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Recent USNRC Results and Program Plans for Elevated Temperature Time Dependent Material Behavior

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Introduction

Responsiblities for nuclear energy development and regulation in the United States are separated into independent agencies. The Nuclear Regulatory Commission, in addition to its titled function, has been chartered to do independent confirmatory research in areas affecting public health and safety which are in any manner open to question.

The NRC Structural Integrity (SI) program contains all of the work on elevated temperature materials behavior. This program has been in the formative stage in FY 77 and is funded at a relatively low level, less than two percent of the Department of Energy (DOE) materials work. However, through cooperation with DOE, expensive tests such as creep-fatigue of a large elbow may be analysed independently, with similar or different methods, at a small fraction of the cost of repeating the experiments.

Objective and Scope

The regulatory function of NRC sets the overall objective of the Structural Integrity Program; safe operation of the plant must be assured throughout

the 40 year lifetime. In the formative year of this program the licensing reviews for the Clinch River Breeder Reactor have helped to focus the active research work. That is, once the necessary review of the DOE/industry work and of foreign programs is encompassed, the extrapolation of test data and design methods over the 40 year lifetime of the plant will require careful planning and selective work programs. In the present plan the active research in the NRC program concentrates on materials tests, analysis methods and in-service-inspection methods which are deemed most useful for extrapolating.

A primary heat transport system for a loop type 1,000 MWe plant is shown in Figure 1. The hot leg piping is 36 in., while the twin return lines are 28 in. in diameter. This design is a satelite design to minimize the primary piping, yet the large volume of pipe wall material with attendant failure sites is apparent.

The key technical issue in long life design at elevated temperatures is creep-fatigue interaction. In the sub-creep range the relatively mature state of design for 304 or 316 SS may be observed in Figure 2. The new curve proposed by the ASME Code Creep/Fatigue Working Group differs by on only a few percent from the existing Code Case 1592-7 curve. Contrasting this mature status, the tentative modification to the linear damage summation rule as published in Code Case 1592 is reproduced in Figure 3. Some scattered data infer that the indicated modification for 304 and 316 SS may not be conservative. In addition most attempts at supplying data for creep-fatigue interaction are high strain and relatively short time tests. Such tests provide trends but long term-low strain data is needed. Furthermore, some component analyses that were reported at this years' 4th SMiRT conference contained about one percent creep although titled as representing creep-fatigue interaction.

Program for SI

With the above brief background, the NRC SI program was formulated with the further restriction that the same personnel should not be utilized by both DOE and NRC for LMFBR applications. The SI program therefore reflects this restriction as well as the technical issues in the functional format shown in Table I.

The term "elevated temperature design" signifies that inelastic analysis of sufficient design margin be provided to allow for creep and plastic deformation. Brookhaven National Laboratory has completed a review (Reference 1) of fracture mechanics methods with potential for elevated temperature design. The next phase is to choose the most promising and carry out further development. Crack growth studies under biaxial loading are being made by Cambridge University. A specimen has been designed and checked for uniform strain in the region where cracks will be introduced. In-phase and out-of-phase tensile and compressive loading will be investigated for 316 SS. The Electric Power Research Institute (EPRI) will cooperate in this work by providing commercial grade steel. NRC has obtained some of the ERDA archival 316 SS for comparison with the EPRI material and with ORNL results on the archival steel.

Analytical capability for inelastic cases is being developed by Sandia. Figures 4 and 5 show the pressure and temperature histories for a pipe ratchetting case reported in Reference 2. Figure 5 shows very good agreement between the loop strain values and measured values. Figures 6 and 7 show the results of computations that were made to check a PNC elbow test. The loading geometry is shown in the corner of Figure 6. Earlier computations using minimum or "design" values gave larger errors ($\sim$x2). By utilizing nominal or "expected" values the relatively good results of Figures 6 and 7 were obtained. As a result of this study, Sandia recommends measuring the properties of the actual test piece for future tests. However the relative accuracy of the various finite element types has been determined for this case. Checking these and other applicable types of elements for an elbow about to be tested by WARD (Westinghouse) will provide an independent check on the element applicability.

