# STRUCTURAL ANALYSIS OF THE BEHAVIOUR OF AN HEXAGONAL WRAPPER TUBE IN A FAST REACTOR ENVIRONMENT

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## SUMMARY

A computer program called STRAW has been developed in order to assess the stress and strain distributions in hexagonal wrapper tubes and their evolution with the time when irradiated under fast reactor conditions. This computer program, which handles in their three-dimensional form the swelling and creep phenomena, considers three main causes of stressing in the tube:

(i) compatibility stresses arising from the non-uniform thermal, swelling and creep strain fields,
(ii) pressure difference between the inside and the outside of the tube and the coolant drag forces,
(iii) restraints to the free bowing of the tube imposed by the core clamping system.

The external constraints acting on the tube (neutron flux, temperature distribution, pressure drop and effects of the clamping system) are all taken into account three-dimensionally and with their time dependence.

The program has been extensively used to investigate the behaviour of the SNR wrapper tubes under irradiation. The main results of this study will be presented here. The study aims at investigating the effects of several parameters on the stress and strain distributions, the bowing of the tube, the cross section deformations by swelling and creep, the residual deflections after shut-down.

In a first stage the effects of creep on the tube are investigated and compared to a situation without creep. A parametric study is then performed on the creep and swelling rate to obtain the envelope of the results covering the zones of uncertainty of these two phenomena.

Calculations are also reported for combination of maximum swelling rate and minimum creep rate and vice-versa for several variations of design parameters as the tube wall thickness, the tube length, the position of the spacer pads with respect to the core. The usefulness of intermediate rotations during the irradiation is also discussed.

Conclusions are then drawn based on the present knowledge in the field of the material behaviour under irradiation.

1. INTRODUCTION.

The provision for steel swelling in the core restraint of fast nuclear reactors is a problem of major concern. Because of the power gradients in the core and of the associated temperature and flux gradients in the subassemblies, the latters tend to be deflected from their original position in a tightly bound hexagonal array. Since small geometry changes are liable to bring about large reactivity differences, the motion of the subassemblies must be adequately controlled by the system of core restraint. However, this restraint must not give rise to excessive stresses in the subassembly ducts or excessive forces on the spacer pads. The feasibility of a system of core restraint satisfying those conflicting requirements has been the subject of persistent debate.

In this connection, the recognition that irradiation - induced creep is in general concurrent to swelling is of major importance. While significantly reducing the stresses in the wrapper tubes and the forces in the core restraint, irradiation - induced creep brings about additional dimensional changes which must also be accommodated for proper operation of the core and unloading of the subassemblies.

The prediction of the behaviour of the whole core taking into account both irradiation-induced creep and swelling is a very difficult task. In practice, one has to proceed in two complementary stages. The first stage consists in the description of the behaviour of each individual subassembly in the actual reactor environment and the response of this subassembly to the loading exerted by the core restraint. The overall behaviour of the entire core is then predicted on the basis of the response of individual subassemblies and of the properties of the core restraint. From this information, the reactivity changes are evaluated and the core restraint optimized with due consideration to the requirements of fuel handling. A discussion of the design problems associated to this second stage can be found in another paper presented at this conference [2].

The computer program STRAW [1] (STRess Analysis of Wrapper tubes) has been developed to meet the first objective. This program incorporates a number of unique features which enable a detailed description of the stresses and of the deformations in the wrapper tubes under very general loading conditions and realistic reactor environment. The results of a parametric study pertaining to the core SNR - 300 will be presented in this paper. On the basis of the stress analysis of representative wrapper tubes, a number of conclusions will be drawn relative to the system of core restraint. It will be gratifying to discover that some of these results are also of great practical significance for the prediction of the behaviour of the entire core.

## 2. DESCRIPTION OF THE PROGRAM "STRAW".

A detailed description of the computer program STRAW has been presented elsewhere [1]. For this reason, only a brief survey of the main features of this program will be given here.

