INFLUENCE OF PELLET SHAPES ON SHEATH STRAINS: ELESTRES PREDICTION VS IRRADIATION MEASUREMENTS

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by N.C. Singhal, M. Tayal and T.J. Carter*

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Abstract

In the quest to reduce cladding strain from power ramps and thereby reduce the incidence of fuel defects, various aspects of pellet geometry have been examined experimentally. In parallel, the ELESTRES code has been developed to calculate the expansion and the hourglassing of fuel pellets. This paper presents the predictions of ELESTRES for the influence of pellet shapes on the pellet expansion, and compares them to measurements from two irradiations involving a total of 23 fuel elements.

The experiments covered various combinations of pellet lengths, diameters, central holes, chamfers and dishes. The linear heat ratings ranged from 40 to 70 kW/m, with burnups up to 200 MW.h/kgU.

The experiments and the predictions show similar trends for strains. Moreover, the predicted strains are generally within the scatter of experimental data. It is concluded that the code is in general agreement with this data.

Effet de la Forme des Pastilles sur la Déformation des Gaines: Comparison Entre les Prévisions du Programme Elestres et les Mesures de Combustion Massique

par N.C. Singhal, M. Tayal and T.J. Carter**

présenté à :

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mai 1989

Résumé

Dans la recherche visant à réduire les déformations des gaines provoquées par les rampes de puissance et par là même réduire la fréquence des ruptures de gaine, différents aspects de la géométrie des pastilles ont été examinés expérimentalement. Parallèlement, on a élaboré le programme de calcul ELESTRES pour calculer la dilatation et la déformation en diablo des pastilles de combustible. La présente communication donne les prévisions d'ELECTRES quant à l'effet de la forme des pastilles sur la dilatation de ces dernières et compare ces chiffres aux mesures effectuées à la suite de deux périodes d'irradiation de 23 éléments combustibles.

Ces expériences ont porté sur des pastilles ayant des longueurs, des diamètres, des trous centraux, des chanfreins et des cuvettes différentes. Les puissances thermiques linéaires étaient comprises entre 40 et 70 kW/m à des combustions massiques allant jusqu'à 200 MWh/kg d'U.

Les données d'expérience et les prévisions indiquent les mêmes tendances aux déformations. En outre, les déformations prévues sont généralement comprises dans les limites du diagramme de diffusion des données expérimentales. On en conclut que le programme de calcul donne des résultats qui concordent assez bien avec les données.

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INFLUENCE OF PELLET SHAPES ON SHEATH STRAINS: ELESTRES PREDICTION VS IRRADIATION MEASUREMENTS

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1. INTRODUCTION

CANDU* fuel has a high rate of integrity: in 500,000 bundles irradiated to date, about 99.9% have completed the irradiation without defecting. In the past, however, some fuel failures have been reported due to stress corrosion cracking during power ramps. These failures have now been eliminated from CANDU fuel by introducing a layer of CANLUB, which reduces the exposure of the sheath to fission products, and by changing to new fuel management schemes that give low stresses in the sheath. However,the level of sheath stresses can change with changing operating conditions,e.g., higher power/burnup, and/or with changing fuel design, e.g.:

- pellet density;
- pellet shape: length; chamfer; dish;
- diametral clearance between the pellets and the sheath; and
- axial clearance between the pellets and the endcaps.

There is thus a continuing need to understand, predict, and control the level of sheath stresses.

Figures 1 to 3 show a typical fuel bundle and identify its parts. The dominant source of stresses in the sheath, is the diametral expansion and the hourglassing of the pellet. The end of the pellet (as opposed to the midplane) has the highest expansion, and thus controls the level of sheath stresses. The ELESTRES code [1]** is often used at Atomic Energy of Canada Limited, to calculate the expansion and the hourglassing of the fuel pellets. This paper presents the predictions of ELESTRES for the influence of pellet shapes on the pellet expansion, and compares them to measurements from three irradiations involving a total of 23 fuel elements.

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* CANDU: CANada Deuterium Uranium

** [ ] Denotes reference listed towards the end of the text.

\+ Atomic Energy of Canada Limited, CRNL.

The objective of the experiments [2] was to study how pellet shapes influence sheath strains. The objective of this paper is to report on how ELESTRES predictions compare against these experiments. The following parameters are covered:

- pellet diameters
- pellet length-to-diameter (l/d) ratios
- chamfers
- central holes
- dish sizes
- element linear ratings in the range 40-70 kW/m
- element burnups up to 200 MW.h/kgU.

This paper first describes the features of the ELESTRES code pertinent to this study, then the experiments. The predictions are then compared to the measurements, and conclusions are drawn.

2. THE ELESTRES CODE

The ELESTRES code evolved from the ELESIM code [3], and models the behaviour of the CANDU nuclear fuel elements under normal operating conditions. It models a single element by accounting for the radial and axial variations in stresses and displacements. The constituent models are physically (rather than empirically) based and include such phenomena as fuel-to-sheath heat transfer; temperature and porosity dependence of fuel thermal conductivity; burnup-dependent neutron flux depression; burnup- and microstructure-dependent fission product gas release; and stress-, dose-,and temperature-dependent constitutive equations for the sheath. Figure 4 shows the sub-models included in ELESTRES.

The finite element model for the pellet deformation includes thermal, elastic, plastic, and creep strains as well as swelling and densification; pellet cracking; and rapid drop of UO_2 yield strength with temperature. It uses the variable stiffness method for plasticity and creep calculations and combines it with a modified Runge-Kutta integration scheme for rapid convergence and accuracy.

We used eight radial nodes to represent the pellet because previous studies have shown that five or more radial nodes give a convergent solution for sheath strains. The number of axial nodes were varied to reflect the length of the pellet. Table 1 summarizes the nodalization.

Previous comparisons of code predictions with experimental data indicate good agreement for the calculation of fission gas release and pellet-midplane and pellet-endplane sheath strains [1] for a variety of power histories.

3. EXPERIMENTAL

Carter's irradiations [2] investigated the effect of pellet shapes on the sheath strains. The following pellet features were studied:

- pellet diameter
- various length-to-diameter (l/d) ratios
- chamfered and non-chamfered pellets
- wide shouldered pellets with dishes
- flat ended hollow pellets.

The objective of these experiments was to determine if the sheath strains could be reduced by:

1. reduction of pellet l/d,
2. increase of shoulder width,
3. addition of a small chamfer.