An analytical study has been initiated under the SI program which looks at the second line of assurance. Typical LMFBR designs have the primary coolant system contained in concrete cells with steel liners. Leaks in the primary system result in sodium spills on these liners. The response of the liners must be determined. Figure 8 shows calculated z axis displacements in an r - z calculation for spills on a 20 in. diameter plate with fixed edges. Sensitivity calculations of material properties and film coefficients are being carried out prior to more explicit liner experiments. Future experimental tests will be conducted involving sodium spills on cell liner features, such as anchors, corners and welded joints to compare with analyses.

The next analytical study noted in Table I will possibly provide a design tool. Reference 3 presents the concept of strain range partitioning as an analysis method for creep-fatigue interaction. The flexibility of strain range partitioning permits the inclusion of stress/strain reversal effects yet presents a simple enough proceedure for design surveys. Further work in this area will be pursued at Case University.

The last element under analytical studies, unified deformation theory, is being worked on in numerous laboratories and universities. The objective of this work is to treat deformation from creep or plastic flow by a unified theory. Sandia will monitor this work and do limited development.

Creep-fatigue interaction is a major constituent in the effort to extrapolate to a 40 year plant lifetime. Sandia has just started a short range program ($\sim$x6 mo.) on 316 SS. These uniaxial tests will check extrapolation techniques and form a basis for biaxial creep-fatigue measurements. Sandia is currently investigating experiment requirements for a long term test, i.e. one of about 3 years. One objective is to define a test such that power interruptions to the equipment will not compromise the experimental results.

The extrapolation to the full plant lifetime is expected to depend upon a complementary development of in-service-inspection (ISI) methods. Increased emphasis will be placed in this area in the future, however some results have been obtained for correlations with material transformations. These results are from measurements on specimens deformed in the creep-fatigue program. Figure 9 shows the variation in shear wave velocity for various specimens which were deformed in creep. Only specimen 6 shows a measurement outside of the statistical control band. In this case the strain at position 5 was large enough to cause visible necking. This technique does not appear promising from these results although a few more specimens will be measured which have been subjected to creep and fatigue.

A different technique which depends upon the preferential annihilation of positrons at voids or dislocations in a lattice is being evaluated. Figure 10 shows the results of measurements on several specimens. Essentially all of the change in the measured parameter occured in the first 10% of fatigue life. Additional apecimens are being prepared at 1, 2, and 5% of life to determine the shape of the step variation to 10% life.

Note that a correlation over the first 10% of fatigue life would be very useful since fatigue design curves typically involve a factor of 20 on cycle life. Thus a typical component design should have most of the material volume operating in the first 5% of the material fatigue life. Assuming that a correlation is obtained for the first 10% of fatigue life, scatter in the correlation may be large just as in the case of fatigue life.

Summary

The SI program thus provides NRC with a consultant capability to monitor the materials and structures efforts of applicants. Also, analytical and experimental work is actively pursued in areas with limited background or limited experimental basis. One major area, the extrapolation of test data from time limited tests to the full 40 year plant lifetime, has been choosen for a significant independent effort. This extrapolation study provides a focus for all creep-fatigue, fracture mode and analysis methods development to be done within the program. The supporting assurance which may be provided by sound in-service-inspection techniques must also be developed to the fullest possible extent.

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Table I

NRC Program for Structural Integrity

Program Element	Contractor
Fracture Mechanics:	
FM at Elevated Temperatures	BNL
Crack Growth under Biaxial Loading	Cambridge U.
In-phase and out-of-phase loading	Cambridge U.
Analytical Studies:	
Creep-buckling studies of a pipe elbow	Sandia
Cell liner deformation calculations	Sandia
Development of Strain Range partitioning as a design tool	Case U.
Unified Deformation theory	Sandia
Creep-fatigue Interaction:	
Creep-fatigue interaction studies	Sandia
Biaxial Creep-fatigue experiments	Sandia
Creep-fatigue interactions with defects	Cambridge U.
Exptapolation to a 40 year Plant Lifetime:	
Basis and extent of valid extrapolation	Case U.
Short range test program for 316 SS extrapolation	Sandia
Detailed experiment requirements for long time tests	Sandia
Correlations with creep-fatigue damage (ultrasonic, positron annihilation)	Sanida
Other Supporting Work	
Annual Summary and report of NRC data	BNL
Benchmark problems	BNL
(Simplified methods)	

