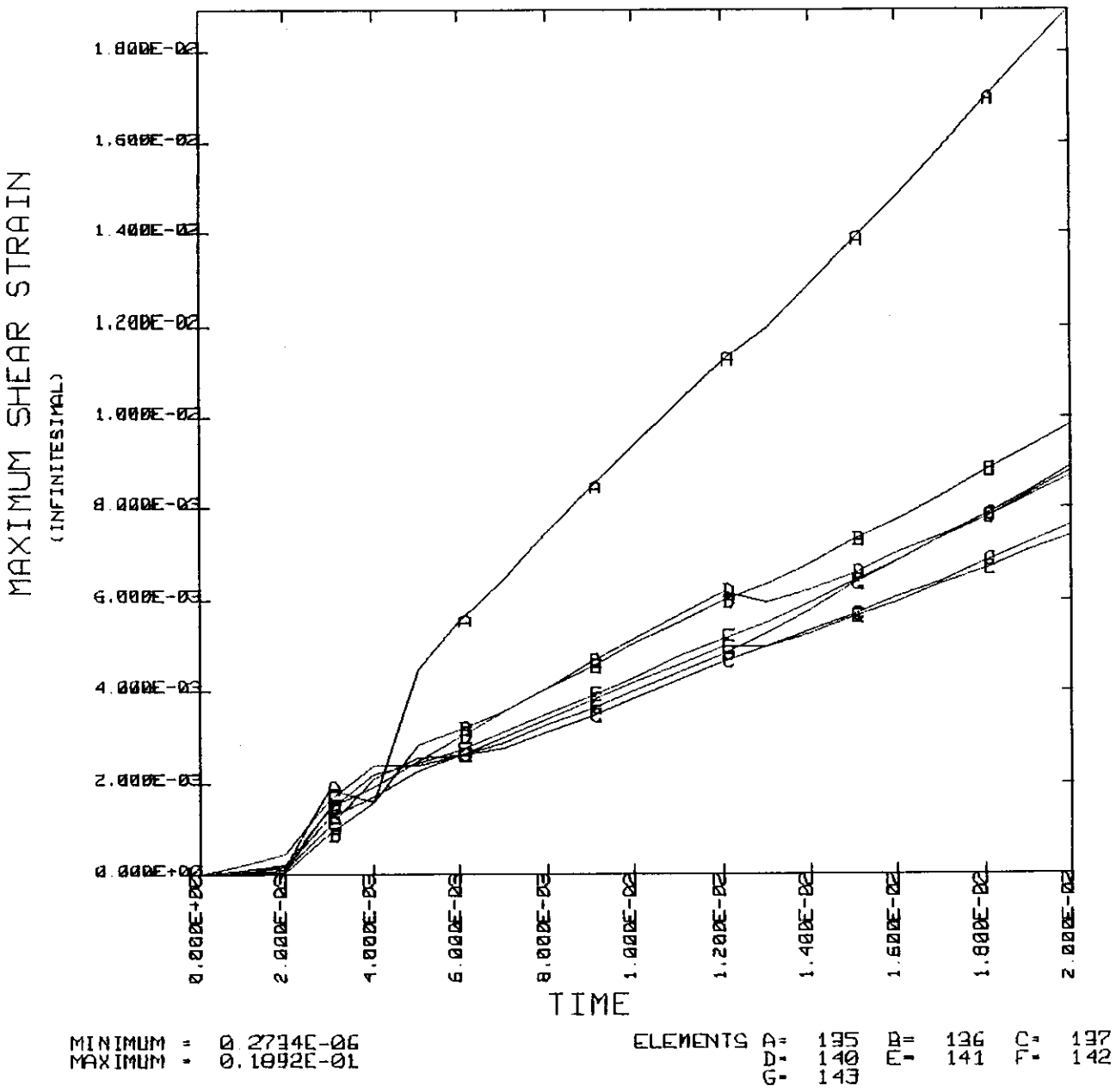


Fig. 39

G-10 NO FRICTION - END SECTION G-10 ELEMENTS

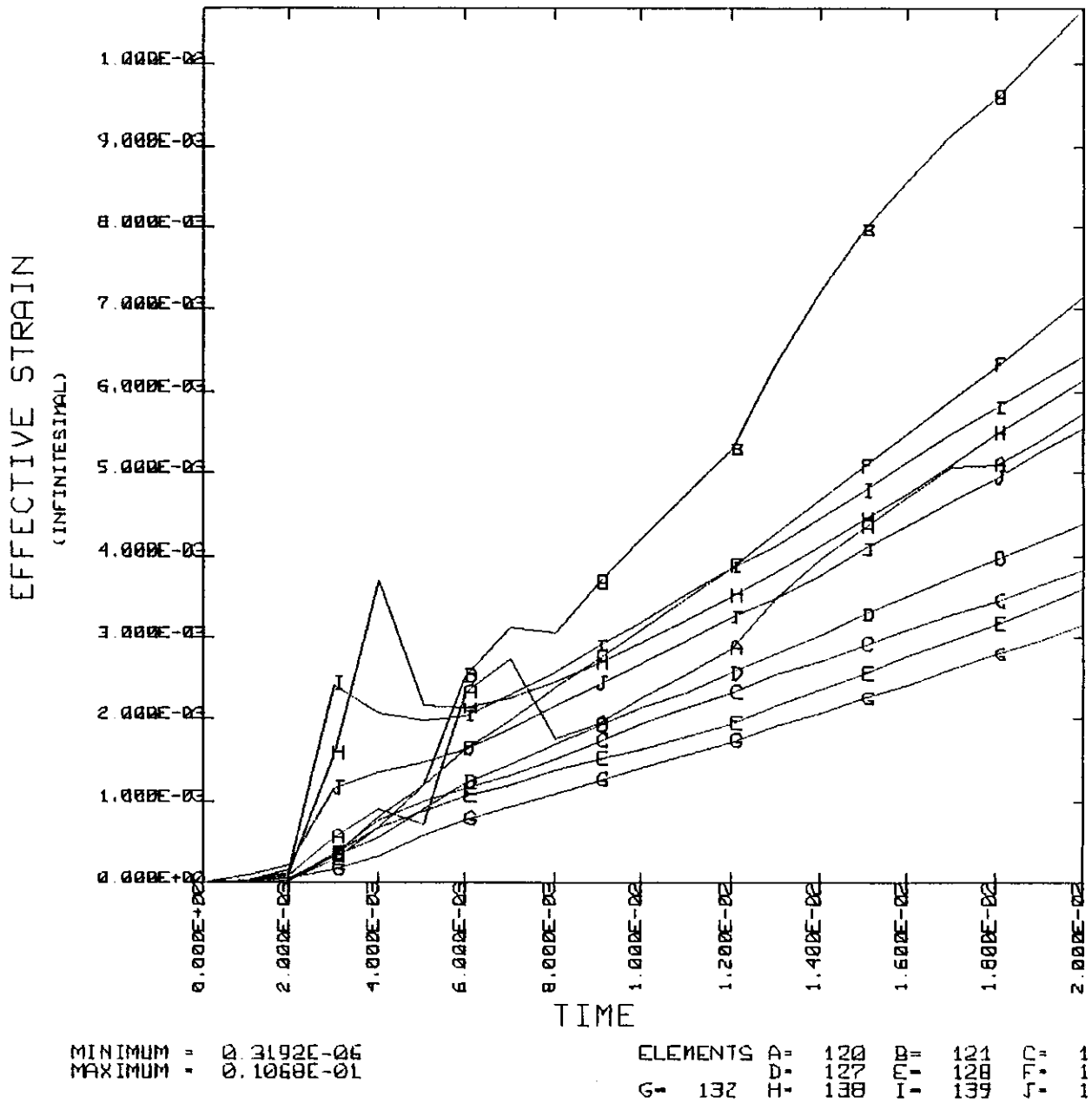


Fig. 40

G-10 NO FRICTION - END SECTION; ASSEMBLY PRESSURE

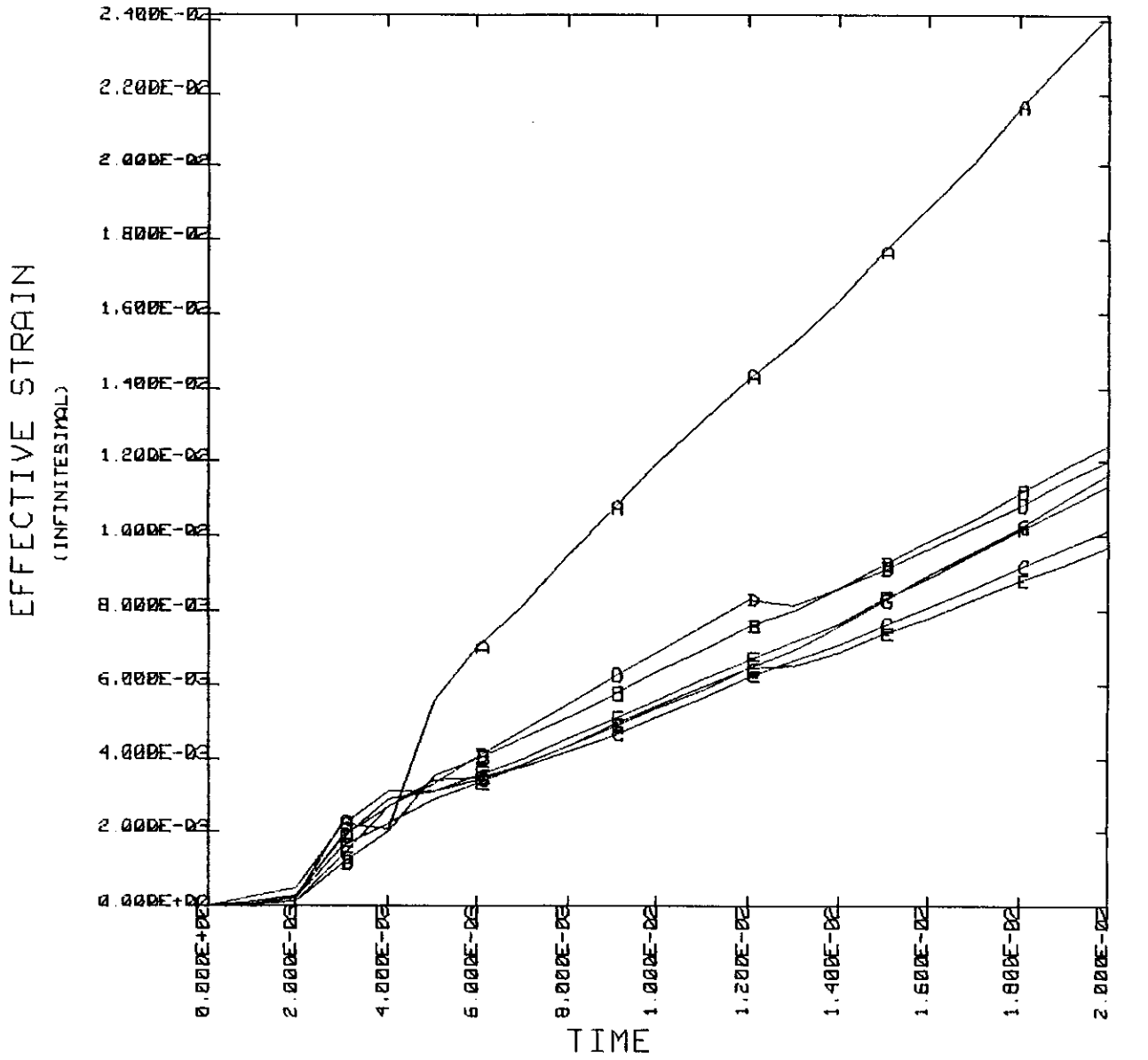


Fig. 41

G-10 NO FRICTION - END SECTION; ASSEMBLY PRESSURE

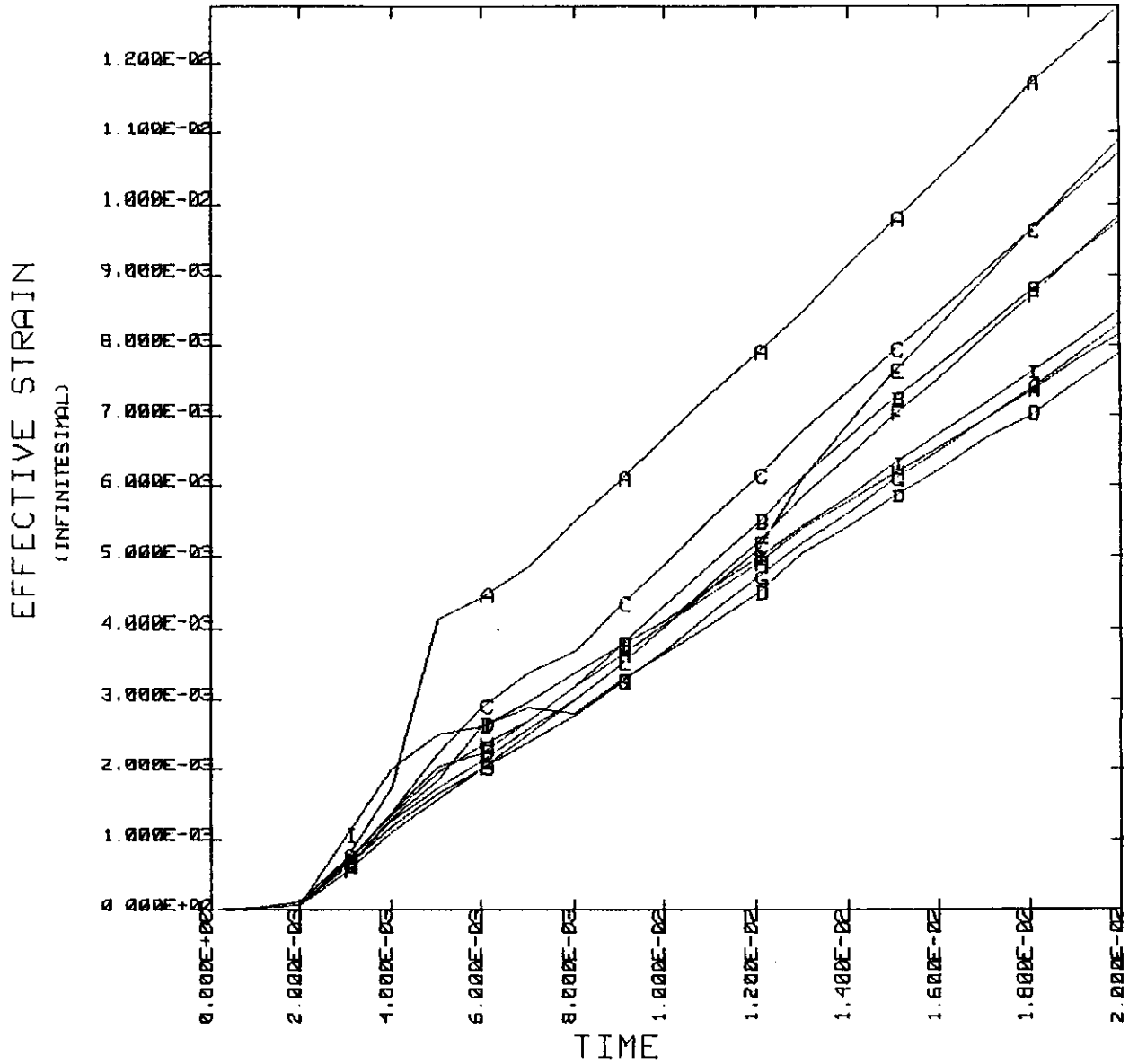


Fig.42

G-10 NO FRICTION - END SECTION, ASSEMBLY PRESSURE

