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W. D. Richins

G. K. Miller

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Idaho National Engineering Laboratory
Lockheed Martin Idaho Technologies
Idaho Falls, Idaho 83415

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REACTOR PROGRAMS ENGINEERING AND PROJECT MANAGEMENT REPORT APPROVAL

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Authors W. D. Richins G. K. Miller	Performing Organization Specialty Engineering & Sciences Dept., Applied Mechanics Group	
Engineering and Project Management Approval D. L. Batt <i>Doyle L Batt</i> <i>11/28/95</i>		

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1. EXECUTIVE SUMMARY

This report documents a detailed evaluation of the swaging process used to connect fuel plates to side plates in Advanced Test Reactor (ATR) fuel elements. The swaging is a mechanical process that begins with fitting a fuel plate into grooves in the side plates. Once a fuel plate is positioned, a lip on each of two side plate grooves is pressed into the fuel plate using swaging wheels to form the joints. Each connection must have a specified strength (measured in terms of a pullout force capacity) to assure that these joints do not fail during reactor operation.

The purpose of this study is to analyze the swaging process and associated procedural controls, and to provide recommendations to assure that the manufacturing process produces swaged connections that meet the minimum strength requirement. The current fuel element manufacturer, Babcock and Wilcox (B&W) of Lynchburg, Virginia, follows established procedures that include quality inspections and process controls in swaging these connections. The procedures have been approved by Lockheed Martin Idaho Technologies and are designed to assure repeatability of the process and structural integrity of each joint. Prior to July 1994, ATR fuel elements were placed in the Hydraulic Test Facility (HTF) at the Idaho National Engineering Laboratory (INEL), Test Reactor Area (TRA) for application of Boehmite (an aluminum oxide) film and for checking structural integrity before placement of the elements into the ATR. The results presented in this report demonstrate that the pullout strength of the swaged connections is assured by the current manufacturing process (with several recommended enhancements) without the need for testing each element in the HTF.

The evaluation of the swaged connections was made using detailed non-linear finite element analysis, using models that appropriately simulate the swaging process. The calculated strengths for the connections were compared with actual strengths obtained from tensile tests performed by B&W on swaged samples. The models were used to assess the sensitivity of the connections to variations in several process variables that can affect joint strength. Results from the analyses were then used to assess adequacy of B&W fabrication and quality control procedures to assure structural integrity of all swaged connections within ATR fuel elements.

Provided the specified gap of the side plate grooves is achieved by the swaging process, these analyses indicate that the strength of the swaged connections is relatively insensitive to variations in most parameters involved in the swaging process. Some sensitivity exists to dimensional tolerances in the side and fuel plates, which requires a tighter tolerance on the width of the side plate grooves than currently listed on the drawings. The pullout capacity is also sensitive to the depth of insertion of the fuel plate into the side plate groove, but only when the gap between the edge of the fuel plate and the base of the side plate groove becomes quite large. The relative insensitivities are largely attributable to the result that the strength of the joint increases rapidly once the side plate lip contacts the fuel plate during the swaging process. The minimum required load capacity of the swaged joint is generally achieved well before B&W's specified gap of the side plate grooves is attained. When the required gap is

reached, the pullout capacity is well above the minimum required and then generally levels off with increased swaging (to a smaller gap size).

This study does result in recommendations for several inspections and verifications to be added to B&W's current procedures. If these additions are made, the fabrication processes and quality controls used by B&W during manufacturing are sufficient to assure that all swaged connections meet the acceptance standard for pullout capacity.

2. HISTORICAL BACKGROUND

**by G. N. Fillmore and A. J. Vinnola,
Lockheed Martin Idaho Technologies**

The ATR was designed as a clover leaf shaped (in the horizontal plane), multi-flux trap reactor to meet demands of experimenters. The design develops a relatively long (4 feet) region with intense neutron flux. The magnitude and uniformity of the thermal neutron flux was not attainable with any other design concept. The high power density required to produce the design flux necessitated a maximum heat transfer area and coolant velocity within the fuel assembly. Thermal hydraulics optimization, within the limits set by corrosion rates and mechanical strength, resulted in a fuel assembly containing 19 fuel plates separated by 0.078-inch coolant channels. The channel spacing tolerance was important due to heat transfer considerations and because of differential mechanical forces acting on a fuel plate separated by two unequal coolant channels. The ATR design concept hinged on the ability to produce a fuel assembly capable of withstanding the thermal hydraulic stresses. Realizing this, and because the fuel assembly was a new shape (wedge) that required tighter tolerances over longer length than any previously fabricated, the Atomic Energy Commission (AEC) funded an extensive development program at Oak Ridge National Laboratory (ORNL). The program was to determine the attainable mechanical tolerances, establish processing methods for fabricating and forming the curved fuel plates, and for attaching the fuel plates to the side plates in such a manner as to minimize channel gap variation and maximize the mechanical integrity of the fuel assembly.

The development program produced acceptable fuel plates using the picture frame assembly technique, rolled to the proper thickness, and formed to curvature. Fuel plates were roll swaged into side plates. The quality of the roll swaged joint is a function of the depth of the side plate grooves (fuel plate / side plate engagement) and the force applied to the swaging wheel.

This evolutionary design was tested at INEL in the HTF, adapted for testing prototype ATR fuel assemblies. The HTF circulated demineralized water through the element at 120% of the ATR flow rate, approximately 1000 gpm, and $340^{\circ}\text{F} \pm 10^{\circ}\text{F}$ creating a pressure drop of approximately 145 psi axially across the element. This demonstrated the mechanical stability and integrity of the fuel elements and created a desirable particular form of aluminum oxide (Boehmite) on the fuel plates in order to improve heat transfer rates. Extensive hydraulic tests were performed to determine whether the design of the fuel element would meet the severe operating requirements of the ATR. Hydraulic tests led to adoption of a fuel element design with a slotted side plate that equalized pressure among coolant channels.

There has not been a mechanical failure of the finalized design of the ATR fuel assembly during the 26 years of successful reactor operation. Nor has there been a failure in the HTF, during proof testing of this final design using the fabrication process controls contained in approved specifications and procedures.

3. INTRODUCTION

This report documents analyses and evaluations performed on the swaged connections between side plates and fuel plates of ATR fuel elements. Prior to July 1994, each fuel element was placed in the HTF prior to loading in the reactor. The intent of the investigations presented here is to provide justification that the structural integrity of the swaged connections can be sufficiently assured within the manufacturer's processes instead of individual testing of each element. The justification is based to a large extent on pull tests and other inspections currently performed by the manufacturer, Babcock and Wilcox (B&W), as part of the swaging procedures. Additional inspections and process controls recommended in this report provide added assurance that the swaged connections meet or exceed the minimum strength requirements.

A standard for acceptability of the swaged connections has been previously established that requires the swaged connections to have a minimum pullout load capacity of 150 lb/in. of side plate length (Refs. 1 and 2). The pullout load is the force required to fail the connection when the force is applied perpendicular to the side plate and essentially parallel to the fuel plate. The approach used in this study was to perform finite element analyses using the ABAQUS (Ref. 3) computer code to simulate the swaged connection between the side plates and fuel plates. The model was first demonstrated to produce pullout loads from the analysis similar in magnitude to those measured by B&W in their pull tests. Once a suitable ABAQUS model was developed, it was used to assess the sensitivity of the pullout load to several parameters: (1) the position of the fuel plate within the fuel element, (2) the size of the gap in the side plate grooves, (3) depth of engagement of the fuel plate into the side plate groove, (4) the location and possible tilt of the swage wheel, (5) wear of the swage wheel surface, and (6) the manufacturer's dimensional tolerances in the fuel plate thickness and side plate grooves. To assess the effects of the fuel plate position within the fuel element, models were developed for three different fuel plates among the nineteen fuel plates in an element. These included the two end fuel plates and a center fuel plate, all of which are tested in B&W's pullout testing program.

A primary result of the calculations is that the pullout capacities of the swaged connections are relatively insensitive to variations in the parameters listed above when criteria specified in B&W's procedures are met. The investigations, though, have resulted in several recommendations (see Section 9) to be added to the swaging process at B&W's plant. Adding these inspections to the procedures already followed by B&W essentially precludes the failure of a swaged connection at a pullout load lower than the acceptable value of 150 lb/in.

The use of the I-DEAS solid modeling and finite element meshing software (Ref. 4) on the INEL CAE system and the CRAY computer time provided by the INEL at no cost to the project greatly facilitated this study. Non-linear analyses typically use large amounts of computer processing time and disk storage. Well over 200 hrs of CRAY CPU time were involved in this project.

4. EXISTING QUALITY INSPECTIONS IN ATR FUEL MANUFACTURER'S SWAGING PROCEDURES

The ATR fuel manufacturer established an operational procedure (Ref. 5) for swaging fuel elements to assure repeatability and uniformity of the process. A testing procedure (Ref. 6) is used to qualify the process. These two procedures will be referred to collectively in this report as QA procedures. The specific quality inspections relating to swaged joint strength that are currently included in these procedures are listed below.

4.1. Procedure OP No. 6101, "Operation Procedure Swaging Fuel Element (ATR)", (Ref. 5)

The scope of OP No. 6101 Rev. 5 is, "To insure swaging operations are performed in a uniform and consistent manner." The following parameters are set and/or verified for production swaging:

- (1) General instructions and preliminary verification of equipment and tooling (Sections 2.0 and 3.0)
 - (a) Swage wheels free of nicks and excessive wear.
 - (b) Swage wheel height from the fixture base (+/- 0.001").
 - (c) Distance between swage wheel and swage bed sides (+/- 0.0005").
 - (d) Carriage limit switches (min 0.045" past either end).
 - (e) Clearance between the carriage rollers and fixture base (within 0.001" or 0.002" if drag occurs).
 - (f) Carriage speed (25, +/- 5 in. per min).
 - (g) Accumulator pressure gage setting (450 +/- 5 psi) and calibration (within 1%).
 - (h) Comparison of digital pressure gage to accumulator pressure gage.
- (2) Process control test samples and requalification (Section 4.0)
 - (a) A Type E sample, as defined and required by ATR fuel manufacturing specifications, is prepared and a tensile test is performed before swaging the first element after equipment start up and after every tenth element. Location of the sample zone position (forward, center, or aft of element) is rotated.
 - (b) Equipment requalification is performed whenever swaging equipment repairs are made, materials/processes are changed, or the equipment

has not been used for 60 calendar days. For requalification, at least one each of swaged samples Type A, B, C, and D, as defined and required by ATR fuel manufacturing specifications, are tested.

(3) Production procedure (Section 4.5)

- (a) Groove closure is monitored against closure limits for every fifth fuel element swaged (forward end only). These are measured in the area where the swage wheel runs past the end of the fuel plate. The procedure states that the average closures are 0.007" less than the nominal fuel plate thickness. Closure limits (maximum allowed) are:

Side Plate Groove Position	Closure Limits
1	0.075"
2 – 18	0.045"
19	0.095"

Note that the closure is referred to in this report as the gap remaining in the side plate grooves after swaging.

- (b) Side plates and fuel plates are free of nicks and burrs. Swage fixture is clean.
- (c) Position of clamps (within 0.001") and side plate end alignment.
- (d) Fuel plate edges are dressed with chamfer if necessary. Verify maximum chamfer (0.005" x 0.005") is not exceeded.
- (e) Fuel plate crown height.
- (f) Comparison of fuel plate with step gage (must be within 0.002").
- (g) Swage tension roller is reset for ultimate channel spacing (channel spacing and parallelism per Drawing 20001).
- (h) Pressure (450 +/- 5 psi).
- (i) Arc height at three locations.
- (j) Visually examine the entire swaged area. If any non-swaged areas are detected, swage again.

(4) Swage head maintenance (Section 5)

- (a) Swage head and wheel assembly is inspected every 6 months. The inspection includes the swage wheel and wheel pins for wear, distortion, etc.).
- (b) All relevant data including actual dimensions are recorded when preventive maintenance is performed.

4.2. Procedure OP No. 6325, "Tensile Sample of Bond at Side Plate to Fuel Plate (ATR)", (Ref. 6)

OP No. 6325, Rev. 1, "...defines the methods and acceptance criteria to be used by Quality Control and Quality Engineering in the verification of ATR element fuel section assemblies of tensile testing." From OP No. 6325, the following parameters are set and/or verified for each test sample:

- (1) Procedure (Section 3)
 - (a) Plates are in proper sequence.
 - (b) No loose plates.
 - (c) Visually examine for any land shearing at the swaged joint.
 - (d) Joint strengths are at least 150 lbs/in.
- (2) Requalification and process controls (Sections 4 and 6)
 - (a) Requalification is performed whenever swaging equipment repairs are made, materials/processes are changed, the equipment has not been used for 60 calendar days, or if a sample fails.
 - (b) Type E samples are prepared and tensile tests performed before swaging the first element and a minimum of every tenth element. If less than ten elements are processed, a Type E sample is tested at the end of the production run.

5. MANUFACTURING PROCESS VARIABLES AFFECTING INTEGRITY OF SWAGED CONNECTIONS

During the manufacturing process, samples of the swaged connections are tested to assure that a minimum pullout load capacity of 150 lb per inch of side plate length is maintained. Based on early considerations of the swaged connections (Ref. 1) and on ATR operational experience, if the swaged connections in an ATR fuel element can sustain a pullout force of this magnitude, they can also sustain the loading conditions experienced during reactor operation. Using this acceptance criteria, there have been no failures of swaged connections in B&W fuel elements in either the HTF or in the ATR reactor since B&W first began to manufacture the elements in 1985.

Details of the fuel element and swaged joint geometry with terms used in this report are shown in Figs. 1 and 2. An examination of the manufacturer's QA procedures, drawings, and other information relating to the swaging process revealed the following variables that could affect the pullout load:

- (1) **Position of the fuel plate within the fuel element** – There are a total of 19 fuel plate positions in a fuel element.
- (2) **Remaining gap in the side plate grooves** – The gap is defined to be the remaining distance between the surfaces in the side plate groove that contact the fuel plate after swaging. Thus, a larger gap value corresponds to a larger opening as shown in Fig. 2. The gap is directly related to the swaging wheel pump pressure such that the greater the force or energy supplied to the swaging wheel, the smaller this gap becomes. In the manufacturing process, the gap is controlled in the swaging procedure by regulating the pump pressure to 450 psig $\pm$ 5 psi. The gap is measured in the manufacturer's QA procedure with a pin gauge in the area where the swage wheel runs past the end of the fuel plate. Note that the QA procedures currently refer to the gap as the closure.
- (3) **Depth of engagement of the fuel plate into the side plate groove** – In a worst case, if there were little or no engagement of the fuel plate into the side plate groove, the connection would not be able to sustain a pullout force and would certainly fail in the HTF.
- (4) **Location and possible tilt of the swage wheel** – The manufacturer's procedure is to place the wheel as near to the side plate landing as possible without the side of the wheel contacting the side plate. It is considered possible, though, that the wheel could be located some distance out from the landing. There is also some potential for wear in the pin to which the wheel is attached, which may cause tilting of the wheel from its normal 45° alignment with a vertical plane. This tilting of the wheel could have some effect on the pullout capacity of the joint.

- (5) **Wear of the wheel surface** – The wheel surface that contacts the side plate lip during the swaging process is much harder (RC 56–59) than the aluminum used in the side plate. With enough applications, however, the wheel surface could show some wear. In this case, the wheel may not contact the side plate lip with its full nominal width.
- (6) **Manufacturer's tolerances** – The tolerances in the dimensions of the side plate grooves and the thicknesses of the fuel plates cause variations in the geometry of the swaged connections.

The sensitivity of the pullout load capacity of a joint to variations in these parameters was determined in the analyses described below. In the analyses, these parameters were allowed to vary to their extremes to encompass the worst case possibilities. In some cases, variations in two or more parameters were considered simultaneously to capture coupling effects among the parameters. The differing fuel plate positions within an element were considered by analyzing the two end fuel plates (positions 1 and 19) and one intermediate fuel plate (position 9). The two end fuel plates are much thicker than the 17 intermediate fuel plates. Fuel plate 9 was considered to be representative of the other intermediate fuel plates.

Figure 1 . Details of ATR Fuel Element

Figure 2 . Details of ATR Fuel Element Swaged Joint

6. FINITE ELEMENT ANALYSIS METHODS AND MODELS

6.1. Analysis Assumptions and Definitions

The swaged connections were modeled in two dimensions with the basic assumption that deformations in the third dimension (along the length of the fuel element) are near zero. This assumption, plane strain, is most appropriate for the class of problems where the deformed body is very large in the third dimension and the forces applied do not vary along the length. The swaging process is, of course, a three dimensional problem with the swage wheel moving along the joint during the swaging process rather than being applied uniformly. The plane strain assumption, however, is valid since: (1) the deformations out of the cross-sections are small due to the existing surrounding material which generally remains elastic and (2) the results are calibrated with actual test data. The assumption of plane strain greatly simplifies the problem, making this study reasonable in terms of available computer resources.

A complete description of the elastic-plastic strain theory used in these analyses is given in the ABAQUS theory manuals (Ref. 3). The following widely accepted analytical modeling characteristics were used here to represent the deformation of the aluminum:

- (1) Isotropic elastic, isotropic material hardening, and Von Mises yield and flow behavior.
- (2) No volumetric plastic strain (incompressible).
- (3) Strain rate independent (constitutive response does not depend on the rate of deformation).
- (4) Elastic strains are small.
- (5) Updated Lagrangian incremental formulation of large deformation and continuity equations.

The following selected terminology is used in this report:

- (1) **Nominal or engineering stress.**

$$\sigma_{nom} = \frac{P}{A_0}$$

where, P = force distributed over cross-section
 A_0 = undeformed cross-sectional area

Nominal stress does not account for the reduction in cross-sectional area that occurs in ductile materials.

(2) **True or Cauchy stress.**

$$\sigma = \frac{P}{A}$$

where, P = force distributed over cross-section
 A = reduced cross-sectional area

True stress does account for the reduction in cross-sectional area.

(3) **Nominal or engineering strain.**

$$\epsilon_{nom} = \frac{\Delta}{L_o}$$

where, Δ = total elongation
 L_o = original length.

Nominal strain does not recognize that the length is continuously changing, which is important in large deformations.

(4) **True or logarithmic strain.**

$$\epsilon = \int_{L_o}^{L_o + \Delta} \frac{dl}{l} = \ln \left(1 + \frac{\Delta}{L_o} \right)$$

where, l = integration variable for length

True strain does account for a continuously changing length.

(5) **Total strain energy.**

*all recoverable strain energy (elastic) +
all energy dissipated in time independent plastic deformation.*

Total strain energy is a direct measure of the work done during swaging.

(6) Von Mises stress.

$$q = \int \sqrt{\frac{3}{2}} \mathbf{S} : \mathbf{S}$$

where, $\mathbf{S} : \mathbf{S}$ is the contraction of the true (Cauchy) deviatoric stress tensor. Von Mises stress is based on a well accepted yield criterion using the assumption that yielding first begins when the distortional strain energy density attains a critical value. The distortional strain energy is the energy associated with stresses that deviate from a hydrostatic stress condition.

(7) Equivalent plastic strain.

$$e = \int \sqrt{\frac{2}{3}} d\epsilon^{pl} : d\epsilon^{pl}$$

where, $d\epsilon^{pl} : d\epsilon^{pl}$ is the contraction of the differential logarithmic plastic strain tensor. Equivalent plastic strain is the total accumulation of plastic strain used in the isotropic hardening plasticity theory to define the yield surface size.

6.2. Material Properties

The analyses required the determination of the elastic and plastic properties for the materials involved. The side plates in the ATR fuel elements manufactured by B&W are machined from 6061 T6 aluminum, while the fuel plates are 6061 T0 or T6 aluminum, which is significantly altered during the forming and annealing process. Material properties for the unaltered 6061 T6 aluminum used in the side plates were obtained from results of tests performed by Kaiser Aluminum and Chemical Corporation (Ref. 7). In these tests, four specimens were tensile tested to failure. Average properties for the four specimens were used in the analyses. The properties for the fuel plate material after fabrication had to account for alterations due to forming of the fuel plates and were obtained from tensile tests performed at the INEL on actual fuel plate samples. Details of these data are described below.