The power histories for the three experiments are shown in Figure 5.

In one of the experiments called DME-143, dished pellets of length-to-diameter (l/d) ratios ranging from 0.2 to 1.0 were irradiated in the U-2 loop of the NRU reactor at CRNL. All six elements were soaked at linear powers of 46 to 59 kW/m to a burnup of approximately 200 MW.h/kgU.

In the second experiment called DME-172 [2] pellets of 13 mm diameter were irradiated in the U-2 loop of the NRU reactor at a linear power of approximately 40 kW/m and up to a burnup of 90 MW.h/kgU. The elements survived a power boost to 53 kW/m followed by power increments to a maximum of 60 kW/m. Four shapes of pellets were studied, representing three different combinations of pellet lengths and of central holes:

- very short pellets
- moderate length pellets(~12 mm length) with no holes
- moderate length pellets (12 mm length) with a central hole
- standard pellets (16 mm length).

In the third experiment called DME-145, single dished and double dished pellets with dimensions similar to those of the conventional 28-element bundles were irradiated in the U-1 and U-2 loops. The pellets were irradiated at low power to burnups of up to 120.9 MW.h/kgU and were then re-irradiated to linear power outputs of up to 64 kW/m to a total burnup of 121.6 MW.h/kgU.

4. RESULTS AND DISCUSSIONS

4.1 Sheath Strains at Pellet Endplane

The ELESTRES predictions for the sheath strains at the pellet endplane are compared to those measured in the experiments DME-143 and DME-172 in Figure 6 and 7 respectively. In the case of DME-172 (Figure 7) we have shown increments in plastic endplane strain from power ramps since only these were readily available from Reference 2.

The results in Figures 6 and 7 show that in 7 of the 9 irradiations the predicted values of the sheath strains at the pellet endplane are similar to those recorded in the experiments. It is only in two cases i.e. for l/d = 0.7 (Figure 6, DME-143) and the wide-shouldered pellet (Figure 7, DME-172) that the ELESTRES predictions of endplane strains are significantly different from those recorded in the experiments. This disagreement between the predicted and the measured endplane strains may be due to present limitation of ELESTRES (correlations for sheath creep, for sheath yield, and for pellet densification) and/or due to measurement uncertainties as discussed below.

For sheath creep, the code uses the correlation developed by Holt,Coleman and Hosbons [4,5]. However other correlations have also been developed e.g. MATPRO [6]. Similarly, for UO_2 densification the code uses the correlation developed by Hastings and Evans [7]. Newer correlations have since been proposed e.g. by Hastings, Fehrenbach and Hosbons [8] and by Assman and Stehle [9]. Use of these correlations will likely have an impact on the predicted sheath strains. Their incorporation into ELESTRES is under review.

For l/d of 0.7, the measurements of sheath strain at the ridge do not seem to follow the trend established by the other values of l/d, see Figure 6. We do not have a convincing explanation for this. Some likely causes are: uncertainties in the power history; scatter in data; unknown event or phenomenon.

A comparison between the predicted and measured endplane strains for the pellets with different l/d ratios (Figure 6) shows that ELESTRES predictions and measurements show similar trends for the endplane strains, i.e. the sheath endplane strains are consistently lower for pellets with smaller length to diameter ratio.

A comparison between the predicted and measured incremental strains (Figure 7) shows that ELESTRES correctly predicts that moderate length pellets with central hole or with chamfers have lower endplane strains as compared with the standard pellets. However, for pellets with wide shoulder, ELESTRES predictions do not agree with the experiments. ELESTRES predicts that pellets with wide shoulders have higher endplane strains as compared to the standard pellets with a narrow shoulder whereas experiments show that the standard pellets have lower endplane strains.

A comparison between the predicted and the measured endplane strains for the single dished and double dished pellets is shown in Figure 8. The results in Figure 8 show that although ELESTRES overestimates the endplane strains for both single and double dished pellets, it correctly predicts the trend observed in the experiments, i.e. that single-dished and doubly-dished pellets have similar sheath strains at the pellet endplane.

4.2 Sheath Strains at Pellet Midplane

The ELESTRES predictions for the sheath strains at the pellet midplane are compared with those recorded in the experiments DME-143 and DME-172 in Figures 9 and 10 respectively. Once again for DME-172 (Figure 10) we have shown increments in plastic midplane strain from power ramps since only these were readily available from Reference 2.

The results in Figures 9 and 10 show that the predicted midplane strains (incremental strains for DME-172) are generally within the scatter of the experimental data in the case of experiments DME-143 and DME-172.

Figure 9 shows that the predicted midplane strains are similar for pellets with length-to-diameter ratios ranging from 0.2 to 1.0. This behaviour is consistent with that observed in experiment DME-143.

A comparison between the predicted and the measured midplane sheath strains for the single and double dished pellets is shown in Figure 8. The results in Figure 8 show that the predicted midplane strains are in good agreement with those recorded in the experiment DME-145. Once again ELESTRES correctly predicts that the doubly-dished pellets have similar midplane strains as compared to the single-dished pellets.

4.3 Overall Comparison

A comparison between all the predicted sheath strains and those measured in all the three irradiations (DME-143, DME-145 and DME-172) is shown in Figure 11. The figure includes sheath strains both at pellet midplanes and at pellet endplanes.

The bars in the figure indicate the measured scatter. The scatter in the measurements for DME-143 is not readily available and therefore is not included in Figure 11.

Figure 11 shows that the ELESTRES predictions for sheath strains are in general agreement with the measurements. The mean deviation of the predictions from the measurements, defined as S (predicted strain-measured strain)/number of measurements, is -0.07% with a standard deviation of 0.18%. The uncertainty in the measurements is 0.2%, and twenty out of the 23 predictions lie within 0.2% of the measurements.

5. CONCLUSIONS

ELESTRES correctly predicts the following trends in the sheath strains at pellet midplanes and at pellet endplanes:

- endplane sheath strains decrease with decreases in the pellet l/d ratio;
- the midplane sheath strains are similar for pellets with length-to-diameter (l/d) ratio ranging from 0.2 to 1.0;
- both midplane and the endplane sheath strains are similar for the doubly-dished pellets and the single-dished pellets.

It is therefore concluded that ELESTRES predictions for sheath strains for different pellet shapes are in general agreement with the experimental data. Further evolution of the code can improve the fit.