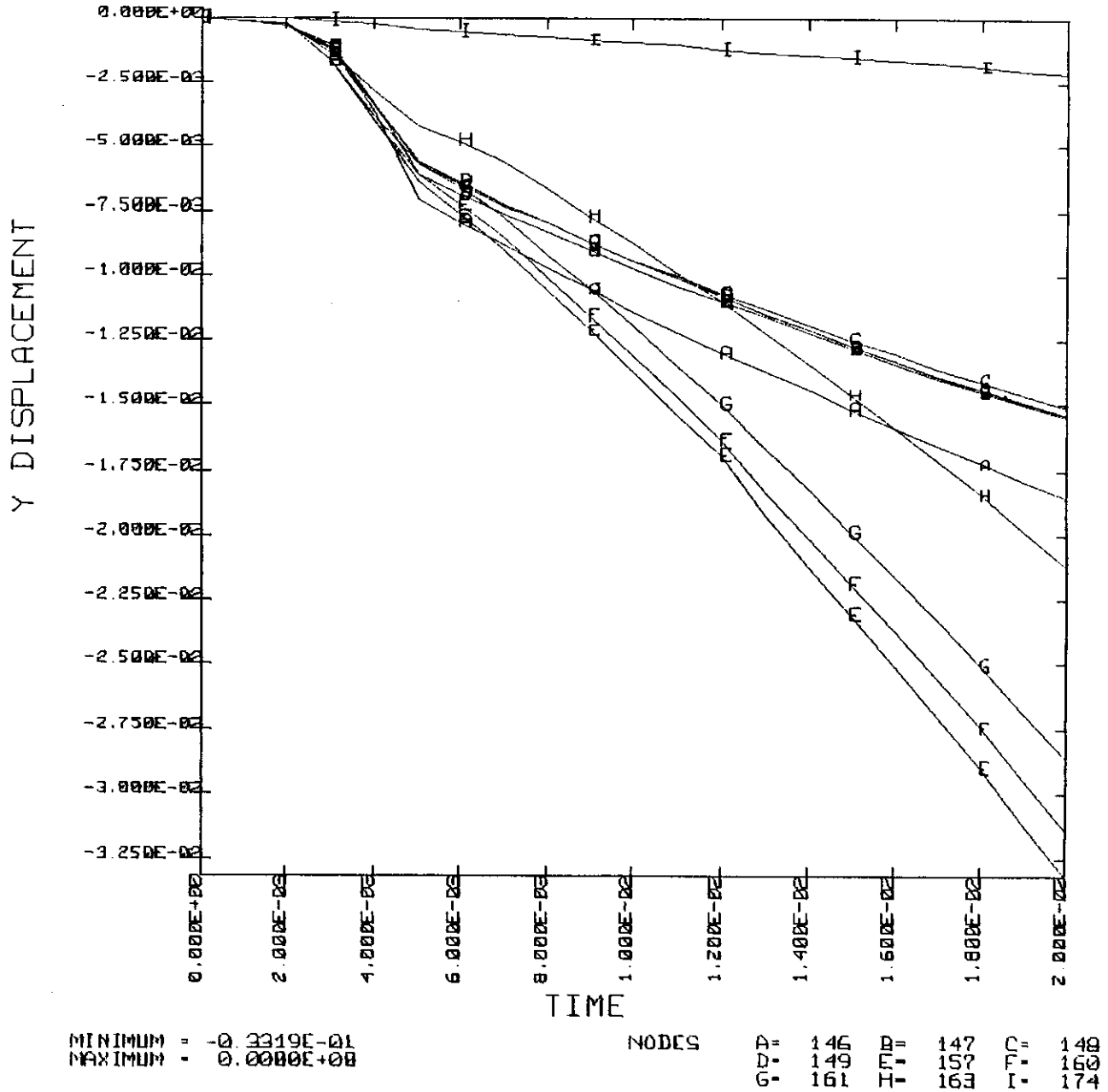


Fig. 43

G-10 NO FRICTION - END SECTION; ASSEMBLY PRESSURE

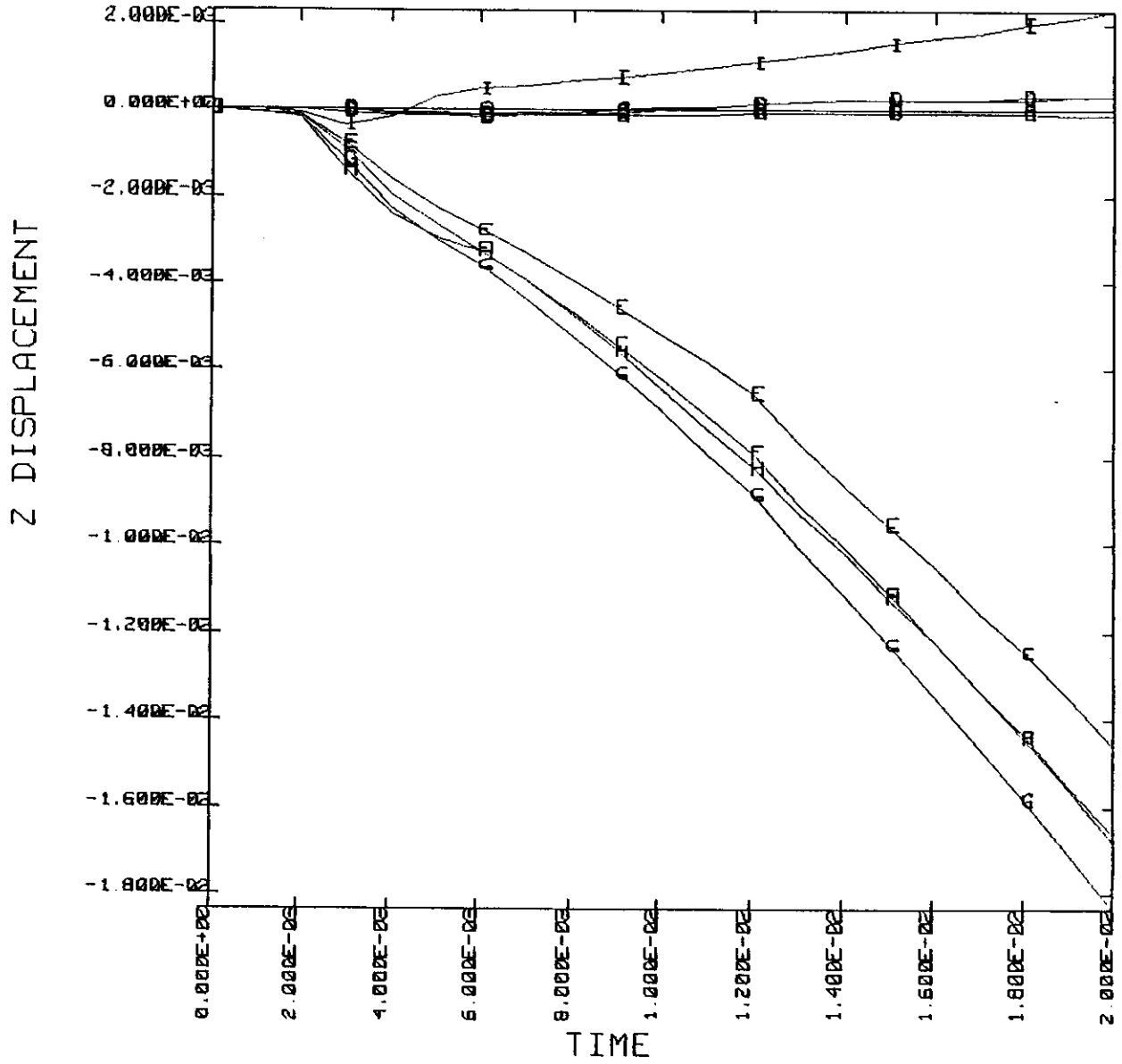


Fig. 44

G-10 NO FRICTION - END SECTION; ASSEMBLY PRESSURE

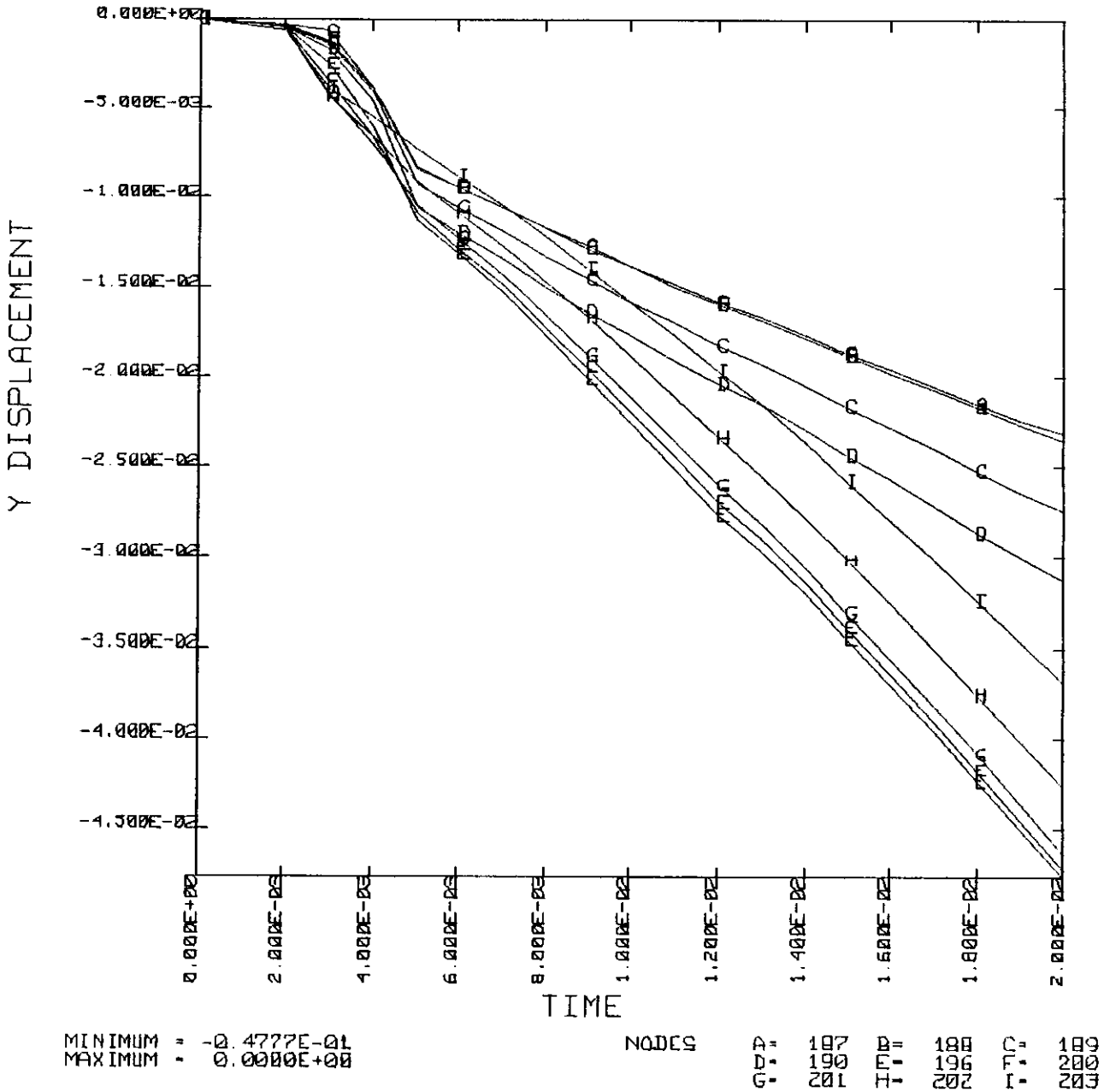


Fig. 45

G-10 NO FRICTION - END SECTION; ASSEMBLY PRESSURE

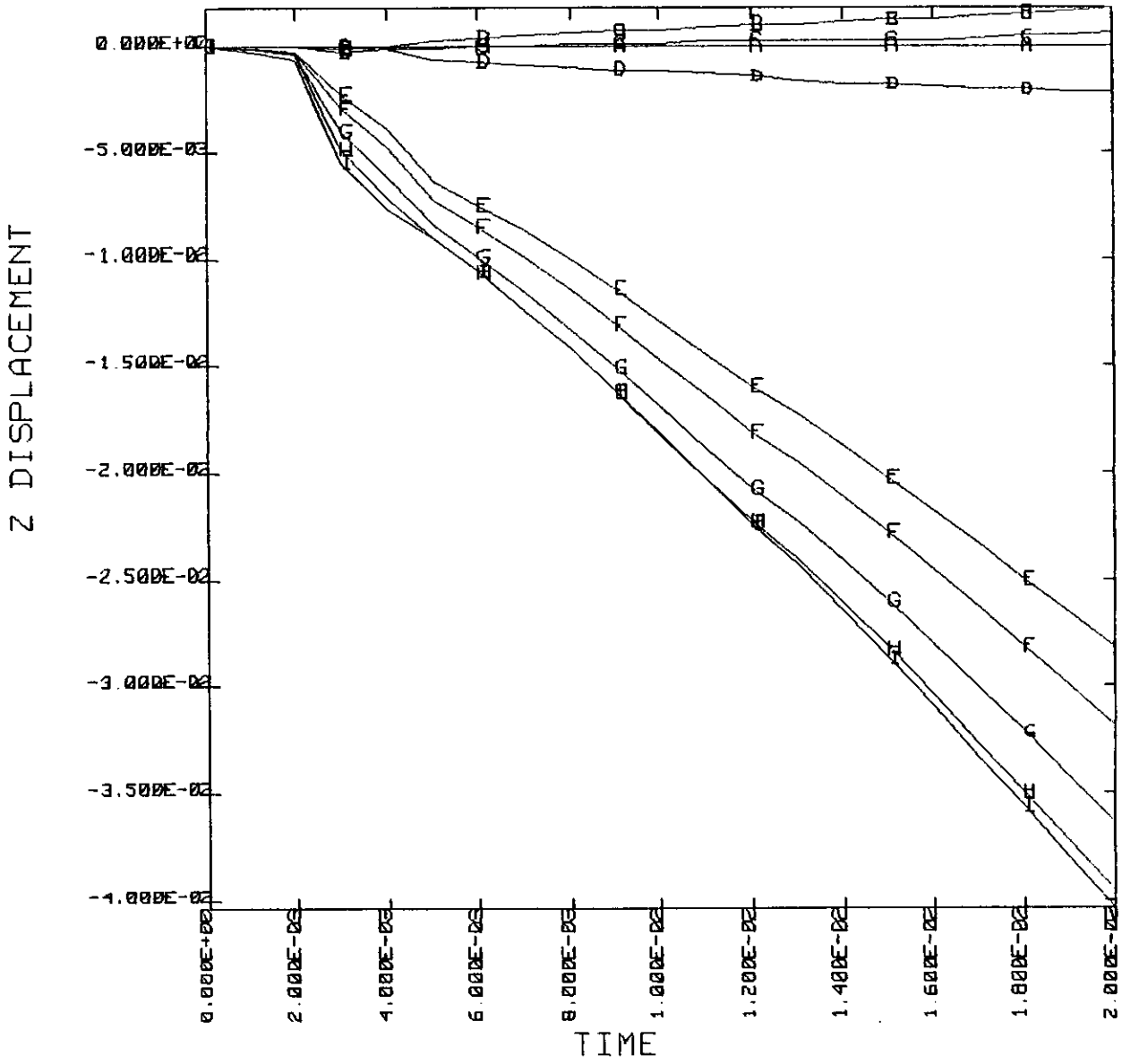
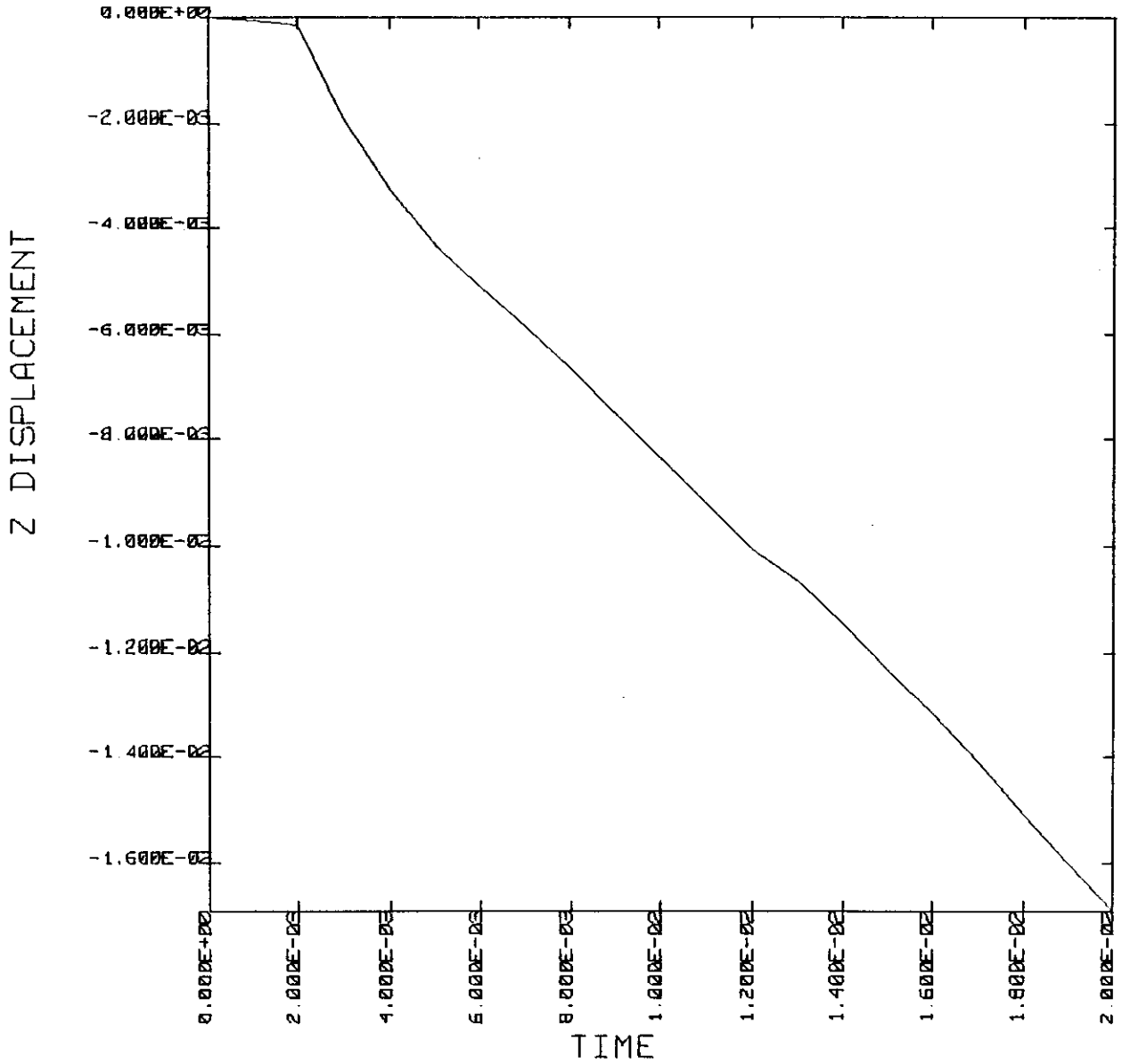