The elastic properties consist of Young's modulus and Poisson's ratio values. Plastic properties are input to ABAQUS in the form of a complete stress – strain curve using true stress and true strain, which are related to the nominal or engineering stress and strain as follows:

$$\sigma = \sigma_{nom}(1 + \epsilon_{nom})$$

$$\epsilon = \ln(1 + \epsilon_{nom})$$

The first of these equations assumes that there is no volumetric change in the material during plastic deformation. The properties used as input to the ABAQUS models and the corresponding nominal values are listed in Table 1 .

Table 1 .Basic Material Properties

Material	Young's Modulus, KSI	Poisson's Ratio	Yield Stress (KSI) and Corresponding Strain (in./in.)	Maximum Stress (KSI) and Corresponding Strain (in./in.)
Fuel Plate 6061 T0 or T6 Altered Aluminum	10,100	0.33	14.45, 0.002 nominal (14.48, 0.002 true)	20.90, 0.09 nominal (22.78, 0.086 true)
Side Plate 6061 T6 Aluminum	10,100	0.33	43.77, 0.002 nominal (43.86, 0.002 true)	47.50, 0.09 nominal (51.78, 0.086 true)

Four points were used to describe the true stress – true strain curve in the ABAQUS analysis. These points are based on the following assumptions: (1) the elastic region ends at approximately 75% of the yield stress, (2) the yield stress is reached at a strain of 0.002, (3) the maximum value for engineering (nominal) stress is reached at a strain of 0.09, and (4) the true stress levels at a true strain of 1.0 are approximately 50,000

psi for the fuel plates and 100,000 for the side plates. This model helped ease the material into the plastic regime, which allowed for a smoother convergence of the ABAQUS finite element solutions.

6.2.1 Side Plate Material

A sample load–elongation curve provided by Kaiser for a uniaxial tensile test on one of the test specimens is shown in Fig. 3. The elongations must be divided by 2 in. (for gauge length), then multiplied by 100, to get the elongation in percent. The load essentially flattens out at slightly less than 6000 lb once the material goes plastic. This specimen had an initial cross-sectional area of 0.127 in.², which gave a peak nominal tensile stress of 46,000 psi. Average values for the peak nominal stress and corresponding strain in the four specimens are approximately 47,500 psi stress at 0.09 strain. At strain values beyond 0.09, the nominal plastic stress was assumed to decrease slightly with increasing strain (true stress still is increasing).

Figure 3. Load–Elongation Curve for Aluminum 6061–T6
Data from Refs. 7 and 8

The stress-strain values were input to the analyses without a limit on strain values. It is not practical to limit the strain in the analyses since the strain limit at each point in a model depends on the stress state at that point. Unless the stress state is very uniform throughout the model, strain levels can only be evaluated after the analysis is complete. A strain limit is of significance in this application because it is possible to overstrain the contact lip on the side plate such that it fails along a shear plane as shown in Fig. 4. A limit on the strain then limits how much the wheel can be pressed into the side plate during the swaging process. An ultimate strain value for the uniaxial tensile tests performed by Kaiser cannot be obtained directly from the load-elongation curves provided. This strain value had to be determined by measuring the reduced area in the necked down region of the test specimens. Such measurements were made by W. Reuter of the INEL (Ref. 8), who reported an average reduced area at fracture of 0.0872 in.² for the four specimens. It is readily shown that the corresponding true strain is found from

$$\epsilon = \ln \frac{A_0}{A}$$

where

A_0 = undeformed cross-sectional area of test specimen

A = reduced cross-sectional area.

Figure 4 . Location of Shear Plane on Side Plate Lip

This equation again is based on the assumption that there is no volumetric change in the material during plastic deformation. Since the four test specimens had an initial average area of 0.1284 in.², the average fracture strain in uniaxial tension for the four specimens was 39%. Because the material in the highly strained region of the side plate is in a multiaxial state of stress, it is not likely to actually fail at a strain of 39%.

The subject of establishing limits on strain for biaxial stress states has been studied extensively for the forming of sheet metal. These forming processes are generally concerned with a state of plane stress with stresses in the plane of the sheet. The strain limits for a particular material are determined either experimentally or analytically and are presented in a 'forming limit diagram' (FLD). In an FLD, the limiting major principal strain is plotted as a function of the minor principal strain. A typical FLD is composed of a right- and a left-hand side as shown in Fig. 5. The FLD shown is taken from Ref. 9 and corresponds to aluminum 2036-T4. On the right-hand side, the state of stress is one of biaxial stretching where the major and minor strains are positive. On the left-hand side, the major strain is positive but the minor strain is negative. The two sides are divided by a state of plane strain where the minor strain in the plane of the sheet is zero. In a state of uniaxial tension in an isotropic material, as in Kaiser's tests, the minor strain is negative and has a magnitude one-half that of the major strain. The state of uniaxial tension is located at the far left on a typical FLD. This is to be expected since a forming process generally imposes a state of biaxial tension and all states of biaxial tension would lie to the right of uniaxial tension on an FLD.

Figure 5 . Forming Limit Diagram for Aluminum 2036-T4

Because the FLDs are developed for forming of sheet metal and generally consider only biaxial tensile stress states, they cannot be used to establish a precise limit on strain for swaging of the ATR fuel elements. They do indicate trends, though, that provide a lower bound for the failure strains in the critical portion of the side plate. This requires an assessment of the state of stress in this portion of the side plate. Ignoring the axial component of stress (which is discussed in Section 7.2.2), the calculations presented in Appendix B show that the material in this region is in a state of stress in which the minor principal stress is compressive while the major principal stress is tensile. This would make for a large negative minor strain, which puts this material to the left of uniaxial tension on an FLD. The general trend on an FLD, as shown in Fig. 5, is that the limit strain increases as the minor strain becomes more negative. Thus, the fact that the material in the critical portion of the side plate is in a stress state to the left of uniaxial tension on an FLD should mean that the limit strain is greater than it would be in uniaxial tension. The material in the critical portion of the side plate, then, should have a failure strain greater than the 39% established in the uniaxial tension tests. This level of strain is used to assess strain magnitudes calculated in the analyses in this report.

6.2.2 Fuel Plate Material

The properties of the aluminum used for the fuel plates are significantly altered by the fabrication process, which includes rolling and annealing steps. The material properties used here were adapted from tensile tests performed at the INEL on actual fuel plate samples (Refs. 8 and 10). The precise strain levels at yield and maximum nominal stresses were not available and were assumed to be the same as the 6061 T6 material.

6.3. Analysis Procedure

The swaging process was simulated in finite element analyses using the ABAQUS program (Ref. 3) run on the INEL CRAY computer. ABAQUS is a general purpose finite element analysis program having the nonlinear capabilities needed to analyze the swaging process and to subsequently determine the pullout capacity of the connection. All model generation was done using the I-DEAS solid modeling and finite element meshing software (Ref. 4). The analyses were generally conducted in the following steps:

- (1) The first step simulated the swaging process for the side plate only, without a fuel plate in the groove. Note that the gap in the side plate groove is measured during the manufacturing process at a location just beyond the fuel plate where the side plate groove is empty. The swage wheel travels a short distance (0.045" minimum, about 1/2" in practice) past the fuel plate during the swaging process. The swage wheel, treated as a rigid surface, was analytically pressed into the side plate contact lip until predetermined gap values were reached. Wheel movement in the analysis was controlled by imposing a steadily increasing displacement of the wheel into the side plate. The total strain energy level associated with each gap value was monitored. In this step, material in the side plate beneath the swage wheel incurred significant plastic deformation such that the nonlinear capabilities of ABAQUS were necessary.
- (2) The next step simulated the swage process with a fuel plate in the side plate groove. Using an undeformed model, the swage wheel was pressed into the side plate contact lip such that the lip engaged the fuel plate. The wheel displacement continued until the system reached the total strain energy level associated with the gap values calculated in step 1. Material in both the side plate and fuel plate beneath the swage wheel incurred significant plastic deformation in this step.
- (3) Next, the swage wheel was withdrawn from the swaged connection by fixing all nodes and removing the rigid surface.
- (4) The fuel plate was then cut (elements and associated restraints were removed) so that a pullout load could be applied essentially in the plane of the fuel plate near the swaged connection. The finite element model in step 2 included one half of the fuel plate so that symmetrical boundary conditions could be used during the swaging process. Because of the curvature of the fuel plate, a pullout load applied to the end of the fuel plate would be offset from the plane of the swaged joint. In the manufacturer's pullout load tests, the fuel plates are flattened in a vise prior to the test, which minimizes the effects of the fuel plate curvature. Cutting the fuel plate in the analysis, after the swaging process calculation, similarly minimized the effect of the fuel plate curvature.

- (5) Finally, a load was applied to the end of the fuel plate to determine the pullout capacity of the joint. The load was increased incrementally in the analysis from an initial value of zero to the load where the joint failed (described in Section 7).

As mentioned above, the displacement of the swage wheel into the side plate was incrementally increased in the analysis until the system reached a specified strain energy level. The energy level specified in a particular analysis depended on the desired gap of the side plate groove. The gap is the width of the groove (see Fig. 2) after swaging is complete, as measured in the area where the wheel runs past the end of the fuel plate. This is not the same as the gap in the groove in the region where the fuel plate is present. This required that a separate analysis (Step 1) be performed on the swaging process where the fuel plate was absent. In this analysis, the wheel was displaced into the side plate until the desired groove gap was attained. The energy level (as calculated by ABAQUS) at which this gap was reached was then used as the specified energy level in the corresponding analysis where the fuel plate was present. At these energy levels, most of the energy was in the form of plastic deformation (typically 90 to 94%).

Since the analyses for Steps 1 and 2 are incremental in nature, some interpolation between the discrete energy levels was necessary. Fig. 6 shows the linear relationship between groove gap and total strain energy for side plate groove 9. Similar plots were prepared for all models showing that linear interpolation is appropriate.

Prior to using the ABAQUS model to assess the sensitivities to variations in the process variables listed above, the model was to be calibrated against actual results obtained by B&W from their pull tests. The calibrations were to be made on a model using nominal values for all the process variables considered in the sensitivity evaluations. There are basically two quantities that can be adjusted in a calibration of the model. These are: (1) the maximum shear stress that can be sustained by the material at the surface of the fuel plate that is in contact with the side plate, and (2) the coefficient of friction between the contacting surfaces of the fuel plate and side plate. The maximum shear stress was initially set to a value equal to about one-half of the ultimate tensile stress of the fuel plate material, or 10,000 psi. The coefficient of friction was set equal to one, based on an expected value for friction involving contact between aluminum surfaces (Ref. 11). In Table 2, results obtained from analyses of typical swaged connections using these two quantities are compared with actual pull test results for fuel plates. Since the analytical results correlate well with the test results, there were no adjustments made to the maximum shear stress or the coefficient of friction to calibrate the models. Of primary interest in this study are the relative effects that variations in the parameters investigated have on the pullout forces. Thus, the models do not have to produce precise values for the absolute magnitude of the pullout forces.

Table 2 .Comparison of B & W Tensile Tests with Analytical Results

Fuel Plate Location	Average of 150 Tensile Tests at B & W, Sample E, 10/91 to 9/93	Range of Tensile Strength Predicted by ABAQUS Models using the Nominal Configuration and Gaps ± 0.002 in of Nominal
Fuel Plate 1	513 lbs / in.	522 – 643 lbs / in.
Fuel Plate 9	492 lbs / in.	518 – 602 lbs / in.
Fuel Plate 19	560 lbs / in.	445 – 552 lbs / in.

In the sensitivity analyses, the parameters were varied to their extremes to encompass the worst case possibilities. In several cases, two or more parameters were varied simultaneously to capture coupling effects among variations in the parameters. Therefore, a matrix of the analyses performed was prepared as described in Appendix C.

As stated above, the finite element analyses of this study were performed using the ABAQUS, Version 5.2, computer code. ABAQUS is a general purpose code having nonlinear capabilities and an extensive element library. It is also capable of treating large deformations such as those experienced in the swaging of ATR fuel elements. The code has had wide industrial use and has been tested on numerous documented sample problems (Ref. 3). Because of the complexity of the models used to simulate the swaging process, convergence problems were encountered in some of the solutions. On two occasions, personnel from Hibbitt, Karlsson, and Sorensen, Inc. (HKS) scrutinized the models to recommend adjustments that would facilitate convergence. The scrutiny provided by HKS, writers of the ABAQUS code, served as a good independent check on the modeling methods used. Further verification of the finite element models used comes from a comparison of a calculated deformed shape with a deformed shape produced in the actual swaging process as discussed below.

Figure 6 . Plot of Total Strain Energy vers Gap for Side Plate Groove 9 (No Fuel Plate)

6.4. Finite Element Models

The geometry of the three fuel plates and associated side plate sections analyzed is shown in Fig. 7 . All dimensions were taken from the drawings (Ref. 12) and are shown in detail in Appendix A. Three basic 2-D finite element models shown in Figs. 8 – 10 were used to simulate the swaging process. Details of the model for fuel plate 9 are shown in Fig. 11 identifying the various element types and the tension loads used to simulate the pull tests. Note that only one half of the fuel plate was modeled due to symmetry. Linear 4-node plane strain elements were used to model the fuel and side plate material. The swaging wheel was modeled as a rigid surface that is analytically displaced into the side plate continuously through the solution. A rigid surface is an unchanging geometric shape that can be incrementally displaced during the solution. The corresponding contact surface on the deforming body is covered with interface elements to model the interaction with the rigid surface. A rigid beam element was attached to the rigid surface to monitor the calculated force required to displace the wheel.

The interfaces between the fuel and side plate were modeled using slide line elements. Slide line elements are constructed using nodes on one interacting surface (fuel plate) that are associated with slide lines made up of connected nodes on a second interacting surface (side plate). Contact between the two surfaces is allowed but penetration is not. The slide line elements also allow the user to specify the coefficient of friction and maximum shear stress at the points of contact.

Symmetry boundary conditions were used at the fuel plate nodes that represent the mid-points. The nodes surrounding the side plate exterior, where the material is held either by the swaging fixture or the surrounding material in the case of side plate groove 9, were fixed in translation (see Fig. 11).

The deformations for three gap values for fuel plate 9 in the nominal configuration are shown in Figs. 12 – 14 . For comparison, a photograph of a cut-away of a typical swaged joint is shown in Fig. 15 . The deformed shapes predicted by analysis correlate well with those of an actual swaged joint.

To evaluate the effects of the manufacturing process variables or sensitivities discussed in Section 5, the three basic models were modified as outlined below:

- (1) **Position of the fuel plate within the fuel element.** The three basic models evaluate a range of fuel plate locations within the fuel element. The end fuel plates 1 and 19 were analyzed due to their unique geometry and the fact that they are considerably thicker than the 17 interior fuel plates. Fuel plate 9 was chosen to represent the interior fuel plates since tension test samples routinely include this fuel plate.
- (2) **Remaining gap in the side plate grooves.** The three basic models using nominal dimensions and swage wheel location were analyzed for a wide range of groove gap values to examine the relationship of this parameter to the tensile strength of the swaged joint. This range exceeds the range of values encountered in normal production. All other models

were evaluated at least for the maximum allowable gap, the average gap as defined in the QA procedures, and a gap of 3 mils less than the average (see further discussion in Section 7.2).

- (3) **Depth of engagement of the fuel plate into the side plate groove.** A range of depth of engagements that exceeds the range expected during production was evaluated as shown in Figs. 16 – 17 for all three fuel plate locations.
- (4) **Location and possible tilt of the swage wheel.** The range of possible wheel positions are shown in Fig. 18 . To evaluate the effects of possible wheel tilt, the wheel was rotated ± 5 degrees. These were evaluated only for fuel plate 9.
- (5) **Wear of the wheel surface.** Wheel wear was simulated by reducing the wheel width by 20% as shown in Fig 18 . Wheel wear was evaluated only for fuel plate 9.
- (6) **Manufacturer's tolerances.** Two variations (based on allowable tolerances listed in the drawings and QA procedures) of the basic model for fuel plate 9 were evaluated. General details are shown in Fig. 19 and specific dimensions are shown in Appendix A. Note that the tolerances listed on the drawings allow for a fuel plate to side plate groove interference fit. Since this case could not be analyzed accurately here, a slide plate groove dimension of 1 mil greater than the minimum allowed on the drawings was used. The installation procedure does prevent the forced installation of fuel plates so an interference fit should not be possible.

Several comparisons are made in these analyses with results from the nominal model or configuration for fuel plate 9. The nominal model is defined here to be the basic model for fuel plate 9 (Fig. 9) with: (1) the fuel plate fully inserted (F1 in Fig. 17), (2) the swage wheel in the mid position (W1 in Fig.18), and (3) with nominal groove, plate, and wheel dimensions from the drawings (see Appendix A).

Two other conditions were examined using the basic model for fuel plate 9. Fig. 20 shows the model used to evaluate the effects of a somewhat curved tensile test sample. When the samples are prepared by B & W, the fuel plates are flattened as much as is practical. Some curvature may remain, however, and this model was designed to test the effects of a larger amount of curvature.

The models shown in Fig. 21 were designed to test the joint under differential pressure loading across the fuel plate. Some differential pressure is possible in the HTF testing currently used to qualify the fuel elements. The pressure in these models was increased until the swaged joint began to slip. In addition, the deflections at the fuel plate 1/4 and 1/2 points were monitored to compare with allowable minimum fuel plate separation. These models are for fuel plate 9, where it is assumed that the joint was swaged just enough to meet B&W's specified maximum gap limit (45 mils) for the side plate groove. All other conditions were nominal.

Figure 7 . Swaging Model Geometry and Locations

Note that only half of the plates are modeled due to symmetry conditions at the midpoint. Shown to scale.

FUEL PLATE 1
Wheel Configuration W1
Fully Inserted Plate (F1)

Figure 8 . Basic FE Model of Fuel Plate 1 and Side Plate Groove 1

FUEL PLATE 9
Wheel Configuration W1
Fully Inserted Plate (F1)

Figure 9 . Basic FE Model of Fuel Plate 9 and Side Plate Groove 9

FUEL PLATE 19
Wheel Configuration W1
Fully Inserted Plate (F1)

Figure 10 . Basic FE Model of Fuel Plate 19 and Side Plate Groove 19

Figure 11 . Details of FE Model with Wheel W1 and Fuel Plate 9 Location F1 (Nominal Configuration)
A cut fuel plate with tension loads is shown. Note that the swage wheel is removed before the tension loads are applied.

ABAQUS

FUEL PLATE 9

45 Mil Gap

Deformation Shape to Scale

Figure 12. Deformed Shape Details after Swaging for 45 Mil Gap, Fuel Plate 9, Nominal Configuration

ABAQUS

FUEL PLATE 9

42 Mil Gap

Deformation Shape to Scale

Figure 13. Deformed Shape Details after Swaging for 42 Mil Gap, Fuel Plate 9, Nominal Configuration

ABAQUS

FUEL PLATE 9

39 Mil Gap

Deformation Shape to Scale

Figure 14 . Deformed Shape Details after Swaging for 39 Mil Gap, Fuel Plate 9, Nominal Configuration

Figure 15 . B & W Photograph of Typical Swage Joint

Figure 16 . Fuel Plate Configurations, Fuel Plates 1 and 19

Figure 17 . Fuel Plate Configurations, Fuel Plate 9

Figure 18 . Swage Wheel Configurations, Fuel Plate 9

Figure 19 . Fuel Plate Tolerance Configurations, Fuel Plate 9 with a fully inserted plate.
See also Appendix A.

FUEL PLATE 9
Wheel Configuration W1
Fully Inserted Plate (F1)

Figure 20 . Details Showing Offset Tension Load Case, Fuel Plate 9, Nominal Configuration

Figure 21 . Fuel Plate Differential Pressure Models, Fuel Plate 9, Nominal Configuration
The maximum allowable gap of 45 mils was used.

Note: The density of the pressure arrows shown is related only to the element density in the models. The pressures are uniform within each model.

7. RESULTS AND ASSESSMENTS OF SENSITIVITY CALCULATIONS

The results presented in this section are generally in the form of plots of predicted pullout force versus side plate groove gap for models with varying parameters as discussed in Section 6. The minimum allowable pullout force and the maximum allowable gap values, based on the current QA procedures, are also shown on these plots. The desirable or "safe" region is the lower right of each plot of this type.

