1-1-2008

Minimization of residual stresses in the closure -weld region of the spent nuclear fuel canisters using induction annealing process

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MINIMIZATION OF RESIDUAL STRESSES IN THE CLOSURE-WELD REGION OF THE SPENT NUCLEAR FUEL CANISTERS USING INDUCTION ANNEALING PROCESS

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A dissertation submitted in partial fulfillment
of the requirements for the degree of

Doctor of Philosophy
Department of Mechanical Engineering
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Graduate College
University of Nevada, Las Vegas
May 2001

UMI Number: 3016345

Bell & Howell Information and Learning Company
300 North Zeeb Road
P.O. Box 1346
Ann Arbor, MI 48106-1346

UNLV

Dissertation Approval

The Graduate College
University of Nevada, Las Vegas

Jan. 18th, 2001

The Dissertation prepared by

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Entitled

Minimization of Residual Stresses in the Closure-Weld Region of the Spent Nuclear Fuel Canisters Using Induction Annealing Process

is approved in partial fulfillment of the requirements for the degree of

Doctor of Philosophy

Examination Committee Chair

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Examination Committee Member

Examination Committee Member

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PR/1017-52/1-00

ABSTRACT

Minimization of Residual Stresses in the Closure-Weld Region of the Spent Nuclear Fuel Canisters Using Induction Annealing Process

by

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This dissertation presents a study of the spent nuclear fuel canisters for maximizing the compressive stress depth through the closure-weld region wall thickness. Induction coil heating technique can be used to relieve the residual stresses from the closure weld and induce a state of compression through the wall thickness. This technique involves localized heating of the material by the surrounding coils. The material is then cooled to the room temperature by quenching.

A three-dimensional finite element model was developed for the canister using the sequential method. This method consisted of a sequential thermal-stress analysis where nodal temperatures from the thermal analysis were applied as body force loads in the subsequent stress analysis. This model, which was computationally intensive, has been used to verify the results of the model developed in two-dimensions and ensure its accuracy.

The effects of induction coil heating and subsequent quenching were also determined by using a two-dimensional axisymmetric finite element model of the canister. This model made use of the direct method. This method included only one type of analysis that uses coupled-field element type containing all necessary degrees of freedom for the heat transfer and the stress analyses. Direct coupling is advantageous when the coupled-field interaction is highly nonlinear and is best solved in a single solution using a coupled formulation. The results of the two-dimensional axisymmetric model were almost identical to the results of the three-dimensional model. Therefore, the computationally efficient two-dimensional axisymmetric model was used for the subsequent optimization problem.

The finite element results were validated using the results obtained from an experimental test. A canister mockup which consists of an outer shell and a support ring was manufactured. The mockup was subject to solution annealing process. At the end of the process, a compressive stress state developed on the shell outer surface. The stresses on the canister outer surface were obtained based on the readings of the strain gages that were attached to several points on the mockup. The results of the experimental test were consistent with the finite element solution.

The parameters of most promising designs were tuned to further maximize the depth of compressive stress through the wall thickness. This was handled as an optimization problem that was subject to geometrical and stress constraints. Two different solution methods were implemented for this purpose. First, ANSYS optimization subroutine was used to obtain an optimum solution. These results were subsequently improved using a successive heuristic quadratic approximation. This

routine provided the dimensions of the best design that result in the maximum compressive stress in the canister closure-weld region.

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ACKNOWLEDGMENTS

I wish to express my gratitude to my advisor and graduate committee chair, Dr. Mohamed B. Trabia, for his guidance and support throughout this research. I also would like to thank Dr. Robert F. Boehm, Dr. Brendan O'Toole, Dr. Woosoon Yim, and Dr. Samaan Ladkany as the serving members of the graduate committee.

I also wish to acknowledge the support of the U.S. Department of Energy, Framatome Cogema Fuels, Lambda Research, and Nooter Fabricators, Inc. I gratefully acknowledge the contributions of Dr. Gerald M. Gordon, in his efforts to support the objective of this research. I also would like to thank my friend Dr. Mehmet Saglam for his earnest support on this study.

Lastly, I am truly grateful to my parents, sisters, and brother for their endless support and encouragement.

CHAPTER 1

INTRODUCTION

Spent Nuclear Fuel (SNF) canisters are being designed to last for 10,000 years. Corrosion may be one of the most critical factors determining the life of the canister in the emplacement-drift environment. An important related phenomenon is the stress corrosion cracking (SCC) [ASM International (1990)]. Three conditions are needed to take place simultaneously to induce the SCC in a structure: a corrosive environment, a material susceptible to corrosion, and a tensile stress. The problem of SCC can be eliminated by removing or reducing the effect of any one of these conditions. The scope of this dissertation is limited to minimizing the tensile stress in the region of the closure-weld, and to the extent possible, maximizing the compressive stress depth through the wall thickness. A heat-treatment technique called "induction coil heating" [Avallone and Baumeister, Editors (1986)] is used to relieve the residual stresses from the closure-weld and induce a state of compression through the wall thickness. This technique involves localized heating of the material by surrounding coils. The material is then cooled to the room temperature by quenching. The resultant effect of this process will ensure that the canister outer surfaces will remain in state of compressive stress and, therefore, the canisters will not be breached due to SCC during their expected design-life.

A potential crack may propagate through the wall thickness if it is perpendicular to the tensile stress. Due to the canister cylindrical shell structure, the stress components in the radial and axial directions are not large enough to cause crack propagation, as will be shown in this study. The only remaining stress component that is perpendicular to any potential crack through the wall thickness is the hoop stress. Therefore, the most important stress component in this problem is the hoop stress, which will be studied in this research.

The literature review is provided in two sections in Chapter 2. The first section presents a review of the technical papers published in relation to the analyses of welded structures, residual stresses, and fabrication processes. The second part is focused on the literature of the finite element modeling and optimization. A description of the SNF canister design and its components in the closure-weld region is given in Chapter 3. Chapter 4 provides a detailed description of the three-dimensional (3-D) finite element model (FEM) developed for the canister using the "sequential method". This model, which is computationally intensive, is used to verify the results of the two-dimensional (2-D) axisymmetric model and ensure its accuracy. The 2-D axisymmetric FEM of the SNF canister is presented in Chapter 5. This model is developed to determine the effects of induction coil heating and subsequent quenching using ANSYS commercial software. This FEM uses the "direct method". The 2-D axisymmetric model can be used in subsequent optimization problem upon verification of its results with the 3-D model. The results of the finite element analyses (FEA) are verified by comparing with the results of an experimental test. Chapter 6 reports the verification process and results in terms of stresses obtained from the FEA and the tests. The parameters of most the promising designs determined from 2-D FEM are adjusted to further maximize the depth of compressive stress through the wall thickness. This is an optimization problem, which is subject to geometrical constraints. Two different optimization methods are explained in Chapter 7. The first section in this chapter describes the solution method and the results obtained by the use of the ANSYS optimization subroutine. The second part includes a description of the successive heuristic quadratic approximation solution. The results and improvements of the heuristic approximation over ANSYS solution are also discussed in the second part of Chapter 7. Finally, the conclusions of this study are provided in Chapter 8.

CHAPTER 2

LITERATURE REVIEW

This section presents a review of the literature regarding the methods of reducing residual stresses in the welds and optimization techniques used to determine the best geometrical solution for stress mitigation. The ultimate goal of this research is, by virtue of mitigating weld residual stresses, to lower the potential for SCC and brittle fracture in the SNF canisters designed for a minimum service life of 10,000 years. The challenging aspect of the proposed research can be seen through the fact that no previous structural component was ever designed to last 10,000 years.

2.1 Literature Review on Welded Structures, Residual Stresses, and Fabrication

The first part of the literature survey includes a group of technical papers published in relation to the analyses of welded structures, residual stress improvement techniques, and low cost fabrication processing. Nickell et.al. (1973) performed thermal and mechanical analyses on welded structures. The numerical method described in their study was applied to an omega seal during the first pass of a multi-pass welding operation in order to examine the residual distortion and stress associated with this flexible geometry. An omega seal is an axisymmetric structure; the radial cross section has a circular geometry and it is welded at a small groove at the top. The details of the radial cross section are provided in Figure 8 in the paper authored by Nickell et.al. (1973). Such structural configurations are in common use for forming flexible, gas-tight seals between support structures and infrequently replaced components. The thermal analysis of the seal was compared to the experimental evidence. The comparison between the predicted thermal history and the thermocouple measurement was favorable. However, predicted residual distortions compared poorly with experimental measurement because a portion of the seal was omitted in the mechanical analysis.

Umemoto et.al. (1980) investigated a different aspect of welds. Their paper presented a method to improve residual stresses in a pipe weld by means of induction heating a pre-flawed pipe. The results showed that the residual stress at the crack tip was successfully reduced by induction heating stress improvement process.

The estimation of welding residual stresses was also performed by Chien et.al. (1989). Their investigation method was, however, different than that of other scientific researchers. Simulated inherent strains were used to estimate the weld residual stresses. This paper made use of a semi-analytic method which combined the optimization technique, the FEM, and the experimental data. The subsequent residual stresses were estimated accurately. The validity of their proposed method was demonstrated by a case study: the residual stresses in slit-type butt welded rectangular plates were analyzed. The results indicated that the semi-analytic method was valid for simulating inherent strains and hence, the residual stress fields in the welded structures. Similar to this research, a technical study of the welding-induced residual stress analysis procedure was also performed by Wilkening (1993). Several 2-D axisymmetric analyses have been performed for pipe girth welds and for several multi-pass girth-like welds attaching small nozzles to large, thick-walled pressure vessels. The numerical procedure used in this paper provided an effective method for selecting the welded joint design that minimized the potential for SCC failure by minimizing the tensile stress level on the wetted surface.

The welding of materials explained above constituted one mechanism for developing residual stresses in structures; a second type of fabrication process that resulted in residual stresses was mold casting. The research on this fabrication process is also included here since the residual stresses originate from thermal gradients inside the material and the finite element methods can be used for modeling purposes. Thermal stresses resulting from non-uniform cooling and hindering of shrinkage frequently cause cracks, which can lead to destruction of permanent mold casts. Fackeldey et.al. (1995) presented a 3-D FEM, which has been used to analyze the origin of thermal and residual stresses. By varying the initial temperature and the mold geometry, the process was evaluated for optimization and assessment of the mold life. A similar study was also performed by Chamis (1998) with a new approach for low cost fabrication processing. A coupled thermal structural behavior was simulated by using a coupled multi-disciplinary computer code. Through this approach, temperature gradients and the evolution of thermomechanical properties during cooling were simultaneously evaluated. This approach was applied to the casting process to fabricate several different components. The components were modeled by 3-D mixed finite element technique, which accommodates solidification, heat transfer, and stress analysis. The results showed that the temperature gradients were functions of the pouring ports. A method was suggested for optimization of the mold pouring ports to minimize the thermal gradients which reduced residual stresses and thereby increased the part service life.

To solve the problem of high residual stresses, this dissertation uses a similar approach to one of the studies described above, authored by Umemoto et.al. (1980). While their scientific research was limited to reducing residual stresses at the crack tip in a pre-flawed pipe, this study will attempt to mitigate residual stress levels in the closure-weld region of the SNF canister. The problem being investigated in this study is, therefore, substantially different in terms of the geometry and the size of the structural components. However, the scientific work carried out in the pre-flawed pipe suggested that the induction annealing of the SNF canister is feasible and is an effective method to reduce residual stresses in the region of the closure-weld.

As suggested by Fackeldey et.al. (1995), a 3-D finite element analysis is an accurate and cost-effective method of predicting the origin of thermal and residual stresses. A similar approach will be taken in this dissertation by developing the appropriate 3-D finite element models of the SNF canister and the canister mock-up. By varying the initial geometry of the canister, the process of induction annealing will be evaluated for optimization.

2.2 Literature Review on Finite Element Modeling and Optimization

The second part of the literature survey includes the technical papers published with regard to the finite element optimization of structures. Chen and Ho (1993) presented a new approach to developing a computer-aided optimum design system for mechanical structures. Their approach allowed the designer to implement design sensitivity analysis in commercial finite element programs without both the knowledge of its programming detail and access to its source code. The usefulness of their approach was demonstrated with examples and the proposed design system was suggested to enhance the role of structural optimization in designing mechanical structures.

A number of technical papers have been published in the area of shape optimization for structures. Schramm et.al. (1993), Le Riche et.al. (1998), Maute et.al. (1998), Hardee et.al (1999), Heller et.al. (1999), and Li et.al. (1999) presented several techniques to solve this problem. In all of these studies, finite element procedures were used to determine the optimized shape of structures to minimize stress concentration factors. The first one of these papers, Schramm et.al. (1993), provided a geometry based approach for coupling CAD with the finite element methods. Non-uniform rational b-splines were used to describe the shape of a structure. Spline curves and surfaces were used in design description and mapping of the finite elements for the parameterization of the structural shape optimization. A cross-sectional torsion problem was employed to demonstrate the proposed mapping techniques for finite element solution and the subsequent shape optimization. The results showed that the proposed technique was efficient. The advantage of the given approach was that the direct use of the CAD geometry description in the numerical model allowed the immediate use of the results of the optimization process for the design improvement in CAD.

In the next paper, Le Riche et.al. (1998) studied the shape optimization using another strategy, mixed heuristic and evolutionary optimization. Two heuristics for minimizing the weight of a structure were implemented: generalized and penalized biological growth. Generalized biological growth was a heuristic that removed and added material depending on the local state of stresses at the boundary. The penalized biological growth further penalized boundary displacements that remove material depending on the global constraints satisfaction of the current design. The results showed that mixing evolutionary search with biological growth improved the efficiency of the optimization.

The third paper mentioned above, written by Maute et.al. (1998), focused on optimization of elastoplastic structures. A procedure optimizing the ductility for given mass by adaptive material topology optimization was presented and verified by numerical examples for plane stress conditions. The results showed that it is important to consider the material non-linear structural response in the optimization process.

The next paper in its chronological order, authored by Hardee et.al. (1999), presented a computer aided design (CAD) based design sensitivity analysis and optimization method using Pro/Engineer software for shape design of structural components. The results of this study showed that an effective design optimization can be performed by the use of the Pro/Engineer software. Following this study, Heller et.al (1999) studied an iterative gradientless method for the shape optimization of stress concentrators to extend the fatigue life of structural components. The key feature of their approach was to achieve constant boundary stresses, in regions of interest, by moving nodes on the stress concentrator boundary by an amount dependent on the sign and magnitude of the local hoop stress obtained from a previous iteration of a standard finite element analysis. The results of an example problem were presented, which included the optimization of hole shapes in flat plates. It was found that significant stress reductions were achieved by local shape changes due to optimization. The method was considered an effective alternative to the use of more expensive and complex gradient-based finite element optimization softwares, which are available commercially.

The last paper mentioned above, written by Li et.al. (1999), included an evolutionary method. In this study, a stress based evolutionary structural optimization method was developed, in which the discrete variable method with the binary decision-making was used to decide the finite element's presence or absence. On the basis of the finite element analysis, a stress sensitivity number was derived to estimate the stress change due to element removal or addition. Following this optimization procedure, an optimal design with a minimized stress profile was achieved by removing or adding those elements which have the lowest or highest stress sensitivity numbers, respectively. A classical example of the fillet weld design was presented to demonstrate the capabilities of the proposed method for solving stress minimization problems.

Some of the scientific researches on shape optimization were conducted for specific structural components such as beams, plates, and shells. The results of structural optimization for such components have been recently reported by Grandhi et.al. (1992), Gotsis (1994), and Mota Soares et.al. (1994). Grandhi et.al. (1992) wrote a paper that presented the generalized compound scaling algorithm and its application to optimum weight design of plate structures. The optimum designs were reached by simply scaling the design variables to an optimum intersection of multiple constraints. A four-noded isoparametric plate element was used for modeling the structure. The procedure was demonstrated by example problems using stress and displacement constraints with side bounds on the design variables. The results showed that the optimization cost was significantly reduced using this algorithm. Gotsis (1994) worked on the structural optimization of thin shell structures that were subjected to stress and displacement constraints. In order to accomplish this, a structural optimization computer program (DESAP1) was modified and improved. The simplification of the program input improved the accuracy of the analysis and saved computation time. In the optimization part of the program, the stress ratio formula, which redesigns the thickness of each finite element of the structure, was solved by an analytical method. This scheme replaced the iterative solution that was previously used in the program, thus increasing the accuracy and speed of the redesign. The modified program was used to design a thin, cylindrical shell structure with optimum weight. The results showed that aforementioned modifications improved the accuracy and efficiency of the program. Thin shells of revolution have also been studied for optimal design by Mota Soares et.al. (1994). Their paper presented the sensitivity analysis for the optimization of axisymmetric shells subjected to arbitrary loading. Thickness and shape design variables were considered. The objective of the design was the minimization of the volume of the shell material, the maximization of the fundamental natural frequency, the minimization of the maximum stresses, or the minimization of the maximum displacement. The constraint functions were displacements, stresses, enclosed volume of the structure, volume of the shell material, or the natural frequency of a specified mode shape. The design sensitivities were calculated analytically and also by global finite difference. The results indicated that sensitivity analysis of static and dynamic constraints of axisymmetric shells were efficiently and accurately obtained using the analytical method described.

The literature survey indicates that no structural component was ever optimized to prevent stress corrosion cracking using induction coil annealing process. Optimization of SNF canisters using two different methods will be explored in this dissertation. One of these methods will employ the optimization subroutines of ANSYS (a commercial FEA software). As described previously, Hardee et.al. (1999) and Schramm et.al. (1993) made use of commercially available softwares for optimization of structures. Consistent with their approach, an optimum solution to the problem of reducing residual stresses in SNF canisters will be obtained using ANSYS software. This optimization process will include the effects of non-linear material behavior, as its importance was pointed out by Maute et.al. (1998). A second method of solution will also be used by developing a successive heuristic quadratic approximation. The solution of this method will be used to verify the results of the first solution form ANSYS. This approach is consistent with the scientific work previously mentioned by Gotsis (1994).

CHAPTER 3

DESCRIPTION OF SPENT NUCLEAR FUEL CANISTER DESIGN AND MATERIAL PROPERTIES

The SNF canister [CRWMS M&O (2000a)] is essentially a right-circular cylinder (see Figure 3.1). It is comprised of two shells, an inner shell of stainless steel that provides structural support and an outer shell of high-nickel alloy (Alloy 22) that provides a corrosion-resistant barrier. The inner structural shell is inserted inside the outer corrosion-resistant shell to form a loosely fitting structure. There are two lower lids that are welded to the shells at the time of fabrication. There are three upper lids that are welded in place after the canisters are loaded with the appropriate waste forms.

The SNF assemblies are loaded into baskets that form a regular array of square apertures. The baskets are formed from interlocking sheets of structural steel and neutron-absorbing material for criticality control. Aluminum sheets are also added to create thermal shunts to enhance heat transfer to the shells of the canister.

Due to potential SCC concerns during its extended period of design life, the particular interest of this study in the canister is focused on the closure-weld region (see Figure 3.2). This region includes a small part of the outer shell and the two upper lids.

These components are made of high-nickel alloy (Alloy 22). The objective of this study is to minimize the tensile stress in the region of the closure-weld, and to the extent possible, maximize the compressive stress depth through the wall thickness.

The material and corrosion properties of Alloy 22 are provided in Appendix I. These properties are used in finite element simulations and also in the discussion of results in subsequent chapters.

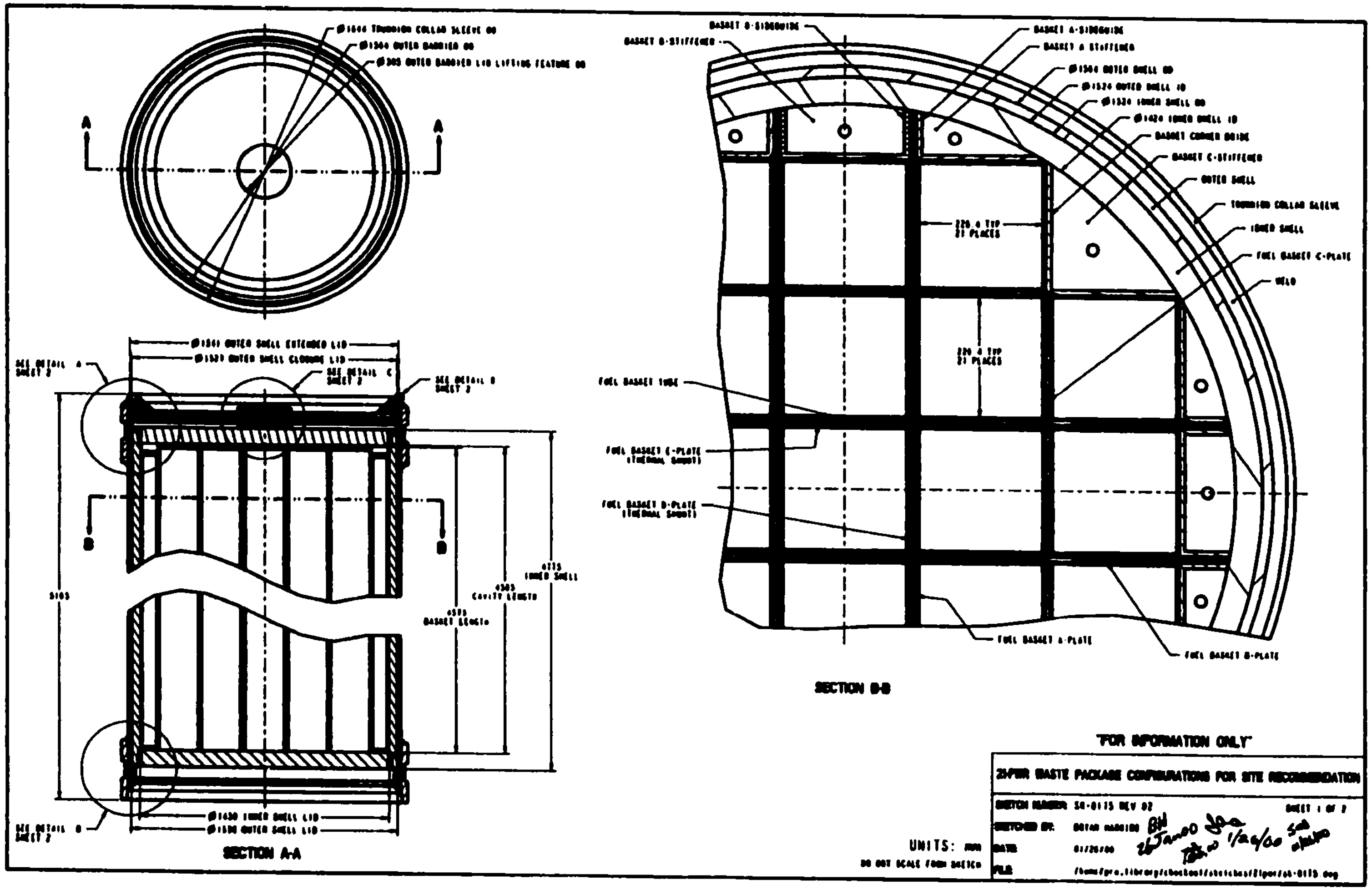


Figure 3.1. Spent Nuclear Fuel Canister Design Sketch (General View)

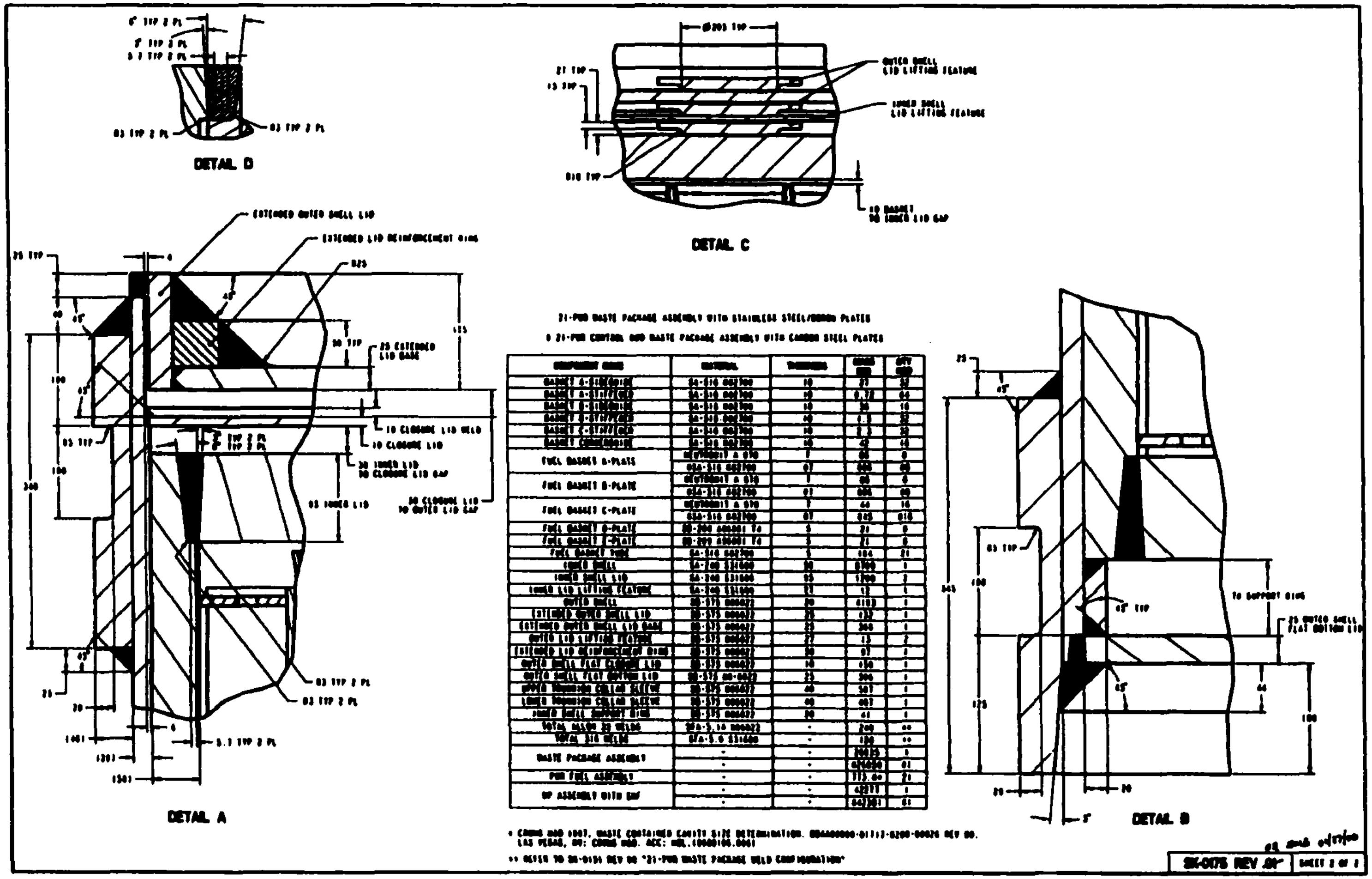


Figure 3.2. Spent Nuclear Fuel Canister Design Sketch (Closure-Weld Section)

CHAPTER 4

THREE DIMENSIONAL FINITE ELEMENT MODEL CONSIDERATIONS

A three-dimensional (3-D) 10° arc finite element model (FEM) of the SNF canister was developed to determine the effects of induction coil heating and subsequent quenching using ANSYS commercial software (see Figures 4.1, 4.2, and Appendix II). The geometry of the induction coil is a ring that covers the top surface of the SNF canister. Therefore, the problem is entirely axisymmetric. The 3-D model was developed by using a 10° arc section. The structural boundary conditions were such that zero-displacement constraints were applied in perpendicular direction to the cutting surfaces. Additionally, half-symmetry was used along the canister length since the canister is essentially symmetric about its mid-length. Although the thermal loading is not symmetric along the length of the canister, the use of the half-length of the canister is appropriate since the heat affected zone is only a small part of the canister in the region of the closure-weld and the displacements are almost zero at the mid-length of the canister.

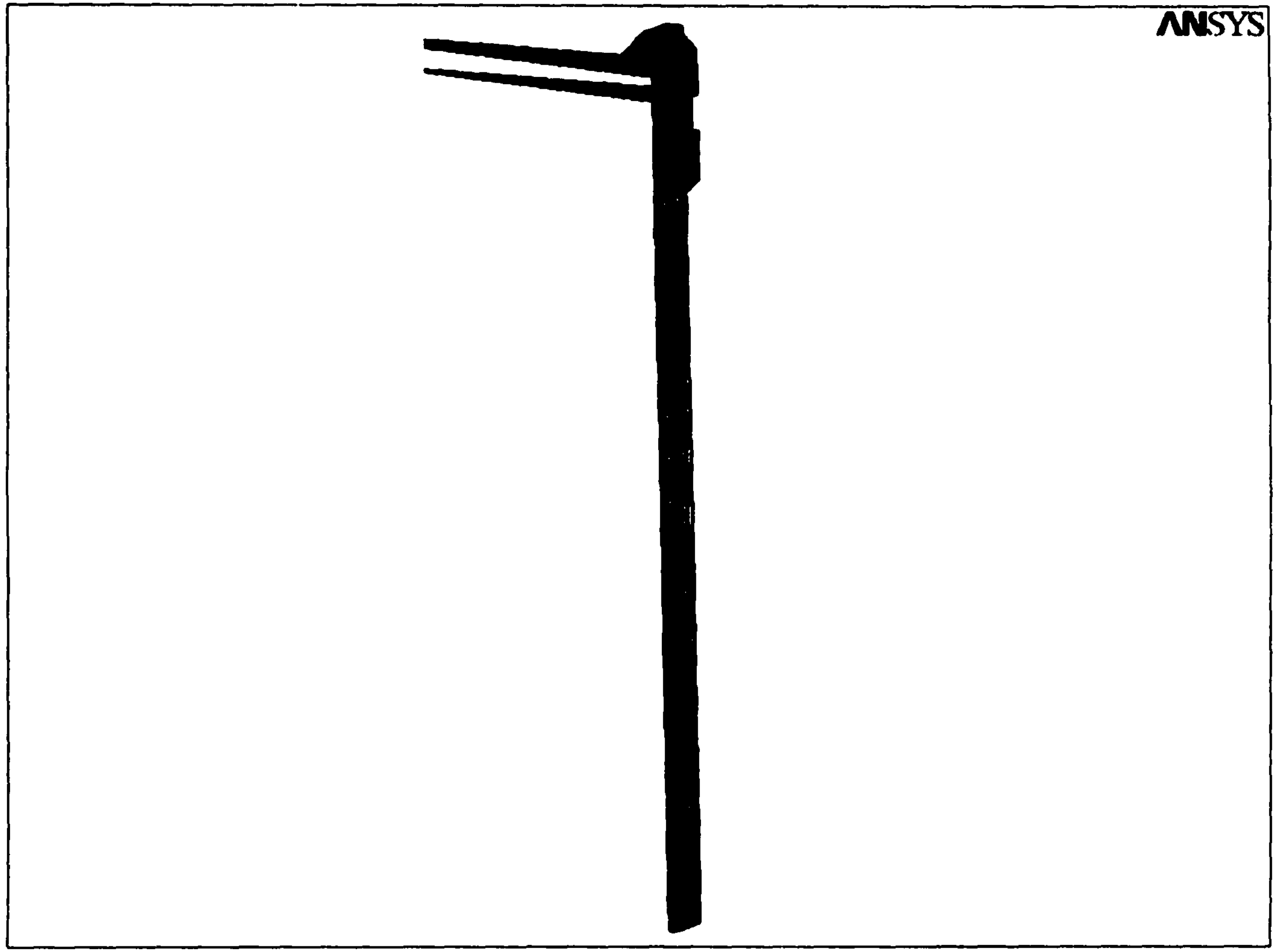


Figure 4.1. 3-D Finite Element Model of SNF Canister

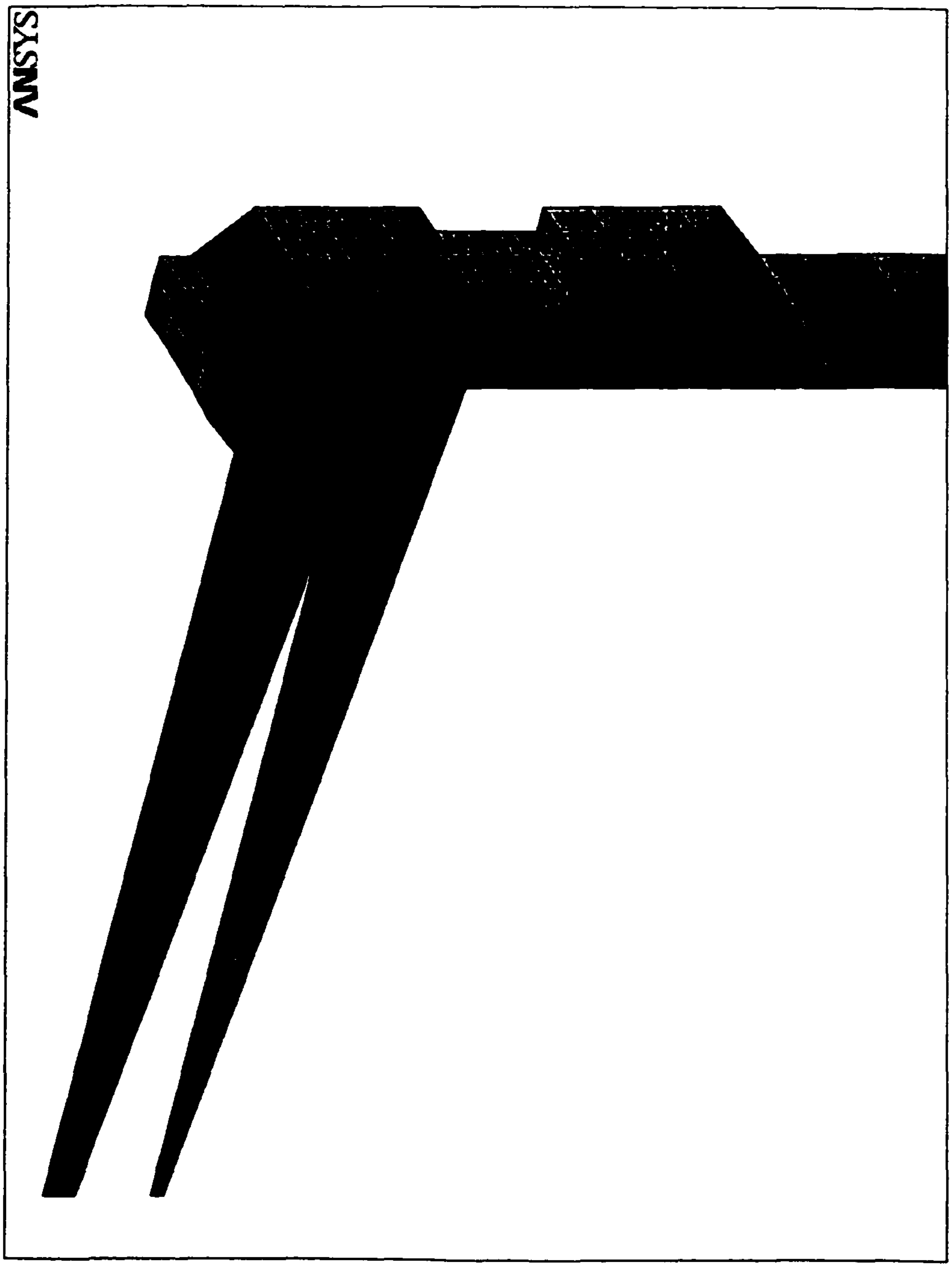


Figure 4.2. Closure-weld Section of the SNF Canister FEM

The solution was obtained using the "sequential method". This method involved two sequential analyses, each belonging to a different field; the two fields were coupled by applying "results" from the first analysis as "loads" for the second analysis [ANSYS, Inc. (1996)]. Using this method, the 3-D model included a sequential thermal-stress analysis where nodal temperatures from the thermal analysis were applied as body force loads in the subsequent stress analysis.

The heat treatment for induction anneal has been simulated using temperature boundary conditions at specific nodes in the finite element model. The canister was initially at room temperature (20 °C). Then, the temperature in the region (volume) of induction anneal was linearly increased to a maximum of 1120 °C, which is the annealing temperature of Alloy 22, in 35 seconds. Figure 4.3 shows the temperature boundary conditions at time equals to 35 seconds. The maximum temperature was 1120 °C at the top surface, the minimum was 20 °C at the bottom of the induction anneal region, and the temperature distribution between the two was linearly decreasing from the top to the bottom. This temperature was held constant for 10 seconds. Then, the canister outer surface in the region of induction anneal was quenched to room temperature in 30 seconds by assuming a linear fast cooling on the outer surface. The first two phases of the heat treatment were parts of an industry standard heat treatment; however, the cooling time in the last phase was the shortest time that resulted in maximum compression on the outer surface of the canister. It should be noted that the minimum hoop stress results on the annealing surface for different cooling rates are discussed in Section 7.1.2. All surfaces outside the region of induction annealing were insulated.

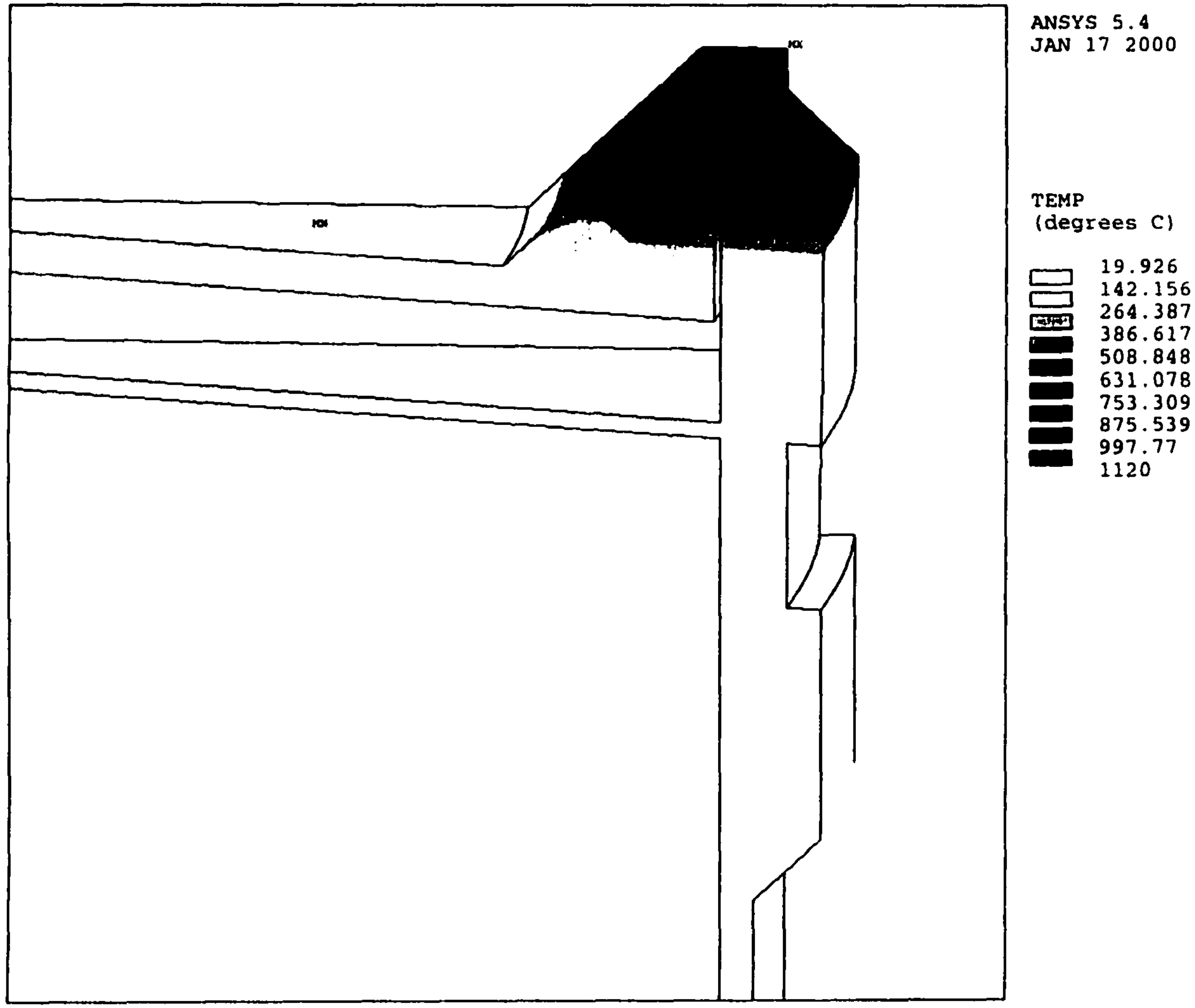


Figure 4.3. Temperature Distribution in the SNF Canister (Time: 35 seconds)

At the end of simulation, the residual stress distribution has been evaluated. The single component of stress important to this study was determined to be the hoop stress. In order for a potential crack to propagate through the wall thickness, the crack would have to be perpendicular to the tensile stress. The stress plots revealed that the radial and axial components of stress were not large enough to cause crack propagation. The hoop stress magnitudes were large compared to other stresses. However, the hoop stress was in compression on the outer surface and in tension on the inner sections of the material (see Figure 4.4). This phenomenon was an indication of the fact that the induction annealing process could not only be used to reduce tensile stresses but it could also be used to generate compressive stresses and, subsequently, prevent any potential stress corrosion cracking in the SNF canister.