Fig. 46

G-10 NO FRICTION - END SECTION G-10 ELEMENTS



MINIMUM = -0.1693E-01
MAXIMUM = 0.0000E+00

NODE 197

Fig. 47

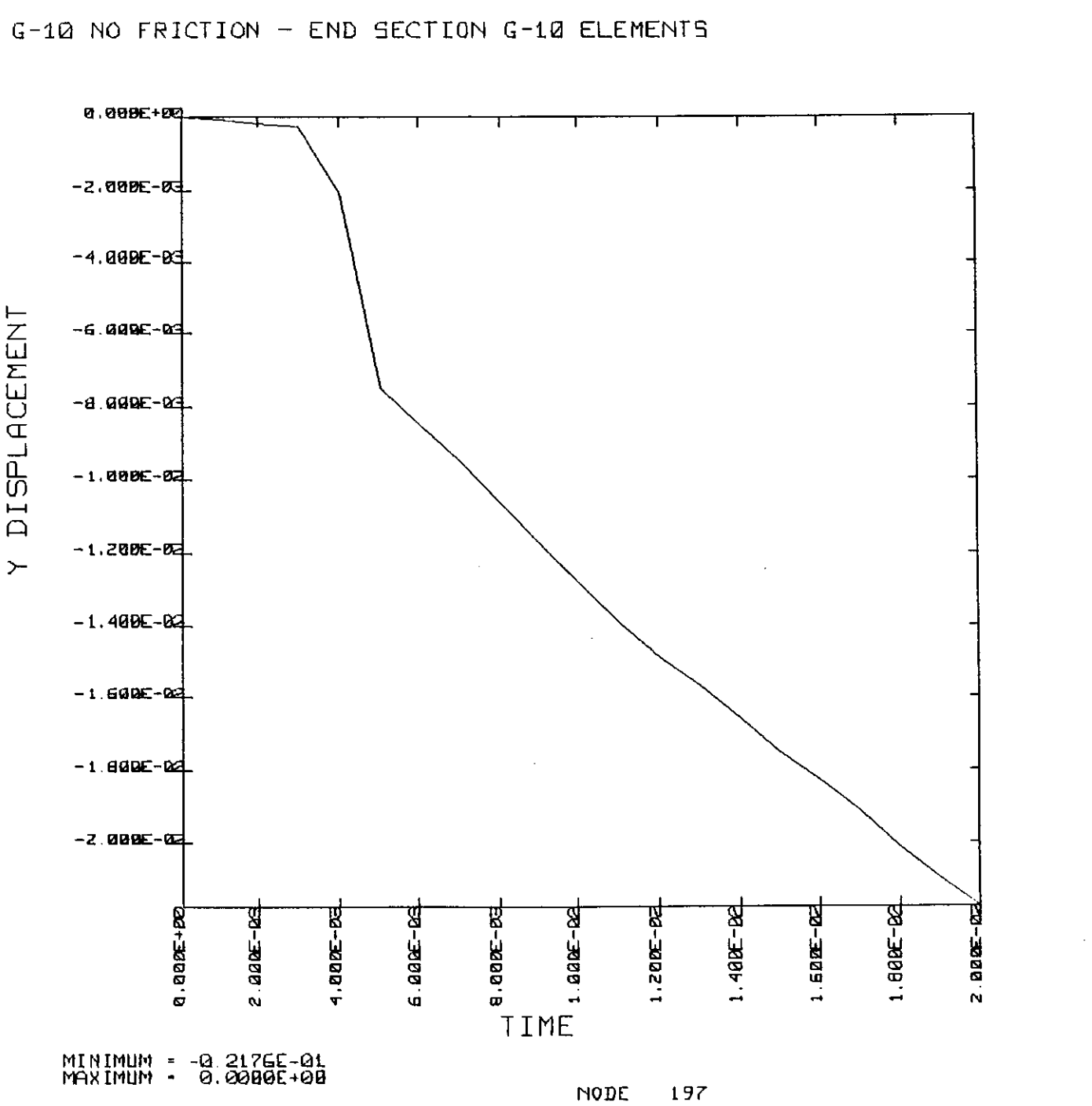
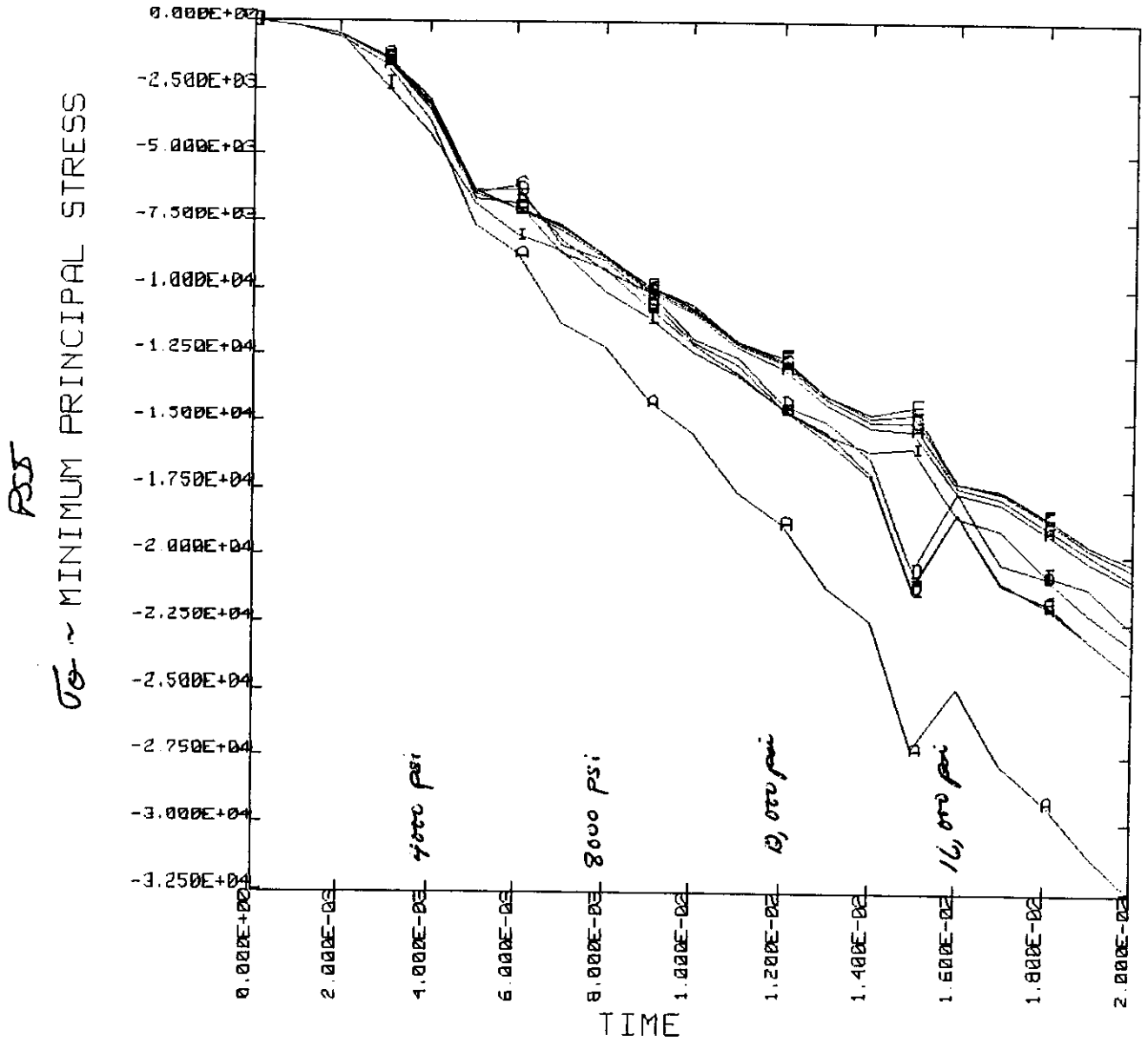

G-10 NO FRICTION - END SECTION G-10 ELEMENTS
Y DISPLACEMENT
0.000E+00
-2.000E-03
-4.000E-03
-6.000E-03
-8.000E-03
-1.000E-02
-1.200E-02
-1.400E-02
-1.600E-02
-1.800E-02
-2.000E-02
0.000E+00
2.000E-03
4.000E-03
6.000E-03
8.000E-03
1.000E-02
1.200E-02
1.400E-02
1.600E-02
1.800E-02
2.000E-02
TIME
MINIMUM = -0.2176E-01
MAXIMUM = 0.0000E+00
NODE 197

Fig. 48

ASSEMBLY PRESSURE - STEEL COLLAR - FRICTION (.3)

COPPER WEDGES



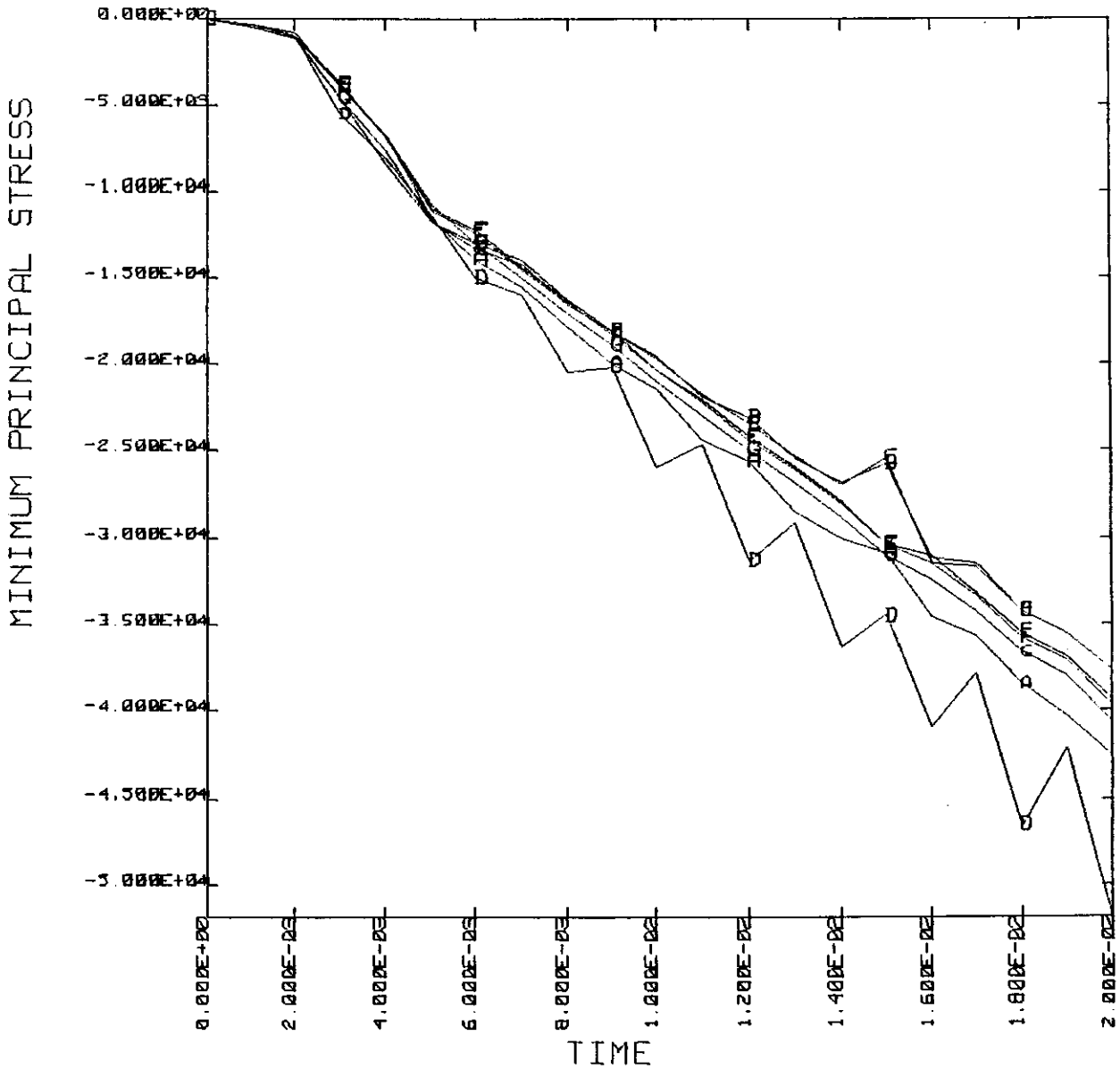
MINIMUM = -0.3265E+05
MAXIMUM = 0.0000E+00

ELEMENTS A= 116 B= 117 C= 118
D= 119 E= 122 F= 123
G= 124 H= 125 I= 129

Fig. 49

Inner Coil Elements

ASSEMBLY PRESSURE - STEEL COLLAR - FRICTION (.3)



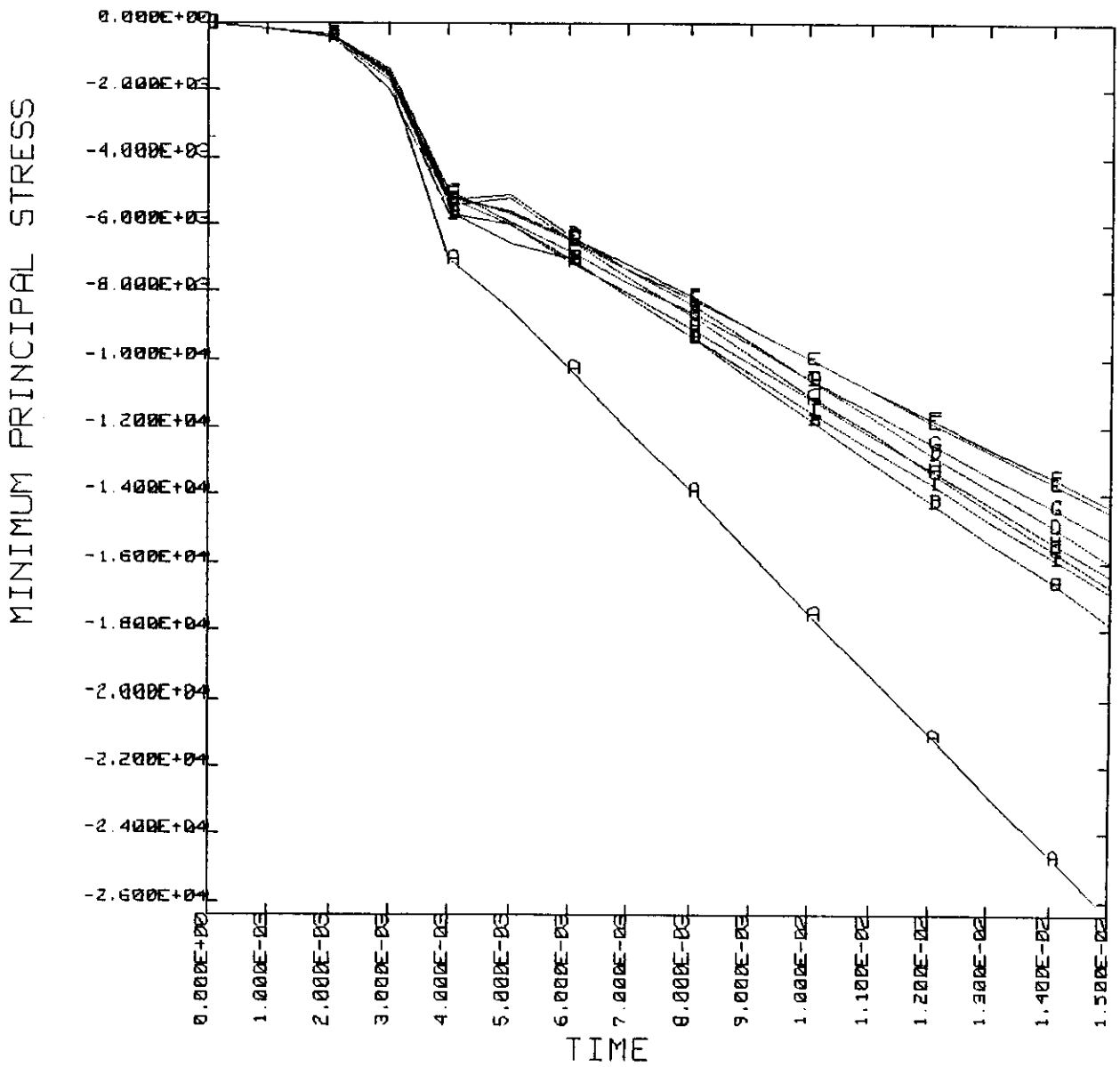
MINIMUM = -0.5107E+05
MAXIMUM = 0.0000E+00