The program takes into account both thermal and irradiation-induced creep, while thermal creep is relatively unimportant in the temperature range considered. The formulation is based on Prandtl-Reuss equations which provide a relationship between the creep strain increment and the stress deviator at a given time. This involves that all calculations are performed in an incremental way and that the irradiation history of the wrapper tube is subdivided into small time intervals over which the stresses can be considered as constant.

The stress analysis of the wrapper tube is performed after each of these time intervals. It is based on the following simplifying assumptions which can be justified from general considerations on the tube geometry and on the nature of the different types of stresses listed above :

(i) Plane strain ;
(ii) No shear stresses in the planes perpendicular to the tube axis ;
(iii) The stresses normal to the tube walls are negligible.

These approximations, however, are not valid in small zones centred on the wear pads. It is further assumed that the consequences of making them everywhere are unimportant as far as the general behaviour of the wrapper tubes is concerned. The stress analysis of the wear pads is a separate problem which is part of the design of the system of radial restraint [2].

The evaluation of the stresses for given thermal, swelling and creep strain fields is based on the strain suppression method. In a first stage, the tube is assumed frozen in the reference configuration. By definition, the total strains in this configuration vanish identically and the stresses are easily computed. The restrictions on the tube deformations are then removed in turn, leaving only those deformations which are compatible with the tube geometry. In this way, the evaluation of the compatibility stresses is reduced to the evaluation of three line integrals and three surface integrals of the strain field over the cross-sections of the tube. These integrals are performed numerically over a fine grid mesh distributed over the tube thickness. Finally, the stresses arising from external loading such as the coolant pressure and the core restraint are calculated by standard methods and superposed to the compatibility stresses.

The detailed inclusion of all major sources of stresses is matched by a realistic description of the environmental conditions in the reactor. Methods inspired from the results of specialized computer programs have been developed for representing the temperature and neutron flux distributions in the tube walls in a way which automatically achieves mutual consistency while remaining flexible enough for a parametric study of the influence of the environmental conditions. For instance, the temperature distribution in the tube walls takes into account the following factors :

(i) the coolant temperature distribution near the tube walls. The latter is based on the flux and the power generated in the subassembly and on the thermohydraulic characteristics of the bundle ;

(ii) the gamma-heating in the tube walls ;

(iii) the heat transfer between neighbouring subassemblies.

3. DESCRIPTION OF THE S NR CORE RESTRAINT.

The system of core restraint of S NR - 300 is of passive type. The subassemblies are held down to the bottom plate by a hydraulic device which allows free rotation of the feet within limits. The subassemblies are free standing. Two levels of radial restraint are provided, one below and one above the core region, by two massive rings surrounding the core. Almost tight compaction is achieved at the level of the lower restraint during reactor operation, while the restraint on the deflections of the subassemblies at the level of the upper load plane is mainly provided by the flexural rigidity of the outer radial blanket and reflector subassemblies. Spacing between the subassemblies is achieved at the load planes by spacer pads attached to the wrapper tubes. A more complete description of the core restraint can be found elsewhere [2]. The main geometrical data relevant to the present study are gathered in Table I.

4. SCOPE OF THE STUDY.

A survey of the entire core reveals that the most loaded wrapper tubes are those from the central subassembly where the fast neutron flux is maximum and from the subassemblies located in the sixth row close to the control subassemblies which are submitted to maximum flux and temperature gradients. For this reason, the central subassembly (100) and subassembly 603 have been choosen for the present study, since they constitute examples of the most severe conditions for the stresses and for the bowing deformations. The average axial distribution of temperature and of fast neutron ($E > 0.1$ MeV) are shown on Fig. 1.

The irradiation life of one subassembly normally lasts three cycles of 117 days each. Reshuffling is not considered. The maximum fluence at the end of irradiation is $1.6\ 10^{23}$ nvt for subassembly 100.