ACKNOWLEDGEMENTS

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REFERENCES

1. M. Tayal, "Modelling CANDU Fuel Under Normal Operating Conditions:ELESTRES Code Description", Atomic Energy of Canada Limited, Report AECL-9331, 1987.

2. T.J. Carter, "Experimental Investigation of Various Pellet Geometries to Reduce Strains in Zirconium Alloy Cladding", Nuclear Technology,Volume 45, 1979 September, pp. 166-176.

3. M.J.F. Notley, "A Computer Program to Predict the Performance of UO_2 Fuel Elements", Nuclear Applications and Technology, Volume 9,1970 August, pages 195-204.

4. R.R. Hobsons, C.E. Coleman and R.A. Holt, Numerical Simulation of Tensile Behaviour of Nuclear Fuel Cladding Materials, AECL-5245,(1975).

5. R.A. Holt, R.R. Hosbons and C.E. Coleman, Simulation of Nuclear Fuel Sheath Deformation Following Fuel Power Transients, AECL-5430.

6. MATPRO-Version 11, NUREG/CR 04976 (Rev. 1) (1980).

7. I.J. Hastings, L.E. Evans, "Densification Term for Irradiated UO_2 Fuel", J. American Ceramic Society, Vol. 62, No. 3-4, p 217 (1979).

8. I.J. Hastings, P.J. Fehrenbach, R.R. Hosbons, "Densification in Irradiated UO_2 Fuel", Communications of the American Ceramic Society,Vol. 67, No.2, p c-24, 1984.

9. H. Assman and H. Stehle, "Thermal and In-Reactor Densification of UO_2; Mechanism and Experimental Results", Nuclear Engineering and Design,V.48(1), page 49-67 (1978).

TABLE 1 SUMMARY OF PELLET MESH NODALIZATION

Ratio of Pellet Length to Diameter	Number of Radial Nodes	Number of Axial Nodes	Number of Elements
0.2	8	5	61
0.3	8	5	61
0.5	8	7	75
0.7	8	9	122
1.0	8	11	151
1.4	8	14	195