ELEMENTS A= 135 B= 136 C= 137
D= 140 E= 141 F= 142
G= 143

Fig. 50

Outer Coil Element

ASSEMBLY PRESSURE - G-10 WEDGES/COLLAR -FRICTION 3/WEDGES BONDED

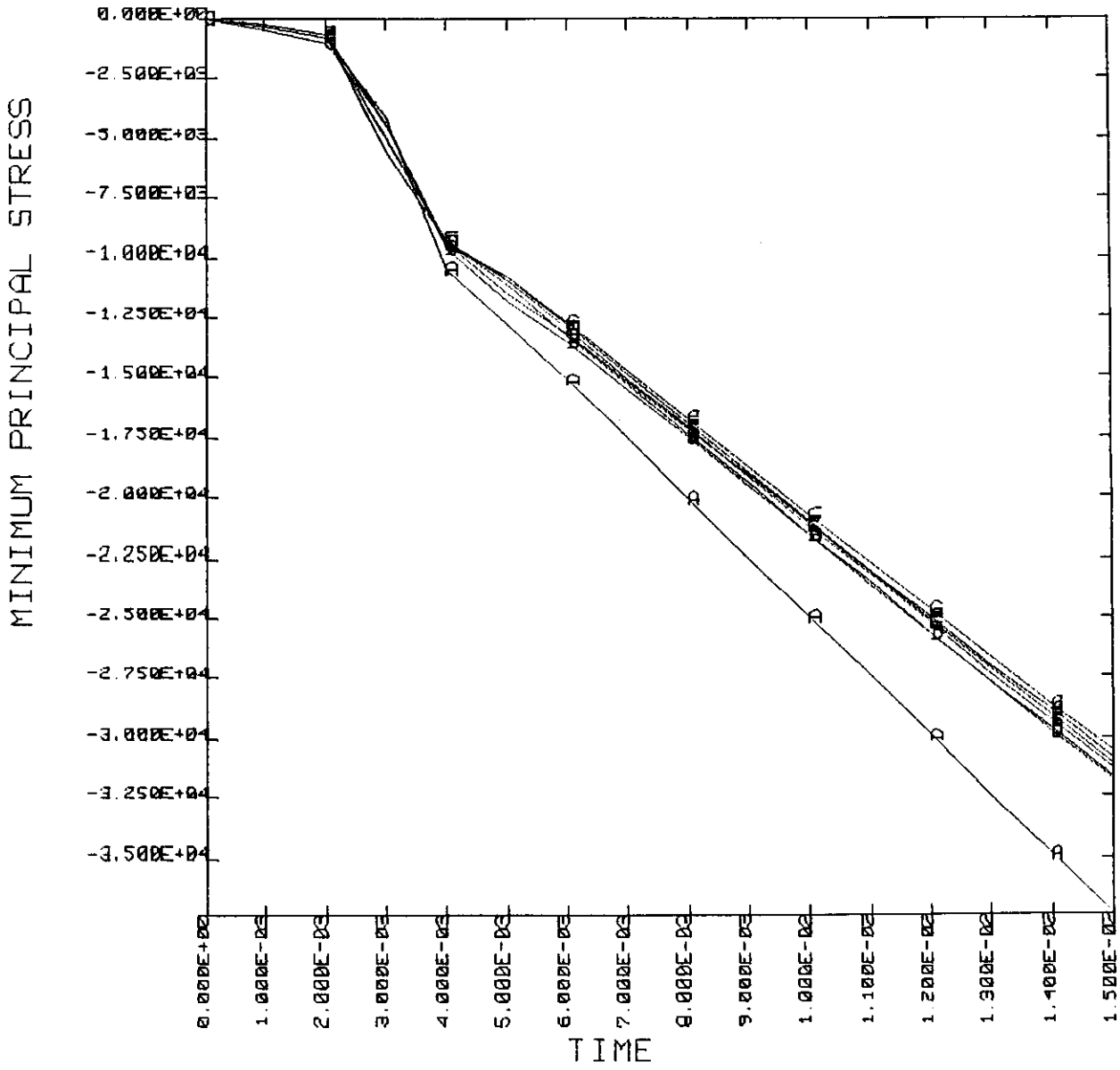


MINIMUM = -0.2644E+05
MAXIMUM = 0.0000E+00

ELEMENTS A= 116 B= 117 C= 118
D= 119 E= 122 F= 123
G= 124 H= 125 I= 129

Fig. 51

ASSEMBLY PRESSURE - G-10 WEDGES/COLLAR -FRICTION .3/WEDGES BONDED

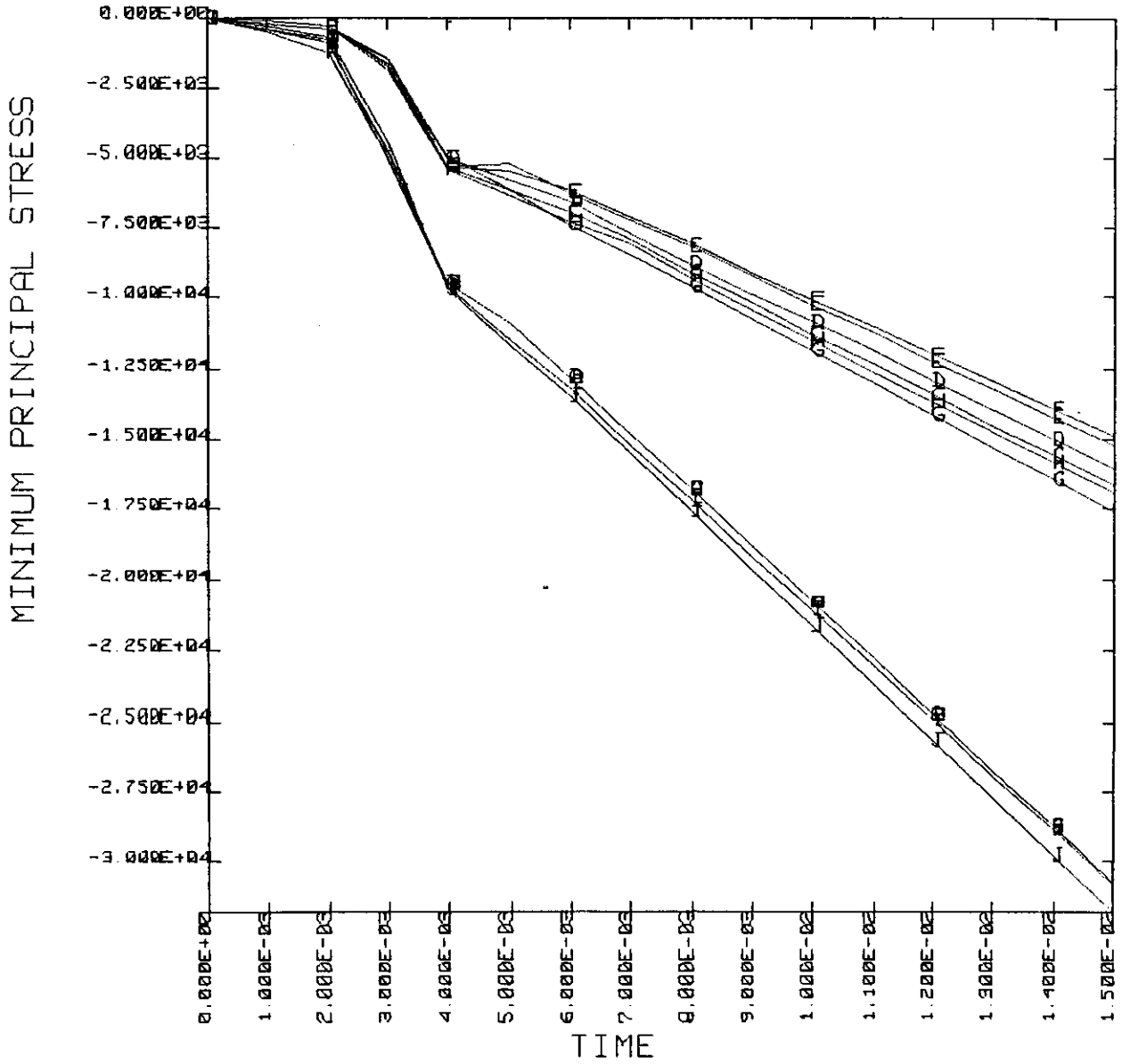


MINIMUM = -0.3741E+05
MAXIMUM = 0.0000E+00

ELEMENTS A= 135 B= 136 C= 137
D= 140 E= 141 F= 142
G= 143

Fig. 52

WEDGES BONDED - FRICTION .3 - G-10 ELEMENTS



MINIMUM = -0.3180E+05
MAXIMUM = 0.0000E+00

ELEMENTS A= 144 B= 145 C= 131
D= 132 E= 120 F= 121
G= 126 H= 128 I= 138 J= 139

Fig. 53

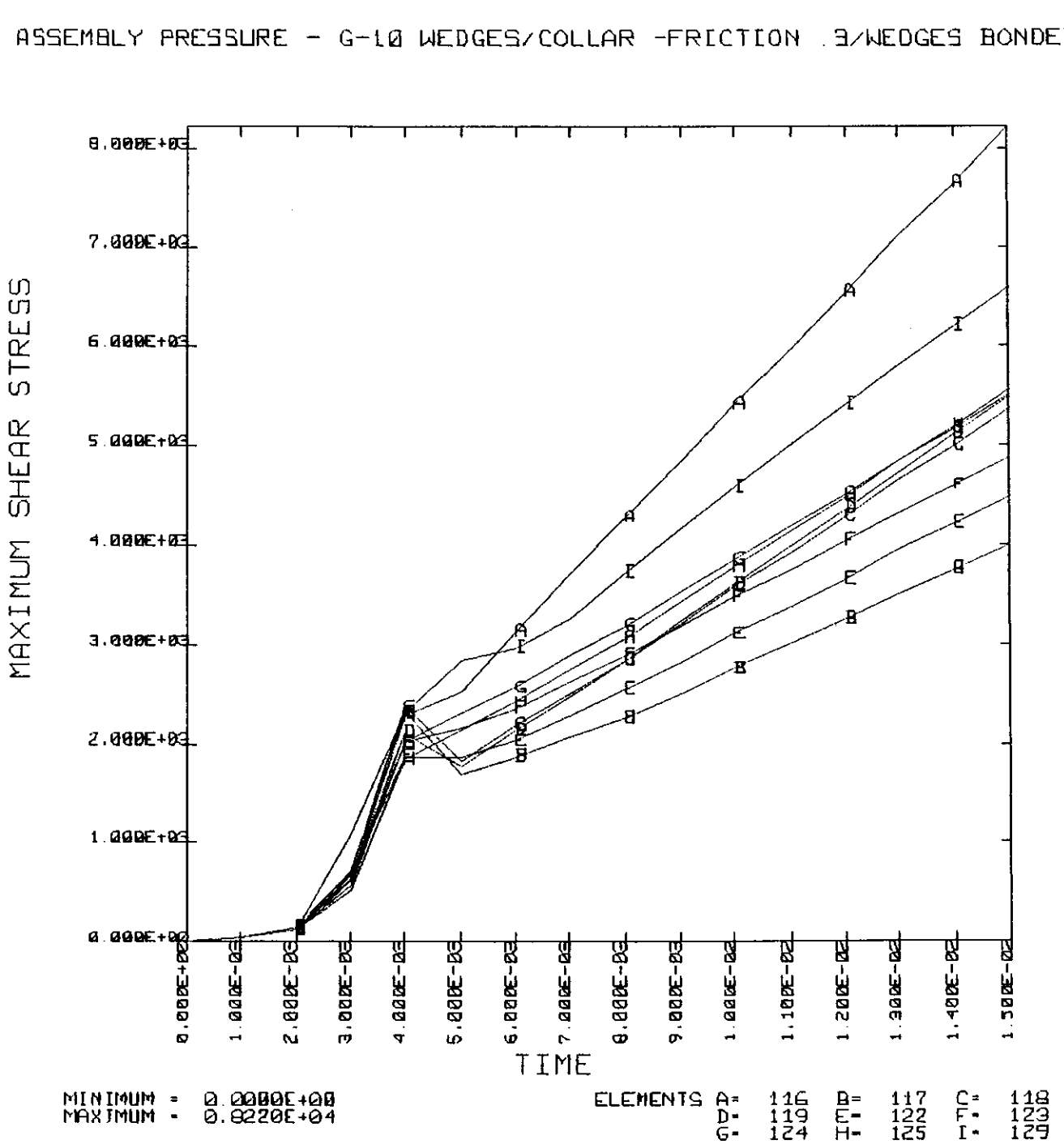

ASSEMBLY PRESSURE - G-10 WEDGES/COLLAR -FRICTION .3/WEDGES BONDED
MAXIMUM SHEAR STRESS
8.000E+03
7.000E+03
6.000E+03
5.000E+03
4.000E+03
3.000E+03
2.000E+03
1.000E+03
0.000E+00
0.000E+00
1.000E-03
2.000E-03
3.000E-03
4.000E-03
5.000E-03
6.000E-03
7.000E-03
8.000E-03
9.000E-03
1.000E-02
1.100E-02
1.200E-02
1.300E-02
1.400E-02
1.500E-02
TIME
MINIMUM = 0.0000E+00
MAXIMUM = 0.8220E+04
ELEMENTS A= 116 B= 117 C= 118
D= 119 E= 122 F= 123
G= 124 H= 125 I= 129

Fig. 54

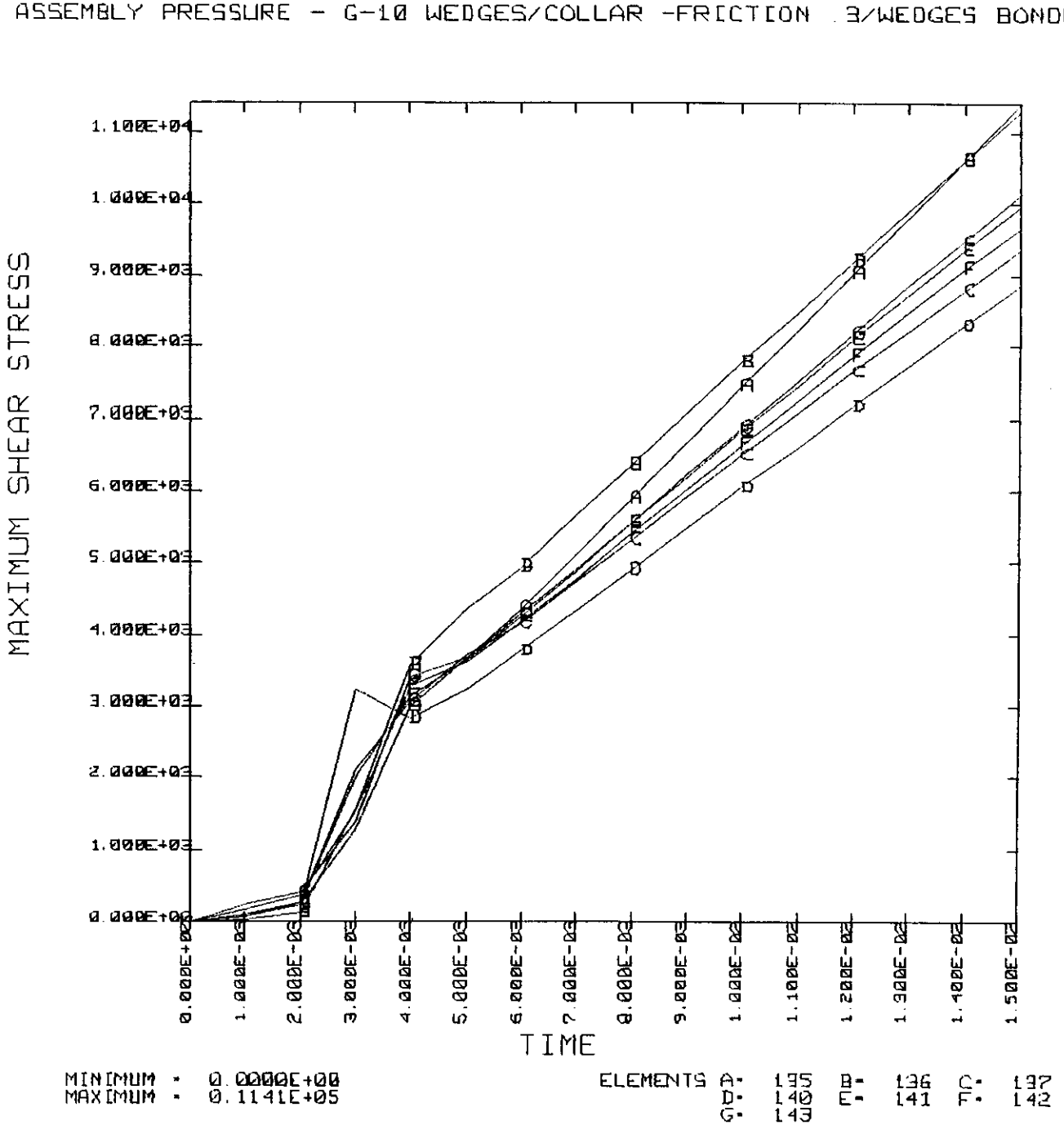

ASSEMBLY PRESSURE - G-10 WEDGES/COLLAR -FRICTION .3/WEDGES BONDED
MAXIMUM SHEAR STRESS
1.100E+04
1.000E+04
9.000E+03
8.000E+03
7.000E+03
6.000E+03
5.000E+03
4.000E+03
3.000E+03
2.000E+03
1.000E+03
0.000E+00
0.000E+00
1.000E-03
2.000E-03
3.000E-03
4.000E-03
5.000E-03
6.000E-03
7.000E-03
8.000E-03
9.000E-03
1.000E-02
1.100E-02
1.200E-02
1.300E-02
1.400E-02
1.500E-02
TIME
MINIMUM = 0.0000E+00
MAXIMUM = 0.1141E+05
ELEMENTS A= 135 B= 136 C= 137
D= 140 E= 141 F= 142
G= 143

Fig. 55

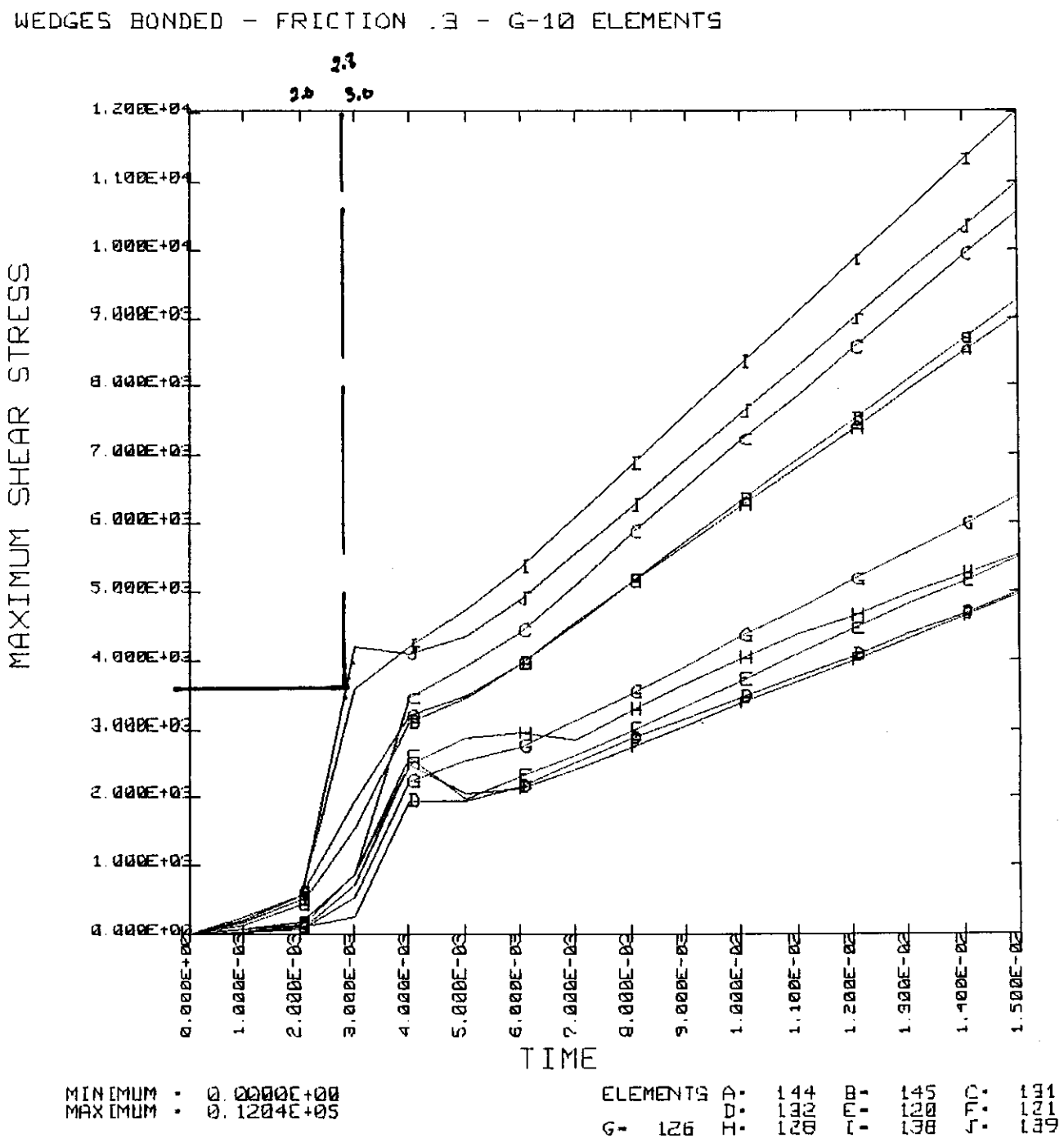

WEDGES BONDED - FRICTION .3 - G-10 ELEMENTS
2.3
2.0
3.0
MAXIMUM SHEAR STRESS
1.200E+04
1.100E+04
1.000E+04
9.000E+03
8.000E+03
7.000E+03
6.000E+03
5.000E+03
4.000E+03
3.000E+03
2.000E+03
1.000E+03
0.000E+00
0.000E+00
1.000E-03
2.000E-03
3.000E-03
4.000E-03
5.000E-03
6.000E-03
7.000E-03
8.000E-03
9.000E-03
1.000E-02
1.100E-02
1.200E-02
1.300E-02
1.400E-02
1.500E-02
TIME
MINIMUM = 0.0000E+00
MAXIMUM = 0.1204E+05
ELEMENTS A= 144 B= 145 C= 131
D= 132 E= 120 F= 121
G= 126 H= 128 I= 138 J= 139