Typical fuel plate displacement behavior during application of the tensile force is shown in Fig. 22 for fuel plate 9 using nominal conditions. Similar curves were produced for all models analyzed to determine the pullout load. Tension forces on the fuel plate were incrementally increased while the horizontal (X-direction in Fig. 11) displacement of a node within the fuel plate and far from the application of the loads was monitored. The state of the slide line interface elements was also monitored. ABAQUS output indicates whether the elements in contact are sticking or slipping. The displacement remains nearly linear within a region where the displacement is caused only by material deformation within the fuel plate. When fuel plate slippage begins to occur along the slide line elements, the slope of the displacement curve increases sharply. At a slightly higher tension load, the slope dramatically increases as the fuel plate slips out of the side plate groove. The ABAQUS analysis terminates at this point when large kinematic displacements begin. Joint failure is defined to occur at this tension load.

7.1. Position of the Fuel Plate within the Fuel Element

The three basic models evaluated here sample the range of the 19 fuel plate locations within the ATR fuel element. Fig. 23 shows the variation of predicted pullout force (tensile strength) with side plate groove gap for nominal models of the three fuel plates analyzed. For clarity, the data were normalized about the maximum allowable gap for each fuel plate since the fuel plate thickness ranges from nominally 49 mils for the interior 17 fuel plates to 99 mils for fuel plate 19 (see Appendix A). The data show that the behavior of the three fuel plates is very similar and that the location of the fuel plate does not significantly affect the strength of the swaged joint. This result applies for swaged joints with nominal dimensions and configurations for the fuel plate, side plate groove, and swage wheel.

7.2. Remaining Gap in the Side Plate Grooves

The range of groove gap values analyzed and the average gap values given in the QA procedures are shown in Table 3. As discussed in Section 6, the effect of side plate groove gap was addressed for all models by evaluating the pullout force for at least the maximum allowable gap, the average gap, and a gap of 3 mils less than the average. In addition, the three basic models and the F3 models (fuel spacing of 20 mils) were evaluated for a range of gap values that exceeds the range encountered in normal production. Since the analysis method employed displaced the swage wheel incrementally into the side plate material, data at a large number of gap values were

readily available.

Table 3 . Range of Side Plate Groove Gaps Analyzed

Fuel Plate Location	Range Evaluated for Basic Models	Maximum Allowable	Average	Average minus 3 mils
Fuel Plate 1	78.5 – 63 MILS	75 MILS	72 MILS	69 MILS
Fuel Plate 9	48.5 – 33 MILS	45 MILS	42 MILS	39 MILS
Fuel Plate 19	97.5 – 83 MILS	95 MILS	92 MILS	89 MILS

The data show that in almost all cases, the swaged joint pullout capacity reaches the minimum allowable of 150 lbs/in. well before the gap reaches the maximum value allowed in the B&W QA procedures. After contact is made between the side plate and fuel plate, the pullout capacity of the joint increases rapidly. Once the maximum allowable gap is attained, the pullout capacity far exceeds the minimum requirement of 150 lbs/in. With further decreases in the groove gap, however, the pullout capacity basically levels off. The pullout capacity of the joint is not particularly sensitive to decreases in the groove gap once the maximum allowable gap is achieved. Exceptions to this typical behavior are noted in the sections below. Two failure modes related to the side plate groove gap are considered here: (1) large side plate groove gap (inadequate pressure of the swage wheel) and (2) small groove gap that may lead to weakening of the side plate aluminum (excessive pressure of the swage wheel).

7.2.1 Potential for Inadequate Pressure of Swage Wheel

A primary concern is that each side plate groove be closed sufficiently during the swaging process. Per the QA procedures, this is monitored for each fifth production fuel element by comparing a measured groove gap with a specified groove gap upper limit. This check is intended to assure that the swage wheel delivers enough pressure to the side plate to attain a satisfactory joint. The results above show that the groove gap limits specified in the QA procedures result in a joint pullout capacity well in excess of the required 150 lb/in.

The groove gap actually attained in a joint is partly dependent on the pump pressure. As stated in the QA procedures, the accumulator pump pressure gage is set at 450 psi with a tolerance of ± 5 psi. The accumulator pressure gage is calibrated to within 1% and is compared with a digital pressure gage. The question arises as to how sensitive the joint pullout capacity is to variations in the pump pressure. Because the cylinder diameters are constant, the pump pressure is directly proportional to the force applied to the swage wheels. As discussed in Section 6.2, the finite element models contained a stiff beam attached to the swage wheel that allowed for a determination of force applied to the wheel throughout the analyses. Since the energy was also calculated at each increment of the analyses, the force can be related to the energy and, in turn, to the groove gap and pullout capacity.

Fig. 24 shows a plot relating the wheel force to the pullout capacity for fuel plate 9 with all parameters at their nominal values. It must be noted that the absolute magnitude of the calculated wheel force shown in Fig. 24 does not equal the actual force on a wheel because the model had a unit (1-in.) length. What is important is the slope of the curve plotted, which shows how sensitive the pullout capacity is to changes in the wheel force and hence the pump pressure. In the range of interest (pullout force ~ 500 lb), a 1% change in the wheel force translates to a 1.5% change in pullout capacity. Since the current QA procedures limit the pressure variation to about 2% (tolerance plus calibration error), the maximum variation in pump pressure permitted by the current QA procedure should cause no more than a 3% loss of pullout capacity for a swaged connection.

7.2.2 Potential for Excessive Pressure of Swage Wheel

A second concern is that a swage wheel may be pressured to a point where the side plate lip fails, which would render the joint ineffective. Failure would be a shearing of the wheel through the side plate as shown in Fig. 4, which would occur when the strain levels in the side plate become excessive.

The ABAQUS analyses performed were capable of calculating strain levels throughout the swaging process. However, because the models did not limit the strain values in the analyses, it is not possible to ascertain from the analysis results alone when failure would occur. A difficulty in determining the failure strain is that it is a function of the multiaxial stress state of the material. This has been a subject of investigation in the metalworking industry for many years. As stated in Section 6.2, the strain limits for any particular material in a biaxial stress state are generally presented in a FLD. An FLD is either determined experimentally or is approximated analytically. Because metal forming generally involves a stress state of biaxial tension in a sheet, these forming limit diagrams focus on strain limits corresponding to such stress states. As stated in Section 6.2 and shown in Appendix B, the stress states along the failure plane of the side plate have tension in the major principal direction and significant compression in the minor principal direction. Therefore, an FLD would not provide an accurate strain limit for the side plate material in the swaging process and a theoretical approximation would not be fully credible without experimental verification. The trends displayed in a typical FLD for an aluminum alloy, however, show that the failure strain for the biaxial stress state of tension and compression should be significantly higher than for the case of uniaxial tension. Test results provided by the Kaiser Aluminum and Chemical Company indicate that the failure strain in uniaxial tension for the side plate material (aluminum 6061-T6) is about 39%. Therefore, the failure strain in the highly strained region of the side plate should exceed 39%.

It is noted that there is a third component of stress (along the axis of the fuel element) not discussed above. Stress contours for this out-of-plane stress, corresponding to nominal conditions in fuel plate 9, are shown in Fig. 25. In the critical region of the side plate, this is a fairly uniform compressive stress in the range of about 0 to 25,000 psi. Since this stress would have a confining effect on the material in this region, it should

delay the onset of failure in the side plate lip. The axial stress should, therefore, further increase the limiting strain for the material.

An example of a stress distribution predicted by the ABAQUS models is shown with stress contours in Fig. 26 , indicating that the highest stresses in the side plate occur directly under the inner edge of the swage wheel. The strain contours for five different gaps of the side plate groove are presented in Figs. 27 – 31 . The strain plotted is the equivalent plastic strain, which allows for a direct comparison of strain levels among uniaxial and multiaxial stress states. The results were obtained from analysis of fuel plate 9, where all swaging parameters were set at nominal values and the fuel plate was fully inserted into the side plate groove. These clearly indicate that the highest strains occur in the region of the shear plane identified in Fig. 4 . Referring to Fig. 29 , which represents an average gap of the side plate groove (42 mils), the calculated strain levels exceed 40% in a portion of the critical region and reach about 100% in a local area directly beneath the edge of the wheel. These results indicate that the strain levels do exceed 40% without failure of the material, in agreement with what is stated above. This conclusion can be reached because the side plates do not, in practice, fail at the average groove gap of 42 mils. The results also indicate that, because of the very high strains directly beneath the edge of the wheel, there is likely to be some local material failure in this area.

Fig. 27 presents the strain levels for the nominal model of fuel plate 9 when the groove gap has closed to 48.5 mils. Since the fuel plate has a thickness of 49 mils, the side plate has just contacted the fuel plate. Prior to this time in the swaging process, essentially all of the energy has gone into deformations in the critical region of the side plate (shear plane identified in Fig. 4) and strains in this region have already increased to significant levels. Fig. 28 shows that strains continue to progress rapidly in the critical region as the gap is closed to 45 mils. As shown in Figs. 29 – 31 , the strain development in the critical region of the side plate slows considerably when the gap is reduced below 45 mils. Since significant contact between the side plate and fuel plate has occurred with gaps less than about 45 mils, much of the additional energy supplied in the swaging process goes into deformation of the contact region and fuel plate.

Comparing Figs. 29 and 30 , it is highly unlikely that the side plate would fail at a gap of 39 mils since it does not fail at 42 mils. Even when the gap reaches 33 mils as shown in Fig. 31 , the strains do not exceed 40% for more than half of the shear plane, indicating that failure is probably not imminent. It is recommended that 39 mils be used as a safe minimum gap of the side plate grooves, and that an inspection for this gap be added to the QA procedures for the swaging process. This would give an acceptance range for the gap of ± 3 mils from the average gap of 42 mils. The same acceptance range of ± 3 mils from the the average gap is recommended for the two end fuel plates. Groove gaps smaller than these values could be qualified by testing.

7.2.3 B&W Production Groove Gap Data

In April 1994, B&W measured and recorded side plate groove gaps at both ends of five consecutively manufactured ATR fuel elements (Ref. 16). The results are presented in

Appendix D and are summarized in Table 4 . These data indicate that the actual groove gap values are relatively consistent, generally ranging within the recommended maximum and minimum values. The QA procedures require that B&W engineering personnel be contacted if the groove gap values monitored exceed the allowable maximum limits (see Table 3). Fuel plates 1, 18, and 19 routinely fail to meet this limit with one swaging pass of the wheel (generally, only for one side of the fuel plate). In these cases, the gap is further reduced by performing a second swaging pass. The first pass is then referred to as a seating pass. Due to the configuration of the swaging hardware, both side plates receive a second pass of the swaging wheel decreasing each gap by about 2 to 3 mils.

Table 4 . Summary of B&W Production Groove Closure Data for Five ATR Fuel Elements

Fuel Plate Location	Range of Gaps, Forward End of Fuel Element	Range of Gaps, Aft End of Fuel Element	Mean Gap, Standard Deviation
Fuel Plate 1 Two Pass	72 – 71 MILS	75 – 71 MILS	72.5 MILS 1.19 SD
Fuel Plates 2–18 Single Pass	45 – 41 MILS	45 – 42 MILS	43.2 MILS 0.87 SD
Fuel Plate 18 Two Pass	44 – 40 MILS	44 – 41 MILS	42.1 MILS 1.59 SD
Fuel Plate 19 Two Pass	94 – 90 MILS	95 – 92 MILS	92.5 MILS 1.28 SD

7.3. Depth of Engagement of the Fuel Plate into the Side Plate Groove

The effects of varying the fuel plate insertion depth for the three basic models using otherwise nominal conditions are shown in Figs. 32 –34 . Fuel plate configurations F1 to F3 correspond to a spacing of no more than 20 mils from the fully inserted fuel plate position (see Figs. 2, 16 , and 17). Fuel plate configurations F4 and F5 increase that spacing to 30 and 40 mils, respectively. The data show that the reduction in the predicted pullout loads are minimal with configurations F1 to F3. With configurations F4 and F5, however, the pullout loads in some cases begin to decrease with decreasing side plate groove gaps indicating a reduction in the amount of material resisting slippage and therefore a weakening joint. Close examination of the ABAQUS output files shows that significantly fewer elements are in contact along the interfaces. The results, therefore, conservatively indicate that the spacing should be limited to about 20 mils, corresponding to configuration F3. If this spacing is measured from the edge of the fuel plate to the base of the side plate groove (see Fig. 2), the value should be 25 mils to account for the 5 mils radius in the corners of the groove.

B&W personnel (Ref. 13) maintain that spacings as large as those of configurations F4 and F5 are not likely due to dimensional tolerances. This spacing is not directly measured, however, using the current manufacturing QA procedures.

7.4. Location and Possible Tilt of the Swage Wheel

Five swage wheel configurations (W1 – W5) were evaluated again using the nominal model for fuel plate 9. The results shown in Fig. 35 indicate that, within the range of wheel configurations analyzed, the pullout force does not vary significantly. The amount of energy required to reach a specific groove gap varies by about 10% among the five models. For a given pump pressure, this corresponds to a gap variation of less than 1 mil (see Fig. 6). The effects of variations in combinations of wheel configuration (W1 – W3), fuel plate insertion depth (F1 – F5), and side plate groove gap (39, 42, and 45 mils) simultaneously can be seen by comparing Fig. 33 with Figs. 36 –37 . Even in combination with other changing parameters, variations of swage wheel location produce only minor changes in the predicted pullout force.

7.5. Wear of the Wheel Surface

Wheel surface wear was modeled by reducing the width of the wheel by 20% as described in Sec. 6.4. The results shown in Fig. 35 for wheel W6 indicate that wheel surface wear within this limit is not a concern.

7.6. Manufacturer's Tolerances

The effects of manufacturing tolerances on the strength of the swaged joint are shown in Fig. 38 . Model T2 (tight fit) is significantly stronger than the model TN with nominal dimensions. The joint weakens, however, as the tolerance stack-up produces a loose fit. Note that model T1 is a worst case loose fit joint. The pullout forces predicted for model T1 are approximately 20 – 50% less than those for model TN over the range of side plate groove gaps encountered during fabrication. In addition, the pullout forces approach the minimum allowable value with fuel plate configuration F5. The recommendation from Sec. 7.3, that the spacing between the edge of the fuel plate and the base of the side plate groove be limited to about 25 mils, is reinforced by the results here. Tolerance models were not analyzed for fuel plates 1 and 19 but results are expected to be similar based on results presented in Sec. 7.1.

The amount of energy required to reach a specific groove gap for the loose tolerance model (T1) is as much as a factor of 2.5 higher than that required to reach the same groove gap for the tight model (T2). Thus, it may not be possible to reach the maximum groove gap for model T1 with the pump pressure set at 450 ± 5 psig. B&W's QA procedures check for this situation by requiring that the gap be monitored for each fifth element. The possibility shown here that a loose tolerance could result in an insufficient gap indicates that all joints should be monitored for groove gap.

B&W personnel (Ref. 13) state that in actual practice, the tolerance of the side plate groove width (the gap before swaging) is much tighter than the ± 5 mils listed on the

drawings. The inspection requirement for this dimension, however, allows a tolerance of ± 5 mils. Several in-process side plate groove widths were measured and found to be within about 1 mil of the nominal dimension. The cutter used to make these grooves has a tolerance of only ± 0.5 mils (Ref. 14). The strength of the swaged joint assuming worst case tolerance variations would be significantly increased if the tolerance in the width of the side plate grooves prior to swaging was reduced (± 2 mils is suggested).

7.7. Curved Tensile Test Sample

The model shown in Fig. 20 was prepared to evaluate the effects of fuel plate curvature that may be left in the test samples before the pullout tests are performed. The pullout capacity of this model is 10 to 18% less than the nominal model for fuel plate 9 for groove gaps of 39, 42, and 45 mils but still significantly above the minimum value of 150 lbs/in. Note that this model evaluates the accuracy of the tensile test (by examining one variation in test sample geometry) rather than the actual strength of the swaged joint. The results from this calculation show that the measured pullout capacity of a swaged joint should not be much affected by remaining curvature after flattening of the fuel plates.

7.8. Fuel Plate Edge Pressure

Two models using fuel plate 9 with the nominal configuration were used to test the effectiveness of a swaged joint under differential pressure loading across the fuel plate. The analyses of these two models assumed that the joint was swaged just enough to meet B&W's gap limit of 45 mils. In each case, the differential pressure was increased until joint failure occurred while displacements were monitored at the 1/4 and 1/2 points along the fuel plate. The results are shown in Table 5. Since the differential pressures across a fuel plate are not expected to exceed 5 psi in ATR operations (Ref. 15), these results show that a connection that just meets B&W's groove gap limit should sustain the differential pressure loading with a significant margin. The fuel plate displacements are also within acceptable limits. These results tend to confirm the appropriateness of the 45 mil gap limit currently used in the B&W procedures. It is noted that the maximum pressures and displacements may be significantly different for fuel plates 1 and 19, and that the effects of dimensional tolerances were not included.

Table 5 .Results for the Fuel Plate Differential Pressure Models

Model	Pressure at Joint Failure	Maximum Radial Displacement at 1/4 Point before Failure	Maximum Radial Displacement at 1/2 Point before Failure
Model 1, Pressure on Concave Side	15.2 psi	0.50 mils	0.41 mils
Model 1, Pressure on Convex Side	16.6 psi	-0.85 mils	0.51 mils

7.9. Joints with Pre-Swaged Grooves

B&W QA procedures allow for the assembly of fuel elements using fuel plates with pre-swaged grooves. The fuel plates for these elements are typically recovered from previously disassembled fuel elements and thus have grooves where the swaging process deformed the original side plates into the fuel plate material (see the deformed shape of the fuel plate in Fig. 15). The fuel elements are recovered by milling slots in the outside of the original side plates until the side plate material fails and the fuel plates can be removed. New side plates are then used to fabricate the new fuel elements using these recovered plates.

The assembly of fuel elements using fuel plates with pre-swaged grooves was qualified in 1988 by B&W (Ref. 17) using a procedure similar to the second pass procedure described in Section 7.2.3. A seating pass of the swaged joint was first made followed by a second pass by reversing the swage carriage with the swage wheels activated at each position. The pump pressure remains the same during both passes of the swage wheel.

B&W measured and recorded side plate groove gaps for four fuel element samples during the qualification. The data is presented in Appendix D and summarized in Table 6 . The pullout loads listed are all slightly higher than average values for normal production fuel element samples. These data indicate that the groove gap values are 1 to 11 mils less than those measured during normal production (see Table 4). The QA procedures require that only fuel plate no. 1 receive a second pass and that B&W engineering personnel be contacted if the groove gap values monitored exceed the allowable maximum limits. B&W personnel (Ref. 13), however, stated that all pre-swaged fuel plates receive a second pass in order to maintain longitudinal strength. The QA procedures should be modified to reflect this practice.

Note also that the side plates deformed to a gap considerably smaller than the recommended minimums discussed in Section 7.2 without any loss of tensile strength of the swaged joint. This supports the conclusion that the recommended minimum values represent safe limits.

Groove gaps for fuel plates with pre-swaged grooves should be required to be within the range of those in Table 6 since these values have been qualified by testing. Larger maximum allowable gaps could be evaluated by testing or by further analyses of the pre-swaged joints similar to the analyses used in this report for new fuel plates. Smaller minimum allowable gaps would have to be qualified by testing.

Table 6 . Summary of B&W Qualification Data for Joints with Pre-Swaged Grooves

Fuel Plate Location	Range of Gaps	Average Pullout Load
Fuel Plate 1 Two Pass	68 – 70 MILS	732 lbs/in
Fuel Plates 2–18 Two Pass	34 – 37 MILS	551 lbs/in
Fuel Plate 19 Two Pass	86 – 88 MILS	676 lbs/in

Figure 22. Horizontal Displacement (X-Direction) of Fuel Plate 9 vers Force Applied

Figure 23 . Plot of Gap vers Pullout Force for Fuel Plates 1, 9, and 19

Note that the gap values have been normalized to the maximum allowable gap for each fuel plate to allow comparison.