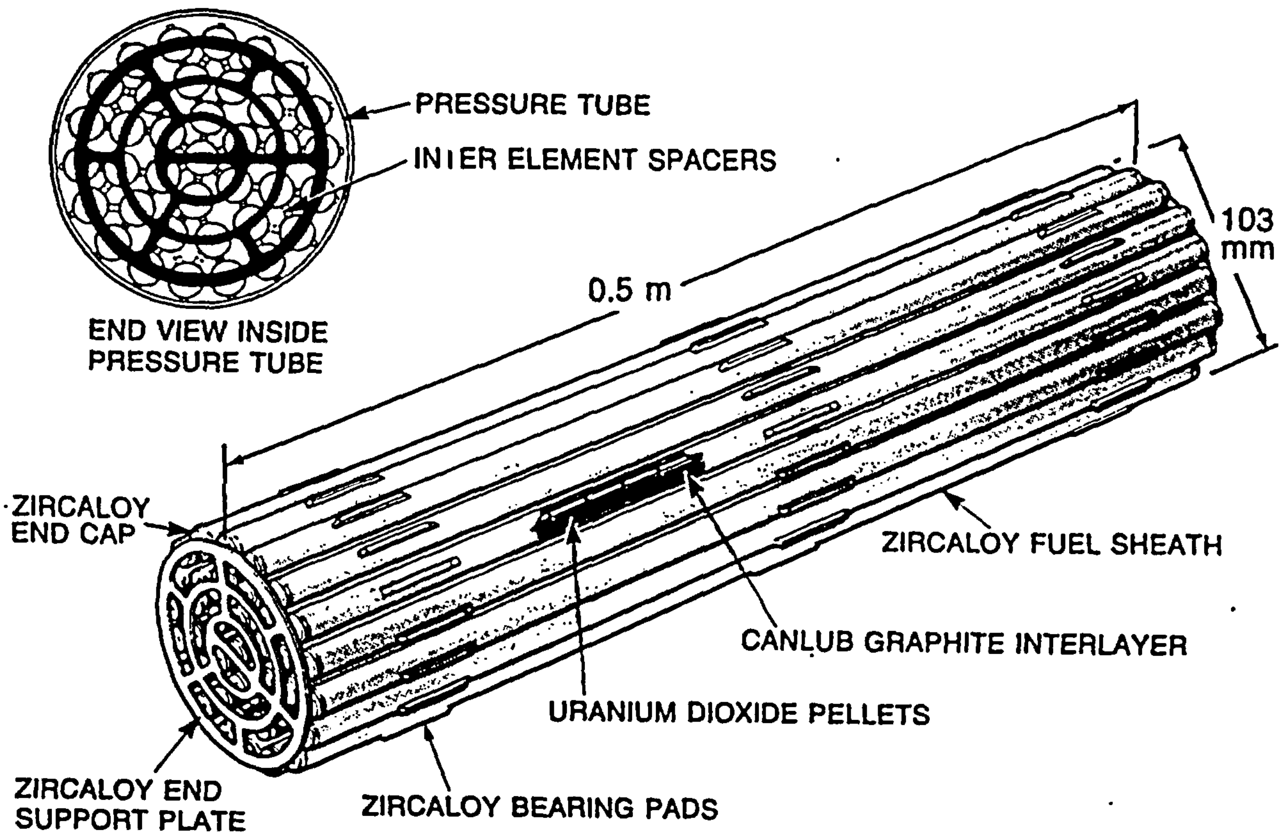

FIGURE 1 · FUEL BUNDLE

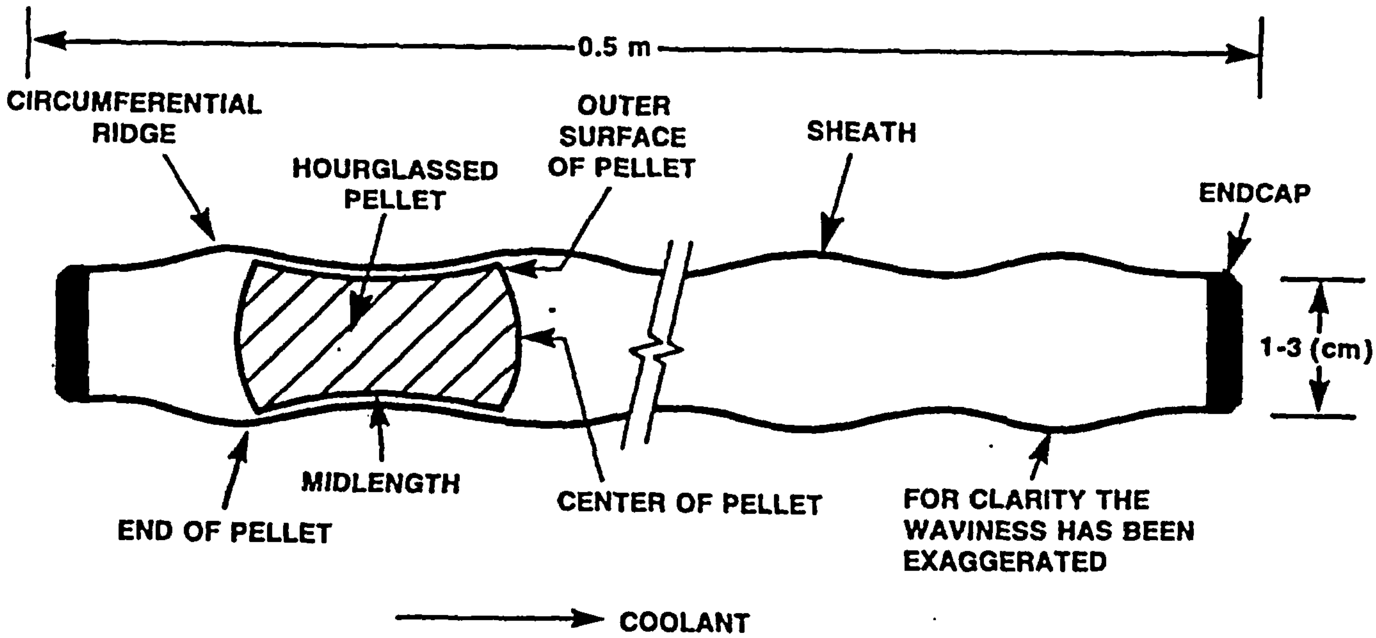

FIGURE 2 FUEL ELEMENT

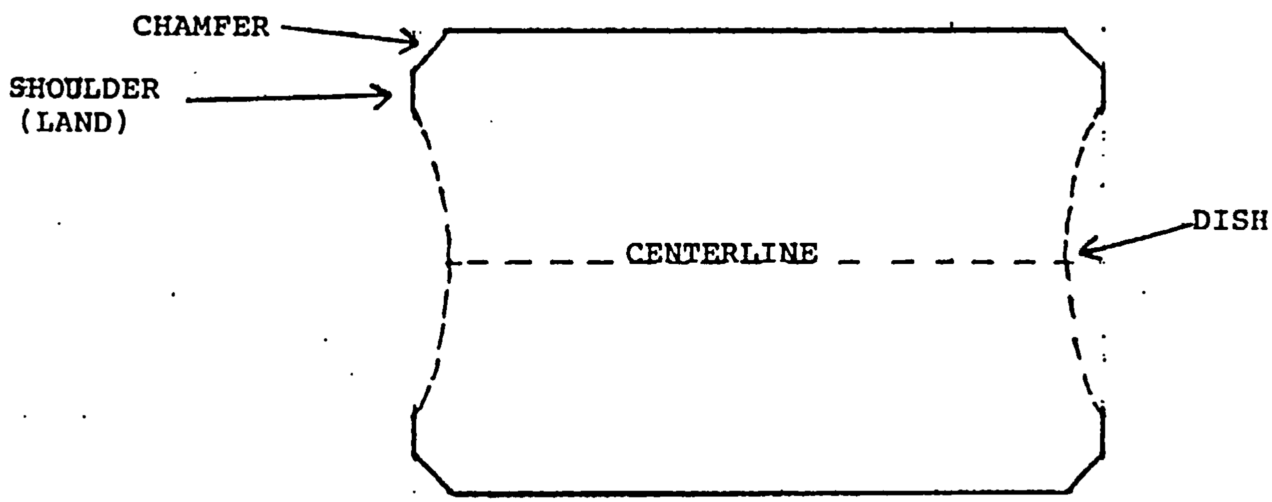

FIGURE 3 STANDARD PELLET DESIGN
(AXIAL CROSS-SECTION)