The 3-D model, which was computationally intensive, was used to verify the results of the two-dimensional (2-D) model and ensure its accuracy. The problem with using 3-D FEM was determined to be the computer execution time. Two identical problems were solved in 3-D and 2-D in order to compare the central processing unit times in HP UNIX 9000 series J2240 workstation. The 3-D model required 24 hours for completion of the solution whereas it took only 10 hours for the 2-D model to finish the solution. This resulted in consideration of using 2-D model for the remaining part of the dissertation in which optimization will also be performed.

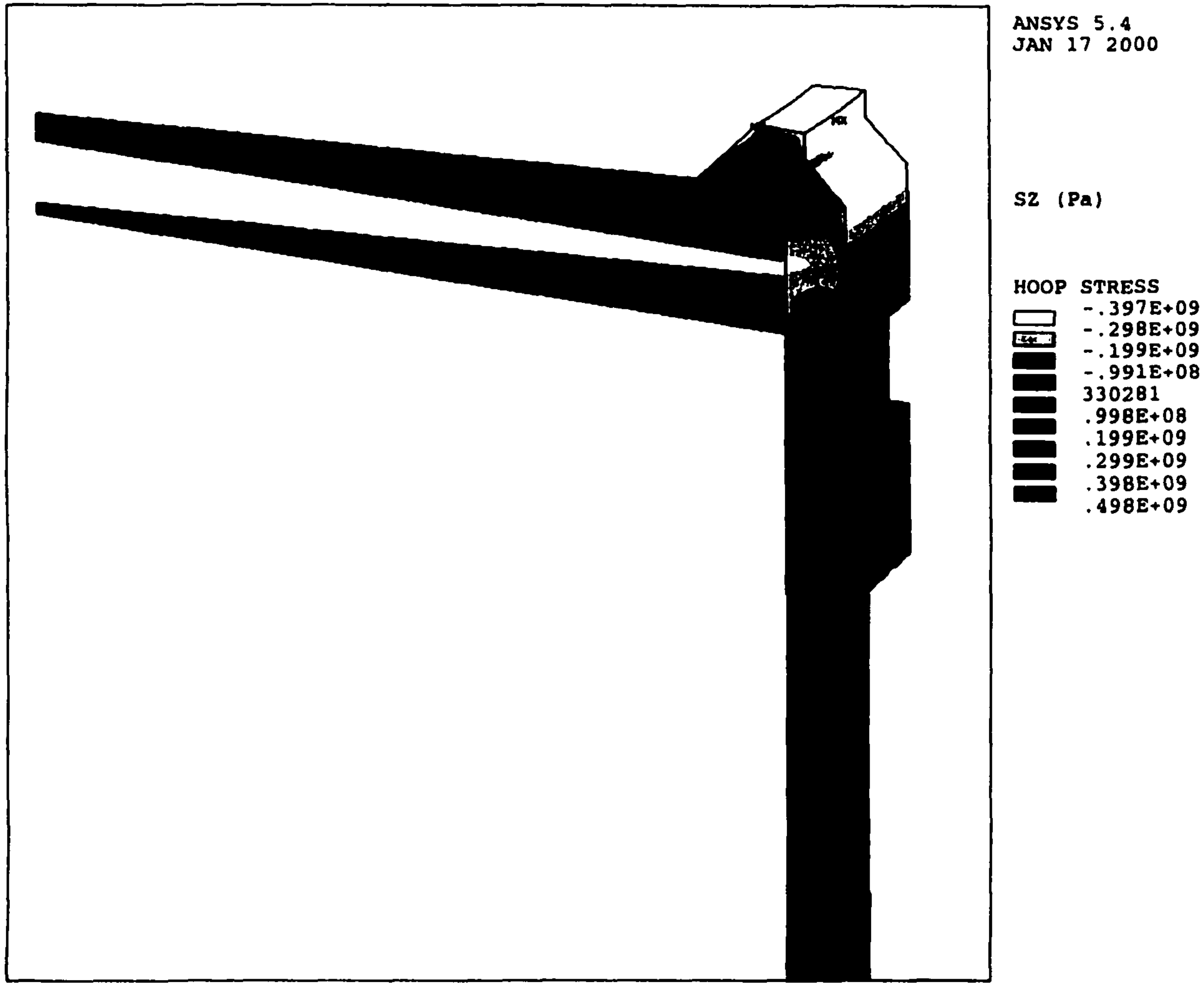


Figure 4.4. Residual Hoop Stress Distribution in the SNF Canister

CHAPTER 5

TWO DIMENSIONAL AXISYMMETRIC FINITE ELEMENT MODEL CONSIDERATIONS

Since the 3-D model was computationally intensive, its use in subsequent optimization routine that consisted of a number of iteration loops would be infeasible. Therefore, a 2-D axisymmetric FEM was developed, later to be used in optimization (see Figure 5.1 and Appendix III). The 2-D axisymmetric FEM was developed using the "direct method". This method involved one type of analysis that used coupled-field element type containing all necessary degrees of freedom for the heat transfer and the stress analysis [ANSYS, Inc. (1996)]. Direct coupling was advantageous when the coupled-field interaction was highly nonlinear and was best solved in a single solution using a coupled formulation. The elements of this formulation were specifically formulated to solve these coupled-field interactions directly. The direct method and the sequential method both resulted in the same accuracy; however, the direct method was more efficient in terms of the time required for solving non-linear problems.

The boundary conditions and the finite element mesh used in the 2-D model were similar to the ones used in the 3-D model.

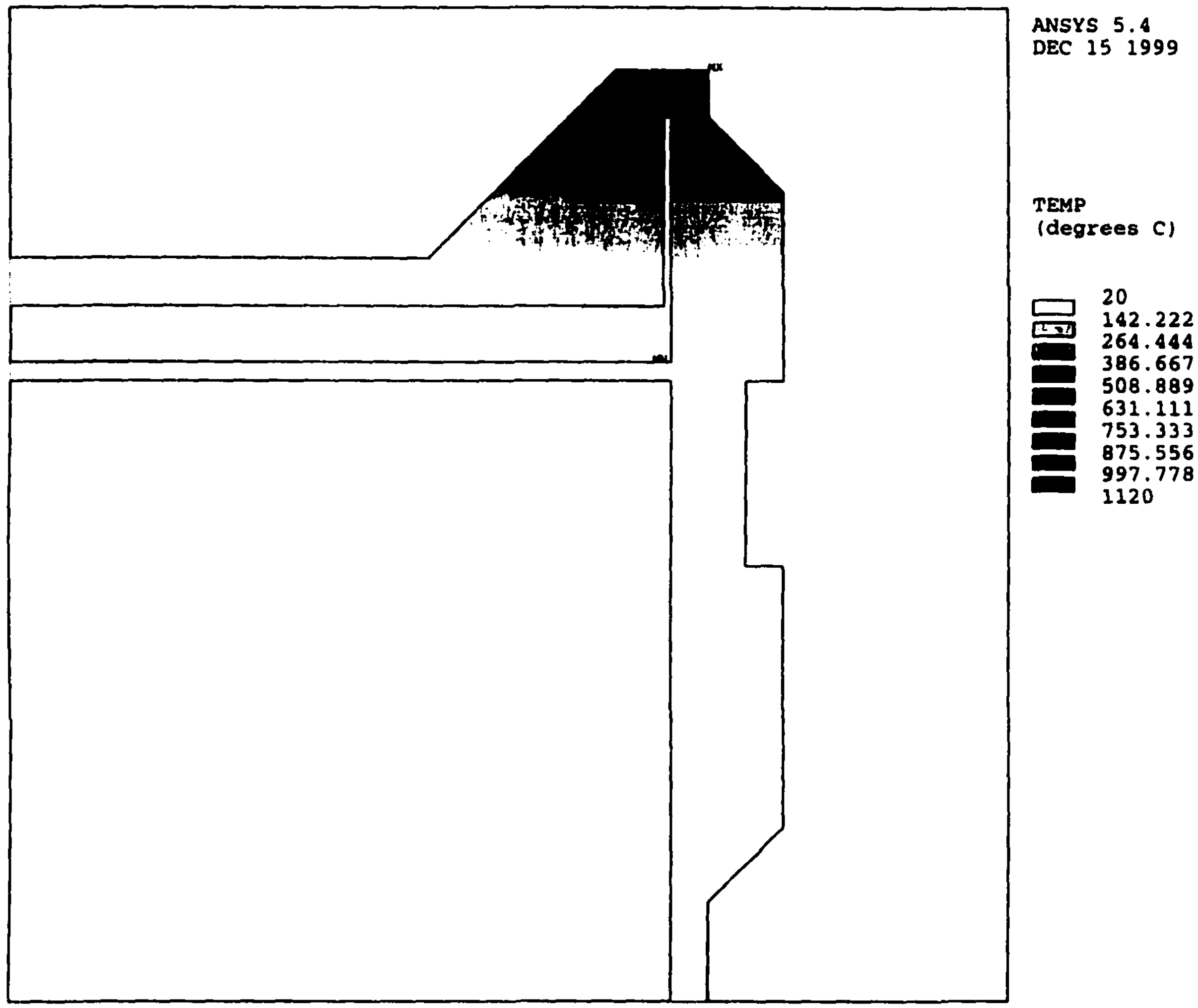


Figure 5.1. Temperature Distribution in the 2-D Axisymmetric FEM (Time: 35 seconds)

The results indicated that the stresses obtained from the 2-D axisymmetric FEM solution were almost identical to the stresses obtained from the 3-D FEM solution. The difference in maximum stresses between the two solutions was less than 1% and there was no significant difference in terms of the stress distribution through wall thickness (see Figure 4.4 and Figure 5.2). The results of the finite element solutions were, therefore, verified by using two different methods. The solution results were acceptable since the outer surface was in a state of compressive stress; however, it was not known if the original design was optimum. Therefore, it was also concluded that the computationally efficient 2-D model could be used for optimization.

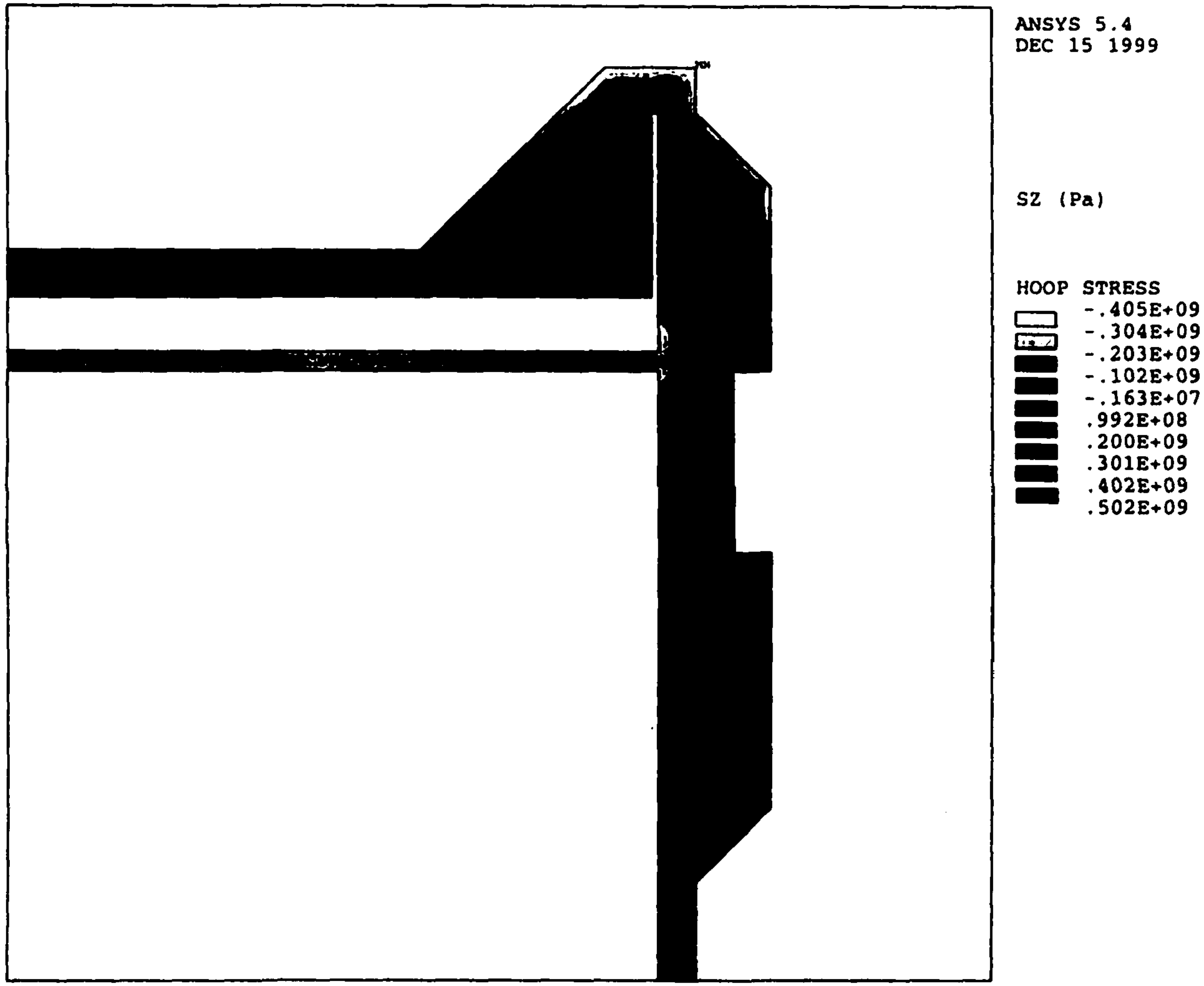


Figure 5.2. Residual Hoop Stress Distribution in the 2-D Axisymmetric FEM

CHAPTER 6

VERIFICATION OF FINITE ELEMENT RESULTS WITH EXPERIMENTAL TEST RESULTS

In order to verify that the finite element solution used in this study is appropriate for predicting residual stresses from annealing, an experimental test was conducted on a SNF canister mock-up (see Figure 6.1). This experimental test included solution annealing of the SNF canister mock-up rather than induction annealing. The difference between the two heat treatment techniques is that the solution annealing is applied to the structural component in its entirety, whereas the induction annealing is applied to one portion of a component that is to be heat treated locally. Since both techniques result in compressive stress on the outer surface of the structural component, substantiation of only one of these heat treatment methods using experimental and finite element methods is necessary to conclude that the annealing process can be properly simulated by the finite element method. Hence, the solution annealing of the canister mock-up and the results of both experimental and finite element studies are discussed in this section.

The SNF canister mock-up consisted of an outer shell and a bottom ring. After the plate was rolled into a cylindrical geometry, the two sides of the shell were welded (groove weld width was 1.25 inches). Then, the ring was welded onto the inner surface of the shell, close to the bottom end (fillet weld widths were 1 inches). All the weld

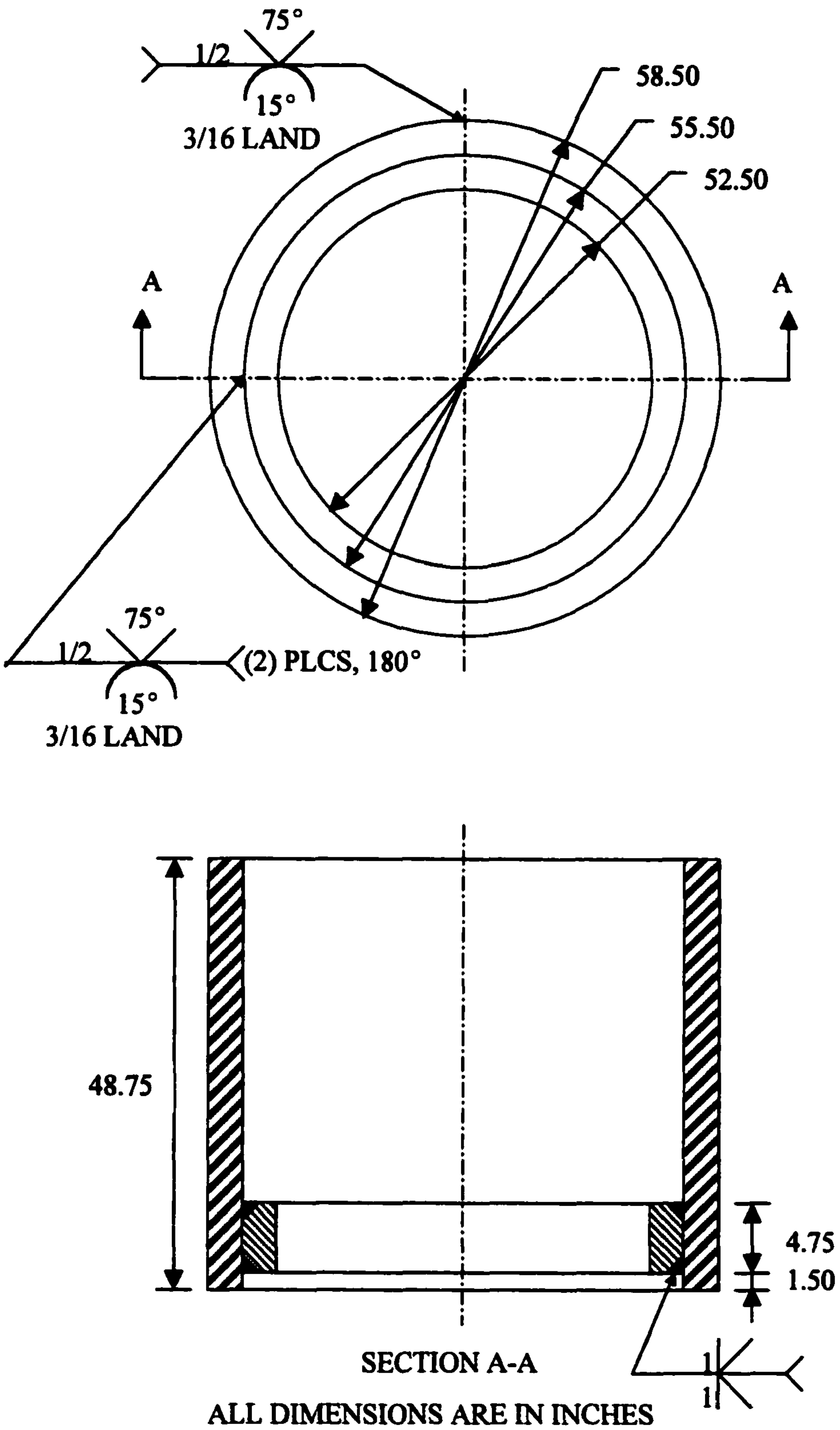


Figure 6.1. SNF Canister Mock-up Sketch

angles were maintained at 45°. Next, the mock-up was subject to solution annealing. At the end of the solution annealing process, the residual stresses were measured using "hole drilling method" [American Society for Testing and Materials (1992)]. Strain rosettes were placed on the outer surface of the shell at various locations and the stresses were recorded upon drilling a hole at the center of each strain rosette (Figure 6.2).

It should be noted that the induction annealing and solution annealing processes took place after all welds were completed in the SNF canister. As a result of this, any residual stress that might have been induced due to the welding process was relieved by the subsequent annealing process. Therefore, the analysis of the welding is not required in the finite element solutions provided in this study. However, one of the welds has been modeled in this study to validate the fact that the resulting stresses are the same at the end of the heat treatment, regardless of the simulation of the welding process prior to the annealing process.

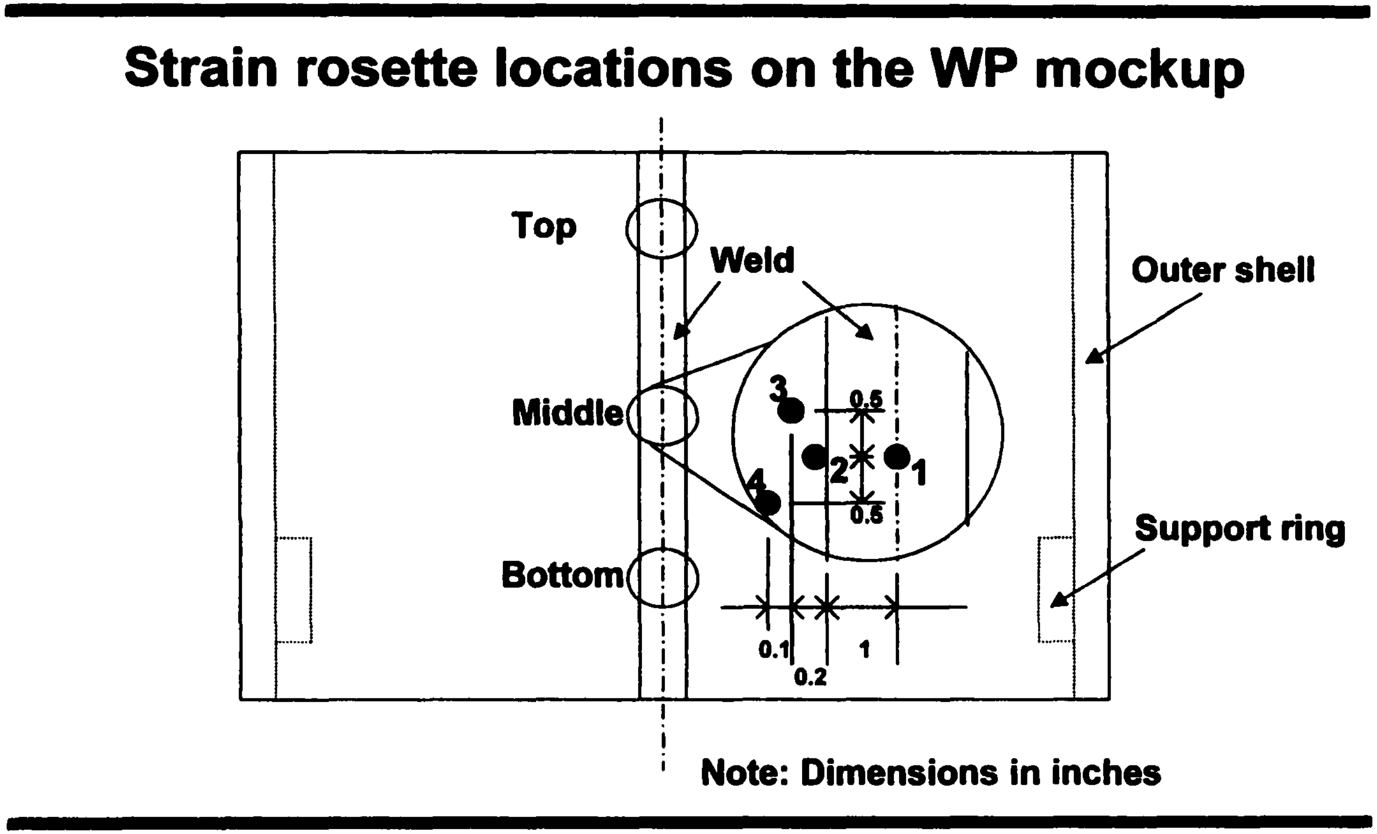


Figure 6.2. SNF Canister Mock-up and Strain Rosette Locations

In order to compare the results of this experimental test with the results of a finite element solution, the spent nuclear fuel canister mock-up welding and solution anneal heat treatment procedures have been simulated using ANSYS software (see Appendix IV). A three-dimensional half-symmetry model was developed (Figure 6.3). The weld seam consisted of three elements through the wall thickness and four elements along the circumference of the mock-up, which improved the accuracy obtained from the finite element solution. The mock-up was initially at 20 °C. The weld was assumed to remain in solid state throughout the simulation and the annealing temperature (1120 °C) was used as the peak welding temperature (see Figure 6.4). The basis for this assumption was that no significant effect on the base metal in terms of the change in stress-state was expected from the weld during the phase transformation from liquid to solid. Using this assumption, the weld seam temperature was increased to 1120 °C in 45 seconds to simulate the effect of the weld on the canister mock-up (Figure 6.4). It should be noted that the time for the weld seam to reach 1120 °C was inconsequential since the weld seam final temperature was essentially the same along the canister mock-up length. Then, the canister mock-up was cooled by conduction to simulate the effect of air cooling. The convection to air was not included since the conduction was expected to be the dominant mode of heat transfer during this process. As a result of air cooling, the maximum temperature decreased to 271 °C in 30 minutes. To ensure that the residual stresses would remain the same until the mock-up cooled down to room temperature, the hoop stress time history was obtained for two elements: one on the outer surface, another in the ring material. The stress evaluation at these two locations indicated that the steady-state values of stresses have been obtained (see Figure 6.5). This concluded the

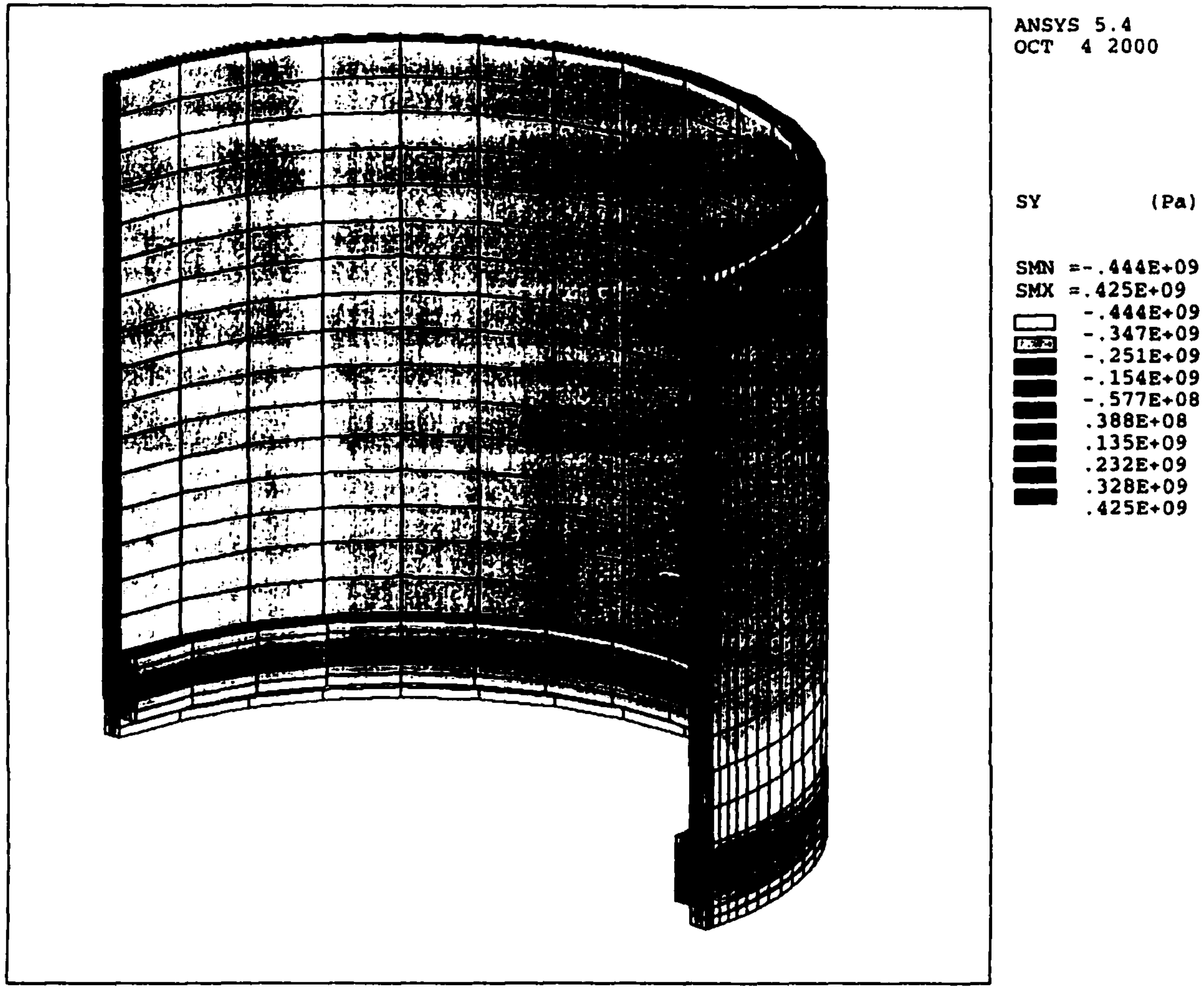


Figure 6.3. SNF Canister Mock-up 3-D FEM – Hoop Stress Plot

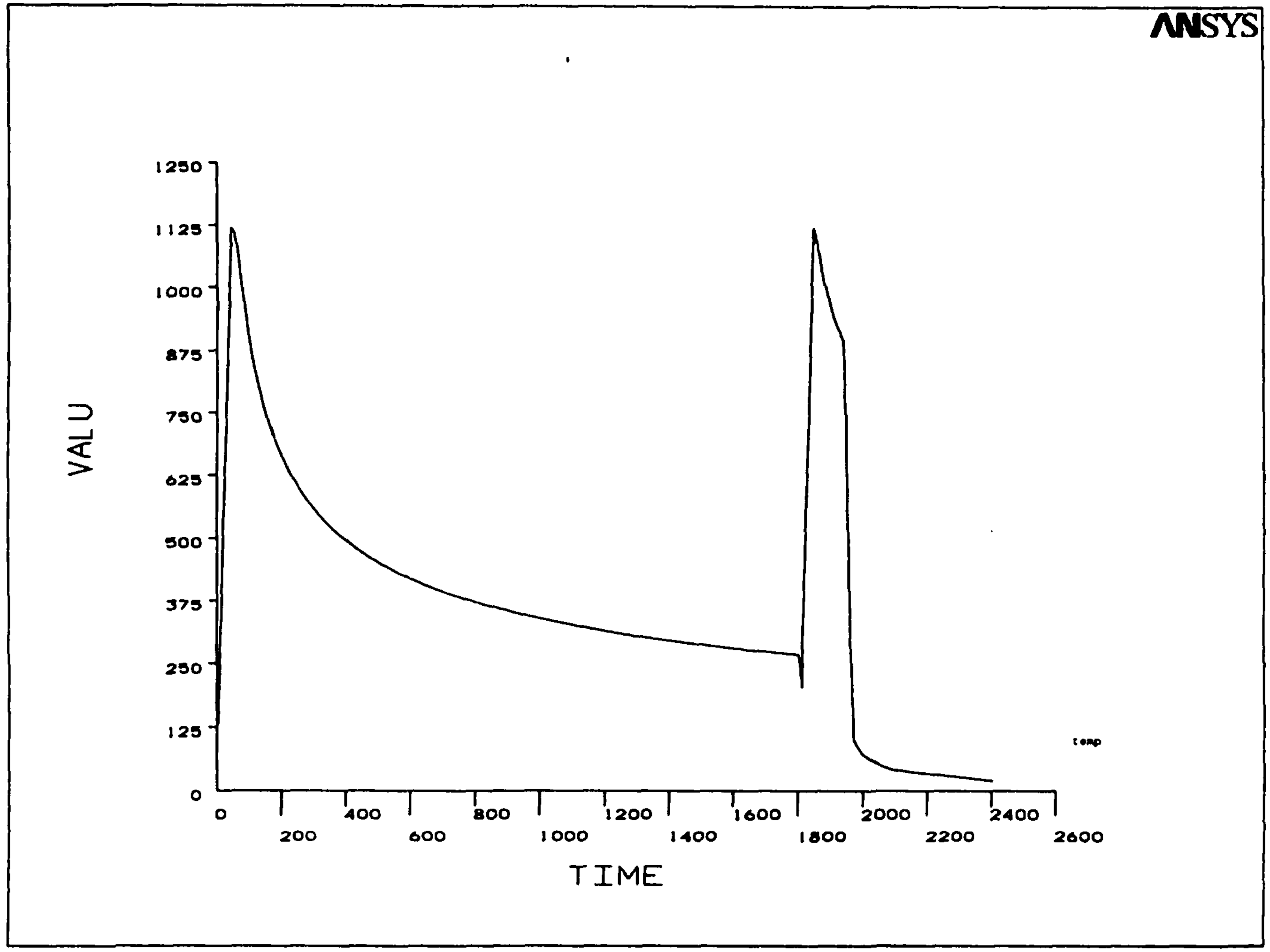


Figure 6.4. SNF Canister Mock-up Outer and Inner Surface Temperature History (Temperature in degrees C, Time in seconds)

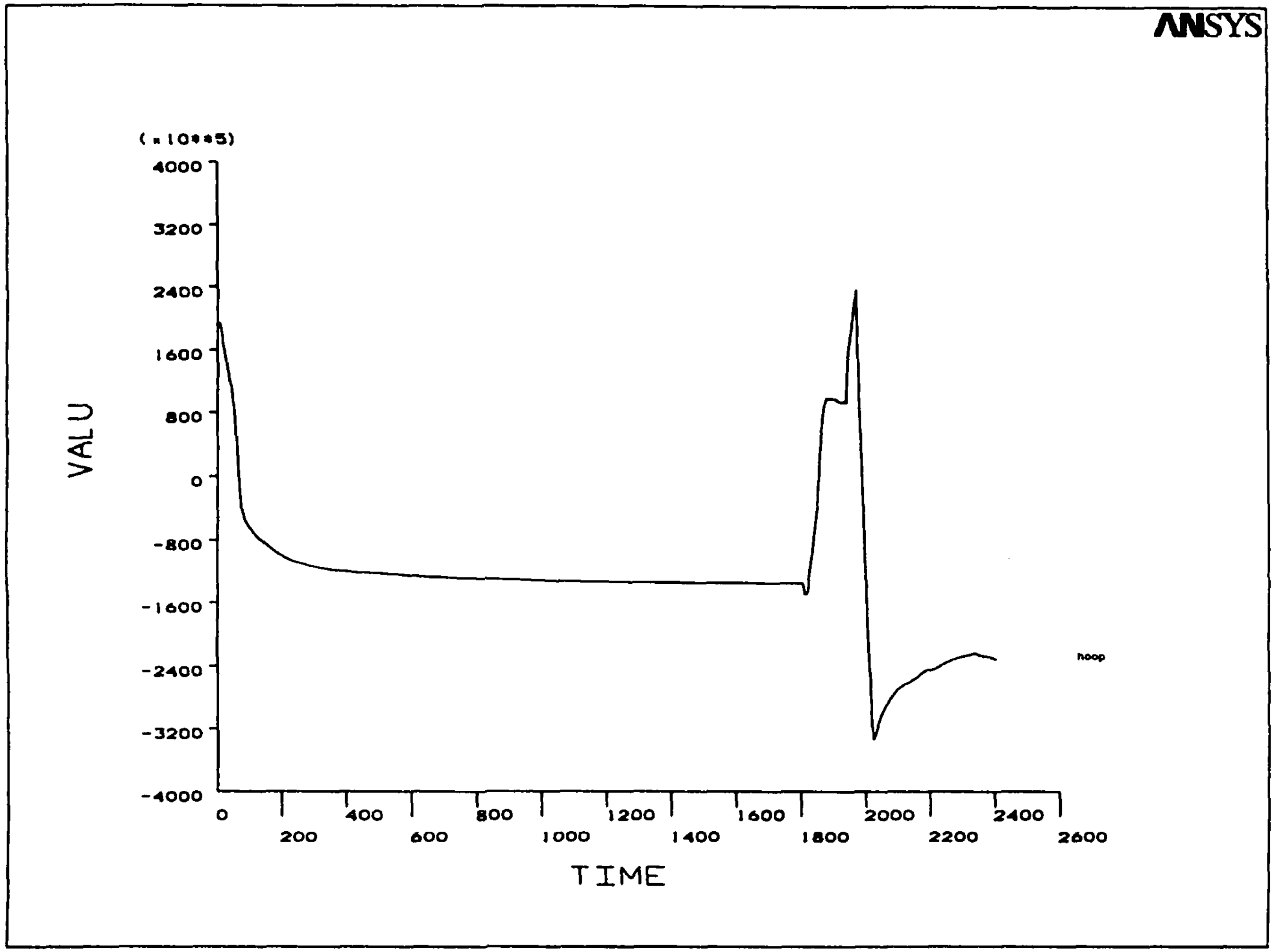


Figure 6.5. SNF Canister Mock-up Ring Area Outer Shell Surface Hoop Stress History (Hoop stress in Pa, Time in seconds)

part of the heat treatment for the welding process. Then, the heat treatment of this model was continued to determine the residual stresses subsequent to solution annealing. The entire volume of the canister was uniformly heated up to 1120 °C in 45 seconds. Then, using the temperature history from the thermocouples used in the experimental test, inner and outer surfaces were quenched to 20 °C in approximately 9 minutes.

The finite element solution indicated that there was variation in the stress values from node to node along the length of the canister mock-up. When the experimental results of the test mockup was compared to the finite element model, it was realized that the locations of some of the strain rosettes fell between the nodes. Therefore, the most appropriate method for reporting these results was to average the stress values for a certain number of nodes within the same distance. A length of approximately 8 cm along the canister mock-up was used in three different locations: top, middle, and bottom (see Figure 6.6). 8 cm covered two nodes at the locations top and the middle since the mesh was coarse in comparison to the bottom. However, the same distance covered five nodes at the bottom due to the large number of elements used. This method of averaging results was implemented in two different places along the circumference: one at the mid-weld and another adjacent to the weld seam.

In experimental tests, the residual stresses have been reported in terms of the maximum and minimum principal stresses and their directions from the circumferencial (hoop) direction (see Table 6.1 and Appendix V). To be able to compare the results of the experimental test with the results of the finite element model, all of the residual stresses obtained from the experimental test have been converted into hoop stresses using Mohr's circle for biaxial stress state. The calculations of this conversion are

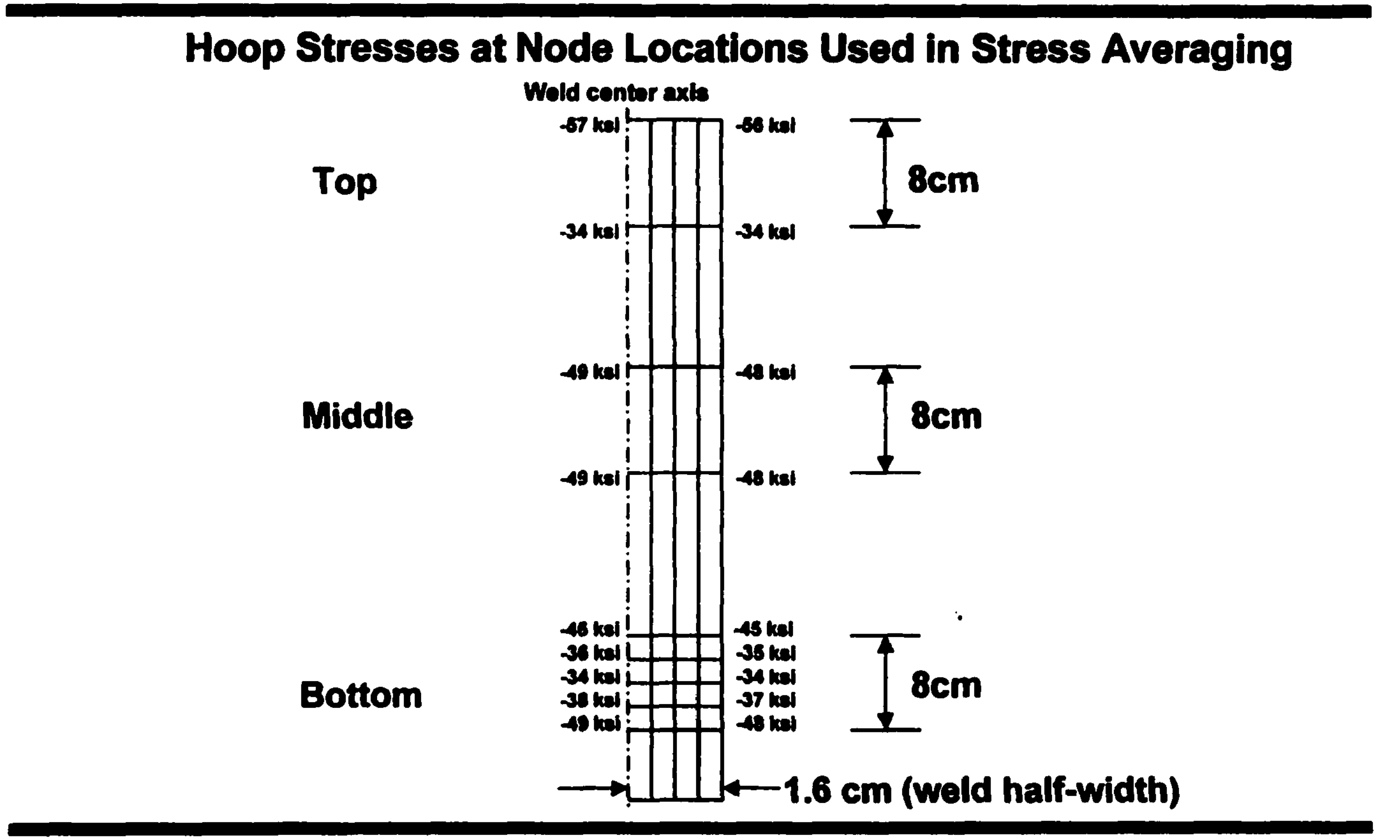


Figure 6.6. SNF Canister Mock-up Hoop Stresses at Nodes Used in Stress Averaging

documented in Appendix VI. Table 6.2 summarizes the results obtained from the test and the FEM in terms of hoop stress. Having the results of the experiment compared to the ones obtained from the finite element solution, it has been determined that the maximum difference between the two solutions was 11%. The difference has been attributed to possible welding distortions and uncertainty in strain gage readings.