Fig.56

ASSEMBLY PRESSURE - G-10 WEDGES/COLLAR -FRICTION 3/WEDGES BONDED

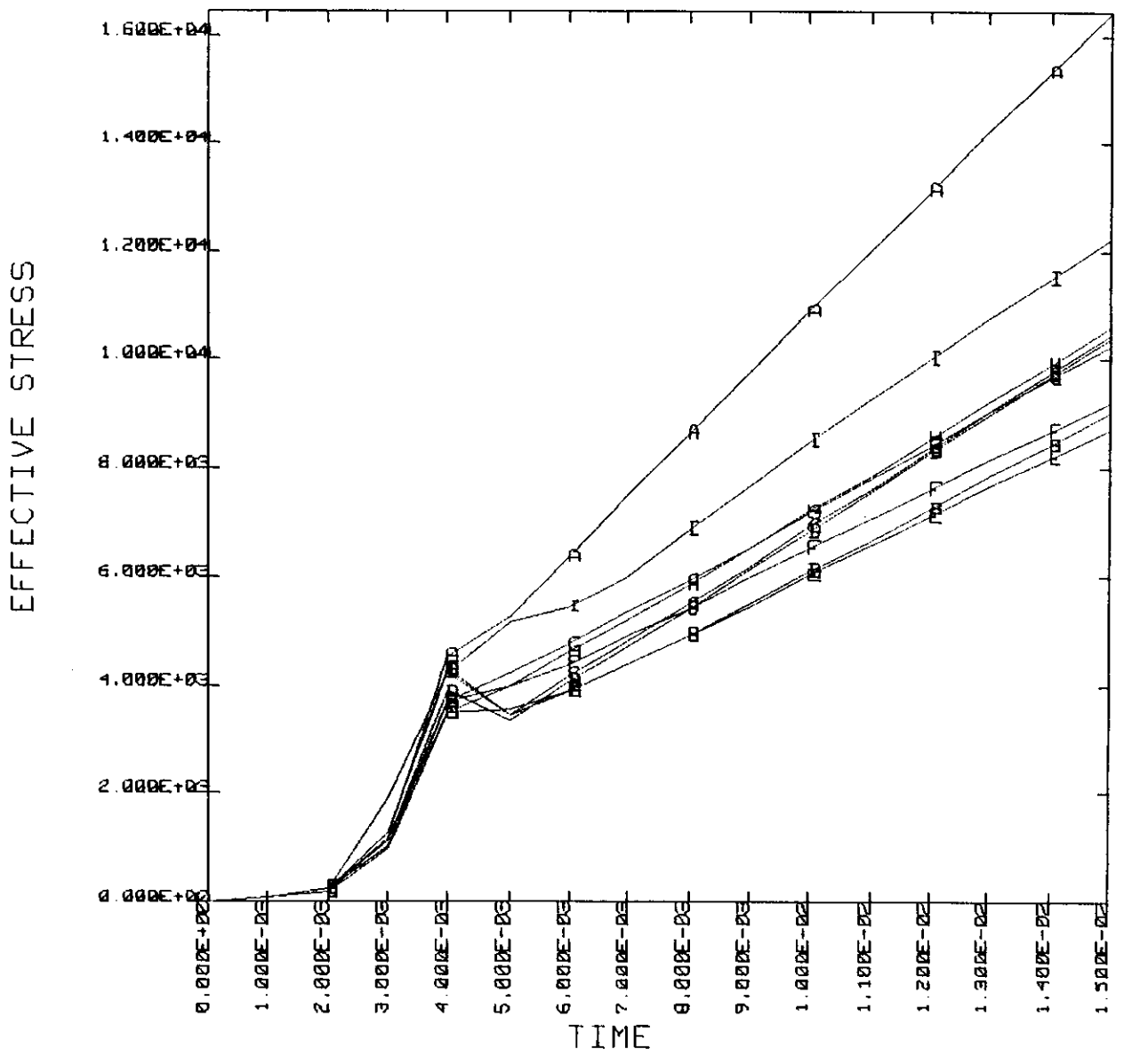


Fig. 57

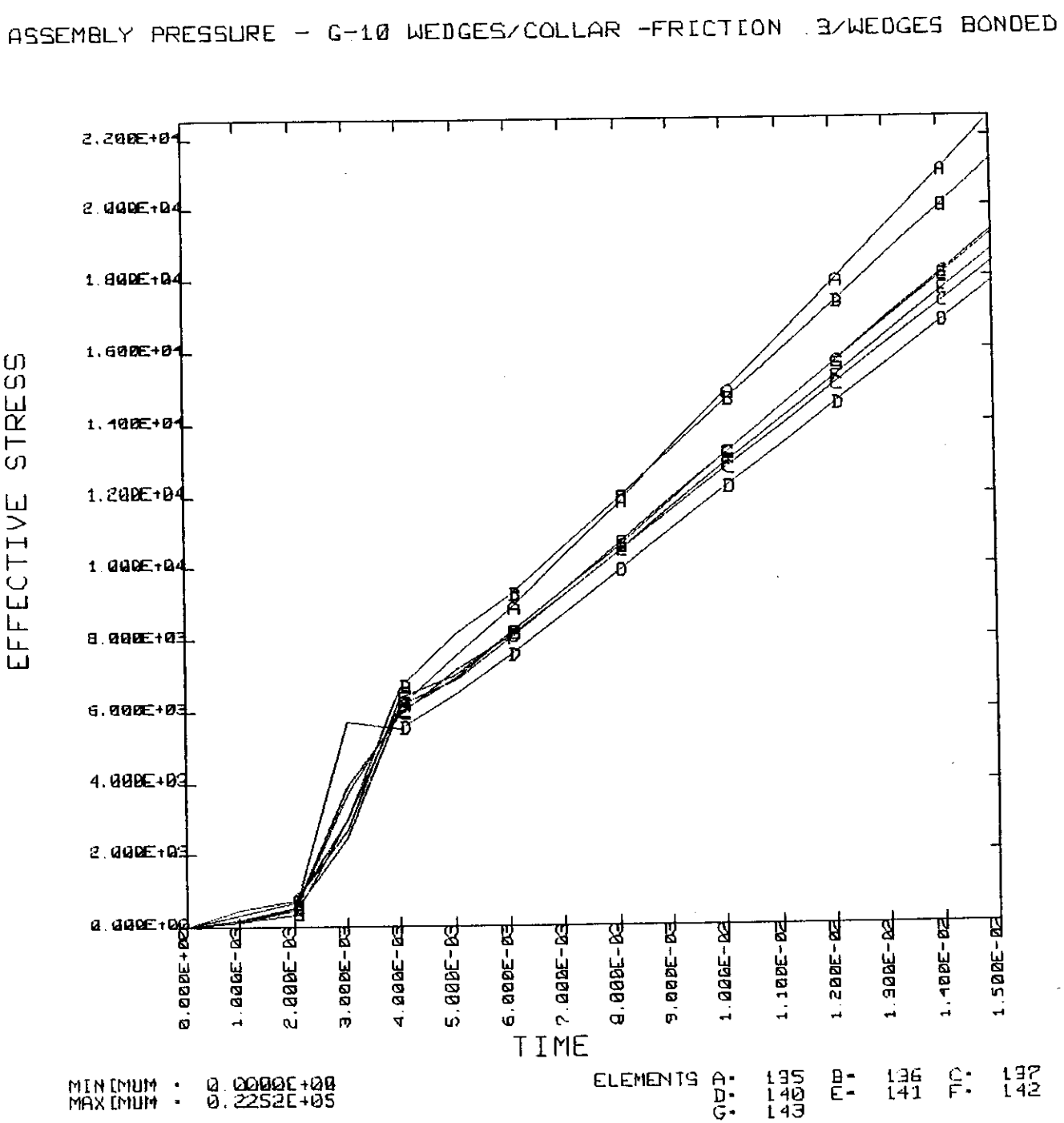

ASSEMBLY PRESSURE - G-10 WEDGES/COLLAR -FRICTION .3/WEDGES BONDED
EFFECTIVE STRESS
2.200E+04
2.000E+04
1.800E+04
1.600E+04
1.400E+04
1.200E+04
1.000E+04
8.000E+03
6.000E+03
4.000E+03
2.000E+03
0.000E+00
0.000E+00
1.000E-03
2.000E-03
3.000E-03
4.000E-03
5.000E-03
6.000E-03
7.000E-03
8.000E-03
9.000E-03
1.000E-02
1.100E-02
1.200E-02
1.300E-02
1.400E-02
1.500E-02
TIME
MINIMUM = 0.0000E+00
MAXIMUM = 0.2252E+05
ELEMENTS A: 135 B: 136 C: 137
D: 140 E: 141 F: 142
G: 143

Fig. 58

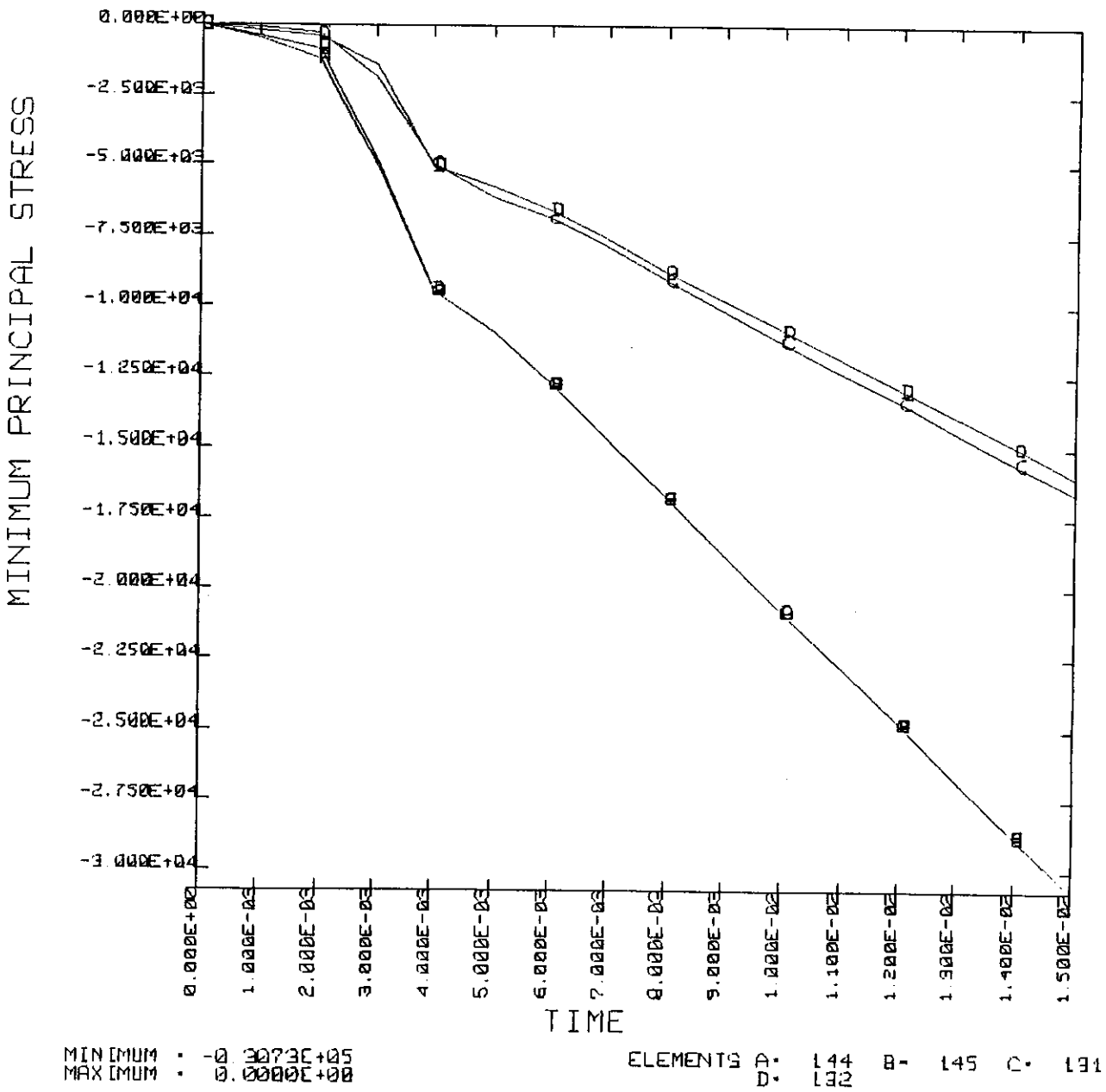

WEDGES BONDED - FRICTION .3 - G-10 ELEMENTS
MINIMUM PRINCIPAL STRESS
0.000E+00
-2.500E+03
-5.000E+03
-7.500E+03
-1.000E+04
-1.250E+04
-1.500E+04
-1.750E+04
-2.000E+04
-2.250E+04
-2.500E+04
-2.750E+04
-3.000E+04
0.000E+00
1.000E-03
2.000E-03
3.000E-03
4.000E-03
5.000E-03
6.000E-03
7.000E-03
8.000E-03
9.000E-03
1.000E-02
1.100E-02
1.200E-02
1.300E-02
1.400E-02
1.500E-02
TIME
MINIMUM : -0.30736E+05
MAXIMUM : 0.00000E+00
ELEMENTS A: 144 B: 145 C: 131
D: 132

