Ring-Type Support Concept for Twisted Coils

(Finite Element Simulation)

S. B. Mukherjee

IPP 2/271 February 1984

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ABSTRACT

A Ring-type support concept is introduced in this report. This is an alternative to the Front support system where a stellarator reactor coil (WENDELSTEIN VII-AS type) is supported at the front region (near to the torus axis) to take up the resultant centering force. A coil is also supported sidewise to stop tilting moments. With the Ring-type support system, a coil is supported all along its circumference and sidewise as well.

The twisted coils within the magnetic field are subjected to forces and moments which are complex in nature. The coils are usually sensitive to support conditions and the stresses response accordingly on how they are being supported. Applying the usual Front support concept the stresses in a coil with superimposed bending stresses may be rather high and critical with the increased magnetic forces. They may even exceed the limit of present technical feasibility. Whereas a Ring-type support system actually tends to reduce the bending moments and thus causes a considerable drop in mechanical stresses within a coil.

The finite element computations have been carried out assuming a coil being a superconducting one and therefore no temperature rise within a coil may be considered. Also the forces and stresses resulting from cooling down and different thermal expansion coefficients are not treated in this report. A Ring support can either be an inward or an outward type and it is applicable also for planar coils.

CONTENTS

1. INTRODUCTION

An engineering study /1/ has been carried out with regards to the computational aspects of a modular stellarator fusion reactor magnet, in which the coil-set of the advanced stellarator WENDELSTEIN VII-AS has been scaled up to reactor dimensions, Tables 1,2 and Fig.1. The system considered has not been optimized for a reactor application. Nevertheless, it has been necessary to make a finite element analysis of a reactor coil and to find out whether the coil could be technically feasible. Beside this engineering study for a coil with the usual Front support system, an alternative Ring-type support concept has been developed.

Because of their lateral deviation, additional forces and moments are acting on twisted coils when compared with the planar ones. The three dimensional forces and moments acting on the coils are to be supported. With the Front support concept these loads and moments are taken up by the structures supporting a coil at the front region (the region nearest to the torus axis) and sidewise. For coils with high magnetic field this type of supporting system would cause stresses (with superimposed bending stresses) and shear stresses which may be rather high and critical.

The finite element simulations of different types of coil's support conditions and investigations of the corresponding stresses and reactions in a coil have lead to the development of a new support concept, which is presented in this report. In this concept a suitably stiffened Ring-type support has been thought of to support a coil all along its circumference either from inside or from outside. The radial forces acting on a coil are then transmitted into the Ring support. The lateral forces are are taken up by the side supports of a coil. This arrangement has an advantage to reduce the bending moments due to the magnetic forces and thus a considerable reduction of mechanical stresses may be expected within a coil when compared with the Front support system.

The FE computations have been carried out for the reactor coils 1 and 5 using both support concepts (Front and the Ring supports) and with the magnetic forces only. The results are presented in this report. Since the coils are superconducting, no temperature rise within the coils are assumed.

2. RING SUPPORT - CONCEPT DEVELOPMENT

A magnetic coil with radial distribution of forces is shown in Fig. 2.

In order to get an idea of the complex interaction of forces between a coil and its supporting structure, a simply supported beam carrying uniformly distributed load over its whole length, Fig. 3a, is thought of. According to the theory of bending, the moment and stress and the curvature are related by the well known equation,

$$\frac{M}{I} = \frac{\sigma}{y} = \frac{E}{R}$$

where M and I are the bending moment and the second moment respectively. σ is the stress at any distance y from the neutral axis. The Young's modulus E for an initially straight (and unstressed) beam which is bent until the radius at the neutral axis is R.

The differential equation of flexure is given by

$$\frac{d^2 y}{d x^2} = \frac{M}{EI}$$

and hence the deflection of a beam is

$$y = \iint \frac{M}{EI} \, dx \, dx$$

Refering to Fig. 3a, the deflection at mid-span 1/2 L due to a uniformly distributed load W (total) alone is

$$\delta 1 = \frac{5 W L^3}{384 EI} \quad \text{(downwards)}$$

and the bending moment at mid-span is

$$M1 = \frac{W L}{8}$$

The shaded region is showing the value of bending moment (B.M.) at each point along the beam.

Refering to Fig. 3b, if the beam is propped at the centre the deflection due to P (the prop reaction) alone is

$$\delta_2 = \frac{P L^3}{48 EI} \quad \text{(upwards)}$$

and the bending moment at the centre is

$$M2 = (-) \frac{P L}{4}$$

If the prop reaction P is as such that it makes M1 = M2, then the Fig. 3b shows the bending moment diagram which is obtained by the method of superposition. If more props are used with their corresponding support stiffnesses as such that the interacting bending moments tend to become zero at the points of application of the props, the resulting B.M. diagram may then be as shown in Fig.3c. Thus the increasing number of props will produce more and more points in the beam structure where the bending moments might tend to vanish.

This simple beam analysis with prop-supports has helped to realize the fact that, if the radial forces acting around a coil are supported with the suitably stiffened props all along its circumference i.e a Ring-type support as shown in Fig.4a or in Fig.4b, a reduction of bending stresses within the coil may then follow.

3. MAGNETIC LOADS

The magnetic loads are computed for the coils using the basic data as shown in Table 1. These coil-data are scaled up from the advanced stellarator WENDELSTEIN VII-AS to reactor dimensions by a factor 10. The reactor coil configuration consists of 5 field periods and each period contains 10 coils, Fig.1.

For the calculations of the magnetic field and forces the code EFFI /2/ is used. The average magnetic flux density on the plasma axis amounts to 5.3 T. The magnetic forces acting on the twisted coils include the self-forces of of the individual coils and the interactive forces between the coils. The distribution of magnetic volume forces, radial and lateral, are shown for coil5 and coil1 in Fig.5 and Fig.6 respectively. The coil5 is mostly loaded whereas the coil1 is mostly twisted.

For computation with the EFFI- code, each coil's continuum is subdivided into 288 general current elements (GC-elements). These elements are the same as those used for the FE- model of coil5 (Fig.9) or of coil1 (Fig.28).

4. SUPPORT CONCEPTS FOR COIL5

Two supporting concepts, the Front support /3/ and the Ring -type Inward support /4/, are discussed below. The supporting of a coil is simulated by setting the boundary spring elements on the nodal points along the supporting regions of the coil.

4.1 FRONT SUPPORT- COIL5

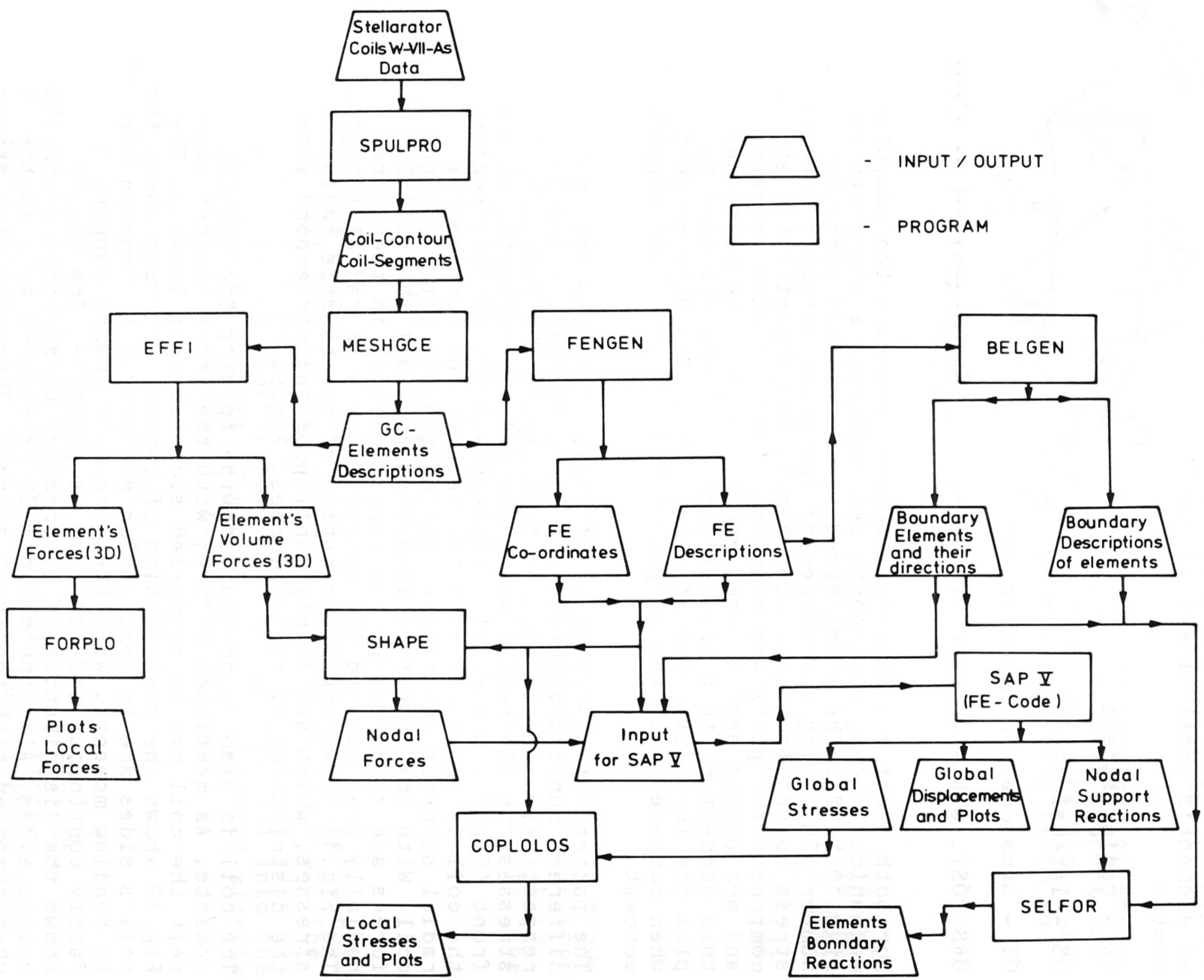
Here the coil5 is supported at the front region to take up the resultant centering force and sidewise to transmit the tilting moments as shown in Fig.7. The supporting regions are optimized by releasing the sides of elements which are in tension. With the Front support system the twisted coil tends to spring back into planar shape and this allows the side support of the coil to be only locally.

4.2 RING-TYPE INWARD SUPPORT- COIL5

In this concept a Ring-type support structure holds the coil from inside, Fig.8. The radial forces, mostly concentrated at the inner edge of a coil, are taken up by the inward Ring support. The coil is also supported sidewise to prevent the tilting moments and the support regions are optimized. Since the Ring support opposes the twisted coil to spring back into planar shape, a fairly continuous support along the sides of the coil is possible.

5. MECHANICAL STRESS ANALYSIS FOR COIL5

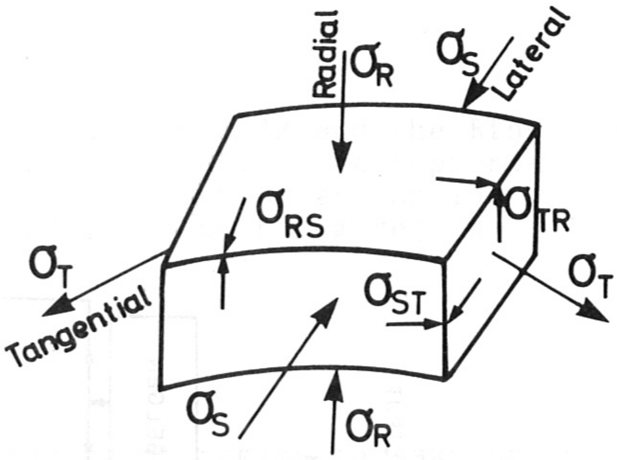
The FE stress analysis is carried out with the code SAPV2 /5/, within the program system STELLA /6/ (see Flowchart). The FE model for the coil5 is shown in Fig.9. Along the circumferential direction the coil is subdivided into 48 groups of elements. Each group consists of 6 micro-elements They are numbered from 1 to 6 respectively. The FE model thus consists of 288 three dimensional, 20 nodes and isoparametric elements. The computations are done with the same nodal forces for the both above mentioned support concepts and using an isotropic idealization of the elastic module $E_{xx} = E_{yy} = E_{zz} = 1.5 \times 10^{11}$ N/m^2 (1:1 mixture of copper and steel), the poisson ratio $\nu_{xy} = \nu_{yz} = \nu_{zx} = 0.3$ and of the shear moduli $G_{xy} = G_{yz} = G_{zx} = 5.8 \times 10^{10}$ N/m^2. The values of the stress components at the centre of an element are obtained for analyses. No filling factor is considered.



DETAILED FLOWCHART OF THE PROGRAM-SYSTEM: - STELLA -

5.1 COMPARISON OF THE RESULTS- COIL5

For analyses of the results the following notations are used for an element's local stress components:



Segment of a Coil

σR - radial stress

σS - lateral stress

σT - tensional or hoop stress

σRS, σST, σTR are shear stresses.

For both Front and Ring-type support concepts the computed mechanical stress components and deflections are shown in Figs.10 to 25. The local stresses are plotted over the number ARG, being the number of the plane on which the six stress output locations lie, Fig.9. For a particular stress component two plots are available (one for each concept) and are placed next to each other. It is to be mentioned in this connection that the different scalings are used to plot the local stresses of a coil using the Ring concept when compared with the graphs ploted for the Front support concept.

The pattern of distribution of radial stresses with two different support concepts are shown in Figs.10 and 11 respectively. As can be seen from Fig.10 the radial stresses, in the region where the coil is supported at the front (Fig.7), are mainly compressive. Beyond this region the coil is overlaped with the tensile and compressive radial stresses due to the bending moments acting on the coil. With the Ring-type inward support all the radial forces are supported by the ring. The coil is therefore radially free outward and remains purely in radial tension. The Fig.11 shows the distribution of the tensile radial stresses, which are fairly continuous and correspond with the distribution of radial forces, Fig.5a.

The coil is also supported sidewise to stop the tilting moments. As mentioned before, with the Front support concept the coil can be supported sidewise only locally. The Fig.12 shows the distribution of lateral stresses where the coil's sides are in compression and partly in tension due to bending moments. With the Ring-type inward support a fairly continuous side support is possible. The Fig.13 shows the distribution of compressive σS stresses along the coil's sides. Also the maximum σS is reduced by a factor 10 when compared with the Front support. There are also strong reductions in σT (hoop) and the shear stresses σRS, σST and σTR are practically negligible using the Ring concept, Figs.14 to 21. The maximum value of σVMH (von Mises) is about 340 MPa using the Front support whereas with the Ring support this amounts to only 43 MPa, Figs.22 to 23. Thus a higher safety factor can be achieved using the latter concept.

The Figs.24 and 25 are showing the deflections of the coil using both support concepts. With the Front support the maximum deflection is about 30.2 mm. With the Ring support this is only about 0.08 mm and thus the coil tends to remain in its original shape.

6. SUPPORT CONCEPTS FOR COIL1

The FE computations are now carried out for the reactor coil1. This coil is twisted most in comparison with the other coils, Fig.1. Here the Front support and the Ring-type Outward support are used for computations. The supporting regions are simulated by the boundary spring elements.

6.1 FRONT SUPPORT- COIL1

The reactor coil1 with its front support system is shown in Fig. 26. Here again the coil is supported at the front region to take up the resultant centering force. It is also supported sidewise to stop the tilting moments. The support regions are optimized.

6.2 RING-TYPE OUTWARD SUPPORT- COIL1

In this concept a ring-type supporting structure to hold the coil from outside is being considered. Here all the radial forces, concentrated mostly at the inner edge of the coil, are then transmitted through the coil into the outward Ring support. The coil is also supported sidewise as shown in Fig. 27 and optimized.

7. MECHANICAL STRESS ANALYSIS FOR COIL1

The FE model for the coil1 is shown in Fig. 28. Again the model consists of 288 elements (three dimensional). The computations are done with the same nodal forces for the both type of supportings. All other parameters are remained identical with the coil5.

7.1 COMPARISON OF THE RESULTS- COIL1

Both for the Front and the Ring-type support concepts, the plots for some of the mechanical stress components are shown in Figs.29 to 36. The local stresses are plotted over the number ARG, being the number of the plane on which the six output locations lie, Fig. 28. The coil's deflection plots are shown in Figs.37 and 38. Comparing all the results a clear advantage of the Ring support concept over the Front support is noticeable.

8. CONCLUSIONS

Modular stellarator coil systems of the WENDELSTEIN VII-AS type with reactor dimensions are investigated. The finite element computations show that using a Ring-type support concept (an inward or an outward type), a considerable reduction of the mechanical stresses within a coil under magnetic loads may be expected when compared with the Front support concept. This reduction of stresses are mainly due to drop of the bending moments within a twisted coil. The bending stresses, need to be eliminated, depend on how a coil is supported and on the stiffness of a support structure. With a Ring concept all the radial magnetic forces are taken up by the support structure. But the choise of correct structural stiffness that may tend to make the bending moments within a coil to disappear, is difficult to achieve. In this paper the Ring or the Front support is simulated simply by using the boundary spring elements. A detailed system study, with the actual generation of the ring structure and with the corresponding support stiffness, is done by E. Harmeyer et al, /7/.

The radial forces within a reactor coil are mostly concentrated at the inner edge because of the high magnetic flux density at that region. A Ring-type inward support of a coil takes up these forces directly, and the coil expands radially outward. With the Ring-type outward support these concentrated radial forces pass through the coil into the outward support structure, thus leading to the radial compression of the coil.

As far as the deflection of a coil is concerned, it is possible to get low deflection of a coil using a Ring concept and the coil tends to retain its original shape.

The finite element computations are done only with the magnetic forces and no temperature rise within the coils are considered, since the coils are superconducting. Also the forces and stresses resulting from cooling down and different thermal expansion coefficients are not treated here. Temperature rise will however produce negative hoop stresses ($-\sigma T$) within a coil supported with a Ring-type structure. For an outward Ring support if soft paddings are used between the support and the coil, this will help the coil to expand accordingly with the temperature rise. It is to be mentioned that with no temperature rise and with the soft paddings, this may lead to higher positive hoop stresses ($+\sigma T$) within a coil under magnetic loads. The $-\sigma T$ due to the temperature rise may be then employed conveniently to counteract the $+\sigma T$ due to the magnetic loads.

A computer program /8/ is developed to generate a coil's supporting structure with paddings. This facilates detailed investigation of the effects of support structure on the stress components of a coil.

ACKNOWLEDGEMENTS

The author is grateful for the valuable assistances provided by H. Gorenflo and E. Springmann and for the fruitful discussions with Dr.U .Brossmann and Dr.M .Soell.

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/3/ Brossmann, U., Mukherjee, S., Sapper, J., Computational Aspects for a Modular Stellarator Fusion Reactor Magnet, Proceedings of the 12th Symposium on Fusion Technology, Juelich, FRG (1982) 985.

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/7/ Harmeyer, E. et al, On Modular Coil Systems of the WENDELSTEIN VII-AS Type with Reactor Dimensions, Report IPP 2/269, August 1983.

/8/ Mukherjee, S.B., Gorenflo, H., Harmeyer, E., PADDING - A Program to Generate Padded Support Structure for Modular Coils, Report IPP (in preparation).