The austenitic stainless steel 316 with 20 % cold-work has been taken as a representative tube material for this study, although the wrapper tubes of S NR - 300 will be fabricated with a stabilized stainless steel having somewhat different properties. The swelling is assumed to be described by the following empirical equation [3] :

$$\Delta V/V = 9.0\ 10^{-37}\ (\Phi_{.1}t)^{1.5} \left[\ 4.028 - 3.712\ 10^{-2}\ T + 1.0145\ 10^{-4}\ T^2 - 7.879\ 10^{-8}\ T^3\ \right], \quad (1)$$

where $\Delta V/V$ is the volume swelling ;
$\Phi_{.1}t$ is the fast fluence ($E > 0.1$ MeV) in n/cm$^2$ ;
$T$ is the temperature in degrees C.

For the irradiation - induced creep, the following equation is used [4] :

$$\frac{\bar{\epsilon}}{\bar{\sigma}} = 2.55\ 10^{-20}\ \bar{E}\,\Phi \left[\ 1 - \exp\left( - \frac{\bar{E}\,\Phi\ t}{3.8\ 10^{21}} \right) \right] + 0.57\ 10^{-26}\ \bar{E}\Phi\ t\ , \quad (2)$$

where $\bar{\epsilon}$ is the equivalent creep strain ;
$\bar{\sigma}$ is the equivalent stress (von Mises) ;
$\bar{E}$ is the average neutron energy in MeV ;
$\Phi$ is the total flux in n/cm$^2$sec.

In addition to the nominal values given above, a limited range of variation for the swelling and the creep rates will be considered in a parametric study ; namely, for swelling + 60 % to - 35 % and for creep + 50 % to - 50 %. These intervals are not regarded as confidence limits. The calculations reported hereafter have been performed for five different combinations between the swelling and the creep rates which are represented schematically on Fig. 2 by the points A B C D E. Finally, the qualitative differences of the wrapper tube behaviour in the presence of irradiation - induced creep will be demonstrated by comparing the results with those obtained without creep (point F on Fig. 2).

## 5. RESULTS.

### 5.1. Stresses.

The axial distribution of maximum stresses at the end-of-life are shown on Fig. 3 and 4, respectively, for subassemblies 100 and 603. These figures demonstrate a number of interesting properties.

In the first place, the relative importance of the different types of stresses listed in section 2 is clearly illustrated.

(i) The compatibility stresses appear as a large peak in the core zone (Fig. 3). The maximum of this peak is shifted below the core mid-plane, where the temperature dependence of the swelling law is larger. The major source of temperature gradient in the tube walls of subassembly 100 is the gamma-heating.

(ii) The hoop stress due to coolant flow drag are continuously decreasing from the bottom to the top of the subassembly and appear on Fig. 3 as a linearly decreasing background.

(iii) The stresses due to the core restraint are evinced by comparing Fig. 3 and 4 since in the case of the central subassembly 100, there is no bowing by symmetry. These stresses peak around the intermediate load plane because the bending moments exerted by the spacer pads are maximum there.

It is also observed on Fig. 3 and 4 that the curves labelled A, B and E give roughly the same distribution of stresses. Reference to Fig. 2 shows that these cases are characterized by the same ratio between the swelling and the creep rates. In other words, the maximum stresses in the wrapper tubes are roughly proportional to this ratio. This finding is confirmed by Table II which gathers the maximum levels of stresses for the different cases considered. As regards the absolute figures, it is found from this table that the maximum stresses fall below the level of 20 kg/mm$^2$ in all cases, excepted case F (no creep) and case D (maximum swelling, minimum creep). These cases are consequently placed in Fig. 2 in a zone of doubtful feasibility from the point of view of mechanical strength.

The dependence of the maximum stresses upon neutron dose is illustrated on Fig. 5 which shows the evolution of the equivalent stress at a point located in the core mid-plane as irradiation proceeds. These stresses are seen to be the sum of three contributions :

(i) the hoop stresses due to coolant flow which are approximately time independent and amount to about 5 kp/mm$^2$ ;

(ii) the thermal stresses which appear at start-up and relax in the presence of creep with a time constant of the order

$$\frac{1}{\tau} = \frac{\dot{\epsilon}_{creep}}{\epsilon_{elastic}} \simeq E\, B\, \bar{E}\, \Phi \;\; (\mathrm{sec}^{-1}) \quad , \qquad (3)$$

where E is the Young modulus and B is the coefficient of the steady state component of irradiation - induced creep in the relationship (2). For the cases considered here, the relaxation time is comprised between 450 and 1350 hours.