Figure 24 . Plot of Swaging Wheel Force vers Pullout Force for Fuel Plate 9

Figure 25 . Out of Plane Stresses in Fuel Plate 9 after Swaging

ABAQUS

FUEL PLATE 9

42 Mil Gap

Out of Plane Stress PSI

Figure 26 . Von Mises Stresses in Fuel Plate 9 after Swaging

ABAQUS

MISES STRESS, PSI

Figure 27 . Equivalent Plastic Strain in the Side Plate Lip for Fuel Plate 9, 48.5 mils Gap

ABAQUS

FUEL PLATE 9
48.5 Mil Gap
Plastic Strain

Figure 28 . Equivalent Plastic Strain in the Side Plate Lip for Fuel Plate 9, 45 mils Gap

ABAQUS

Figure 29 . Equivalent Plastic Strain in the Side Plate Lip for Fuel Plate 9, 42 mils Gap

ABAQUS

FUEL PLATE 9
42 Mil Gap
Plastic Strain

Figure 30 . Equivalent Plastic Strain in the Side Plate Lip for Fuel Plate 9, 39 mils Gap

ABAQUS

FUEL PLATE 9
39 Mil Gap
Plastic Strain

Figure 31 . Equivalent Plastic Strain in the Side Plate Lip for Fuel Plate 9, 33 mils Gap

ABAQUS

FUEL PLATE 9
33 Mil Gap
Plastic Strain

Figure 32 . Plot of Gap vers Pullout Force for Fuel Plate 1 Showing the Effects of Fuel Plate Insertion Depth

Figure 33 . Plot of Gap vers Pullout Force for Fuel Plate 9 Showing the Effects of Fuel Plate Insertion Depth

Figure 34 . Plot of Gap vers Pullout Force for Fuel Plate 19 Showing the Effects of Fuel Plate Insertion Depth

Figure 35 . Plot of Gap vers Pullout Force for Fuel Plate 9 Showing the Effects of Swage Wheel Configuration

Figure 36 . Plot of Gap vers Pullout Force for Fuel Plate 9 Showing the Combined Effects of Swage Wheel Configuration W2 and Fuel Plate Insertion Depth

Figure 37 . Plot of Gap vers Pullout Force for Fuel Plate 9 Showing the Combined Effects of Swage Wheel Configuration W3 and Fuel Plate Insertion Depth

Figure 38 . Plot of Gap vers Pullout Force for Fuel Plate 9 Showing the Effects of Manufacturing Tolerances
Tolerance model T1 is shown with three fuel plate locations.

8. CONCLUSIONS

An evaluation of the swaging process used to fabricate the joints between the side and fuel plates in the ATR fuel elements was performed. The basic concern addressed here is whether the integrity of these connections is sufficiently assured during the manufacturing process and, if not, to determine additional measures that may be necessary to provide adequate assurance. This evaluation was made primarily by performing non-linear finite element analyses on the swaged joints. Once the finite element models were shown to appropriately simulate the swaging process, they were used to assess the sensitivity of a connection to variations in several process variables that can affect the strength of a joint. These variations in the process are controlled by procedures and inspections currently used by B&W. Results from the analyses were used to assess whether these controls are sufficient to assure adequacy of all joints.

Provided the specified gap of the side plate grooves is achieved by the swaging process, these analyses indicate that the strength of the swaged connections is relatively insensitive to variations in most parameters involved in the swaging process. The pullout capacity is somewhat sensitive to the dimensional tolerances in the side plate and fuel plate, indicating a need for a tighter tolerance on the width of the side plate grooves than currently listed on the drawings. The pullout capacity is also sensitive to the depth of insertion of the fuel plate into the side plate groove, but only when the spacing between the edge of the fuel plate and the base of the side plate groove becomes quite large.

These results are based on several limits and controls established for the process by B&W in their procedures. These include calibrating and monitoring the pressure gage in the hydraulic system that drives the swaging wheels, measuring the gap in the side plate grooves and limiting the maximum size of this gap, establishing the tolerances in dimensions of the manufactured pieces, measuring the crown height of each fuel plate in an element as it is swaged, periodically inspecting the swage head and wheel assembly, checking the swage wheels for wear, and tensile testing a sample from a minimum of one in every ten fuel elements. It has been found in this study that, with the addition of several inspections and verifications to the procedure used in the swaging process, the pullout capacity of the swaged connections is sufficiently assured during manufacturing by the fabrication processes and quality controls used by B&W.

9. RECOMMENDED QUALITY INSPECTIONS TO BE INCLUDED IN MANUFACTURER'S SWAGING PROCEDURE

Provided the specified gap of the side plate grooves is achieved by the swaging process, the analyses performed indicate that the strength of the swaged connections is relatively insensitive to variations in most parameters involved in the swaging process. An exception is the dimensional tolerances in the side plate and fuel plate. Based on the analyses results, variations in the pullout capacity of the swaged connections are largely attributable to these dimensional tolerances. This indicates a need for a tighter tolerance on the width of the side plate grooves than currently listed on the drawings. The pullout capacity is also sensitive to the depth of insertion of the fuel plate into the side plate groove, but only when the spacing between the edge of the fuel plate and the side plate becomes quite large. These results are based on several limits and controls established for the process by B&W in their procedures. These include calibrating and monitoring the pressure gage in the hydraulic system that drives the swaging wheels, measuring the gap in the side plate grooves and limiting the maximum size of this gap, establishing tolerances in dimensions of the manufactured pieces, measuring the crown height of each fuel plate in an element as it is swaged, periodically inspecting the swage head and wheel assembly, checking the swage wheels for wear, and tensile testing a sample from a minimum of one in every ten fuel elements.

The calculations show that the pullout capacity of the swaged joint increases quickly once the side plate lip contacts the fuel plate. The minimum pullout capacity of 150 lb/in. is generally achieved at an energy level well under the energy needed to reach B&W's specified maximum gap in the side plate grooves. When the required gap is reached, the pullout capacity is well above the minimum required and then generally levels off with further swaging. Ultimately, swaging to a small enough gap size would produce excessive strains in the lip of the side plate, causing it to fail. While the methods used here do not provide a precise analytical determination of the side plate groove gap where failure would occur, a safe minimum has been established for the gap (as specified below) that should preclude a failure of the side plate lip.

As stated above, the pullout capacity for a swaged joint is somewhat sensitive to the dimensional tolerances in the side plate and fuel plate. The specific dimensions of concern are the initial opening size in the side plate groove and the fuel plate thickness. A set of analyses were performed in which the initial groove opening was set at a maximum, the fuel plate thickness was set at a minimum, and gap of the side plate groove in the swaging process was assumed to just meet B&W's specified limit. In this set of analyses, the fuel plate was assumed to be inserted to differing depths into the side plate groove. Based on the results of these analyses, it is recommended that a limit be imposed on the spacing between the edge of the fuel plate and the base of the side plate groove. The tensile tests that are performed on samples from at least one of every ten elements provide further assurance of the integrity of the swaged connections.

Aside from the variables in the swaging process evaluated here, there are two other possible causes for producing inadequate swaged connections: (1) an initial bias in the system, or (2) technician error. An initial bias would be attributable to a misalignment in the equipment. Misalignments are largely avoided by the preliminary verification of equipment and tooling and the equipment requalification requirements contained in the operating procedure. An initial bias in the equipment is not a process variable, but instead would be responsible for repeated errors in the swaging process. If any bias of significant magnitude had been present in the process throughout the past, it should have been discovered in the form of faulty fuel elements in: (1) B&W's pullout tests, (2) the HTF tests, or (3) reactor operations. With adherence to the operational procedures, it is improbable that any new biases should be developed in the system.

There is always a finite probability for a technician error during the swaging process. The chances for this are greatly diminished by the fact that the technician that swages the ATR fuel elements is well trained, as required by Ref. 2. At the time of preparation of this report there was only one B&W technician designated for swaging of the ATR fuel elements. Further, any technician error should be revealed by the quality assurance inspections and the use of a checklist.

The intent of this investigation was to verify that procedures followed in the swaging process preclude having a swaged connection fail to meet the established pullout capacity requirement. Based on the results of the investigation summarized above, several additional measures are recommended to be added to the current procedure to provide this assurance:

- (1) Monitor the hydraulic pressure applied to the swaging wheel by installing a pressure transducer which would cause an audible alarm when the pump pressure is outside the allowable range ($450 \text{ psig} \pm 5 \text{ psi}$).

(Calculations in this report show that the pullout capacity of a swaged joint is not much affected by small fluctuations in pump pressure, however, continual monitoring assures that the pressure stays within the specified range throughout the process.)

- (2) Update operating procedures and route cards to require measurement of the side plate groove gap after the fuel plate is swaged into place for all fuel plates in each element. Measurements shall be made on the run-out or upper end of each element. The minimum and maximum values listed below should be used in procedures for other than pre-swaged fuel plates.

Recommended Allowable Side Plate Groove Gaps
(Fuel Plates without Pre-Swaged Grooves)

Fuel Plate Location	Maximum Allowable	Average	Minimum Allowable
Fuel Plate 1	75 MILS	72 MILS	69 MILS
Fuel Plates 2-18	45 MILS	42 MILS	39 MILS
Fuel Plate 19	95 MILS	92 MILS	89 MILS

- (3) Update operating procedures and route cards for routine fuel element swaging to require that only fuel plate 1 receives a seating/additional swage wheel pass. All other fuel plates are to receive only one swage wheel pass during normal routine swaging.

If seating/additional swaging wheel passes are deemed necessary for any of the fuel plates 2 – 19, subcontractor engineering will evaluate the need prior to proceeding.

For the rare occasion when a pre-swaged fuel plate is used, a second pass (seating pass) will be necessary for all fuel plates with pre-swaged grooves used in the fuel element.

- (4) For swaging of pre-swaged fuel plates, operating procedures and route cards should be updated to provide caution notes that the minimum and maximum side plate groove gap values for other than pre-swaged fuel plates are not applicable, and that a revised set of values are allowed for pre-swaged fuel plates. The ranges of side plate groove gaps used with pre-swaged fuel plates are established by pull-out testing summarized below. Any change to these values for pre-swaged fuel plates shall be justified only by additional testing and analyses and approved by the customer. It should be noted that swaging of pre-swaged fuel plates is an off-normal situation and will be performed only with special, approved procedures.

Range of Side Plate Groove Gaps Qualified by Testing
(Fuel Plates with Pre-Swaged Grooves)

Fuel Plate Location	Range of Gaps
Fuel Plate 1, Two Swage Wheel Passes	68 – 70 MILS
Fuel Plates 2-18, Two Swage Wheel Passes	34 – 37 MILS
Fuel Plate 19, Two Swage Wheel Passes	86 – 88 MILS

- (5) Change operating procedures and route cards to require the operator to visually monitor placement of each fuel plate within the side plate grooves prior to and after swaging. (These checks are to ensure each fuel plate is correctly aligned and centered prior to swaging, and to ensure that the plates do not shift during the swaging operation). This visual check should include a check of the spacing between the edge of the fuel plate and the base of the side plate groove and should be made on both side plates at both ends of each fuel element when possible. The recommended maximum spacing is 0.045 inches.

The spacing should also be measured on all tensile test samples to provide a data base for future engineering evaluations and to check for possible misalignment of the swaging hardware, etc.

If the spacing exceeds 0.045", a fuel element can be qualified by testing. Subcontractor engineering should evaluate the test results and receive customer approval prior to accepting the fuel element.

- (6) Tolerances of the entry groove width for the side plates on design and manufacturing drawings should be tightened to ± 2 mils.

(This should increase the strength of the worst case loose fit joint. Also, reducing the tolerances will eliminate the possibility of an interference fit of the fuel plate into the side plate groove.)

- (7) Operating procedures and route cards should be revised so that use of the swage log is formalized to require including the recording of data listed in these recommendations. The revised swage log then should be forwarded with each fuel element route card, which then becomes part of the fuel element certification.
- (8) Operating procedures and route cards should be updated to change the term "side plate groove closure" to "side plate groove gap."

When these recommended quality assurance checks are added to those already included in B&W's procedure, all swaged connections should meet the acceptance standard for pullout capacity.

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APPENDIX A

MODELING DETAILS

This appendix consists of two parts:

- (1) Figures showing the dimensional details of the side plates and fuel plates used in the finite element models.
- (2) An example ABAQUS input file for fuel plate 9 using the nominal configuration including the fuel plate tension load steps.

FIGURES SHOWING DIMENSIONAL DETAILS

Figure 42 . Tolerance Model 1 (Loose Fit), Largest Dimensions for Side Plate Groove 9, Inches

Figure 43. Tolerance Model 2 (Tight Fit), Smallest Dimensions for Side Plate Groove 9, Inches

Figure 44 . Nominal Dimensions for 1/2 of Fuel Plate 1, Inches

Figure 45. Nominal Dimensions for 1/2 of Fuel Plate 9, Inches

Figure 46 . Nominal Dimensions for 1/2 of Fuel Plate 19, Inches

ABAQUS INPUT DATA

The following consists of sample ABAQUS input data for fuel plate 9 using the nominal configuration including the fuel plate tension load steps.

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SDRC I-DEAS ABAQUS FILE TRANSLATOR 10-FEB-94 16:13:04

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*NODE, SYSTEM=

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59, -4.5209E-02, -7.6687E-02, 0.0000E+00
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62, -1.5959E-02, -7.8092E-02, 0.0000E+00

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64, 3.5408E-03, -6.8631E-02, 0.0000E+00
65, 3.5408E-03, -5.8234E-02, 0.0000E+00
66, 3.5408E-03, -4.7837E-02, 0.0000E+00
67, 3.5408E-03, -3.7440E-02, 0.0000E+00
68, 1.7827E-02, -2.2326E-02, 0.0000E+00
69, 2.7112E-02, -2.2610E-02, 0.0000E+00
70, 3.6398E-02, -2.2894E-02, 0.0000E+00
71, 4.5684E-02, -2.3177E-02, 0.0000E+00
72, 5.4969E-02, -2.3461E-02, 0.0000E+00
73, 6.4255E-02, -2.3745E-02, 0.0000E+00
74, 6.6378E-02, -6.8654E-03, 0.0000E+00
75, 6.0164E-02, -6.5159E-04, 0.0000E+00
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82, 6.2406E-02, 2.7837E-02, 0.0000E+00
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1860, 3.3303E-02, 1.1101E-01, 0.0000E+00
1861, 3.5319E-02, 1.1157E-01, 0.0000E+00
1862, 3.7301E-02, 1.1170E-01, 0.0000E+00
1863, 3.9419E-02, 1.1172E-01, 0.0000E+00
1864, 4.1641E-02, 1.1173E-01, 0.0000E+00
1865, 4.3934E-02, 1.1175E-01, 0.0000E+00
1866, 4.6281E-02, 1.1181E-01, 0.0000E+00
1867, 4.8674E-02, 1.1189E-01, 0.0000E+00
1868, 5.1097E-02, 1.1199E-01, 0.0000E+00
1869, 5.3475E-02, 1.1207E-01, 0.0000E+00
1870, 5.5455E-02, 1.1190E-01, 0.0000E+00
1871, 5.7227E-02, 1.1177E-01, 0.0000E+00
1872, 5.8978E-02, 1.1171E-01, 0.0000E+00
1873, 6.0760E-02, 1.1168E-01, 0.0000E+00
1874, 6.2590E-02, 1.1163E-01, 0.0000E+00
1875, 6.4524E-02, 1.1150E-01, 0.0000E+00
1876, 6.6674E-02, 1.1149E-01, 0.0000E+00
1877, 6.6217E-02, 1.0679E-01, 0.0000E+00
1878, 6.3419E-02, 1.0710E-01, 0.0000E+00
1879, 6.0943E-02, 1.0657E-01, 0.0000E+00
1880, 5.8671E-02, 1.0651E-01, 0.0000E+00
1881, 5.6417E-02, 1.0671E-01, 0.0000E+00
1882, 5.4021E-02, 1.0739E-01, 0.0000E+00
1883, 5.1205E-02, 1.0721E-01, 0.0000E+00
1884, 4.8642E-02, 1.0717E-01, 0.0000E+00
1885, 4.6157E-02, 1.0717E-01, 0.0000E+00
1886, 4.3707E-02, 1.0720E-01, 0.0000E+00
1887, 4.1286E-02, 1.0727E-01, 0.0000E+00
1888, 3.8894E-02, 1.0738E-01, 0.0000E+00
1889, 3.6515E-02, 1.0764E-01, 0.0000E+00
1890, 3.3991E-02, 1.0836E-01, 0.0000E+00
1891, 3.1116E-02, 1.0809E-01, 0.0000E+00
1892, 2.8539E-02, 1.0802E-01, 0.0000E+00
1893, 2.6043E-02, 1.0804E-01, 0.0000E+00
1894, 2.3556E-02, 1.0812E-01, 0.0000E+00
1895, 6.6598E-02, 1.0924E-01, 0.0000E+00
1896, 6.0675E-02, 1.0997E-01, 0.0000E+00
1897, 6.0640E-02, 1.0832E-01, 0.0000E+00
1898, 5.8885E-02, 1.1002E-01, 0.0000E+00
1899, 5.8783E-02, 1.0833E-01, 0.0000E+00
1900, 4.8667E-02, 1.0955E-01, 0.0000E+00
1901, 4.6237E-02, 1.0951E-01, 0.0000E+00
1902, 4.3845E-02, 1.0949E-01, 0.0000E+00
1903, 4.1502E-02, 1.0952E-01, 0.0000E+00
1904, 3.9237E-02, 1.0958E-01, 0.0000E+00
1905, 3.7133E-02, 1.0970E-01, 0.0000E+00
1906, 3.5481E-02, 1.0988E-01, 0.0000E+00
1907, 5.7106E-02, 1.1009E-01, 0.0000E+00
1908, 5.5375E-02, 1.1011E-01, 0.0000E+00
1909, 5.3497E-02, 1.0980E-01, 0.0000E+00
1910, 5.1117E-02, 1.0964E-01, 0.0000E+00

1911, 5.6938E-02, 1.0844E-01, 0.0000E+00
1912, 5.5445E-02, 1.0865E-01, 0.0000E+00
1913, 6.4239E-02, 1.0943E-01, 0.0000E+00
1914, 6.2415E-02, 1.0987E-01, 0.0000E+00
1915, 6.2158E-02, 1.0843E-01, 0.0000E+00
1916, 7.1219E-02, 1.0636E-01, 0.0000E+00
1917, 7.1484E-02, 1.0850E-01, 0.0000E+00
1918, 7.1915E-02, 1.1010E-01, 0.0000E+00
1919, 7.2057E-02, 1.1153E-01, 0.0000E+00
1920, 7.0558E-02, 1.1169E-01, 0.0000E+00
1921, 7.0579E-02, 1.1034E-01, 0.0000E+00
1922, 1.3851E-02, 1.7080E-01, 0.0000E+00
1923, 1.8253E-02, 1.7081E-01, 0.0000E+00
1924, 2.2525E-02, 1.7073E-01, 0.0000E+00
1925, 2.6608E-02, 1.7055E-01, 0.0000E+00
1926, 3.0425E-02, 1.7020E-01, 0.0000E+00
1927, 3.3902E-02, 1.6966E-01, 0.0000E+00
1928, 3.7243E-02, 1.6920E-01, 0.0000E+00
1929, 4.0592E-02, 1.6876E-01, 0.0000E+00
1930, 4.3882E-02, 1.6825E-01, 0.0000E+00
1931, 4.6545E-02, 1.6755E-01, 0.0000E+00
1932, 4.9085E-02, 1.6736E-01, 0.0000E+00
1933, 5.1940E-02, 1.6695E-01, 0.0000E+00
1934, 5.4912E-02, 1.6766E-01, 0.0000E+00
1935, 5.7575E-02, 1.6811E-01, 0.0000E+00
1936, 6.0206E-02, 1.6839E-01, 0.0000E+00
1937, 6.2845E-02, 1.6870E-01, 0.0000E+00
1938, 6.5477E-02, 1.6879E-01, 0.0000E+00
1939, 6.8059E-02, 1.6885E-01, 0.0000E+00
1940, 7.0743E-02, 1.6834E-01, 0.0000E+00
1941, 2.6907E-02, 1.4198E-01, 0.0000E+00
1942, 2.6944E-02, 1.4440E-01, 0.0000E+00
1943, 2.7007E-02, 1.4688E-01, 0.0000E+00
1944, 2.7036E-02, 1.4944E-01, 0.0000E+00
1945, 2.6925E-02, 1.5224E-01, 0.0000E+00
1946, 2.6775E-02, 1.5541E-01, 0.0000E+00
1947, 2.6769E-02, 1.5892E-01, 0.0000E+00
1948, 2.6568E-02, 1.6271E-01, 0.0000E+00
1949, 2.6486E-02, 1.6658E-01, 0.0000E+00
1950, 4.4296E-02, 1.4146E-01, 0.0000E+00
1951, 4.4334E-02, 1.4289E-01, 0.0000E+00
1952, 4.4345E-02, 1.4441E-01, 0.0000E+00
1953, 4.4440E-02, 1.4605E-01, 0.0000E+00
1954, 4.4301E-02, 1.4791E-01, 0.0000E+00
1955, 4.4050E-02, 1.4985E-01, 0.0000E+00
1956, 4.3686E-02, 1.5196E-01, 0.0000E+00
1957, 4.3531E-02, 1.5430E-01, 0.0000E+00
1958, 4.3337E-02, 1.5675E-01, 0.0000E+00
1959, 4.3146E-02, 1.5938E-01, 0.0000E+00
1960, 4.3361E-02, 1.6231E-01, 0.0000E+00
1961, 4.3488E-02, 1.6530E-01, 0.0000E+00
1962, 4.5671E-02, 1.4148E-01, 0.0000E+00
1963, 4.5882E-02, 1.4285E-01, 0.0000E+00
1964, 4.5863E-02, 1.4432E-01, 0.0000E+00
1965, 4.6467E-02, 1.4595E-01, 0.0000E+00
1966, 4.6296E-02, 1.4805E-01, 0.0000E+00
1967, 4.6239E-02, 1.5007E-01, 0.0000E+00
1968, 4.6091E-02, 1.5219E-01, 0.0000E+00
1969, 4.6083E-02, 1.5445E-01, 0.0000E+00
1970, 4.5976E-02, 1.5684E-01, 0.0000E+00
1971, 4.6065E-02, 1.5933E-01, 0.0000E+00
1972, 4.6706E-02, 1.6209E-01, 0.0000E+00
1973, 4.6402E-02, 1.6503E-01, 0.0000E+00
1974, 5.3278E-02, 1.6459E-01, 0.0000E+00
1975, 5.4190E-02, 1.6245E-01, 0.0000E+00
1976, 5.5040E-02, 1.6023E-01, 0.0000E+00