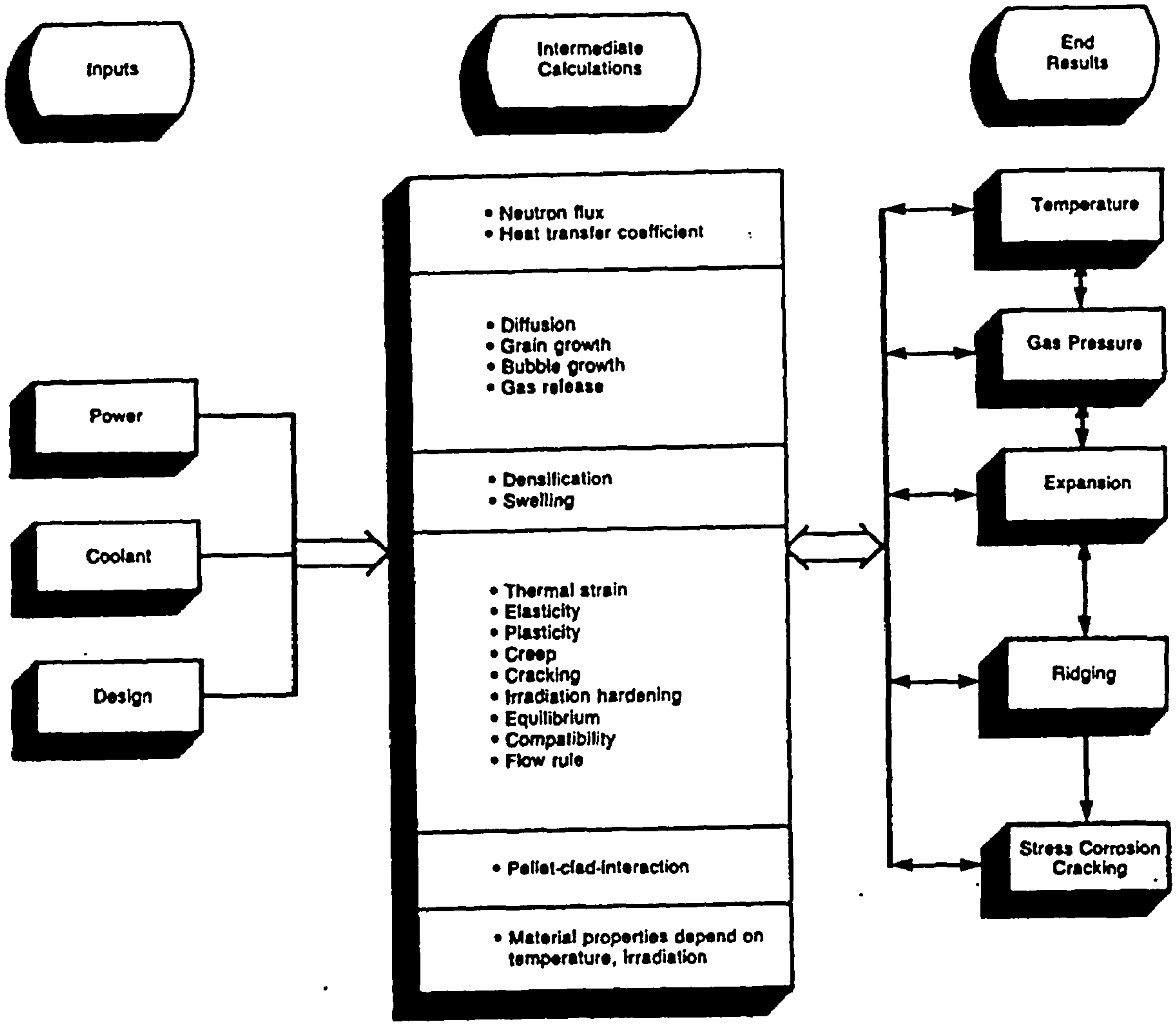

FIGURE 4 MAJOR CALCULATIONS IN ELESTRES

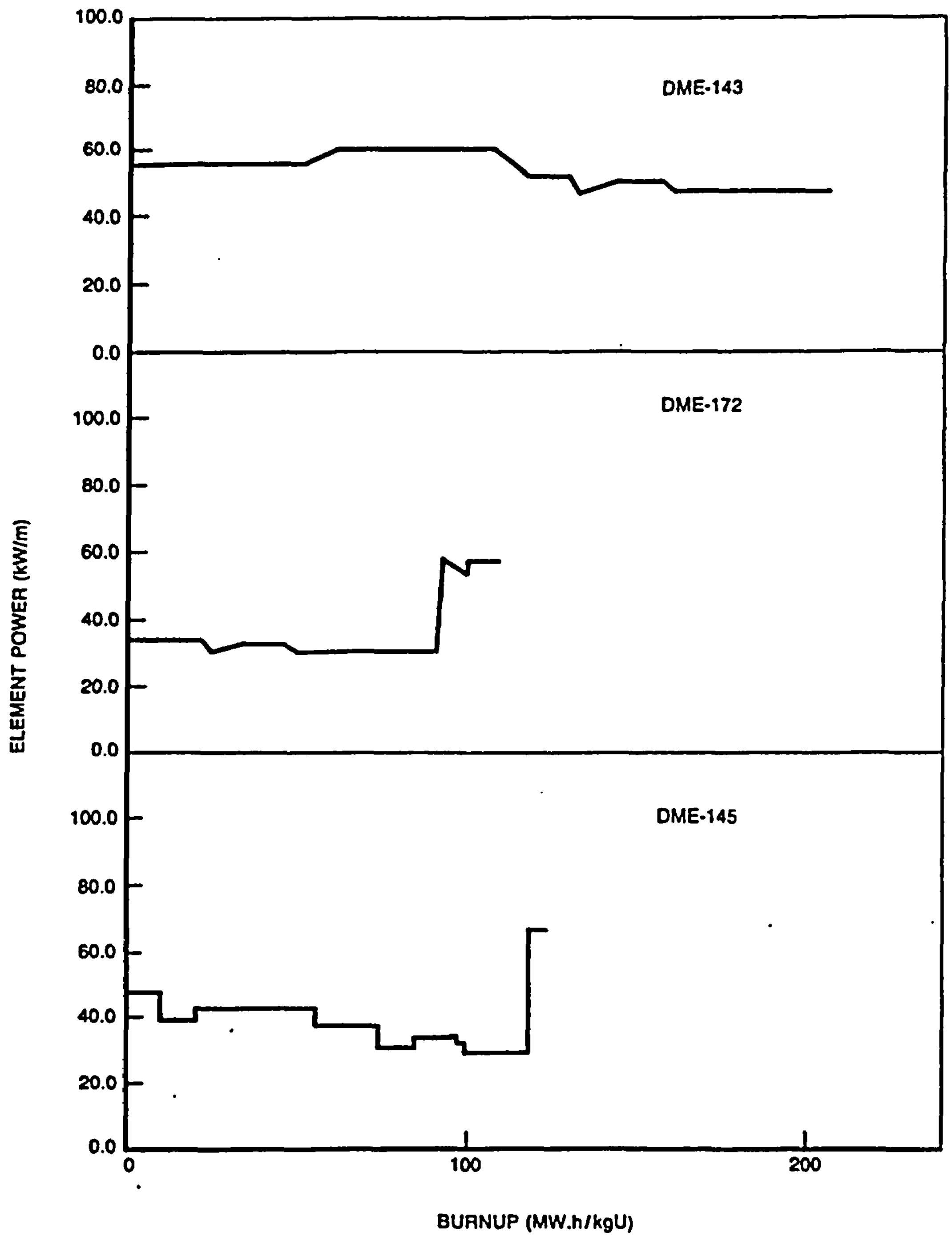

FIGURE 5 POWER HISTORIES FOR EXPERIMENTS DME-143, DME-172 AND DM-145

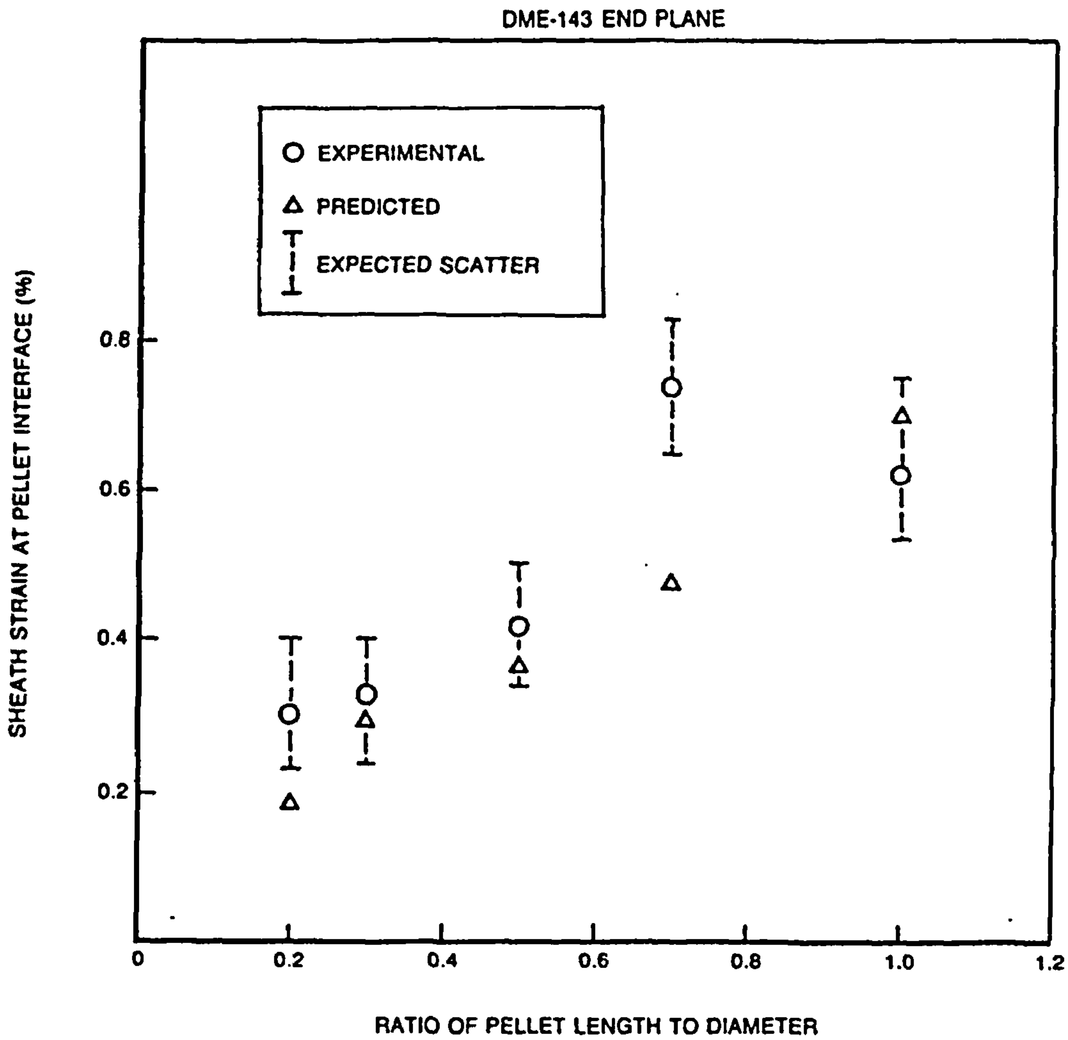

FIGURE 6 COMPARISON OF PREDICTED INCREMENTAL