Fig. 59

WEDGES BONDED - FRICTION .3 - G-10 ELEMENTS

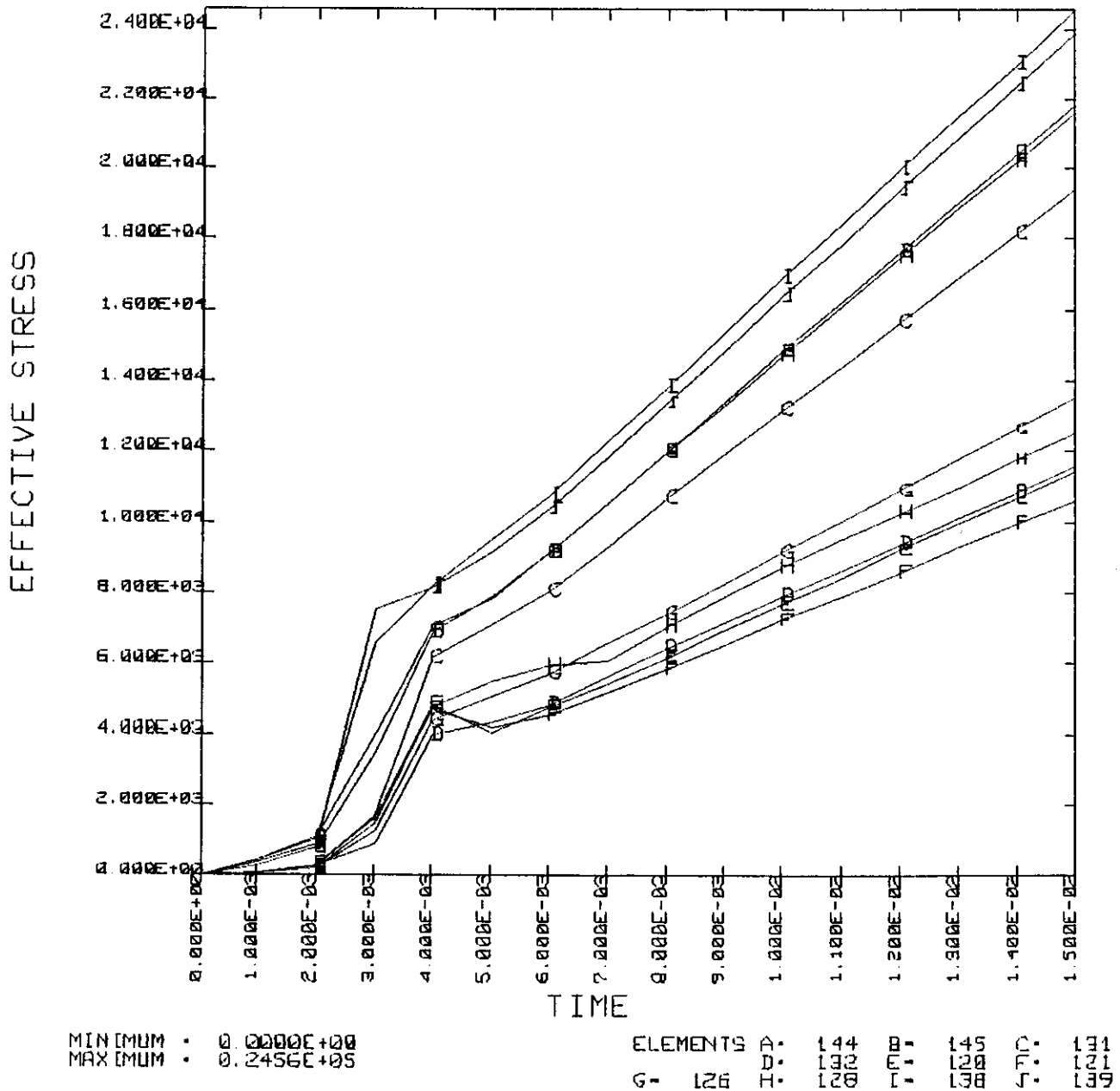


Fig. 60

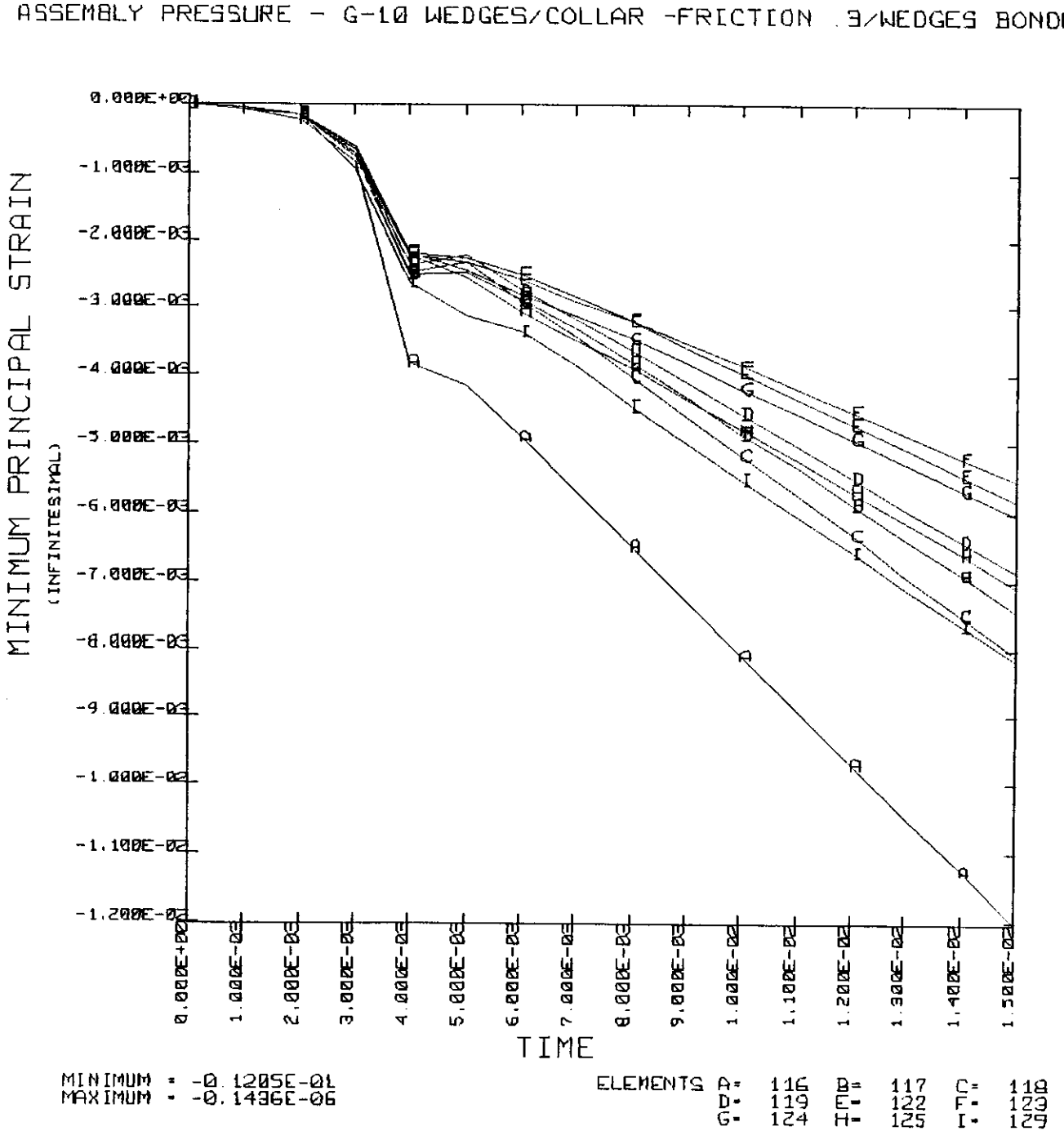

ASSEMBLY PRESSURE - G-10 WEDGES/COLLAR -FRICTION .3/WEDGES BONDED
MINIMUM PRINCIPAL STRAIN
(INFINITESIMAL)
0.000E+00
-1.000E-03
-2.000E-03
-3.000E-03
-4.000E-03
-5.000E-03
-6.000E-03
-7.000E-03
-8.000E-03
-9.000E-03
-1.000E-02
-1.100E-02
-1.200E-02
0.000E+00
1.000E-03
2.000E-03
3.000E-03
4.000E-03
5.000E-03
6.000E-03
7.000E-03
8.000E-03
9.000E-03
1.000E-02
1.100E-02
1.200E-02
1.300E-02
1.400E-02
1.500E-02
TIME
MINIMUM = -0.1205E-01
MAXIMUM = -0.1436E-06
ELEMENTS A= 116 B= 117 C= 118
D= 119 E= 122 F= 123
G= 124 H= 125 I= 129

Fig. 61

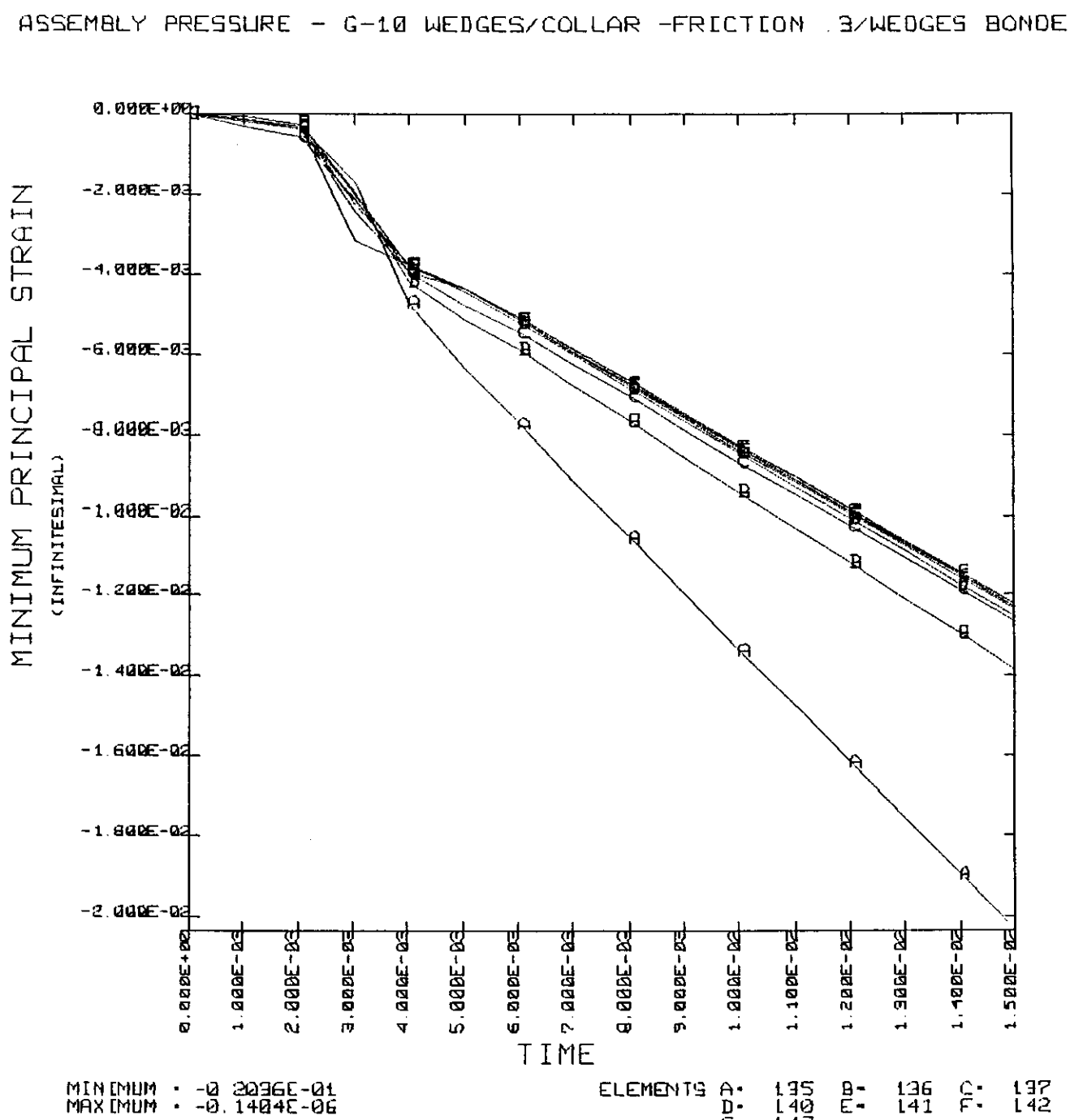

ASSEMBLY PRESSURE - G-10 WEDGES/COLLAR -FRICTION .3/WEDGES BONDED
MINIMUM PRINCIPAL STRAIN
(INFINITESIMAL)
0.000E+00
-2.000E-03
-4.000E-03
-6.000E-03
-8.000E-03
-1.000E-02
-1.200E-02
-1.400E-02
-1.600E-02
-1.800E-02
-2.000E-02
0.000E+00
1.000E-03
2.000E-03
3.000E-03
4.000E-03
5.000E-03
6.000E-03
7.000E-03
8.000E-03
9.000E-03
1.000E-02
1.100E-02
1.200E-02
1.300E-02
1.400E-02
1.500E-02
TIME
MINIMUM = -0.2036E-01
MAXIMUM = -0.1404E-06
ELEMENTS A= 135 B= 136 C= 137
D= 140 E= 141 F= 142
G= 143

Fig. 62

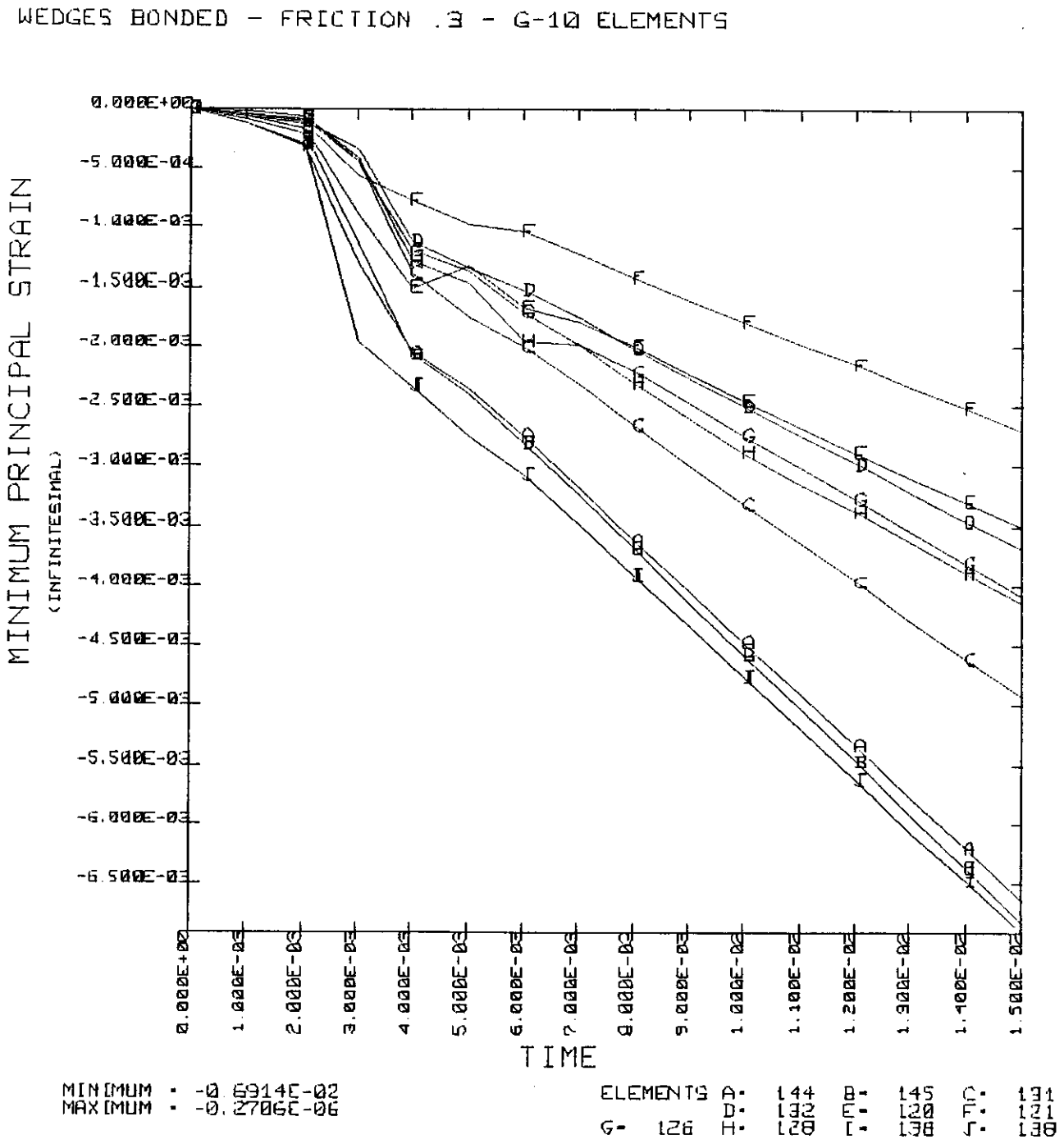

WEDGES BONDED - FRICTION .3 - G-10 ELEMENTS
MINIMUM PRINCIPAL STRAIN
(INFINITESIMAL)
0.000E+00
-5.000E-04
-1.000E-03
-1.500E-03
-2.000E-03
-2.500E-03
-3.000E-03
-3.500E-03
-4.000E-03
-4.500E-03
-5.000E-03
-5.500E-03
-6.000E-03
-6.500E-03
0.000E+00
1.000E-03
2.000E-03
3.000E-03
4.000E-03
5.000E-03
6.000E-03
7.000E-03
8.000E-03
9.000E-03
1.000E-02
1.100E-02
1.200E-02
1.300E-02
1.400E-02
1.500E-02
TIME
MINIMUM = -0.6914E-02
MAXIMUM = -0.2706E-06
ELEMENTS A= 144 B= 145 C= 131
D= 132 E= 120 F= 121
G= 126 H= 128 I= 138 J= 130

Fig. 63

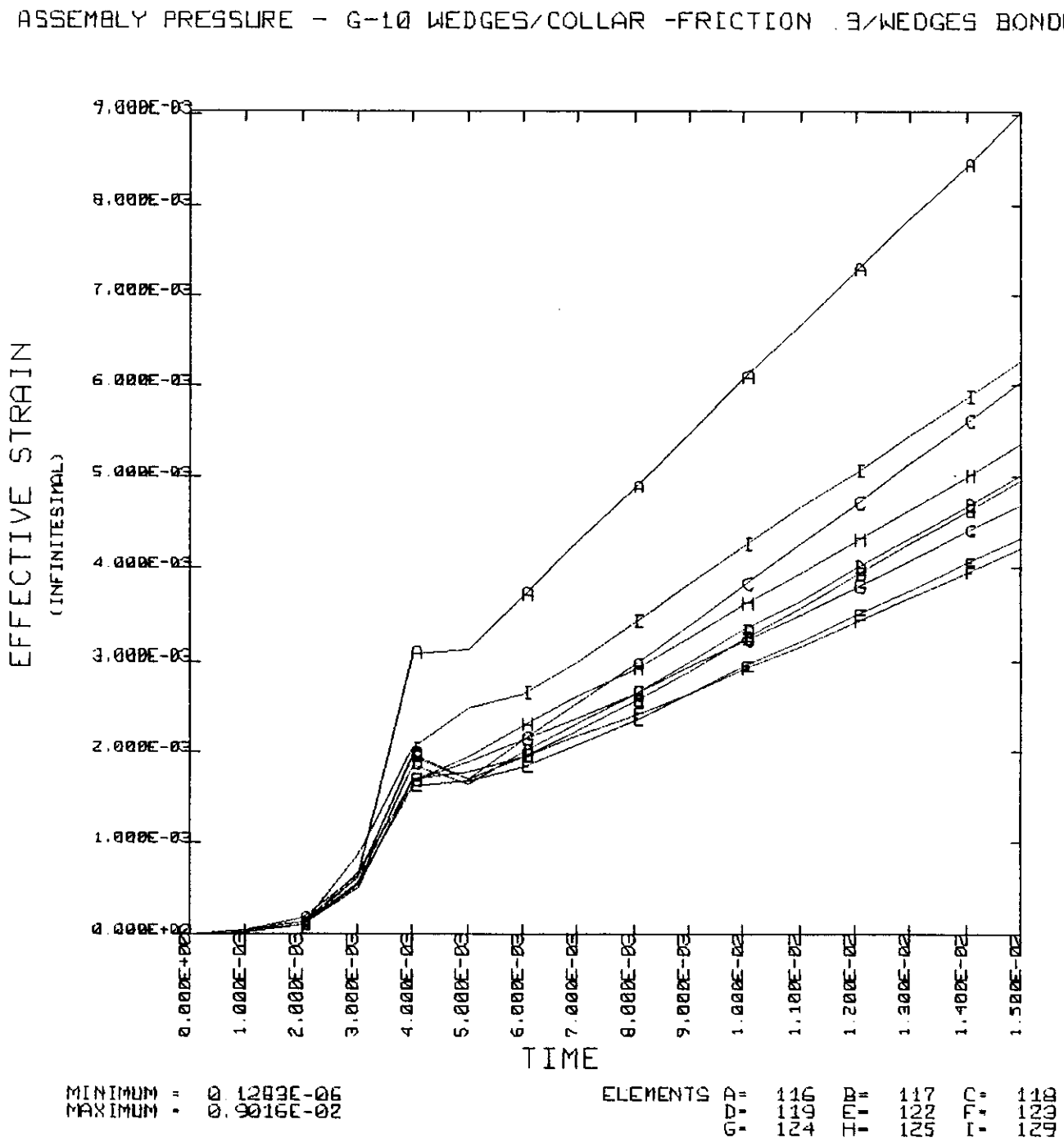

ASSEMBLY PRESSURE - G-10 WEDGES/COLLAR -FRICTION .3/WEDGES BONDED
EFFECTIVE STRAIN
(INFINITESIMAL)
TIME
MINIMUM = 0.1283E-06
MAXIMUM = 0.9016E-02
ELEMENTS A= 116 B= 117 C= 118
D= 119 E= 122 F= 123
G= 124 H= 125 I= 129