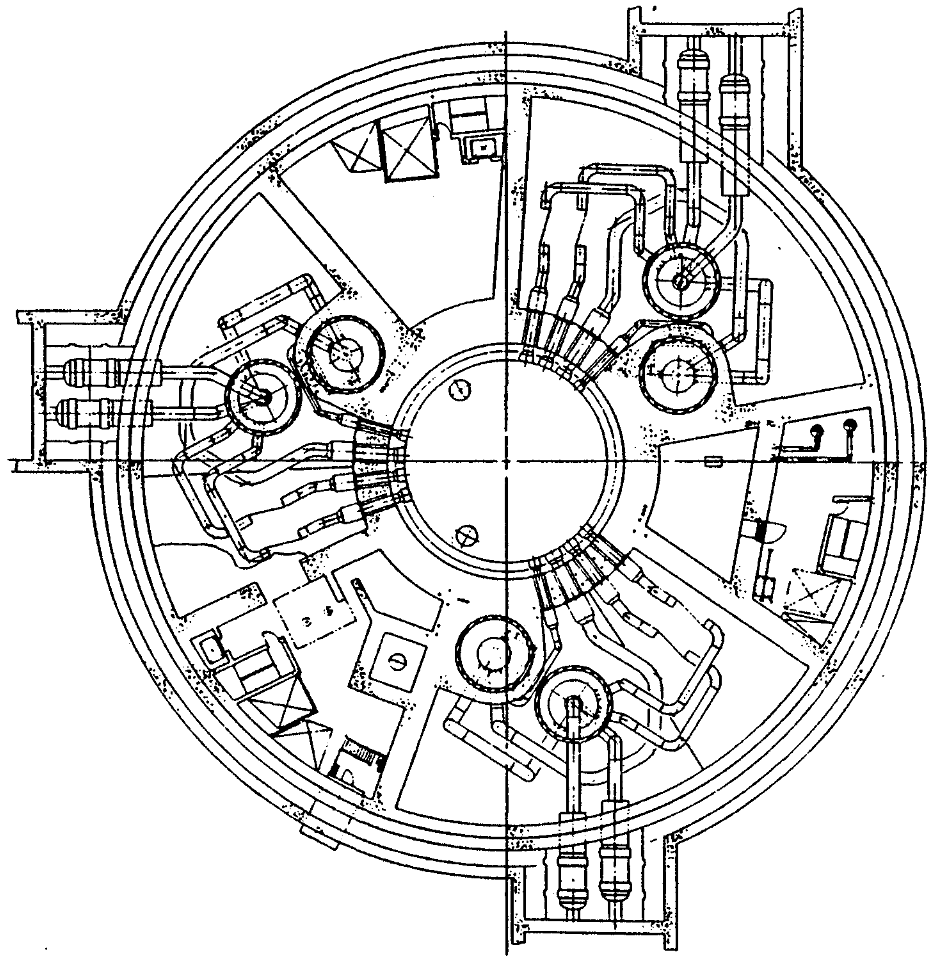