Table 6.1. Experimental Test Results (Stress Magnitudes and Directions)

	Top			Middle			Bottom		
	σ_1 (ksi)	σ_2 (ksi)	θ (°)	σ_1 (ksi)	σ_2 (ksi)	θ (°)	σ_1 (ksi)	σ_2 (ksi)	θ (°)
Location # 1	-51	-62	+11	-72	-86	-54	-49	-54	-43
Location # 2	-42	-48	-23	-37	-39	+1	-47	-52	+4
Location # 3	-39	-44	+42	-46	-51	0	-44	-50	+2
Location # 4	-30	-53	+54	-46	-51	+9	-28	-43	+53

Note: σ_1 is the maximum principal stress, σ_2 is the minimum principal stress, and θ is the angle of the maximum principal stress form the direction of the hoop stress

Table 6.2. Comparison of Experimental Test Results and FEM Results

	Hoop Stress (ksi)					
	Top		Middle		Bottom	
	Test Results	FEM Results (2 nodes)	Test Results	FEM Results (2 nodes)	Test Results	FEM Results (5 nodes)
Location # 1	-51	-57 -34	-81	-49 -49	-51	-46 -36 -34 -38 -49
Location # 2	-43	-56 -34	-37	-48 -48	-47	-45 -35 -34 -37 -48
Location # 3	-41		-46		-44	
Location # 4	-45		-46		-38	
Average	-45	-45	-53	-49	-45	-40
Difference	0 %		8 %		11 %	

Note: Middle and bottom locations show relatively larger difference between the test and the FEM results, possibly due to welding distortions or uncertainty in strain gage readings

CHAPTER 7

OPTIMIZATION

The design analyzed in 3-D and 2-D was acceptable in terms of the maximum stresses; however, it was not determined if the design solution was optimum. Therefore, the design needed to be optimized for further improvement of compressive stress on the outer surface.

7.1 Optimization Using ANSYS Optimization Code

7.1.1 Minimization of Hoop Stress by Design Variables

The problem of optimization was first solved using the commercially available ANSYS software. The following discussion provides the technique and the procedure used for design optimization.

The optimization technique used in ANSYS was "sub-problem approximation" method. This was an advanced zero-order method, which required only the values of the dependent variables, not their derivatives. The relation between the objective function (OF) and the design variables (DV) was established by curve fitting (least squares fit); the resulting curve was called "approximation". The state variables (SV) were handled the same way as the design variables. In this method, the approximation was minimized instead of the objective function. The constrained problem was converted into an unconstrained one by adding "penalties" to the objective function approximation to account for the imposed constraints. This approach increased the efficiency of the solution. The convergence (termination) was made at the end of each optimization loop (iteration). The problem converges if any of the following conditions were satisfied for a feasible design:

- Change in objective function from the best feasible design to the current design is less than the objective function tolerance.
- Change in objective function between the last two designs is less than the objective function tolerance.
- Changes in all design variables from the current design to the best feasible design are less than their respective tolerances.
- Changes in all design variables between the last two designs are less than their respective tolerances.

The procedure used for design optimization consisted of four major steps:

1. An analysis file was created to be used during looping. The model was built parametrically (see Appendix VII); the solution was obtained; the parameters that were used as objective function and state variables were defined.
2. Optimization module was called. At this step, the objective function, design variables, and state variables were declared; the optimization method and the maximum number of optimization loops were specified.
3. Optimization analysis was initiated.
4. The resulting design sets were reviewed and the results were post-processed.

The objective function for the SNF canister optimization problem was defined as follows: minimize maximum hoop stress on the outer surface of the closure-weld region. It should be noted that the surface was identified by selecting nodes on the outer surface boundary. The maximum hoop stress was determined among these nodes using appropriate commands in ANSYS software (see Appendix VII).

The original design and its dimensions were given on Figures 3.1 and 3.2. The design geometry was such that all the angles in the closure-weld region were either 90° or 45°. It should be noted that after annealing, this design without optimization resulted in 70 MPa in compression.

Seven independent design variables have been identified as shown on Figure 7.1. The lower and upper limits for these design variables have been specified as follows:

85 mm < V1 < 150 mm

10 mm < V2 < 25 mm

30 mm < V3 < 60 mm

10 mm < V4 < 60 mm

10 mm < V5 < 50 mm

10 mm < V6 < 80 mm

10 mm < V7 < 80 mm

These independent design parameters have been determined based on the design geometry including the inner and outer shells, lids, the lifting feature, and the manufacturing requirements. The minimum values were estimated based on the minimum plate sizes that can be ordered from the manufacturers. Similarly, the maximum sizes were estimated by considerations of the realistic plate sizes that can be used to fabricate the SNF canister structural components. No other independent design parameters were identified in relation to the optimization of the induction anneal region since the rest of the dimensions were constrained by other design requirements such as lifting, handling, and emplacement.

In this study, four different optimization problems, starting from simple to more complex, have been considered. First three problems have the same initial geometry. The dimensions of the initial design variables are given in Tables 7.1, 7.2, and 7.3. The fourth problem is identical to the third problem except that it used the final answer of the third problem as an initial guess. The fourth problem also includes additional constraints.

The first optimization problem included only one design variable, which was used to obtain a simple solution to the problem as an initial attempt to determine the feasibility of the solution method. In this problem, the design variable defined as the sum of V3 and V4 was replaced with one design variable, V0. The lower and upper limits for this design variable have been specified as follows: 50 mm < V0 < 120 mm. This parameter represents the total height of the induction annealing region from the closure lid. Table 7.1 shows the initial guess value and the optimized solution in terms of the design variable and the objective function values. The results of the first solution attempt indicated that the resulting stress magnitude can be improved to 75 MPa (see Table 7.1 and Figure 7.2).

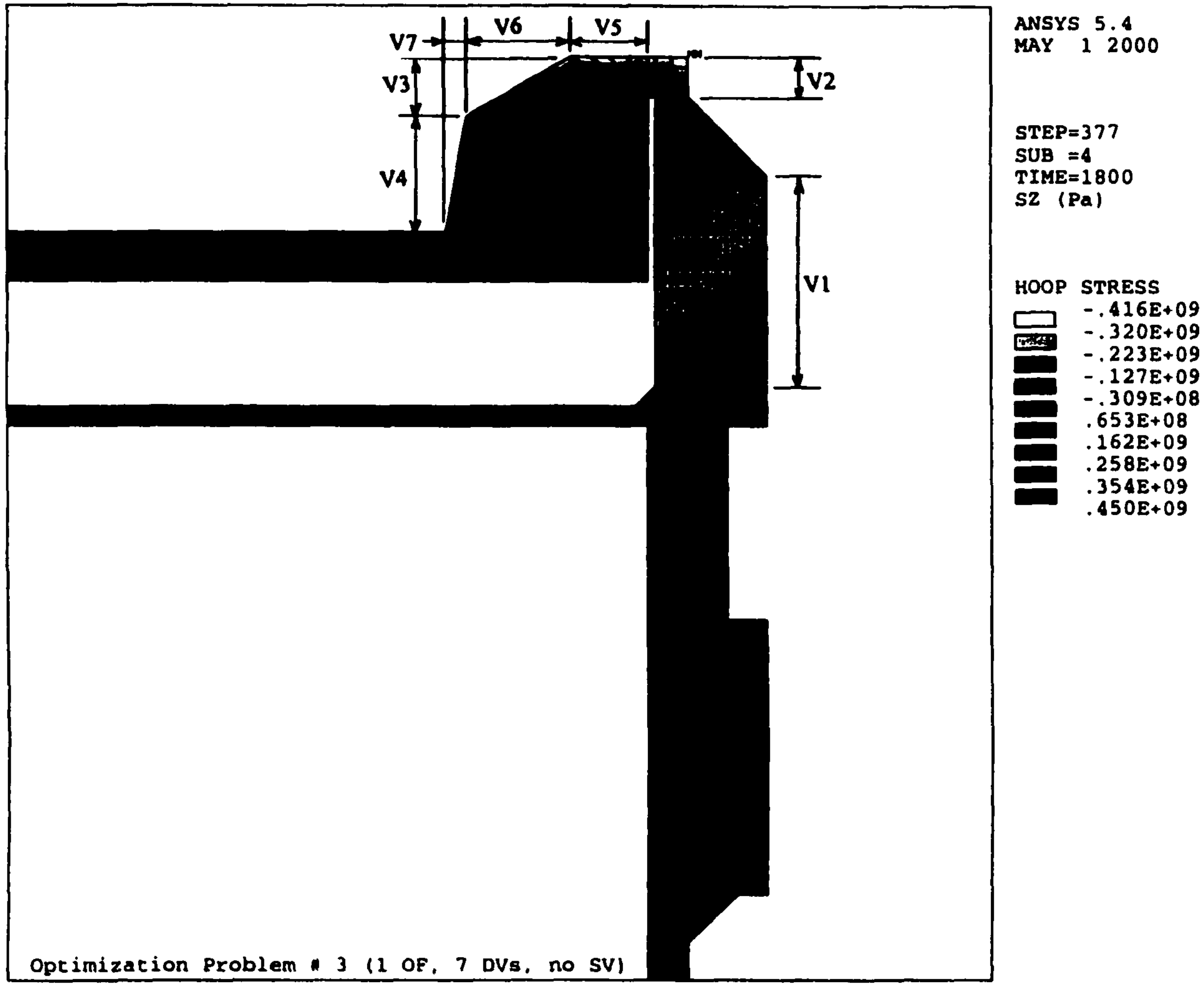


Figure 7.1. Optimization Problem #3 – Optimum Design Variables

Table 7.1. Optimization Problem # 1 (1 OF, 1 DV, no SV)

Design Variable	V0 = V3 + V4
Initial Value of Design Variable (mm)	100
Optimized Value of Design Variable (mm)	97
Optimized Objective Function Value (Maximum Compressive Hoop Stress) (MPa)	-75
Number of Function Evaluations	5

The second optimization problem was solved using three design variables (see Figure 7.3). It has been concluded from the results of this study that the compressive stress can be further improved to 98 MPa. The inputs and the results are summarized in Table 7.2.

Table 7.2. Optimization Problem # 2 (1 OF, 3 DVs, no SV)

Design Variables	V2	V5	V7
Initial Values of Design Variables (mm)	25	25	50
Optimized Values of Design Variables (mm)	44	28	37
Optimized Objective Function Value (Maximum Compressive Hoop Stress) (MPa)	-98		
Number of Function Evaluations	6		

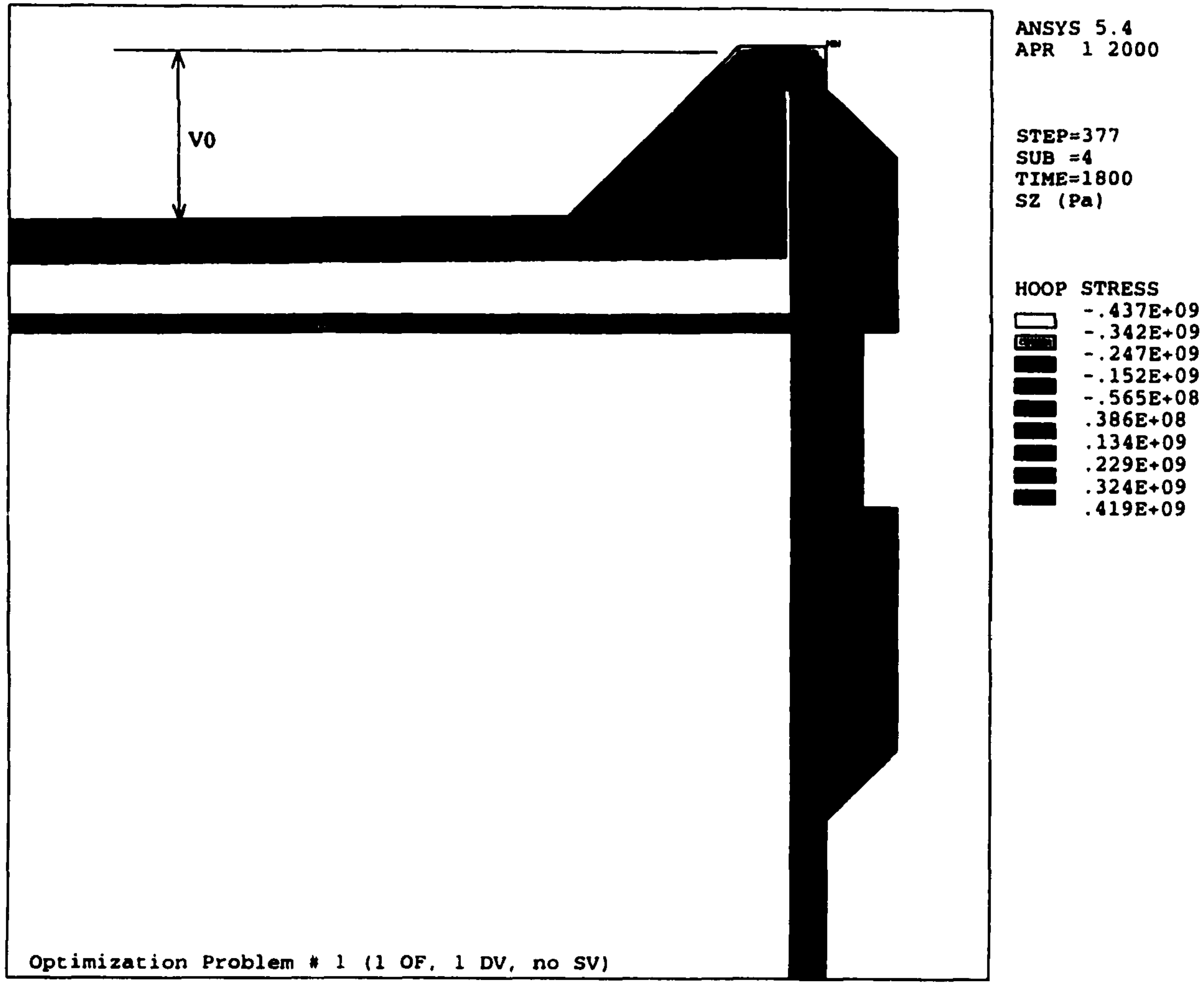


Figure 7.2. Optimization Problem #1 – Optimum Design Variable

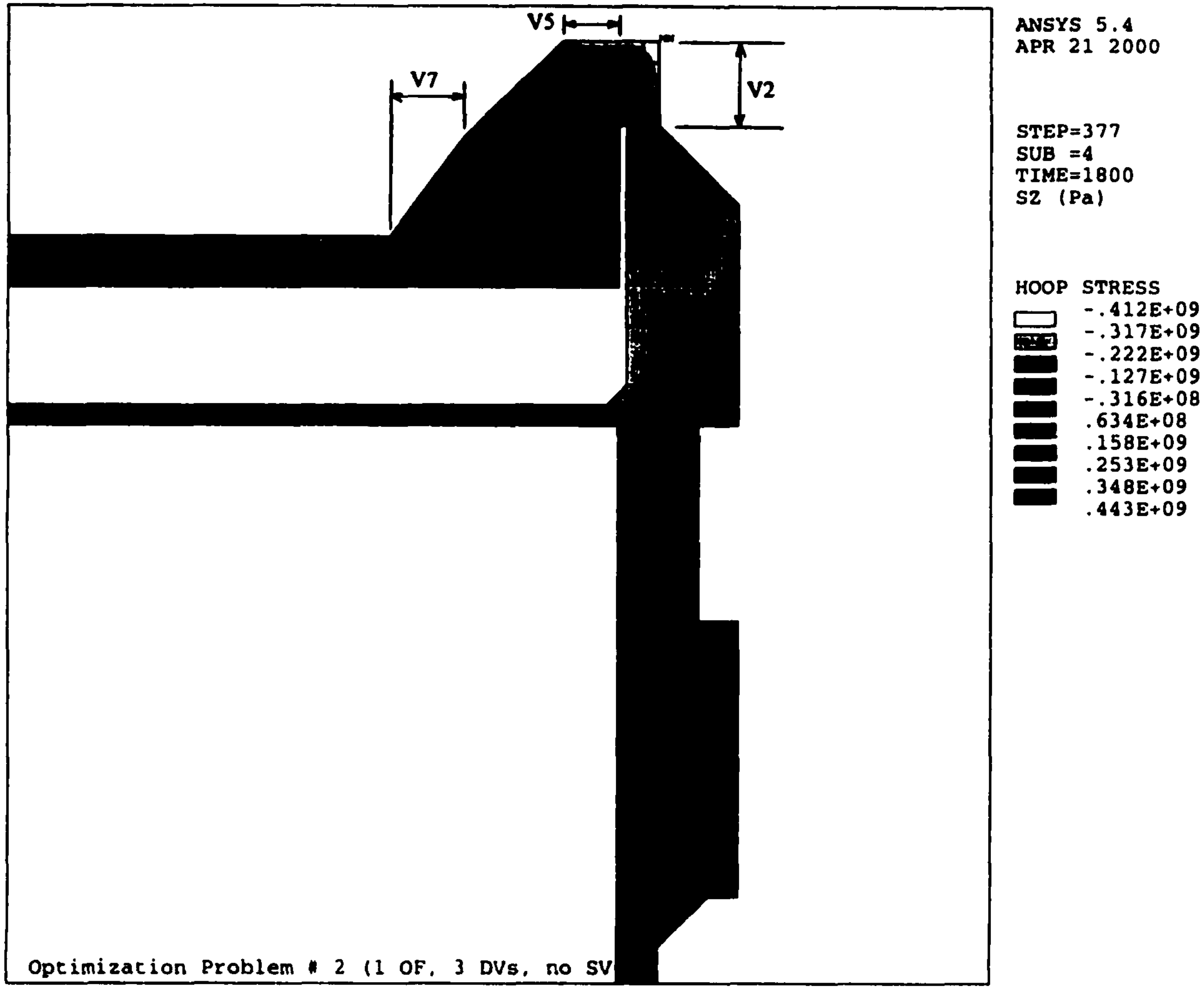


Figure 7.3. Optimization Problem #2 – Optimum Design Variables

The third optimization problem was performed using seven design variables shown in Figure 7.1. The results have clearly shown that the compressive stress can still be improved up to 130 MPa (see Table 7.3).

Table 7.3. Optimization Problem # 3 (1 OF, 7 DVs, no SV)

Design Variables	V1	V2	V3	V4	V5	V6	V7
Initial Values of Design Variables (mm)	90	25	50	50	25	50	50
Optimized Values of Design Variables	107	21	31	59	39	53	10
Optimized Objective Function Value (Maximum Compressive Hoop Stress) (MPa)	-130						
Number of Function Evaluations	17						

First three problems mentioned above had the same initial geometry. To ensure that the third problem provided the best solution, the fourth problem used the final dimensions of the third problem as initial guess values. The fourth problem also included the following six state variables:

Dimensional constraints (four defined):

$(V1 + V2) - (V3 + V4) \geq 5$ mm

$V5 + V6 + V7 \leq 200$ mm

$V3 - V2 \geq 3$ mm

$V3 + V4 \leq 150$ mm

The first constraint ensured that the gap between the two lids was greater than 30 mm. The second constraint set an upper limit to the summation of three design variables. The third constraint was defined by the geometry of the problem. Finally the fourth constraint set an upper limit to the summation of the two design variables.

Stress constraints (two defined):

Maximum radial stress ≤ 0.20 * Yield strength of the canister material

Maximum axial stress ≤ 0.20 * Yield strength of the canister material

These constraints were set to ensure that the maximum stresses in radial and axial directions did not exceed 20% of the material yield strength, which was the threshold limit for stress corrosion cracking [CRWMS M&O (2000b)].

After the state variables were added and the solution was obtained, it has been determined that the results of the third optimization problem remained the same (see Table 7.4).

Table 7.4. Optimization Problem # 4 (1 OF, 7 DVs, 6 SVs)

Design Variables	V1	V2	V3	V4	V5	V6	V7
Initial Values of Design Variables (mm)	107	21	31	59	39	53	10
Optimized Values of Design Variables	107	21	31	59	39	53	10
Optimized Objective Function Value (Maximum Compressive Hoop Stress) (MPa)	-130						
Number of Function Evaluations	11						

In summary, aforementioned results showed that all three solutions improved the initial design. The best result was obtained from the third solution, which improved the resultant compressive hoop stress by 86% compared to the original design which was not optimized.

7.1.2 Minimization of Hoop Stress by Changing the Cooling Rate

The effect of different cooling rates on the residual stresses is determined using optimization problem #3, given in previous section. Five different cooling time periods are considered for this problem: 300 seconds, 90 seconds, 60 seconds, 35 seconds, and 30 seconds. The results of the finite element solutions are summarized in Table 7.5. The results clearly indicate that the faster cooling rate results in lower hoop stress. Therefore, a minimum practically possible cooling rate of 30 seconds is selected for the heat treatment process. The finite element solution file supporting this analysis is documented in Appendix III.

Table 7.5. Effect of Cooling Rate on Hoop Stress

Cooling Rate	Minimized Maximum Hoop Stress in the Region of Annealing
300 seconds	38 MPa
90 seconds	-63 MPa
60 seconds	-84 MPa
35 seconds	-119 MPa
30 seconds	-130 MPa

7.2 Optimization Using Successive Quadratic Approximation

The problem of optimization discussed in previous section resulted in higher compressive hoop stress in the close-weld region than the stress obtained from the original design. However, the solution obtained from ANSYS subroutine can be further improved by using a separate solution. In order to accomplish this, the problem has been solved using a successive quadratic approximation.

The methodology used in the successive quadratic approximation is summarized in the flowchart in Figure 7.4. Using this approach, optimization of the currently available finite element models of canisters was performed. The results indicate that the compressive stress on the closure-weld outer surface can be further improved in comparison with the stress that has already been obtained from ANSYS optimization module.

The first step to solving this optimization problem is to determine a second degree polynomial surface with seven independent variables. For this purpose, the objective function should be evaluated for "m" data points using ANSYS. The minimum number of data points are determined from the following relation:

[*MathSoft, Inc.* (1997)]

$$m > \left[\frac{(n+k-1)\cdot(n+k-2)}{k!}\right]\cdot\frac{n+k}{n}$$

[*MathSoft, Inc.* (1997)]

where "n" is the number of independent variables, "k" is the degree of the desired polynomial, and "m" is the number of data points. In this study, "n" is 7, "k" is 2. Solving for the equation given above, "m" should be greater than 36:

m > (8*7 / (2!)) * ((7 + 2) / 7)

m > 36

Therefore, a total of thirty-seven data points are used.

The same upper and lower bounds, L_j and U_j, respectively, of the previous section are used here. These bounds were defined on page 42.

Thirty-six initial data points are generated using the steps given below:

1. Generate six (given as "s" in Figure 7.4) equally-spaced values for seven design variables.

2. The first set of design variable values to calculate the first function value consists of the first data point of the first design variable and the third data points of all other design variables. Then, the second set of design variable values to calculate the second function value consists of the second data point of the first design

variable and the third data points of all other design variables. The third, fourth, fifth, and the sixth set of design variable values follow the same pattern.

3. The seventh set of design variable values to calculate the seventh function value consists of the first data point of the second design variable and the third data points of all other design variables. Following the same pattern described in step #2, except for the common set of values on the third data point, five sets of design variable values are created by using the equally-spaced values of the second design variable. The same procedure is repeated for the third, fourth, fifth, sixth, and seventh design variables to create in total of thirty-six initial data points. All sets of data points created by this procedure are clearly given on the second page in Appendix VIII.

The calculation of the design variable values required to generate the thirty-six initial data points is mathematically described below:

Number of data points, i

Number of design variables, j

Number of equally-spaced intervals, s

Design variable values, V

Size of intervals, Δ

$\Delta_j = (U_j - L_j) / (s - 1) \quad (j = 1 \ldots 7)$

Using the parameters defined above, the following algorithm specifies the required sets of design variable values for the thirty-six initial data points:

```
start
for     i = 1 ... 6
        V_i1 = L_1 + Δ_1 (i - 1)
        for     j = 2 ... 7
                V_ij = L_j + Δ_j (2)
        end
end
for     i = 1 ... 6
        for     j = 1 ... 5
                ii = (i - 1) 5 + j + 6
                V_ii 1 = L_1 + Δ_1 (2)
                for     k = 2 ... 7
                        if      k = i + 1
                                V_ii k = L_k + Δ_k (k - 2)
                        else    V_ii k = L_k + Δ_k (2)
                end
        end
end
stop
```

The finite element solution for all data points are obtained using ANSYS. The best solution obtained by ANSYS optimization are added to these data points to increase the total number of data points to thirty-seven. Then, a quadratic polynomial is fitted to these data points (see Appendices VIII and X). The minimum point of the quadratic surface is found using Monte Carlo Programming Technique (see Appendix IX). This solution is then input into ANSYS to obtain the actual value of the hoop stress.

The next step in this algorithm is to identify the maximum hoop stress among all function evaluations performed (σ_{max}). The termination criterion depends on the comparison of the minimum hoop stress obtained from ANSYS solution (σ) with the maximum hoop stress value (σ_{max}). If the calculated minimum hoop stress is less than the maximum hoop stress value among all function evaluations, then the maximum hoop stress is replaced with the minimum hoop stress value and the process feeds back to the point of determining approximate objective function by fitting a second degree polynomial to the new set of data points. However, if the calculated minimum hoop stress is more than or equal to the maximum hoop stress value among all function evaluations, then the minimum of all function evaluation values is determined to be the optimum solution.

For this problem, the termination criterion was reached after a total number of fourteen iterations in addition to the initial data points (see Figure 7.5 and Appendix VIII, pp. 214-242). The results of this optimization algorithm are given in terms of the minimum quadratic and function values in Figure 7.5. In this figure, the minimum quadratic and function values are depicted by diamonds and squares, respectively. It is noted that the maximum compressive hoop stress increased to 136 MPa at iteration number four, when the minimum quadratic value exceeded the initial minimum function value. The subsequent values of the minimum quadratic curve also indicate that a better minimum function value cannot be obtained; having met the previously set termination criterion, the program is terminated after iteration number fourteen.

A resulting compressive stress of 136 MPa is 5% better than the compressive stress obtained from ANSYS subroutine. This solution is also 94% better than the original design. For this solution, the maximum compressive hoop stress and the corresponding values of design variables are given in Table 7.6. The optimum design solution using successive quadratic approximation with stress distribution is shown in Figure 7.6. A comparison of the optimized design variable values between the ANSYS solution (Table 7.4) and the successive quadratic approximation solution (Table 7.6) showed that the change in V1, V5, and V6 did not have a significant effect on the optimized objective function value.

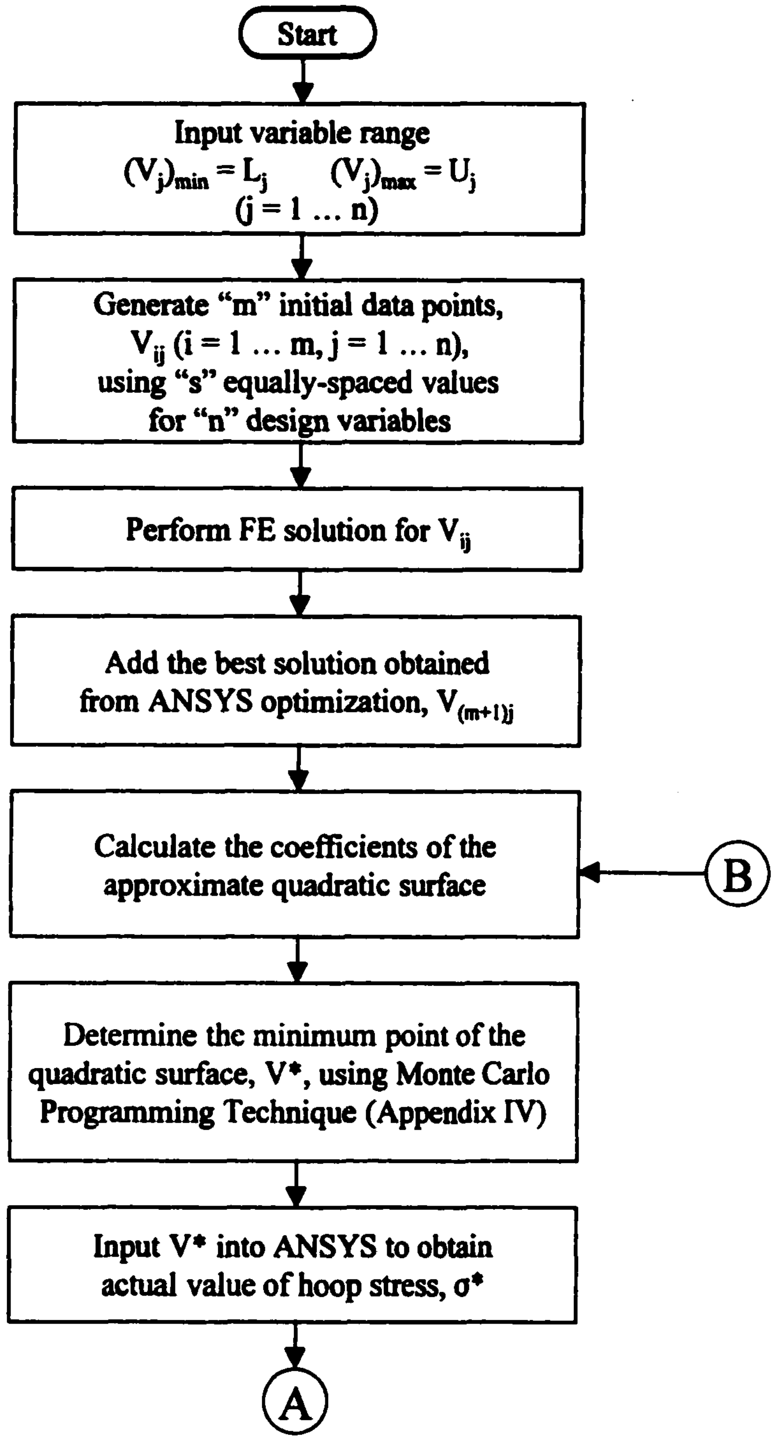


Figure 7.4. Flowchart for Successive Quadratic Approximation

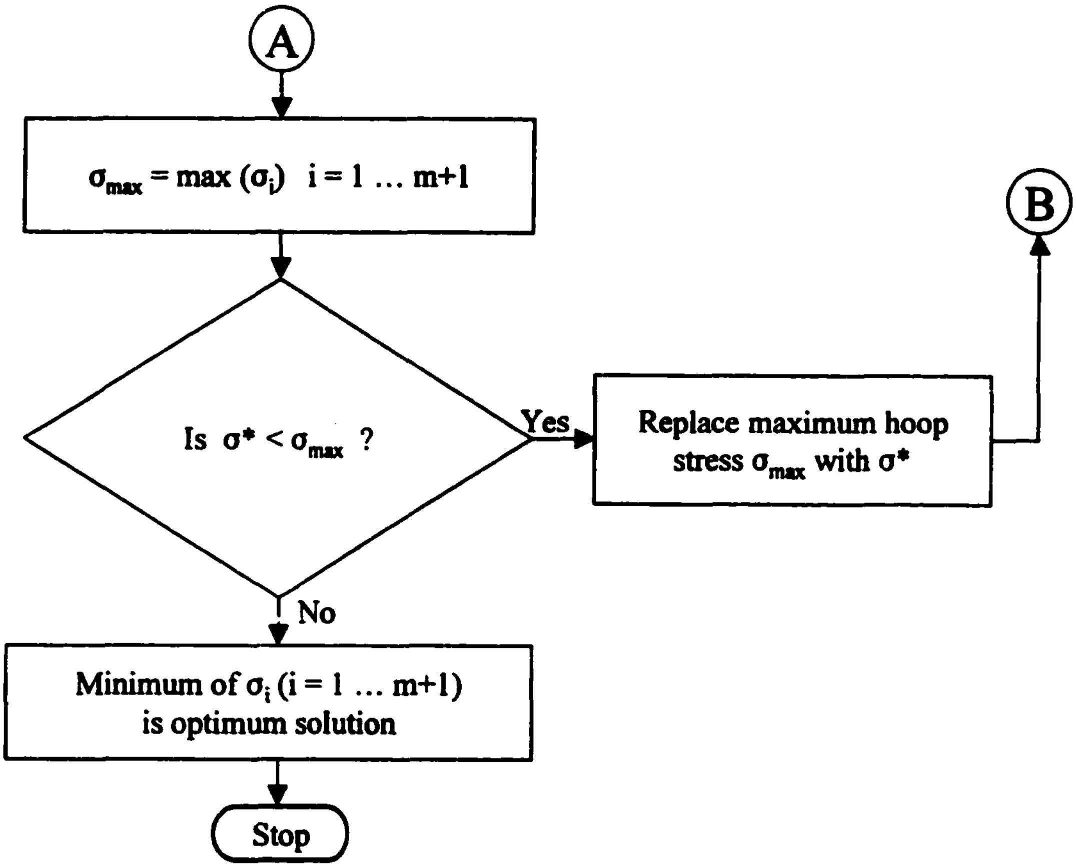


Figure 7.4. Flowchart for Successive Quadratic Approximation (continued)

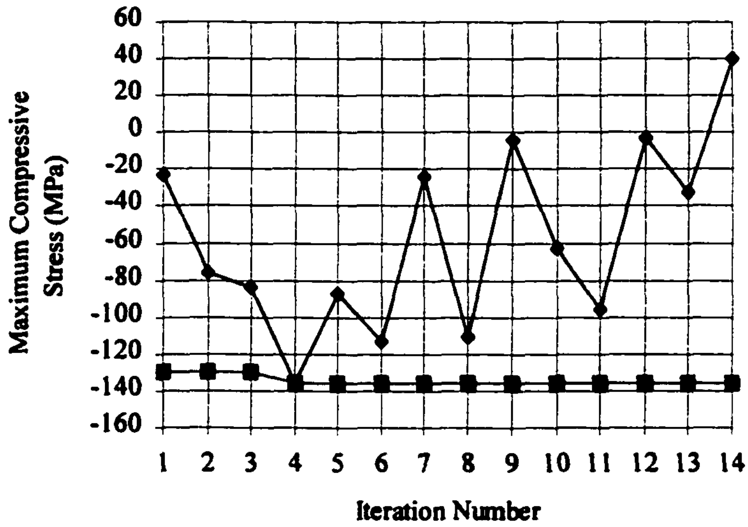


Figure 7.5. Quadratic Approximation Minimum Values (Diamonds) and Overall Function Minimum Values (Squares) for the Successive Quadratic Approximation

Table 7.6. Solution from Successive Quadratic Approximation

Design Variables	V1	V2	V3	V4	V5	V6	V7
Optimized Values of Design Variables	97	24	31	58	14	79	12
Optimized Objective Function Value (Maximum Compressive Hoop Stress) (MPa)	-136						
Number of Function Evaluations	14						

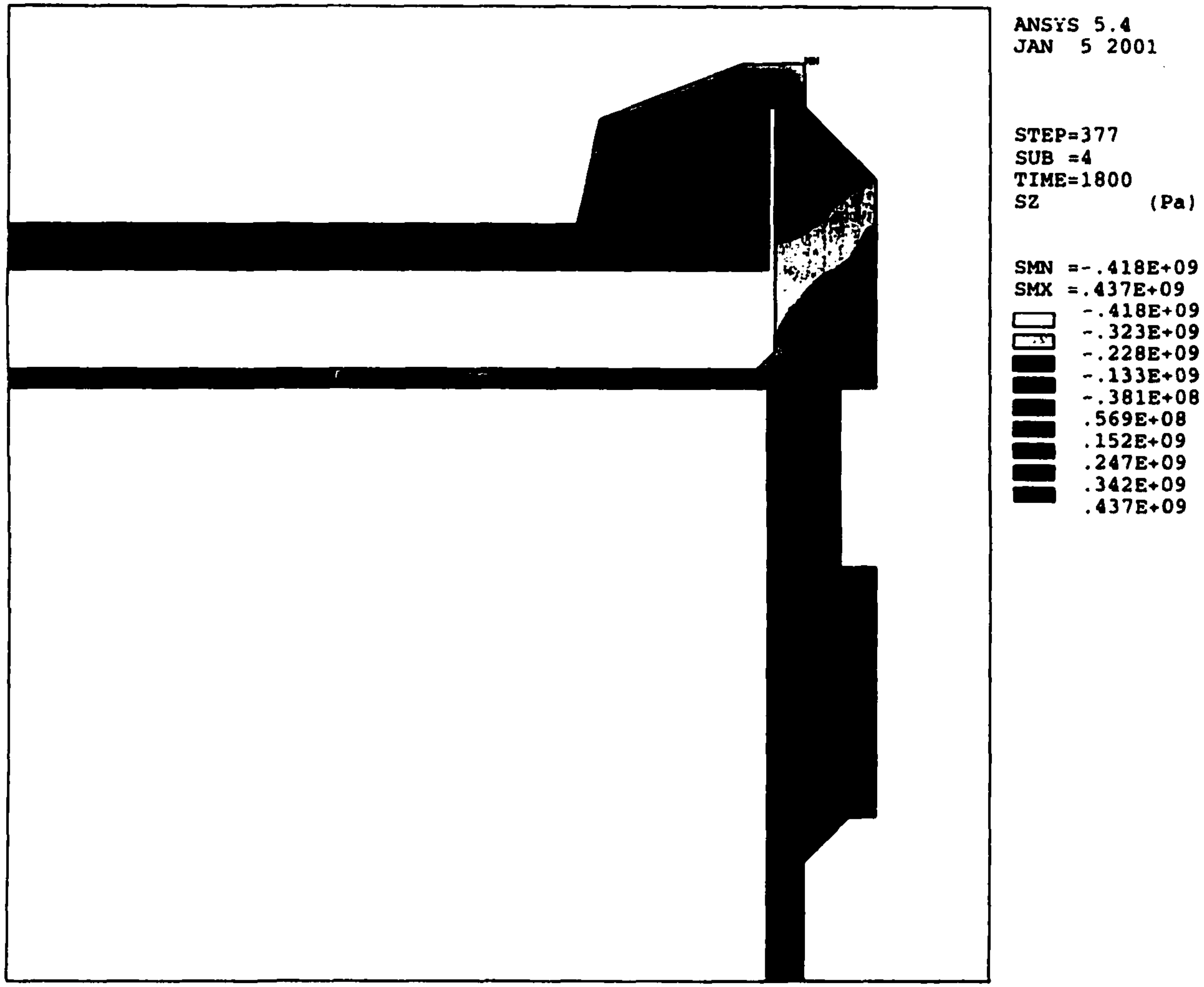


Figure 7.6. Hoop Stress Distribution for the Successive Quadratic Approximation Solution (Time: 1800 seconds)

7.3 Optimization Using Successive Heuristic Quadratic Approximation

Successive quadratic approximation, presented in previous section, resulted in higher compressive hoop stress in the close-weld region than the stress obtained from ANSYS subroutine. However, it is worthy of note to determine if the results can still be improved by using a separate solution. Therefore, the problem has been solved using a novel method, which is labeled the successive heuristic quadratic approximation.

The methodology used in the successive heuristic quadratic approximation is illustrated in Figure 7.7, for the case of a two-variable problem. The solution starts in the first domain identified as #1. A quadratic polynomial is fitted to the data points in this domain. Then, the minimum point of the quadratic surface is determined using Monte Carlo Programming Technique. This solution is then input into ANSYS to obtain the actual value of the hoop stress. The next domain is generated around "K" number of points with the lower function value. These points are complemented by "m-K" that are randomly generated. Next, the point corresponding to the minimum function value of the quadratic curve fitting is added to the current set of data points. This process is repeated as shown in Figure 7.7. The solution is terminated only when one of the termination criteria is satisfied as outlined in Figure 7.8.