Table 1 Reactor Design Parameters

No. of twisted coils per field period	10
Total number of field periods	5
Major plasma radius	20.6 m
Average minor plasma radius	1.25 m
Mean minor coil radius	4.82 m
Radial coil thickness	1.12 m
Lateral coil thickness	0.71 m
Field at the superconductor	< 9 T
Average field on the plasma axis	5.3 T
Gross current density	1.33×10^7 A/m^2

Table 2 Reactor Coil Configuration

Stainless steel	40 %
Copper	40 %
Superconductor	1 %
Fibreglass epoxy	9 %
Liquid helium	10 %

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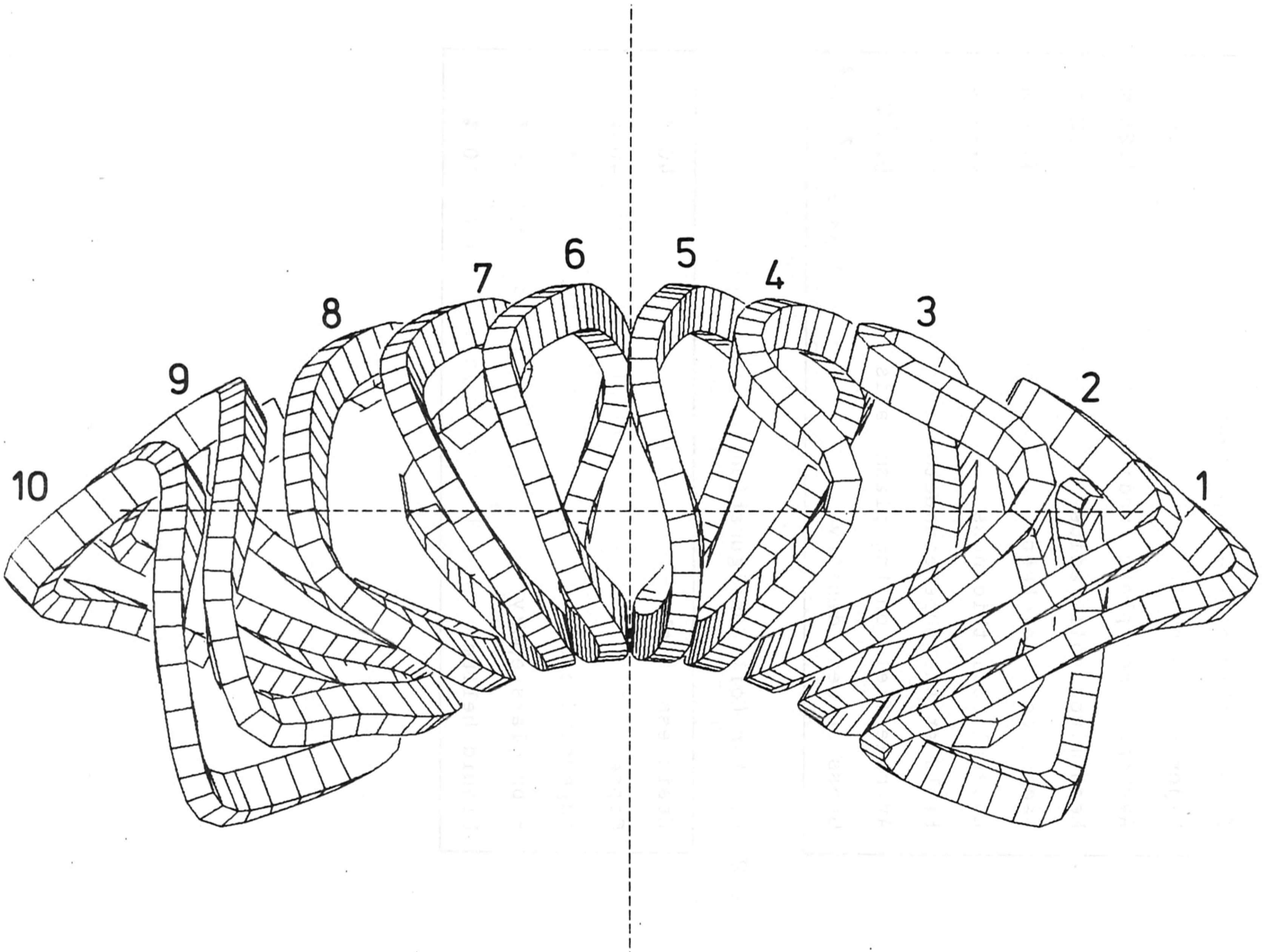

COIL1-10 S=.1/Z= 36.0/T=2.0/Z= 00./Y=-90./X=00./S=.8/T=-5.0/D=0.2

Fig. 1 A Modul of Reactor Coils

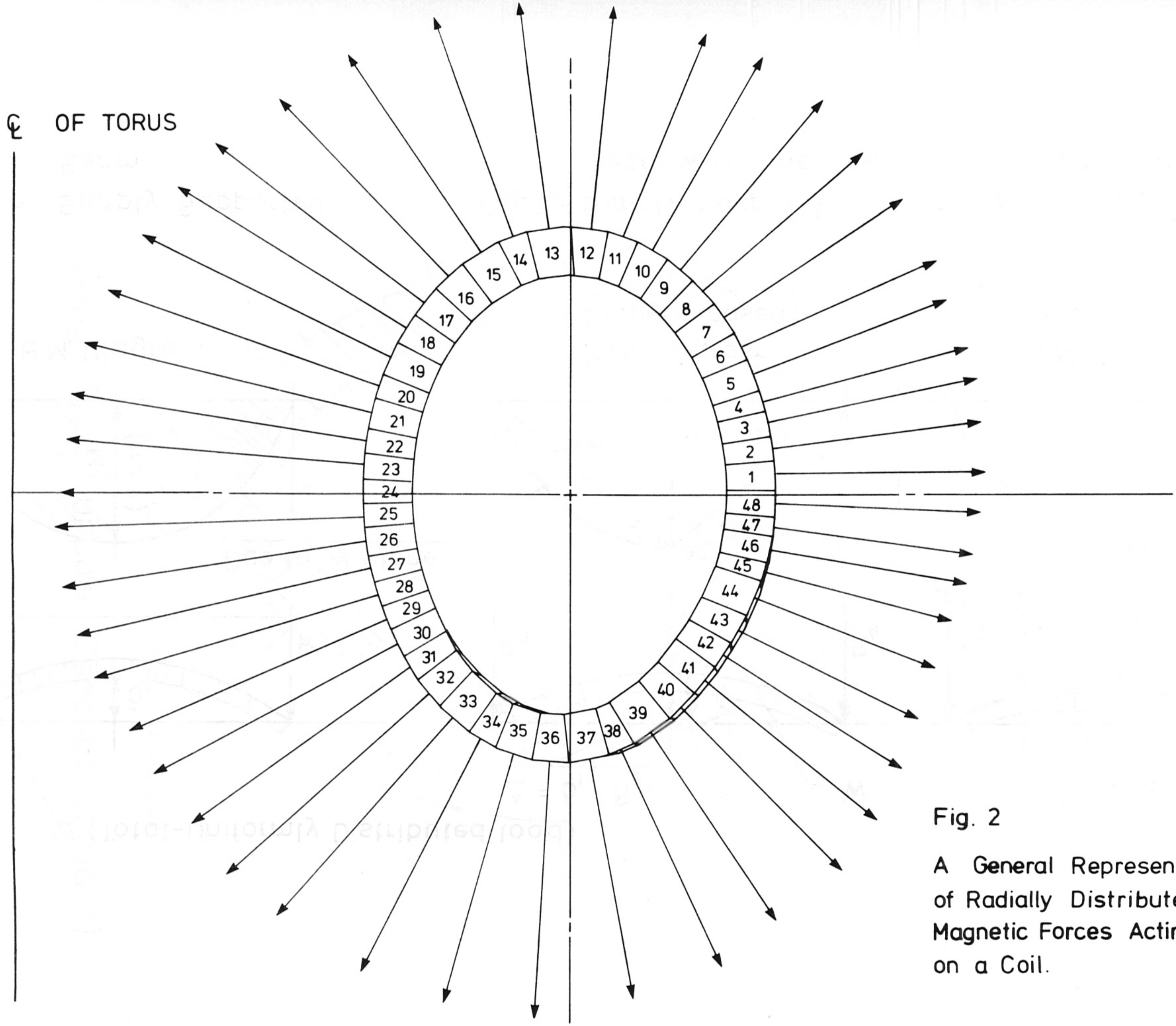

Fig. 2

A General Representation of Radially Distributed Magnetic Forces Acting on a Coil.

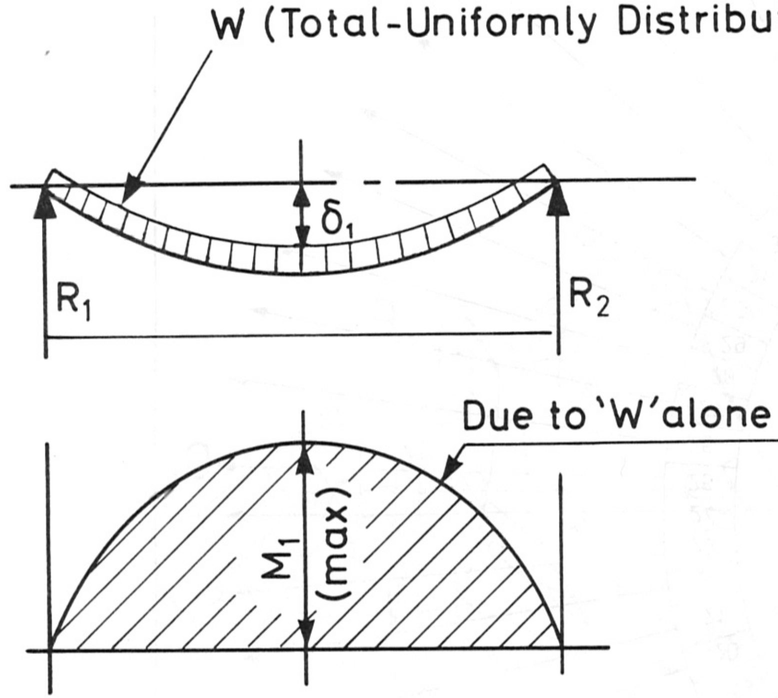

Fig.3a Simply Supported Beam

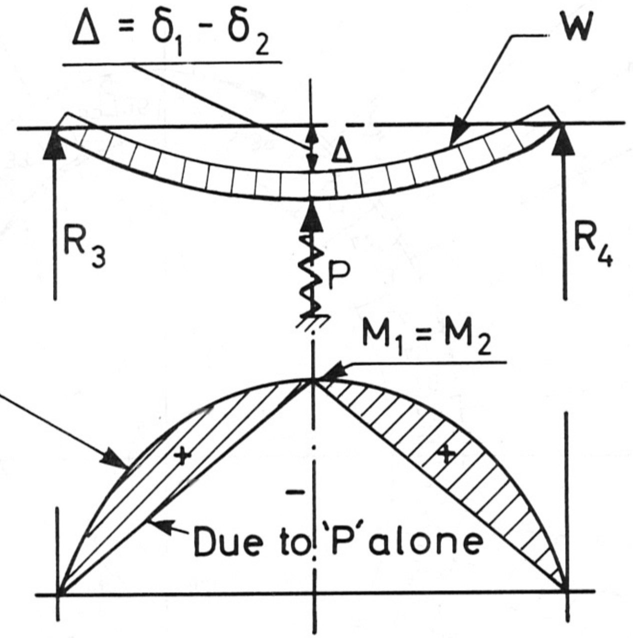

Fig.3b Simply Supported Beam with one Prop

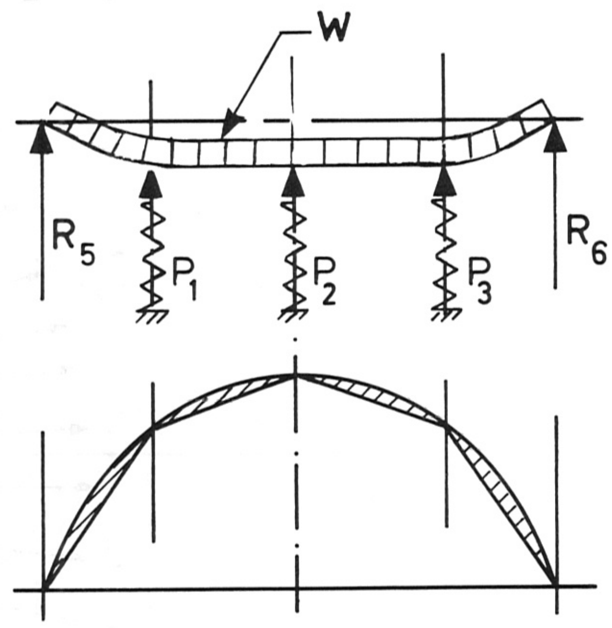

Fig.3c Simply Supported Beam with more Props

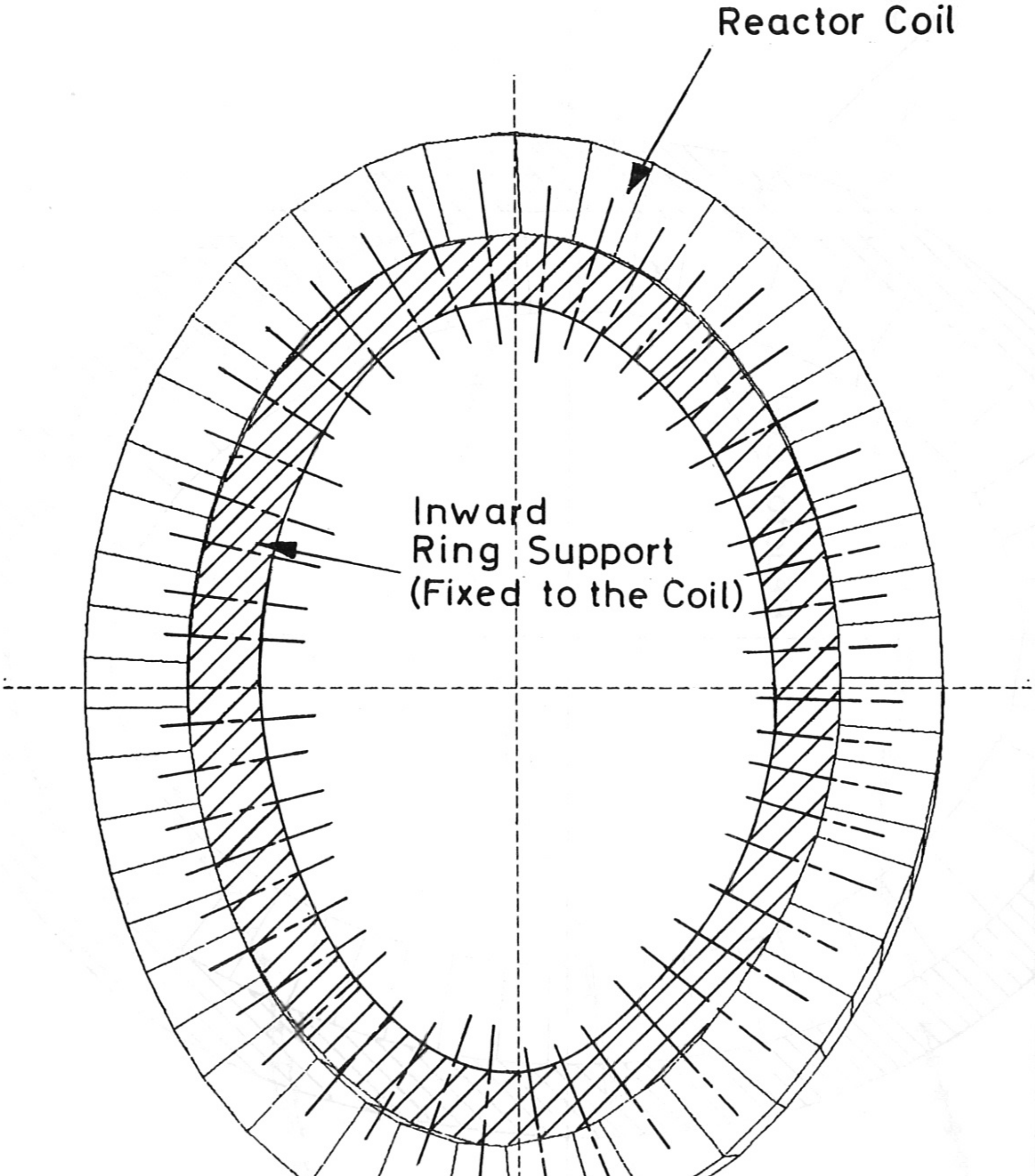

Fig. 4a Ring-Type Support Concept (Inward)

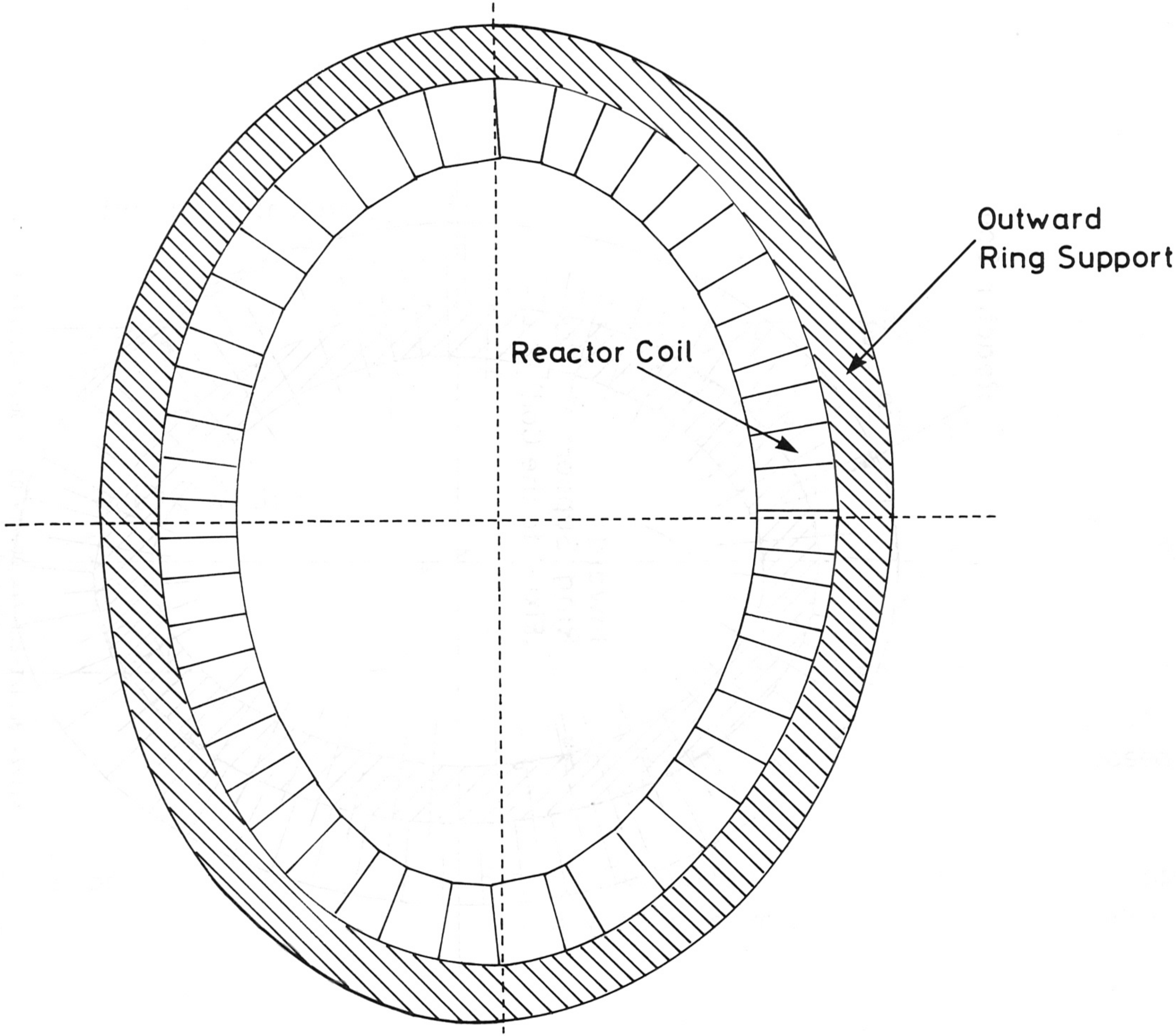

Fig. 4b Ring - Type Support Concept (Outward)

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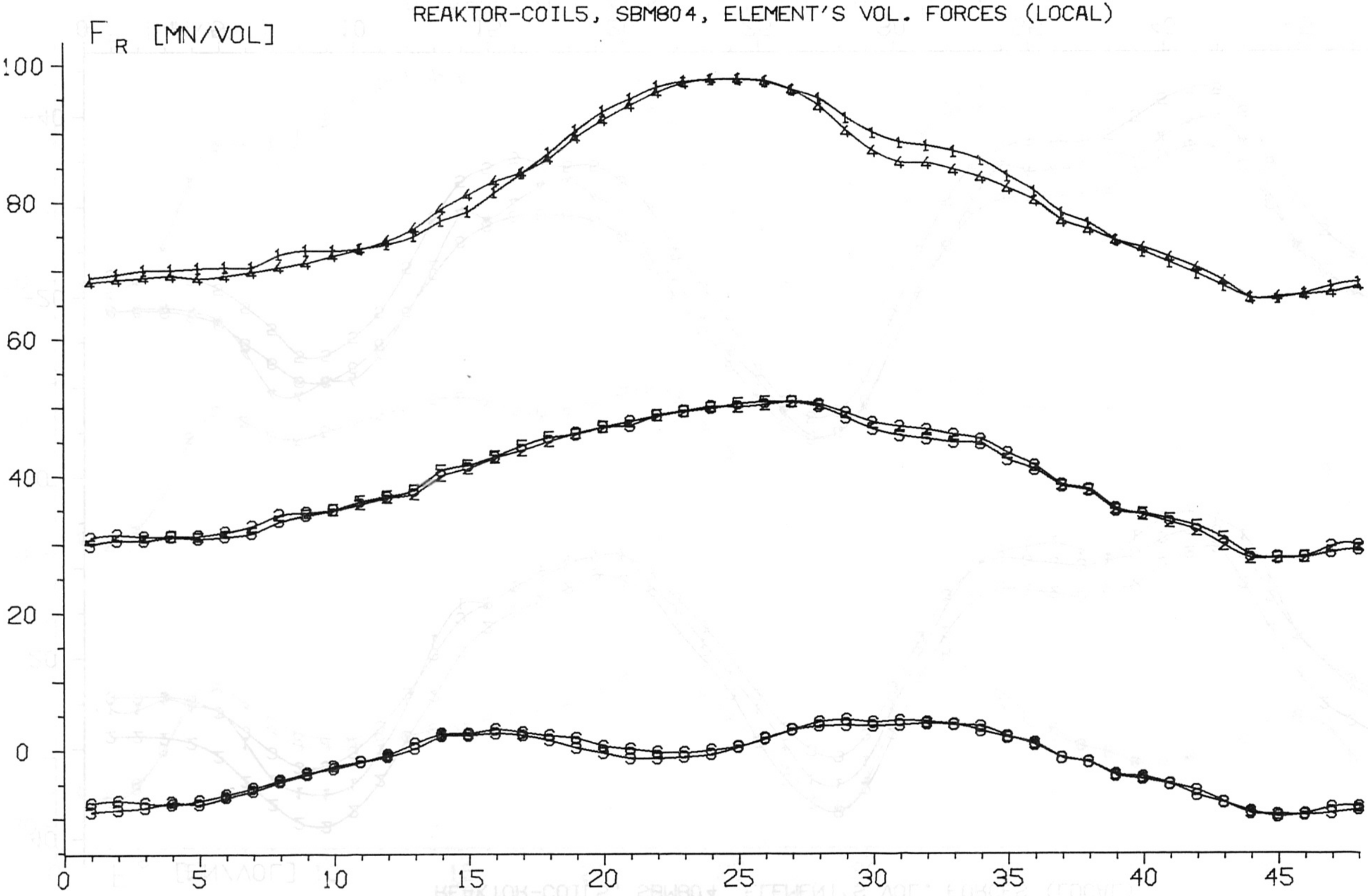