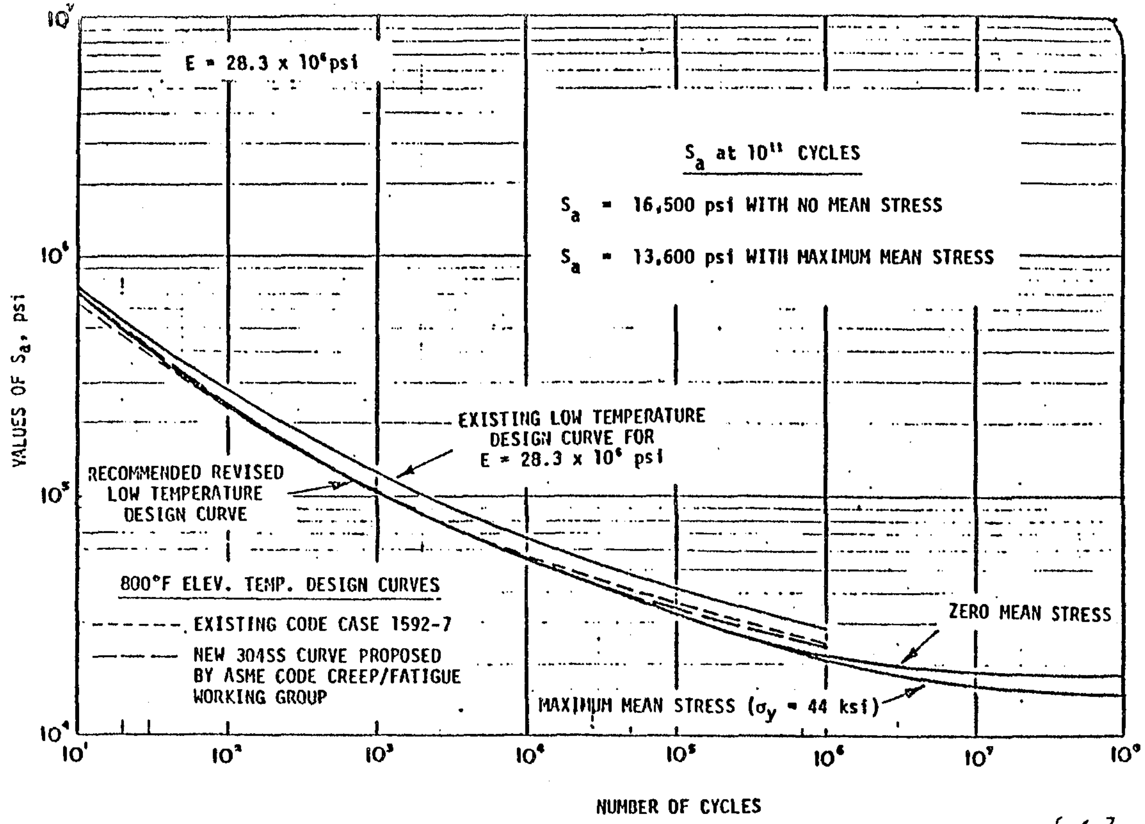