(iii) The stresses due to differential swelling.

As pointed out before, these stresses depend almost exclusively on the ratio between the swelling and creep rates. This is evinced here by the fact that cases A, B and E yield almost identical results. Moreover, Fig. 5 shows that the time dependence of the stresses due to swelling is also dominated by this ratio. Indeed, the curves labelled A, B, C, D and E all follow a time dependence of the form :

$$\frac{\text{swelling rate}}{\text{creep rate}} \approx (\Phi t)^{0.5}$$

On the other hand, in the absence of creep, a power law $(\Phi t)^{1.5}$ characteristic of swelling is followed (curve F). This qualitative difference in the fluence dependence of the stresses in the presence of irradiation - induced creep is of major importance for extrapolating the results to higher fluence.

5.2. Bowing deformations.

As pointed out before, subassembly 603 exhibits maximum bowing deformations because of the large flux and temperature gradients associated with the proximity of a control subassembly. The results are shown on Fig. 6.

The upper curves refer to the bowing deflections at end-of-life in the hot restrained configuration. The deflections are taken positive in the direction of the core centre. It appears that the deflections of the core zone are directed towards the core centre for all cases considered. However, the magnitude of these deflections is significantly reduced by irradiation - induced creep. Here again, the relevant quantity is the ratio between the swelling and the creep rates.

The lower curves show the corresponding free deflections in the cold state after shutdown. The same qualitative conclusions can be made about the relative magnitude of the deflections and the beneficial influence of creep. For the ranges of creep and swelling rates considered in this study, the subassembly heads are always bowing outwards, away from the core centre. However, for ratios between the swelling and the creep rates smaller than for case C, inward bowing would almost certainly result.

The maximum free bowing and restrained bowing deflections are gathered in Table III and compared to the situation without creep. The absolute figures of the free deflections should be compared to the deflection limit of 25 mm for insertion of the subassembly by the fuel handling equipment [2].

5.3. Cross-sectional deformations.

The radial deformations of the wrapper tube sections result from two main causes :

- steel swelling ;
- irradiation - induced creep.

As regards the dimensional changes due to creep, the main driving force is the inner pressure arising from the coolant flow. Significant creep deformations can also be driven by differential steel swelling across the wall thickness or over the tube section. To evaluate these deformations, one must resort the integration of the total strain field over the tube sections. An example is shown on Fig. 7 which represents the cross-sectional deformation of subassembly 603 at core mid-plane and at the end-of-life, for case E (maximum swelling - maximum creep). This figure shows that in the proximity of a control element, the deformations may become rather asymmetric.

The maximum radial deformations are found in the central subassembly (100) where neutron flux and the pressure drop are maximum. The dilation at core centre between opposite faces is given in Table III for the different combinations of swelling and creep rates.

It is interesting to note that about half of this dilation is accounted for by swelling only. The rest is distributed about equally between thermal expansion and elastic plus creep deformations. In other words, for the range investigated in this study, the cross-sectional deformations are not dominated by creep. This situation may however be reversed for larger creep rates.

One of the requirements on the dilation and on the bowing of the wrapper tubes is that they should not exhaust the spacings provided between the subassemblies. An estimate of the residual spacing at end-of-life would require a more complete analysis involving the restrained deformations of all the subassemblies along a spoke of the core. Nevertheless, it appears from Table III that the provision of sufficient spacing between the wrapper tubes could become a serious problem in cases F, D and E.

5.4. Forces on the spacer pads.

If one excludes the frictional forces, there are basically two types of forces exerted on the spacer pads. These are the bending forces which are needed to limit the free bowing of the subassemblies and the compressive forces which result from the superposition of the bending forces over the entire core. The evaluation of these forces is a very difficult problem which is related to the prediction of the core geometry.