Fig.5a Distribution of Radial Volume Forces along Coil 5

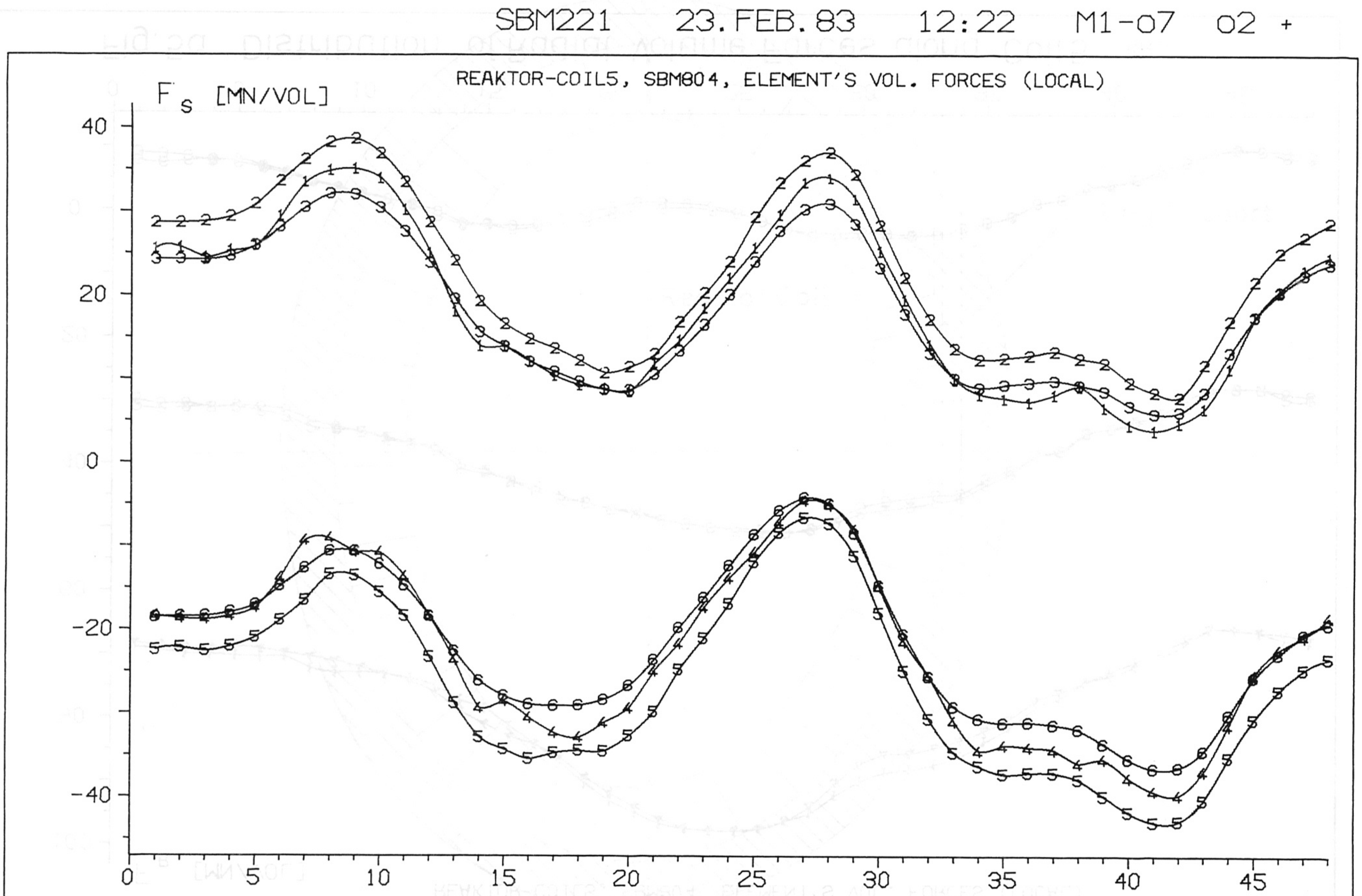

Fig. 5b Distribution of Lateral Volume Forces along Coil 5

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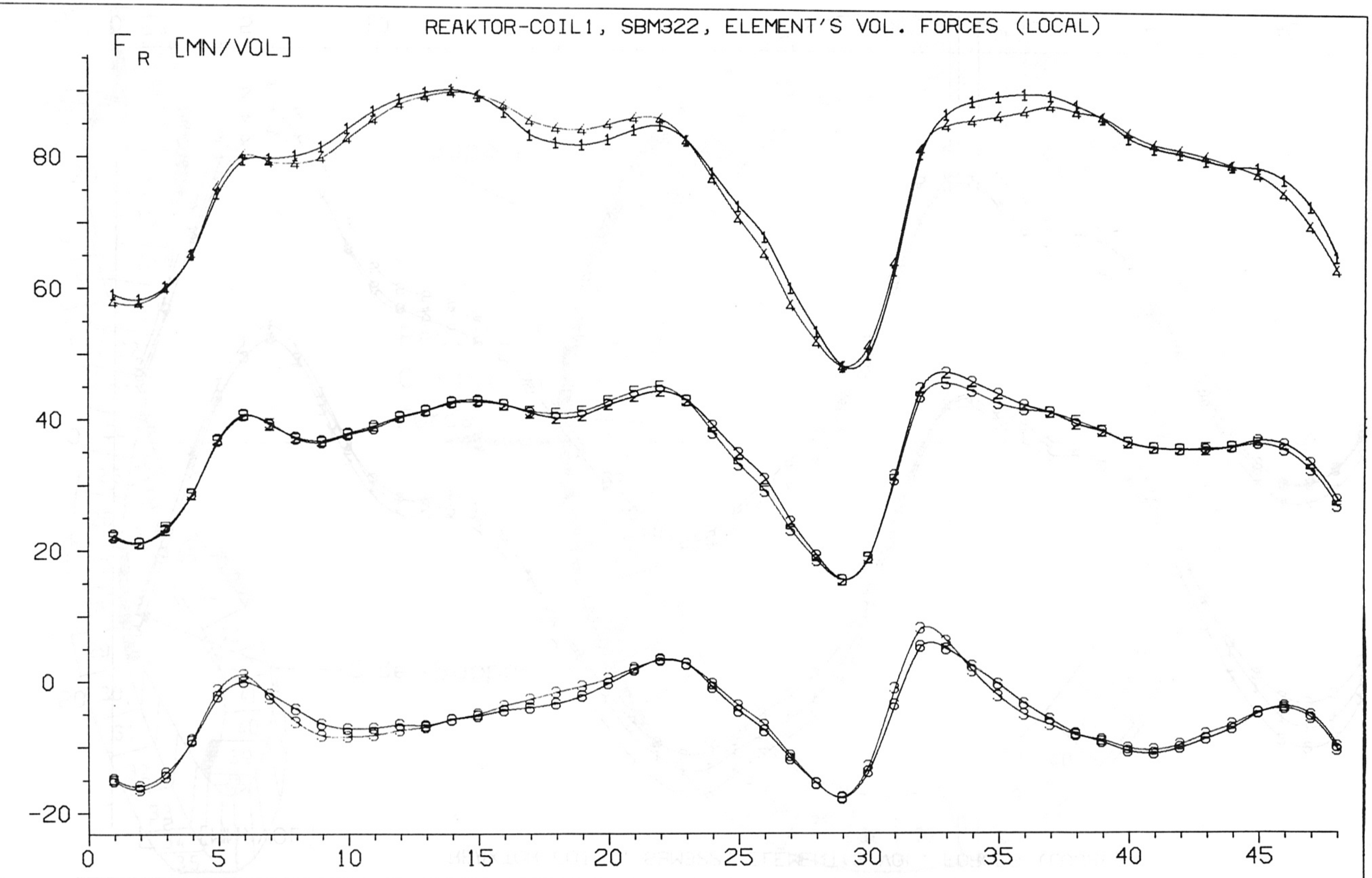