Figure 1. Primary Heat Transport System



[4]

Figure 2.

Recommended fatigue design curve for austenitic steels, nickel-iron-chromium Alloy 800, and nickel-chromium-iron Alloy 600.

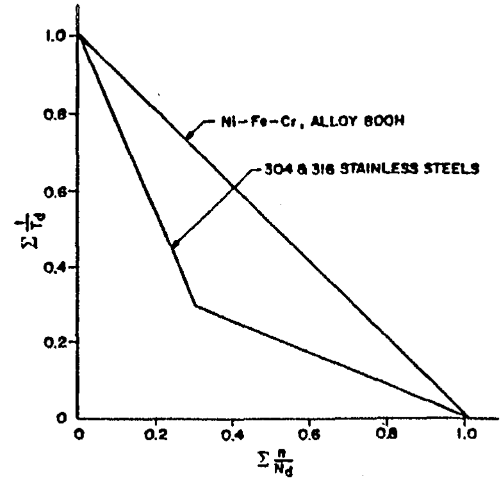


Figure 3.

Code Case 1592 Creep-fatigue Damage Envelope

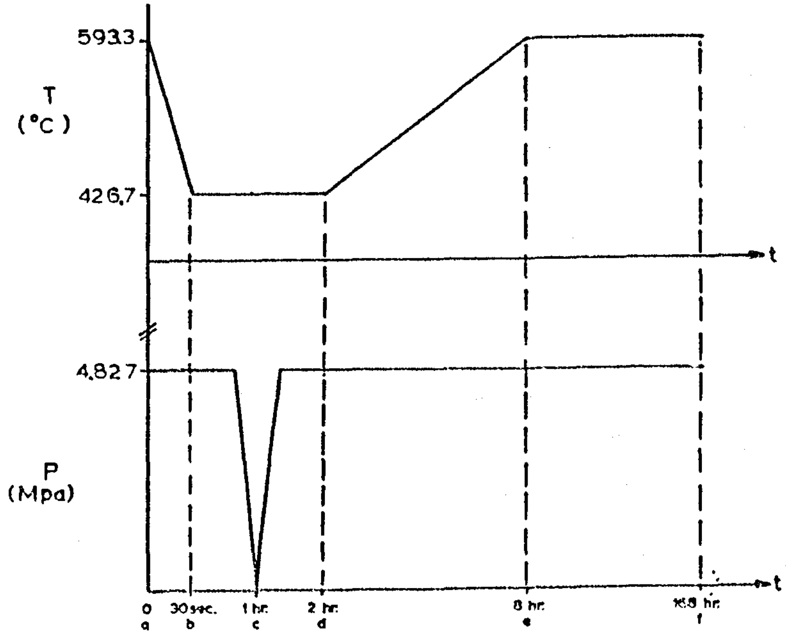


Figure 4.

Sodium Temperature and Pressure Histories for Each Cycle

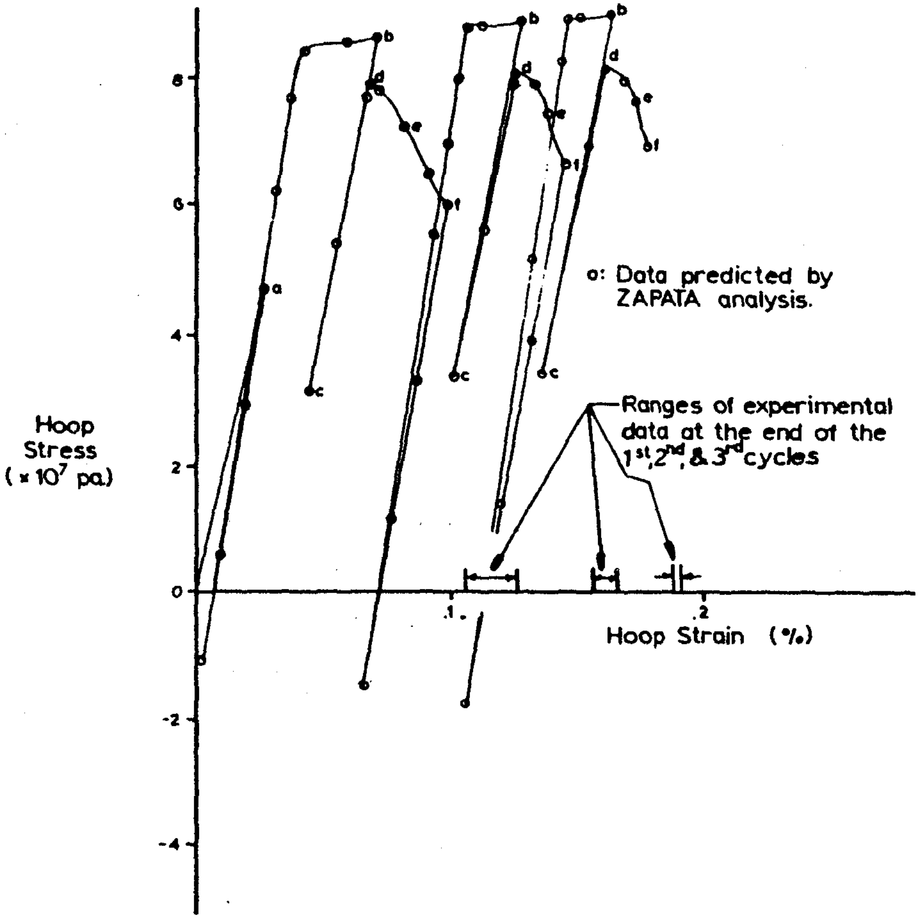


Figure 5.