Nevertheless, an estimate of the bending forces can be obtained for each individual subassembly by assuming no displacement of the spacer pads at the levels of radial restraint. The resulting forces at the intermediate load plane are given in Table II for the different combinations of swelling and creep. These results are qualitatively similar as for the stresses. The forces are seen to decrease rapidly with the onset of irradiation - induced creep. They are nearly identical for cases B, A and E which is again an evidence that the relevant quantity is the ratio between the swelling and the creep rates. As for the maximum stresses, the bending forces are roughly proportional to this ratio and obey the same characteristic time (fluence) dependence as that shown on Fig. 5.

The limit imposed to the compressive forces is of the order of 1000 kp [2]. These compressive forces are not simply related to the bending forces exerted on the individual subassemblies. However, it is not difficult to imagine that this limit can be exceeded when bending forces of the order of 500 kp as those found in cases F and D are superposed.

From the above discussion, it can be concluded that the maximum stresses and bending forces are almost completely determined by the competition between the swelling and the creep rates. One of the most interesting consequences of this property is demonstrated on Fig. 8. This figure shows the trajectory of the vector representing the force exerted by the core restraint on the intermediate spacer pad of subassembly 603, as irradiation proceeds. In this example, the swelling and creep rates are nominal. Three different trajectories are represented corresponding to three different displacements imposed by the core restraint to the upper spacer pad : $\Delta X = 0$ (no displacement) and $\Delta X = \pm 2.5$ mm (displacements of 2.5 mm in direction X which is horizontal on the figure).

Starting with a fresh subassembly in the cold state, the irradiation history is followed to the end-of-life (8424 hrs). The forces at the beginning of irradiation are due to the bowing of the wrapper tube in the presence of a strong thermal gradient. From there on, the forces are seen to increase because of the differential swelling strains which develop in the tube walls. They are also concurrently relieved by the radiation - induced creep. The net result is that the forces corresponding to the three different positions of the upper spacer pads converge to the same limit after a short time. This limit keeps increasing because the swelling rate is not constant but increases with fluence.

From this example, it can be concluded that after a certain residence time in the reactor under steady conditions, the bending forces become independent from the positions of the spacer pads. The convergence time depends on the irradiation - induced creep rate and amounts typically to less than one cycle (2808 hrs). After convergence, the forces are essentially determined by the ratio between the swelling and the creep rates.

This property has significant practical implications. In particular, the bending forces on the spacer pads can be evaluated by any equilibrium configuration of the core without a precise knowledge of this configuration. The two complementary problems of evaluating the behaviour of individual wrapper tubes and of predicting the core configuration under steady conditions are therefore separated and simplified. For example, the equilibrium configuration of the core can be obtained in three successive stages, as follows :

- Evaluation of the bending forces on the spacer pads for all subassemblies in the core as shown above for subassembly 603 ;
- Determination of the resulting possible equilibrium configurations of the spacer pads. It should be pointed out that this determination can be carried out independently for each level of radial restraint ;
- Evaluation of the restrained bowing deformations of the subassemblies from the new positions of the spacer pads.

## 6. CONCLUSIONS.

The stress - strain analysis of the behaviour of the wrapper tubes presented in this paper has led to a number of significant results pertaining to the design of a passive core restraint like that of S NR - 300. The most important are summarized hereafter :

(i) The radiation - induced creep reduces the stresses in the wrapper tube walls and the forces in the system of core restraint to acceptable levels. As far as these quantities are concerned, the most determining factor is the ratio between the swelling and the creep rates ;

(ii) For the range of swelling and creep rates investigated, the wrapper tube deformations are still domintated by swelling. However, it can be anticipated that for faster creep rates a qualitatively different behaviour would result. The main problem would be associated to the provision of sufficient spacings between the wrapper tube walls in the core region ;

(iii) The irradiation - induced creep enables to evaluate the bending forces on the spacer pads independently of a limited displacement of these spacer pads allowed by the core restraint. This property can be used to determine the configuration of the entire core under steady conditions ;

(iv) On the basis of the present knowledge and characterization of irradiation - induced creep and swelling, the present study has revealed no evidence against a successful operation of the S NR - 300 core.