Fig. 6a Distribution of Radial Volume Forces along Coil 1

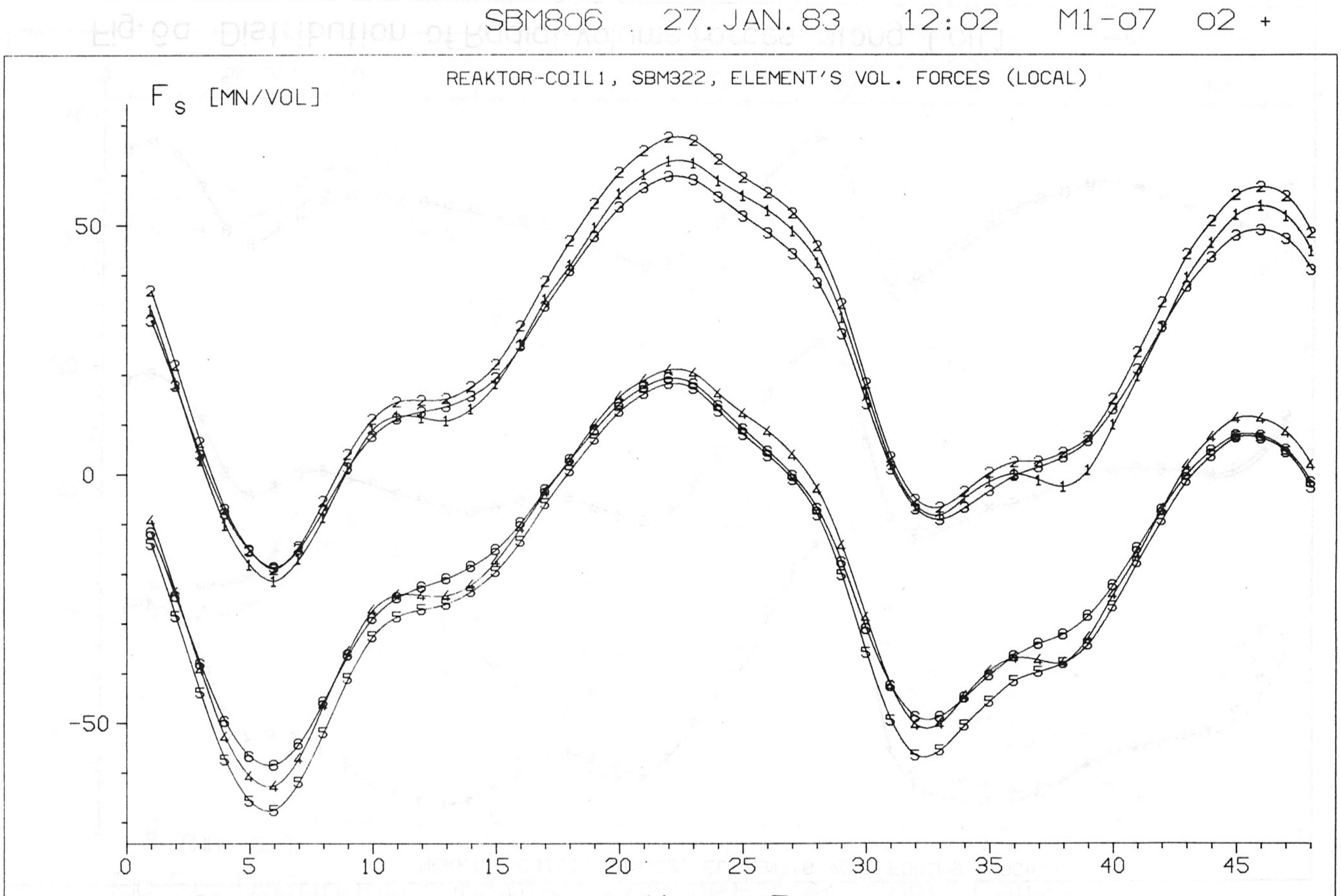

Fig. 6b Distribution of Lateral Volume Forces along Coil 1

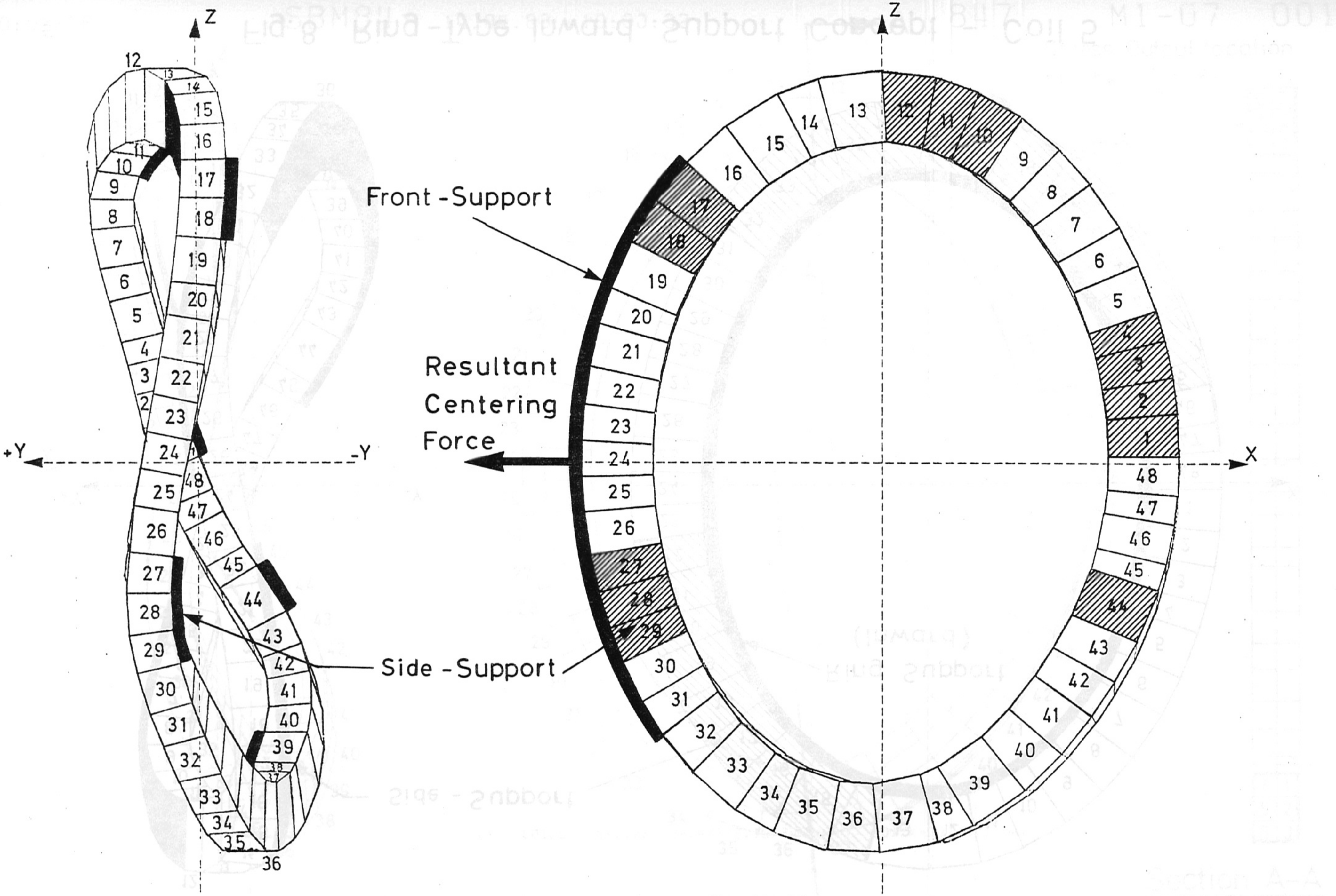

Fig. 7 Front Support Concept - Coil 5

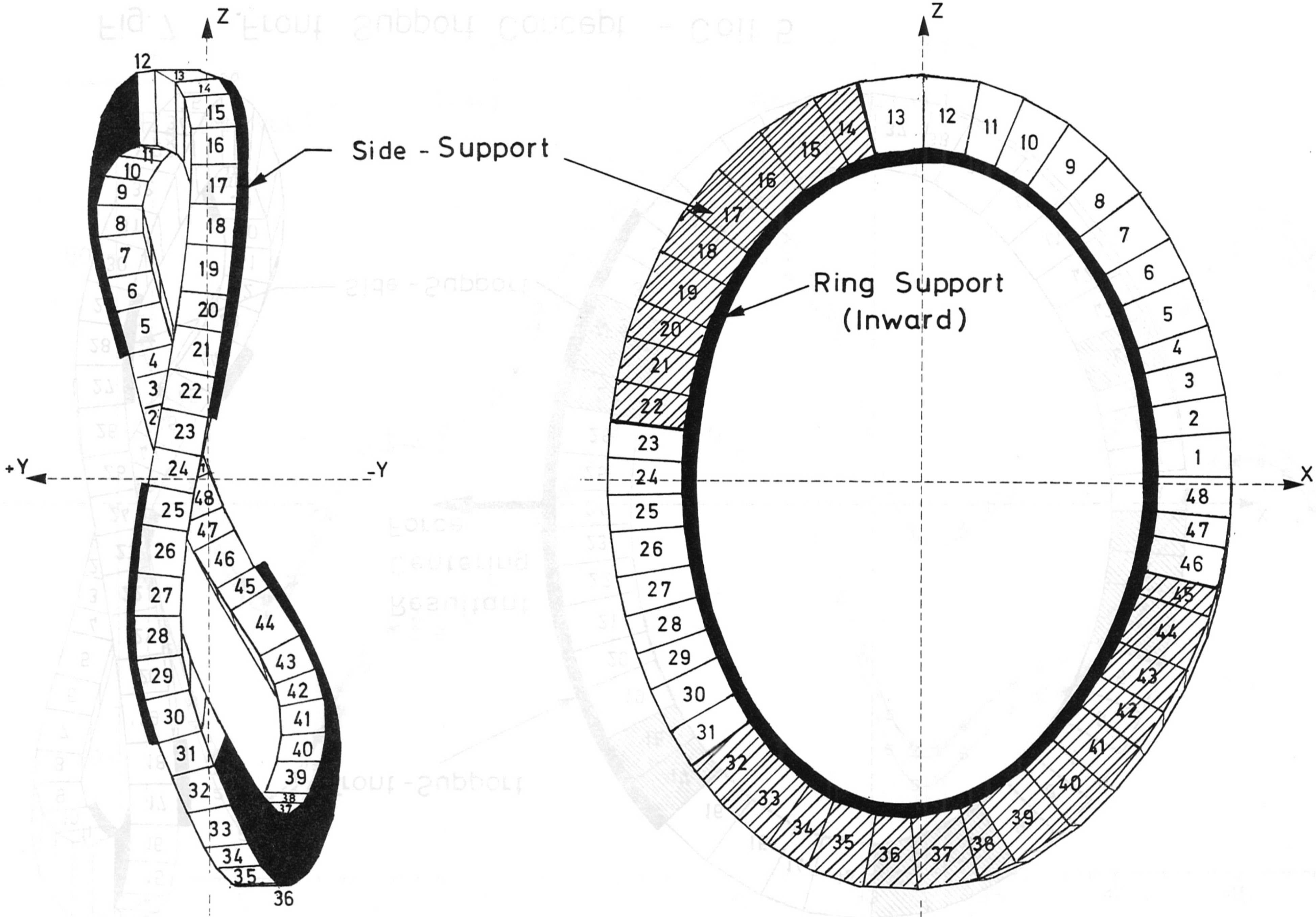

Fig. 8 Ring-Type Inward Support Concept - Coil 5

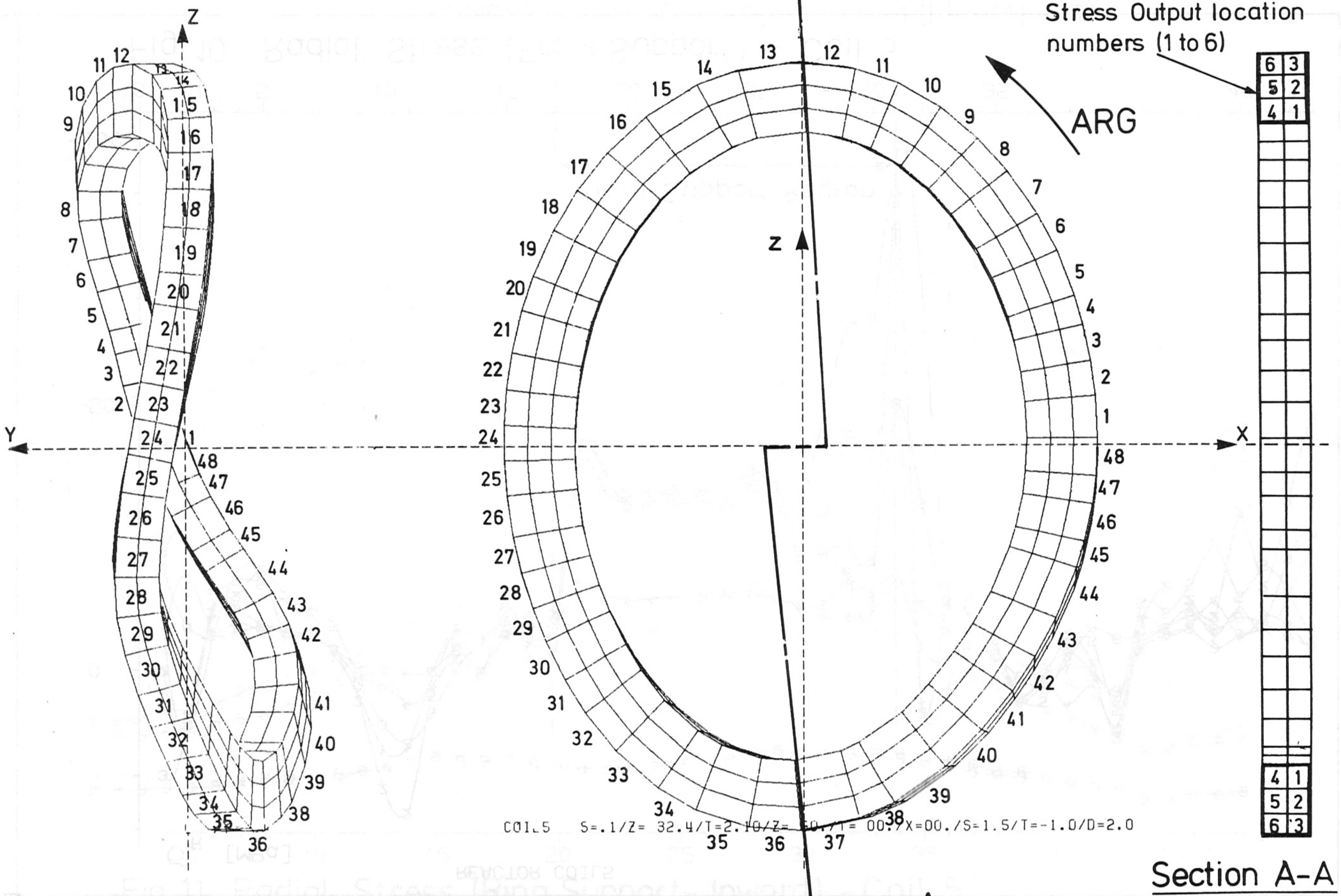

Fig. 9 FE Model for Coil 5

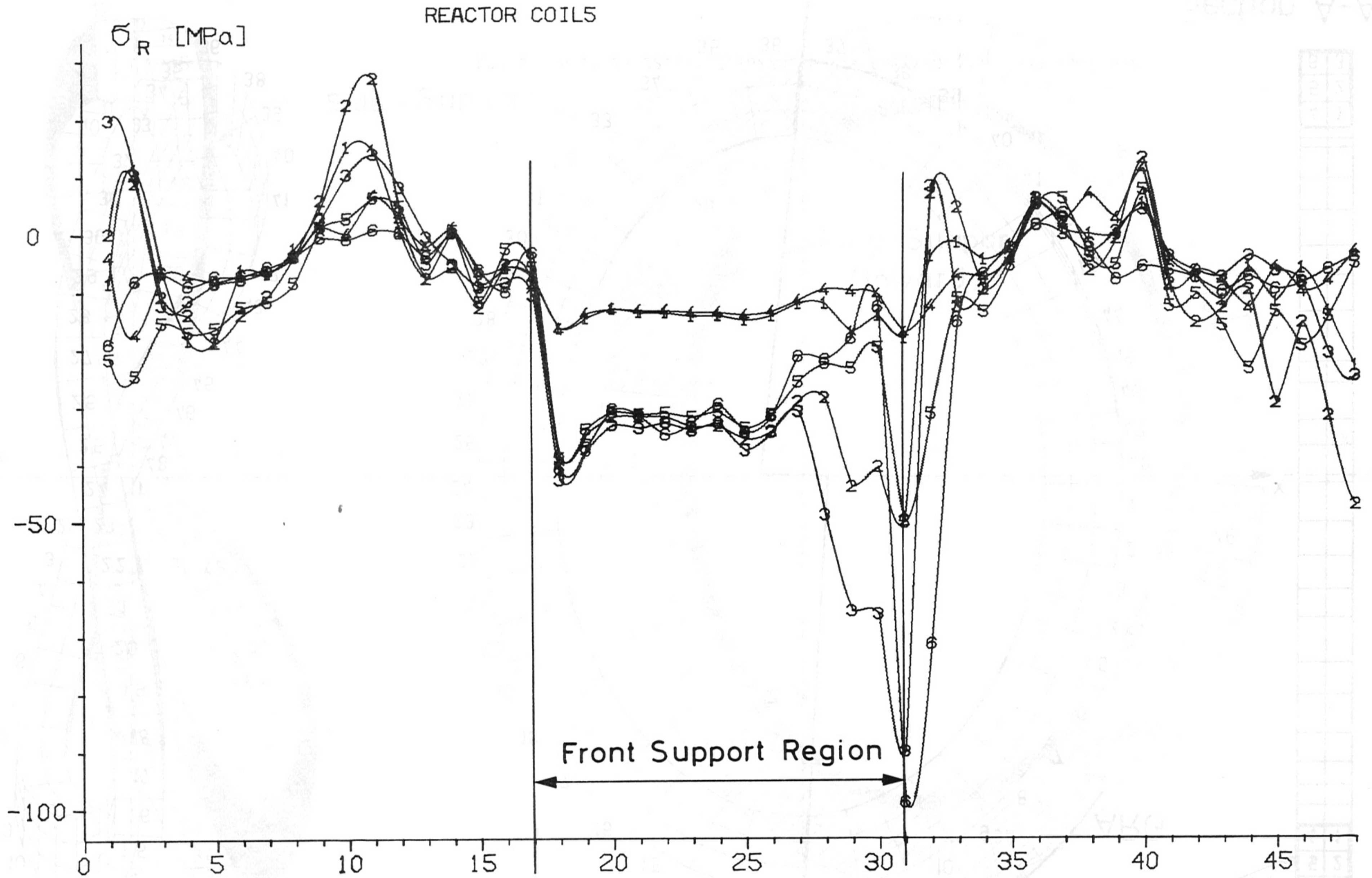

Fig. 10 Radial Stress (Front Support) - Coil 5

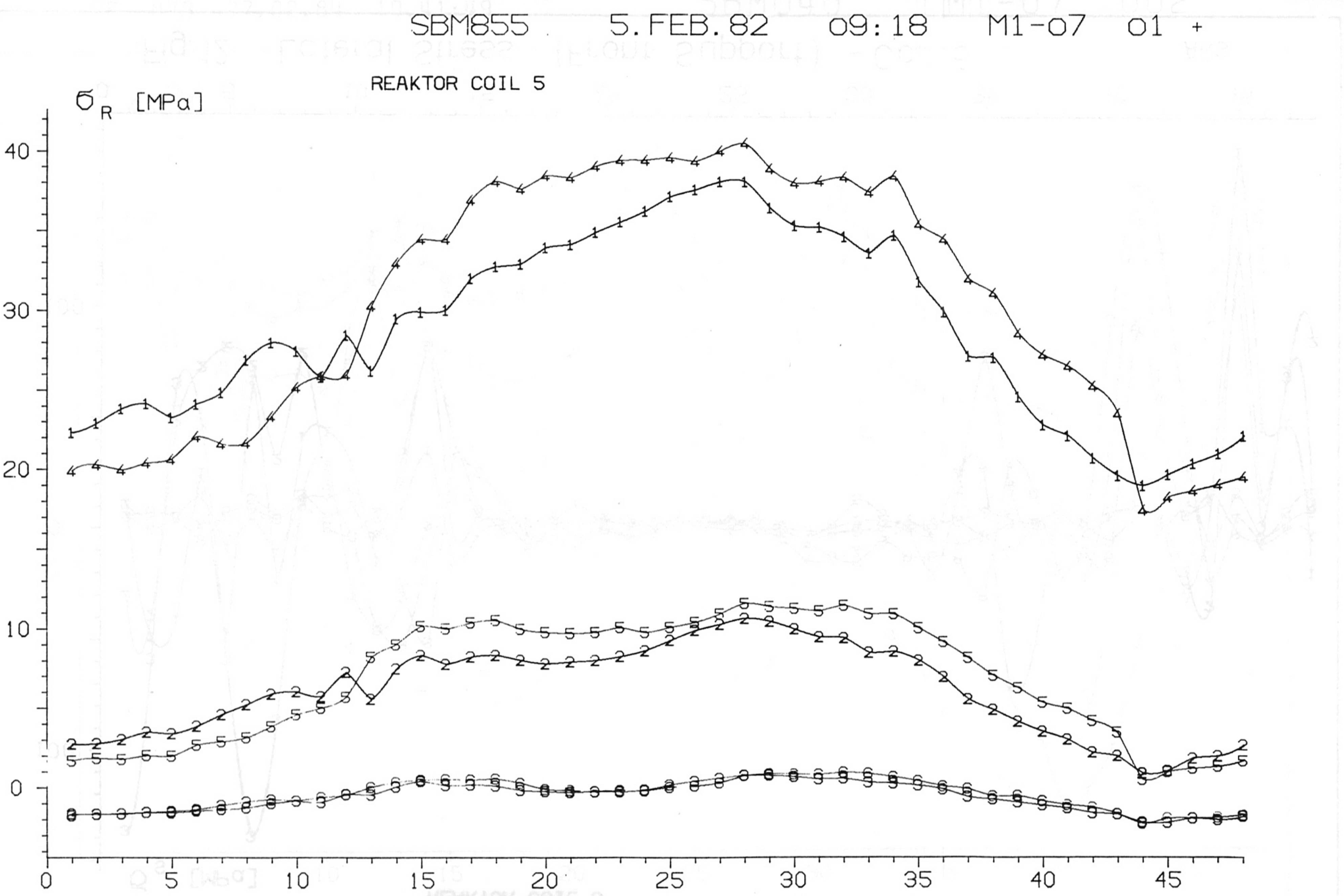

Fig. 11 Radial Stress (Ring Support - Inward) - Coil 5

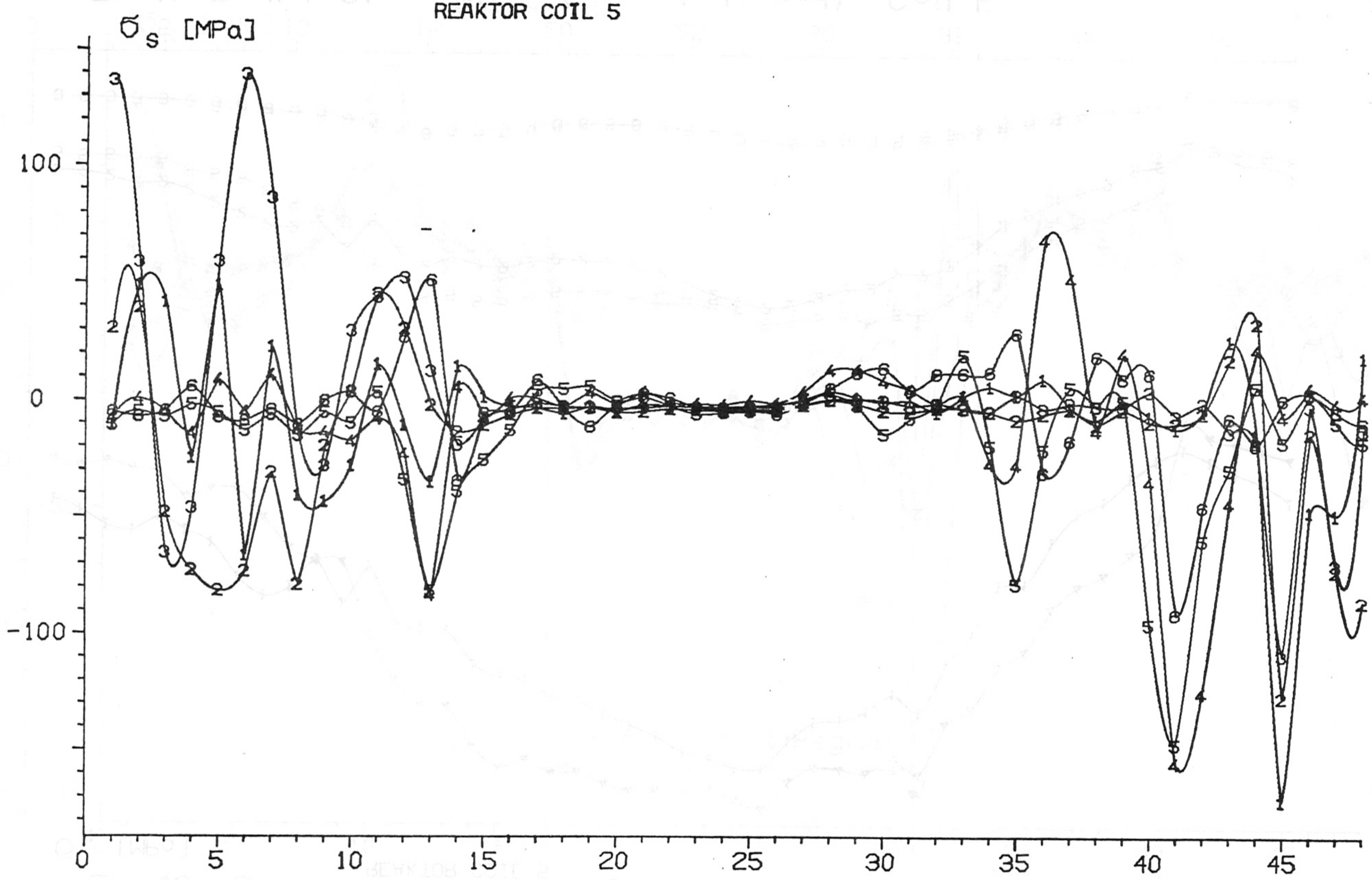

Fig. 12 Lateral Stress (Front Support) - Coil 5

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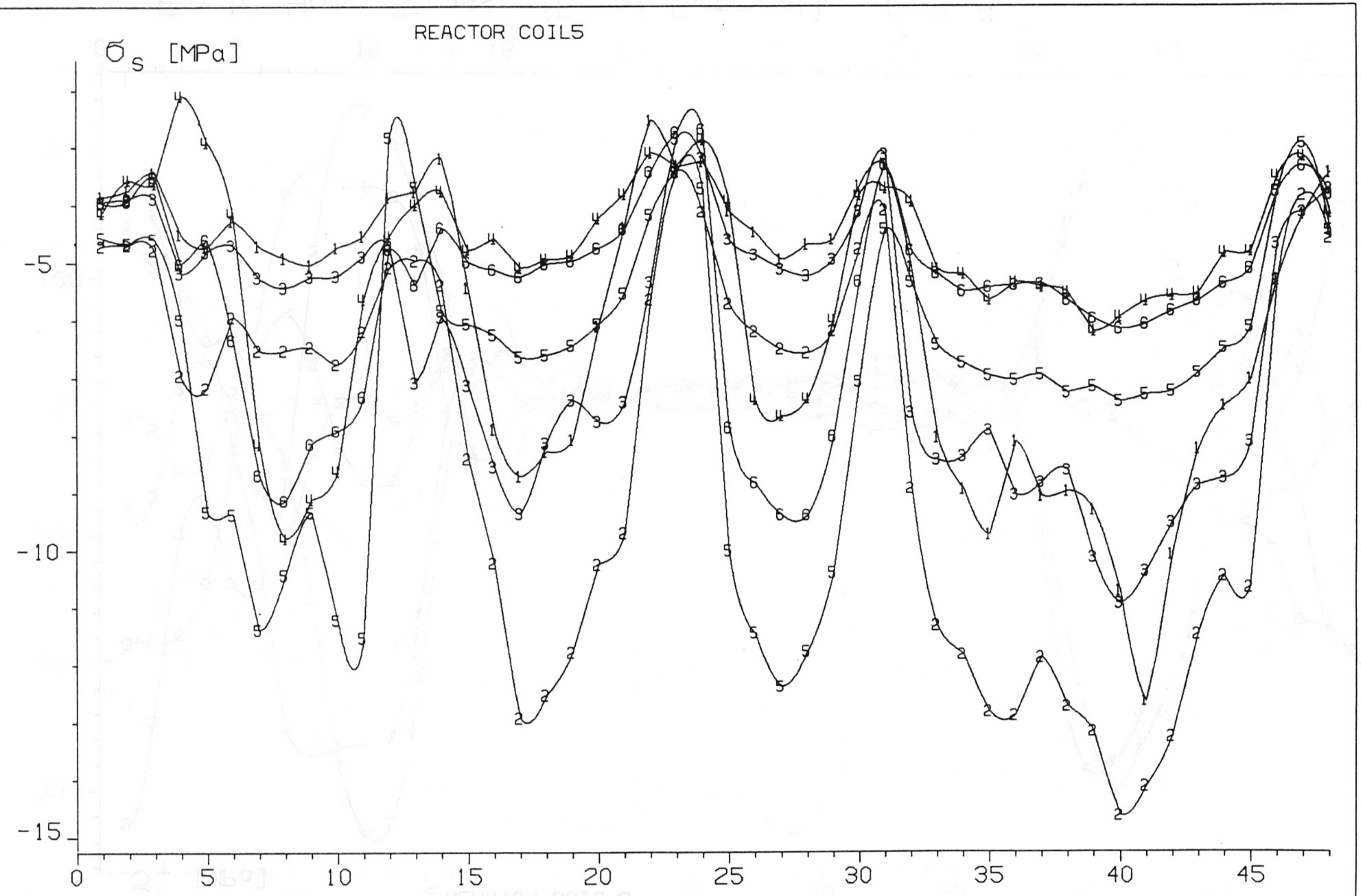