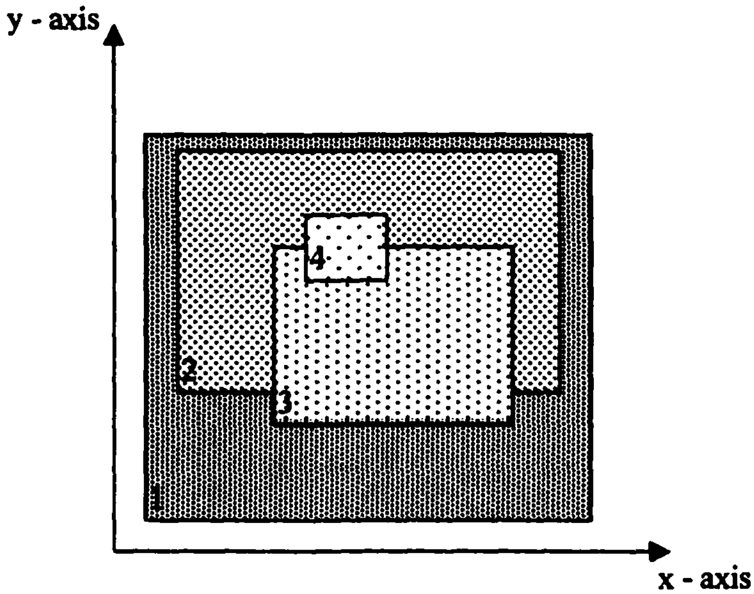


Figure 7.7. Two Dimensional Illustration of Optimization Algorithm

The following steps are used in the successive heuristic quadratic approximation method:

1. The same upper and lower bounds, L_j and U_j, respectively, of the previous section are also used here. "m" number of initial data points are generated using "s" equally-spaced values for "n" design variables between the bounds as described in the previous section. The finite element solution for these data points are obtained using ANSYS. The best solution obtained by ANSYS optimization are added to these data points. Then, a quadratic polynomial is fitted to these data points (see Appendix X). The minimum point of the quadratic surface is found using Monte Carlo Programming Technique (see Appendix IX). This solution is then input into ANSYS to obtain the actual value of the hoop stress.

2. The second part of this algorithm incorporates a different method of convergence to the optimum solution (see Figure 7.8). First, the range of the function values for all data points is identified. Then, the points in the lower half of the function value range are selected. New upper and lower bounds of the design variables are identified based on these points. The new bounds are expanded by a factor "α" to avoid over-constraining the search. Additional (m-K) data points are randomly generated. The function values of these data points are determined by an input file that uses multiple design variable values (see Appendix XI). These (m-K) data points replace the ones outside the new bounds. At the end of this process, the point corresponding to the minimum function value of the quadratic curve fitting is added to the current set of data points. The difference between the maximum and minimum values of all design variables and also the minimum function value among the "m+1" data points are recorded for subsequent data processing.

3. At this point in the algorithm, specific criteria are checked for termination:

   a. If the minimum function value recorded in the current loop is less than the function value recorded in the previous loop, the second termination criterion has to be checked for termination. If the current function value is more than or equal to the previously recorded value, then the previously recorded minimum function value is the optimum solution.

   b. The second termination criterion is based on the comparison of the calculated design variable intervals with an acceptable set of design variable intervals. The acceptable set of design variables was determined by dividing the original intervals (see Section 7.1) by two. The acceptable set of design variable intervals are given in Appendix X, page 265. These intervals are monitored to ensure their convergence to desired values (indicated as "D" on Figure 7.8). If this criterion is not satisfied, the program then returns to the point where the approximate objective function was determined by quadratic curve fitting. However, if it is met, then the third termination criterion is checked.

c. The third criterion enforces completion of the algorithm if the maximum number of iterations, "I_{max}", is reached. If the third termination criterion is not satisfied, the program again returns to the point where the approximate objective function was determined by quadratic curve fitting. However, if this criterion is met, the fourth and the final criterion is checked for termination.

d. The final criterion requires the calculation of the ratio of the standard deviation of the function evaluations to their average value, as indicated in Figure 7.8. If this ratio is larger than "ϵ", the program again returns to the point where the approximate objective function was determined by quadratic curve fitting. If the ratio is less than "ϵ", then the last recorded minimum function value is the optimum solution.

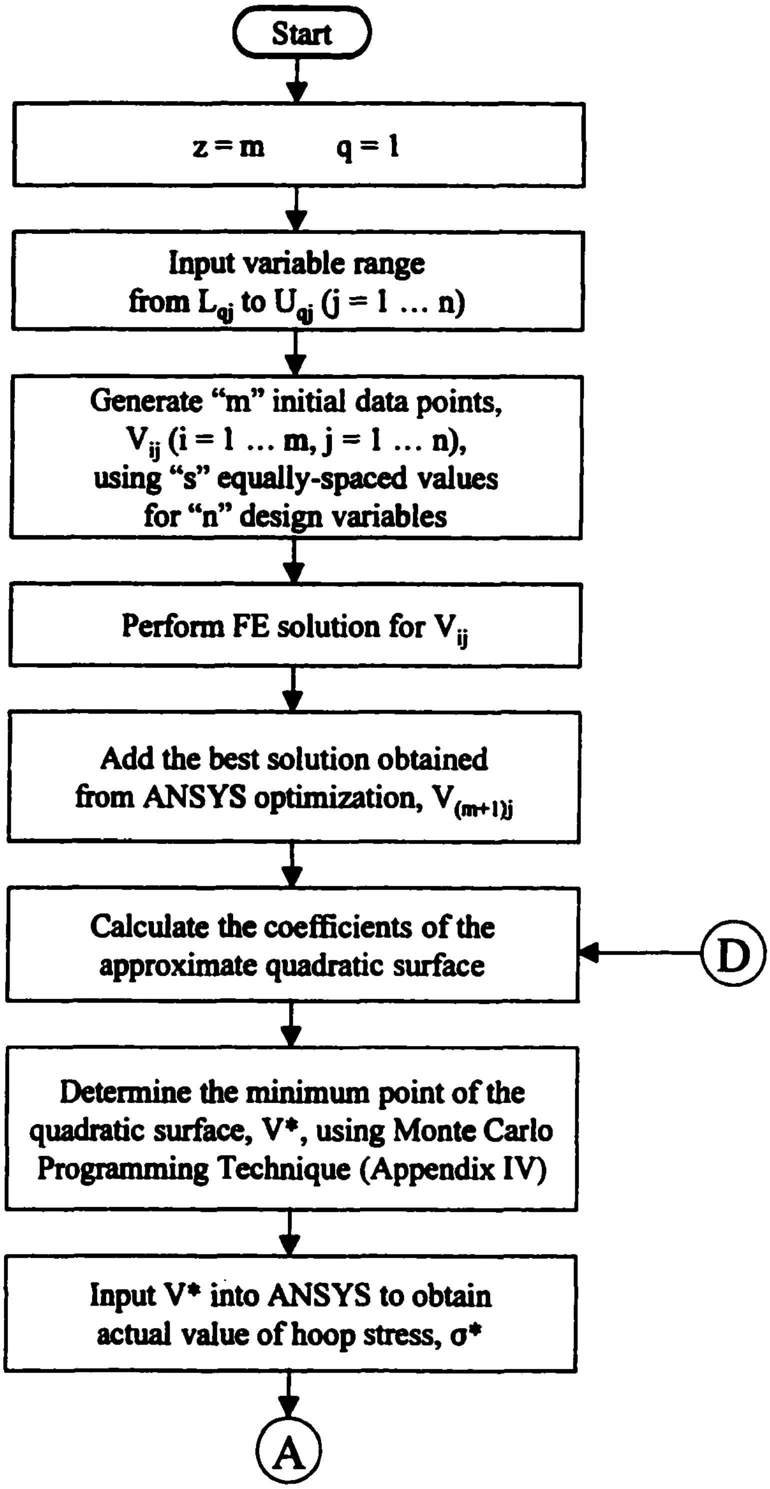


Figure 7.8. Flowchart for Successive Heuristic Quadratic Approximation

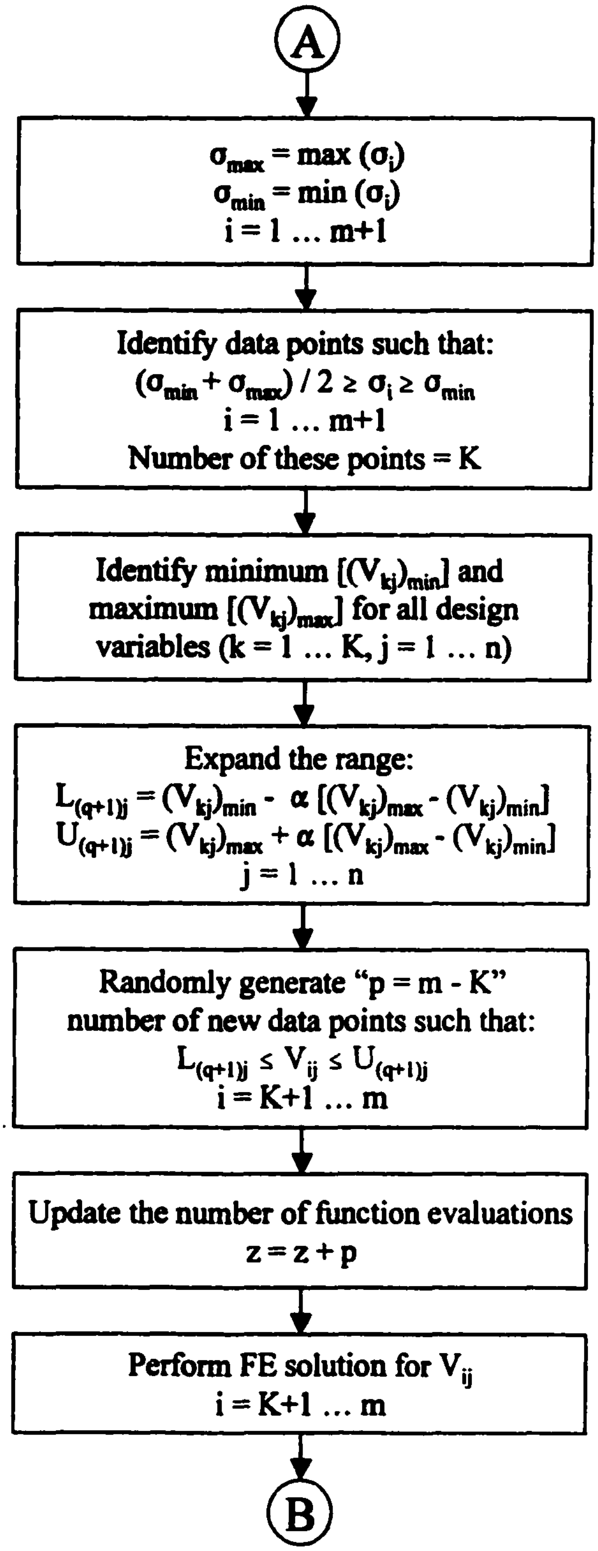


Figure 7.8. Flowchart for Successive Heuristic Quadratic Approximation (continued)

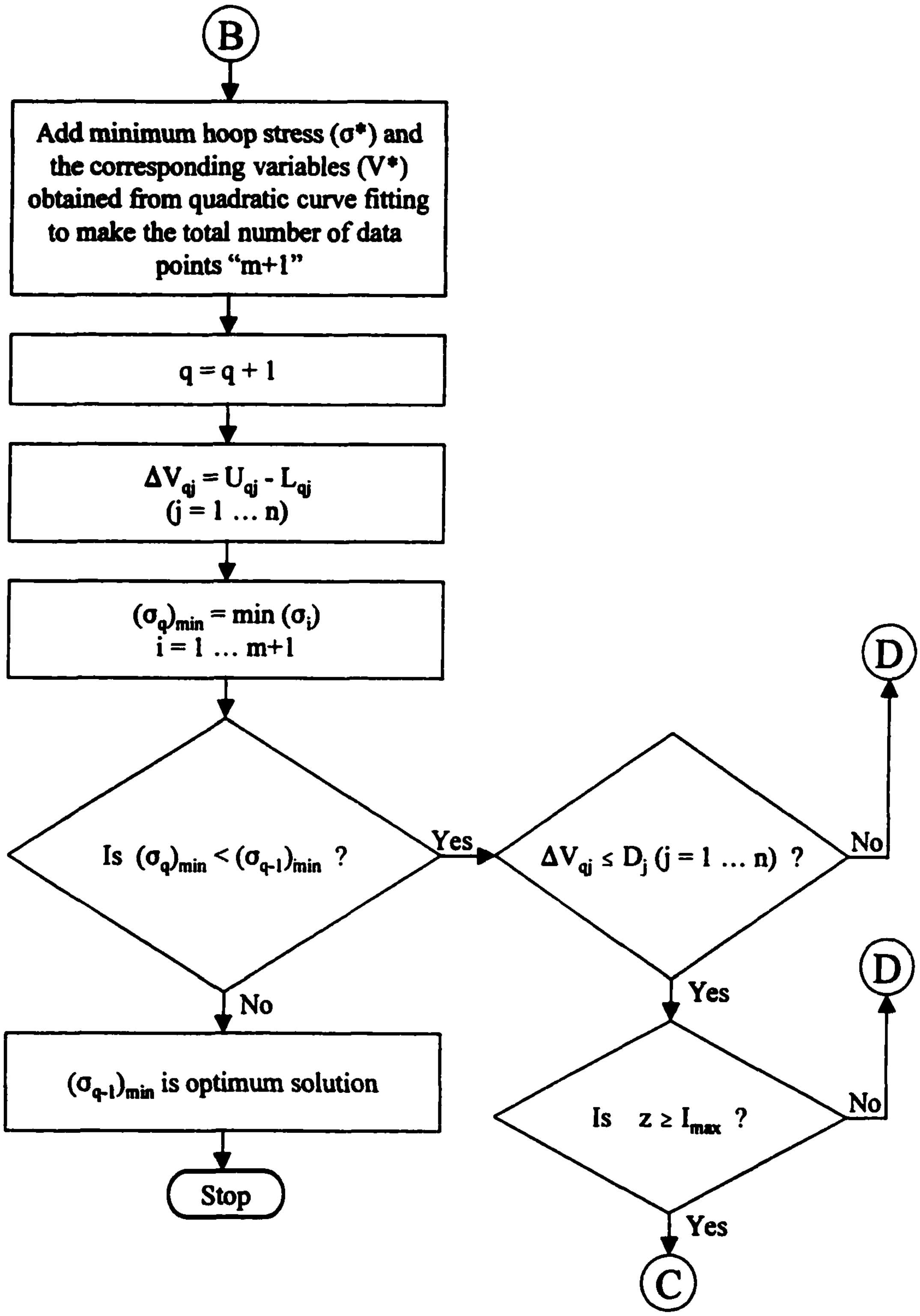


Figure 7.8. Flowchart for Successive Heuristic Quadratic Approximation (continued)

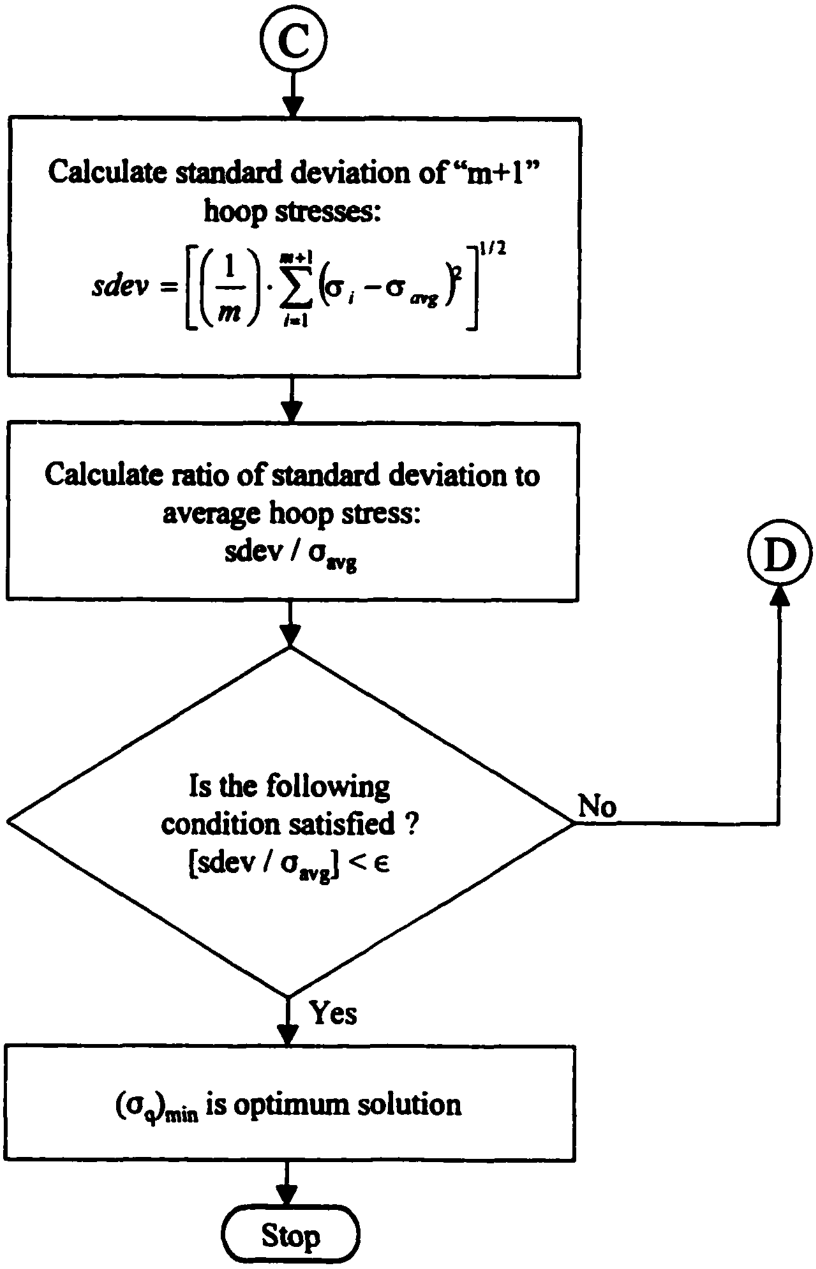


Figure 7.8. Flowchart for Successive Heuristic Quadratic Approximation (continued)

The numerical values of all parameters defined for this optimization problem are given in Table 7.7.

Table 7.7. Numerical Values of Parameters Used in Successive Heuristic Quadratic Approximation Algorithm

Parameter Description	Numerical Value
Number of Initial Data Points, m	36
Number of Equal-Size Spaces between Data Points, s	6
Number of Independent Variables, n	7
Factor of Expansion for the Range of Design Variables, α	0.2
Maximum Number of Iterations, I_{max}	100
Ratio of the Standard Deviation of the Function Evaluations to Their Average Value, ϵ	0.3

The total number of function evaluations for this optimization is 124. The calculations for each function evaluation are provided in Appendix X. The termination criterion was reached after a total number of four iterations (see Figure 7.9). The results of this optimization algorithm are given in terms of the minimum quadratic and function values in Figure 7.9. In this figure, the minimum quadratic and function values are depicted by diamonds and squares, respectively. It is noted that the minimum quadratic value did not improve the minimum function value. Having met the previously set termination criterion, the program is terminated after iteration number four. As a result of these iterations in accordance with the algorithm given in Figure 7.8, the final optimum solution is determined to provide a minimum hoop stress of 158 MPa. The corresponding dimensions of the design variables are given in Table 7.8. For this "best" solution, the distribution of temperature and the hoop stress at different time steps are given in Figures 7.10 through 7.23. These figures indicate that the hoop stress on the outer surface of the induction annealing region is initially tensile because of the fast cooling of the outer surface as opposed to the inner section. As the cooling of the inner sections of the material takes place, the layer of tensile stress moves away from the outer surface of the closure-weld into the deep section of the material volume. This behavior is explained by the shrinking of the inner sections, and therefore, forming a compressive stress layer on the outer surface, later in the cooling process.

The results of the successive heuristic quadratic approximation indicate that the minimum hoop stress is improved by 22% compared to the solution obtained form ANSYS optimization. When compared to the original design (see Section 7.1.1), the improvement is 126%. The optimum design solution with stress distribution is shown in Figure 7.23.

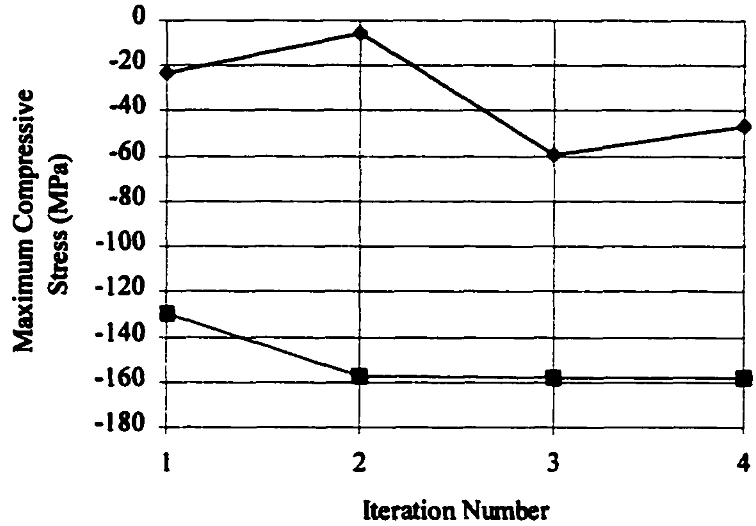


Figure 7.9. Quadratic Approximation Minimum Values (Diamonds) and Overall Function Minimum Values (Squares) for the Successive Heuristic Quadratic Approximation

Table 7.8. Solution from Successive Heuristic Quadratic Approximation

Design Variables	V1	V2	V3	V4	V5	V6	V7
Optimized Values of Design Variables	107	21	31	57	47	75	10
Optimized Objective Function Value (Maximum Compressive Hoop Stress) (MPa)	-158						
Number of Function Evaluations	124						

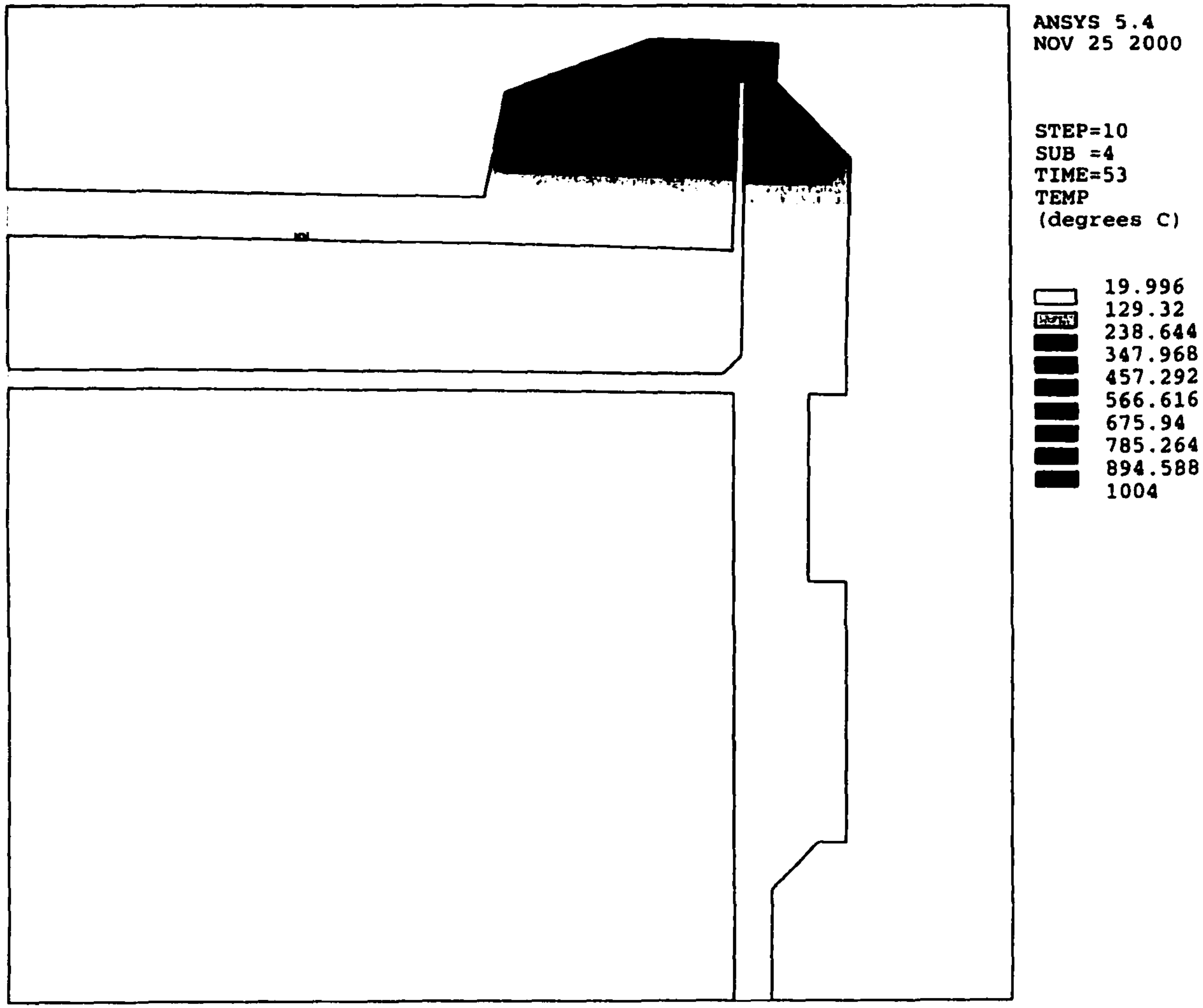


Figure 7.10. Temperature Distribution for the Successive Heuristic Quadratic Approximation Solution (Time: 53 seconds)

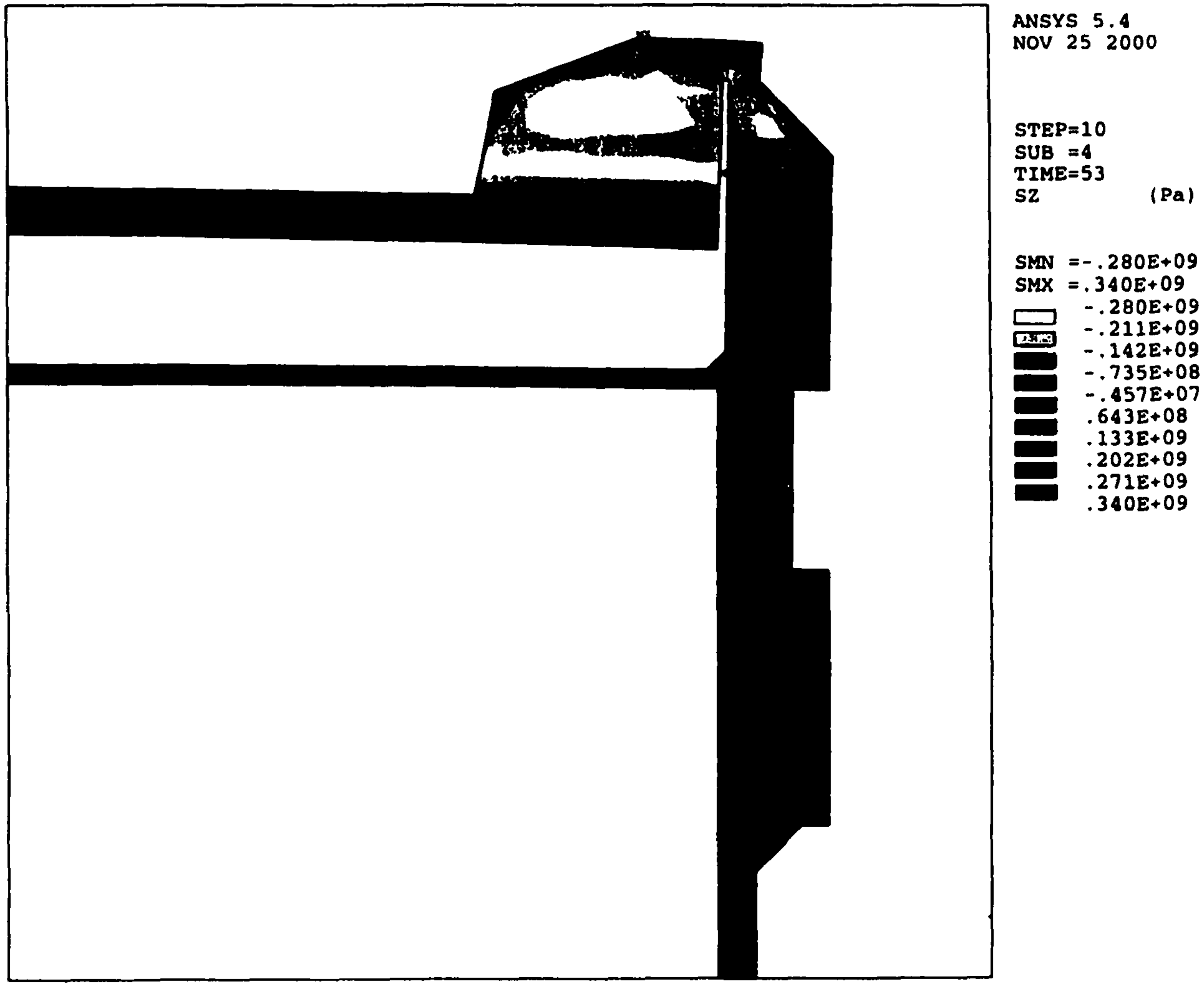


Figure 7.11. Hoop Stress Distribution for the Successive Heuristic Quadratic Approximation Solution (Time: 53 seconds)

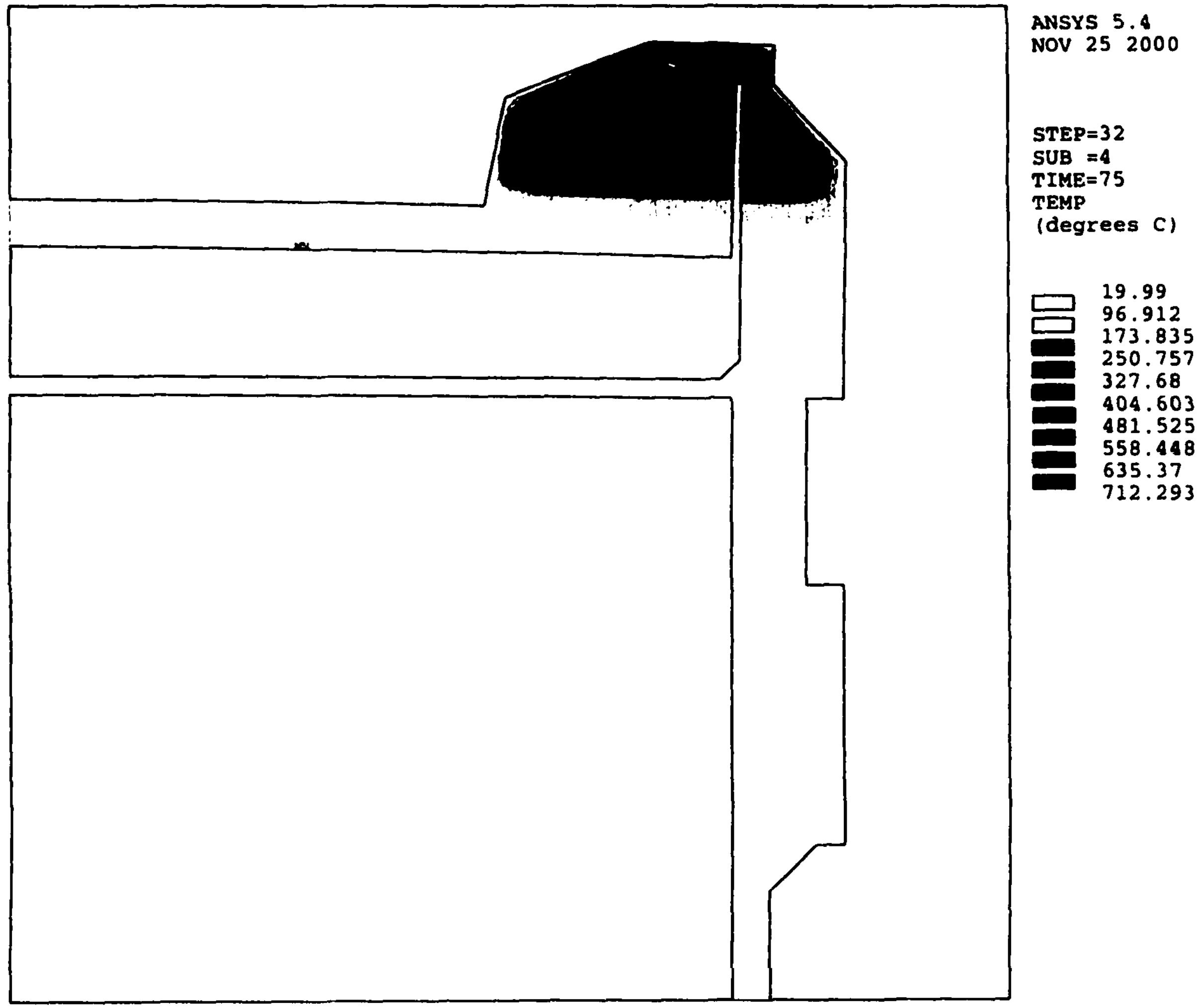


Figure 7.12. Temperature Distribution for the Successive Heuristic Quadratic Approximation Solution (Time: 75 seconds)

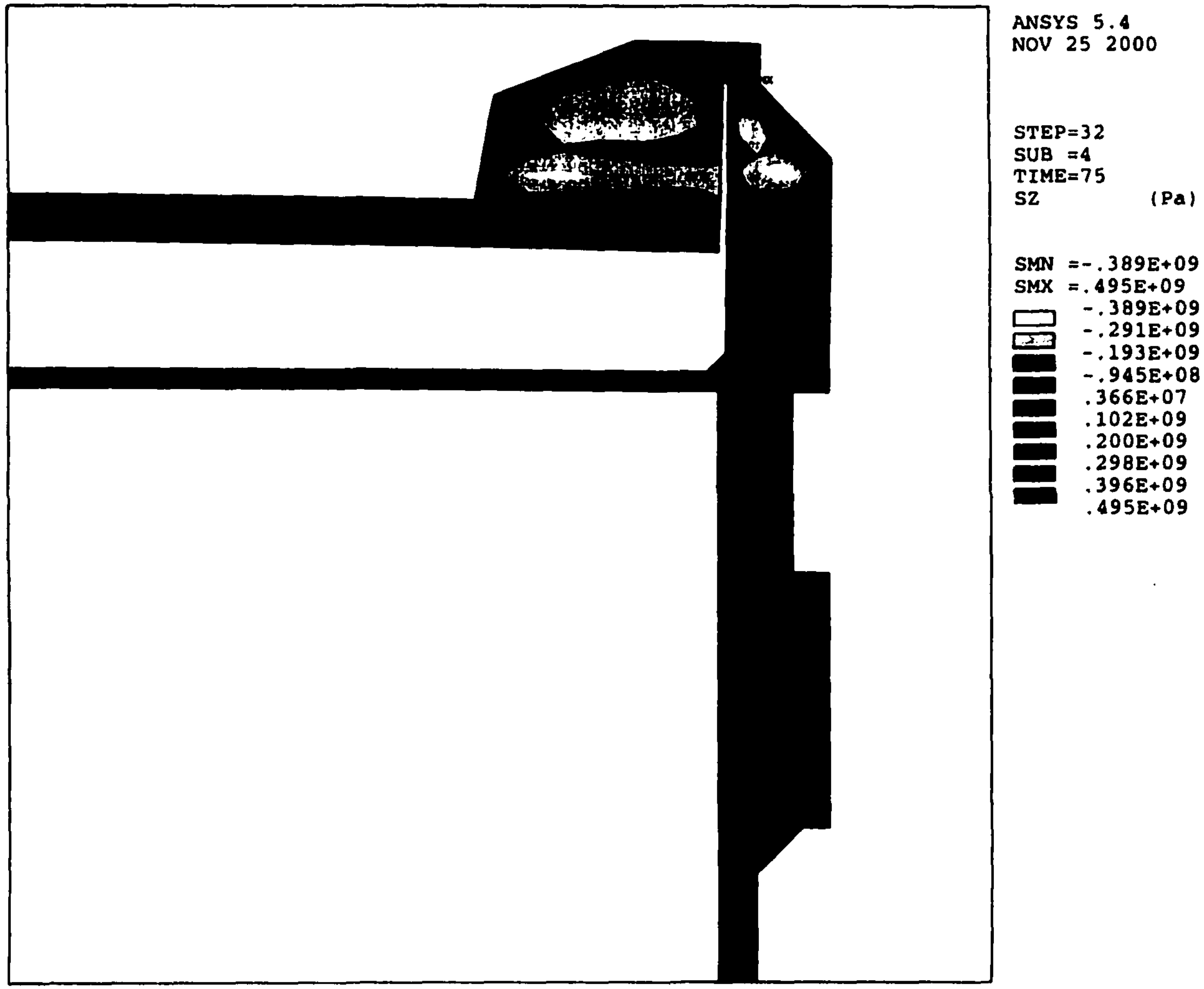


Figure 7.13. Hoop Stress Distribution for the Successive Heuristic Quadratic Approximation Solution (Time: 75 seconds)

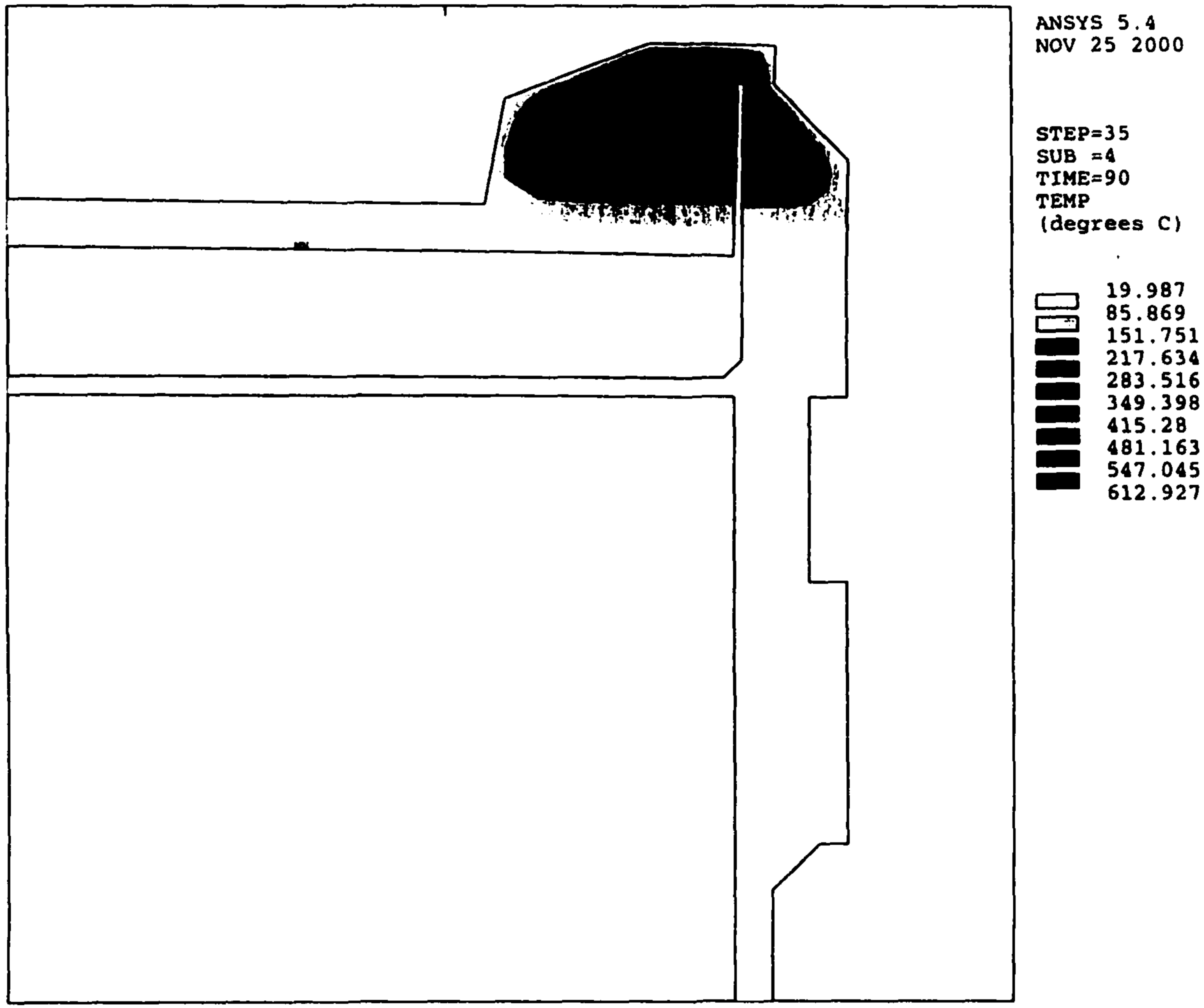


Figure 7.14. Temperature Distribution for the Successive Heuristic Quadratic Approximation Solution (Time: 90 seconds)