Fig. 64

ASSEMBLY PRESSURE - G-10 WEDGES/COLLAR -FRICTION .3/WEDGES BONDED

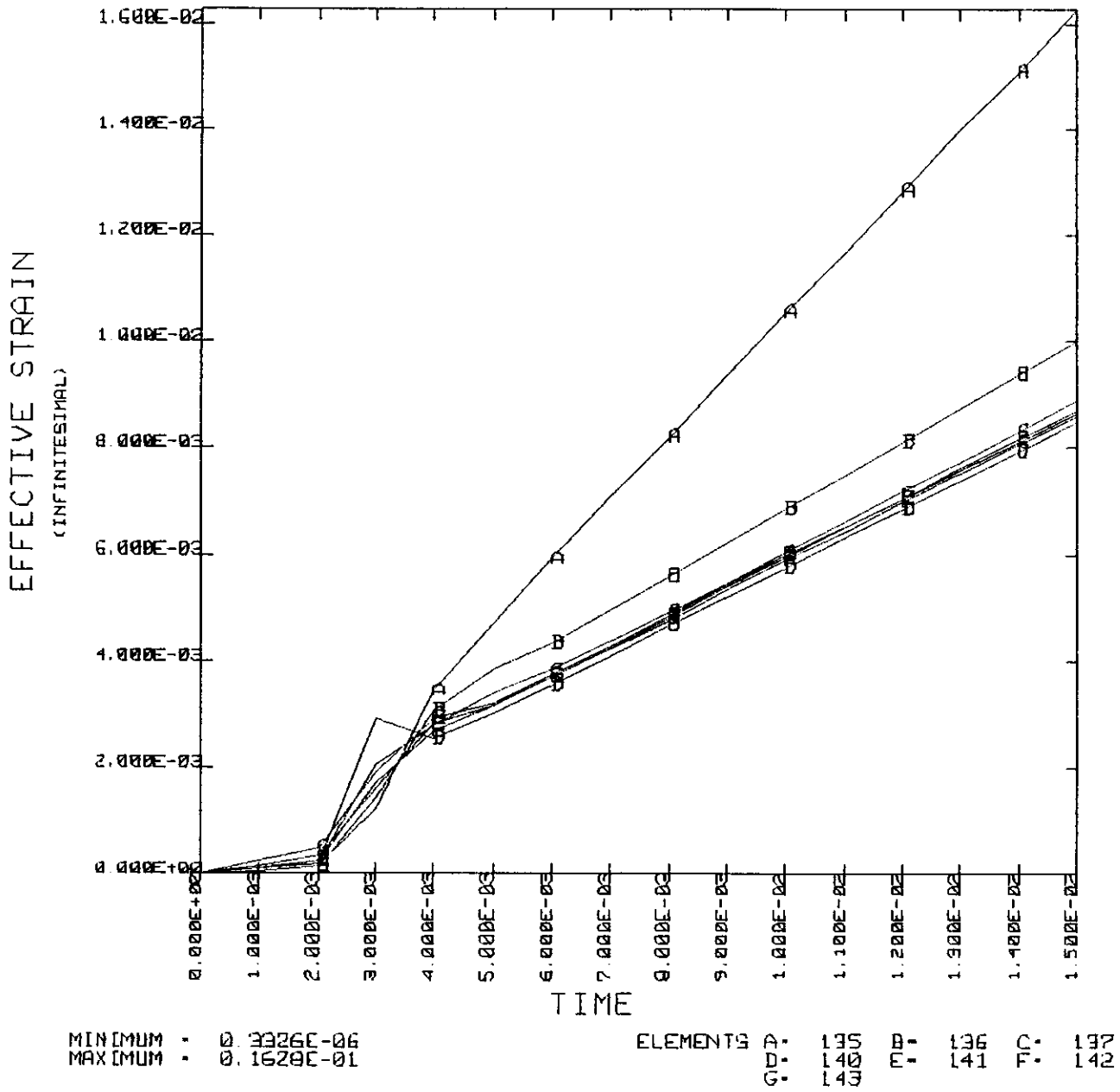
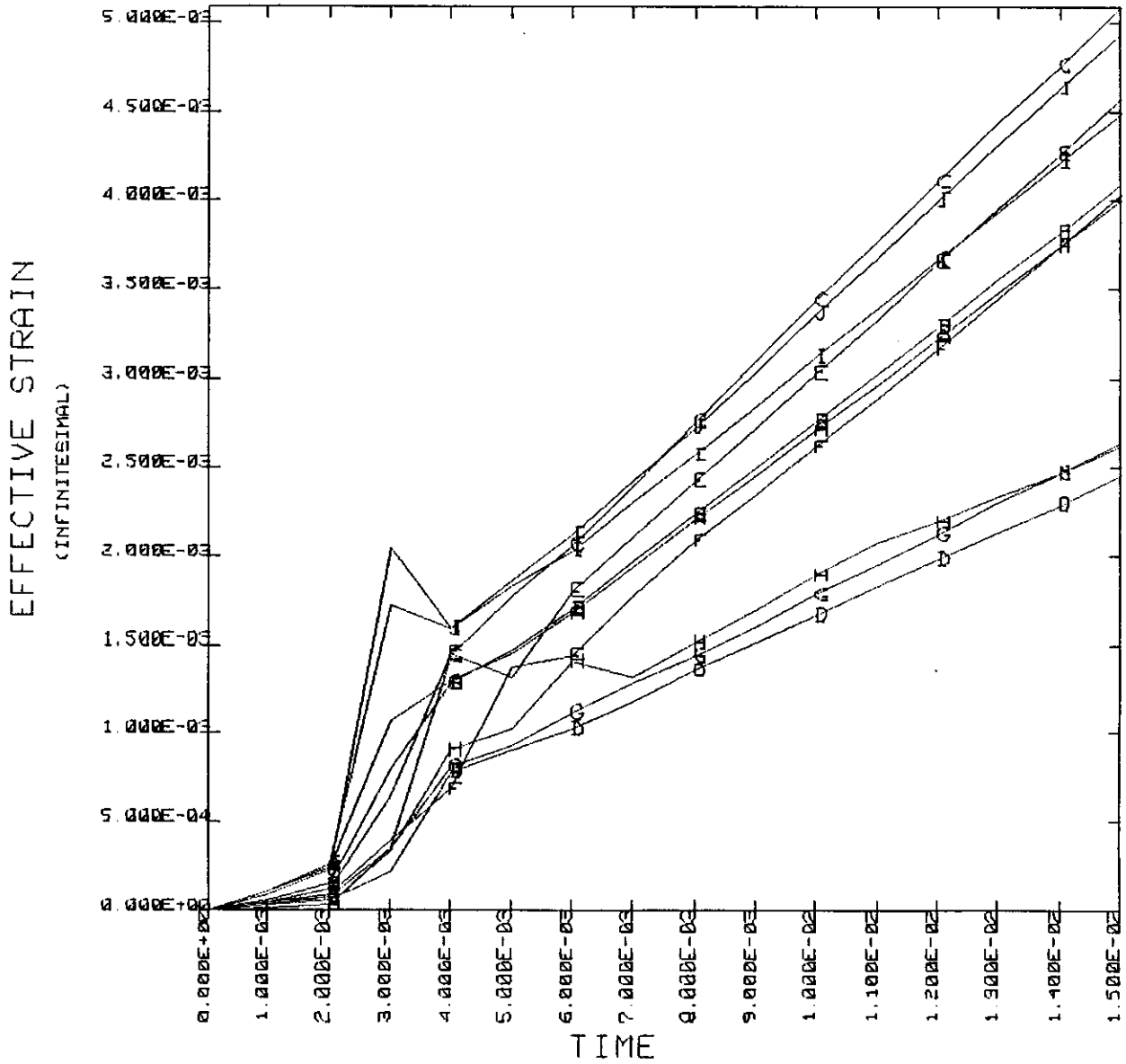


Fig. 65

WEDGES BONDED - FRICTION .3 - G-10 ELEMENTS



MINIMUM : 0.3073E-06
MAXIMUM : 0.5098E-02

ELEMENTS A: 144 B= 145 C: 131
D: 132 E: 120 F: 121
G= 126 H: 128 I= 138 J: 139

Fig. 66

ASSEMBLY PRESSURE - G-10 WEDGES/COLLAR -FRICTION .3/WEDGES BONDED

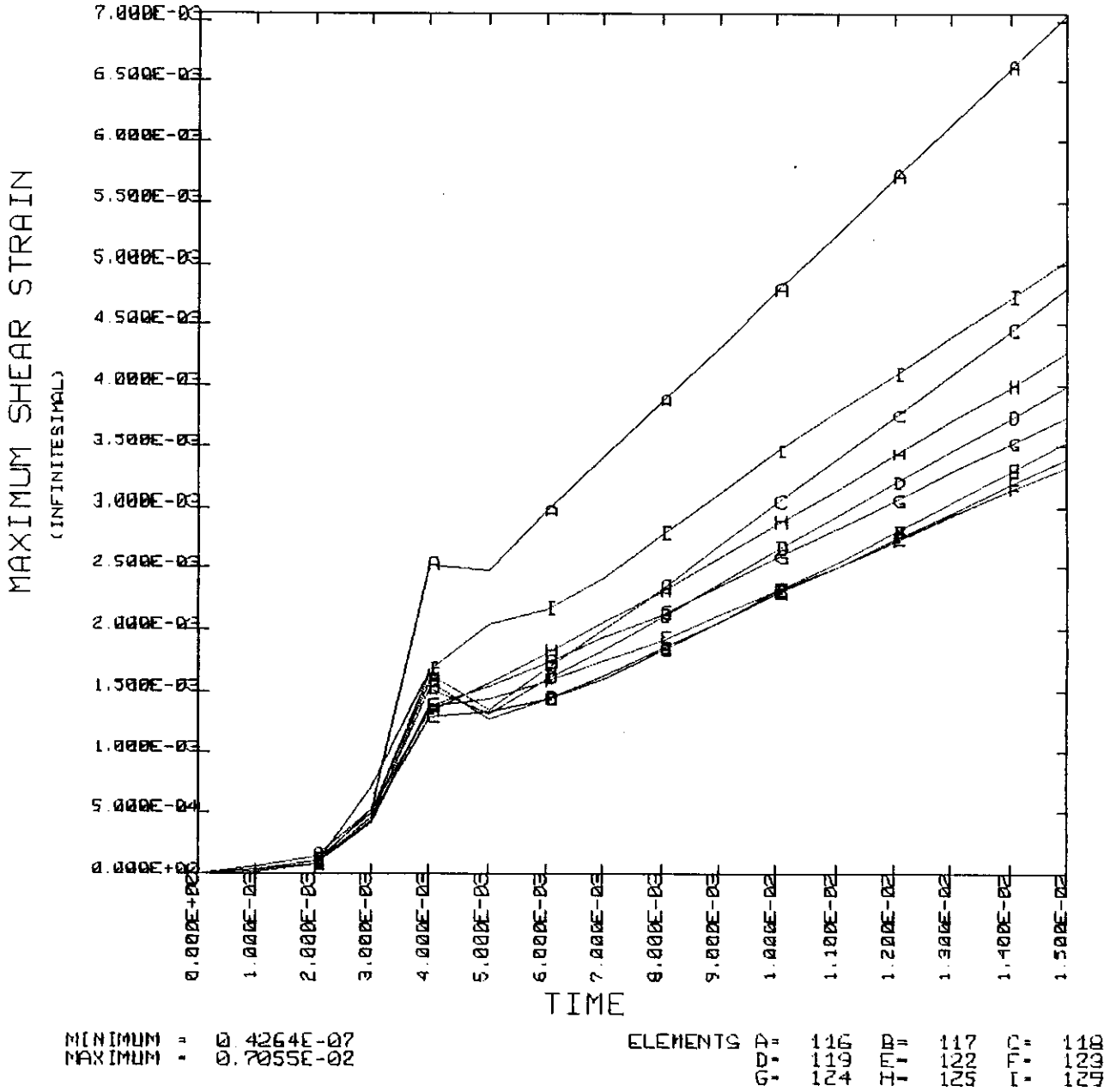


Fig. 67

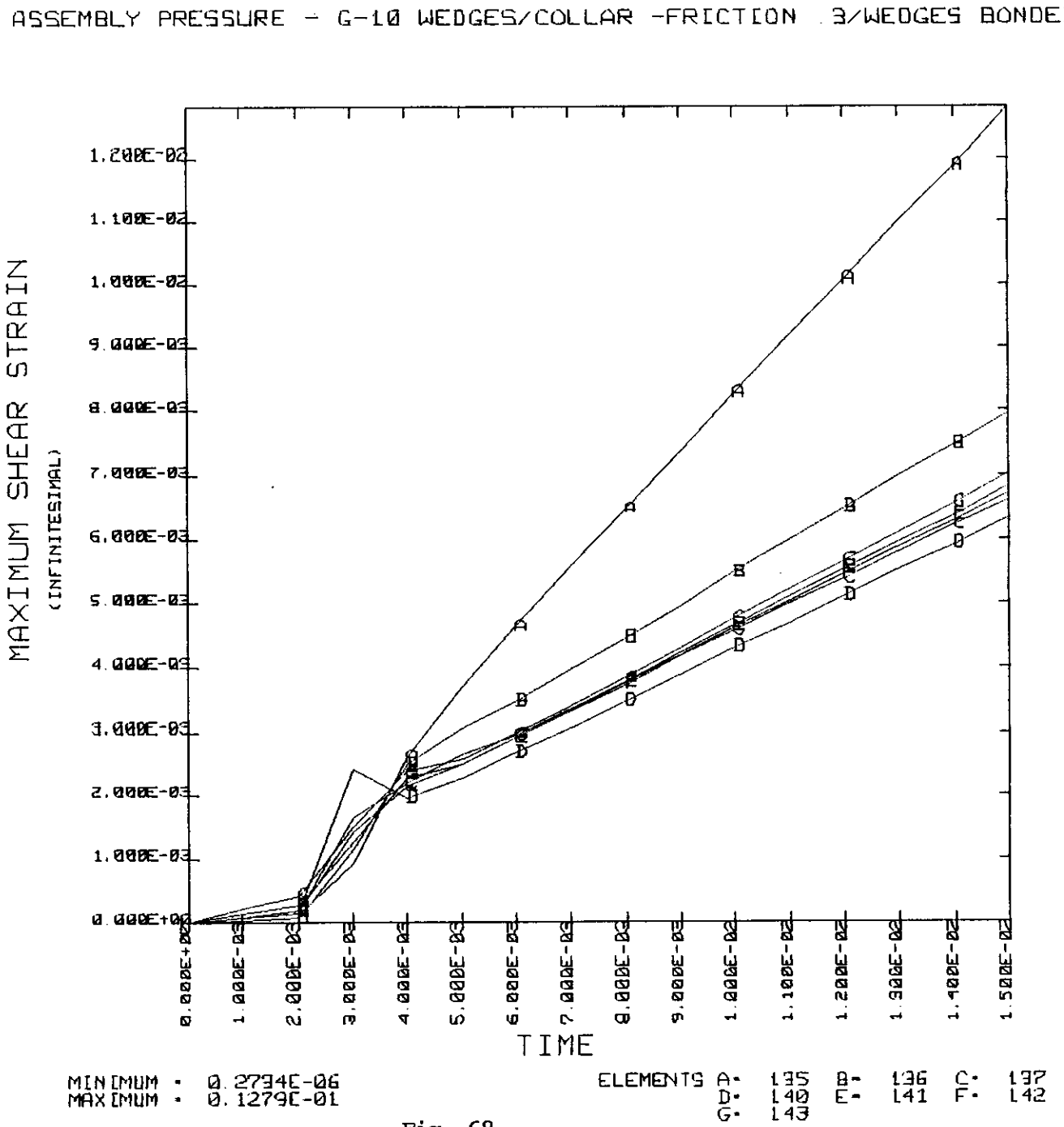

ASSEMBLY PRESSURE - G-10 WEDGES/COLLAR -FRICTION .3/WEDGES BONDED
MAXIMUM SHEAR STRAIN
(INFINITESIMAL)
1.200E-02
1.100E-02
1.000E-02
9.000E-03
8.000E-03
7.000E-03
6.000E-03
5.000E-03
4.000E-03
3.000E-03
2.000E-03
1.000E-03
0.000E+00
0.000E+00
1.000E-03
2.000E-03
3.000E-03
4.000E-03
5.000E-03
6.000E-03
7.000E-03
8.000E-03
9.000E-03
1.000E-02
1.100E-02
1.200E-02
1.300E-02
1.400E-02
1.500E-02
TIME
MINIMUM = 0.2734E-06
MAXIMUM = 0.1279E-01
ELEMENTS A= 135 B= 136 C= 137
D= 140 E= 141 F= 142
G= 143