Fig. 13 Lateral Stress (Ring Support - Inward) - Coil 5

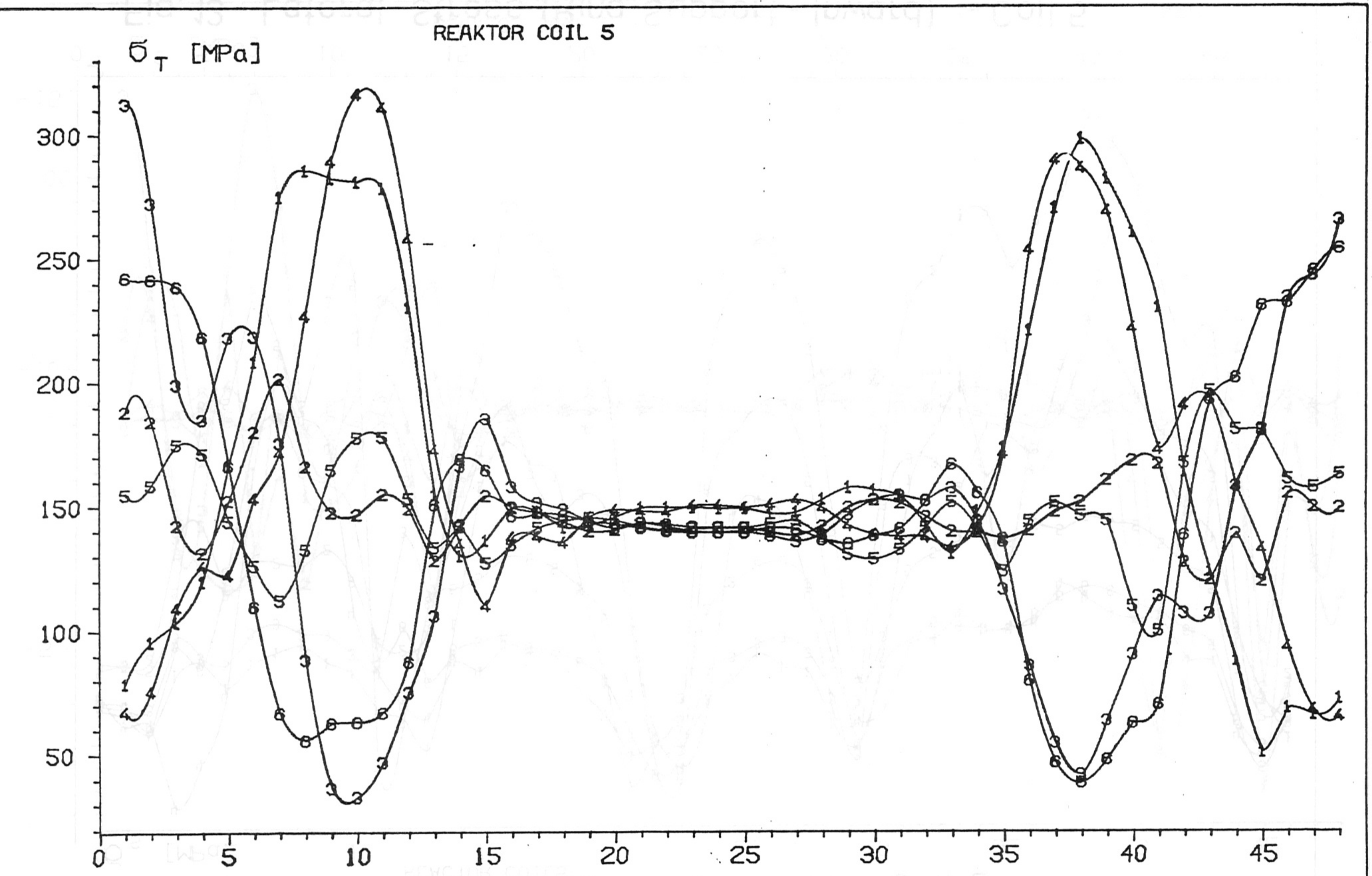

Fig. 14 Hoop Stress (Front Support) - Coil 5

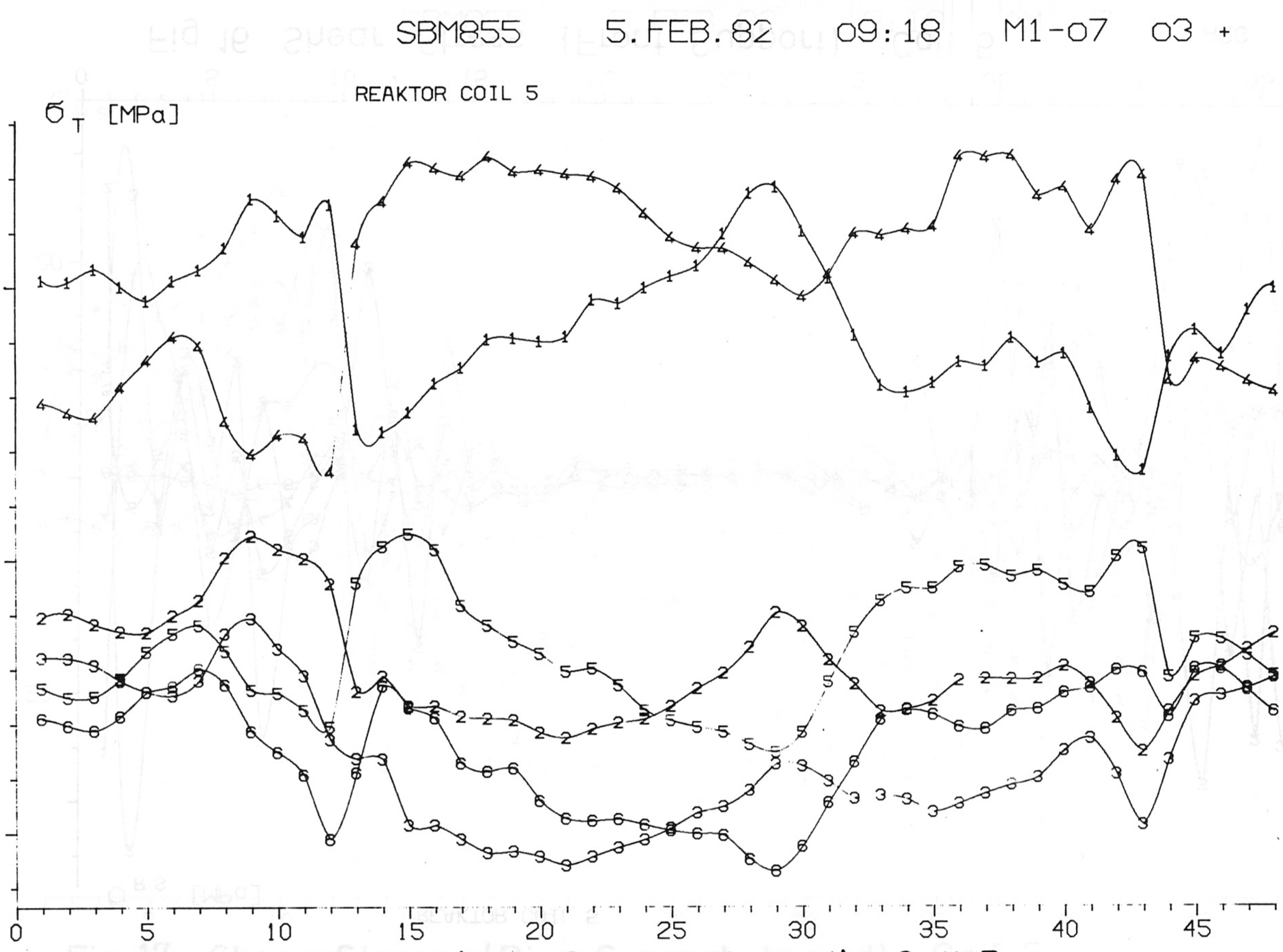

Fig. 15 Hoop Stress (Ring Support - Inward) - Coil 5

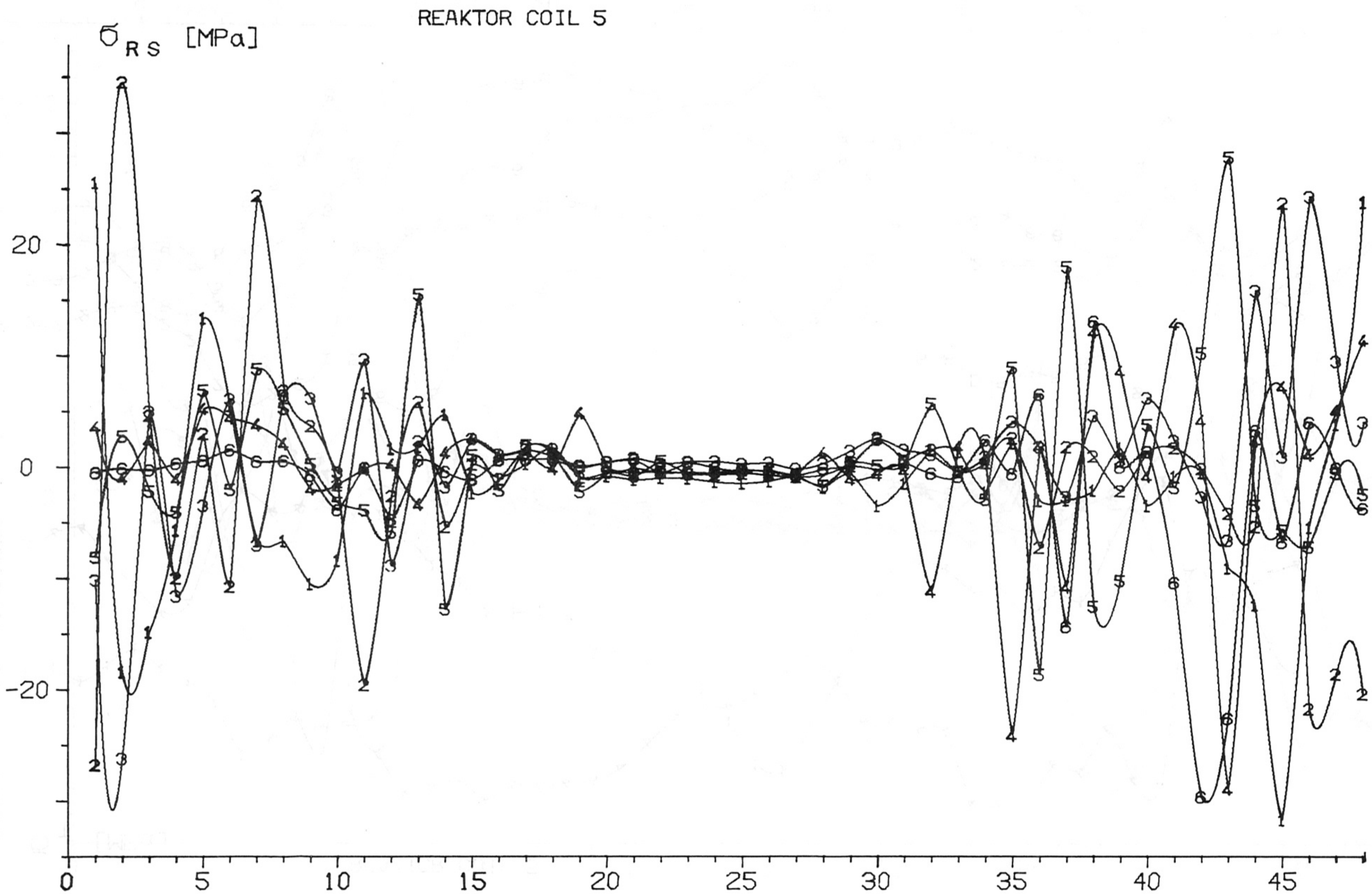

Fig. 16 Shear Stress (Front Support) - Coil 5

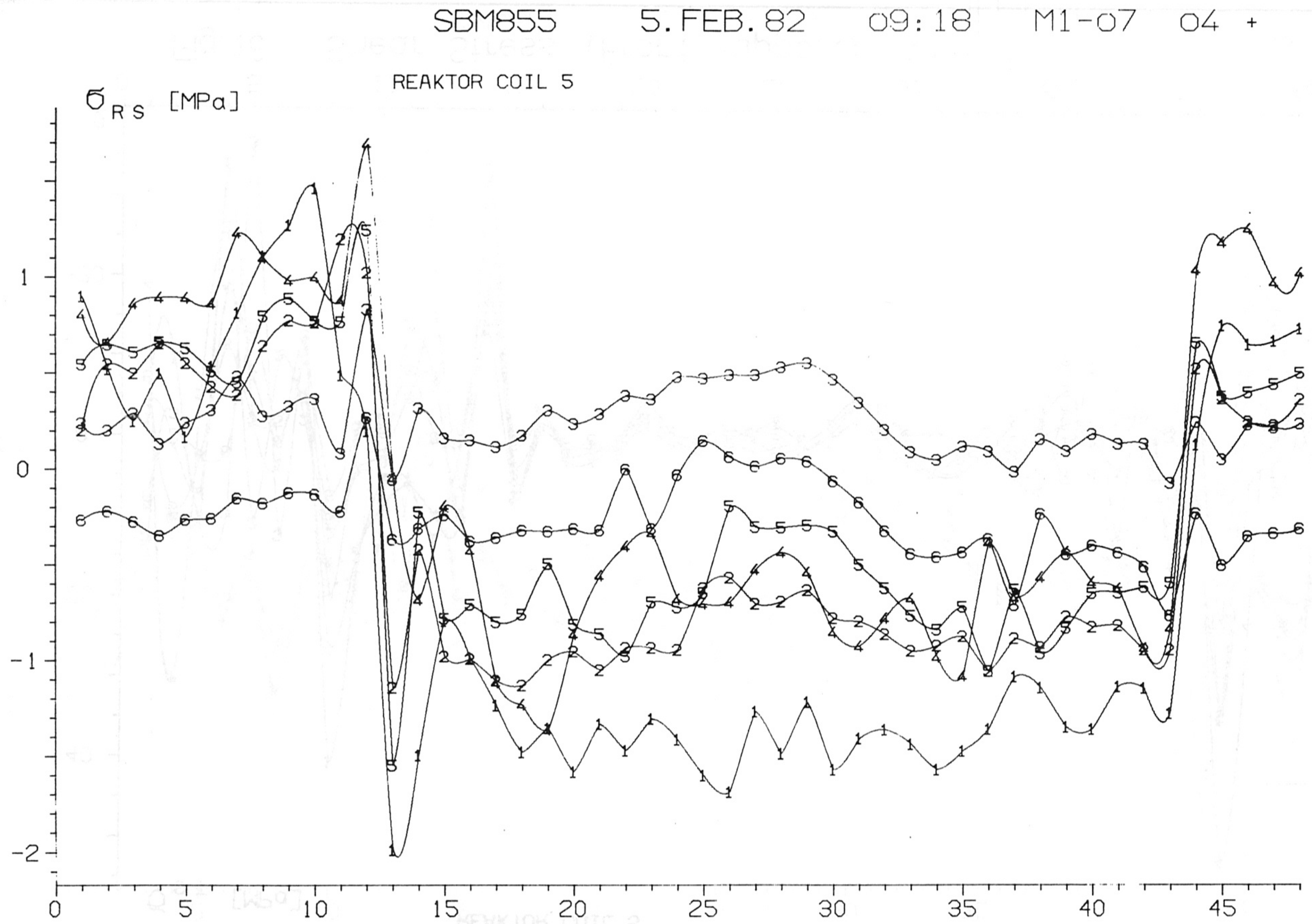

Fig. 17 Shear Stress (Ring Support - Inward) - Coil 5

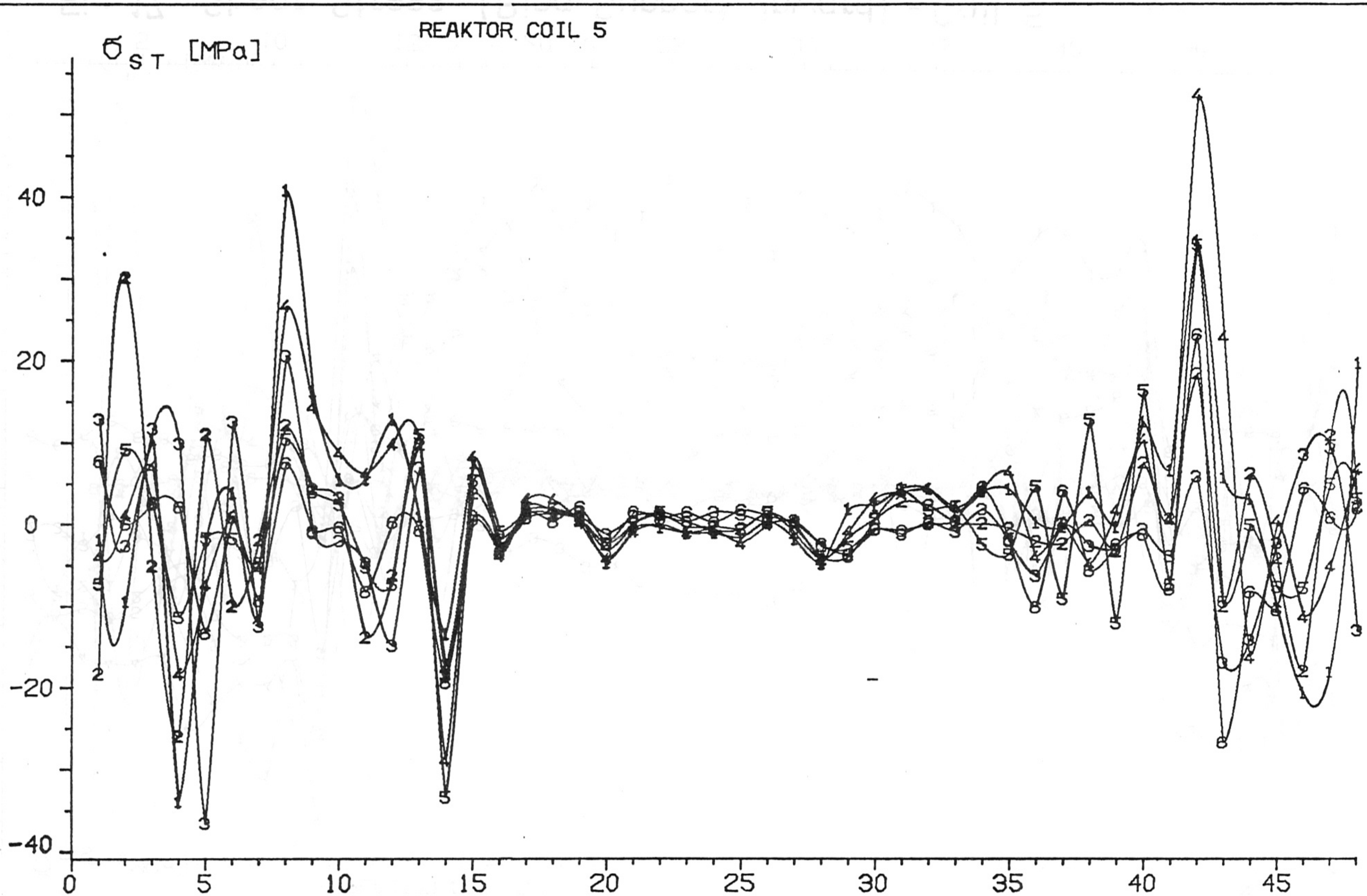

Fig. 18 Shear Stress (Front Support) - Coil 5

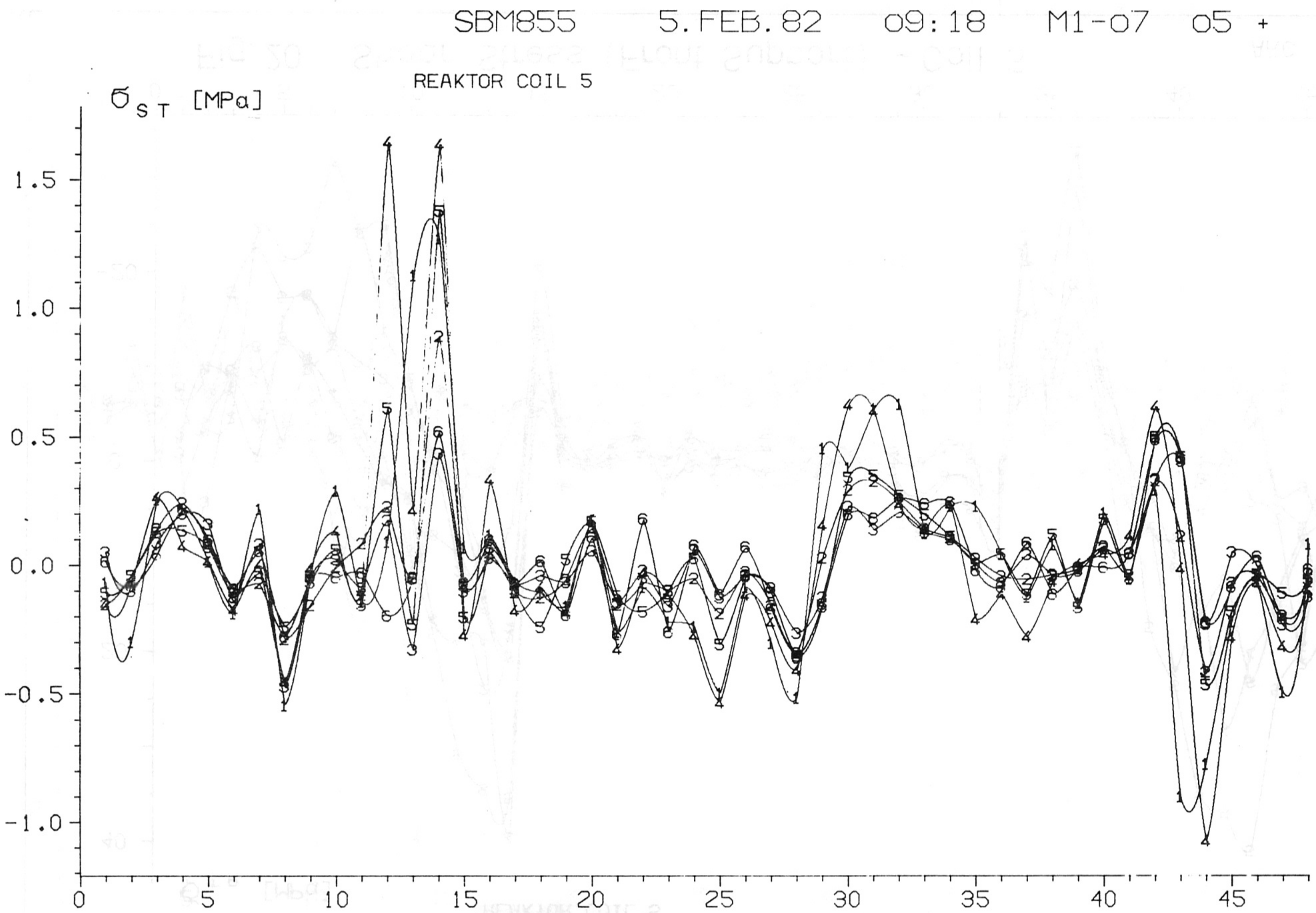

Fig. 19 Shear Stress (Ring Support - Inward) - Coil 5

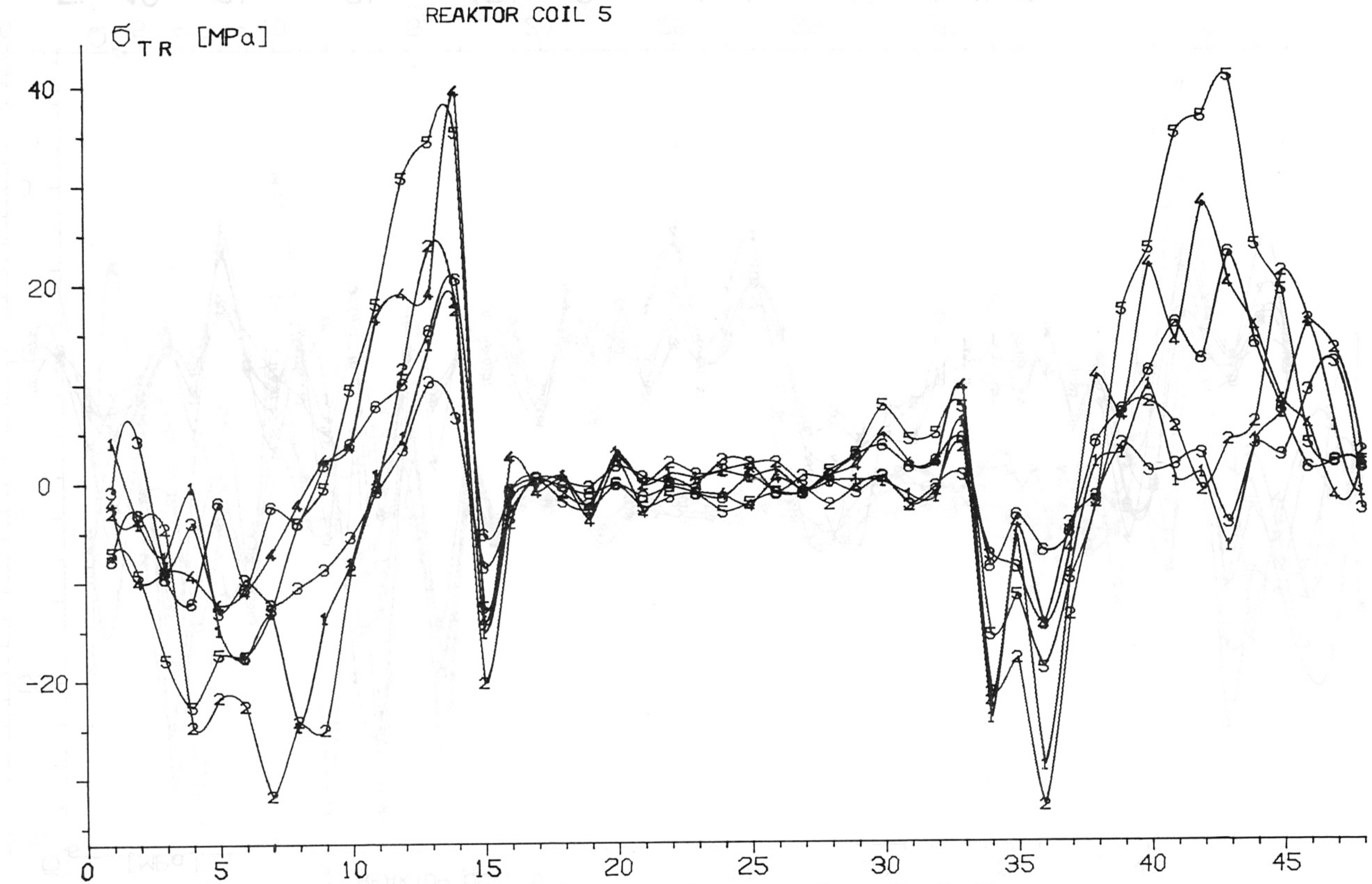