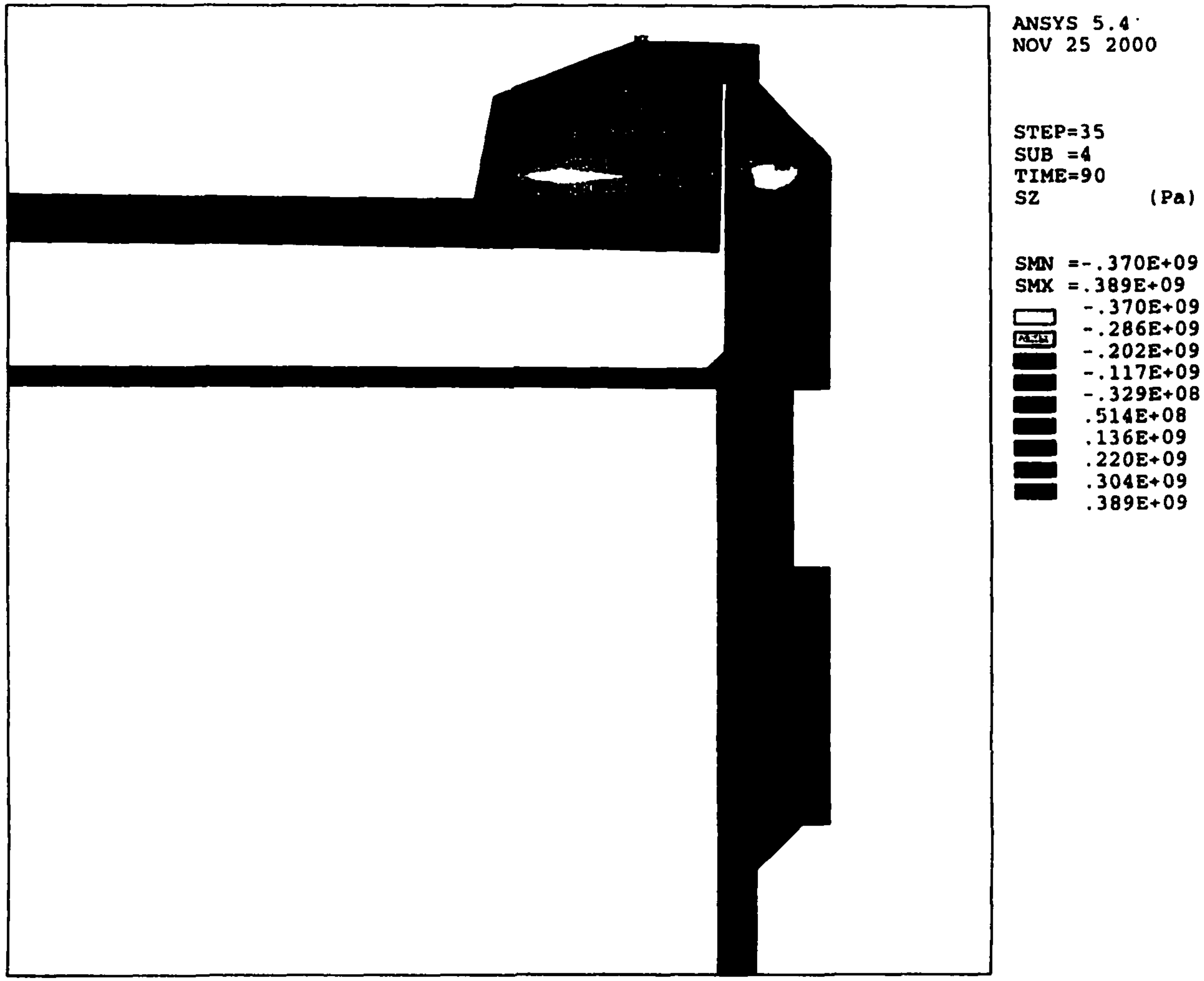


Figure 7.15. Hoop Stress Distribution for the Successive Heuristic Quadratic Approximation Solution (Time: 90 seconds)

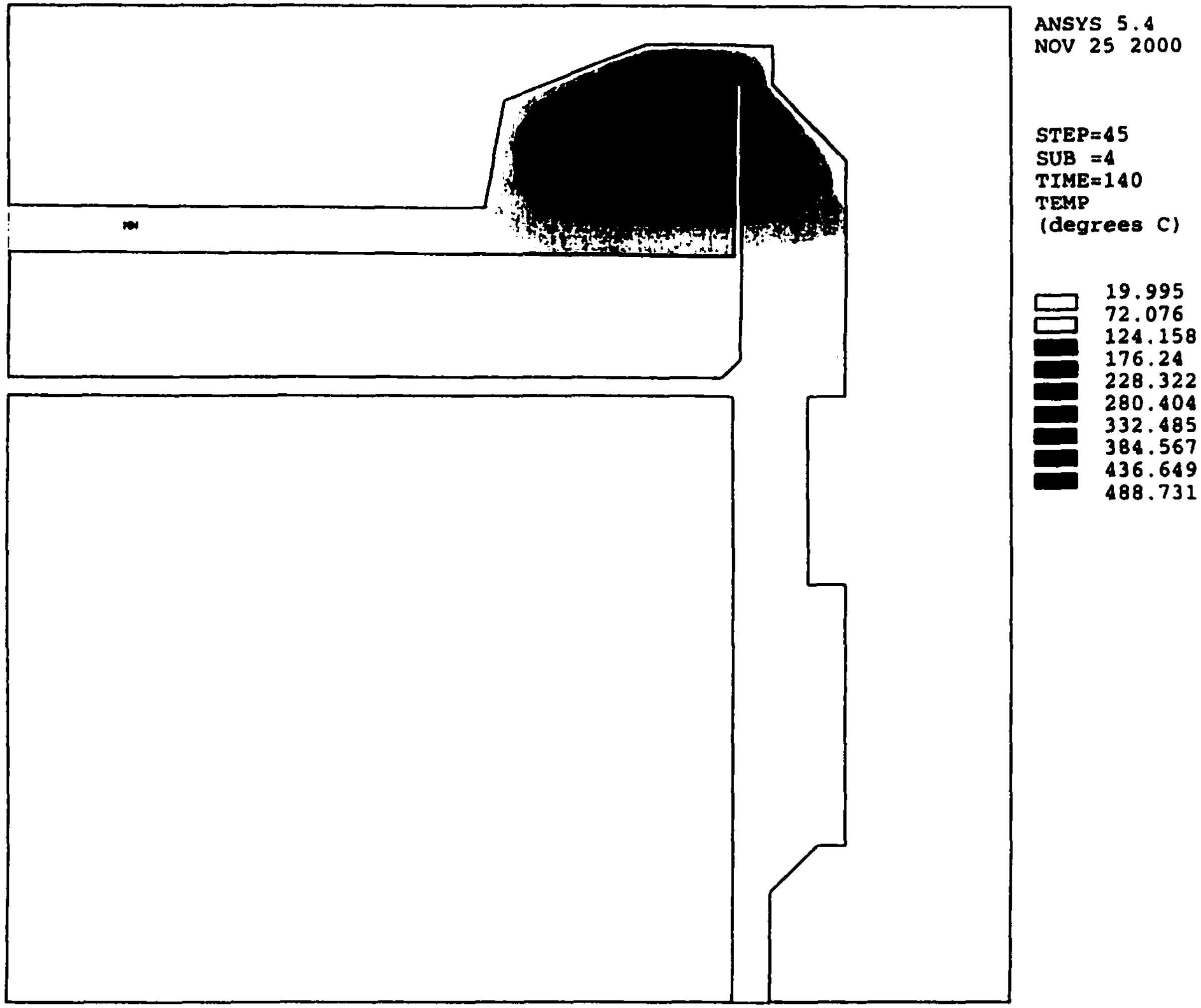


Figure 7.16. Temperature Distribution for the Successive Heuristic Quadratic Approximation Solution (Time: 140 seconds)

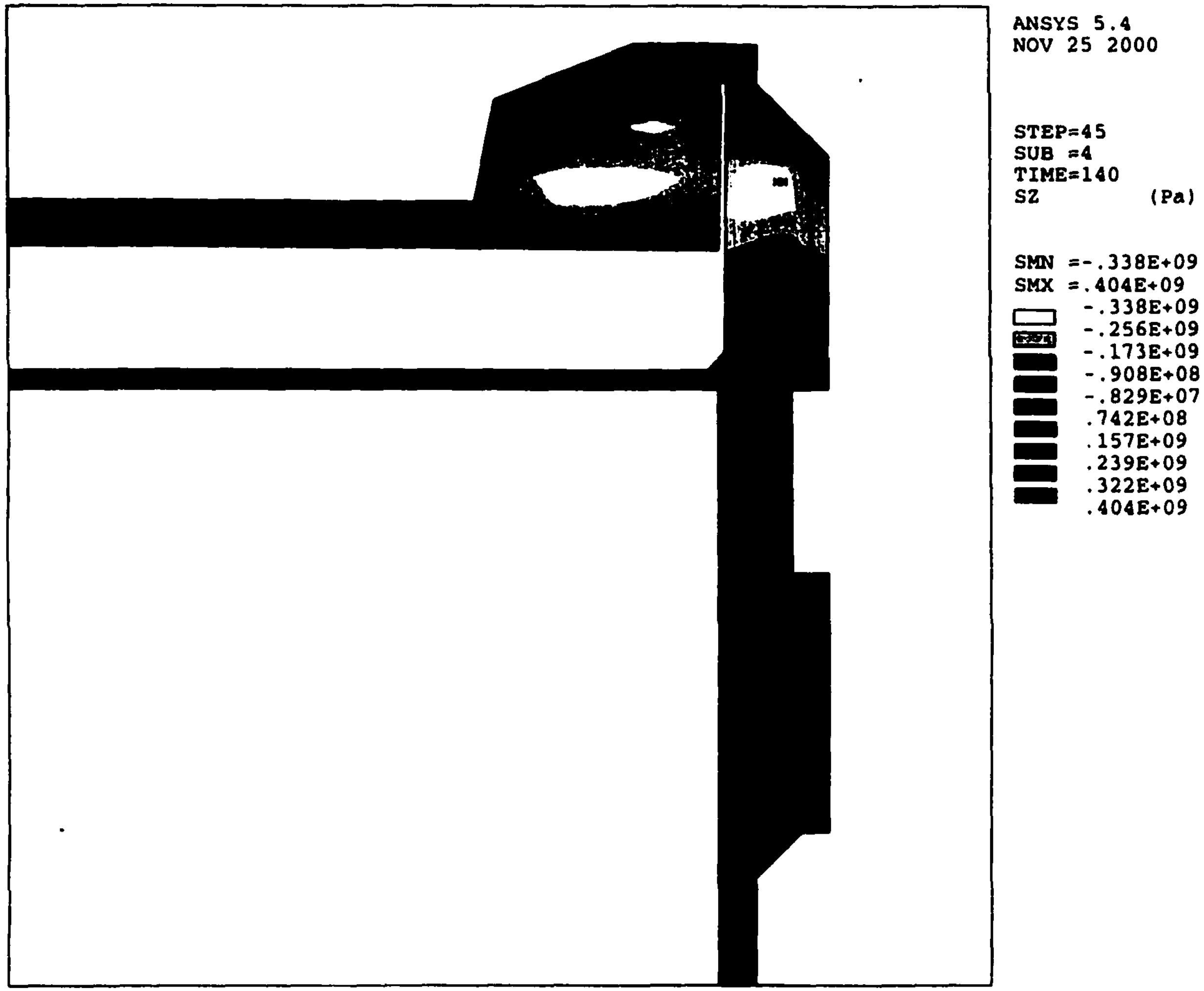


Figure 7.17. Hoop Stress Distribution for the Successive Heuristic Quadratic Approximation Solution (Time: 140 seconds)

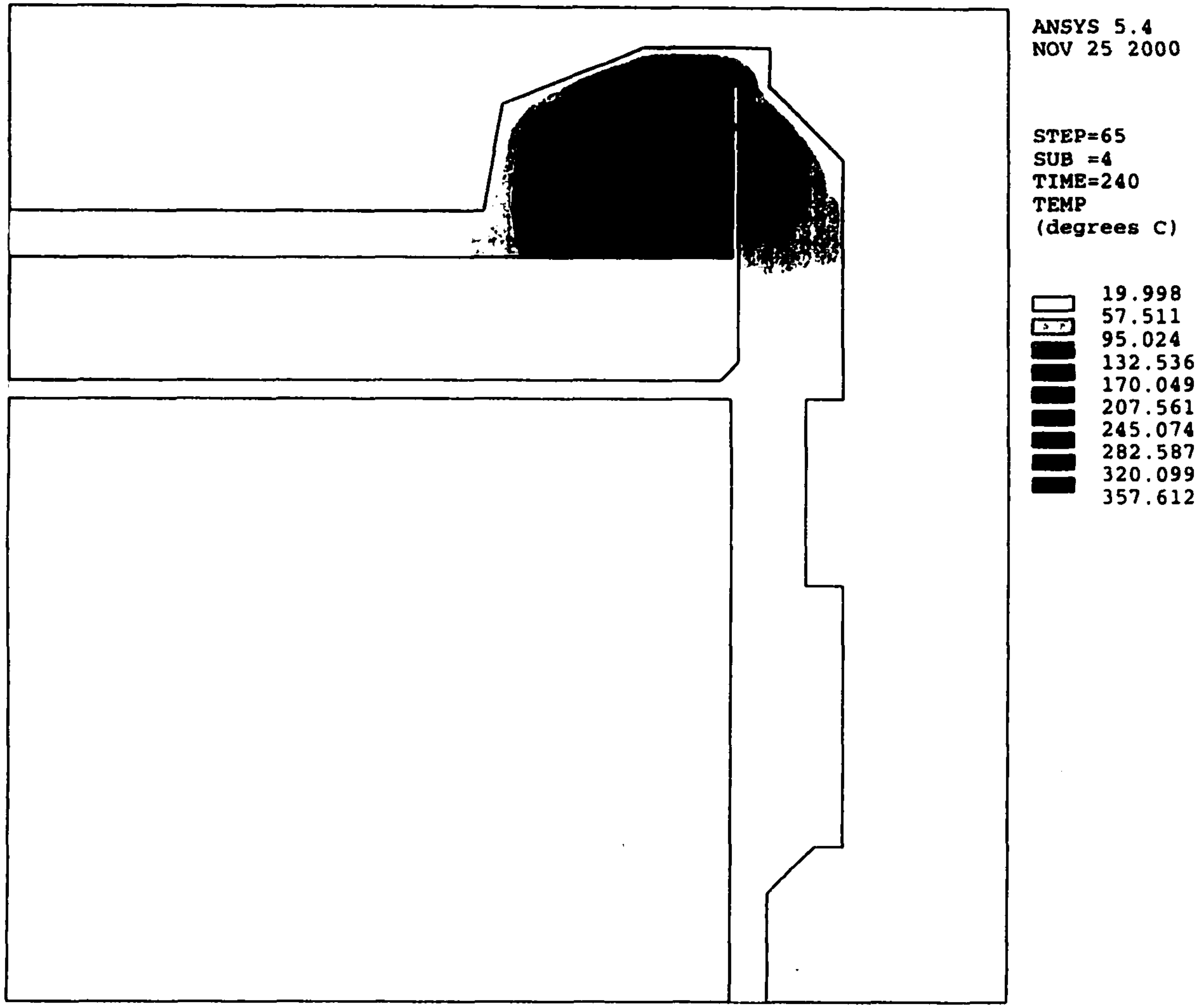


Figure 7.18. Temperature Distribution for Successive Heuristic Quadratic Approximation Solution (Time: 240 seconds)

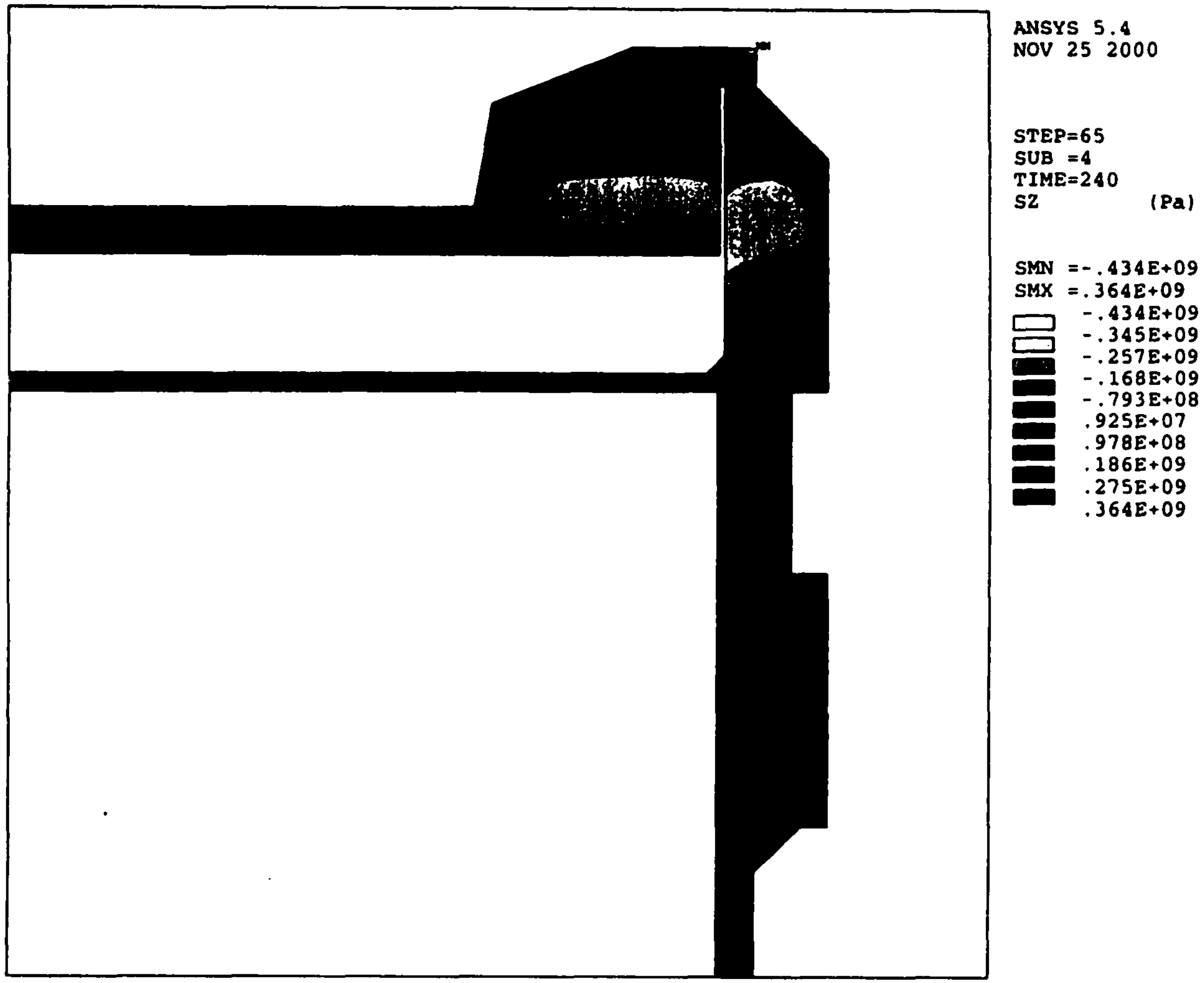


Figure 7.19. Hoop Stress Distribution for the Successive Heuristic Quadratic Approximation Solution (Time: 240 seconds)

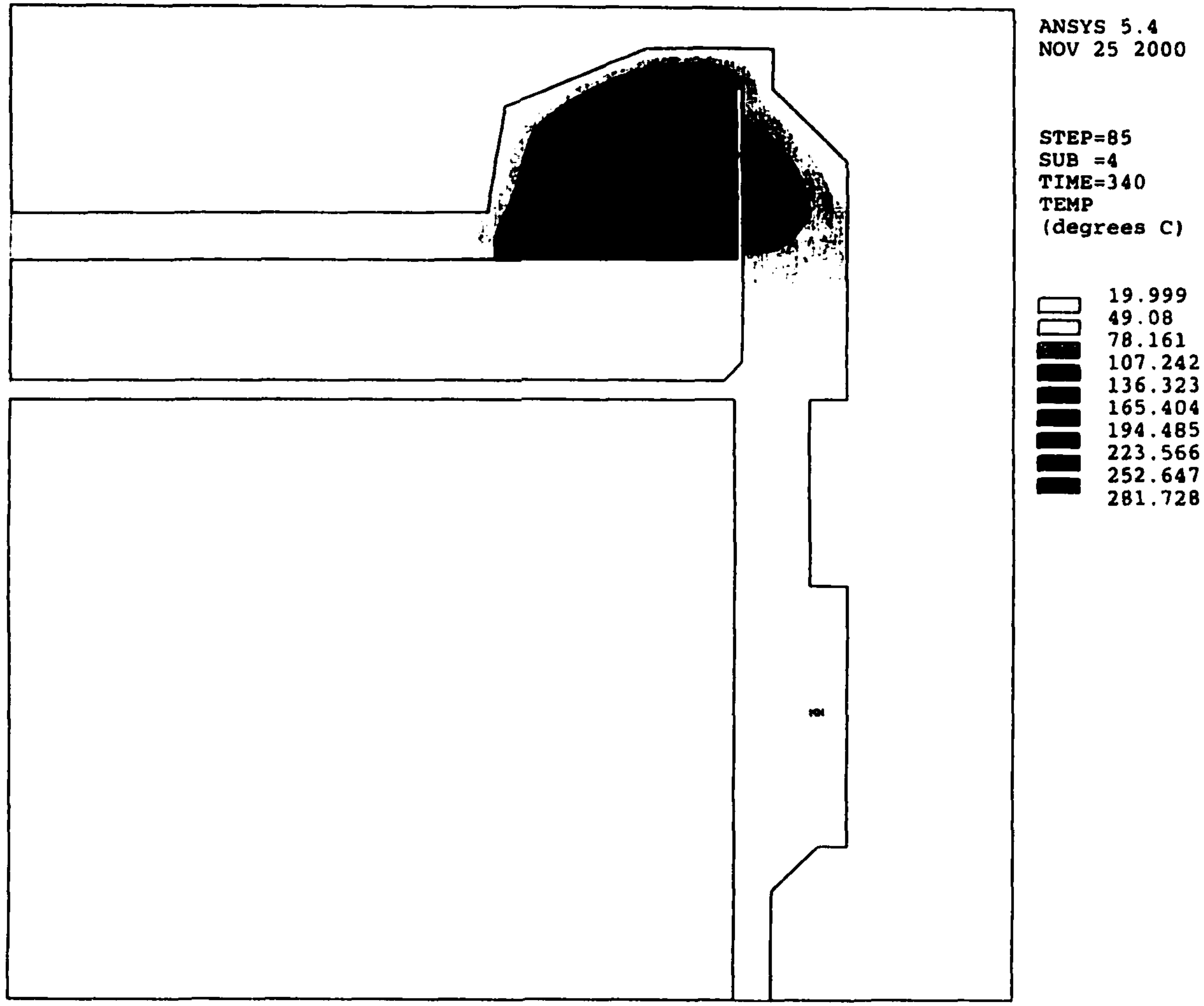


Figure 7.20. Temperature Distribution for the Successive Heuristic Quadratic Approximation Solution (Time: 340 seconds)

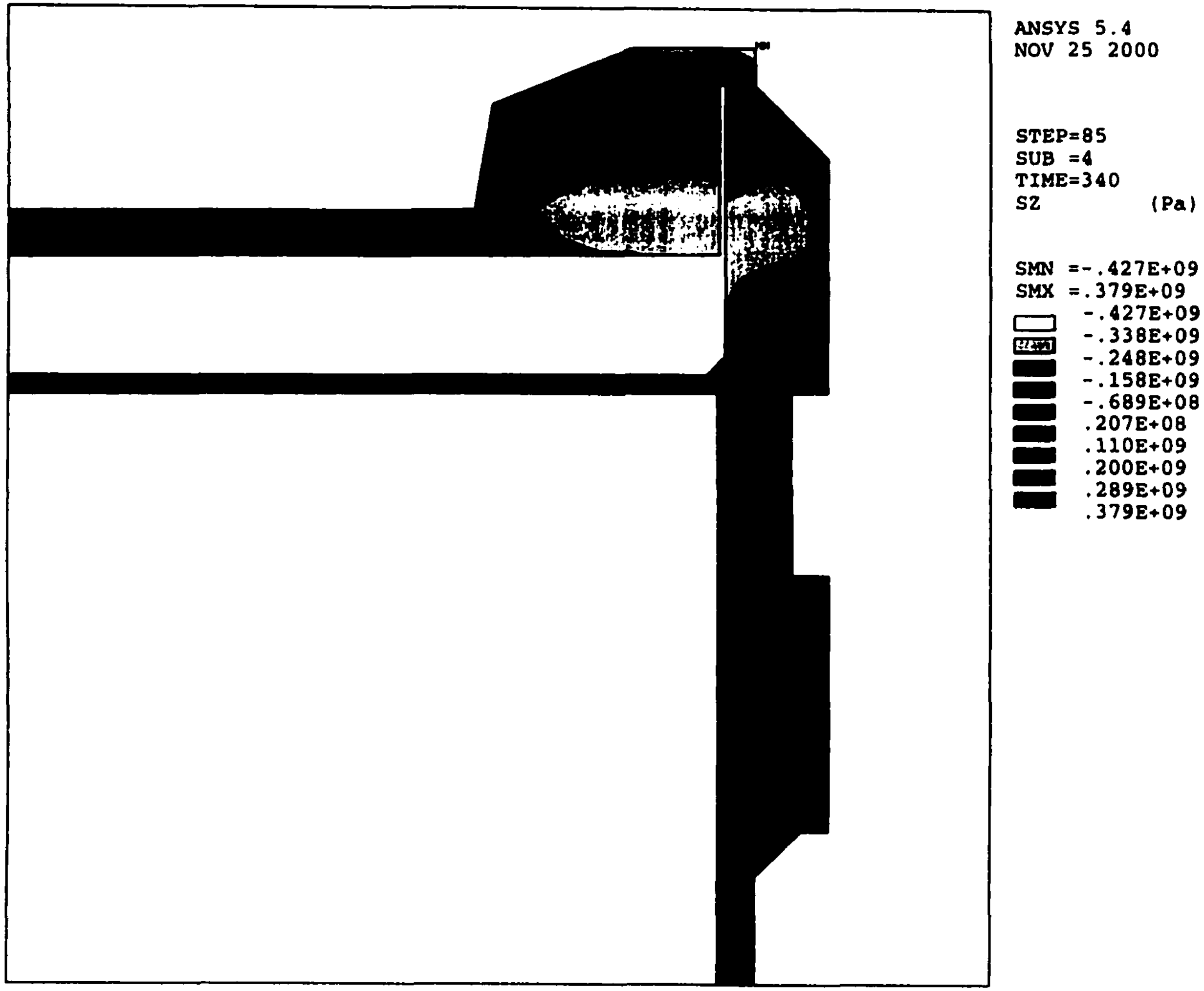


Figure 7.21. Hoop Stress Distribution for the Successive Heuristic Quadratic Approximation Solution (Time: 340 seconds)

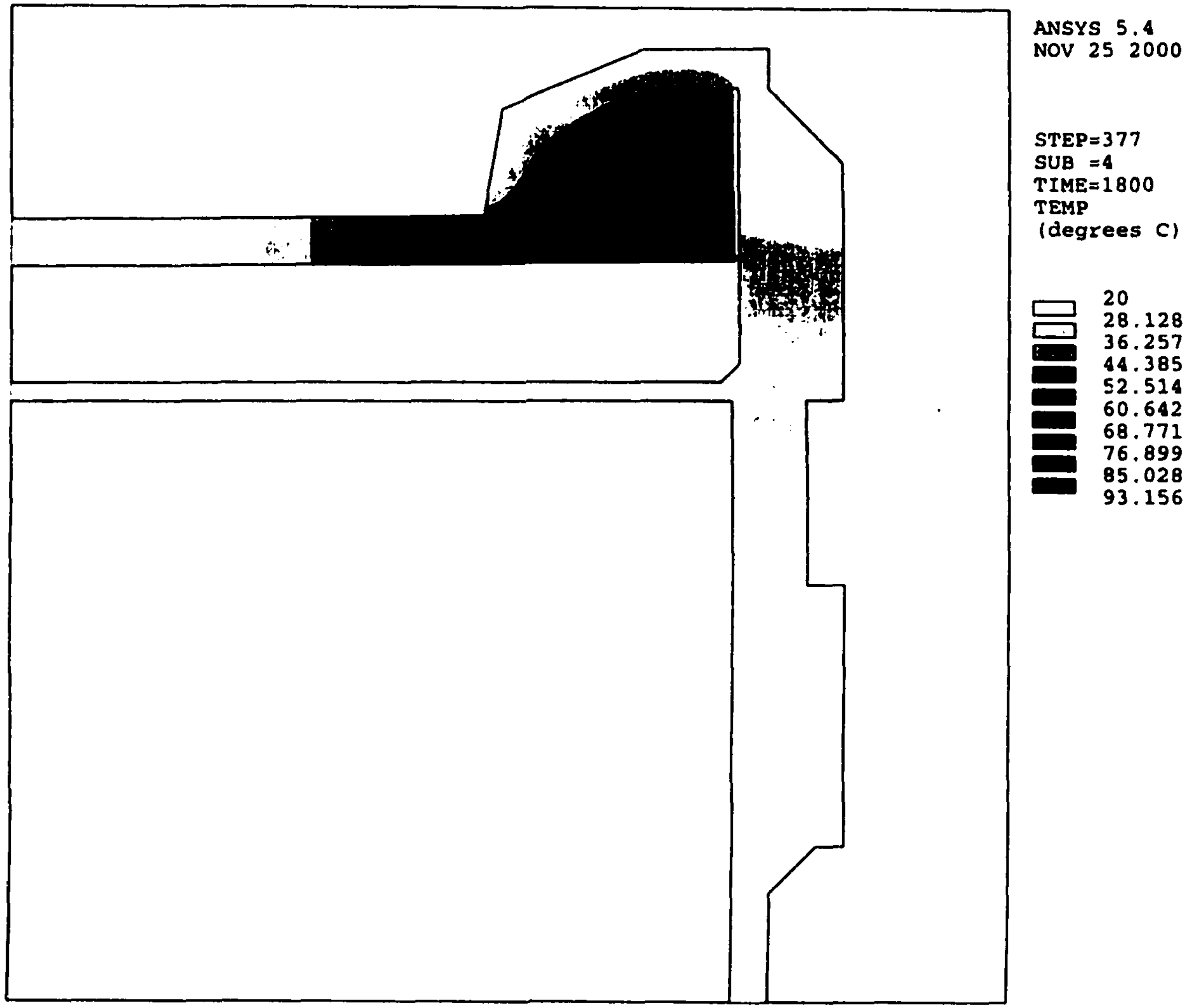


Figure 7.22. Temperature Distribution for the Successive Heuristic Quadratic Approximation Solution (Time: 1800 seconds)

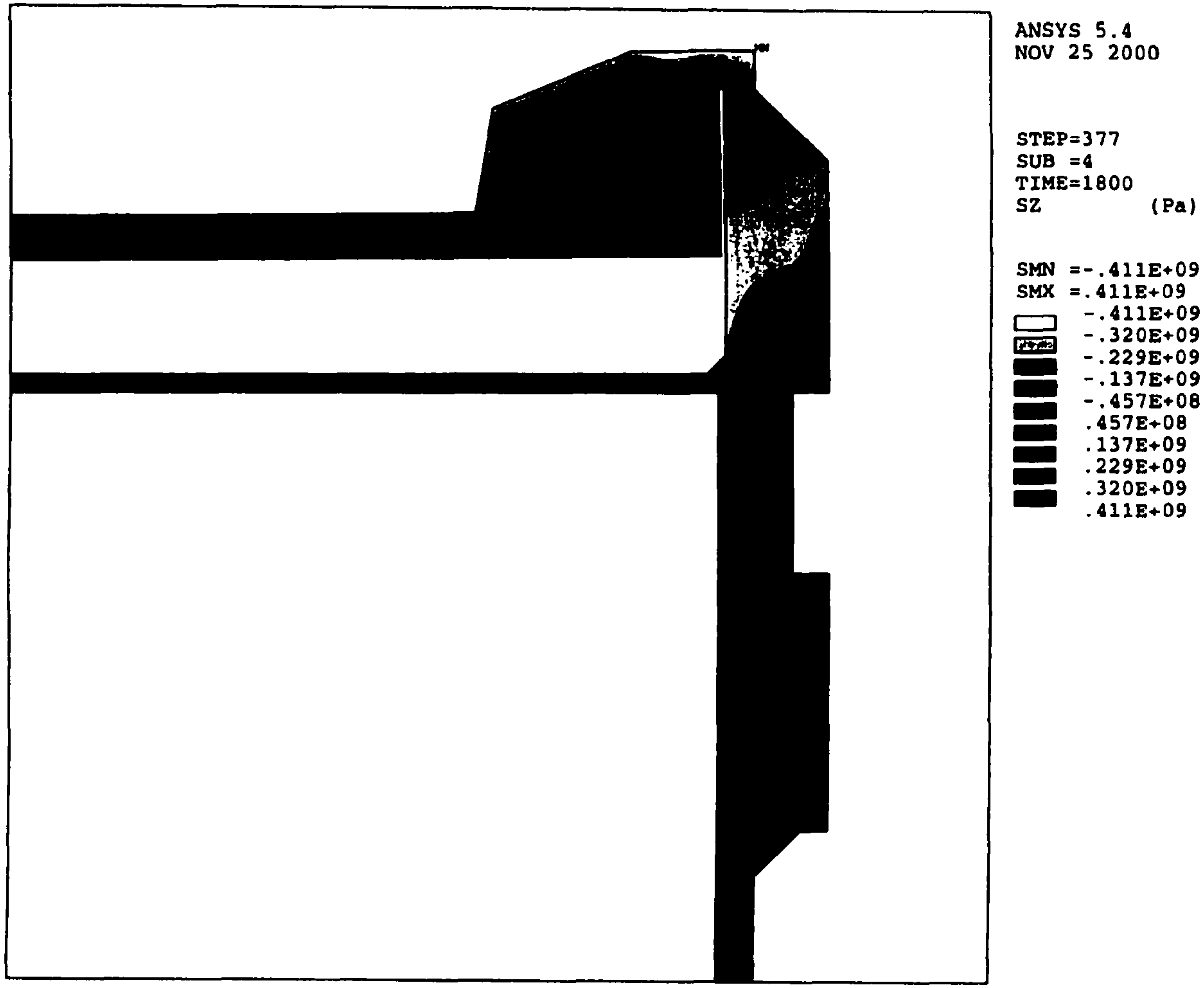


Figure 7.23. Hoop Stress Distribution for the Successive Heuristic Quadratic Approximation Solution (Time: 1800 seconds)

7.4 Sensitivity Analysis of the Best Solution and the Design Variables

Tables 7.4, 7.6, and 7.8 indicate the results obtained from three different optimization solutions. A comparison of these results suggest that the change in variable V1 has the least significant effect on the results. The reason for this is the fact that V1 is the dimension from the upper end of the lifting trunnion collar to the inner closure lid weld (see Figure 7.1), which is essentially outside the closure-weld region. Therefore, this is an expected behavior from variable V1. These tables also show that the system response to the change in variables V2, V3, and V4 are slightly more pronounced than the system response to the change in variables V5 and V6. This can be explained by the fact that all three variables, V2, V3, and V4 determine the height of the closure-weld region whereas the two dimensions, V5 and V6 relate to the radial distance of the closure-weld region. In other words, the change in height of the weld has slightly more effect on the results than the change in the radial distance. Although there is a small difference in the system response to change in these variables, the significance of the design variables V2 through V6 are still considered to remain almost the same.

In addition to the analysis described above, a sensitivity analysis of all seven design variables was conducted by changing one variable while holding the rest as constant values (see Appendix X, page 253). This evaluation showed that although all seven variables affect the results for a certain extent, the most sensitive design variables are V2, V3, V4, V5, and V6. The effect of change of these sensitive design variables on the resulting residual stresses is significantly larger than that of the rest of the design variables. Therefore, any potential design change in SNF canisters should consider the sensitivity of these specific design variables.

To ensure that the solution obtained from the successive heuristic quadratic approximation is a minimum, it should be surrounded by higher hoop stress values. For this reason, six different function evaluations, including the best solution obtained from the successive heuristic quadratic approximation are considered. V4 and V6 are the two design variables selected for varying the value of the objective function. The reason for selecting these two variables is that they are the most sensitive. All design variable values and resulting hoop stress magnitudes are given in Appendix XII, pp. 279-280. A graphical representation of the change in V4 and V6 indicated that the best function value was surrounded by higher values in terms of the hoop stress (see Figure 7.24). Therefore, it is concluded that 158 MPa is the minimum optimized hoop stress obtained form the successive heuristic quadratic approximation.

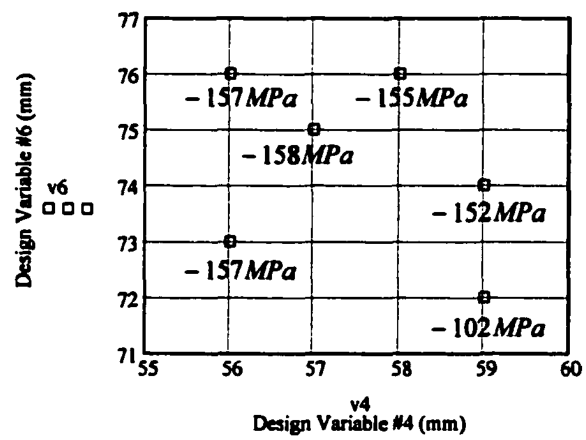


Figure 7.24. Sensitivity Analysis of the Best Solution

7.5 Evaluation of Optimization Results for ANSYS Solutions and the Successive Heuristic Quadratic Approximation Solution

The results of optimization, including the original design, are summarized in Table 7.9. The second column in this table gives the penetration depths of compressive stress up to a limit of 0.2*Sy (62 MPa). These penetration depths are obtained by defining stress paths along the perpendicular directions to the outer surface at the locations where the penetration is minimum. Figures 25 through 39 show iso-stress curves and the stress paths defined to determine these penetration depths. The first stress path (path #1) is in a location where the iso-stress curve is closest to the outer surface. However, the second path is located only in the region of the closure-weld, perpendicular to the top surface. The results given in the second column of the same table is obtained using the stress profile along the second path. The third column of the same table shows the results of the minimized values of the maximum hoop stresses among the nodes selected 2.72 mm from the outer surface of the canister. This is the amount of corrosion of Alloy 22 outer shell in 10,000 years (see Appendix I).

The results indicate that all compressive stress depths are more than 2.72 mm, which is the amount of general corrosion for Alloy 22 in 10,000 years. The results also show that all design concepts provide a layer of compressive stress of more than 6.8 mm from the top closure-weld surface. More importantly, the third column in the same table indicates that the largest design margin to prevent SCC within 2.72 mm form the outer surface of the outer shell is obtained with a compressive stress magnitude of 158 MPa. All the nodes within a layer of 2.72 mm from the outer surface were selected to be included in the optimization process as previously explained in this chapter. Since this optimization process resulted in a maximum compression of 158 MPa, the best design is deemed to be the design given in Table 7.8.