1977	5.6561E-02	1.5865E-01	0.0000E+00
1978	5.7771E-02	1.5706E-01	0.0000E+00
1979	5.9135E-02	1.5552E-01	0.0000E+00
1980	4.8734E-02	1.5448E-01	0.0000E+00
1981	5.0765E-02	1.5525E-01	0.0000E+00
1982	5.2465E-02	1.5559E-01	0.0000E+00
1983	5.4095E-02	1.5583E-01	0.0000E+00
1984	5.5996E-02	1.5591E-01	0.0000E+00
1985	4.8357E-02	1.5228E-01	0.0000E+00
1986	5.0083E-02	1.5229E-01	0.0000E+00
1987	5.1648E-02	1.5252E-01	0.0000E+00
1988	5.3195E-02	1.5294E-01	0.0000E+00
1989	5.4634E-02	1.5339E-01	0.0000E+00
1990	5.5976E-02	1.5381E-01	0.0000E+00
1991	5.7526E-02	1.5424E-01	0.0000E+00
1992	5.3696E-02	1.5160E-01	0.0000E+00
1993	5.4455E-02	1.5025E-01	0.0000E+00
1994	4.8522E-02	1.5017E-01	0.0000E+00
1995	5.0284E-02	1.5079E-01	0.0000E+00
1996	5.2001E-02	1.5096E-01	0.0000E+00
1997	4.8177E-02	1.4829E-01	0.0000E+00
1998	4.9610E-02	1.4833E-01	0.0000E+00
1999	5.0814E-02	1.4877E-01	0.0000E+00
2000	5.1881E-02	1.4927E-01	0.0000E+00
2001	5.2908E-02	1.4988E-01	0.0000E+00
2002	4.9897E-02	1.4687E-01	0.0000E+00
2003	5.0858E-02	1.4594E-01	0.0000E+00
2004	4.8281E-02	1.4660E-01	0.0000E+00
2005	4.8583E-02	1.4532E-01	0.0000E+00
2006	4.9092E-02	1.4423E-01	0.0000E+00
2007	4.8014E-02	1.4345E-01	0.0000E+00
2008	4.6959E-02	1.4324E-01	0.0000E+00
2009	4.6759E-02	1.4409E-01	0.0000E+00
2010	4.7456E-02	1.4470E-01	0.0000E+00
2011	4.7452E-02	1.4196E-01	0.0000E+00
2012	4.7182E-02	1.4258E-01	0.0000E+00
2013	4.7734E-02	1.4279E-01	0.0000E+00
2014	4.8006E-02	1.4234E-01	0.0000E+00
2015	4.6687E-02	1.4156E-01	0.0000E+00
2016	4.6584E-02	1.4233E-01	0.0000E+00
2017	5.0029E-02	1.4500E-01	0.0000E+00
2018	4.9503E-02	1.4573E-01	0.0000E+00
2019	5.1897E-02	1.4684E-01	0.0000E+00
2020	5.1235E-02	1.4773E-01	0.0000E+00
2021	5.2332E-02	1.4843E-01	0.0000E+00
2022	5.2914E-02	1.4768E-01	0.0000E+00
2023	5.3297E-02	1.4905E-01	0.0000E+00
2024	5.3846E-02	1.4845E-01	0.0000E+00
2025	5.4101E-02	1.4944E-01	0.0000E+00
2026	5.4551E-02	1.4901E-01	0.0000E+00
2027	5.0531E-02	1.4974E-01	0.0000E+00
2028	4.9554E-02	1.4941E-01	0.0000E+00
2029	5.1471E-02	1.4999E-01	0.0000E+00
2030	5.5863E-02	1.5121E-01	0.0000E+00
2031	5.5134E-02	1.5226E-01	0.0000E+00
2032	5.6342E-02	1.5284E-01	0.0000E+00
2033	5.7021E-02	1.5205E-01	0.0000E+00
2034	5.7239E-02	1.5325E-01	0.0000E+00
2035	5.7848E-02	1.5267E-01	0.0000E+00
2036	5.1314E-02	1.5389E-01	0.0000E+00
2037	5.2802E-02	1.5425E-01	0.0000E+00
2038	5.4233E-02	1.5456E-01	0.0000E+00
2039	5.5402E-02	1.5476E-01	0.0000E+00
2040	5.0044E-02	1.5355E-01	0.0000E+00
2041	5.0548E-02	1.5705E-01	0.0000E+00
2042	5.0809E-02	1.5907E-01	0.0000E+00

2043	5.0159E-02	1.6116E-01	0.0000E+00
2044	4.9271E-02	1.6302E-01	0.0000E+00
2045	4.8869E-02	1.6517E-01	0.0000E+00
2046	5.2127E-02	1.6180E-01	0.0000E+00
2047	5.2812E-02	1.5991E-01	0.0000E+00
2048	5.3273E-02	1.5856E-01	0.0000E+00
2049	5.3688E-02	1.5727E-01	0.0000E+00
2050	5.2199E-02	1.5703E-01	0.0000E+00
2051	5.2093E-02	1.5822E-01	0.0000E+00
2052	5.5186E-02	1.5766E-01	0.0000E+00
2053	5.4500E-02	1.5881E-01	0.0000E+00
2054	5.1349E-02	1.6367E-01	0.0000E+00
2055	5.0719E-02	1.6526E-01	0.0000E+00
2056	4.8422E-02	1.5684E-01	0.0000E+00
2057	4.8432E-02	1.5900E-01	0.0000E+00
2058	4.8432E-02	1.6075E-01	0.0000E+00
2059	6.0640E-02	1.5674E-01	0.0000E+00
2060	5.9393E-02	1.5814E-01	0.0000E+00
2061	5.8246E-02	1.5966E-01	0.0000E+00
2062	5.7141E-02	1.6130E-01	0.0000E+00
2063	5.6313E-02	1.6320E-01	0.0000E+00
2064	5.5635E-02	1.6528E-01	0.0000E+00
2065	6.0657E-02	1.6559E-01	0.0000E+00
2066	6.1958E-02	1.6368E-01	0.0000E+00
2067	6.2937E-02	1.6205E-01	0.0000E+00
2068	6.3911E-02	1.6043E-01	0.0000E+00
2069	6.1429E-02	1.6132E-01	0.0000E+00
2070	5.9889E-02	1.6055E-01	0.0000E+00
2071	5.8965E-02	1.6210E-01	0.0000E+00
2072	5.8287E-02	1.6376E-01	0.0000E+00
2073	5.8038E-02	1.6569E-01	0.0000E+00
2074	6.0545E-02	1.6279E-01	0.0000E+00
2075	5.9830E-02	1.6405E-01	0.0000E+00
2076	6.2036E-02	1.5787E-01	0.0000E+00
2077	6.0916E-02	1.5912E-01	0.0000E+00
2078	6.2346E-02	1.5990E-01	0.0000E+00
2079	6.3127E-02	1.5873E-01	0.0000E+00
2080	6.5823E-02	1.6605E-01	0.0000E+00
2081	6.7187E-02	1.6402E-01	0.0000E+00
2082	6.5806E-02	1.6338E-01	0.0000E+00
2083	6.4449E-02	1.6277E-01	0.0000E+00
2084	6.3692E-02	1.6429E-01	0.0000E+00
2085	6.3254E-02	1.6616E-01	0.0000E+00
2086	6.5107E-02	1.6457E-01	0.0000E+00
2087	6.5362E-02	1.6134E-01	0.0000E+00
2088	6.6482E-02	1.6214E-01	0.0000E+00
2089	6.8090E-02	1.6669E-01	0.0000E+00
2090	6.8839E-02	1.6496E-01	0.0000E+00
2091	6.9637E-02	1.6690E-01	0.0000E+00
2092	7.0079E-02	1.6568E-01	0.0000E+00
2093	2.9802E-02	1.4939E-01	0.0000E+00
2094	3.2516E-02	1.4907E-01	0.0000E+00
2095	3.4632E-02	1.4831E-01	0.0000E+00
2096	3.6853E-02	1.4787E-01	0.0000E+00
2097	3.8746E-02	1.4847E-01	0.0000E+00
2098	4.0367E-02	1.4886E-01	0.0000E+00
2099	4.1978E-02	1.4947E-01	0.0000E+00
2100	2.9360E-02	1.4435E-01	0.0000E+00
2101	3.1689E-02	1.4423E-01	0.0000E+00
2102	3.3861E-02	1.4403E-01	0.0000E+00
2103	3.5889E-02	1.4380E-01	0.0000E+00
2104	3.7903E-02	1.4347E-01	0.0000E+00
2105	3.9611E-02	1.4396E-01	0.0000E+00
2106	4.1171E-02	1.4421E-01	0.0000E+00
2107	4.2745E-02	1.4436E-01	0.0000E+00
2108	4.2849E-02	1.4141E-01	0.0000E+00

2109,	4.1402E-02,	1.4135E-01,	0.0000E+00
2110,	3.9997E-02,	1.4131E-01,	0.0000E+00
2111,	3.8667E-02,	1.4136E-01,	0.0000E+00
2112,	3.7307E-02,	1.4170E-01,	0.0000E+00
2113,	3.5602E-02,	1.4190E-01,	0.0000E+00
2114,	3.3705E-02,	1.4193E-01,	0.0000E+00
2115,	3.1565E-02,	1.4196E-01,	0.0000E+00
2116,	2.9274E-02,	1.4198E-01,	0.0000E+00
2117,	4.2815E-02,	1.4285E-01,	0.0000E+00
2118,	4.1332E-02,	1.4276E-01,	0.0000E+00
2119,	3.9944E-02,	1.4263E-01,	0.0000E+00
2120,	3.8838E-02,	1.4249E-01,	0.0000E+00
2121,	2.9536E-02,	1.4680E-01,	0.0000E+00
2122,	3.1976E-02,	1.4657E-01,	0.0000E+00
2123,	3.4166E-02,	1.4618E-01,	0.0000E+00
2124,	3.6196E-02,	1.4581E-01,	0.0000E+00
2125,	3.7878E-02,	1.4539E-01,	0.0000E+00
2126,	3.9429E-02,	1.4553E-01,	0.0000E+00
2127,	4.1001E-02,	1.4575E-01,	0.0000E+00
2128,	4.2651E-02,	1.4596E-01,	0.0000E+00
2129,	4.2421E-02,	1.4766E-01,	0.0000E+00
2130,	4.0754E-02,	1.4732E-01,	0.0000E+00
2131,	3.9228E-02,	1.4702E-01,	0.0000E+00
2132,	3.7986E-02,	1.4676E-01,	0.0000E+00
2133,	3.0329E-02,	1.6268E-01,	0.0000E+00
2134,	3.3736E-02,	1.6285E-01,	0.0000E+00
2135,	3.6929E-02,	1.6277E-01,	0.0000E+00
2136,	4.0105E-02,	1.6246E-01,	0.0000E+00
2137,	3.0772E-02,	1.5875E-01,	0.0000E+00
2138,	3.3956E-02,	1.5973E-01,	0.0000E+00
2139,	3.6822E-02,	1.5982E-01,	0.0000E+00
2140,	3.9822E-02,	1.5914E-01,	0.0000E+00
2141,	4.1077E-02,	1.5150E-01,	0.0000E+00
2142,	3.8709E-02,	1.5187E-01,	0.0000E+00
2143,	3.6452E-02,	1.5194E-01,	0.0000E+00
2144,	3.3657E-02,	1.5202E-01,	0.0000E+00
2145,	3.0125E-02,	1.5225E-01,	0.0000E+00
2146,	3.0119E-02,	1.5535E-01,	0.0000E+00
2147,	3.2805E-02,	1.5499E-01,	0.0000E+00
2148,	3.4754E-02,	1.5550E-01,	0.0000E+00
2149,	3.6672E-02,	1.5573E-01,	0.0000E+00
2150,	3.8620E-02,	1.5592E-01,	0.0000E+00
2151,	4.0699E-02,	1.5646E-01,	0.0000E+00
2152,	4.1019E-02,	1.5405E-01,	0.0000E+00
2153,	3.8770E-02,	1.5392E-01,	0.0000E+00
2154,	3.6736E-02,	1.5384E-01,	0.0000E+00
2155,	3.5049E-02,	1.5379E-01,	0.0000E+00
2156,	3.4495E-02,	1.5749E-01,	0.0000E+00
2157,	3.6583E-02,	1.5765E-01,	0.0000E+00
2158,	3.8342E-02,	1.5757E-01,	0.0000E+00
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2161,	3.8539E-02,	1.5013E-01,	0.0000E+00
2162,	3.9994E-02,	1.5016E-01,	0.0000E+00
2163,	3.5000E-02,	1.5012E-01,	0.0000E+00
2164,	3.0244E-02,	1.6642E-01,	0.0000E+00
2165,	3.3734E-02,	1.6622E-01,	0.0000E+00
2166,	3.7054E-02,	1.6595E-01,	0.0000E+00
2167,	4.0310E-02,	1.6562E-01,	0.0000E+00
2168,	1.4166E-02,	1.6646E-01,	0.0000E+00
2169,	1.8410E-02,	1.6660E-01,	0.0000E+00
2170,	2.2527E-02,	1.6664E-01,	0.0000E+00
2171,	1.9527E-02,	1.4168E-01,	0.0000E+00
2172,	1.9464E-02,	1.4455E-01,	0.0000E+00
2173,	1.9686E-02,	1.4746E-01,	0.0000E+00
2174,	2.0440E-02,	1.5070E-01,	0.0000E+00

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2180,	2.3292E-02,	1.5516E-01,	0.0000E+00
2181,	2.3767E-02,	1.5184E-01,	0.0000E+00
2182,	2.4413E-02,	1.4928E-01,	0.0000E+00
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2185,	2.4517E-02,	1.4195E-01,	0.0000E+00
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3730	8.2480E-02	7.2861E-02	0.0000E+00
3731	8.2636E-02	7.5500E-02	0.0000E+00
3732	8.2698E-02	7.8121E-02	0.0000E+00
3733	8.2605E-02	8.0739E-02	0.0000E+00
3734	8.2160E-02	8.3613E-02	0.0000E+00
3735	8.2826E-02	8.6732E-02	0.0000E+00
3736	8.3257E-02	8.9739E-02	0.0000E+00
3737	8.3526E-02	9.2737E-02	0.0000E+00
3738	8.0415E-02	7.5550E-02	0.0000E+00
3739	8.0243E-02	7.2944E-02	0.0000E+00
3740	8.0046E-02	7.0411E-02	0.0000E+00
3741	7.9810E-02	6.8068E-02	0.0000E+00
3742	7.9561E-02	6.6225E-02	0.0000E+00
3743	8.0588E-02	7.8096E-02	0.0000E+00
3744	8.0680E-02	8.0448E-02	0.0000E+00
3745	8.0672E-02	8.2298E-02	0.0000E+00
3746	8.4329E-02	5.5797E-02	0.0000E+00
3747	8.4431E-02	5.8945E-02	0.0000E+00
3748	8.4325E-02	6.2119E-02	0.0000E+00
3749	8.3882E-02	6.4840E-02	0.0000E+00
3750	8.4196E-02	6.7425E-02	0.0000E+00
3751	8.4559E-02	7.0063E-02	0.0000E+00
3752	8.4820E-02	7.2757E-02	0.0000E+00
3753	8.4953E-02	7.5468E-02	0.0000E+00
3754	8.4965E-02	7.8150E-02	0.0000E+00
3755	8.4885E-02	8.0774E-02	0.0000E+00
3756	8.4854E-02	8.3343E-02	0.0000E+00
3757	8.5546E-02	8.5994E-02	0.0000E+00
3758	8.5987E-02	8.9132E-02	0.0000E+00
3759	8.6261E-02	9.2293E-02	0.0000E+00
3760	8.7392E-02	7.5464E-02	0.0000E+00
3761	8.7288E-02	7.2638E-02	0.0000E+00
3762	8.7000E-02	6.9830E-02	0.0000E+00
3763	8.6539E-02	6.7163E-02	0.0000E+00
3764	8.6015E-02	6.5020E-02	0.0000E+00
3765	8.7324E-02	7.8236E-02	0.0000E+00
3766	8.7115E-02	8.0864E-02	0.0000E+00
3767	8.6828E-02	8.2992E-02	0.0000E+00
3768	1.6424E-01	6.9094E-02	0.0000E+00
3769	1.5514E-01	6.9749E-02	0.0000E+00
3770	1.4660E-01	7.0475E-02	0.0000E+00
3771	1.4005E-01	7.1486E-02	0.0000E+00
3772	1.3457E-01	7.0988E-02	0.0000E+00
3773	1.2920E-01	7.0433E-02	0.0000E+00
3774	1.2383E-01	7.0111E-02	0.0000E+00
3775	1.1851E-01	7.0067E-02	0.0000E+00
3776	1.1332E-01	7.0305E-02	0.0000E+00
3777	1.0838E-01	7.0836E-02	0.0000E+00
3778	1.0389E-01	7.1622E-02	0.0000E+00
3779	9.9746E-02	7.2268E-02	0.0000E+00
3780	9.6100E-02	7.2337E-02	0.0000E+00
3781	1.1749E-01	5.3568E-02	0.0000E+00
3782	1.1789E-01	5.9337E-02	0.0000E+00
3783	1.1826E-01	6.4857E-02	0.0000E+00
3784	9.5800E-02	6.8756E-02	0.0000E+00
3785	9.5230E-02	6.5338E-02	0.0000E+00
3786	9.4595E-02	6.2099E-02	0.0000E+00
3787	9.4170E-02	5.8861E-02	0.0000E+00
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3793	1.1168E-01	5.3760E-02	0.0000E+00

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3795	1.1275E-01	6.5175E-02	0.0000E+00
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BDRY, 2,, 0.0000E+00
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*RESTART, WRITE, FREQUENCY=1
*STEP, AMPLITUDE=RAMP, NLGEOM, INC=300
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*BOUNDARY
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PUSHND, 1
PUSHND, 2,2,-0.02
SYMNODES, 1,, 0.0000E+00
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SYMNODES, 6,, 0.0000E+00
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*NODE PRINT, GLOBAL=NO, FREQUENCY=1, NSET=CLOSURE
U,COOR2
*NODE PRINT, GLOBAL=NO, FREQUENCY=1, NSET=SLIPNODE
U
*NODE PRINT, GLOBAL=NO, FREQUENCY=1, NSET=PLNODES
U
*EL PRINT, FREQUENCY=1, ELSET=SLIDEEL

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S
*NODE FILE, GLOBAL=YES, FREQUENCY=4
U
CF
RF
*EL FILE, POSITION=NODES, FREQUENCY=4
S
E
SF
LOADS
ENER
ELEN
NFORC
*END STEP

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*HEADING
PULL FUEL PLATE OUT OF SLOT
*PREPRINT, ECHO=NO, MODEL=NO
**
**RESTART, READ, STEP=1, INC=134, END STEP, WRITE, FREQUENCY=1
**
** STEP 2, FIX NODES AND REMOVE WHEEL AND EXTRA PLATE LENGTH
**
**
*STEP, AMPLITUDE=RAMP, NLGEOM, INC=1
*STATIC
1., 1., 1., 1.
*BOUNDARY, FIXED
FIX1,1,2
FIX2,1,2
*MODEL CHANGE, REMOVE
SURFACE, BEAM, EXTRA
*END STEP
**
**
** STEP 3, FUEL PLATE PULL
**
**
*STEP, AMPLITUDE=RAMP, NLGEOM, INC=200
*STATIC
0.001, 1.0, 0.00001, 0.01
*CONTROLS, ANALYSIS=DISCONTINUOUS
*BOUNDARY, OP=NEW
BDY, 1,, 0.0000E+00
BDY, 2,, 0.0000E+00
*CLOAD, OP=NEW
PULLNDS, 1, 2.0000E+02
*ENERGY PRINT, FREQUENCY=1
*NODE PRINT, GLOBAL=YES, FREQUENCY=1, NSET=SLIPNODE
U1
*EL PRINT, FREQUENCY=1, ELSET=SLIDEEL
S12
*END STEP

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APPENDIX B MATERIAL DATA CALCULATIONS

STRESS STATES IN THE CRITICAL REGION OF THE SIDE PLATE

Calculations are performed below to show trends in the state of stress along the potential failure plane of the side plate. These stress states are used to establish a lower bound for the failure strains in this critical region of the side plate. Pressing of the swage wheel into the side plate imposes a significant shear stress and therefore significant straining along the plane shown (dashed) below. The calculations below estimate the principal stresses along this plane. Only the stresses in the plane of the paper are considered.