Outer Fiber Stress-Strain Path (3 Cycles)

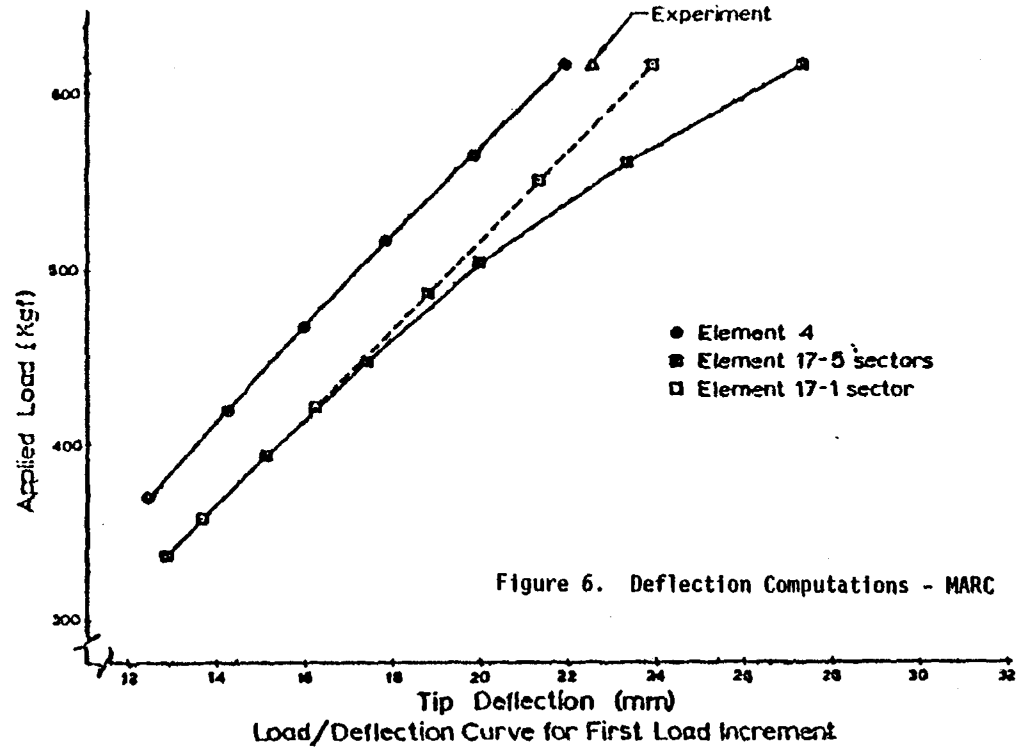


Figure 6. Deflection Computations - MARC

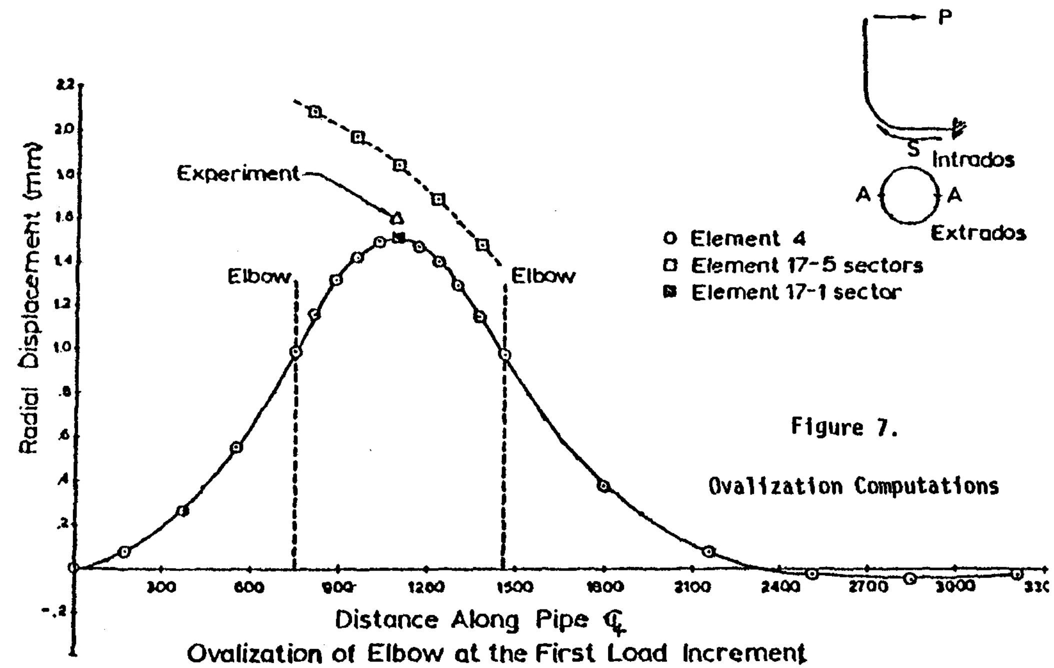


Figure 7.