Table 7.9. Summary of Optimization Results

	Compressive Stress Penetration Depth up to 0.2*Sy (62 MPa)		
	Minimum Distance between the Outer Surface and the 62 MPa Iso-Stress Curve	Distance between the Top Closure-Weld Outer Surface and the 62 MPa Iso-Stress Curve	Minimized Maximum Hoop Stress within a 2.72 mm Thick Layer from the Outer Surface
Original design	5.8 mm > 2.72 mm*	9.7 mm > 6.8 mm**	-70 MPa < 62 MPa
Optimization Problem #1	6.3 mm > 2.72 mm*	7.8 mm > 6.8 mm**	-75 MPa < 62 MPa
Optimization Problem #2	3.9 mm > 2.72 mm*	11.7 mm > 6.8 mm**	-98 MPa < 62 MPa
Optimization Problem #3	4.7 mm > 2.72 mm*	8.5 mm > 6.8 mm**	-130 MPa < 62 MPa
Successive Heuristic Quadratic Approximation	4.6 mm > 2.72 mm*	9.4 mm > 6.8 mm**	-158 MPa < 62 MPa

* Alloy 22 general corrosion rate including microbial influenced corrosion (MIC)
** Alloy 22 general corrosion rate including MIC and also the thermal aging effect in the closure weld
Note: Penetration depth calculations are provided in Appendix XIII