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## - TABLE I -

| | |
|---|---|
| Wrapper tube dimensions : | |
| Distance across flats | 104.5 mm |
| Wall thickness | 2.8 mm |
| Tube length (approximate) | 3.5 m |
| Axial dimensions of the core : | |
| Core length | 950 mm |
| Upper blanket | 400 mm |
| Lower blanket | 400 mm |
| Gas plenum | 650 mm |
| Levels of the load planes with respect to the core centre : | |
| Foot | - 1930.5 mm |
| Lower load plane | - 675.5 mm |
| Upper load plane | + 1092.5 mm |

## - TABLE II -

MAXIMUM STRESSES IN THE WRAPPER TUBES AND BENDING FORCES AT THE INTERMEDIATE LOAD PLANE AT END-OF-LIFE

| Case<br>Swelling<br>Creep | F<br>nominal<br>nominal | D<br>maximum<br>minimum | B<br>minimum<br>minimum | A<br>nominal<br>nominal | E<br>maximum<br>maximum | C<br>minimum<br>maximum |
|---|---|---|---|---|---|---|
| Subassembly | Equivalent stresses ($kp/mm^2$) | | | | | |
| 100 | 58.9 | 23.5 | 12.7 | 11.1 | 11.5 | 9.6 |
| 603 | 54.0 | 27.1 | 11.7 | 9.9 | 10.7 | 6.1 |
| | Bending forces (kp) | | | | | |
| 603 | 492 | 419 | 178 | 168 | 189 | 78 |
| Comments | doubtful | doubtful | feasible | feasible | feasible | feasible |

## - TABLE III -

MAXIMUM BOWING DEFORMATIONS AND CROSS-SECTIONAL DEFORMATIONS AT END-OF-LIFE

| Case<br>Swelling<br>Creep | F<br>nominal<br>nominal | D<br>maximum<br>minimum | B<br>minimum<br>minimum | A<br>nominal<br>nominal | E<br>maximum<br>maximum | C<br>minimum<br>maximum |
|---|---|---|---|---|---|---|
| Subassembly | Maximum restrained bowing deflections (mm) | | | | | |
| 603 | 4.8 | 5.7 | 2.8 | 3.3 | 4.8 | 2.4 |
| | Free bowing (mm) cold state | | | | | |
| 603 | 20.0 | 16.5 | 7.0 | 4.8 | 5.8 | 0.8 |
| | Dilation across flats (mm) | | | | | |
| 100 | 3.7 | 5.3 | 3.1 | 4.1 | 5.7 | 3.5 |
| Comments | doubtful | doubtful | feasible | feasible | doubtful | feasible |