Ovalization Computations

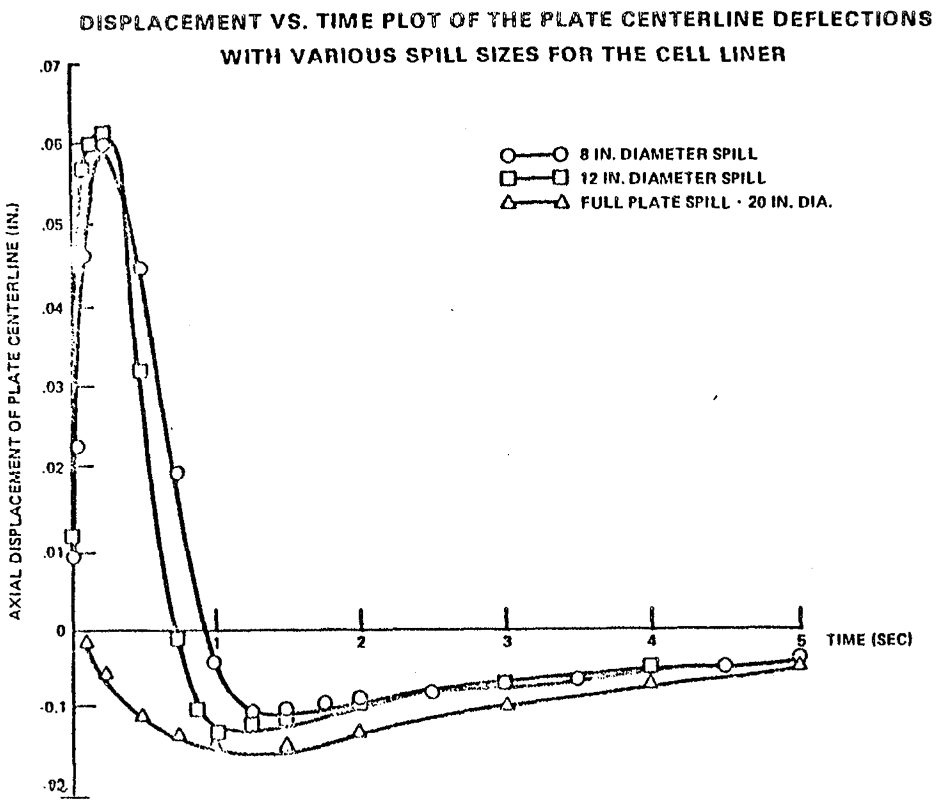


Figure 8. Computations of Cell Liner Displacements

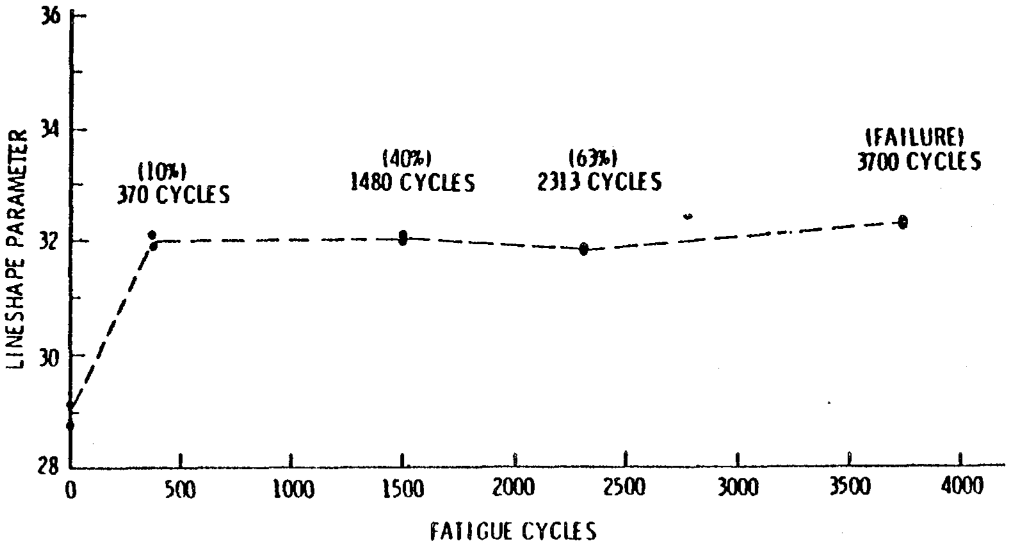