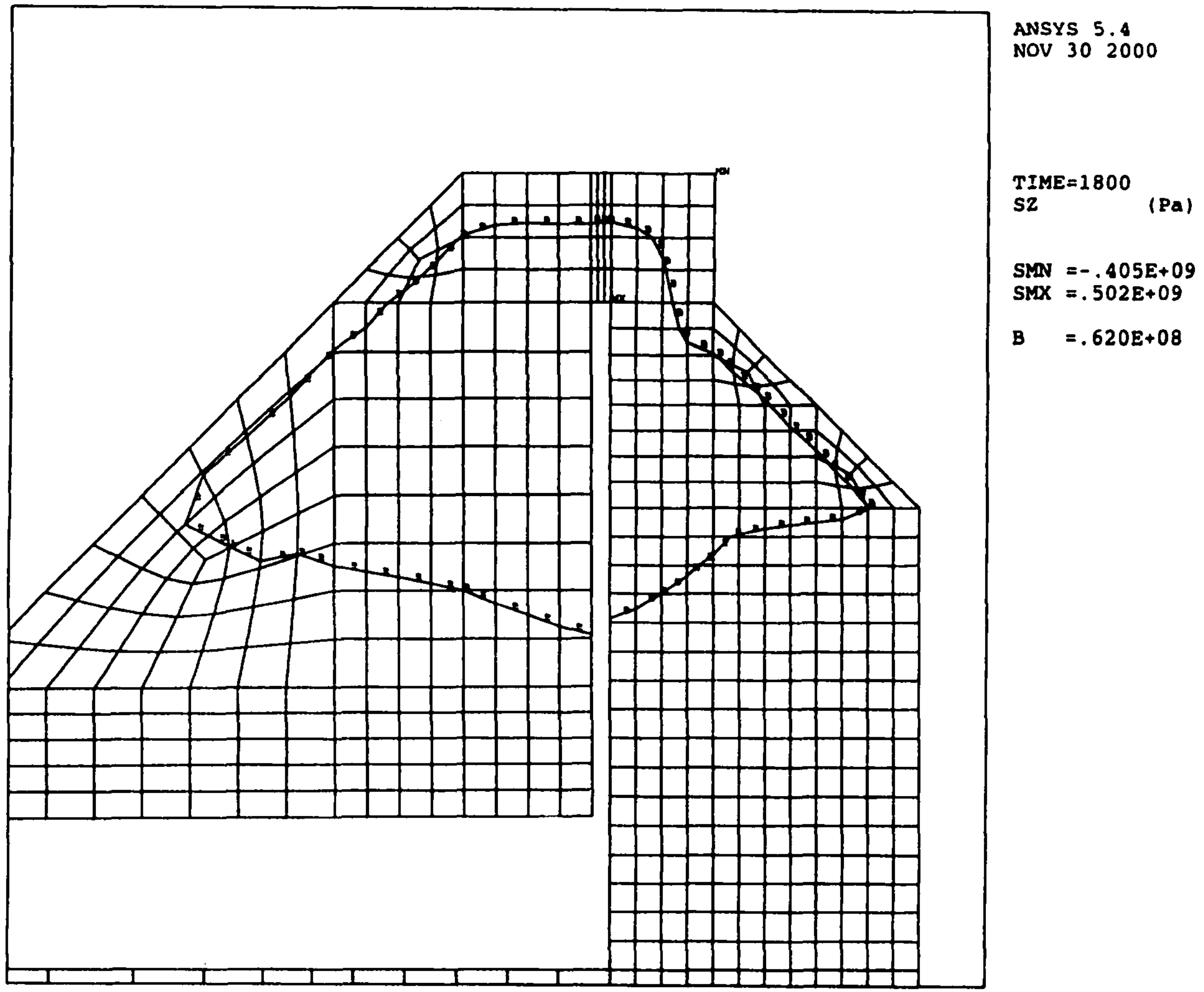


Figure 7.25. Iso-stress Curve (62 MPa) for the Original Design

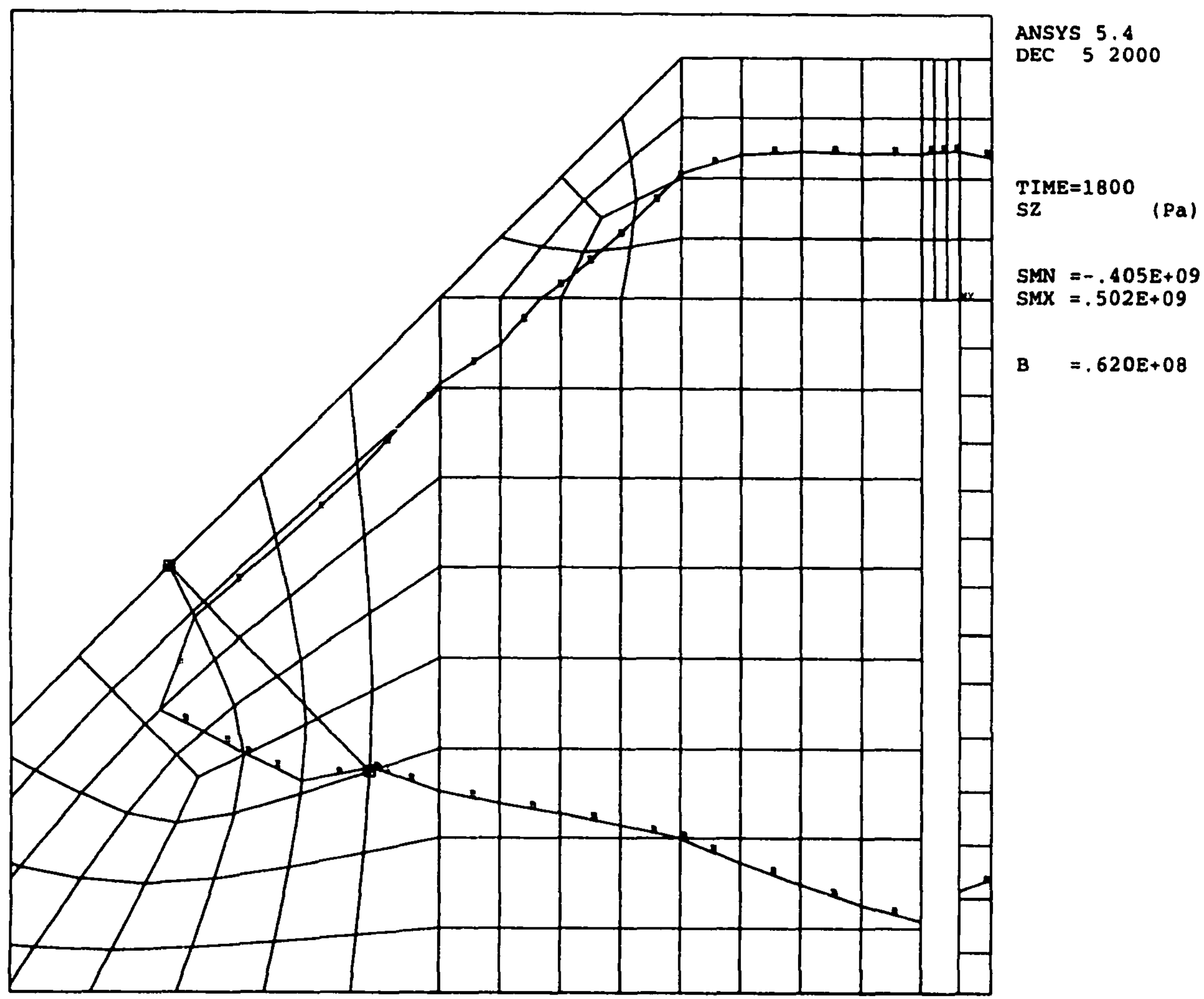


Figure 7.26. Stress Path #1 for the Original Design

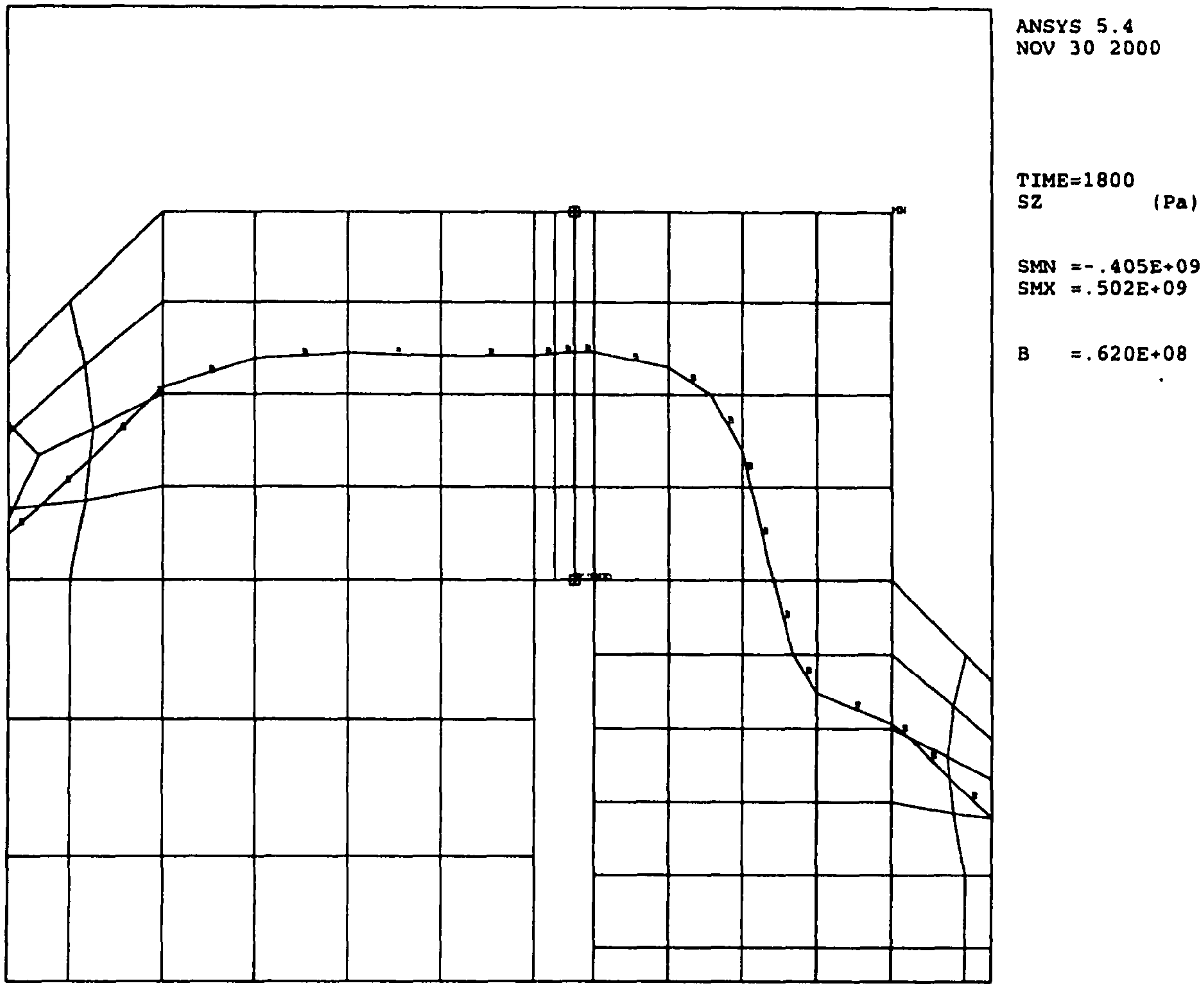


Figure 7.27. Stress Path #2 for the Original Design

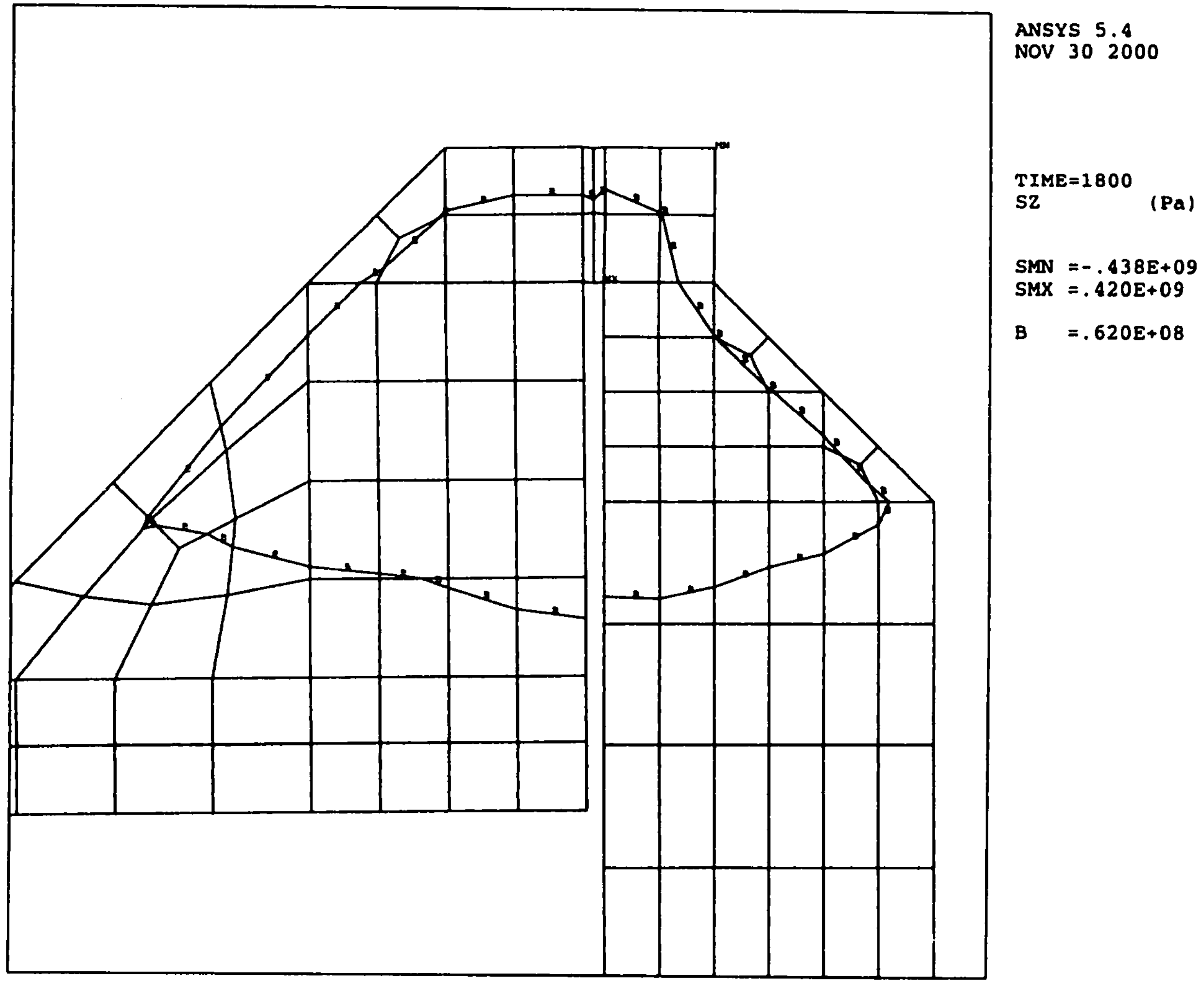


Figure 7.28. Iso-stress Curve (62 MPa) for Optimization Problem #1

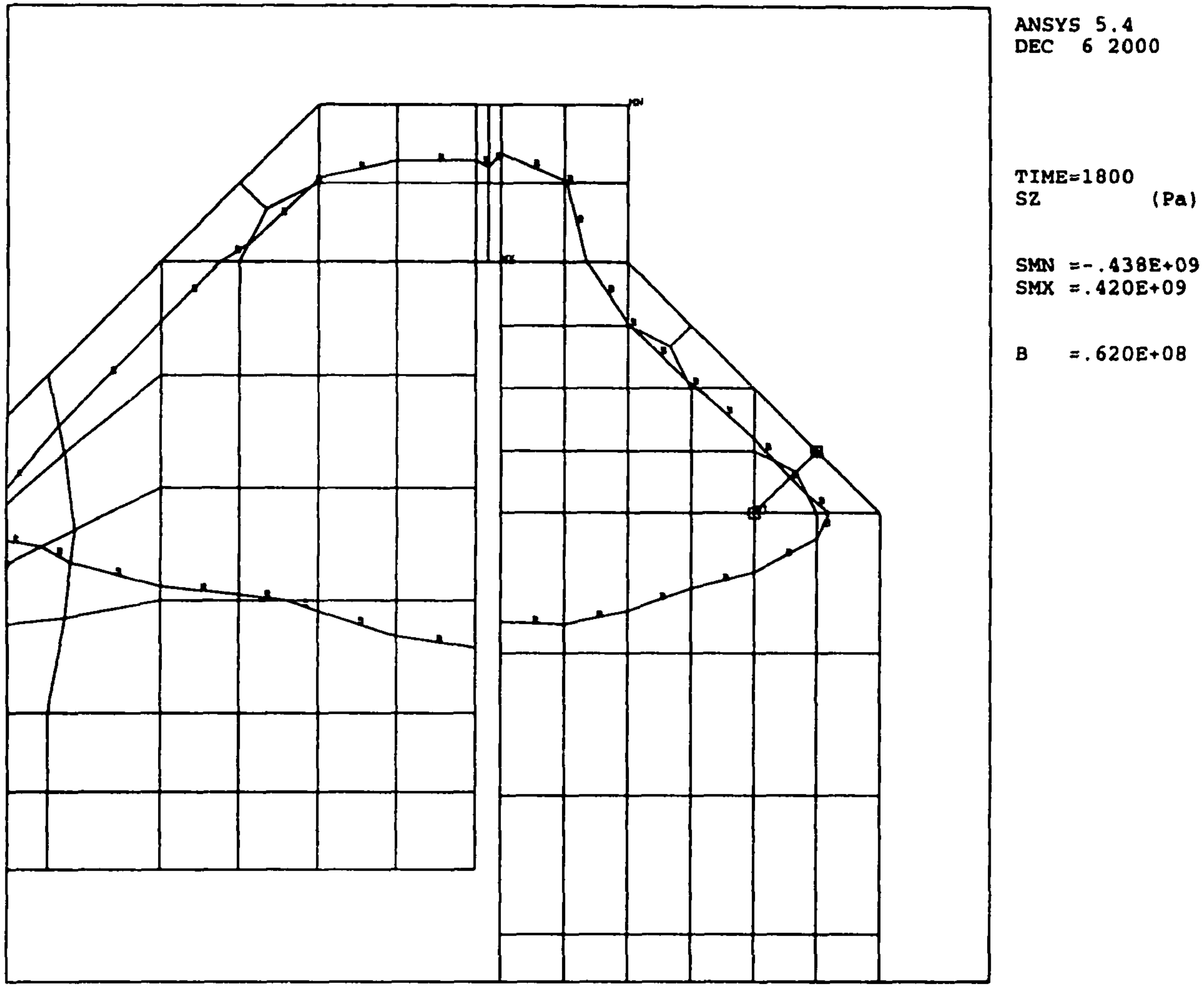


Figure 7.29. Stress Path #1 for Optimization Problem #1

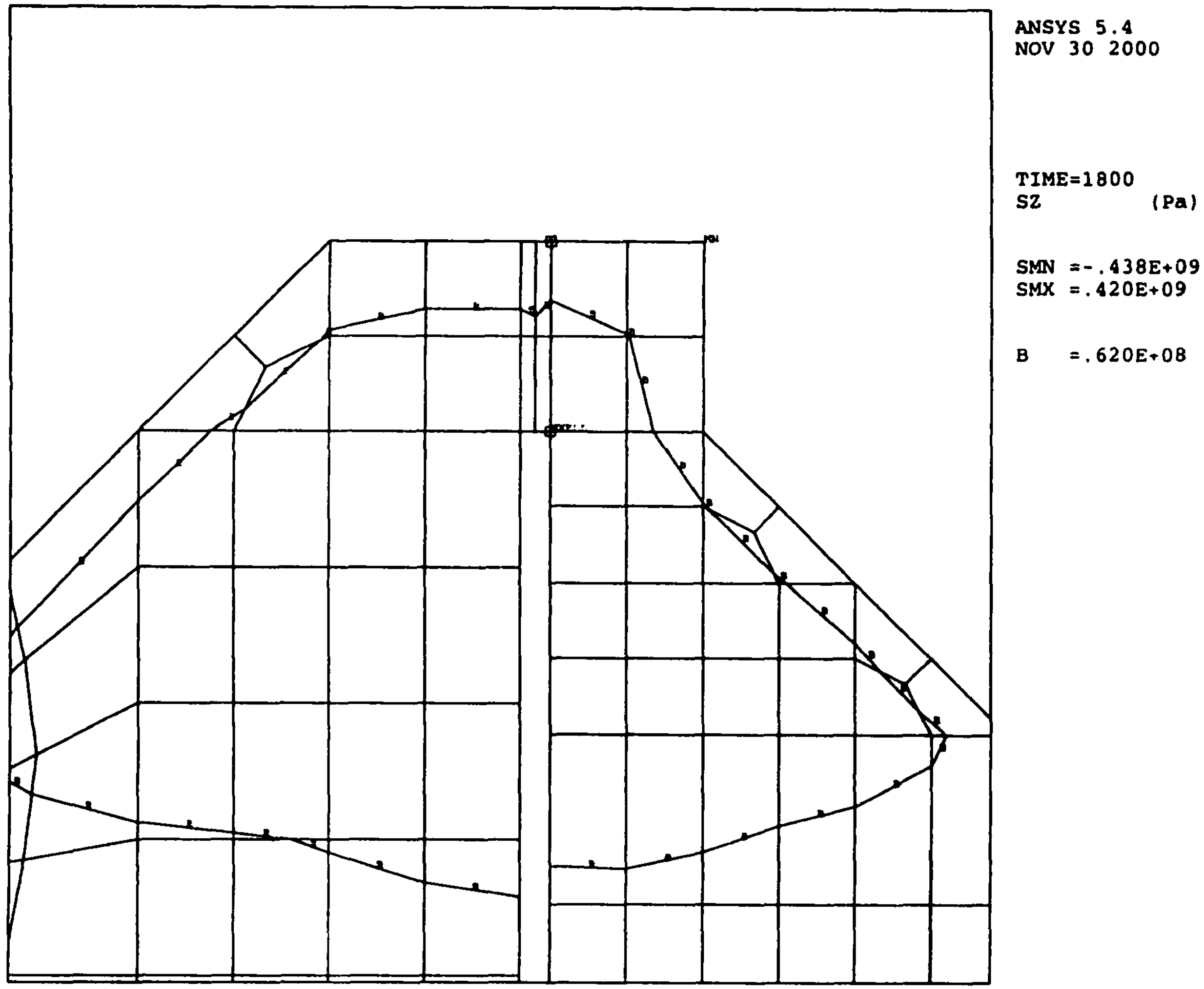


Figure 7.30. Stress Path #2 for Optimization Problem #1

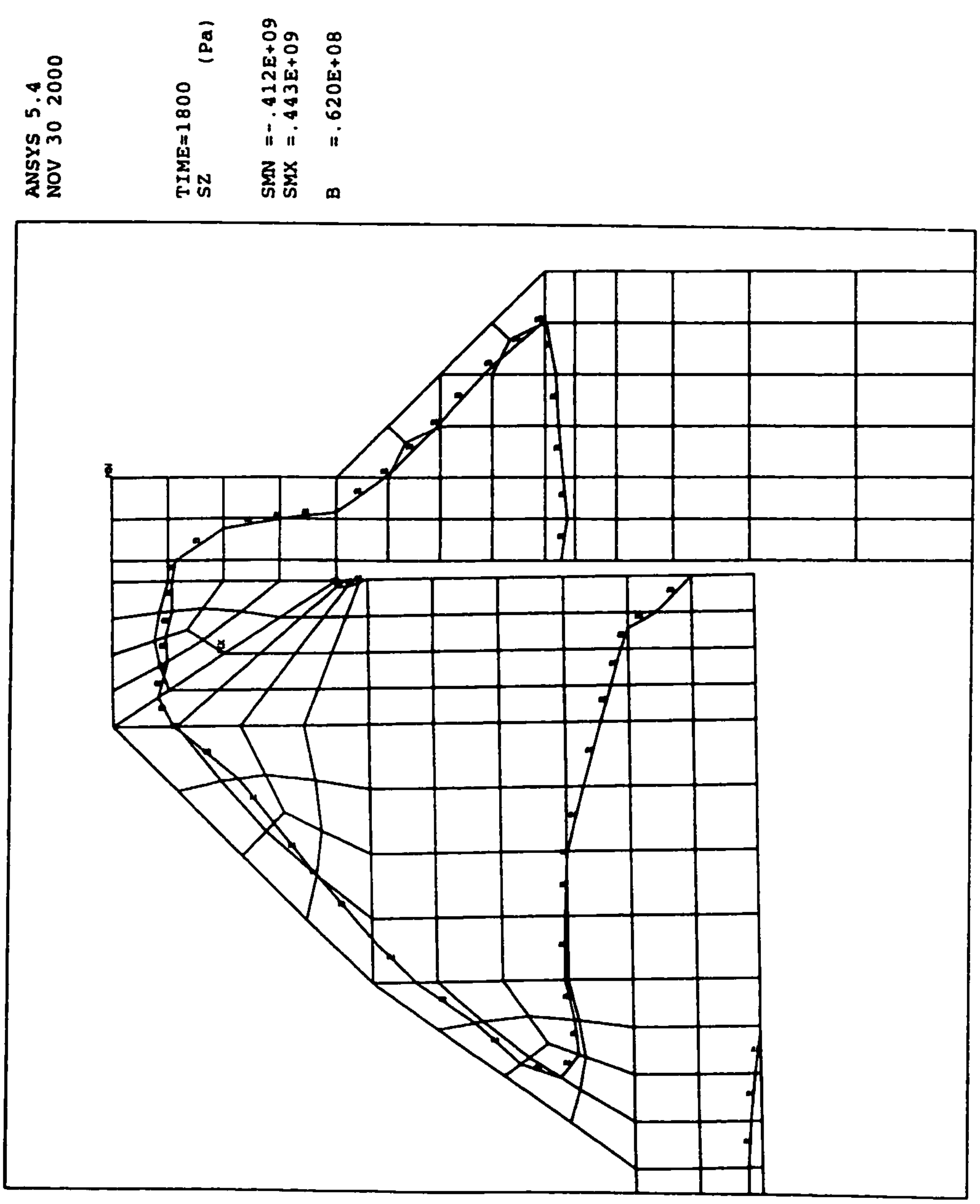


Figure 7.31. Iso-stress Curve (62 MPa) for Optimization Problem #2

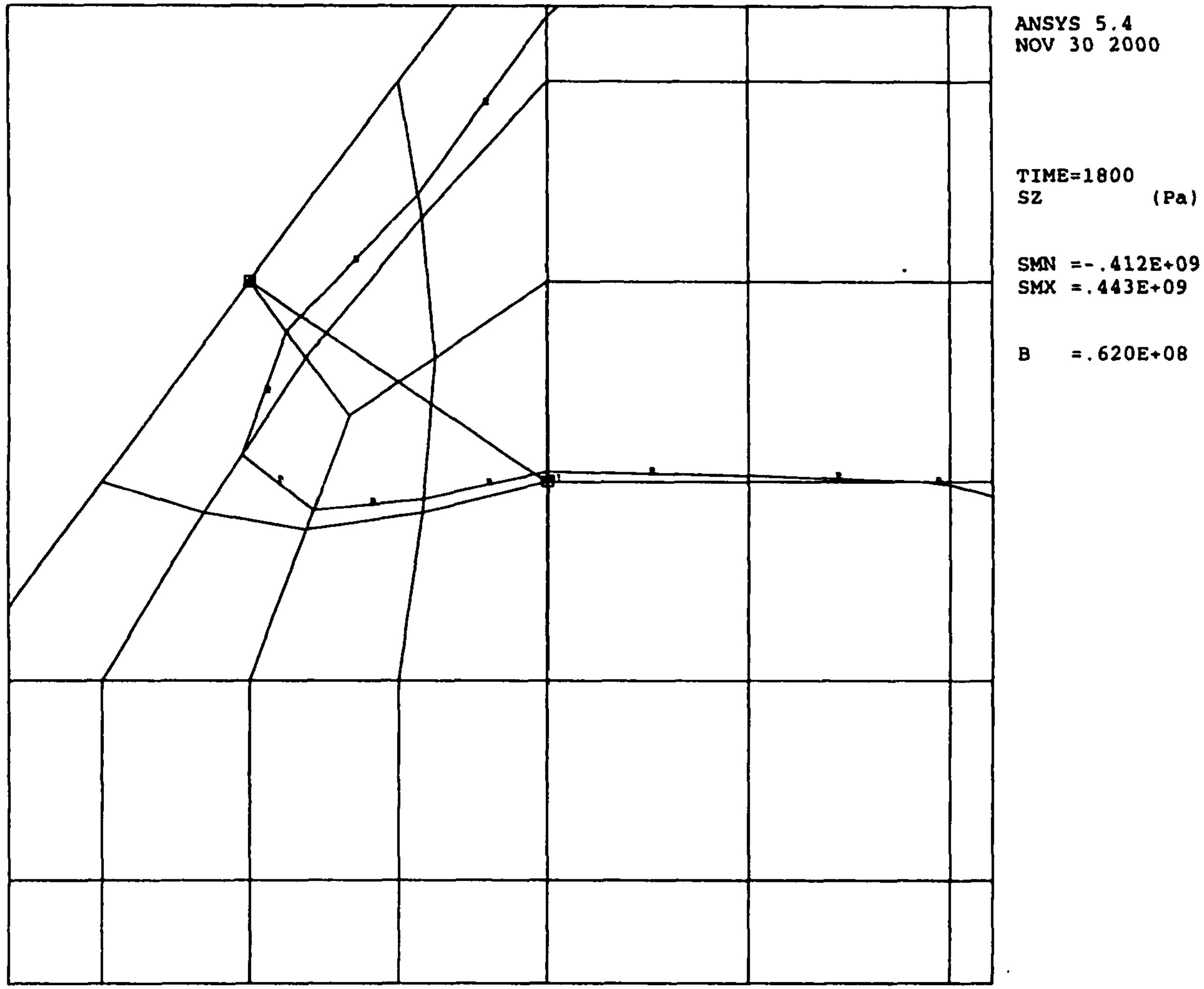


Figure 7.32. Stress Path #1 for Optimization Problem #2

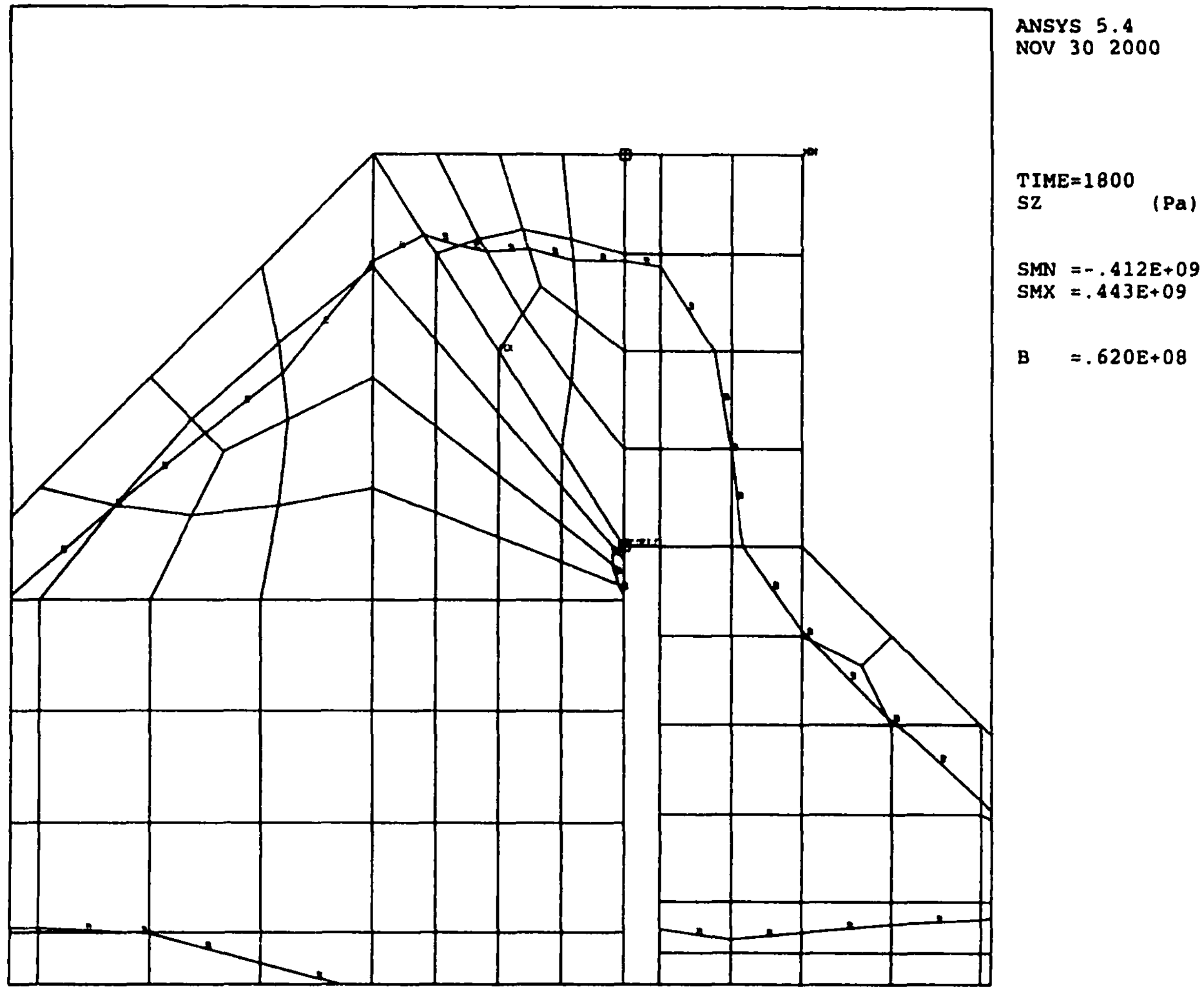


Figure 7.33. Stress Path #2 for Optimization Problem #2

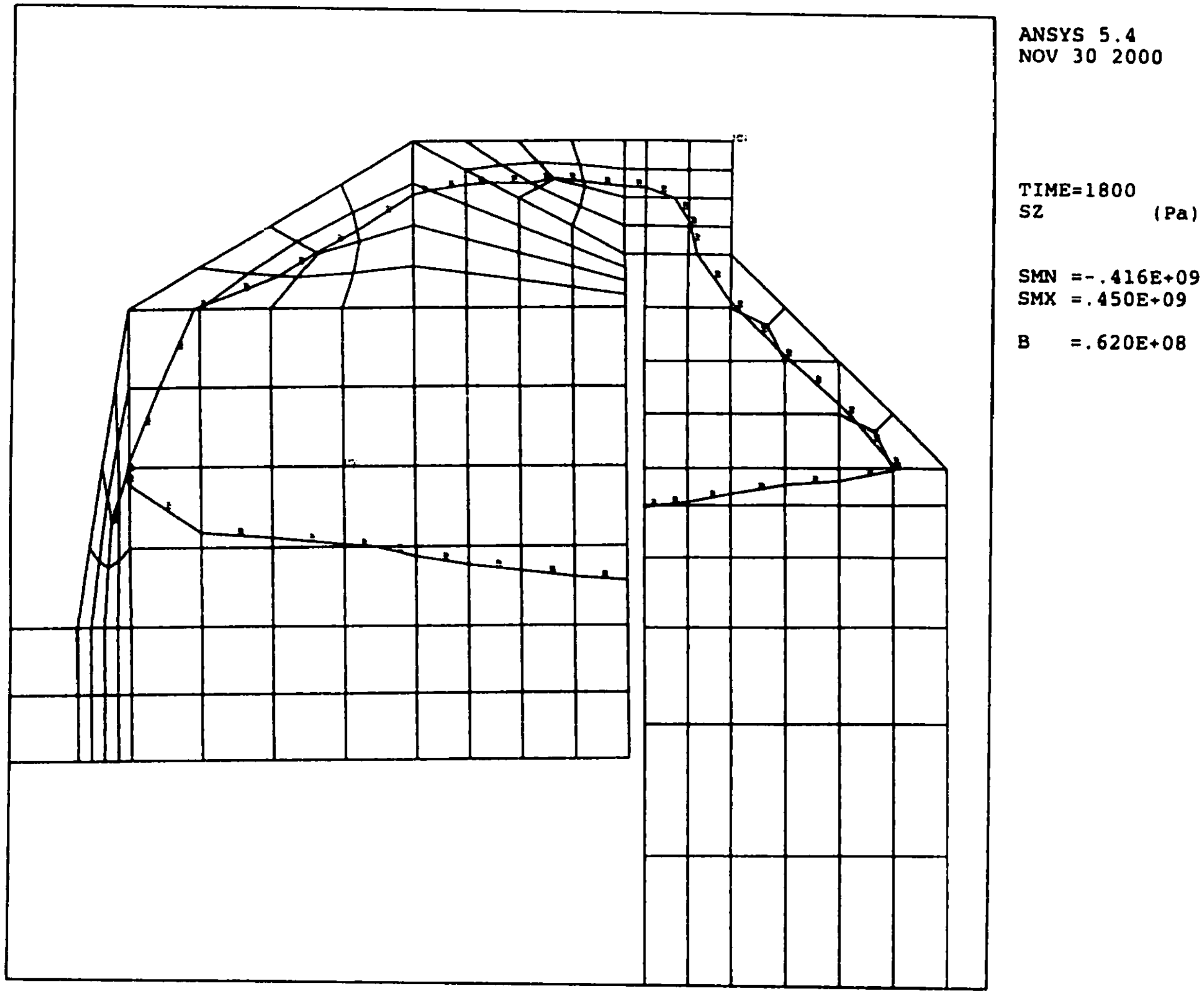


Figure 7.34. Iso-stress Curve (62 MPa) for Optimization Problem #3

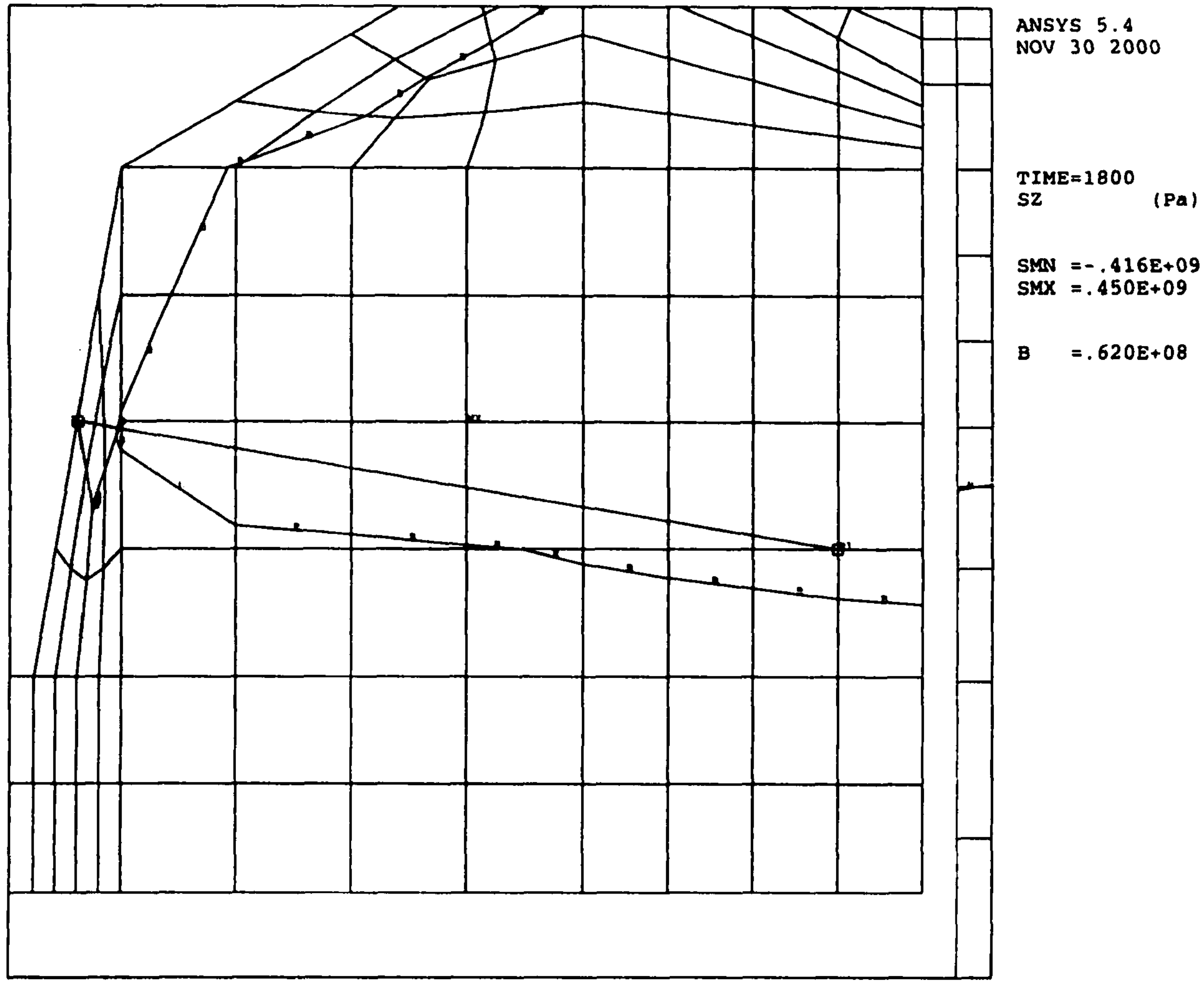


Figure 7.35. Stress Path #1 for Optimization Problem #3

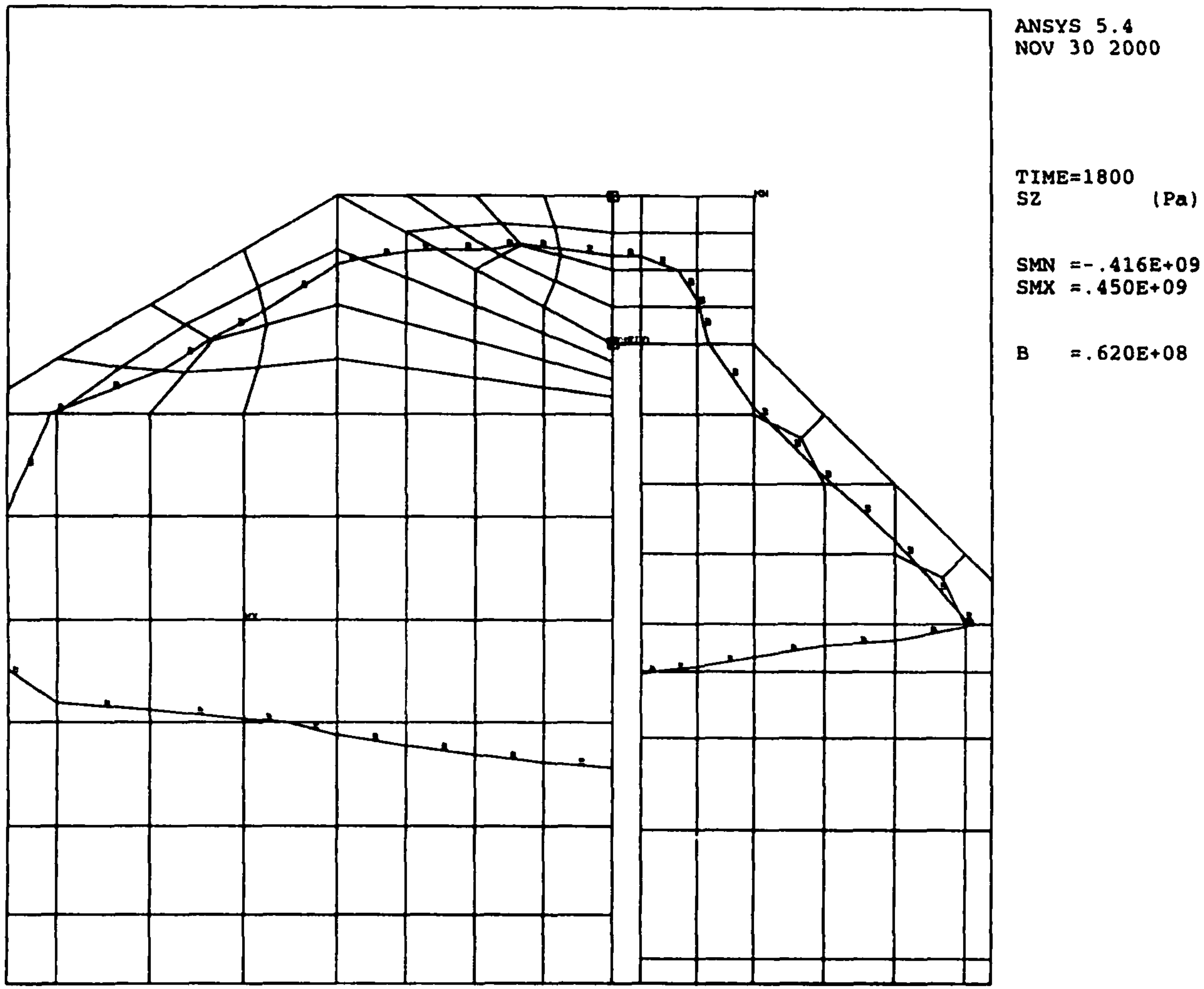


Figure 7.36. Stress Path #2 for Optimization Problem #3

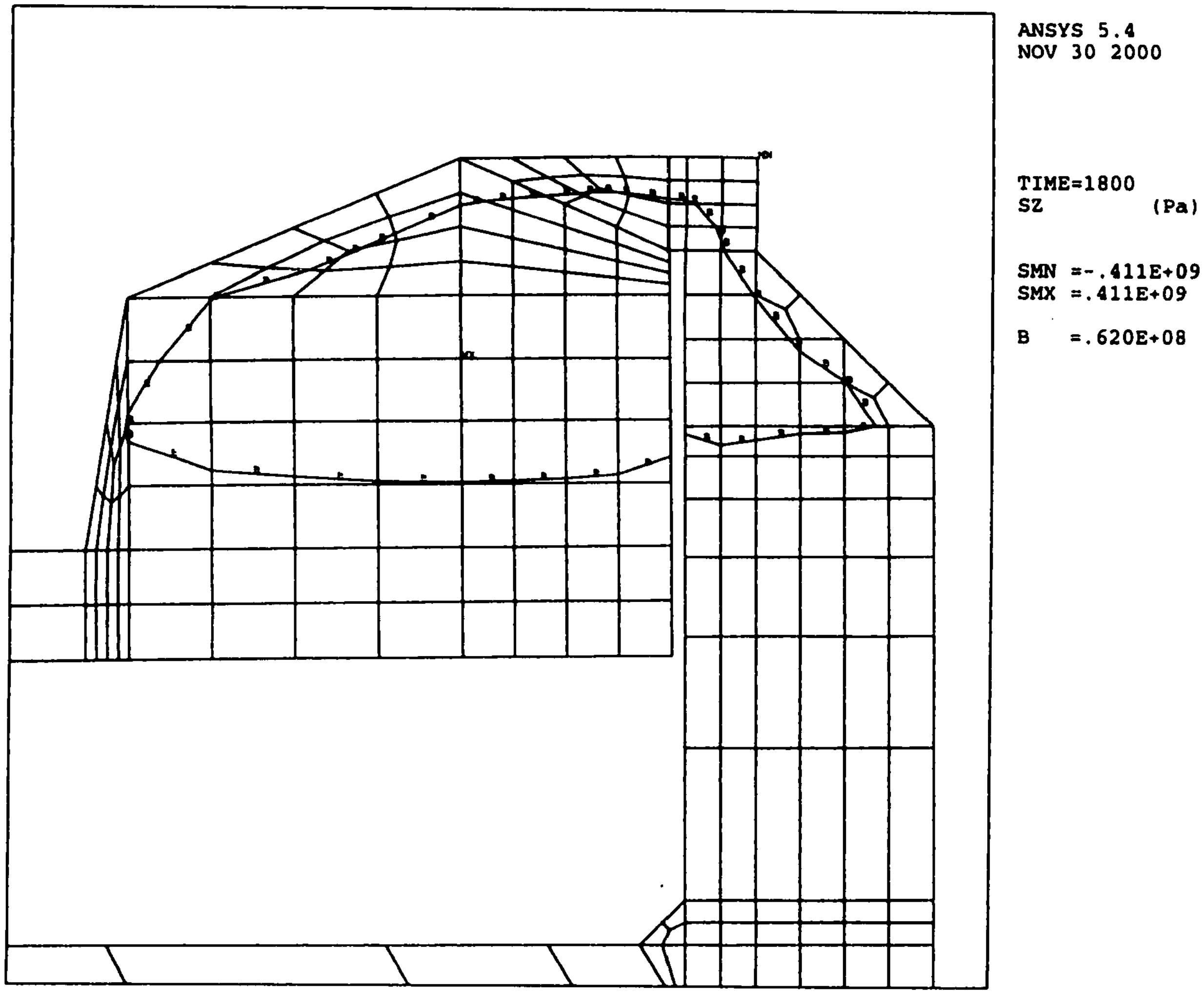


Figure 7.37. Iso-stress Curve (62 MPa) for the Successive Heuristic Quadratic Approximation Solution

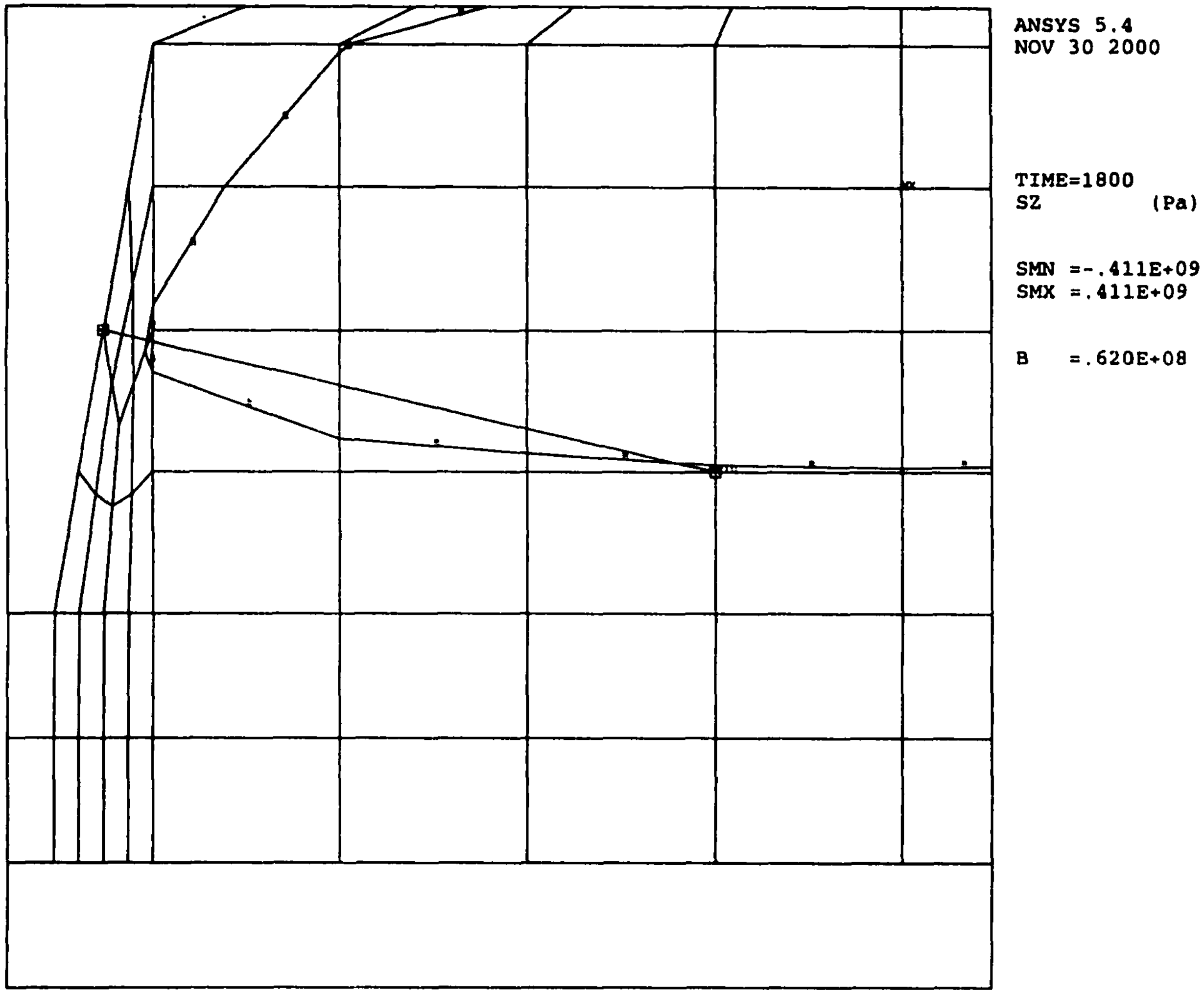


Figure 7.38. Stress Path #1 for the Successive Heuristic Quadratic Approximation Solution

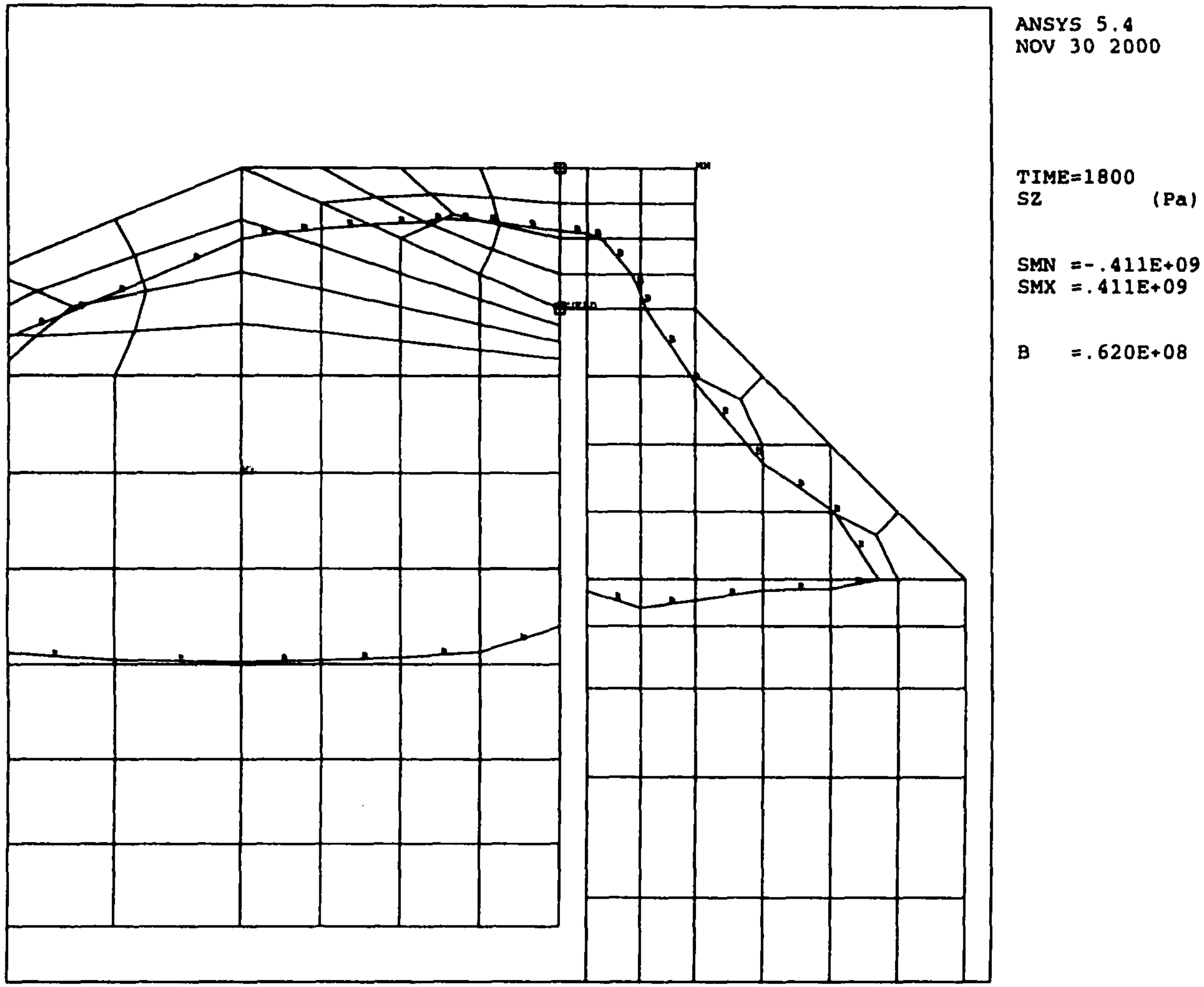


Figure 7.39. Stress Path #2 for the Successive Heuristic Quadratic Approximation Solution

CHAPTER 8

CONCLUSIONS

This dissertation presented a study of the SNF canisters for maximizing the compressive stress on the outer surface of the closure-weld region. Induction coil heating technique was used in order to relieve the residual stresses from the closure weld and induce a state of compression through the wall thickness. This technique involved localized heating of the material by surrounding coils. The material was then cooled to room temperature by quenching.

A three-dimensional finite element model was developed for the canister using the sequential method. This method consisted of a sequential thermal-stress analysis where nodal temperatures from the thermal analysis were applied as body force loads in the subsequent stress analysis. This model, which was computationally intensive, has been used to verify the results of the model developed in two-dimensions and ensure its accuracy.

A two-dimensional axisymmetric finite element model of the canister was developed. This model made use of the direct method. This method included only one type of analysis that used coupled-field element type containing all necessary degrees of freedom for the heat transfer and the stress analyses. Direct coupling was advantageous when the coupled-field interaction was highly nonlinear and was best solved in a single solution using a coupled formulation. The results obtained from 3-D and 2-D finite element models were almost identical, indicating that the solution methods were appropriate and highly accurate.

The finite element results were validated using the results obtained from an experimental test. A canister mock-up which consisted of an outer shell and a support ring was manufactured. The mock-up was subject to solution annealing process. At the end of the process, a compressive stress state developed on the shell outer surface. The stresses on the canister outer surface were obtained based on the readings of the strain gages that were attached to several points on the mock-up. The results of the experimental test were consistent with the finite element solution; therefore, the method of solution has been validated.

The parameters of most promising designs were tuned to further maximize the compressive stress through the wall thickness. This was handled as an optimization problem that was subject to geometrical constraints. This optimization problem was first solved using commercially available ANSYS software. The optimization results provided the dimensions of a better design to result in maximum compressive stress in the canister closure-weld region. It was concluded that the resultant compressive hoop stress has been improved by 86%.

A second method of optimization was developed by using successive quadratic approximation algorithm. Using this approach, optimization was performed using a separate optimization routine and the results of this method have shown that the resultant compressive hoop stress was improved by 94% in comparison to the original design.

This method of solution was concluded to provide an additional 5% improvement over the solution obtained from ANSYS optimization.

A third method of optimization was developed by using a successive heuristic quadratic approximation. The methodology used in the successive heuristic quadratic approximation implemented two processes of optimization into one algorithm: self-improvement of the results by iteratively converging to the best solution within specific solution intervals and a quadratic curve-fit to an expected functional behavior. In this unique, improved optimization algorithm, a quadratic polynomial was fitted to the data points in the first domain of solution. Then, the minimum point of the quadratic surface was determined using Monte Carlo Programming Technique. This solution was then input into ANSYS to obtain the actual value of the hoop stress. The next domain was generated around a sub-set of data points with the lower function value. The complement of these points were then randomly re-generated. Finally, the point corresponding to the minimum function value of the quadratic curve fitting was added to the original set of data points. This process was repeated until one of the termination criteria has been satisfied. The results of this method have shown that the resultant compressive hoop stress was improved by 126% in comparison to the original design. This method of solution was concluded to provide an additional 22% improvement over the solution obtained from ANSYS optimization.

A sensitivity analysis of all seven design variables showed that although all seven variables affect the results for a certain extent, the most sensitive design variables were V2, V3, V4, V5, and V6. The effect of change of these sensitive design variables on the resulting residual stresses was significantly larger than that of the rest of the design variables. Therefore, any potential design change in SNF canisters should consider the sensitivity of these specific design variables.

Additional future studies on optimization of the SNF canisters can be performed by using different methods available in the literature such as the simplex method or genetic algorithms. These studies may also include investigation of different geometries of the SNF canister closure-weld region in order to minimize residual stresses.

APPENDIX I

MATERIAL PROPERTIES

Table I.1. Material Property List for Alloy 22 (SB-575 N06022) (ASTM B 575) (Outer Shell Material, see Figure 3.1)

Material Property	Value	Reference
Density	8690 kg/m^3	ASTM (1997)
Yield Strength	310 MPa (20 °C) 214 MPa (760 °C)	ASTM (1997) Haynes International (1997)
Tensile Strength	690 MPa (20 °C) 524 MPa (760 °C)	ASTM (1997) Haynes International (1997)
% Elongation	62 (20 °C) 68 (760 °C)	Haynes International (1997) Haynes International (1997)
Poisson's Ratio	0.278 (20 °C)	American Society for Metals (1980)
Melting Temperature	1357 °C	Haynes International (1997)
Mean Coefficient of Thermal Expansion	$12.4 * 10^{-6}$ m / m K (24 °C - 93 °C) $16.2 * 10^{-6}$ m / m K (24 °C - 982 °C)	Haynes International (1997) Haynes International (1997)

Table I.2. Modulus of Elasticity for Alloy 22 [Haynes International (1997)]

Temperature (°C)	Modulus of Elasticity (GPa)
20	206
871	154
982	145

Table I.3. Thermal Conductivity for Alloy 22 [Haynes International (1997)]

Temperature (°C)	Thermal Conductivity (W / m K)
48	10.1
100	11.1
200	13.4
300	15.5
400	17.5
500	19.5
600	21.3

Table I.4. Specific Heat for Alloy 22 [Haynes International (1997)]

Temperature (°C)	Specific Heat (J / kg K)
52	414
100	423
200	444
300	460
400	476
500	485
600	514

The finite element solutions include elastic and plastic deformations for all materials. When the materials are driven into the plastic range, the slope of the stress-strain curve continuously changes. Thus, a simplification for this curve is needed to incorporate plasticity into the finite element solution. A standard approximation is commonly used in engineering by using a straight line segment that connects the yield point to the ultimate tensile strength point of the material. The following parameters are used in subsequent calculations:

S_y = Yield strength of the material

S_u = Ultimate tensile strength

e_1, e_2, e_3 = Strain magnitudes

E = Elastic modulus (slope of the line in the elastic region)

E_l = Tangent modulus (slope of the line in the plastic region)

v = Poisson's ratio

The slope, E_l is determined by:

$e_1 = S_y / E$ and $e_2 = e_3 - e_1$ where e_3 = elongation specified for material.

Hence, for SB-575 N06022:

$E_l = (S_u - S_y) / e_2 = (0.690 - 0.310) / (0.45 - (0.310 / 203)) = 0.847$ GPa

Linear interpolation and extrapolation are used in the following calculations:

E (at 1120 °C) = 154 – ((1120 – 871) * (154 – 145) / (982 – 871)) = 134 GPa

v (at 1120 °C) = 0.5 – ((1357 – 1120) * (0.5 – 0.278) / (1357 – 20)) = 0.46 (note that Poisson's ratio of a solid material approaches to 0.5 at melting temperature)

S_y (at 1120 °C) = 214 – (214 * (1120 – 760) / (1357 – 760)) = 85 MPa (note that the yield strength approaches to zero as the temperature approaches to melting temperature)

S_u (at 1120 °C) = 524 – (524 * (1120 – 760) / (1357 – 760)) = 208 MPa (note that the ultimate tensile strength approaches to zero as the temperature approaches to melting temperature)

e_3 (at 1120 °C) = 0.62 + ((1120 – 20) * (0.68 – 0.62) / (760 – 20)) = 0.71

E_l (at 1120 °C) = (0.208 – 0.085) / (0.71 – (0.085 / 134)) = 0.173 GPa

Corrosion properties of Alloy 22 are given below:

Long term structural performance of the SNF canisters depends to a large extent on the general corrosion rate of Alloy 22. The general corrosion rate takes place independent of the stress state inside the material. However, the stress corrosion cracking is a function of the stress inside a material. An earlier study [CRWMS M&O (2000b)] indicates that Alloy 22 is susceptible to SCC if the tensile stress is more than 20% of the yield strength of the material (0.2 * 310 MPa = 62 MPa). Once this stress threshold is exceeded, the crack propagation is significantly faster than the general corrosion rate of Alloy 22.

To ensure that SCC does not take place, the canister should have a compressive outer layer with a minimum thickness equal to the amount of the general corrosion in

10,000 years. The general corrosion rate of Alloy 22 is obtained from CRWMS M&O 2000c and 2000d as follows:

General corrosion rate = 73 nm/year = 0.73 mm/10,000 years [CRWMS M&O (2000c)]

General corrosion rate correction for the maximum bias due to silica scale deposit formation = 0.063 μm/year = 0.63 mm/10,000 years [CRWMS M&O (2000d)]

Therefore:

General corrosion rate = 0.73 + 0.63 = 1.36 mm/10,000 years

There is one additional factor that needs to be added to this corrosion rate for the base metal. This factor is called the microbial influenced corrosion (MIC). A factor of multiplication of 2 was determined for this effect [CRWMS M&O (2000c)]. Including the factor of MIC, the general corrosion rate of the base metal Alloy 22 increases up to 2.72 mm/10,000 years (2 * 1.36 = 2.72 mm/10,000 years).

For the welded sections of Alloy 22 in the SNF canister, there is one more factor that needs to be considered: thermal aging of Alloy 22. A factor of multiplication of 2.5 was determined to include this effect [CRWMS M&O (2000c)]. Thus, a general corrosion rate of 6.8 mm/10,000 years (2.5 * 2.72 = 6.8 mm/10,000 years) is applicable for the welded but not fully annealed section of the SNF canister. This section is the final closure-weld section in the SNF canister.

APPENDIX II

THREE DIMENSIONAL FINITE ELEMENT MODEL INPUT FILE

(SEQUENTIAL METHOD)

```
/config,nres,10000
/config,nproc,2
/units,si
/prep7
/title, Residual Stresses from Induction Annealing - Sequential Method
/vcon,,0
et,1,solid70          ! 3-D thermal solid element for the outer shell
mp,dens,1,8690.0      ! Alloy 22
! Thermal properties of Alloy 22
/COM,    Define conductivity
MPTEMP
MPTEMP,   1,  48,   100,  200,   300,  400,  500,
MPTEMP,   7,  600,
MPDATA, KXX, 1, 1,  10.1,  11.1,  13.4,  15.5,  17.5,  19.5,
MPDATA, KXX, 1, 7,  21.3,
/COM,
/COM,    Define specific heat
MPTEMP,   1,  52,   100,  200,   300,  400,  500,
MPTEMP,   7,  600,
MPDATA, C, 1, 1,  414,  423,  444,  460,  476,  485,
MPDATA, C, 1, 7,  514,
/com, Define Parameters
osor=.782        ! Outer shell outer radius
ost=.02          ! Outer shell thickness
ist=.05          ! Inner shell thickness
ostl=5.035       ! Outer shell total length
oslid=.025       ! Outer shell lid thickness
islid=.095       ! Inner shell lid thickness
osbr=.1         ! Outer shell bending radius
gap=.03          ! Gap between the lids
oswh=.025        ! Outer shell weld height
trbe=.475         ! Trunion ring bottom end
trte=.025         ! Trunion ring top end
trt=.04           ! Trunion ring thickness
tct=.02           ! Trunion collar thickness
tcue=.195         ! Trunion collar upper end from WP end
tcle=.295         ! Trunion collar upper end from WP end
gols=.004        ! Gap between the outer lid and outer shell
plth=.01          ! Plate thickness (first outer lid)
/com, Define keypoints
csys,0
k,1,osor-ost-ist,
k,2,osor-ost,
k,3,osor,
k,4,osor-ost-ist,ostl/2-trbe
k,5,osor-ost,ostl/2-trbe
k,6,osor,ostl/2-trbe
k,7,osor-ost-ist,ostl/2-trbe+trt-tct
k,8,osor-ost,ostl/2-trbe+trt-tct
k,9,osor,ostl/2-trbe+trt-tct
k,10,osor+trt-tct,ostl/2-trbe+trt-tct
k,11,osor-ost-ist,ostl/2-trbe+trt
k,12,osor-ost,ostl/2-trbe+trt
k,13,osor,ostl/2-trbe+trt
k,14,osor+trt-tct,ostl/2-trbe+trt
k,15,osor+trt,ostl/2-trbe+trt
k,16,osor-ost-ist,ostl/2-tcle
```

```
k,17,osor-ost,ostl/2-tcle
k,18,osor,ostl/2-tcle
k,19,osor+trt-tct,ostl/2-tcle
k,20,osor+trt,ostl/2-tcle
k,21,0,ostl/2-osbr-oslid-gap-islid
k,22,osor-ost-ist,ostl/2-osbr-oslid-gap-islid
k,23,osor-ost,ostl/2-osbr-oslid-gap-islid
k,24,osor,ostl/2-osbr-oslid-gap-islid
k,25,osor+trt-tct,ostl/2-osbr-oslid-gap-islid
k,26,osor+trt,ostl/2-osbr-oslid-gap-islid
k,27,0,ostl/2-tcue
k,28,osor-ost-ist,ostl/2-tcue
k,29,osor-ost,ostl/2-tcue
k,30,osor,ostl/2-tcue
k,31,osor+trt-tct,ostl/2-tcue
k,32,osor+trt,ostl/2-tcue
k,33,0,ostl/2-tcue+plth
k,34,osor-ost-ist,ostl/2-tcue+plth
k,35,osor-ost,ostl/2-tcue+plth
k,36,osor,ostl/2-tcue+plth
k,37,osor+trt-tct,ostl/2-tcue+plth
k,38,osor+trt,ostl/2-tcue+plth
k,39,0,ostl/2-osbr-oslid
k,40,osor-ost-gols-oslid-osbr,ostl/2-osbr-oslid
k,41,osor-ost-gols-oslid-oswh,ostl/2-osbr-oslid
k,42,osor-ost-gols-oslid,ostl/2-osbr-oslid
k,43,osor-ost-gols,ostl/2-osbr-oslid
k,44,0,ostl/2-osbr
k,45,osor-ost-gols-oslid-osbr,ostl/2-osbr
k,46,osor-ost-gols-oslid-oswh,ostl/2-osbr
k,47,osor-ost-gols-oslid,ostl/2-osbr
k,48,osor-ost-gols,ostl/2-osbr
k,49,osor-ost,ostl/2-trte-trt
k,50,osor,ostl/2-trte-trt
k,51,osor+trt-tct,ostl/2-trte-trt
k,52,osor+trt,ostl/2-trte-trt
k,53,osor-ost,ostl/2-trte-trt+tct
k,54,osor,ostl/2-trte-trt+tct
k,55,osor+trt-tct,ostl/2-trte-trt+tct
k,56,osor-ost-gols-oslid-oswh,ostl/2-oswh
k,57,osor-ost-gols-oslid,ostl/2-oswh
k,58,osor-ost-gols,ostl/2-oswh
k,59,osor-ost,ostl/2-trte
k,60,osor,ostl/2-trte
k,61,osor-ost-gols-oslid,ostl/2
k,62,osor-ost-gols,ostl/2
k,63,osor-ost,ostl/2
k,64,osor,ostl/2
csys,0
/com, Horizontal lines in inner shell
l,1,2
l,4,5
l,7,8
l,11,12
l,16,17
l,22,23
l,28,29
```

```
1,34,35
/com, Horizontal lines in inner lid
1,21,22
1,27,28
1,33,34
/com, Horizontal lines in outer shell
1,2,3
1,5,6
1,8,9
1,12,13
1,17,18
1,23,24
1,29,30
1,35,36
1,49,50
1,53,54
1,59,60
1,63,64
/com, Horizontal lines in trunion ring and verticals in triangular
areas
1,4,7
1,5,8
1,6,9
1,6,10
1,9,10
1,13,14
1,18,19
1,24,25
1,30,31
1,36,37
1,50,51
1,54,55
1,55,60
1,54,60
1,53,59
1,7,11
1,8,12
1,9,13
1,10,14
1,10,15
1,14,15
1,19,20
1,25,26
1,31,32
1,37,38
1,51,52
1,52,55
1,51,55
1,50,54
1,49,53
/com, Horizontal lines in the outer lid inner region
1,39,40
1,44,45
/com, Horizontal and vertical lines in the outer lid 45 degree section
1,40,41
1,45,46
1,45,56
```

```
l,46,56
l,47,57
l,48,58
/com, Vertical lines in the outer weld section
l,41,42
l,46,47
l,56,57
l,56,61
l,57,61
l,58,62
l,59,63
l,60,64
/com, Horizontal lines in the outer lid outer radius
l,42,43
l,47,48
l,57,58
l,61,62
/com, Vertical lines in shells starting from symmetry axis
lsel,none
l,1,4
l,2,5
l,3,6
lesize,all,,,16,.5,1
alls
/com, Vertical lines in the region two levels below inner lid
l,11,16
l,12,17
l,13,18
l,14,19
l,15,20
/com, Vertical lines in the region below inner lid
l,16,22
l,17,23
l,18,24
l,19,25
l,20,26
/com, Vertical lines in the region of inner lid lower section
l,21,27
l,22,28
l,23,29
l,24,30
l,25,31
l,26,32
/com, Vertical lines in the region of inner lid upper section
lsel,none
l,27,33
l,28,34
l,29,35
l,30,36
l,31,37
l,32,38
lesize,all,,,2,1,1
alls
/com, Vertical lines in trunion ring upper section
lsel,none
l,35,49
l,36,50
```

```
l,37,51
l,38,52
lesize,all,,,8,1,1
alls
/com, Vertical lines in outer lid
l,39,44
l,40,45
l,41,46
l,42,47
l,43,48
/com, Horizontal lines in the gap
lsel,none
l,58,59
l,62,63
lesize,all,,,2,1,1
alls
/com, Define areas starting from the region close to bottom symmetry
plane
allsel
al,1,75,2,74
al,12,76,13,75
al,2,25,3,24
al,13,26,14,25
al,26,27,28
al,3,40,4,39
al,14,41,15,40
al,28,42,29,41
al,42,43,44
al,4,78,5,77
al,15,79,16,78
al,29,80,30,79
al,44,81,45,80
al,5,83,6,82
al,16,84,17,83
al,30,85,31,84
al,45,86,46,85
al,9,88,10,87
al,6,89,7,88
al,17,90,18,89
al,31,91,32,90
al,46,92,47,91
al,10,94,11,93
al,7,95,8,94
al,18,96,19,95
al,32,97,33,96
al,47,98,48,97
al,19,100,20,99
al,33,101,34,100
al,48,102,49,101
al,20,52,21,53
al,34,51,35,52
al,49,50,51
al,21,37,22,38
al,35,36,37
al,22,69,23,68
al,108,68,109,67
al,54,104,55,103
```

```
al,56,105,57,104
al,62,106,63,105
al,70,107,71,106
al,57,59,58
al,63,60,64,59
al,71,61,72,60
al,64,66,65
al,72,67,73,66
/com, Outer shell and lid mesh
asel,s,,,2
asel,a,,,4,5
asel,a,,,7,9
asel,a,,,11,13
asel,a,,,15,16
asel,a,,,20,21
asel,a,,,23,46
/com, Create volumes by rotating areas about two keypoints defining the
axis of rotation
arcang=10
esize,,4
vrotat,all,,,,,,39,44,arcang,1
type,1   ! solid70
mat,1    ! Alloy 22
mshkey,1
vmesh,all
allsel
save
/nerr,,100000
/SOLU
ANTYPE,TRAN,NEW,
NROPT,FULL,,ON,
TRNOPT,FULL,
ALLS
TIME,35
/COM,           Thermal initial boundary condition for the WP at 20
degrees C
TUNIF,20
/COM,           Apply loads and solve for 0 to 35 seconds
nsel,s,loc,y,ostl/2-oswh/2,ostl/2     ! Select volume of first HAZ from
coil induction
D,ALL,TEMP,1120
nsel,s,loc,y,ostl/2-((trte+oswh)/2),ostl/2-(.00001+oswh/2)     ! Select
volume of second HAZ from coil induction
D,ALL,TEMP,750
nsel,s,loc,y,ostl/2-trte-trt-.00001,ostl/2-(.00001+((trte+oswh)/2))
! Select volume of third HAZ from coil induction
D,ALL,TEMP,500
nsel,s,loc,y,ostl/2-osbr+.00001,ostl/2-trte-trt-.00001     ! Select
volume of fourth HAZ from coil induction
D,ALL,TEMP,250
/COM,           Set time integration parameters for the first time
interval
ALLS
NSUBST,5,10,4,ON,
KBC,0
AUTOTS,ON
OUTRES,ALL,ALL
```

```
SOLVE
*get,ls1ss,active,0,solu,ncmss
!
!
/COM,           Solve from 35 to 45 seconds
TIME,45
nsel,s,loc,y,ostl/2-oswh/2,ostl/2      ! Select volume of first HAZ from
coil induction
D,ALL,TEMP,1120
nsel,s,loc,y,ostl/2-((trte+oswh)/2),ostl/2-(.00001+oswh/2)     ! Select
volume of second HAZ from coil induction
D,ALL,TEMP,750
nsel,s,loc,y,ostl/2-trte-trt-.00001,ostl/2-(.00001+((trte+oswh)/2))
! Select volume of third HAZ from coil induction
D,ALL,TEMP,500
nsel,s,loc,y,ostl/2-osbr+.00001,ostl/2-trte-trt-.00001     ! Select
volume of fourth HAZ from coil induction
D,ALL,TEMP,250
ALLS
OUTRES,ALL,ALL
SOLVE
*get,ls2ss,active,0,solu,ncmss
!
!
/COM,           Solve from 45 to 75 seconds
nsel,all
DDELE,ALL,TEMP                       ! Delete previously set boundary
conditions
TM_START=46
TM_END=75
TM_INC=1
ALLS
*DO,TM,TM_START,TM_END,TM_INC
        TIME,TM,
! Select first surface area for quenching
nsel,s,loc,y,ostl/2-oswh/2,ostl/2
FLST,5,75,1,ORDE,26
FITEM,5,2618
FITEM,5,2620
FITEM,5,-2625
FITEM,5,2627
FITEM,5,-2628
FITEM,5,2630
FITEM,5,-2631
FITEM,5,2633
FITEM,5,-2634
FITEM,5,2636
FITEM,5,-2657
FITEM,5,2728
FITEM,5,-2737
FITEM,5,3388
FITEM,5,3392
FITEM,5,-3395
FITEM,5,3409
FITEM,5,-3410
FITEM,5,3412
FITEM,5,-3415
```

```
FITEM,5,3417
FITEM,5,-3418
FITEM,5,3420
FITEM,5,-3421
FITEM,5,3458
FITEM,5,-3472
NSEL,R, , ,P51X
cm,bcnode1,node
D,ALL,TEMP,1120-((1000/29)*(TM-46))
! Select second surface area for quenching
nsel,s,loc,y,ostl/2-((trte+oswh)/2),ostl/2-(.00001+oswh/2)
FLST,5,20,1,ORDE,16
FITEM,5,2468
FITEM,5,2472
FITEM,5,-2475
FITEM,5,2619
FITEM,5,2626
FITEM,5,2629
FITEM,5,2632
FITEM,5,2635
FITEM,5,3163
FITEM,5,3167
FITEM,5,-3170
FITEM,5,3408
FITEM,5,3411
FITEM,5,3416
FITEM,5,3419
FITEM,5,3422
NSEL,R, , ,P51X
cm,bcnode2,node
D,ALL,TEMP,750-((730/29)*(TM-46))
! Select third surface area for quenching
nsel,s,loc,y,ostl/2-trte-trt-.00001,ostl/2-(.00001+((trte+oswh)/2))
FLST,5,48,1,ORDE,22
FITEM,5,2078
FITEM,5,2086
FITEM,5,-2089
FITEM,5,2338
FITEM,5,2342
FITEM,5,-2345
FITEM,5,2418
FITEM,5,-2432
FITEM,5,2568
FITEM,5,-2572
FITEM,5,2574
FITEM,5,-2575
FITEM,5,2577
FITEM,5,-2582
FITEM,5,3184
FITEM,5,-3185
FITEM,5,3187
FITEM,5,-3190
FITEM,5,3192
FITEM,5,-3193
FITEM,5,3195
FITEM,5,-3196
NSEL,R, , ,P51X
```

```
cm,bcnode3,node
D,ALL,TEMP,500-((480/29)*(TM-46))
! Select fourth surface area for quenching
nsel,s,loc,y,ostl/2-osbr+.00001,ostl/2-trte-trt-.00001
FLST,5,15,1,ORDE,15
FITEM,5,2084
FITEM,5,-2085
FITEM,5,2095
FITEM,5,-2096
FITEM,5,2102
FITEM,5,-2103
FITEM,5,2109
FITEM,5,-2110
FITEM,5,2116
FITEM,5,-2117
FITEM,5,3183
FITEM,5,3186
FITEM,5,3191
FITEM,5,3194
FITEM,5,3197
NSEL,R, , ,P51X
cm,bcnode4,node
D,ALL,TEMP,250-((230/29)*(TM-46))
        ALLS
        NSUBST,2,4,1,ON,
        OUTRES,ALL,ALL
        SOLVE
*ENDDO
*get,ls3ss,active,0,solu,ncmss
*get,ls3ls,active,0,solu,ncmls
!
!
/COM,          Solve from 75 to 1800 seconds
nsel,s,,,bcnode1
nsel,a,,,bcnode2
nsel,a,,,bcnode3
nsel,a,,,bcnode4
D,ALL,TEMP,20
TM_START=80
TM_END=1800
TM_INC=5
ALLS
*DO,TM,TM_START,TM_END,TM_INC
        TIME,TM,
        NSUBST,2,4,1,ON,
        OUTRES,ALL,ALL
        SOLVE
*ENDDO
*get,ls4ss,active,0,solu,ncmss
*get,ls4ls,active,0,solu,ncmls
!
!
FINISH
physics,clear
/prep7
et,1,solid45          ! Switch to 3-D structural solid element for the
outer shell
```

```
mp,dens,1,8690.0    ! Alloy 22
!
mptemp,1,20,1120
mpdata,ex,1,1,206e9,134e9 ! Alloy 22 Elastic Modulus
mpdata,nuxy,1,1,0.278,0.46   ! Alloy 22 Poisson's ratio
! Material properties of outer shell
tb,biso,1
tbtemp,20
tbdata,,310e6,0.847e9  ! Alloy 22
tbtemp,1120
tbdata,,85e6,0.173e9   ! Alloy 22
!
mpdata,alpx,1,1,12.4e-6,16.2e-6   ! Alloy 22
alls
/com, Apply displacement/symmetry constraints
csys,0
nsel,s,loc,y,0
d,all,uy,0
local,11,1,,,,,-90,
nsel,s,loc,y,0
nsel,a,loc,y,arcang
nrot,all
d,all,uy,0
nsel,s,loc,x,0
d,all,ux,0
alls
save
finish
/solu
ANTYPE,TRAN,NEW,
NROPT,FULL,,ON,
TRNOPT,FULL,
ALLS
/COM,           Solve from 0 to 35 seconds
TM=35
*DO,ss,1,ls1ss,1
        TIME,(TM/ls1ss)*ss,
        ldread,temp,1,ss,,,seqarc1,rth
        AUTOTS,OFF
        NSUBST,1,,,off
        OUTRES,ALL,ALL
        SOLVE
*ENDDO
!
!
/COM,           Solve from 35 to 45 seconds
TM=45
*DO,ss,2,ls2ss,1
        TIME,35+((TM-35)/ls2ss)*ss,
        ldread,temp,1,ss,,,seqarc1,rth
        AUTOTS,OFF
        NSUBST,1,,,off
        OUTRES,ALL,ALL
        SOLVE
*ENDDO
!
!
```

```
/COM,           Solve from 45 to 75 seconds
TM=75
*DO,ls,3,ls3ls,1
        *DO,ss,1,ls3ss,1
              TIME,45+((TM-45)/(ls3ls-2))*(ls-2)+(ss/ls3ss)
              ldread,temp,ls,ss,,,seqarcl,rth
              AUTOTS,OFF
              NSUBST,1,,,off
              OUTRES,ALL,ALL
              SOLVE
        *ENDDO
*ENDDO
!
!
/COM,           Solve from 75 to end of simulation
TM=1800
*DO,ls,ls3ls+1,ls4ls,1
        *DO,ss,1,ls4ss,1
              TIME,75+((TM-75)/(ls4ls-ls3ls))*(ls-ls3ls)+((TM-
75)/(ls4ls-ls3ls))*(ss/ls4ss)
              ldread,temp,ls,ss,,,seqarcl,rth
              AUTOTS,OFF
              NSUBST,1,,,off
              OUTRES,ALL,ALL
              SOLVE
        *ENDDO
*ENDDO
!
!
FINISH
/EXIT,NOSA
/EOF
```