Fig. 20 Shear Stress (Front Support) - Coil 5

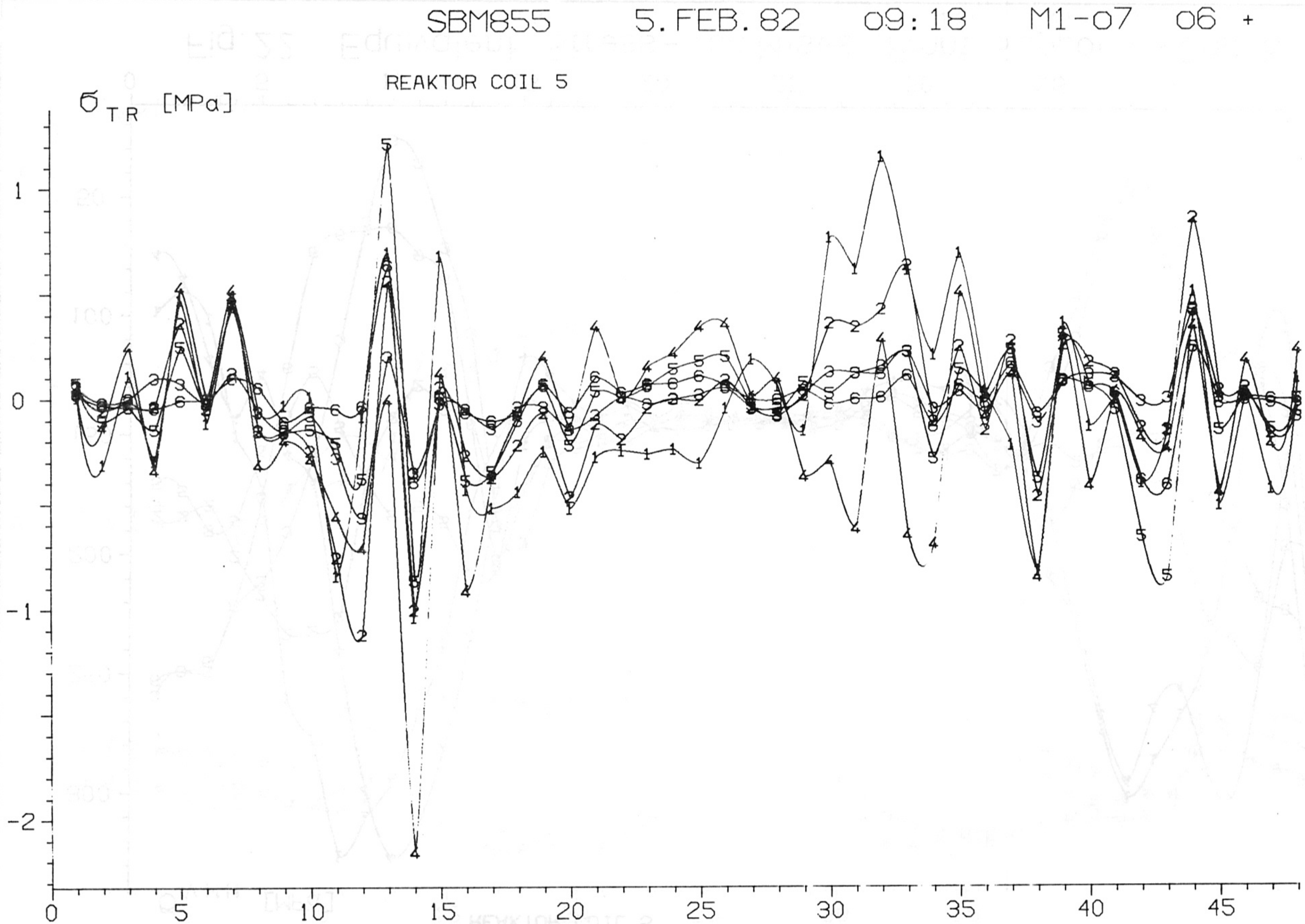

Fig. 21 Shear Stress (Ring Support - Inward) - Coil 5

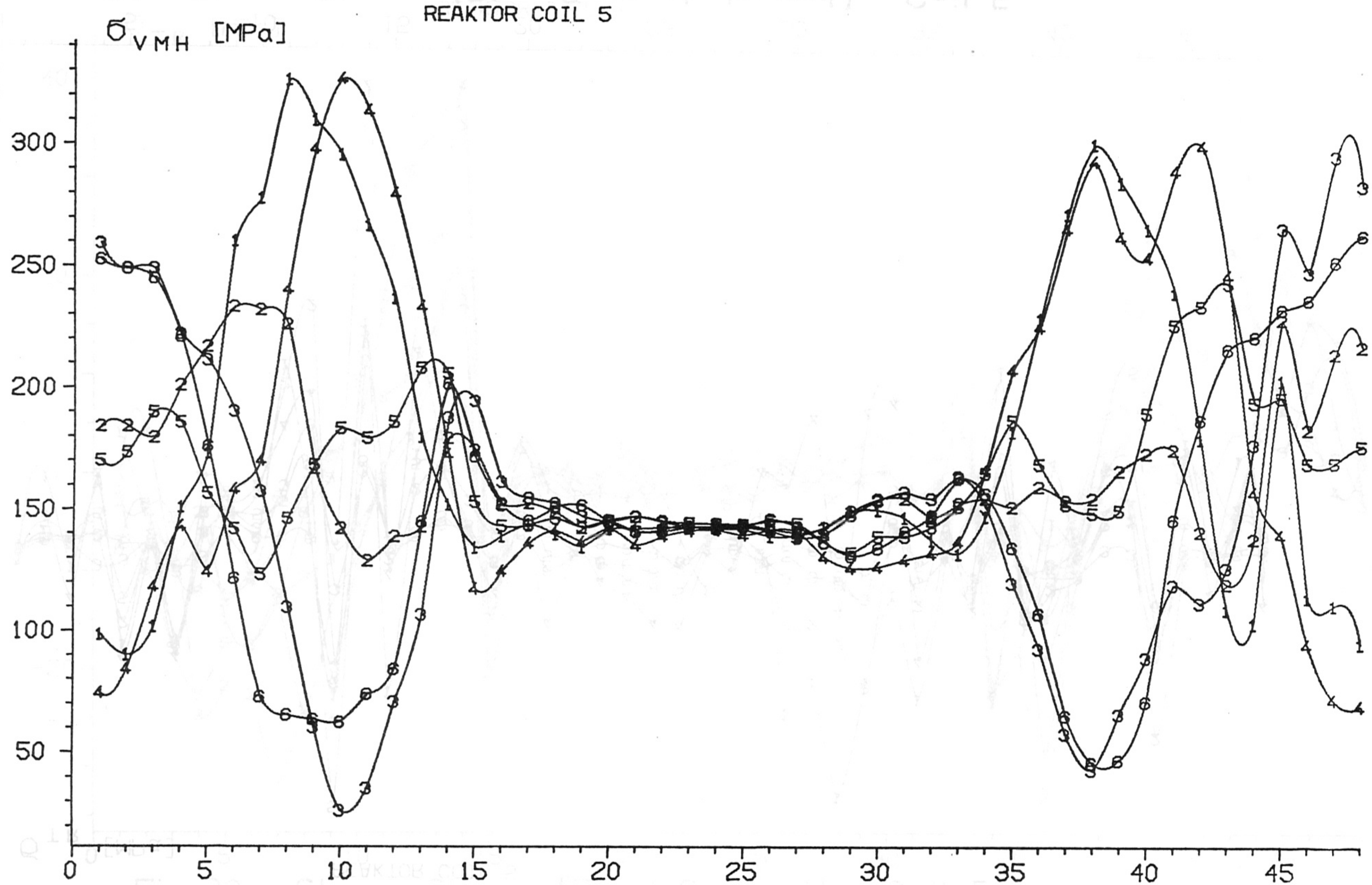

Fig. 22 Equivalent Stress - von Mises (Front Support) - Coil 5

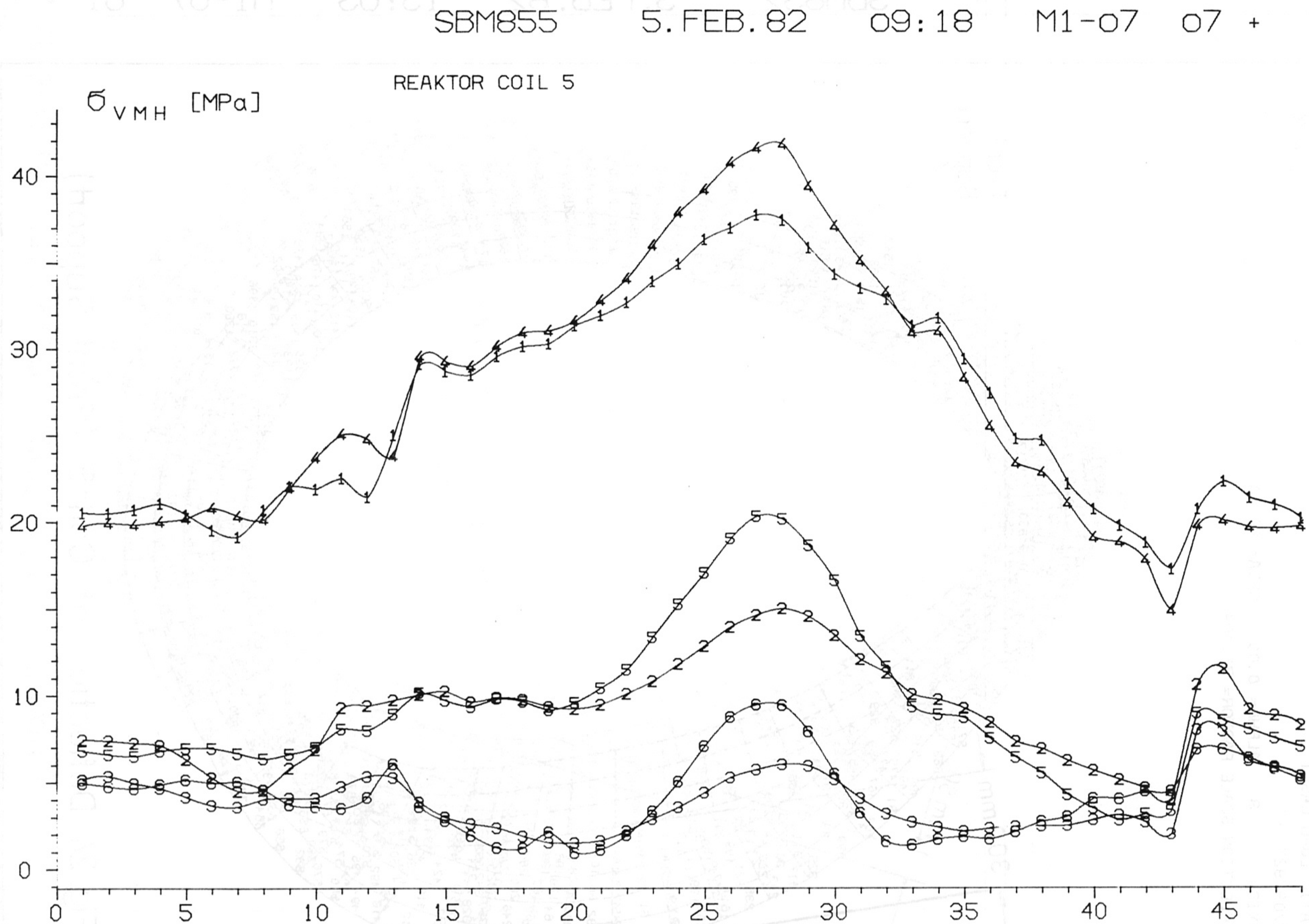

Fig. 23 Equivalent Stress-von Mises (Ring Support-Inward) - Coil 5

STRESSES FOR REACTOR: (CU+STAHL) COIL=5 EX4 SAP5

STATIC LOAD CASE1

02/03/82

IAXIS= 3 ALPHA= 0.00 BETA= 90.00

DEFLECTION SCALE FACTOR= 76.084

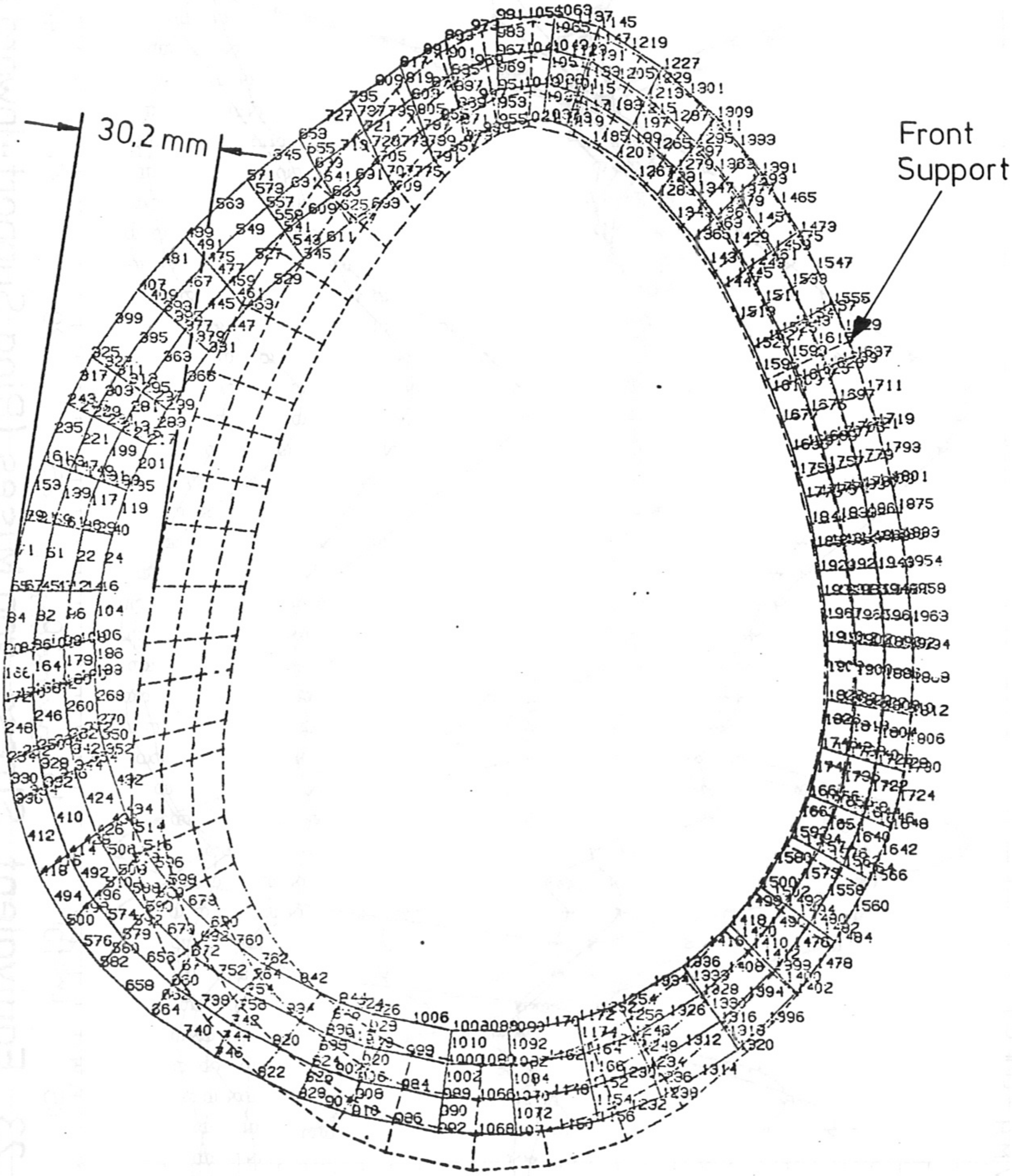

Fig. 24 Deflection of Coil 5 (Front Support)

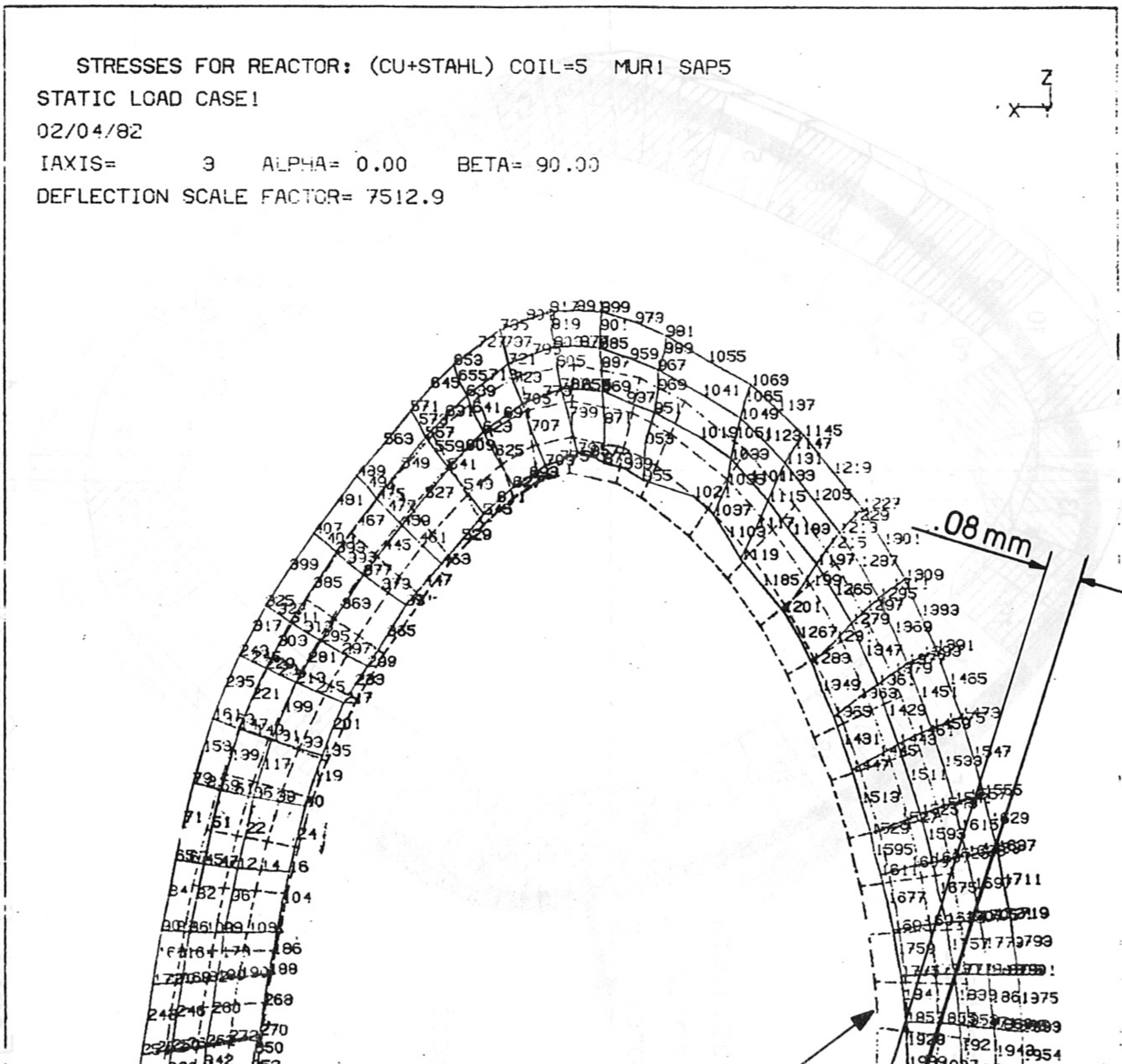

Fig.25 Deflection of Coil 5 (Ring Support - Inward)