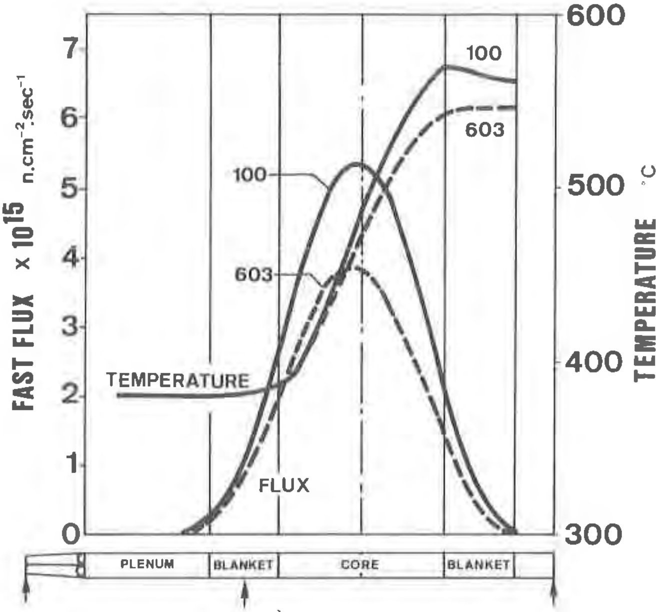


FIG. 1 Irradiation Conditions for Subassemblies 100 and 603

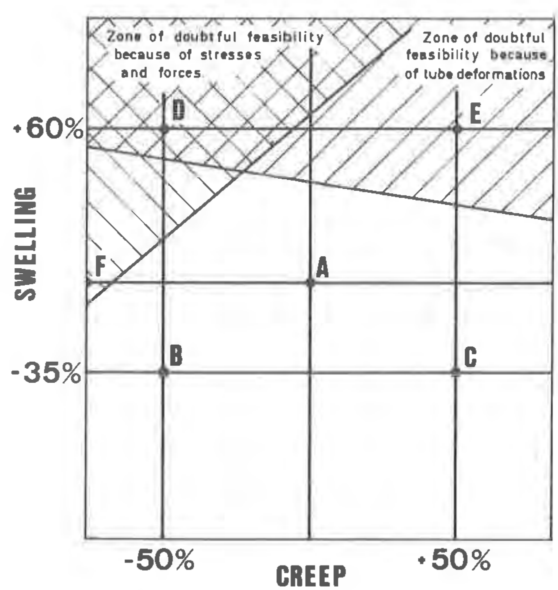


FIG. 2 Range of the Design Equations for Irradiation-induced Creep and Swelling.

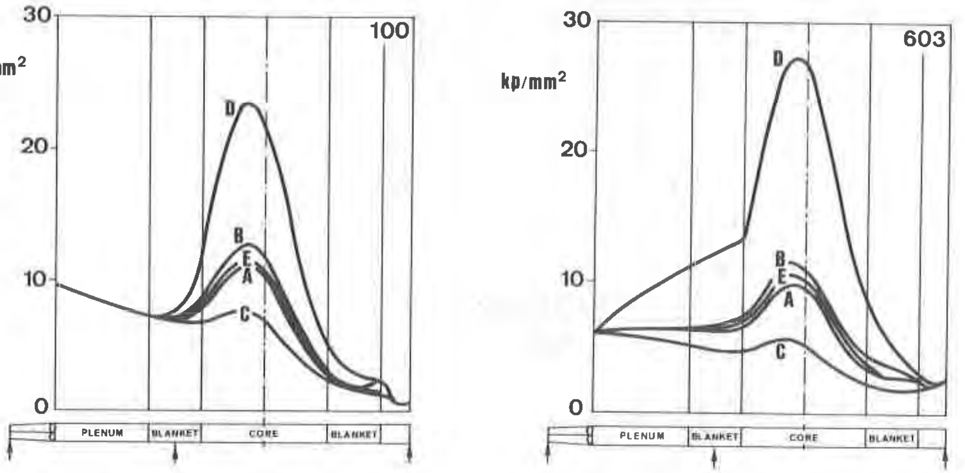


FIG. 3 and 4 Axial Distribution of Maximum Equivalent Stresses in Subassemblies 100 and 603.

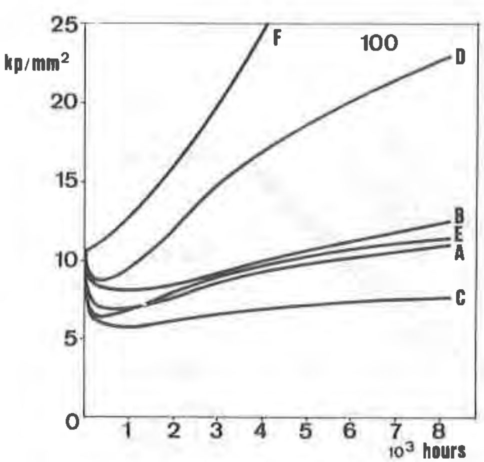


FIG. 5 Time Dependence of the Equivalent Stress in the Core Mid-Plane for Subassembly 100.