SHEATH STRAINS WITH THOSE MEASURED AT PELLET END PLANE IN DME-143

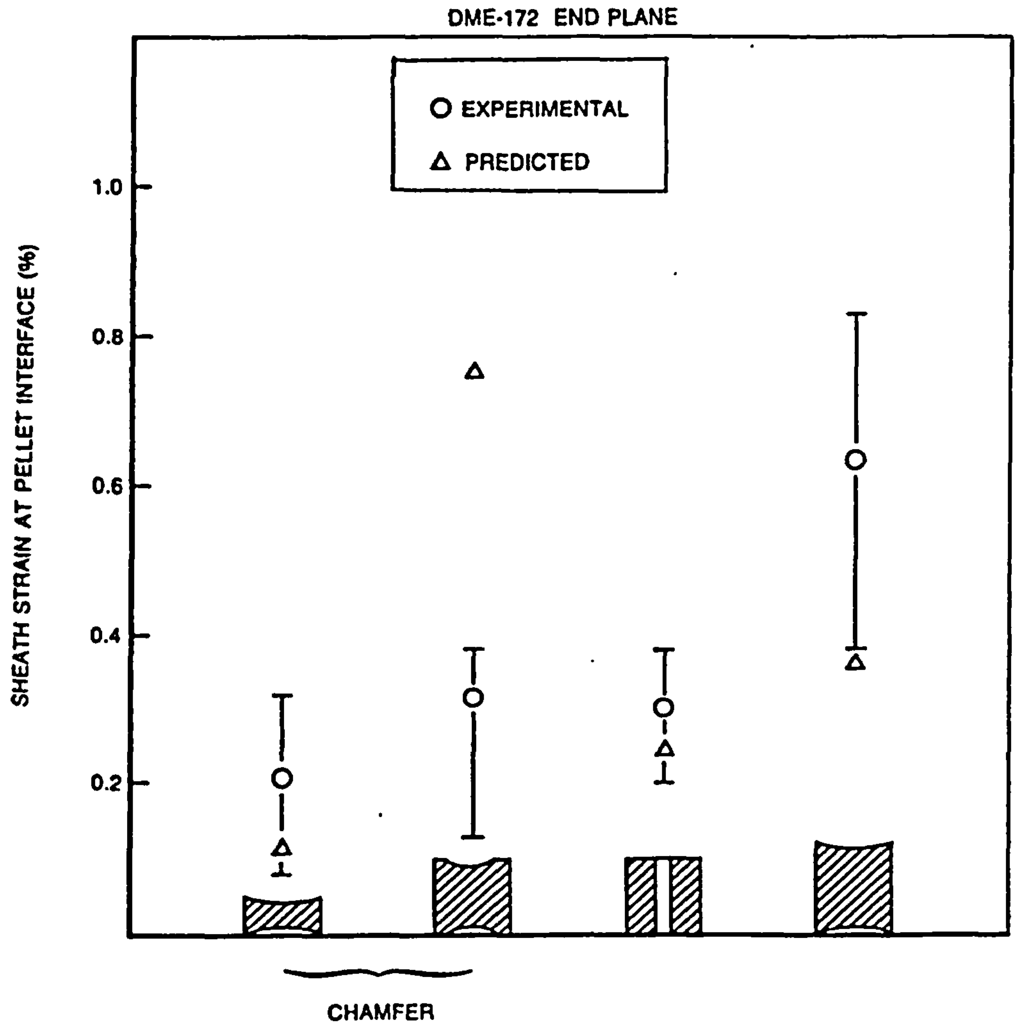

FIGURE 7 COMPARISON OF PREDICTED SHEATH STRAINS WITH THE MEASURED AT PELLET END PLANE IN DME-172

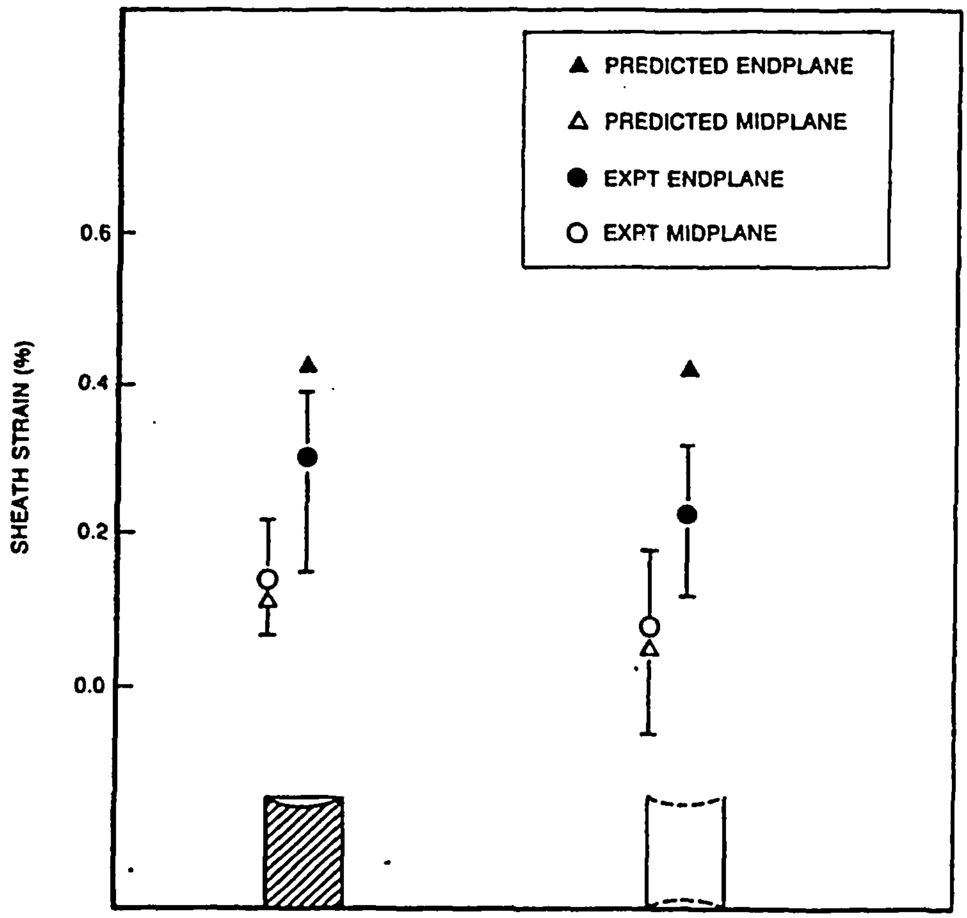