SBM853 4.FEB.82 15:56 M1-07 01 +

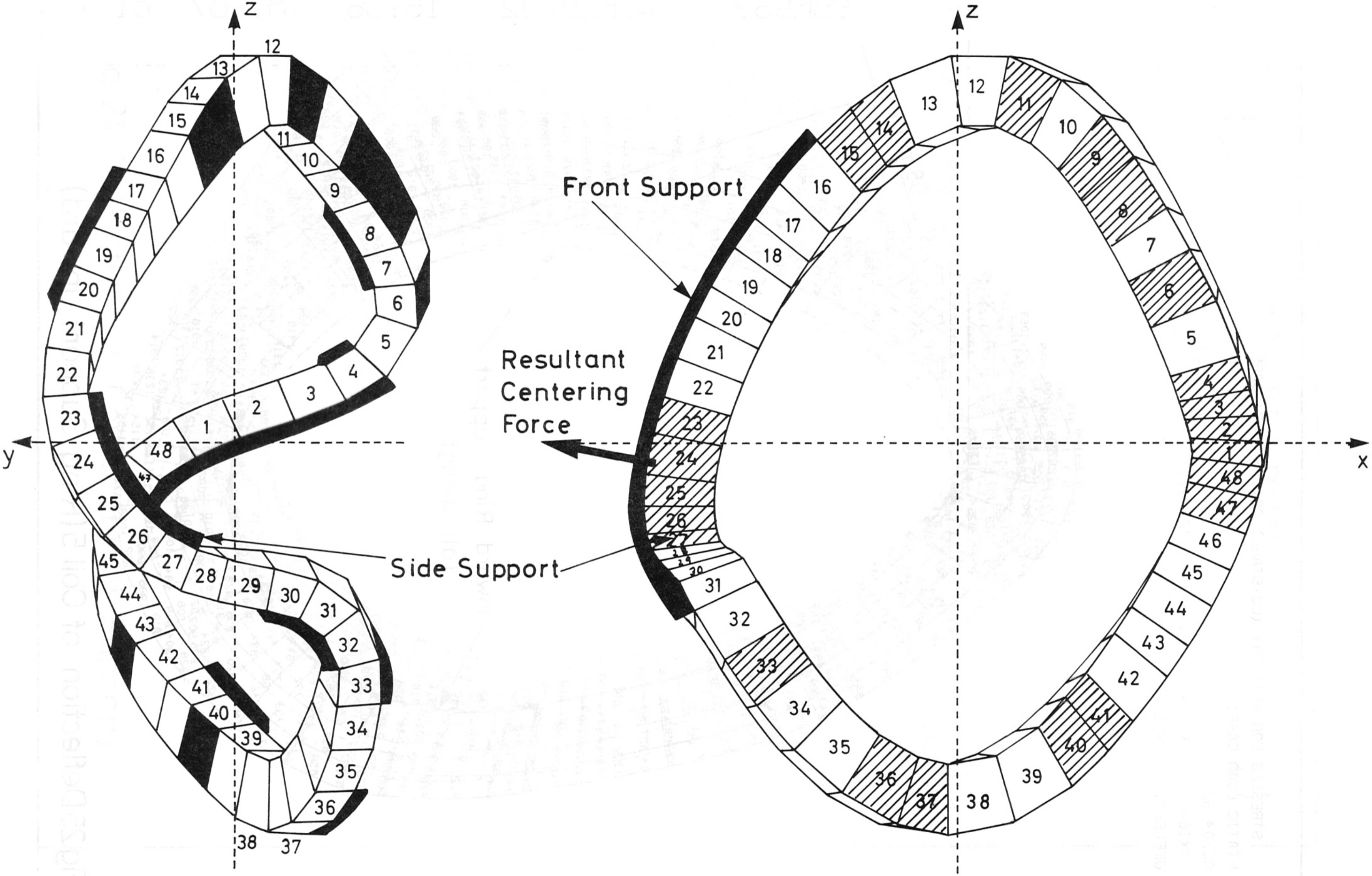

Fig.26 Front Support Concept - Coil 1

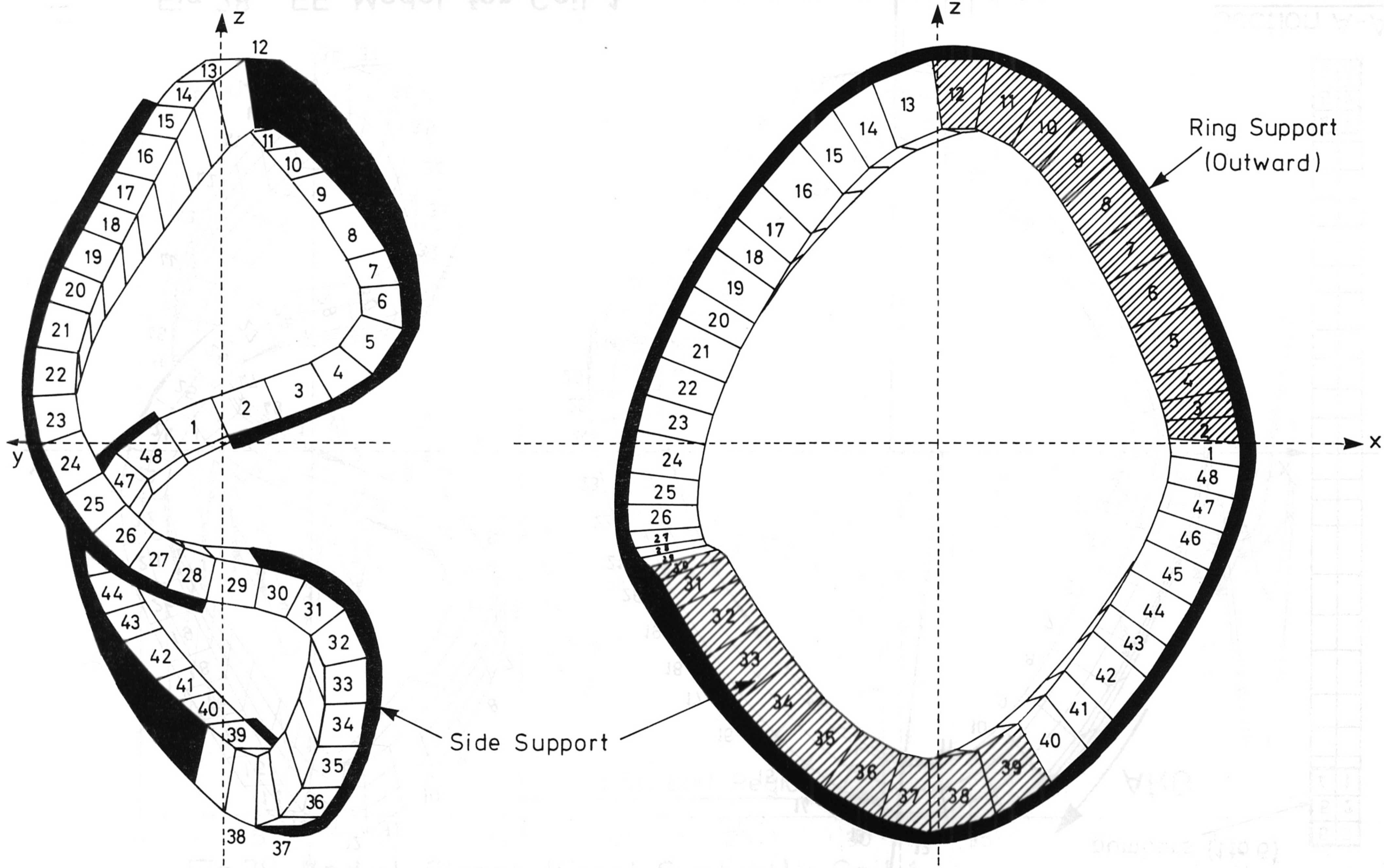

Fig. 27 Ring-Type Outward Support Concept - Coil 1

SBM856

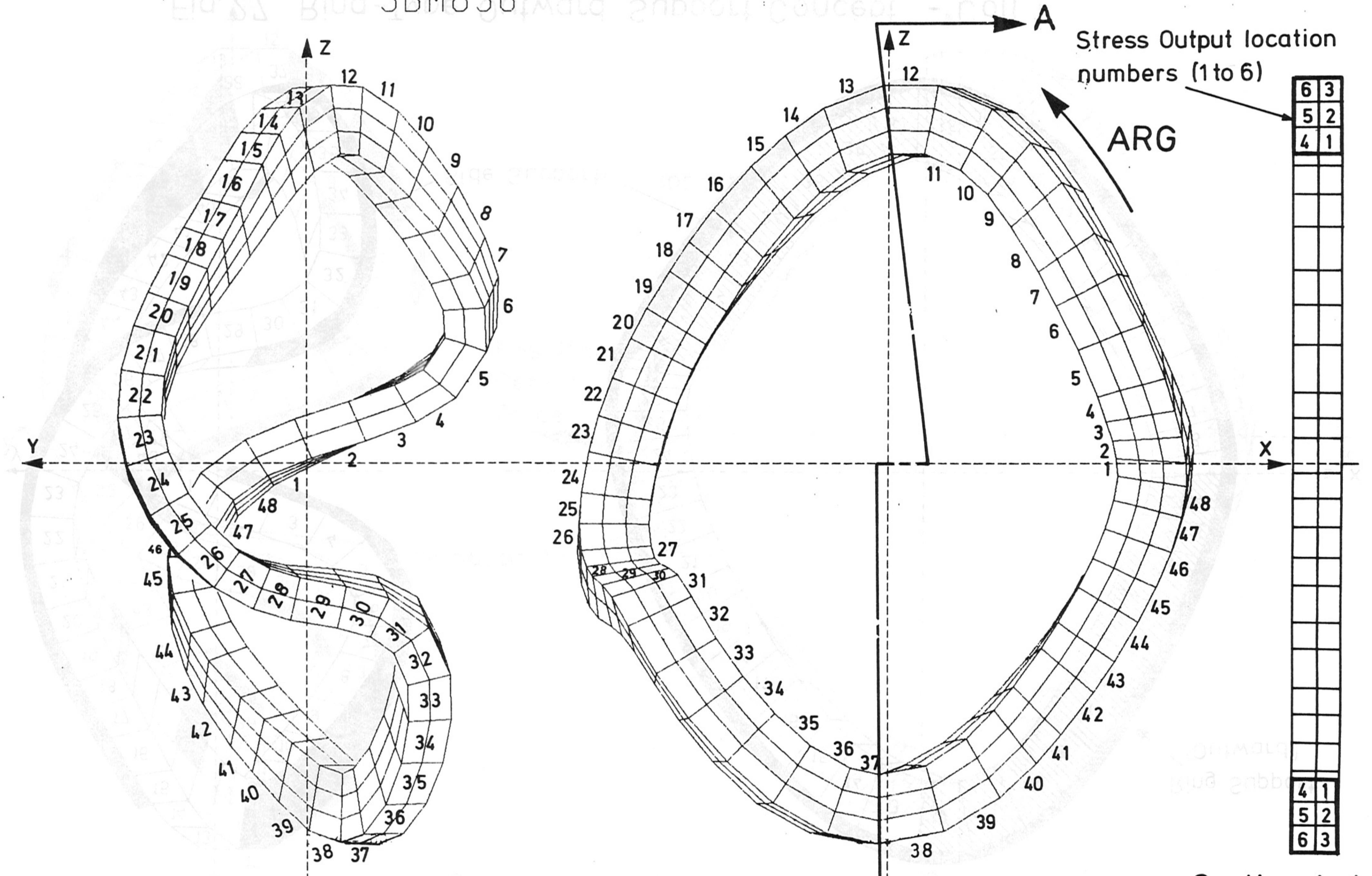

Fig. 28 FE Model for Coil 1

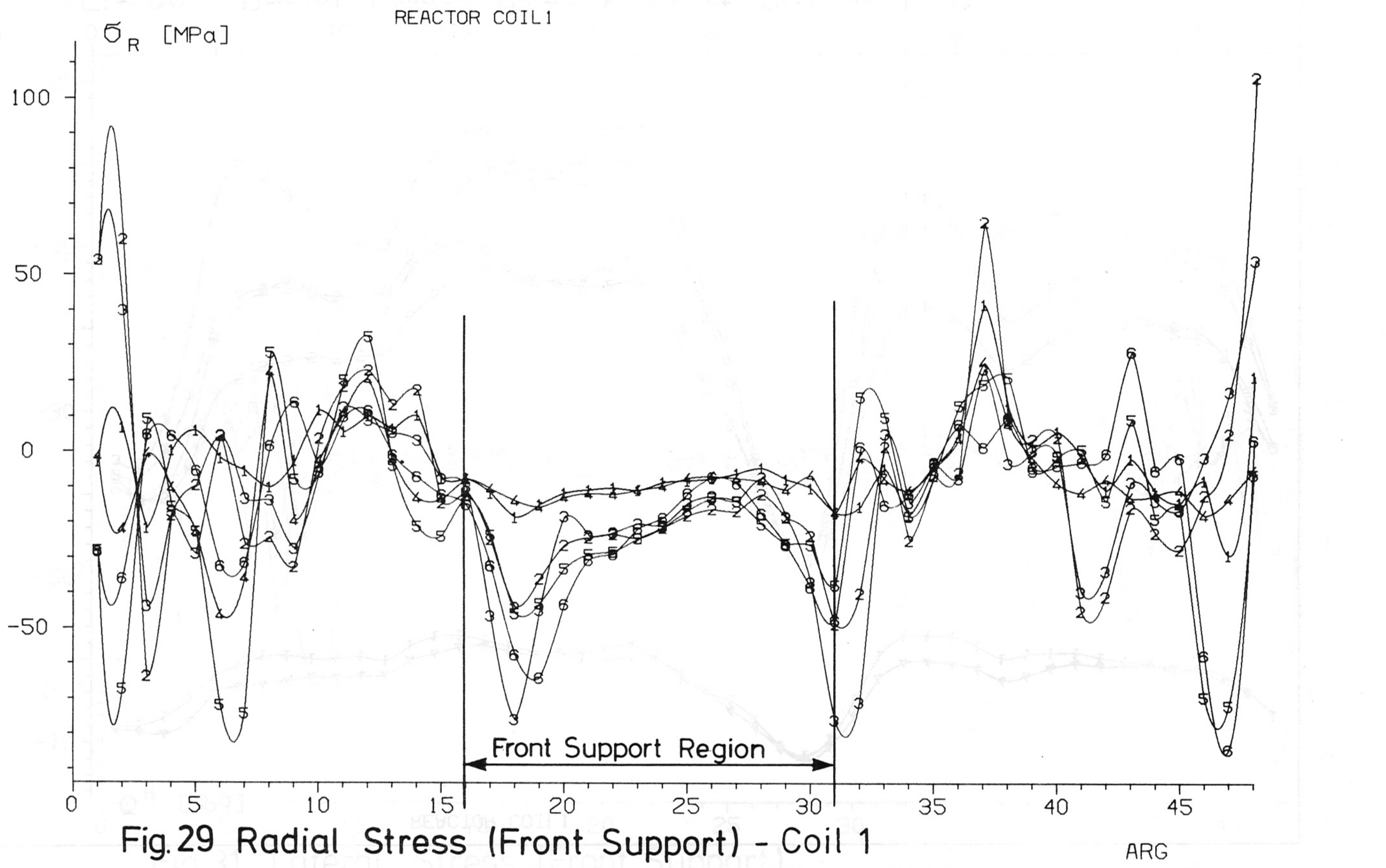

Fig. 29 Radial Stress (Front Support) - Coil 1

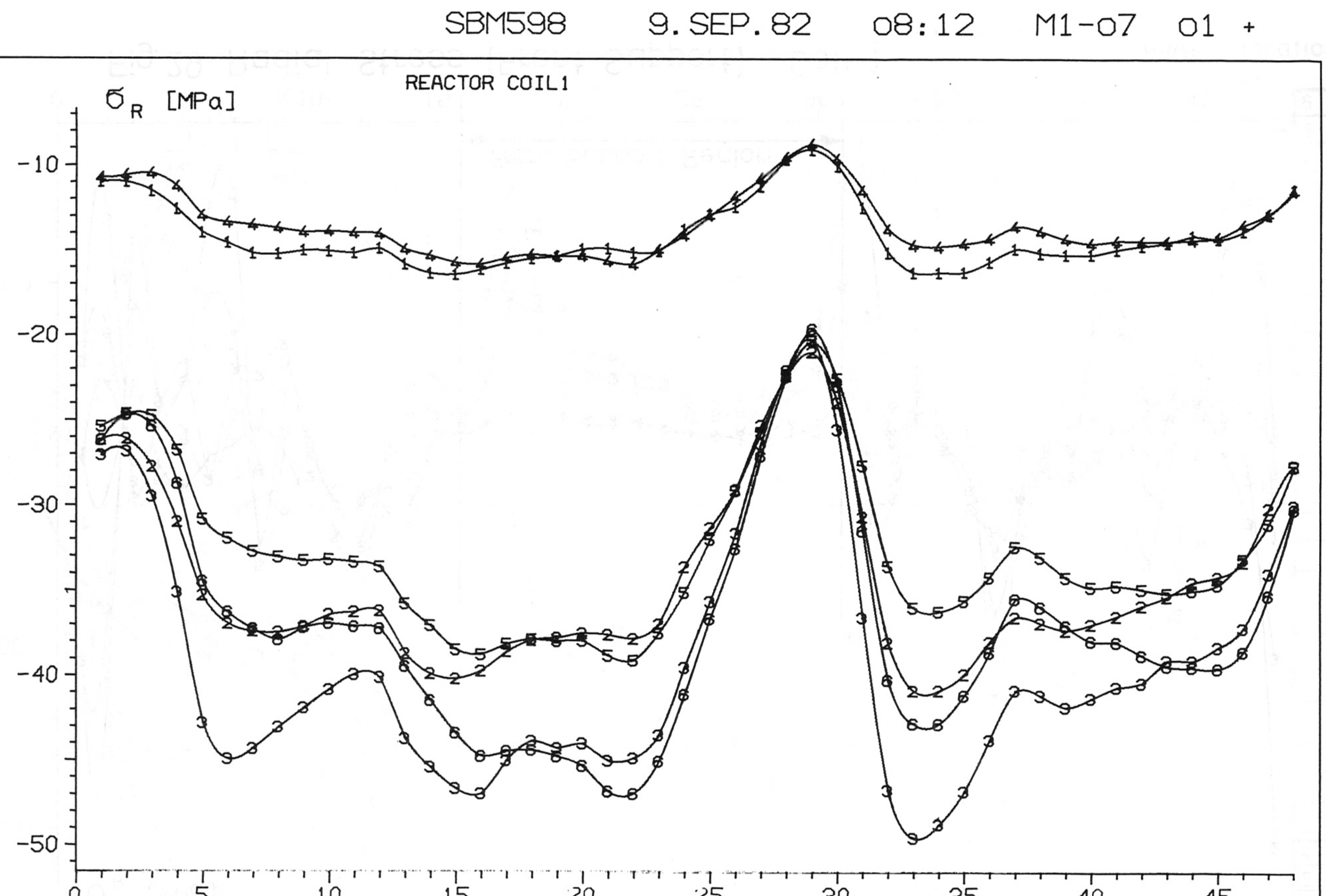

Fig. 30 Radial-Stress (Ring Support-Outward) - Coil 1

SBM5oo 24. AUG. 82 17:o4 M1-o7 o2 +

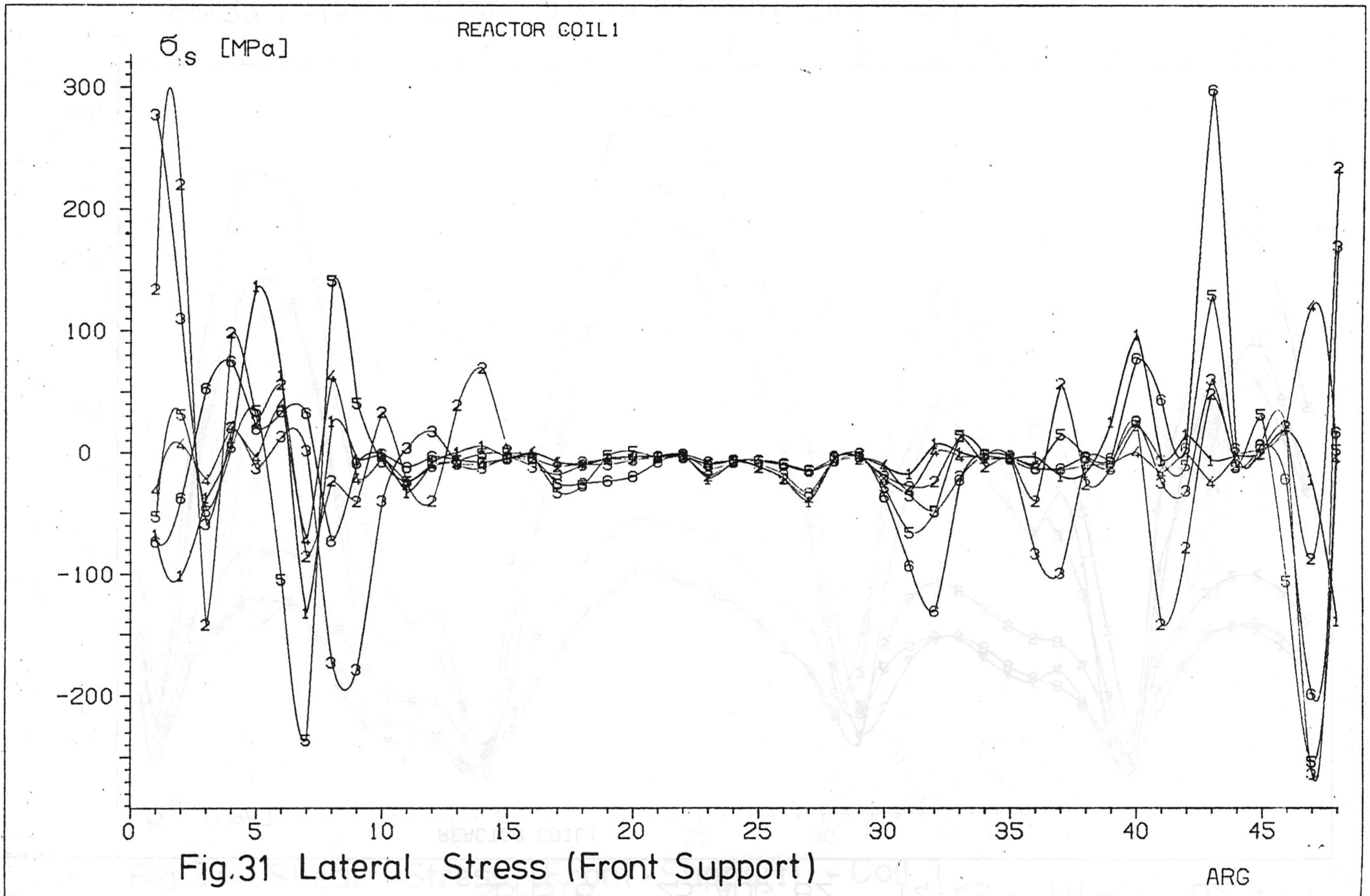

Fig.31 Lateral Stress (Front Support)

SBM516 25. AUG. 82 14:45 M1-07 02 +

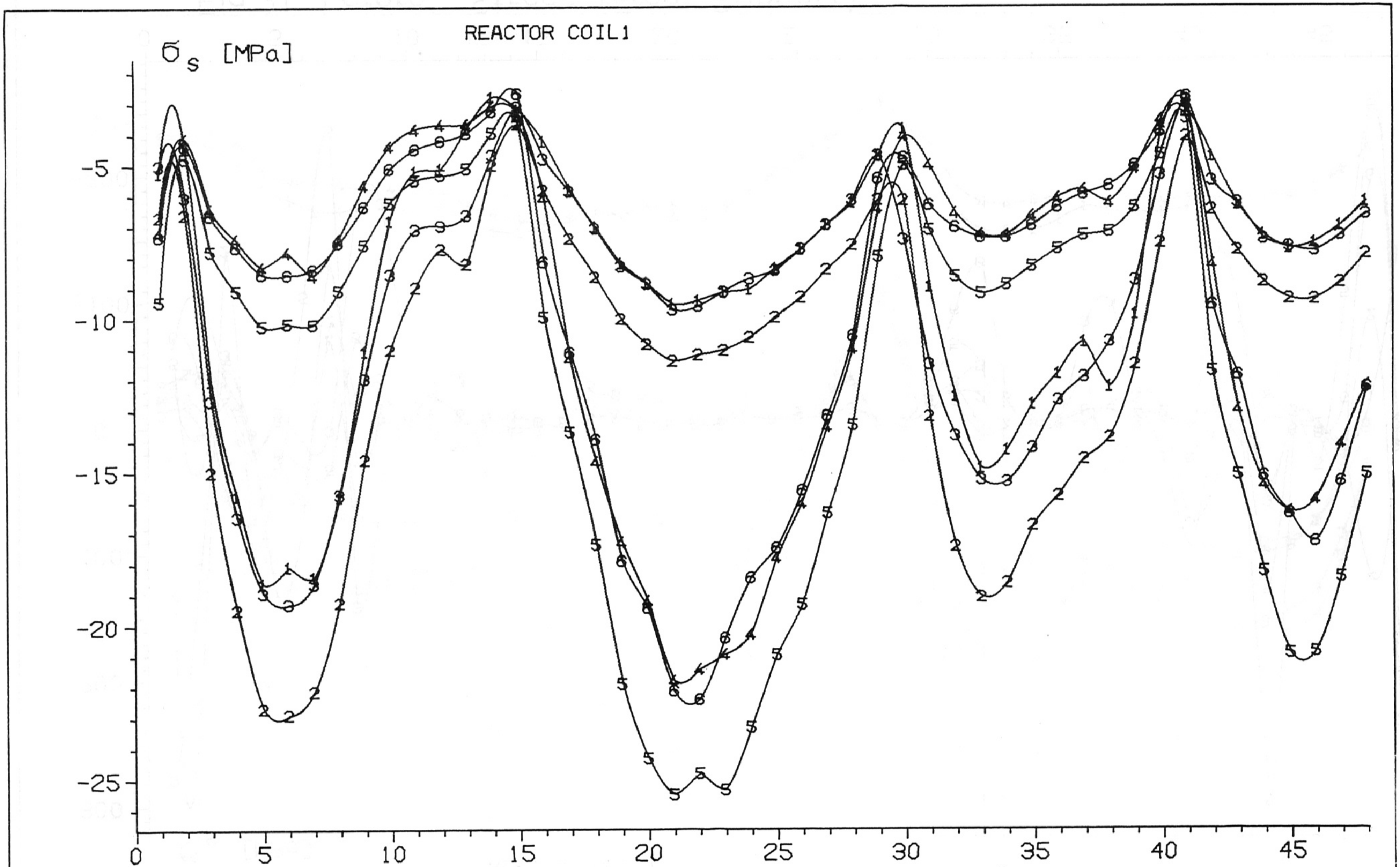

Fig.32 Lateral Stress (Ring Support - Outward)