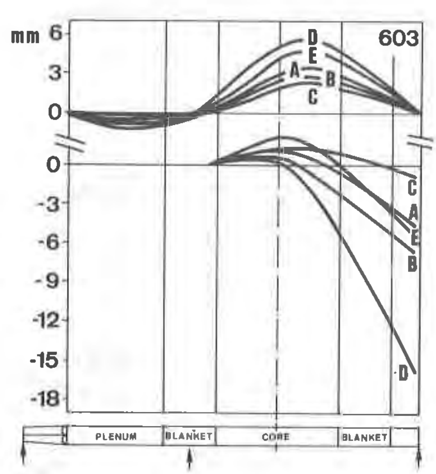


FIG. 6 Restrained Bowing Deformations (Above) and Free Bowing Deformations (Below) of Subassembly 603 at End-of-Life.

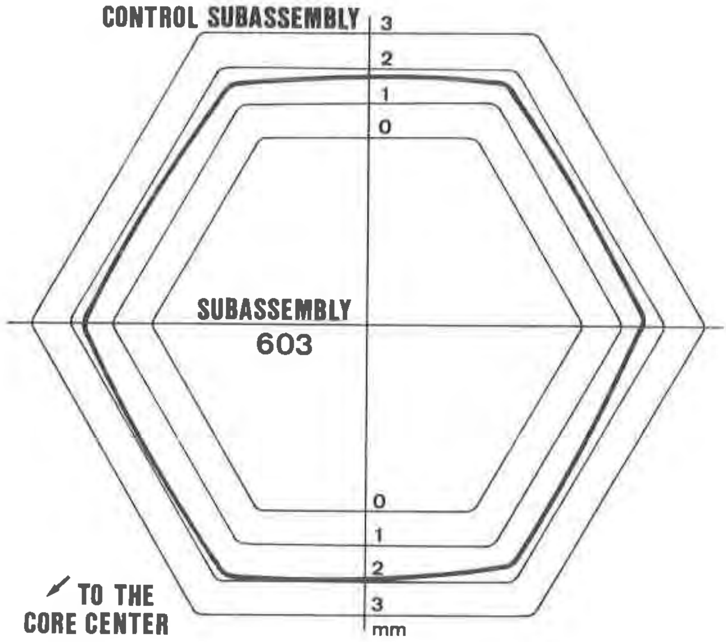


FIG. 7 Cross-Sectional Deformations of Subassembly 603 at the Core Mid-Plane for Case E.

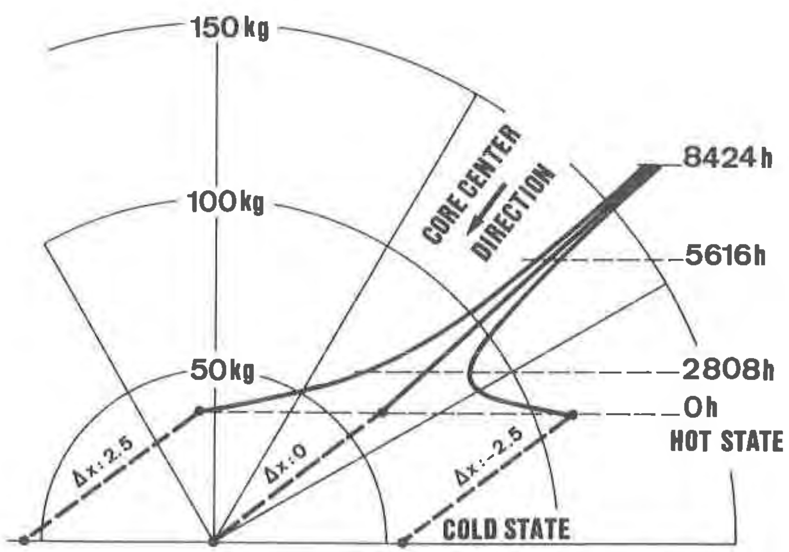


FIG. 8 Trajectory of the Vector representing the Bending Force on the Intermediate Spacer Pad of Subassembly 603 for three Different Deflections of the Upper Spacer Pad.