FIGURE 8 COMPARISON OF SHEATH STRAINS WITH THOSE MEASURED AT PELLET END-PLANE AND MID-PLANE IN DME-145

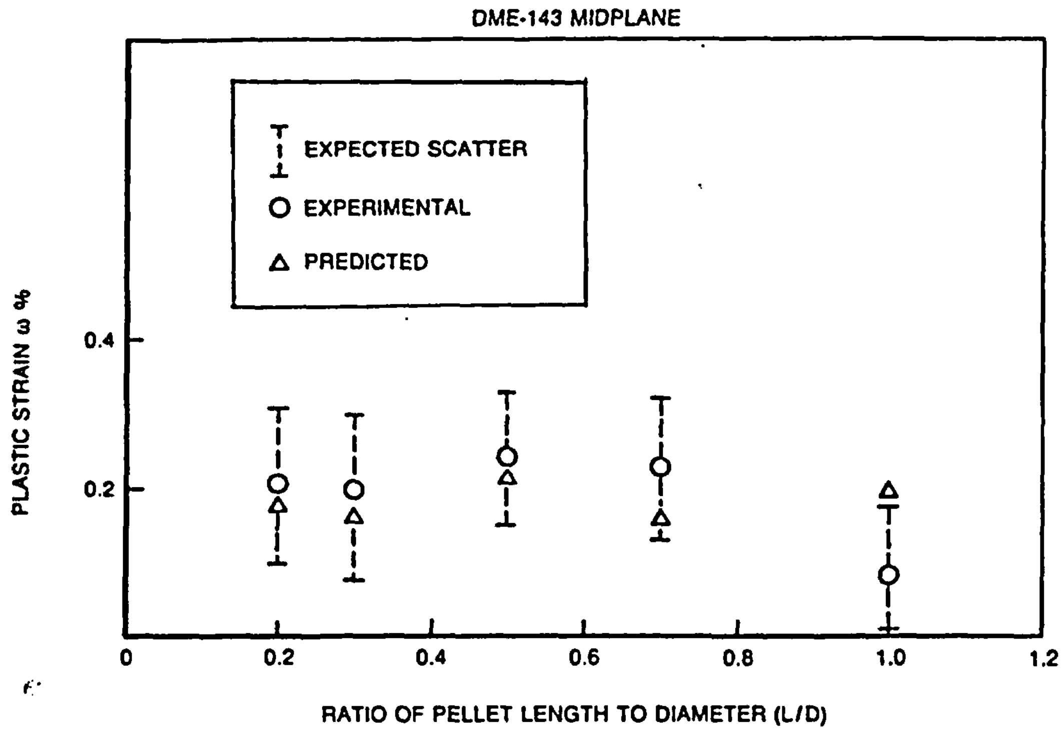

FIGURE 9 COMPARISON OF PREDICTED SHEATH STRAINS WITH THOSE MEASURED AT PELLET MID-PLANE IN DME-143

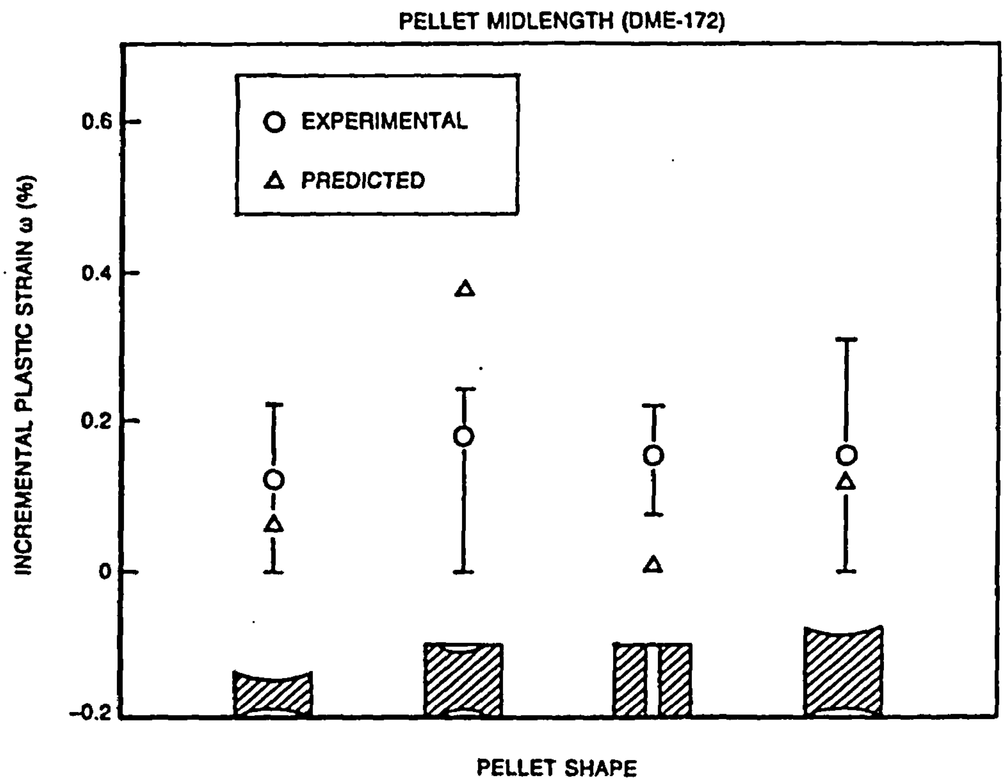