Based on equilibrium requirements,

$$pd(.707) + F(.707) = V(.707) + qe$$

$$pd(.707) - F(.707) = V(.707)$$

On solving,

$$V = pd - .707qe$$

$$F = .707qe$$

The corresponding average shear stress (τ) and compressive stress (σ) on the plane are

$$\tau = \frac{V}{A}$$

$$\sigma = \frac{F}{A}$$

where A is the area of the plane. For a 1-in. length of the side plate, $A = h$. Based on the ABAQUS finite element calculations, the wheel force is typically about 2300 lb/in. The contact pressure, q , is about equal to the plastic stress for the fuel plate (per the stress-strain curve) of 20,000 psi. The quantities d and h are geometric dimensions for the wheel and side plate. The length e depends on the extent of contact between the side plate and fuel plate surfaces, which can be obtained from the finite element analyses. These quantities take the following typical values:

$$d = 0.029 \quad \text{in.}$$

$$h = 0.0474 \quad \text{in.}$$

$$e = 0.042 \quad \text{in.}$$

$$p = \frac{2300}{0.029} = 79,310 \quad \text{psi}$$

$$q = 20,000 \quad \text{psi}$$

On substitution of these quantities, the forces V and F become (for a 1-in. length)

$$V = 1706 \quad \text{lb}$$

$$F = 594 \quad \text{lb}$$

and the corresponding stresses become

$$\tau = 39,582 \quad \text{psi}$$

$$\sigma = -13,781 \quad \text{psi}$$

A negative sign is shown on the stress, σ , to indicate that it is a compressive stress.

Determining bending moment M requires distance h , which has value $h = 0.0474$ in. when the wheel is positioned at the center of the side plate lip. Then,

$$M = \frac{pd^2}{2} - qe(.0192) = \frac{79310(.029)^2}{2} - 20000(.042)(.0192) = 17.22 \quad \text{in.-lb}$$

Assuming this moment to be linearly distributed across distance h , this would produce the following maximum value for bending stress

$$\sigma_b = \frac{6M}{h^2} = 45990 \quad \text{psi}$$

At point A, then, the total stresses are approximately

$$\tau = 39,582 \quad \text{psi}$$

$$\sigma = -13781 - 45990 = -59770 \quad \text{psi}$$

while those at point B are

$$\tau = 39,582 \quad \text{psi}$$

$$\sigma = -13781 + 45990 = 32210 \quad \text{psi}$$

The stresses midway between A and B are as shown above

$$\tau = 39,582 \quad \text{psi}$$

$$\sigma = -13,781 \quad \text{psi}$$

These stresses are by no means exact because the bending stress distribution is not truly linear and the shear stress varies somewhat across the plane. The stresses are only used to establish the basic stress states.

The corresponding principal stresses can be found by using Mohr's circle. At the point midway between A and B:

Using the geometry of the circle,

$$\left(\frac{\sigma}{2}\right)^2 + \tau^2 = R^2$$

$$R = \sqrt{\left(\frac{\sigma}{2}\right)^2 + \tau^2}$$

$$\sigma_1 = \frac{\sigma}{2} - R$$

$$\sigma_2 = \frac{\sigma}{2} + R$$

from which the principal stresses become

$$\sigma_1 = -47,067 \quad \text{psi}$$

$$\sigma_2 = 33,286 \quad \text{psi}$$

The Mohr's circle is slightly to the left of a pure shear situation.

At point A:

The principal stresses become:

$$\sigma_1 = -79,480 \text{ psi}$$

$$\sigma_2 = 19,712 \text{ psi}$$

This is well to the left of a pure shear situation.

Finally, at point B:

and the principal stresses are

$$\sigma_1 = -26,630 \text{ psi}$$

$$\sigma_2 = 58,834 \text{ psi}$$

This Mohr's circle is to the left of but approaching a uniaxial tensile stress state. All three states are to the left of uniaxial tension on Mohr's circle and on a forming limit diagram.

APPENDIX C

SOFTWARE QA AND DATA FILES

This appendix consists of three parts:

- (1) Computer Program Quality Assurance Discussion and Description of Computer File Storage.
- (2) Tables 7 – 9 identifying computer files and showing gap data and strain energy for the side plate only models.
- (3) Tables 10 – 14 identifying computer files and showing results for models with both side plates and fuels plate.

The software requirements for this project are detailed in Quality Manual QP-21 (Ref. 18) and the Mechanical Engineering and Design Analysis Group Software Configuration Control, Validation, and Verification Policy (Ref. 19). Computer Software Configuration Summaries (as required by Ref. 19), which include software validation and verification information and meet or exceed the requirements of Ref. 18, are available from the Applied Mechanics Unit. ABAQUS version 5.2 and I-DEAS version 6.i are approved by this documentation for Quality Level A, B, and C application. In addition, this appendix includes a Computer Program Configuration Documentation which identifies the specific software and hardware used for this project.

ABAQUS is a general purpose code having nonlinear capabilities and an extensive element library. The code has had wide industrial use especially with nuclear applications and has been tested on numerous documented sample problems. ABAQUS version 4.9 recently received the Lloyd's Register Type Approval certificate after an extensive validation of the software including an assessment of the QA procedures used by Hibbitt, Karlsson, and Sorenson, Inc., the developer of ABAQUS.

The files listed in Tables 7 – 14 are stored on an 8mm archive tape in standard UNIX TAR format in ASCII. Three copies of this tape were made. One informal copy is stored with Applied Mechanics Unit files while two record copies were transferred to ATR personnel. These files are the input data used to generate all ABAQUS results (filename.inp) and the associated ABAQUS generated data files (filename.dat).

COMPUTER PROGRAM CONFIGURATION DOCUMENTATION

The following documentation presents the traceability for computer programs used in the analysis reported here.

Task: Structural Analysis

Report Title: ANALYSIS OF THE ATR FUEL ELEMENT SWAGING PROCESS

Authors: W. D. Richins & G. K. Miller **Date:** December 1995

Program Used: I-DEAS **Version:** VI.1

Computer Used: WCD512

Model: DECstation 5000/200

Verification Manual/Test Problem Manual/Example Manual:

W. D. Richins letter to Applied Mechanics, December 18, 1991, "Verification of SDRC I-DEAS VI Software," WDR-28-91

Author: W. D. Richins **Date:** December 18, 1991

Comments: Also have "SDRC I-DEAS V Verification Manual"

Program Used: ABAQUS **Version:** 5.2

Computer Used: CRAY XMP **Model:** 2/16

Verification Manual/Test Problem Manual/Example Manual:

ABAQUS Example Problems Manual, Providence Rhode Island, Hibbitt, Karlsson, and Sorenson, Inc., 1992.

Table 7 .Results from Side Plate Only Model for Side Plate Groove 1

MODEL s1w1, wheel 1	
GAP mils	ENERGY in – lbs/in
78.21	5.72
76.92	7.20
76.00	8.27
75.08	9.37
74.16	10.5
73.24	11.6
72.31	12.7
71.84	13.3
70.91	14.5
69.99	15.6
69.08	16.8
68.16	18.1
67.24	19.3
66.32	20.5
64.92	22.4
63.97	23.6
63.39	24.3

Table 8 .Results from Side Plate Only Models for Side Plate Groove 9

MODEL s9w1, wheel 1	
GAP mils	ENERGY in - lbs/in
49.52	4.47
49.06	4.97
48.59	5.48
48.13	6.00
47.85	6.33
47.21	7.08
46.75	7.62
46.28	8.16
45.82	8.72
45.36	9.27
44.89	9.83
44.42	10.4
44.30	10.5
44.13	10.7
43.86	11.1
42.99	12.1
42.06	13.3
41.12	14.4
40.18	15.6
39.71	16.2
39.23	16.8
38.75	17.4
38.27	18.0
37.79	18.6
37.30	19.1
36.82	19.7
36.33	20.3
35.86	20.8
35.39	21.4
34.92	22.0
34.45	22.5
33.99	23.1
33.06	24.3

MODEL s9w2, wheel 2	
GAP mils	ENERGY in – lbs/in
47.13	7.98
46.19	9.17
45.23	10.4
44.27	11.6
43.80	12.2
43.31	12.8
42.83	13.4
42.35	14.0
41.86	14.7
40.88	15.9
40.39	16.5
39.89	17.1
38.91	18.4
38.43	19.0
37.95	19.6
37.48	20.2
37.01	20.9

MODEL s9w3, wheel 3	
GAP mils	ENERGY in – lbs/in
46.25	7.53
45.80	8.03
45.35	8.54
44.90	9.05
43.98	10.1
43.07	11.1
42.50	11.8
42.07	12.3
41.22	13.3
40.29	14.4
39.35	15.4
38.39	16.5
37.42	17.5

MODEL s9w4, wheel 4	
GAP mils	ENERGY in - lbs/in
45.77	8.63
45.29	9.16
44.81	9.68
43.85	10.7
42.89	11.8
41.92	12.9
40.95	14.0
39.97	15.1
38.99	16.2
38.00	17.2

MODEL s9w5, wheel 5	
GAP mils	ENERGY in - lbs/in
46.14	9.06
45.25	10.3
44.80	10.9
42.98	13.5
42.07	14.8
41.50	15.6
40.69	16.8
39.78	18.2
39.34	18.9
38.89	19.6
38.00	21.1

MODEL s9ws, wheel 6	
GAP mils	ENERGY in – lbs/in
48.80	4.99
47.90	5.96
46.98	6.96
46.06	7.98
45.16	9.03
44.26	10.1
43.33	11.2
42.86	11.7
41.92	12.8
41.00	13.9
40.07	15.0
39.13	16.1
38.18	17.2
37.25	18.3
36.33	19.4

MODEL s9tol1, wheel 1 (tolerance model 1)	
GAP mils	ENERGY in - lbs/in
49.79	9.02
48.84	10.1
47.88	11.1
46.92	12.2
45.95	13.3
44.98	14.4
44.00	15.5
43.02	16.6
42.04	17.7
41.07	18.8
40.11	20.0
39.14	21.1
38.18	22.3
37.60	23.1

MODEL s9tol2, wheel 1 (tolerance model 2)	
GAP mils	ENERGY in - lbs/in
49.08	1.16
48.57	1.62
48.24	1.96
47.70	2.51
46.78	3.48
46.34	3.97
45.67	4.75
45.22	5.28
44.32	6.37
43.41	7.50
42.96	8.07
42.06	9.24
41.15	10.4
40.24	11.6
39.33	12.8
38.41	14.0
37.48	15.2
36.57	16.5

Table 9 .Results from Side Plate Only Model for Side Plate Groove 19

MODEL s19w1, wheel 1	
GAP mils	ENERGY in - lbs/in
98.75	3.76
98.41	4.08
97.91	4.53
97.55	4.87
97.09	5.34
96.28	6.17
95.33	7.15
94.87	7.65
94.46	8.10
93.81	8.83
92.88	9.89
91.95	11.0
91.37	11.7
91.19	11.9
90.54	12.6
89.63	13.8
88.71	14.9
87.80	16.1
86.89	17.2
85.98	18.4
85.52	19.0
84.60	20.2
84.14	20.7
83.68	21.3
83.22	21.9
82.74	22.5
82.71	22.6

Table 10 .Results from Models for Side Plate Groove 1 with Fuel Plate 1

FILE ID	DESCRIPTION	GAP mils	PULLOUT lbs	ENERGY in - lbs/in	ABAQUS INCREMENT (f model)
FUEL PLATE FULLY INSERTED MODELS					
f161w1	side plate with fuel plate, wheel 1, using s1w1 data				
p061	fuel plate pulled	78.40	234	5.51	81
p261	fuel plate pulled	76.98	358	7.13	99
p361	fuel plate pulled	75.98	401	8.30	105
p461	fuel plate pulled	75.08	455	9.38	111
p561	fuel plate pulled	73.99	522	10.7	115
p661	fuel plate pulled	73.15	568	11.7	126
p761	fuel plate pulled	71.84	603	13.3	129
p861	fuel plate pulled	70.99	643	14.4	135
p1061	fuel plate pulled	69.46	667	16.3	141
p1161	fuel plate pulled	67.55	691	18.9	144
p1261	fuel plate pulled	64.60	733	22.8	148
p1361	fuel plate pulled	63.72	739	23.9	149
p1461	fuel plate pulled	62.80	745	25.0	150

FILE ID	DESCRIPTION	GAP mils	PULLOUT lbs	ENERGY In - lbs/in	ABAQUS INCREMENT (f model)
FUEL PLATE OUT 20 mil					
f361w1	side plate with fuel plate, wheel 1, using s1w1 data				
p31161	fuel plate pulled	75.12	417	9.33	111
p31261	fuel plate pulled	71.99	542	13.1	131
p31361	fuel plate pulled	68.87	619	17.1	143
p31461	fuel plate pulled	66.47	637	20.3	154
p31561	fuel plate pulled	65.00	643	22.3	158
p31661	fuel plate pulled	63.80	649	23.8	161
p31761	fuel plate pulled	63.22	651	24.5	162
FUEL PLATE OUT 40 mil					
f561w1	side plate with fuel plate, wheel 1, using s1w1 data				
p511e61	fuel plate pulled	75.62	266	8.73	101
p511d61	fuel plate pulled	73.91	394	10.8	115
p51261	fuel plate pulled	71.84	479	13.3	121
p51361	fuel plate pulled	69.15	457	16.7	132

Table 11 .Results from Models for Side Plate Groove 9 with Fuel Plate 9

FILE ID	DESCRIPTION	GAP mils	PULLOUT lbs	ENERGY in - lbs/in	ABAQUS INCREMENT (f model)
FUEL PLATE FULLY INSERTED MODELS					
f169w1	side plate with fuel plate, wheel 1, using s9w1 data				
pa169	fuel plate pulled	48.58	90	5.50	54
pb169	fuel plate pulled	48.12	157	6.02	65
pc169	fuel plate pulled	47.65	235	6.56	73
pd169	fuel plate pulled	47.28	281	6.99	81
pe169	fuel plate pulled	46.86	333	7.49	91
p169	fuel plate pulled	46.01	422	8.49	107
p269	fuel plate pulled	45.02	483	9.67	116
p369	fuel plate pulled	44.06	518	10.8	125
p469	fuel plate pulled	42.99	544	12.1	128
p569	fuel plate pulled	41.89	575	13.5	134
p669	fuel plate pulled	41.12	589	14.4	136
p769	fuel plate pulled	40.34	602	15.4	138
p869	fuel plate pulled	38.83	634	17.3	140
p969	fuel plate pulled	37.95	647	18.4	141
p1069	fuel plate pulled	36.98	656	19.5	142
p1269	fuel plate pulled	36.14	666	20.5	143
p1369	fuel plate pulled	35.00	687	21.9	145
p1469	fuel plate pulled	34.07	695	23.0	147
p1569	fuel plate pulled	32.52	709	25.0	149

FILE ID	DESCRIPTION	GAP mils	PULLOUT lbs	ENERGY in - lbs/in	ABAQUS INCREMENT (f model)
FUEL PLATE FULLY INSERTED MODELS, CONT.					
f169w1, cont.					
p2a69	p269 with Tmax of 15000 psi, Friction =1.0	45.02	490	9.67	116
p2b69	p269 with Tmax of 5000 psi, Friction =1.0	45.02	no conv.	9.67	116
p2c69	p269 with Tmax of 8000 psi, Friction =1.0	45.02	470	9.67	116
p2d69	p269 with Tmax of 10000 psi, Friction =0.75	45.02	442	9.67	116
p2e69	p269 with Tmax of 10000 psi, Friction =0.50	45.02	377	9.67	116
p169off	offset tension load model, fuel plate pulled	45.02	396	9.67	116
p269off	offset tension load model, fuel plate pulled	41.89	494	13.5	134
p369off	offset tension load model, fuel plate pulled	38.83	567	17.3	140
f169ps2	side plate plus fuel plate, wheel 1, pressure model				
p169pr1f	differential pressure model 1 (concave side)	failure during incr 81, see text for results			
p169pr2f	differential pressure model 2 (convex side)	failure during incr 88, see text for results			

FILE ID	DESCRIPTION	GAP mils	PULLOUT lbs	ENERGY in - lbs/in	ABAQUS INCREMENT (f model)
FUEL PLATE FULLY INSERTED MODELS, CONT.					
f169w2	side plate with fuel plate, wheel 2, using s9w2 data				
p2169	fuel plate pulled	45.23	514	10.4	99
p2269	fuel plate pulled	41.86	610	14.7	114
p2369	fuel plate pulled	39.29	659	17.9	119
f169w3	side plate with fuel plate, wheel 3, using s9w3 data				
p3169	fuel plate pulled	45.12	458	8.80	101
p3269	fuel plate pulled	41.81	554	12.6	113
p3369	fuel plate pulled	39.54	603	15.2	118
f169w4	side plate with fuel plate, wheel 4, using s9w4 data				
p4169	fuel plate pulled	45.16	433	9.30	103
p4269	fuel plate pulled	41.92	552	12.9	117
p4369	fuel plate pulled	39.17	602	16.0	127
f169w5	side plate with fuel plate, wheel 5, using s9w5 data				
p5169	fuel plate pulled	45.10	496	10.5	141
p5269	fuel plate pulled	41.93	593	15.0	154
p5369	fuel plate pulled	39.02	657	19.4	160
f169ws	side plate with fuel plate, wheel 6, using s9ws data				
p169ws	fuel plate pulled	45.12	452	9.08	107
p269ws	fuel plate pulled	41.92	567	12.8	127
p369ws	fuel plate pulled	38.95	623	16.3	133