Fig. 68

WEDGES BONDED - FRICTION .3 - G-10 ELEMENTS

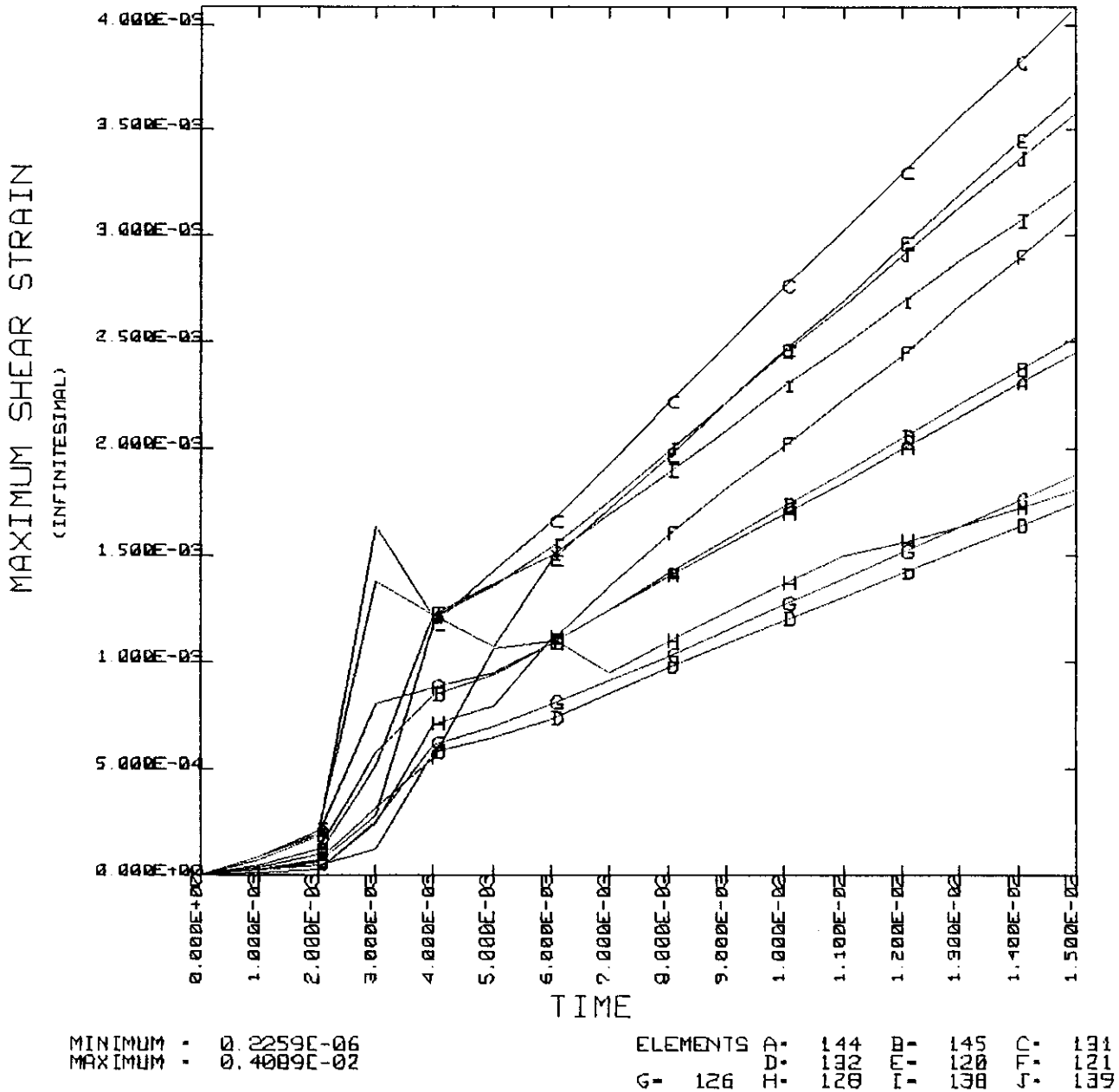


Fig. 69

ASSEMBLY PRESSURE - G-10 WEDGES/COLLAR -FRICTION .3/WEDGES BONDED

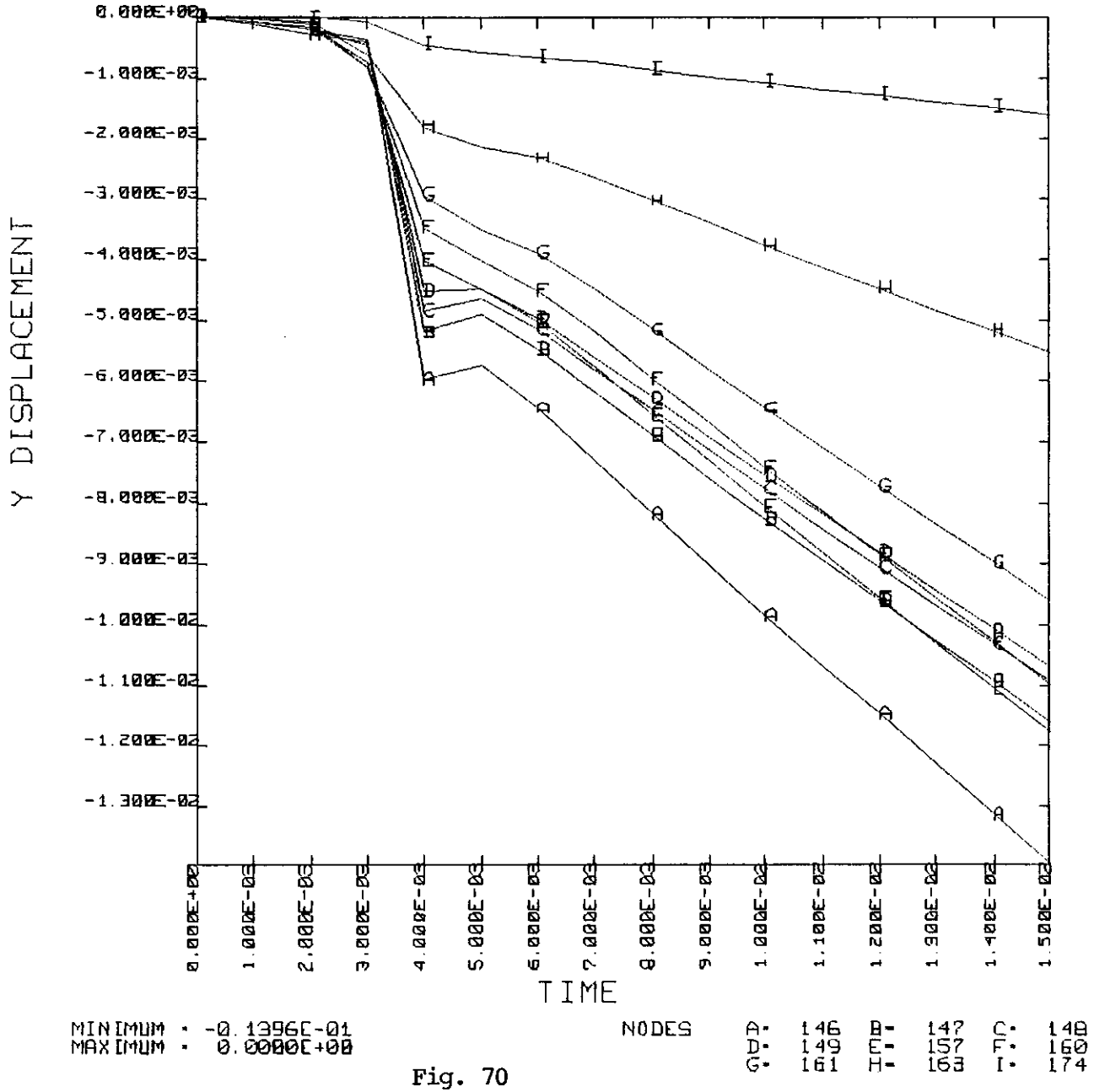


Fig. 70

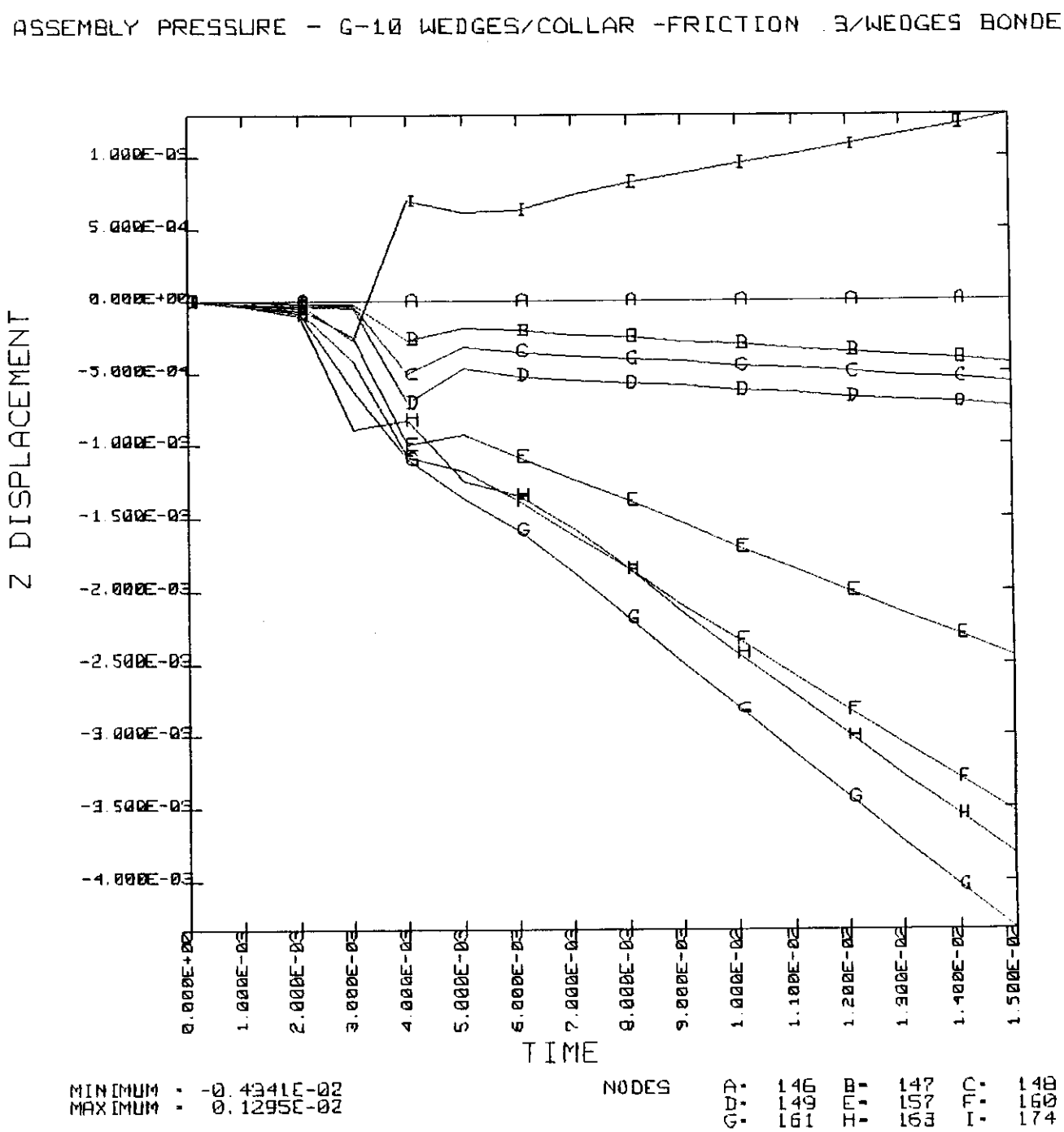
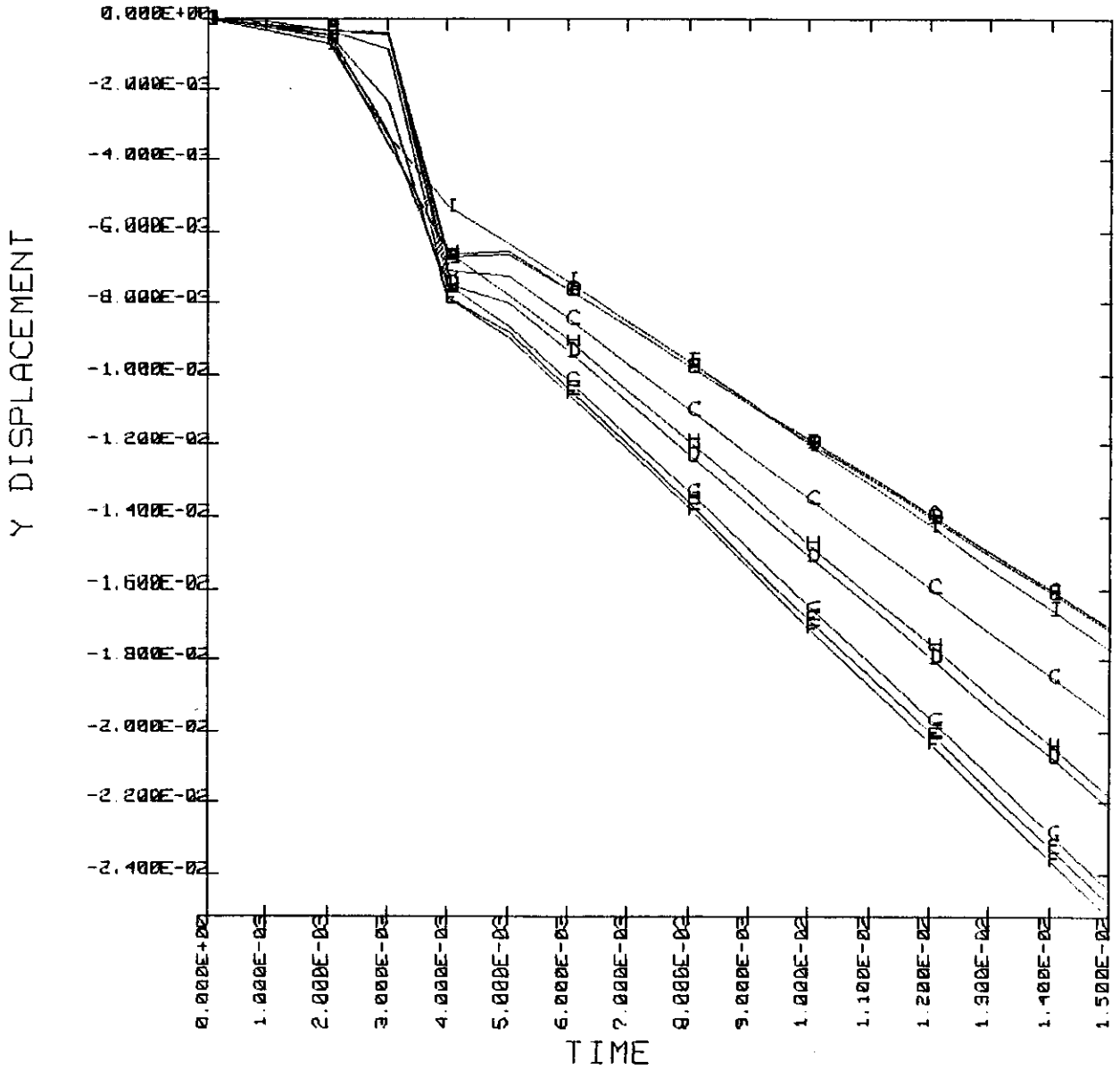

ASSEMBLY PRESSURE - G-10 WEDGES/COLLAR -FRICTION .3/WEDGES BONDED
Z DISPLACEMENT
1.000E-03
5.000E-04
0.000E+00
-5.000E-04
-1.000E-03
-1.500E-03
-2.000E-03
-2.500E-03
-3.000E-03
-3.500E-03
-4.000E-03
0.000E+00
1.000E-03
2.000E-03
3.000E-03
4.000E-03
5.000E-03
6.000E-03
7.000E-03
8.000E-03
9.000E-03
1.000E-02
1.100E-02
1.200E-02
1.300E-02
1.400E-02
1.500E-02
TIME
MINIMUM = -0.4341E-02
MAXIMUM = 0.1295E-02
NODES
A: 146 B: 147 C: 148
D: 149 E: 157 F: 160
G: 161 H: 163 I: 174

Fig. 71

ASSEMBLY PRESSURE - G-10 WEDGES/COLLAR -FRICTION .3/WEDGES BONDED



MINIMUM = -0.2523E-01
MAXIMUM = 0.0000E+00

NODES A= 187 B= 188 C= 189
D= 190 E= 196 F= 200
G= 201 H= 202 I= 203

Fig. 72

ASSEMBLY PRESSURE - G-10 WEDGES/COLLAR -FRICTION .3/WEDGES BONDED

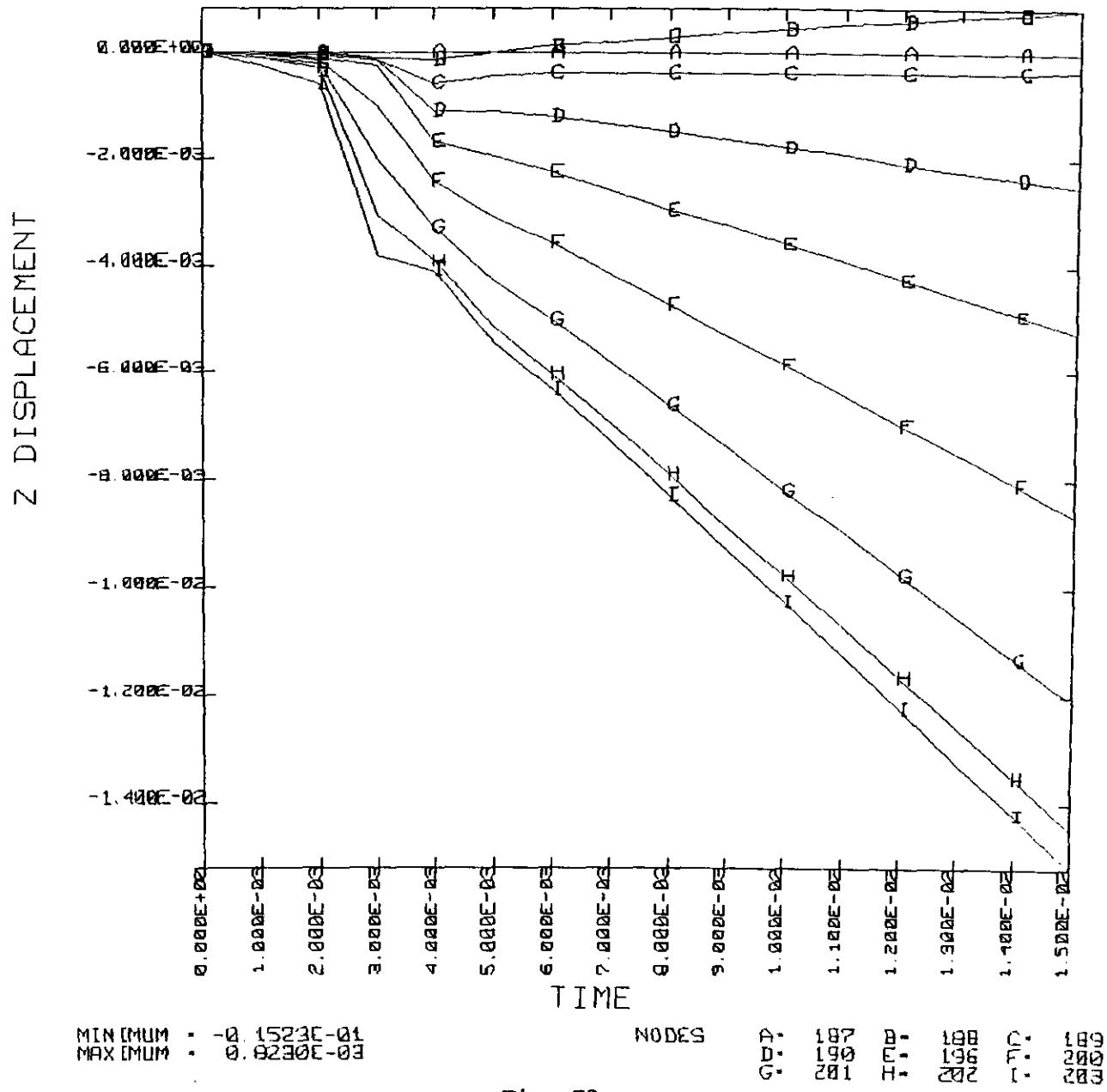


Fig. 73