Figure 10 Positron Annihilation (Doppler Broadening Method)

SHEAR WAVE VELOCITIES IN CREEP-DAMAGED 2¼ CR-1 MO STEEL

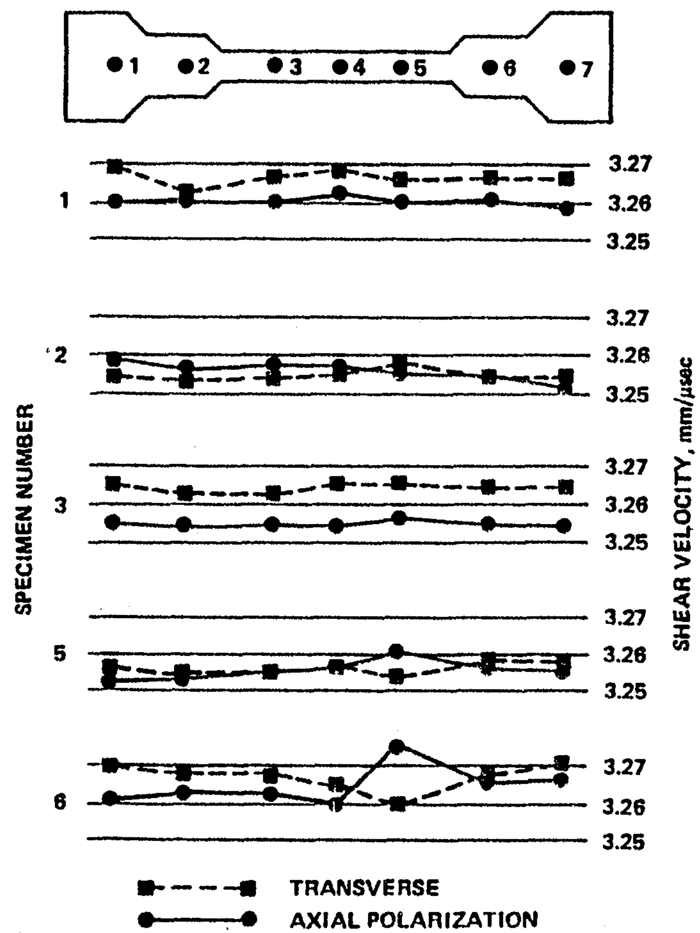


Figure 9. Shear Wave Velocity Measurements