FILE ID	DESCRIPTION	GAP mils	PULLOUT lbs	ENERGY In - lbs/in	ABAQUS INCREMENT (f model)
FUEL PLATE OUT 10 mil					
f269w1	side plate with fuel plate, wheel 1, using s9w1 data				
p21169	fuel plate pulled	45.03	463	9.66	79
p21269	fuel plate pulled	42.06	544	13.3	91
p21369	fuel plate pulled	38.83	600	17.3	97
f269w2	side plate with fuel plate, wheel 2, using s9w2 data				
p22169	fuel plate pulled	44.99	505	10.7	97
p22269	fuel plate pulled	42.28	575	14.1	109
p22369	fuel plate pulled	39.06	625	18.2	115
f269w3	side plate with fuel plate, wheel 3, using s9w3 data				
p23169	fuel plate pulled	45.02	446	8.91	101
p23269	fuel plate pulled	42.07	532	12.3	109
p23369	fuel plate pulled	39.63	581	15.1	114

FILE ID	DESCRIPTION	GAP mils	PULLOUT lbs	ENERGY in - lbs/in	ABAQUS INCREMENT (f model)
FUEL PLATE OUT 20 mil					
f369w1	side plate with fuel plate, wheel 1, using s9w1 data				
p31169	fuel plate pulled	45.10	430	9.58	88
p31269	fuel plate pulled	41.80	510	13.6	104
p31369	fuel plate pulled	38.99	542	17.1	109
p31469	fuel plate pulled	37.40	554	19.0	111
p31569	fuel plate pulled	36.58	559	20.0	112
p31669	fuel plate pulled	34.92	568	22.0	114
p31769	fuel plate pulled	34.07	574	23.0	115
p31869	fuel plate pulled	32.52	583	25.0	117
f369w2	side plate with fuel plate, wheel 2, using s9w2 data				
p32169	fuel plate pulled	45.07	456	10.6	103
p32269	fuel plate pulled	42.07	520	14.4	114
p32369	fuel plate pulled	38.99	567	18.3	120
f369w3	side plate with fuel plate, wheel 3, using s9w3 data				
p33169	fuel plate pulled	45.10	417	8.82	97
p33269	fuel plate pulled	41.90	495	12.5	104
p33369	fuel plate pulled	39.17	533	15.6	108

FILE ID	DESCRIPTION	GAP mils	PULLOUT lbs	ENERGY in - lbs/in	ABAQUS INCREMENT (f model)
FUEL PLATE OUT 30 mil					
f469w1	side plate with fuel plate, wheel 1, using s9w1 data				
p41169	fuel plate pulled	45.06	379	9.63	87
p41269	fuel plate pulled	41.98	446	13.4	93
p41369	fuel plate pulled	38.43	480	17.8	98
f469w2	side plate with fuel plate, wheel 2, using s9w2 data				
p42169	fuel plate pulled	45.23	388	10.4	83
p42269	fuel plate pulled	42.21	462	14.2	92
p42369	fuel plate pulled	39.59	494	17.5	97
f469w3	side plate with fuel plate, wheel 3, using s9w3 data				
p43169	fuel plate pulled	44.58	387	9.41	87
p43269	fuel plate pulled	42.07	436	12.3	91
p43369	fuel plate pulled	38.48	469	16.4	96

FILE ID	DESCRIPTION	GAP mils	PULLOUT lbs	ENERGY In - lbs/in	ABAQUS INCREMENT (f model)
FUEL PLATE OUT 40 mil					
f569w1	side plate with fuel plate, wheel 1, using s9w1 data				
p51169	fuel plate pulled	44.94	320	9.77	88
p51269	fuel plate pulled	42.06	366	13.3	96
p51369	fuel plate pulled	39.15	360	16.9	106
f569w2	side plate with fuel plate, wheel 2, using s9w2 data				
p52169	fuel plate pulled	45.07	303	10.6	72
p52269	fuel plate pulled	41.54	372	15.1	85
p52369	fuel plate pulled	38.35	361	19.1	90
f569w3	side plate with fuel plate, wheel 3, using s9w3 data				
p53169	fuel plate pulled	45.30	304	8.59	76
p53269	fuel plate pulled	42.15	358	12.2	83
p53369	fuel plate pulled	39.26	365	15.5	90

Table 12 .Results from Models for Side Plate Groove 9 with Fuel Plate 9, Tolerance Model 1

FILE ID	DESCRIPTION	GAP mils	PULLOUT lbs	ENERGY In - lbs/in	ABAQUS INCREMENT (f model)
FUEL PLATE FULLY INSERTED MODELS					
f169tol1	side plate with fuel plate, wheel 1, using s9tol1 data				
p169t1	fuel plate pulled	48.35	50	10.6	50
p269t1	fuel plate pulled	47.01	114	12.1	60
p369t1	fuel plate pulled	45.95	206	13.3	68
p469t1	fuel plate pulled	45.07	248	14.3	84
p569t1	fuel plate pulled	44.08	301	15.4	98
p669t1	fuel plate pulled	43.02	358	16.6	111
p769t1	fuel plate pulled	42.04	406	17.7	122
p869t1	fuel plate pulled	41.07	446	18.8	134
p969t1	fuel plate pulled	40.11	477	20.0	144
p1069t1	fuel plate pulled	39.06	501	21.2	150
p1169t1	fuel plate pulled	38.11	518	22.4	156
p1269t1	fuel plate pulled	37.01	545	23.9	161

FILE ID	DESCRIPTION	GAP mils	PULLOUT lbs	ENERGY In - lbs/in	ABAQUS INCREMENT (f model)
FUEL PLATE OUT 20 mil					
f369tol1	side plate with fuel plate, wheel 1, using s9tol1 data				
p3169t1	fuel plate pulled	44.98	254	14.4	96
p3269t1	fuel plate pulled	42.04	380	17.7	125
p3369t1	fuel plate pulled	39.32	432	20.9	138
FUEL PLATE OUT 40 mil					
f569tol1	side plate with fuel plate, wheel 1, using s9tol1 data				
p5169t1	fuel plate pulled	45.07	174	14.3	88
p5269t1	fuel plate pulled	42.13	282	17.6	101
p5369t1	fuel plate pulled	39.06	324	21.2	109

Table 13 .Results from Models for Side Plate Groove 9 with Fuel Plate 9, Tolerance Model 2

FILE ID	DESCRIPTION	GAP mils	PULLOUT lbs	ENERGY in – lbs/in	ABAQUS INCREMENT (f model)
FUEL PLATE FULLY INSERTED MODELS					
f169tol2	side plate with fuel plate, wheel 1, using s9tol2 data				
p169t2	fuel plate pulled	48.20	463	2.00	46
p269t2	fuel plate pulled	47.33	525	2.90	53
p369t2	fuel plate pulled	45.94	578	4.44	59
p469t2	fuel plate pulled	44.61	618	6.02	61
p569t2	fuel plate pulled	44.02	631	6.74	64
p669t2	fuel plate pulled	43.24	647	7.72	67
p769t2	fuel plate pulled	41.90	684	9.45	69
p869t2	fuel plate pulled	41.08	697	10.5	70
p969t2	fuel plate pulled	40.32	708	11.5	71
p1069t2	fuel plate pulled	38.64	730	13.7	73
p1169t2	fuel plate pulled	37.64	741	15.0	76

Table 14 .Results from Models for Side Plate Groove 19 with Fuel Plate 19

FILE ID	DESCRIPTION	GAP mils	PULLOUT lbs	ENERGY in - lbs/in	ABAQUS INCREMENT (f model)
FUEL PLATE FULLY INSERTED MODELS					
f179w1	side plate with fuel plate, wheel 1, using s19w1 data				
p379	fuel plate pulled	97.55	230	4.86	95
p479	fuel plate pulled	97.07	265	5.36	105
p579	fuel plate pulled	96.28	347	6.16	113
p679	fuel plate pulled	94.88	415	7.64	128
p879	fuel plate pulled	93.77	445	8.87	136
p1079	fuel plate pulled	91.95	517	11.0	149
p1279	fuel plate pulled	90.64	552	12.5	153
p1479	fuel plate pulled	87.63	612	16.3	167
p1579	fuel plate pulled	86.21	639	18.1	169
p1679	fuel plate pulled	84.68	654	20.1	171
p1779	fuel plate pulled	83.76	661	21.2	172
p1879	fuel plate pulled	82.90	678	22.3	173

FILE ID	DESCRIPTION	GAP mils	PULLOUT lbs	ENERGY in - lbs/in	ABAQUS INCREMENT (f model)
FUEL PLATE OUT 20 mil					
f379w1	side plate with fuel plate, wheel 1, using s19w1 data				
p31179	fuel plate pulled	95.08	389	7.42	117
p31279	fuel plate pulled	92.20	464	10.7	143
p31379	fuel plate pulled	88.96	524	14.6	154
p31479	fuel plate pulled	87.88	555	16.0	162
p31579	fuel plate pulled	86.28	577	18.0	165
p31679	fuel plate pulled	84.60	616	20.2	169
p31779	fuel plate pulled	83.76	624	21.2	171
p31879	fuel plate pulled	83.06	630	22.1	172
FUEL PLATE OUT 40 mil					
f579w1	side plate with fuel plate, wheel 1, using s19w1 data				
p51079	fuel plate pulled	95.09	207	7.41	119
p510a79	fuel plate pulled	94.06	352	8.55	125
p51179	fuel plate pulled	93.26	389	9.43	128
p51279	fuel plate pulled	90.47	432	13.3	141
p51379	fuel plate pulled	87.22	480	16.7	151

APPENDIX D

B&W Side Plate Groove Gap Data

This appendix consists of two parts:

- (1) A copy of Ref. 16 showing B&W measured side plate groove gaps for five consecutively manufactured ATR fuel elements completed in 1994.
- (2) Excerpts from Ref. 17 showing B&W measured side plate groove gaps for fuel elements using fuel plates with pre-swaged grooves.

REFERENCE 16

Babcock & Wilcox

a McDermott company

Naval Nuclear Fuel Division

April 6, 1994

P. O. Box 785
Lynchburg, Virginia 24505-0785
(804) 522-6000

A.J. Vinnola, Jr.
EG&G Idaho, Inc.
P.O. Box 1625
Idaho Falls, Idaho 83415-2072

RE: EG&G Request For Swage Closure Data

Gentlemen:

Enclosed is the requested closure data on five (5) consecutive fuel elements. Telecon with EG&G identified the required data as follows:

1. Direction of swage.
2. Can closure limits be established on both ends?
3. Closure readings to be taken on the left/right side plate and on both ends if feasible.
4. Identify which plates require a seating pass and provide closure readings before and after the seating pass.

All of the above information is provided on the swage groove closure data sheets. Additional information is provided; such as, side plate thickness and swage parameters if needed.

Please advise if B&W can be of further assistance.

Sincerely yours,

BABCOCK & WILCOX COMPANY

E.E. Hamlett
RTRFE Manufacturing Engineer

EEH11/dac

pc: D. Ren
G. Gale

J. Mays
K. Catlett

SWAGE GROOVE CLOSURE DATAELEMENT S/N: XA-926RSIDE PLATE THICKNESS: .185 RIGHT .1845 LEFTSWAGE WHEEL TO WALL SETTING: .1545SWAGE WHEEL TO BASE SETTING: .150SWAGE DIRECTION: AFT TO FORWARD/BOTTOM END TO TOP END

FORWARD END

AFT END

PLT POS	LEFT SIDE	RIGHT SIDE	SEATING PASS	LEFT SIDE	RIGHT SIDE
1	.075/.072	.075/.072	*	.077/.074	.075/.073
2	.043	.043		.044	.043
3	.043	.042		.044	.043
4	.043	.043		.044	.044
5	.043	.042		.044	.043
6	.042	.042		.043	.043
7	.042	.042		.043	.044
8	.043	.042		.044	.044
9	.043	.042		.044	.044
10	.043	.043		.044	.044
11	.043	.043		.044	.044
12	.043	.043		.044	.044
13	.043	.043		.044	.044
14	.043	.044		.044	.045
15	.043	.044		.044	.045
16	.042	.043		.043	.044
17	.042	.043		.043	.044
18	.043/.040	.044/.042	*	.045/.042	.046/.044
19	.093/.091	.095/.093	*	.095/.092	.096/.093

- NOTES: 1. Asterisk indicates a seating pass was performed
 2. Note that the closure readings are .001" - .002" greater on the aft end whereas the increase in the readings can be expected.
 3. A before and after reading was performed respectively after each seating pass.

SWAGE GROOVE CLOSURE DATA

ELEMENT S/N: XA-927RSIDE PLATE THICKNESS: .185 RIGHT .185 LEFTSWAGE WHEEL TO WALL SETTING: .1545SWAGE WHEEL TO BASE SETTING: .150SWAGE DIRECTION: AFT TO FORWARD/BOTTOM END TO TOP END

FORWARD END

AFT END

PLT POS	LEFT SIDE	RIGHT SIDE	SEATING PASS	LEFT SIDE	RIGHT SIDE
1	.075/.072	.075/.072	*	.077/.075	.074/.072
2	.042	.042		.044	.043
3	.043	.042		.044	.043
4	.044	.043		.045	.044
5	.043	.042		.044	.044
6	.042	.042		.044	.043
7	.042	.042		.043	.043
8	.043	.042		.044	.044
9	.043	.042		.044	.043
10	.044	.043		.045	.044
11	.043	.043		.043	.044
12	.043	.044		.044	.044
13	.043	.044		.044	.044
14	.042	.044		.043	.044
15	.042	.044		.044	.045
16	.042	.043		.043	.045
17	.042	.043		.042	.044
18	.043/.040	.045/.043	*	.045/.041	.046/.044
19	.093/.091	.095/.093	*	.095/.092	.096/.094

- NOTES: 1. Asterisk indicates a seating pass was performed.
 2. Note that the closure readings are .001" - .002" greater on the aft end whereas the increase in the readings can be expected.
 3. A before and after reading was performed respectively after each seating pass.

SWAGE GROOVE CLOSURE DATA

APR 07 '94 11:05AM

ELEMENT S/N: XA-928RSIDE PLATE THICKNESS: .185 RIGHT .185 LEFTSWAGE WHEEL TO WALL SETTING: .1545SWAGE WHEEL TO BASE SETTING: .150SWAGE DIRECTION: AFT TO FORWARD/BOTTOM END TO TOP END

FORWARD END

AFT END

PLT POS	LEFT SIDE	RIGHT SIDE	SEATING PASS	LEFT SIDE	RIGHT SIDE
1	.075/.072	.075/.072	*	.077/.074	.075/.073
2	.043	.042		.044	.044
3	.043	.042		.043	.043
4	.043	.042		.044	.044
5	.043	.041		.044	.044
6	.042	.042		.043	.043
7	.043	.042		.043	.043
8	.043	.043		.044	.044
9	.042	.042		.043	.044
10	.043	.044		.044	.043
11	.042	.043		.043	.043
12	.043	.043		.044	.044
13	.042	.043		.043	.044
14	.042	.043		.043	.045
15	.042	.044		.043	.044
16	.042	.044		.043	.044
17	.041	.043		.043	.044
18	.042/.040	.044/.042	*	.045/.042	.046/.044
19	.093/.090	.095/.093	*	.094/.093	.096/.094

- NOTES: 1. Asterisk indicates a seating pass was performed
 2. Note that the closure readings are .001" - .002" greater on the aft end whereas the increase in the readings can be expected.
 3. A before and after reading was performed respectively after each seating pass.

SERLOC

SWAGE GROOVE CLOSURE DATAELEMENT S/N: XA-930RSIDE PLATE THICKNESS: .185 RIGHT .184 LEFTSWAGE WHEEL TO WALL SETTING: .1545SWAGE WHEEL TO BASE SETTING: .150SWAGE DIRECTION: AFT TO FORWARD/BOTTOM END TO TOP END**FORWARD END****AFT END**

PLT POS	LEFT SIDE	RIGHT SIDE	SEATING PASS	LEFT SIDE	RIGHT SIDE
1	.075/.072	.074/.071	*	.077/.074	.075/.071
2	.043	.042		.044	.043
3	.042	.041		.044	.043
4	.044	.042		.045	.043
5	.042	.041		.044	.043
6	.043	.042		.044	.043
7	.043	.042		.044	.043
8	.043	.042		.044	.044
9	.042	.041		.043	.044
10	.043	.043		.044	.043
11	.042	.042		.044	.044
12	.043	.043		.044	.044
13	.043	.043		.044	.043
14	.042	.043		.044	.044
15	.043	.043		.044	.044
16	.042	.042		.043	.043
17	.041	.042		.043	.043
18	.043	.044		.045	.045
19	.094/.091	.095/.092	*	.095/.093	.095/.093

- NOTES: 1. Asterisk indicates a seating pass was performed
 2. Note that the closure readings are .001" - .002" greater on the aft end whereas the increase in the readings can be expected.
 3. A before and after reading was performed respectively after each seating pass.

KEH108

TOTAL P.07

SWAGE GROOVE CLOSURE DATA

APR 07 '94 11:06AM

ELEMENT S/N: XA-929RSIDE PLATE THICKNESS: .185 RIGHT .185 LEFTSWAGE WHEEL TO WALL SETTING: .1545SWAGE WHEEL TO BASE SETTING: .150SWAGE DIRECTION: AFT TO FORWARD/BOTTOM END TO TOP END

FORWARD END

AFT END

PLT POS	LEFT SIDE	RIGHT SIDE	SEATING PASS	LEFT SIDE	RIGHT SIDE
1	.074/.071	.074/.071	*	.077/.074	.075/.073
2	.043	.043		.044	.043
3	.043	.043		.044	.043
4	.043	.043		.044	.044
5	.043	.042		.043	.043
6	.043	.043		.044	.043
7	.042	.042		.043	.044
8	.043	.043		.044	.044
9	.042	.042		.044	.043
10	.042	.043		.043	.044
11	.043	.043		.044	.044
12	.043	.044		.043	.044
13	.043	.044		.044	.044
14	.043	.044		.043	.044
15	.043	.045		.044	.045
16	.041	.044		.042	.044
17	.041	.044		.043	.045
18	.042/.040	.046/.044	*	.045/.042	.046/.044
19	.093/.091	.096/.094	*	.095/.092	.097/.095

- NOTES: 1. Asterisk indicates a seating pass was performed
 2. Note that the closure readings are .001" - .002" greater on the aft end whereas the increase in the readings can be expected.
 3. A before and after reading was performed respectively after each seating pass.

G. N. FILLMORE

FUEL PLATE PRE-SWAGE GROOVE
QUALIFICATION REPORT

op. 6101

RECEIVED 10.3.88
EG & G IDAHO, INC.
CONTRACT NO. DE-AC07-76ID01570
P.O. NO. C49000 NB
SPEC. NO.
EQUIP. ITEM NO.
C. S. NO. 22-12.01

EXCERPTS FROM REFERENCE 17

ATTACHMENT I
(INTRODUCTION)

SDT- 661
PAGE 3 OF 8

ENCLOSED WITH THIS SUBMITTAL IS THE DOCUMENTATION AND DATA WHICH FORMULATE THE ATR FUEL PLATE PRE-SWAGE GROOVE QUALIFICATION RESULTS. B&W CHOSE TO ADDITIONALLY QUALIFY THE FUEL PLATES WITH EXISTING COMB PIN HOLES CONTRARY TO THE WORK SCOPE IDENTIFIED VIA TASK ORDER #31 OF SUB CONTRACT C29-000113. THE FULL LENGTH DUMMY ELEMENT SHALL BE REPRESENTATIVE OF THE TWO PHASE QUALIFICATION METHOD.

B&W SHALL UPGRADE THE EXISTING SWAGE PROCEDURE OP-6101 SUBMITTED VIA SDT-315 PENDING ANY PARAMETER CHANGES SUBJECT TO THE QUALIFICATION TECHNIQUE RATHER THAN FORMULATE AND SUBMIT AN ADDITIONAL SWAGE OPERATION PROCEDURE. THE EXISTING DISASSEMBLY PROCEDURE OP-6108 SUBMITTED VIA SDT-322 SHALL BE USED IN THE DISASSEMBLY OF DUMMY ELEMENTS 3-A AND 4-A. SATISFACTORY RESULTS OBTAINED VIA THE DISASSEMBLY OF THESE TWO (2) DUMMY ELEMENTS SHALL VOID FURTHER UPGRADE OF OP-6108, EXCEPT REUSE OF FUEL PLATES WITH EXISTING COMB PIN HOLES AND REFORMING IF NECESSARY PENDING QUALIFICATION DISPOSITION.

BASED ON THE RESULTS OF THE QUALIFICATION AND EG&G DISPOSITION OF REVISED PROCEDURES, B&W WILL ADDITIONALLY QUALIFY THE WORK SCOPE IDENTIFIED VIA TASK ORDER #26 WITHOUT FURTHER TESTING.