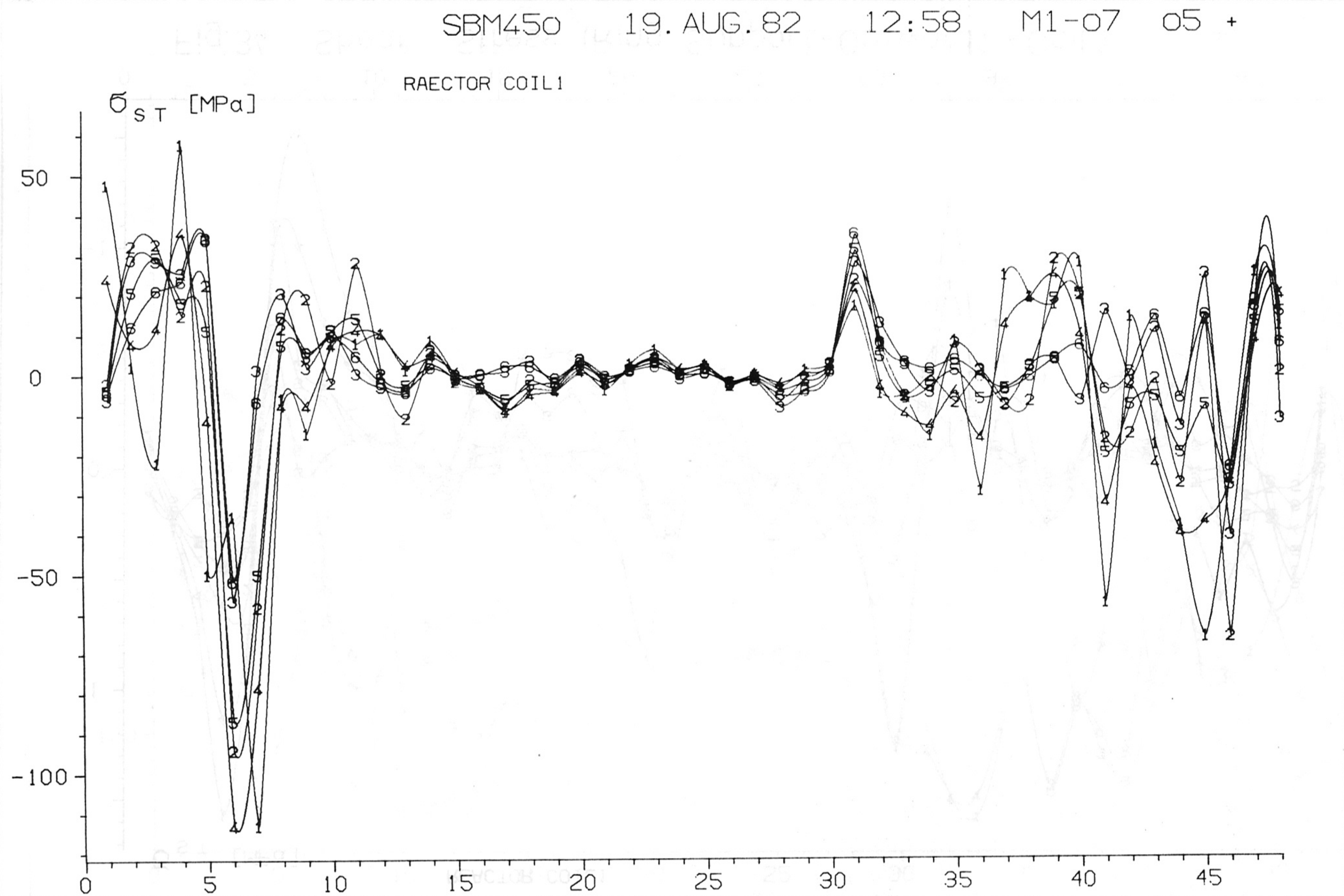

Fig.33 Shear Stress (Front-Support) - Coil 1

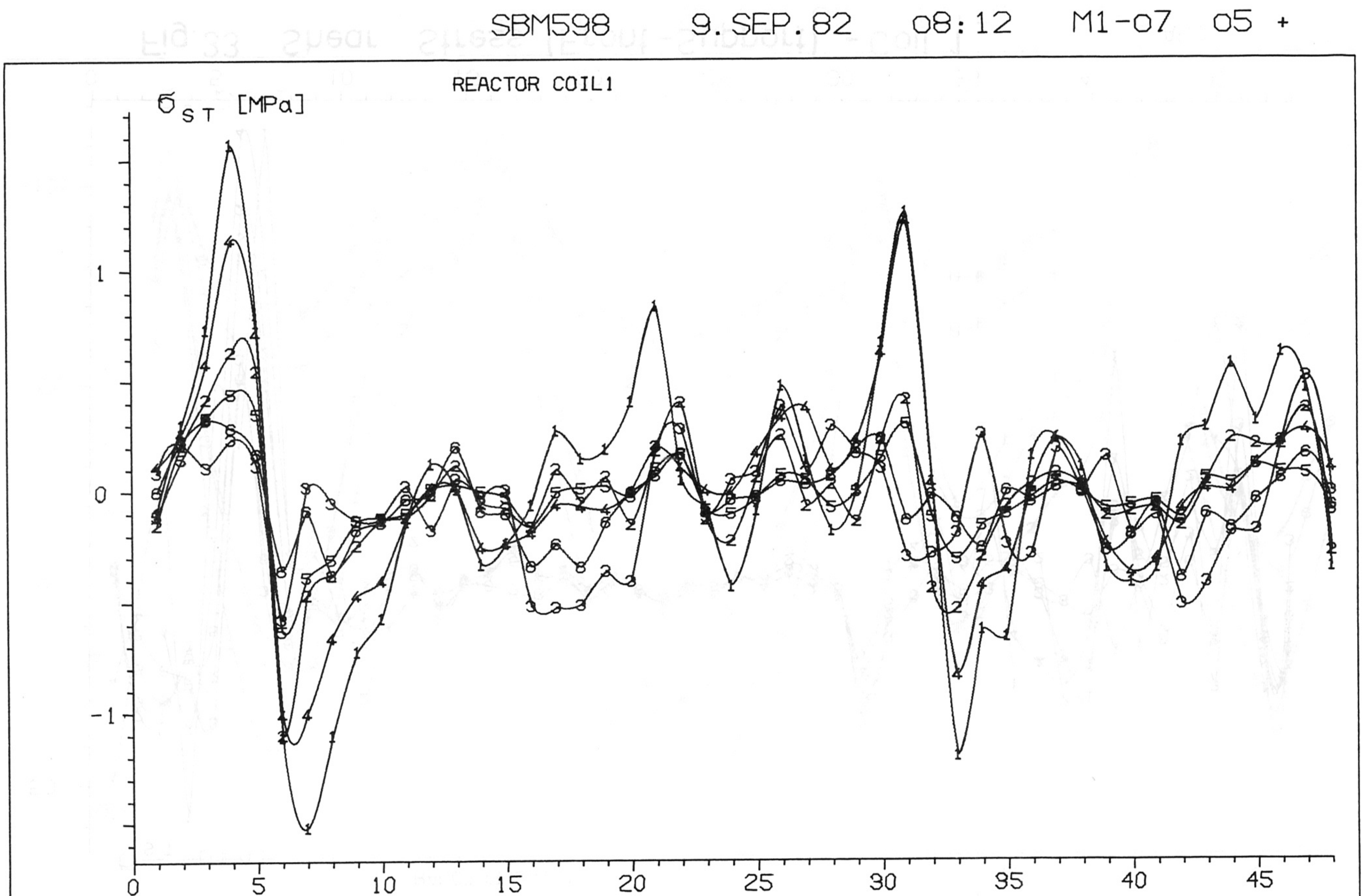

Fig.34 Shear Stress (Ring Support-Outward) - Coil 1

SBM45o 19. AUG. 82 12:58 M1-o7 o7 +

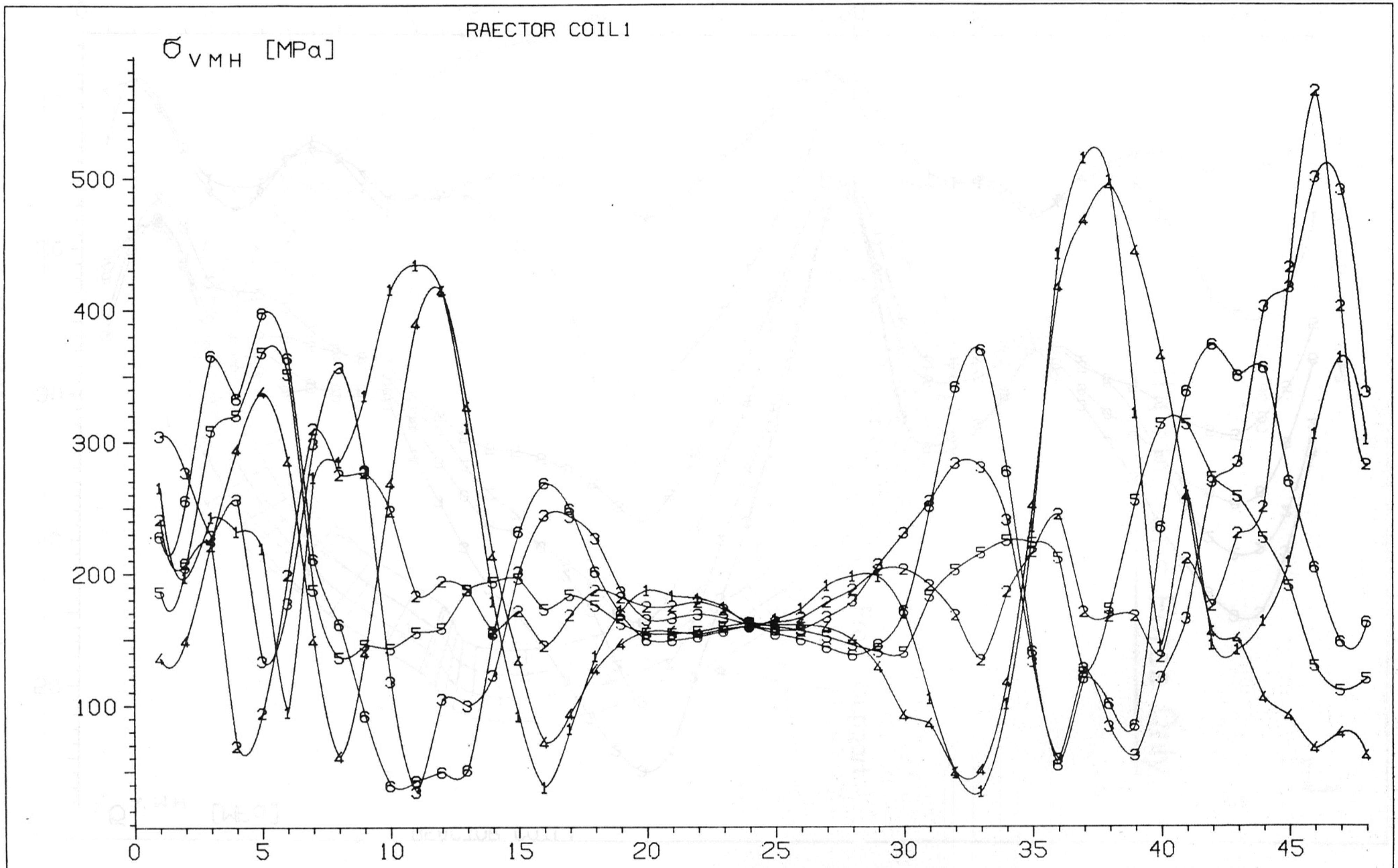

Fig. 35 Equivalent Stress - von Mises (Front Support) - Coil 1

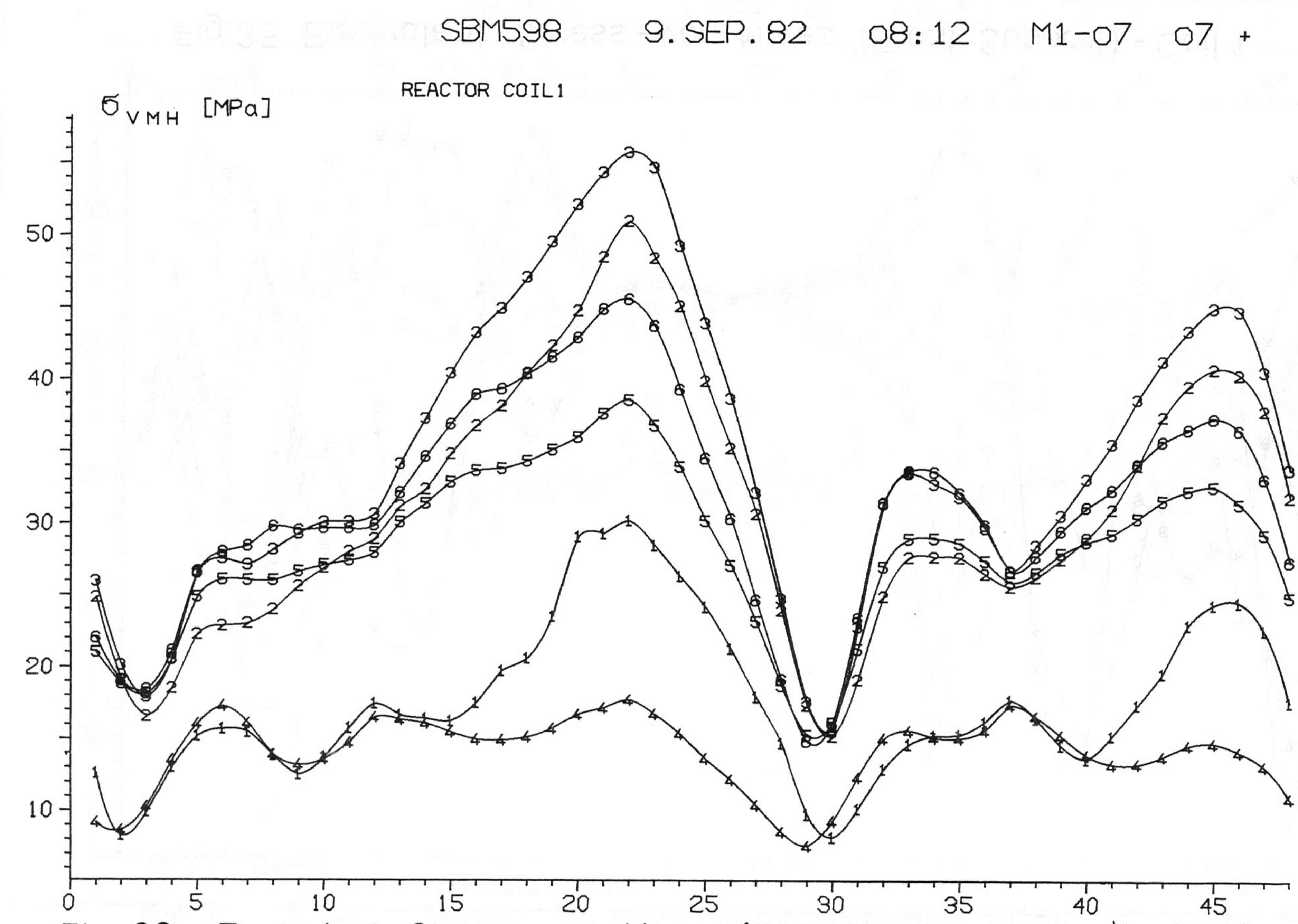

Fig. 36 Equivalent Stress -von Mises (Ring Support-Outward) -.Coil 1

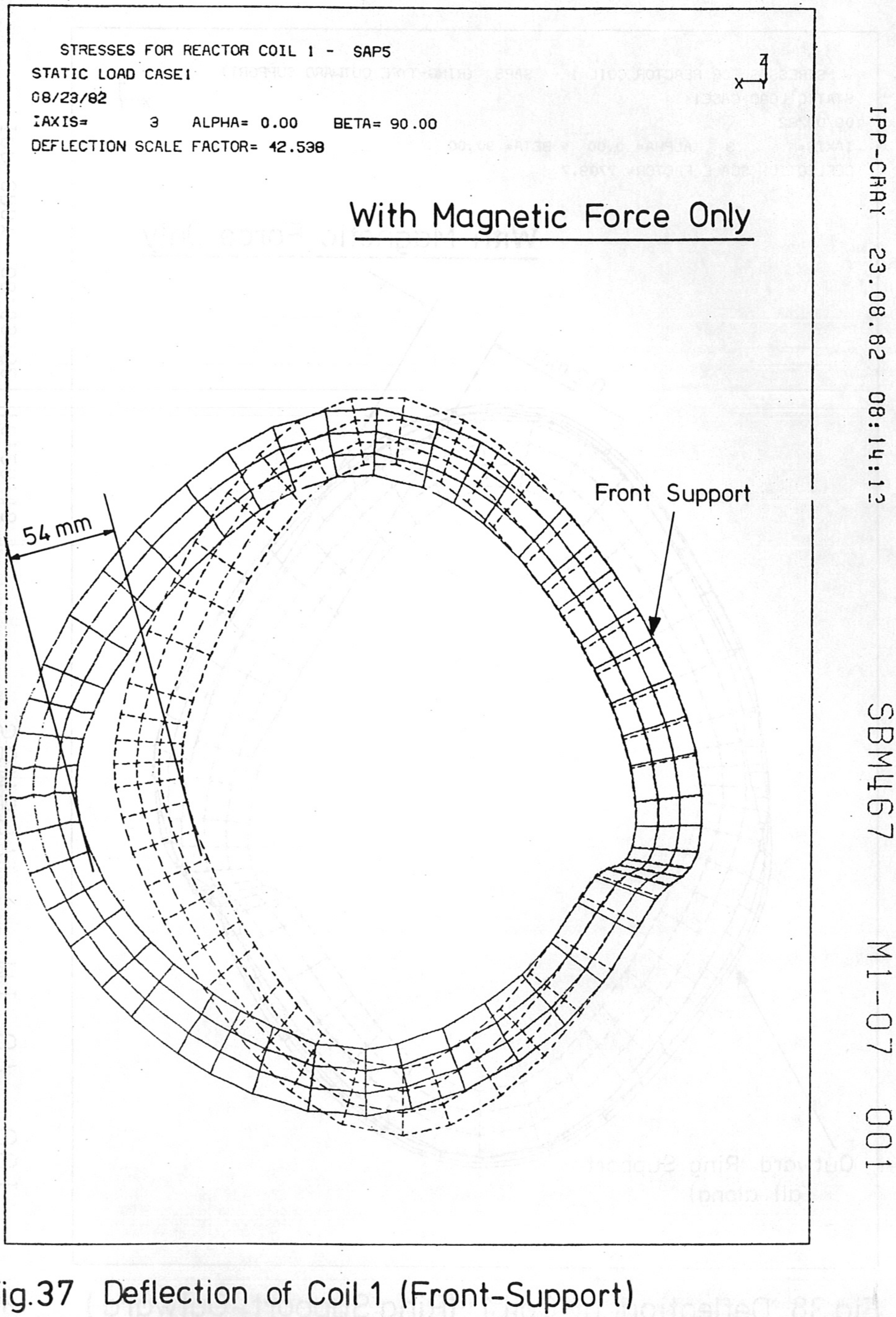

Fig.37 Deflection of Coil 1 (Front-Support)

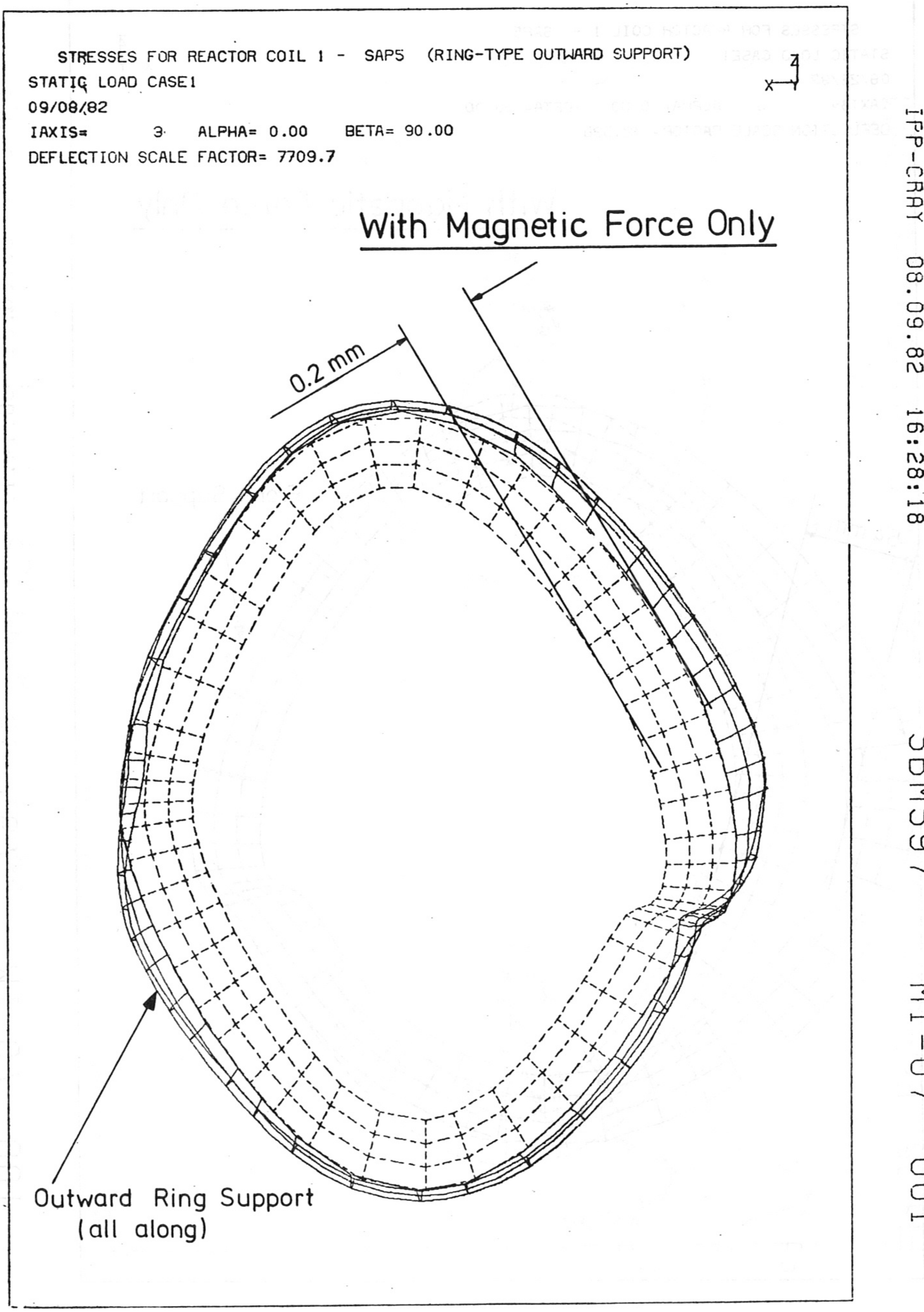

Fig.38 Deflection of Coil 1 (Ring Support-Outward)