FIGURE 10 COMPARISON OF PREDICTED INCREMENTAL SHEATH STRAINS WITH THOSE MEASURED AT PELLET MID-PLANE IN DME-172

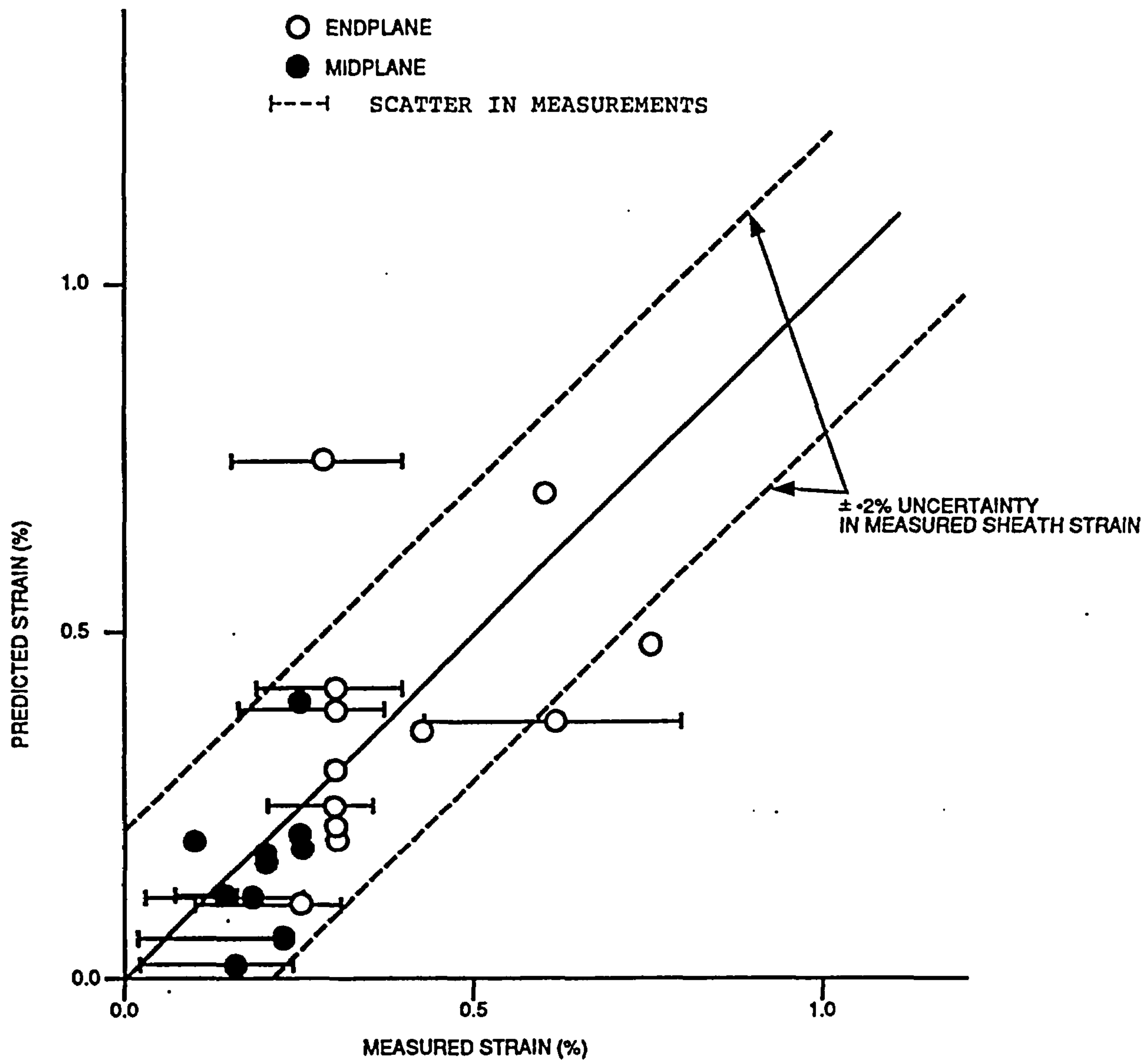

FIGURE 11 OVERALL COMPARISON OF SHEATH PLASTIC STRAINS: PREDICTED VS MEASURED (DME-143, DME-145, DME-172)

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