PERFORMANCE OF THIS TASK WAS DELINEATED FROM BABCOCK & WILCOX PROPOSAL NO. CP-276, DATED APRIL 7, 1988. THE REASSEMBLED ELEMENT SHALL BE FORWARDED TO EG&G IDAHO INC. FOR ADDITIONAL TESTING. B&W ADDITIONALLY REQUEST THAT THE COMB/PIN INSTALLATION BE EVALUATED TO QUALIFY EXISTING PRE-DRILLED HOLES IN THE DUMMY FUEL PLATES.

QUALIFIED PERSONNEL AND APPROVED PROCEDURES WERE USED FOR THE PRE-SWAGE GROOVE QUALIFICATION OF FUEL PLATES.

ATTACHMENT II
(WORK SCOPE)

8
SDT- 661
PAGE 4 OF 8

THE WORK SCOPE CONSISTED OF A TWO PHASE QUALIFICATION PROGRAM THAT DEPICTS A METHOD WHICH ALLOWS THE UTILIZATION OF PREVIOUSLY SWAGED FUEL PLATES WITH PIN HOLES. THE WORK SCOPE CONSISTED OF DISASSEMBLY OF DUMMY FUEL ELEMENTS XX-003A AND XX-004A WHERE FOUR LEU UALx FUEL PLATES WERE REMOVED FROM EACH ELEMENT FOR URANIUM RECOVERY. EIGHT DUMMY PLATES WERE FABRICATED TO REPLACE THE FOUR (4) LEU UALx FUEL PLATES IN THE FULL LENGTH ELEMENT AND PROVIDE SUFFICIENT QUANTITIES FOR EVALUATING THE MECHANICAL INTEGRITY OF THE SWAGE JOINT. THE REPLACEMENT DUMMY PLATES (REPRESENT PLATE TYPES 62, 67, 75, AND 78) SHALL BE USED IN THE TEST PHASE ASSEMBLIES AND WILL NOT HAVE PRE-SWAGE GROOVE MARKS OR PRE DRILLED COMB PIN HOLES.

THE DISASSEMBLY OF THE FOREMENTIONED ELEMENTS WAS PERFORMED VIA ROUTE CARD 317-08 AND OPERATION PROCEDURE (6108). A PROCESS MOVE TICKET WAS ISSUED IN CONJUNCTION WITH THE TENSILE TEST EVALUATION. ONE EACH OF TENSILE TYPE "A" AND "E" WAS EVALUATED WITH NO PARAMETER CHANGE TO ESTABLISH THE NEED OF CHANGE. SUBSEQUENTLY ONE EACH OF TENSILE SAMPLE "B" AND "E" WAS PROCESSED WITH A SWAGE- WHEEL- TO- FIXTURE PARAMETER CHANGE WHEREAS THESE SAMPLES WILL BE COMPARED WITH THE PREVIOUS SAMPLES. THE SWAGE- WHEEL- TO- FIXTURE DIMENSION WAS SET AT .145 INCH +/- .001 INCH IN LIEU OF THE EXISTING .150 INCH +/- .001 INCH WHICH ALLOWS AN EXTENDED PENETRATION OF THE SWAGE WHEEL INTO THE SIDE PLATE. ONE "E" SAMPLE WAS PROCESSED WITHOUT PARAMETER CHANGE HOWEVER THIS SAMPLE WAS SUBJECTED TO A SEATING PASS OF THE SWAGE JOINT. THE SEATING PASS WAS PERFORMED BY REVERSING THE SWAGE CARRIAGE WITH THE SWAGE WHEELS ACTIVATED AT EACH POSITION.

ENGINEERING EVALUATED ALL SAMPLES VIA THE MECHANICAL INTEGRITY OF THE SWAGE JOINT AND VISUAL EXAMINATION. GROOVE CLOSURE DATA WAS INCLUDED VIA THE LAST FOUR SAMPLES PROCESSED FOR INFORMATION. B&W BELIEVES THAT THE EXISTING GROOVE IN FUEL PLATES WILL NOT REDUCE THE SWAGE JOINT STRENGTH USING EXISTING PARAMETERS, AS EXPERIENCED ON OTHER CONTRACTS. PROVIDING THAT THE SAMPLES PROCESSED WITHOUT CHANGE IS OF EQUAL VALUE OF THOSE PROCESSED WITH CHANGE WILL DEPICT THE PROCESS METHOD TO MANUFACTURE THE FULL LENGTH DUMMY ELEMENT. SUBSEQUENTLY, FOUR (4) ADDITIONAL TENSILE SAMPLES WILL BE TESTED TO THE SELECTED METHOD. THE SAMPLE TYPES SHALL BE ONE EACH OF TYPE "C"/"D" AND TWO EACH OF SAMPLE "E".

THE FULL LENGTH DUMMY ELEMENT SHALL BE PROCESSED VIA ROUTE CARD 317-01 WHICH INCORPORATES ALL MANUFACTURING PROCESSES AND SUBSEQUENTLY FORWARDED TO EG&G FOR EVALUATION. A REPORT OF DIMENSIONAL STATUS SHALL BE ENCLOSED.

THE TENSILE TEST SECTIONS WERE EVALUATED PER IN-F-9-ATR, SECTIONS 3.4.2.2, AND 4.15. OPERATION PROCEDURE (6101) WAS USED FOR THIS OPERATION. EXCEPTION TO THE GEOMETRY OF THE TENSILE SECTION RELATES TO THE SHIFT OF DUMMY PLATES INBOARD .500 INCH TO ALLOW SWAGE GROOVE MONITORING OF EACH PLATE POSITION. MINIMUM PULL TEST VIA THE EXISTING 2.5 INCH SPAN OF SWAGE JOINT SHALL BE 375 LBS. IN LIEU OF 450 LBS. SUBJECT TO THE 3.0 INCH SAMPLE. A PROPORTIONAL RATIO SHALL BE USED WHEN COMPARED WITH EXISTING MAXIMUM STRENGTH. THE LAST FOUR SAMPLES PROCESSED AFTER THE SELECTED METHOD WILL BE SUBJECT OF THIS CHANGE.

THE FULL LENGTH DUMMY ELEMENT SHALL BE FORWARDED TO EG&G FOR HYDRAULIC (SIMULATED SERVICE) TEST PER IN- F-9-ATR, SECTION 6.2.1. B&W UNDERSTANDS THAT RESULTS OBTAINED VIA THIS TEST WILL IMPACT THE DISPOSITION OF THIS QUALIFICATION. DIMENSIONAL DATA IS ENCLOSED TO SATISFY THE COMPLIANCE OF THE HYDRAULIC TEST PHASE.

THE FOLLOWING CHART REPRESENTS AN OVERVIEW OF TEST RESULTS SUBJECT TO THE MECHANICAL INTEGRITY OF THE SWAGE JOINT. SAMPLES FIVE (5) THROUGH EIGHT (8) ADDITIONALLY FORMULATE THE GROOVE CLOSURE DATA ASSOCIATED WITH EACH PLATE POSITION. THE TENSILE PLATES WERE SHIFTED INBOARD .500" RELATIVE OF THE 3" SAMPLE TO ACHIEVE ACCESS FOR GROOVE CLOSURE MONITORING. TENSILE RESULTS FOR THESE SAMPLES ARE BASED ON A 2.5" SPAN WHEREAS THE CALCULATED EQUIVALENT BASED ON THE 3" TENSILE IS ENCLOSED. TEST #3 AND #5 SHOWS PLATES 62/78 AND 67/75, RESPECTIVELY, TO BE FREE OF PRE-SWAGE GROOVES AND ARE NOT RELEVANT TO THE QUALIFICATION RESULTS OTHER THAN COMPARISON. THESE SAME PLATE POSITIONS ARE APPLICABLE TO THE QUALIFICATION DUMMY ELEMENT. CLOSURE DATA SHALL BE EXPRESSED IN MILS.

TEST SEQ.	SAMPLE TYPE	SAMPLE POSITION	PLATE ARRANGEMENT	METHOD APPLIED	TENSILE RESULTS (LBS)	CALCULATED EQUIVALENT 450\375 1.2 X ACTUAL	CLOSURE L / R (MILS)
#1	"A"	FWD.	61-65-69-73 -77	NO CHANGE IN PARAMETER	1800 (61) 1190 (65) 1470 (69) 1480 (73) 1670 (77)	N/A N/A N/A N/A N/A	N/A N/A N/A N/A N/A
#2	"E"	CTR.	61-65-69-73 -79	NO CHANGE IN PARAMETER	1590 (61) 1240 (65) 1710 (69) 1470 (73) 1850 (79)	N/A N/A N/A N/A N/A	N/A N/A N/A N/A N/A

ATTACHMENT III
(EVALUATION CON,T)

SDT-661
PAGE 6 OF 8

TEST SEQ.	SAMPLE TYPE	SAMPLE POSITION	PLATE ARRANGEMENT	METHOD APPLIED	TENSILE RESULTS (LBS)	CALCULATED EQUIVALENT 450/375 1.2 X ACTUAL	CLOSURE L / R (MILS)
#3	"B"	AFT.	62-66-70-74 -78	.145" SWAGE WHEEL TO FIXTURE	1410 (62) 1620 (66) 1720 (70) 1630 (74) 1780 (78)	N/A N/A N/A N/A N/A	N/A N/A N/A N/A N/A
#4	"E"	FWD.	61-65-69-73 -79	.145" SWAGE WHEEL TO FIXTURE	2000 (61) 1050 (65) 1300 (69) 1580 (73) 1580 (79)	N/A N/A N/A N/A N/A	N/A N/A N/A N/A N/A
#5	"C"	CTR.	63-67-71-75 -79	SWAGE SEATING PASS	1180 (63) 1150 (67) 1150 (71) 1080 (75) 1680 (79)	1416 1380 1380 1296 2016	36 - 35 36 - 36 36 - 36 36 - 36 88 - 88
#6	"D"	AFT.	64-68-72-76	SWAGE SEATING PASS	1130 (64) 1220 (68) 1350 (72) 1320 (76)	1356 1464 1620 1584	37 - 36 36 - 36 35 - 36 35 - 37
#7	"E"	FWD.	61-65-69-73 -79	SWAGE SEATING PASS	1800 (61) 1130 (65) 1140 (69) 1210 (73) 1690 (79)	2160 1356 1368 1452 2028	70 - 67 36 - 34 35 - 35 35 - 35 86 - 87
#8	"E"	CTR.	61-65-69-73 -79	SWAGE SEATING PASS	1800 (61) 1250 (65) 1230 (69) 1150 (73) 1780 (79)	2160 1500 1476 1380 2136	68 - 67 34 - 34 34 - 35 34 - 35 86 - 88
#9	"E"	FWD.	61-65-69-73 -79	SWAGE SEATING PASS	2000 (61) 1420 (65) 1420 (69) 1580 (73) 1560 (79)	N/A N/A N/A N/A N/A	N/A N/A N/A N/A N/A

SELECTION OF SAMPLE #9 PROCESS WAS APPLIED TO THE QUALIFICATION ELEMENT.
THE SWAGE SEATING PASS SUBJECT TO SAMPLES #5 THROUGH #9 CONSISTED OF A
REVERSE ORIENTATION OF THE SWAGE CARRIAGE. THE SWAGE WHEELS REMAINED ACTIVATED
SUBSEQUENT TO THE INITIAL SWAGE PASS TO FORMULATE THE SIDE PLATE TO DUMMY PLAT
INTERFACE.

EVALUATION OF THE ENCLOSED DATA SHOWS THAT THE ACCEPTANCE CRITERIA RELEVANT TO THE TENSILE STRENGTH OF THE SWAGE JOINT WAS MAINTAINED. THE THREE (3) TEST MODES EXCEEDED THE 150 LBS. PER LINEAR INCH MINIMUM REQUIREMENT IN MOST CASES BY A MARGIN OF 3 TO 1 OR GREATER. B&W CHOSE THE METHOD IDENTIFIED VIA TENSILE SAMPLE #9 WHICH WAS PROCESSED SUBSEQUENT TO SAMPLE #4 AS THE METHOD OF QUALIFICATION TO BE APPLIED TO DUMMY ELEMENT XX-005A. THE BASIS FOR THIS SELECTION IS ILLUSTRATED BELOW, RELEVANT TO PERFORMING A SWAGE SEATING PASS ON PRE-SWAGED PLATES.

- 1- SAMPLE #9 SHOWED THAT FOUR (4) OF THE FIVE (5) PLATE POSITIONS WERE ONLY SEPERATED BY 160 LBS. MAXIMUM STRENGTH. THIS CONDITION INDICATED THAT CONSISTANT PRESSURES WERE APPLIED AT EACH PLATE POSITION.
- 2- B&W BELIEVES THAT SWAGING WITHOUT PARAMETER CHANGES SUBJECT TO TENSILE SAMPLE #1 AND #2 WILL PRODUCE ACCEPTABLE MECHANICAL INTEGRITY OF THE SWAGE JOINT VIA THE DIRECTION OF TRANSVERSE PULL. A PARTIAL INTERLOCK WITHIN AN EXISTING PLATE GROOVE WOULD ASSURE ACCEPTABLE RESULTS. THE REASON THIS METHOD WAS NOT RECOMMENDED WAS DUE TO THE LACK OF STRENGTH IN THE LONGITUDNAL DIRECTION WHICH COULD CAUSE THE PLATES TO BE LOOSE OR RATTLE IF THE SIDE PLATE MATERIAL WAS NOT PROPERLY SEATED WITHIN THE EXISTING PLATE PRE-SWAGE GROOVE. B&W BELIEVES THE SEATING PASS ASSURES CONTACT WITHIN THE EXISTING PLATE GROOVE BOTTOM SURFACE WITHOUT FURTHER INDENT OF THE PLATE CONDITION.
- 3- USING THE .145" SWAGE - WHEEL - TO - FIXTURE SIDE WALL DIMENSION IN LIEU OF .150" QUALIFIED WILL ASSURE THE MECHANICAL INTEGRITY OF THE SWAGE JOINT AND (OVER SEATING OF THE PARENT MATERIALS). THERE WAS SOME INDICATION THAT THE EXTREME PRESSURE APPLIED TO THE SIDE PLATE IN VIEW OF THE STATED PARAMETER SHOWED A SLIGHT SHEAR OF THE SIDE PLATE PRE-SWAGE GROOVE. B&W BELIEVES THAT ADDED PRESSURES CAN AFFECT THE GEOMETICAL CONDITION OF THE ELEMENT, ESPECIALLY IN THE COOLANT CHANNEL AREA AND SHOULD BE AVOIDED IF POSSIBLE. THESE REASONS SUPPORT THE REJECTION OF THIS METHOD RELEVANT TO TENSILE SAMPLES #3 AND #4.

THE COMB INSTALLATION IN THE DUMMY ELEMENT WAS SUCESSFUL. A CHANGE IN PROCESS WILL REQUIRE UPGRADE OF OP-6101 AND OP-6107 FOR PROCESSING FUEL PLATES WITH EXISTING PIN HOLES. THESE CHANGES ARE ILLUSTRATED IN THE FOLLOWING PARAGRAPHS AND SHALL BE INCORPORATED IN APPLICABLE PROCEDURES PENDING DISPOSITION OF THIS QUALIFICATION REPORT.

- 1- ALL FUEL PLATES WITH EXISTING PIN HOLES THAT WERE REMOVED FROM A SINGLE FUEL ELEMENT SHALL BE USED IN THE NEW ASSEMBLY WHEN FEASIBLE. THE FUEL PLATE STACKING SHEET SHALL INDICATE THIS SEQUENCE. ADD ON FUEL PLATES WITHOUT PIN HOLES WILL NOT AFFECT THE ASSEMBLY PROCESS. THIS METHOD WILL ASSURE PROPER ALIGNMENT OF THE EXISTING PIN HOLES AT REASSEMBLY BECAUSE THESE FUEL PLATES WERE PREVIOUSLY DRILLED AS AN ASSEMBLY BASED ON THE EXISTING LENGTH. ADDING FUEL PLATES WITH EXISTING PIN HOLES REMOVED FROM SEVERAL FUEL ELEMENTS MAY CAUSE MISALIGNMENT ON THE OPPOSITE ALIGNMENT END OF THE FUEL ELEMENT. USING THE STANDARD ALIGNMENT SHIM AT THE SWAGE OPERATION CAN ASSURE THE EXISTING PIN HOLES ARE REASONABLY ALIGNED.
- 2- COMB INSTALLATION SHALL INCLUDE THE FOLLOWING:
 - A- USE THE DRILL FIXTURE FOR ALIGNMENT OF THE ASSEMBLY ONLY TO ASSURE A PARALLEL PLANE WITH THE DRILL BIT.
 - B- ALIGN THE DRILL BIT WITH THE EXISTING PIN HOLE IN THE FUEL PLATE AND DRILL THROUGH EACH. OPERATORS SHALL EXERCISE CAUTION DURING THE DRILLING PHASE BECAUSE BURRS OR SLIGHT MISALIGNED HOLES IN THE TRANSVERSE DIRECTION MAY CAUSE THE DRILL BIT TO SHIFT POSITION. DRILLING FEED SHALL BE MINIMIZED.
 - C- INSTALL THE COMB TO MAINTAIN ALIGNMENT WITH THE PRE-DRILLED HOLES. FINAL DRILL AND INSTALL PINS.

THE FOLLOWING PROCEDURES WILL REQUIRE UPGRADE TO INCORPORATE THE PROCESSES APPLICABLE TO THIS QUALIFICATION REPORT.

- OP-6101----- INCORPORATE SWAGING SEQUENCE RELATIVE TO PRE-SWAGED FUEL PLATES AND WITH EXISTING COMB PIN HOLES.
- OP-6108----- INCORPORATE ACCEPTANCE OF PRE-SWAGED FUEL PLATES AND FUEL PLATES WITH EXISTING PIN HOLES.
INCORPORATE RE-FORMING IF NECESSARY BASED ON INSPECTION RESULTS.
INCORPORATE REASSIGNMENT OF FUEL PLATES AND REFERENCE VIA THE STACKING SHEET.
- OP-6107----- INCORPORATE ALL REFERENCED DATA ASSOCIATED WITH COMB INSTALLATION SUBJECT TO PRE-DRILLED PIN HOLES IN THE FUEL PLATES.

THE FOLLOWING MISSOURI PROCEDURES WILL REQUIRE THE SAME UPGRADE PENDING DISPOSITION OF THE PRE-SWAGE GROOVE QUALIFICATION.

- OP-3127 ROLL SWAGE
OP-3136 REMOVE SIDE PLATES
OP-3131 INSTALL COMBS

IN CONCLUSION, B&W CONSIDERS THE FUEL PLATE PRE-SWAGE GROOVE AND PRE-DRILLED PIN HOLE QUALIFICATION TO BE A SUCCESS. BASED ON THE FOREMENTIONED TEST RESULTS AND SUBSEQUENT HYDRAULIC TESTING OF THE QUALIFICATION ELEMENT, B&W REQUESTS A FAVORABLE DISPOSITION OF THE SUBJECT QUALIFICATION.

DUMMY PLATES FOR FULL LENGTH
PRE-SWAGE GROOVE QUALIFICATION

- 61-D6 PRE-SWAGE GROOVE
- 62-D2 NON PRE-SWAGE GROOVE
- 63-D5 PRE-SWAGE GROOVE
- 64-D5 PRE-SWAGE GROOVE
- 65-D7 PRE-SWAGE GROOVE
- 66-D8 PRE-SWAGE GROOVE
- 67-D1 NON PRE-SWAGE GROOVE
- 68-D8 PRE-SWAGE GROOVE
- 69-D8 PRE-SWAGE GROOVE
- 70-D8 PRE-SWAGE GROOVE
- 71-D5 PRE-SWAGE GROOVE
- 72-D6 PRE-SWAGE GROOVE
- 73-D7 PRE-SWAGE GROOVE
- 74-D8 PRE-SWAGE GROOVE
- 75-D1 NON PRE-SWAGE GROOVE
- 76-D8 PRE-SWAGE GROOVE
- 77-D8 PRE-SWAGE GROOVE
- 78-D1 NON-PRE-SWAGE GROOVE
- 79-D5 PRE-SWAGE GROOVE