APPENDIX III

TWO DIMENSIONAL AXISYMMETRIC FINITE ELEMENT MODEL INPUT FILE

(DIRECT METHOD)

```
/config,nres,2000
/config,nproc,2
/units,si
/prep7
/title, FEA to determine residual stresses due to induction coil
heating of closure welds
/vcon,,0
et,1,plane13,4,,1   ! Axisymmetric model for the outer shell
et,2,plane13,4,,1   ! Inner shell is not meshed; it's geometry
developed for future use
!
mptemp,1,20,1120
mpdata,ex,1,1,206e9,134e9 ! Alloy 22 Elastic Modulus
mpdata,ex,2,1,195e9,195e9 ! 316 Stainless Steel Elastic Modulus at room
temperature
mpdata,nuxy,1,1,0.278,0.46   ! Alloy 22 Poisson's ratio
mpdata,nuxy,2,1,0.298,0.298  ! 316 SS Poisson's ratio
! Material properties of outer shell
tb,biso,1
tbtemp,20
tbdata,,310e6,0.847e9  ! Alloy 22
tbtemp,1120
tbdata,,85e6,0.173e9   ! Alloy 22
! Material properties of inner shell (316 SS temperature does not
significantly change
! during quenching.  No change in material properties required)
tb,biso,2
tbtemp,20
tbdata,,207e6,0.777e9  ! 316 SS
tbtemp,1120
tbdata,,207e6,0.777e9  ! 316 SS
!
mp,dens,1,8690.0    ! Alloy 22
mp,dens,2,7980.0    ! 316 SS
mpdata,alpx,1,1,12.4e-6,16.2e-6   ! Alloy 22
mpdata,alpx,2,1,15.2e-6,15.2e-6   ! 316 SS
! Thermal properties of Alloy 22
/COM,    Define conductivity
MPTEMP
MPTEMP,   1,  48,   100,  200,   300,  400,  500,
MPTEMP,   7,  600,
MPDATA, KXX, 1, 1,  10.1,  11.1,  13.4,  15.5,  17.5,  19.5,
MPDATA, KXX, 1, 7,  21.3,
/COM,
/COM,    Define specific heat
MPTEMP,   1,  52,   100,  200,   300,  400,  500,
MPTEMP,   7,  600,
MPDATA, C, 1, 1,  414,  423,  444,  460,  476,  485,
MPDATA, C, 1, 7,  514,
! Thermal properties of 316L SS (To be modified for 316 SS)
/COM,             Define K and C for materials 80
MPTEMP,   1,   21.11,   37.78,   65.56,   93.33,  121.11,  148.89,
MPTEMP,   7,  176.67,  204.44,  232.22,  260.00,  287.78,  315.56,
MPTEMP,  13,  343.33,  371.11,  398.89,  426.67,  454.44,  482.22,
MPTEMP,  19,  510.00,  537.78,  565.56,  593.33,  621.11,  648.89,
MPTEMP,  25,  676.67,  704.44,  732.22,  760.00,  787.78,  815.56,
MPDATA, KXX, 2, 1,  13.33,  13.67,  14.19,  14.54,  15.06,  15.58,
```

```
MPDATA, KXX, 2, 7,  15.92,  16.44,  16.96,  17.31,  17.83,  18.17,
MPDATA, KXX, 2,13,  18.52,  19.04,  19.38,  19.90,  20.25,  20.77,
MPDATA, KXX, 2,19,  21.11,  21.46,  21.98,  22.33,  22.67,  23.02,
MPDATA, KXX, 2,25,  23.54,  23.88,  24.23,  24.58,  24.92,  25.27,
MPDATA,   C, 2, 1, 483.04, 488.08, 499.30, 500.73, 511.39, 521.75,
MPDATA,   C, 2, 7, 522.32, 528.67, 538.26, 538.80, 544.52, 544.63,
MPDATA,   C, 2,13, 548.35, 553.62, 553.56, 558.56, 558.69, 566.50,
MPDATA,   C, 2,19, 566.33, 566.33, 573.82, 573.70, 576.34, 576.19,
MPDATA,   C, 2,25, 583.19, 582.69, 585.35, 587.96, 587.41, 589.93,
/com, Define Parameters
osor=.782       ! Outer shell outer radius
ost=.02         ! Outer shell thickness
ist=.05         ! Inner shell thickness
ostl=5.035      ! Outer shell total length
oslid=.025      ! Outer shell lid thickness
islid=.065      ! Inner shell lid thickness
osbr=.1        ! Outer shell bending radius
gap=.03         ! Gap between the lids
oswh=.025       ! Outer shell weld height
trbe=.445        ! Trunion ring bottom end
trte=.025        ! Trunion ring top end
trt=.04          ! Trunion ring thickness
tct=.02          ! Trunion collar thickness
tcue=.165        ! Trunion collar upper end from WP end
tcle=.265        ! Trunion collar upper end from WP end
gols=.004       ! Gap between the outer lid and outer shell
plth=.01         ! Plate thickness (first outer lid)
/com, Define local cylindrical coordinate system for the lid curved
section
! local,11,1,osor-ost-gols-oslid-osbr,ostl/2,  ! for future use
/com, Define keypoints
csys,0
k,1,osor-ost-ist,
k,2,osor-ost,
k,3,osor,
k,4,osor-ost-ist,ostl/2-trbe
k,5,osor-ost,ostl/2-trbe
k,6,osor,ostl/2-trbe
k,7,osor-ost-ist,ostl/2-trbe+trt-tct
k,8,osor-ost,ostl/2-trbe+trt-tct
k,9,osor,ostl/2-trbe+trt-tct
k,10,osor+trt-tct,ostl/2-trbe+trt-tct
k,11,osor-ost-ist,ostl/2-trbe+trt
k,12,osor-ost,ostl/2-trbe+trt
k,13,osor,ostl/2-trbe+trt
k,14,osor+trt-tct,ostl/2-trbe+trt
k,15,osor+trt,ostl/2-trbe+trt
k,16,osor-ost-ist,ostl/2-tcle
k,17,osor-ost,ostl/2-tcle
k,18,osor,ostl/2-tcle
k,19,osor+trt-tct,ostl/2-tcle
k,20,osor+trt,ostl/2-tcle
k,21,0,ostl/2-osbr-oslid-gap-islid
k,22,osor-ost-ist,ostl/2-osbr-oslid-gap-islid
k,23,osor-ost,ostl/2-osbr-oslid-gap-islid
k,24,osor,ostl/2-osbr-oslid-gap-islid
k,25,osor+trt-tct,ostl/2-osbr-oslid-gap-islid
```

```
k,26,osor+trt,ostl/2-osbr-oslid-gap-islid
k,27,0,ostl/2-tcue
k,28,osor-ost-ist,ostl/2-tcue
k,29,osor-ost,ostl/2-tcue
k,30,osor,ostl/2-tcue
k,31,osor+trt-tct,ostl/2-tcue
k,32,osor+trt,ostl/2-tcue
k,33,0,ostl/2-tcue+plth
k,34,osor-ost-ist,ostl/2-tcue+plth
k,35,osor-ost,ostl/2-tcue+plth
k,36,osor,ostl/2-tcue+plth
k,37,osor+trt-tct,ostl/2-tcue+plth
k,38,osor+trt,ostl/2-tcue+plth
k,39,0,ostl/2-osbr-oslid
k,40,osor-ost-gols-oslid-osbr,ostl/2-osbr-oslid
k,41,osor-ost-gols-oslid-oswh,ostl/2-osbr-oslid
k,42,osor-ost-gols-oslid,ostl/2-osbr-oslid
k,43,osor-ost-gols,ostl/2-osbr-oslid
k,44,0,ostl/2-osbr
k,45,osor-ost-gols-oslid-osbr,ostl/2-osbr
k,46,osor-ost-gols-oslid-oswh,ostl/2-osbr
k,47,osor-ost-gols-oslid,ostl/2-osbr
k,48,osor-ost-gols,ostl/2-osbr
k,49,osor-ost,ostl/2-trte-trt
k,50,osor,ostl/2-trte-trt
k,51,osor+trt-tct,ostl/2-trte-trt
k,52,osor+trt,ostl/2-trte-trt
k,53,osor-ost,ostl/2-trte-trt+tct
k,54,osor,ostl/2-trte-trt+tct
k,55,osor+trt-tct,ostl/2-trte-trt+tct
k,56,osor-ost-gols-oslid-oswh,ostl/2-oswh
k,57,osor-ost-gols-oslid,ostl/2-oswh
k,58,osor-ost-gols,ostl/2-oswh
k,59,osor-ost,ostl/2-trte
k,60,osor,ostl/2-trte
k,61,osor-ost-gols-oslid,ostl/2
k,62,osor-ost-gols,ostl/2
k,63,osor-ost,ostl/2
k,64,osor,ostl/2
csys,0
/com, Horizontal lines in inner shell
l,1,2
l,4,5
l,7,8
l,11,12
l,16,17
l,22,23
l,28,29
l,34,35
lesize,all,,,5,1,1
lsel,none
/com, Horizontal lines in inner lid
l,21,22
l,27,28
l,33,34
lesize,all,,,16,.0625,1
lsel,none
```

```
/com, Horizontal lines in outer shell
l,2,3
l,5,6
l,8,9
l,12,13
l,17,18
l,23,24
l,29,30
l,35,36
l,49,50
l,53,54
l,59,60
l,63,64
lesize,all,,,4,1,1
lsel,none
/com, Horizontal lines in trunion ring and verticals in triangular
areas
l,4,7
l,5,8
l,6,9
l,6,10
l,9,10
l,13,14
l,18,19
l,24,25
l,30,31
l,36,37
l,50,51
l,54,55
l,55,60
l,54,60
l,53,59
l,7,11
l,8,12
l,9,13
l,10,14
l,10,15
l,14,15
l,19,20
l,25,26
l,31,32
l,37,38
l,51,52
l,52,55
l,51,55
l,50,54
l,49,53
lesize,all,,,4,1,1
lsel,none
/com, Horizontal lines in the outer lid inner region
l,39,40
l,44,45
lesize,all,,,16,.0625,1
lsel,none
/com, Horizontal and vertical lines in the outer lid 45 degree section
l,40,41
l,45,46
```

```
l,45,56
l,46,56
l,47,57
l,48,58
lesize,all,,,8,1,1
lsel,none
/com, Vertical lines in the outer weld section
l,41,42
l,46,47
l,56,57
l,56,61
l,57,61
l,58,62
l,59,63
l,60,64
lesize,all,,,4,1,1
lsel,none
/com, Horizontal lines in the outer lid outer radius
l,42,43
l,47,48
l,57,58
l,61,62
lesize,all,,,4,1,1
lsel,none
/com, Vertical lines in shells starting from symmetry axis
l,1,4
l,2,5
l,3,6
lesize,all,,,24,.06,1
lsel,none
/com, Vertical lines in the region two levels below inner lid
l,11,16
l,12,17
l,13,18
l,14,19
l,15,20
lesize,all,,,6,1,1
lsel,none
/com, Vertical lines in the region below inner lid
l,16,22
l,17,23
l,18,24
l,19,25
l,20,26
lesize,all,,,7,1,1
lsel,none
/com, Vertical lines in the region of inner lid lower section
l,21,27
l,22,28
l,23,29
l,24,30
l,25,31
l,26,32
lesize,all,,,8,1,1
lsel,none
/com, Vertical lines in the region of inner lid upper section
l,27,33
```

```
l,28,34
l,29,35
l,30,36
l,31,37
l,32,38
lesize,all,,,3,1,1
lsel,none
/com, Vertical lines in trunion ring upper section
l,35,49
l,36,50
l,37,51
l,38,52
lesize,all,,,16,1,1
lsel,none
/com, Vertical lines in outer lid
l,39,44
l,40,45
l,41,46
l,42,47
l,43,48
lesize,all,,,5,1,1
lsel,none
/com, Horizontal lines in the gap
l,58,59
l,62,63
lesize,all,,,3,1,1
/com, Define areas starting from the region close to bottom symmetry
plane
allsel
al,1,75,2,74
al,12,76,13,75
al,2,25,3,24
al,13,26,14,25
al,26,27,28
al,3,40,4,39
al,14,41,15,40
al,28,42,29,41
al,42,43,44
al,4,78,5,77
al,15,79,16,78
al,29,80,30,79
al,44,81,45,80
al,5,83,6,82
al,16,84,17,83
al,30,85,31,84
al,45,86,46,85
al,9,88,10,87
al,6,89,7,88
al,17,90,18,89
al,31,91,32,90
al,46,92,47,91
al,10,94,11,93
al,7,95,8,94
al,18,96,19,95
al,32,97,33,96
al,47,98,48,97
al,19,100,20,99
```

```
al,33,101,34,100
al,48,102,49,101
al,20,52,21,53
al,34,51,35,52
al,49,50,51
al,21,37,22,38
al,35,36,37
al,22,69,23,68
al,108,68,109,67
al,54,104,55,103
al,56,105,57,104
al,62,106,63,105
al,70,107,71,106
al,57,59,58
al,63,60,64,59
al,71,61,72,60
al,64,66,65
al,72,67,73,66
/com, Outer shell and lid mesh
asel,s,,,2
asel,a,,,4,5
asel,a,,,7,9
asel,a,,,11,13
asel,a,,,15,16
asel,a,,,20,21
asel,a,,,23,46
type,1    ! plane13
mat,1     ! Alloy 22
smrt,off
mshkey,1
amesh,all
/com, Inner shell and lid mesh
!asel,s,,,1,3,2
!asel,a,,,6,10,4
!asel,a,,,14
!asel,a,,,18,19
!asel,a,,,23,24
!type,2    ! plane13
!mat,2     ! 316 SS
!amesh,all
/com, Apply displacement/symmetry constraints
nsel,s,loc,y,0
d,all,uy,0
nsel,s,loc,x,-.001,.001
d,all,ux,0
allsel
save
/nerr,,100000
/SOLU
ANTYPE,TRAN,NEW,
NROPT,FULL,,ON,
TRNOPT,FULL,
ALLS
TIME,35
/COM,          Thermal initial boundary condition for the WP at 20
degrees C
TUNIF,20
```

```
/COM,           Apply loads and solve for 0 to 35 seconds
nsel,s,loc,y,ostl/2-oswh/2,ostl/2      ! Select volume of first HAZ from
coil induction
D,ALL,TEMP,1120
nsel,s,loc,y,ostl/2-((trte+oswh)/2),ostl/2-(.00001+oswh/2)      ! Select
volume of second HAZ from coil induction
D,ALL,TEMP,750
nsel,s,loc,y,ostl/2-trte-trt-.00001,ostl/2-(.00001+((trte+oswh)/2))
! Select volume of third HAZ from coil induction
D,ALL,TEMP,500
nsel,s,loc,y,ostl/2-osbr+.00001,ostl/2-trte-trt-.00001      ! Select
volume of fourth HAZ from coil induction
D,ALL,TEMP,250
/COM,           Set time integration parameters for the first time
interval
ALLS
NSUBST,5,10,4,ON,
KBC,0
AUTOTS,ON
OUTRES,ALL,ALL
SOLVE
!
!
/COM,           Solve from 35 to 45 seconds
TIME,45
nsel,s,loc,y,ostl/2-oswh/2,ostl/2      ! Select volume of first HAZ from
coil induction
D,ALL,TEMP,1120
nsel,s,loc,y,ostl/2-((trte+oswh)/2),ostl/2-(.00001+oswh/2)      ! Select
volume of second HAZ from coil induction
D,ALL,TEMP,750
nsel,s,loc,y,ostl/2-trte-trt-.00001,ostl/2-(.00001+((trte+oswh)/2))
! Select volume of third HAZ from coil induction
D,ALL,TEMP,500
nsel,s,loc,y,ostl/2-osbr+.00001,ostl/2-trte-trt-.00001      ! Select
volume of fourth HAZ from coil induction
D,ALL,TEMP,250
ALLS
OUTRES,ALL,ALL
SOLVE
!
!
/COM,           Solve from 45 to 75 seconds
nsel,all
DDELE,ALL,TEMP                    ! Delete previously set boundary
conditions
TM_START=46
TM_END=75
TM_INC=1
ALLS
*DO,TM,TM_START,TM_END,TM_INC
        TIME,TM,
! Select first surface area for quenching
FLST,5,16,1,ORDE,10
FITEM,5,834
FITEM,5,836
FITEM,5,-841
```

```
FITEM,5,857
FITEM,5,-859
FITEM,5,1182
FITEM,5,1187
FITEM,5,-1188
FITEM,5,1196
FITEM,5,-1198
NSEL,S, , ,P51X
D,ALL,TEMP,1120-((1000/29)*(TM-46))
! Select second surface area for quenching
FLST,5,4,1,ORDE,4
FITEM,5,804
FITEM,5,835
FITEM,5,1067
FITEM,5,1186
NSEL,S, , ,P51X
D,ALL,TEMP,750-((730/29)*(TM-46))
! Select third surface area for quenching
FLST,5,12,1,ORDE,8
FITEM,5,694
FITEM,5,778
FITEM,5,794
FITEM,5,-796
FITEM,5,824
FITEM,5,-826
FITEM,5,1078
FITEM,5,-1081
NSEL,S, , ,P51X
D,ALL,TEMP,500-((480/29)*(TM-46))
! Select fourth surface area for quenching
FLST,5,7,1,ORDE,4
FITEM,5,706
FITEM,5,-709
FITEM,5,1075
FITEM,5,-1077
NSEL,S, , ,P51X
D,ALL,TEMP,250-((230/29)*(TM-46))
        ALLS
        NSUBST,2,4,1,ON,
        OUTRES,ALL,ALL
        SOLVE
*ENDDO
!
!
/COM,           Solve from 75 to 1800 seconds
FLST,5,39,1,ORDE,21
FITEM,5,694
FITEM,5,706
FITEM,5,-709
FITEM,5,778
FITEM,5,794
FITEM,5,-796
FITEM,5,804
FITEM,5,824
FITEM,5,-826
FITEM,5,834
FITEM,5,-841
```

```
FITEM,5,857
FITEM,5,-859
FITEM,5,1067
FITEM,5,1075
FITEM,5,-1081
FITEM,5,1182
FITEM,5,1186
FITEM,5,-1188
FITEM,5,1196
FITEM,5,-1198
NSEL,S, , ,P51X
D,ALL,TEMP,20
TM_START=80
TM_END=1800
TM_INC=5
ALLS
*DO,TM,TM_START,TM_END,TM_INC
        TIME,TM,
        NSUBST,2,4,1,ON,
        OUTRES,ALL,ALL
        SOLVE
*ENDDO
!
!
FINISH
/EXIT,NOSA
/EOF
```

APPENDIX IV

THREE DIMENSIONAL FINITE ELEMENT MODEL INPUT FILE FOR THE SNF CANISTER MOCK-UP

```
!
!     3-D model for the WP mockup
!     Simulation of both welding and subsequent solution anneal
!     Solution anneal cooling time is obtained from Lambda Research
!     SEQUENTIAL METHOD - TWO STEP SOLUTION
!
/config,nres,100000
/units,si
/prep7
/title, FEA to determine residual stresses due to induction coil
heating of closure welds
/vcon,,0
et,1,solid70         ! 3-D thermal solid element for the outer shell
mp,dens,1,8690.0     ! Alloy 22
! Thermal properties of Alloy 22
/COM,    Define conductivity
MPTEMP
MPTEMP,   1,  48,   100,  200,   300,  400,  500,
MPTEMP,   7,  600,
MPDATA, KXX, 1, 1,  10.1,  11.1,  13.4,  15.5,  17.5,  19.5,
MPDATA, KXX, 1, 7,  21.3,
/COM,
/COM,    Define specific heat
MPTEMP,   1,  52,   100,  200,   300,  400,  500,
MPTEMP,   7,  600,
MPDATA, C, 1, 1,  414,  423,  444,  460,  476,  485,
MPDATA, C, 1, 7,  514,
/com, Define Parameters
!
! Local cylindrical coordinate system to be used in "vrotate"
!
local,11,1,0,0,0,0,-90
!
! Parameters along x-axis
!
ro=1.4859/2          ! Outer shell outer radius
osth=0.0381          ! Outer shell thickness
ri=ro-osth           ! Outer shell inner radius
rgth=0.0381           ! Ring thickness
rgr=ri-rgth           ! Ring inner radius
wdw=0.03175/2           ! Weld width (half-symmetry)
!
! Parameters along y-axis
!
lth=1.23825          ! Length of the mockup
roff=0.0381           ! Ring offset from the bottom end
rlt=0.12065           ! Ring length
!
! Number of elements
!
neos=3               ! number of elements through outer shell thickness
nerg=3               ! number of elements through ring thickness
narc1=4                 ! number of elements along arc length in the weld
seam
narc2=17                ! number of elements along arc length #2
narc3=8                 ! number of elements along arc length #3
!
```

```
! Arc angles (degrees)
!
arcweld=(wdw/ro)*180/3.14159
arc90=90-arcweld
/com, Define keypoints
csys,0
k,1,ri
k,2,ro
k,3,rgr,roff
k,4,ri,roff
k,5,ro,roff
k,6,rgr,roff+rlt
k,7,ri,roff+rlt
k,8,ro,roff+rlt
k,9,ri,lth
k,10,ro,lth
k,11,0,0            ! Symmetry axis point #1
k,12,0,lth          ! Symmetry axis point #2
/com, Horizontal lines in the outer shell
l,1,2
l,4,5
l,7,8
l,9,10
lesize,all,,,neos,1,1
lsel,none
/com, Horizontal lines in the ring
l,3,4
l,6,7
lesize,all,,,nerg,1,1
lsel,none
/com, Vertical lines, region 1 from the bottom end
l,1,4
l,2,5
lesize,all,,,2,1,1
lsel,none
/com, Vertical lines, region 2 from the bottom end
l,3,6
l,4,7
l,5,8
lesize,all,,,6,1,1
lsel,none
/com, Vertical lines, region 3 from the bottom end
l,7,9
l,8,10
lesize,all,,,16,1,1
lsel,none
/com, Define areas starting from the region close to bottom end
allsel
al,1,8,2,7
al,5,10,6,9
al,2,11,3,10
al,3,13,4,12
/com, Rotate areas to obtain volumes, starting from the weld seam
alls
vrota,all,,,,,,11,12,arcweld,1
csys,11
asel,s,loc,y,arcweld
```

```
vrota,all,,,,,,11,12,arc90,1
asel,s,loc,y,90
vrota,all,,,,,,11,12,90,1
/com, Define number of line divisions along three arc-lengths
lsel,s,loc,y,arcweld/2
lesize,all,,,narc1,1,1
lsel,s,loc,y,arcweld+(arc90/2)
lesize,all,,,narc2,8,1
lsel,s,loc,y,135
lesize,all,,,narc3,1,1
/com, Outer shell and ring mesh
alls
type,1    ! solid70
mat,1     ! Alloy 22
smrt,off
mshkey,1
vmesh,all
allsel
save
/nerr,,100000
!
!                 Start solution
!
/SOLU
ANTYPE,TRAN,NEW,
NROPT,FULL,,ON,
TRNOPT,FULL,
ALLS
NEQIT,150
TIME,44.99
/COM,             Thermal initial boundary condition for the WP at 20
degrees C
TUNIF,20
/COM,             Apply loads and solve for 0 to 45 seconds, welding
simulation
vsel,s,,,1,4
nslv,s,1
D,ALL,TEMP,1120
/COM,             Set time integration parameters for the first time
interval
ALLS
NSUBST,10,10,10
KBC,0
AUTOTS,ON
OUTRES,ALL,ALL
SOLVE
!
!
/COM,             Solve from 44.99 to 45 seconds
nsel,all
DDELE,ALL,TEMP                       ! Delete previously set boundary
conditions
TIME,45
ALLS
NSUBST,1,1,1
OUTRES,ALL,ALL
SOLVE
```

```
!
!
/COM,           Solve from 45 to 1805 seconds
nsel,all
DDELE,ALL,TEMP                       ! Delete previously set boundary
conditions
TM_START=55
TM_END=1805
TM_INC=10
ALLS
NEQIT,150
*DO,TM,TM_START,TM_END,TM_INC
        TIME,TM,
        ALLS
        NSUBST,1,1,1
        OUTRES,ALL,ALL
        SOLVE
*ENDDO
!
!
TIME,1850
/COM,           Solution anneal starts here
TUNIF,20
/COM,           Apply loads and solve from 1805 to 1850 seconds
D,ALL,TEMP,1120
/COM,           Set time integration parameters for the first time
interval
ALLS
NSUBST,6,6,6
KBC,0
AUTOTS,ON
OUTRES,ALL,ALL
SOLVE
!
!
/COM,           Solve from 1850 to 1850.01 seconds
nsel,all
DDELE,ALL,TEMP                       ! Delete previously set boundary
conditions
TIME,1850.01
ALLS
NSUBST,1,1,1
OUTRES,ALL,ALL
SOLVE
!
!
/COM,           Solve from 1850.01 to 1880 seconds
nsel,all
DDELE,ALL,TEMP                       ! Delete previously set boundary
conditions
TM_START=1851
TM_END=1880
TM_INC=1
ALLS
NEQIT,150
*DO,TM,TM_START,TM_END,TM_INC
        TIME,TM,
```

```
        ! Identify and group all surface nodes for quenching
        asel,s,,,1,4
        asel,a,,,7,11,2
        asel,a,,,14
        asel,a,,,16,17
        asel,a,,,21
        asel,a,,,24,28,2
        asel,a,,,31,33,2
        asel,a,,,34
        asel,a,,,38
        asel,a,,,41,45,2
        asel,a,,,48
        asel,a,,,50,51
        asel,a,,,55
        asel,inve
        nsla,s,1
        cm,s_nodes,node
        D,ALL,TEMP,1120-((103/29)*(TM-1851))
        ALLS
        NSUBST,1,1,1
        OUTRES,ALL,ALL
        SOLVE
*ENDDO
!
!
/COM,           Solve from 1880 to 1910 seconds
nsel,all
DDELE,ALL,TEMP                          ! Delete previously set boundary
conditions
TM_START=1881
TM_END=1910
TM_INC=1
ALLS
NEQIT,150
*DO,TM,TM_START,TM_END,TM_INC
        TIME,TM,
        ! Re-select all surface nodes for continued cooling
        nsel,s,,,s_nodes
        D,ALL,TEMP,1017-((76/29)*(TM-1881))
        ALLS
        NSUBST,1,1,1
        OUTRES,ALL,ALL
        SOLVE
*ENDDO
!
!
/COM,           Solve from 1910 to 1940 seconds
nsel,all
DDELE,ALL,TEMP                          ! Delete previously set boundary
conditions
TM_START=1911
TM_END=1940
TM_INC=1
ALLS
NEQIT,150
*DO,TM,TM_START,TM_END,TM_INC
        TIME,TM,
```

```
        ! Re-select all surface nodes for continued cooling
        nsel,s,,,s_nodes
        D,ALL,TEMP,941-((45/29)*(TM-1911))
        ALLS
        NSUBST,1,1,1
        OUTRES,ALL,ALL
        SOLVE
*ENDDO
!
!
/COM,           Solve from 1940 to 1970 seconds
nsel,all
DDELE,ALL,TEMP                      ! Delete previously set boundary
conditions
TM_START=1941
TM_END=1970
TM_INC=1
ALLS
NEQIT,150
*DO,TM,TM_START,TM_END,TM_INC
        TIME,TM,
        ! Re-select all surface nodes for continued cooling
        nsel,s,,,s_nodes
        D,ALL,TEMP,896-((795/29)*(TM-1941))
        ALLS
        NSUBST,1,1,1
        OUTRES,ALL,ALL
        SOLVE
*ENDDO
!
!
/COM,           Solve from 1970 to 2000 seconds
nsel,all
DDELE,ALL,TEMP                      ! Delete previously set boundary
conditions
TM_START=1971
TM_END=2000
TM_INC=1
ALLS
NEQIT,150
*DO,TM,TM_START,TM_END,TM_INC
        TIME,TM,
        ! Re-select all surface nodes for continued cooling
        nsel,s,,,s_nodes
        D,ALL,TEMP,101-((29/29)*(TM-1971))
        ALLS
        NSUBST,1,1,1
        OUTRES,ALL,ALL
        SOLVE
*ENDDO
!
!
/COM,           Solve from 2000 to 2030 seconds
nsel,all
DDELE,ALL,TEMP                      ! Delete previously set boundary
conditions
TM_START=2001
```

```
TM_END=2030
TM_INC=1
ALLS
NEQIT,150
*DO,TM,TM_START,TM_END,TM_INC
        TIME,TM,
        ! Re-select all surface nodes for continued cooling
        nsel,s,,,s_nodes
        D,ALL,TEMP,72-((12/29)*(TM-2001))
        ALLS
        NSUBST,1,1,1
        OUTRES,ALL,ALL
        SOLVE
*ENDDO
!
!
/COM,           Solve from 2030 to 2060 seconds
nsel,all
DDELE,ALL,TEMP                      ! Delete previously set boundary
conditions
TM_START=2031
TM_END=2060
TM_INC=1
ALLS
NEQIT,150
*DO,TM,TM_START,TM_END,TM_INC
        TIME,TM,
        ! Re-select all surface nodes for continued cooling
        nsel,s,,,s_nodes
        D,ALL,TEMP,60-((11/29)*(TM-2031))
        ALLS
        NSUBST,1,1,1
        OUTRES,ALL,ALL
        SOLVE
*ENDDO
!
!
/COM,           Solve from 2060 to 2090 seconds
nsel,all
DDELE,ALL,TEMP                      ! Delete previously set boundary
conditions
TM_START=2061
TM_END=2090
TM_INC=1
ALLS
NEQIT,150
*DO,TM,TM_START,TM_END,TM_INC
        TIME,TM,
        ! Re-select all surface nodes for continued cooling
        nsel,s,,,s_nodes
        D,ALL,TEMP,49-((7/29)*(TM-2061))
        ALLS
        NSUBST,1,1,1
        OUTRES,ALL,ALL
        SOLVE
*ENDDO
!
```

```
!
/COM,           Solve from 2090 to 2405 seconds
nsel,all
DDELE,ALL,TEMP                      ! Delete previously set boundary
conditions
TM_START=2091
TM_END=2405
TM_INC=1
ALLS
NEQIT,150
*DO,TM,TM_START,TM_END,TM_INC
        TIME,TM,
        ! Re-select all surface nodes for continued cooling
        nsel,s,,,s_nodes
        D,ALL,TEMP,42-((22/314)*(TM-2091))
        ALLS
        NSUBST,1,1,1
        OUTRES,ALL,ALL
        SOLVE
*ENDDO
FINISH
physics,clear
/prep7
et,1,solid45        ! Switch to 3-D structural solid element
mp,dens,1,8690.0    ! Alloy 22
!
mptemp,1,20,1120
mpdata,ex,1,1,206e9,134e9 ! Alloy 22 Elastic Modulus
mpdata,nuxy,1,1,0.278,0.46   ! Alloy 22 Poisson's ratio
! Material properties of outer shell
tb,biso,1
tbtemp,20
tbdata,,310e6,0.847e9  ! Alloy 22
tbtemp,1120
tbdata,,85e6,0.173e9   ! Alloy 22
!
mpdata,alpx,1,1,12.4e-6,16.2e-6   ! Alloy 22
alls
/com, Apply displacement/symmetry constraints
csys,0
nsel,s,loc,z,0
d,all,uz,0
alls
save
finish
/solu
ANTYPE,TRAN,NEW,
NROPT,FULL,,ON,
TRNOPT,FULL,
ALLS
/COM,           Solve from 0 to 44.99 seconds
TM=44.99
*DO,ss,1,10,1
        TIME,(TM/10)*ss,
        ldread,temp,1,ss,,,mock3d,rth
        AUTOTS,OFF
        NSUBST,1,,,off
```

```
        OUTRES,ALL,ALL
        SOLVE
*ENDDO
!
!
/COM,           Solve from 44.99 to 45 seconds
TIME,45
ldread,temp,2,1,,,mock3d,rth
AUTOTS,OFF
NSUBST,1,,,off
OUTRES,ALL,ALL
SOLVE
!
!
/COM,           Solve from 45 to 1805 seconds
TM=1805
*DO,ls,3,178,1
        TIME,45+(TM-45)*(ls-2)/176,
        ldread,temp,ls,1,,,mock3d,rth
        AUTOTS,OFF
        NSUBST,1,,,off
        OUTRES,ALL,ALL
        SOLVE
*ENDDO
!
!
/COM,           Solve from 1805 to 1850 seconds
TM=1850
*DO,ss,1,6,1
        TIME,1805+((TM-1805)/6)*ss,
        ldread,temp,179,ss,,,mock3d,rth
        AUTOTS,OFF
        NSUBST,1,,,off
        OUTRES,ALL,ALL
        SOLVE
*ENDDO
!
!
/COM,           Solve from 1850 to 1850.01 seconds
TIME,1850.01
ldread,temp,180,1,,,mock3d,rth
AUTOTS,OFF
NSUBST,1,,,off
OUTRES,ALL,ALL
SOLVE
!
!
/COM,           Solve from 1850.01 to 2405 seconds
TM=2405
*DO,ls,181,735,1
        TIME,1850+(TM-1850)*(ls-180)/555,
        ldread,temp,ls,1,,,mock3d,rth
        AUTOTS,OFF
        NSUBST,1,,,off
        OUTRES,ALL,ALL
        SOLVE
*ENDDO
```

```
!
!
FINISH
/EXIT,NOSA
/EOF
```

APPENDIX V

WASTE PACKAGE MOCK-UP EXPERIMENTAL TEST DOCUMENTATION, DESIGN SPECIFICATIONS, AND DRAWINGS

FRAMATOME COGEMA FUELS

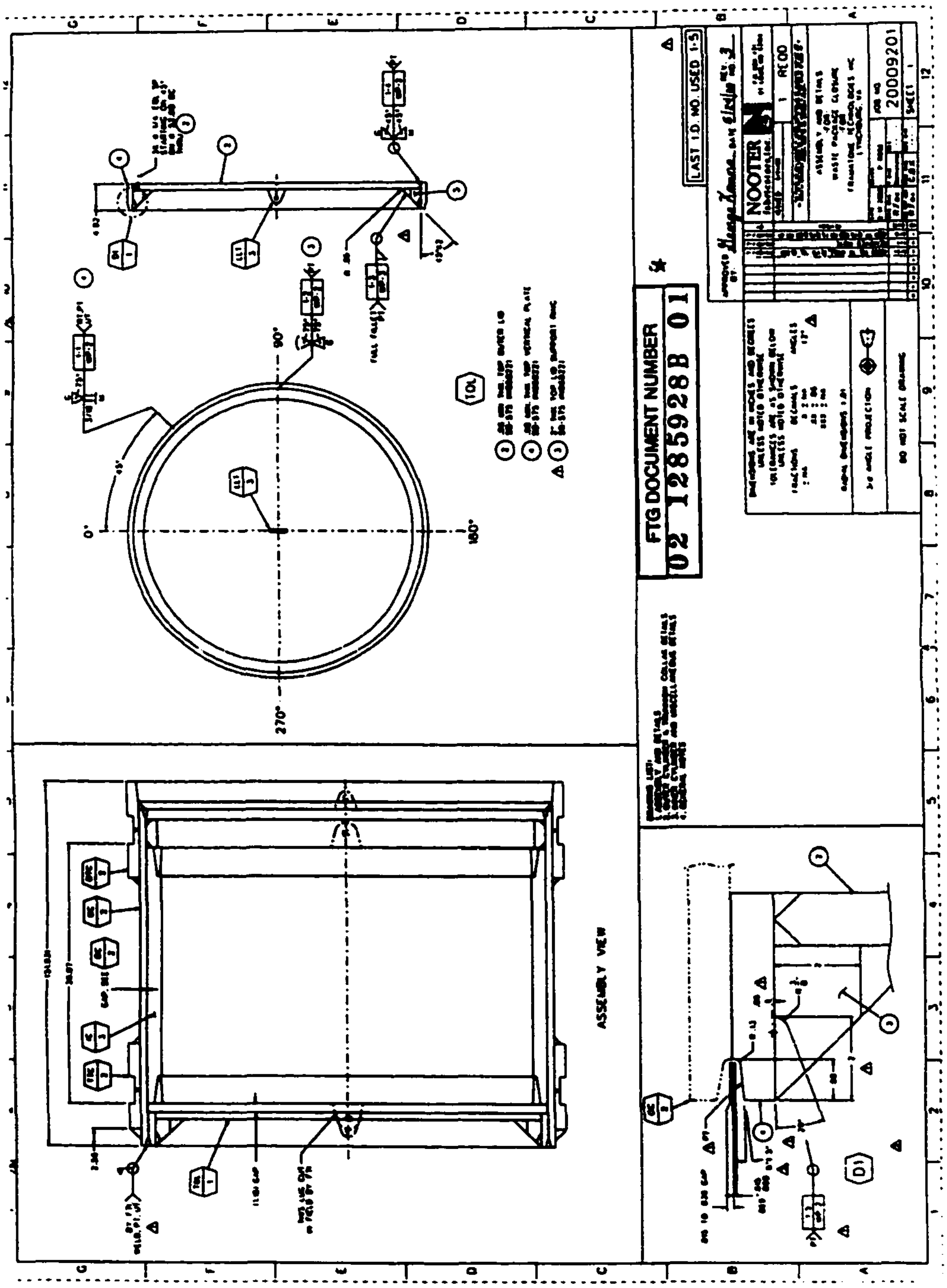
10/30/00

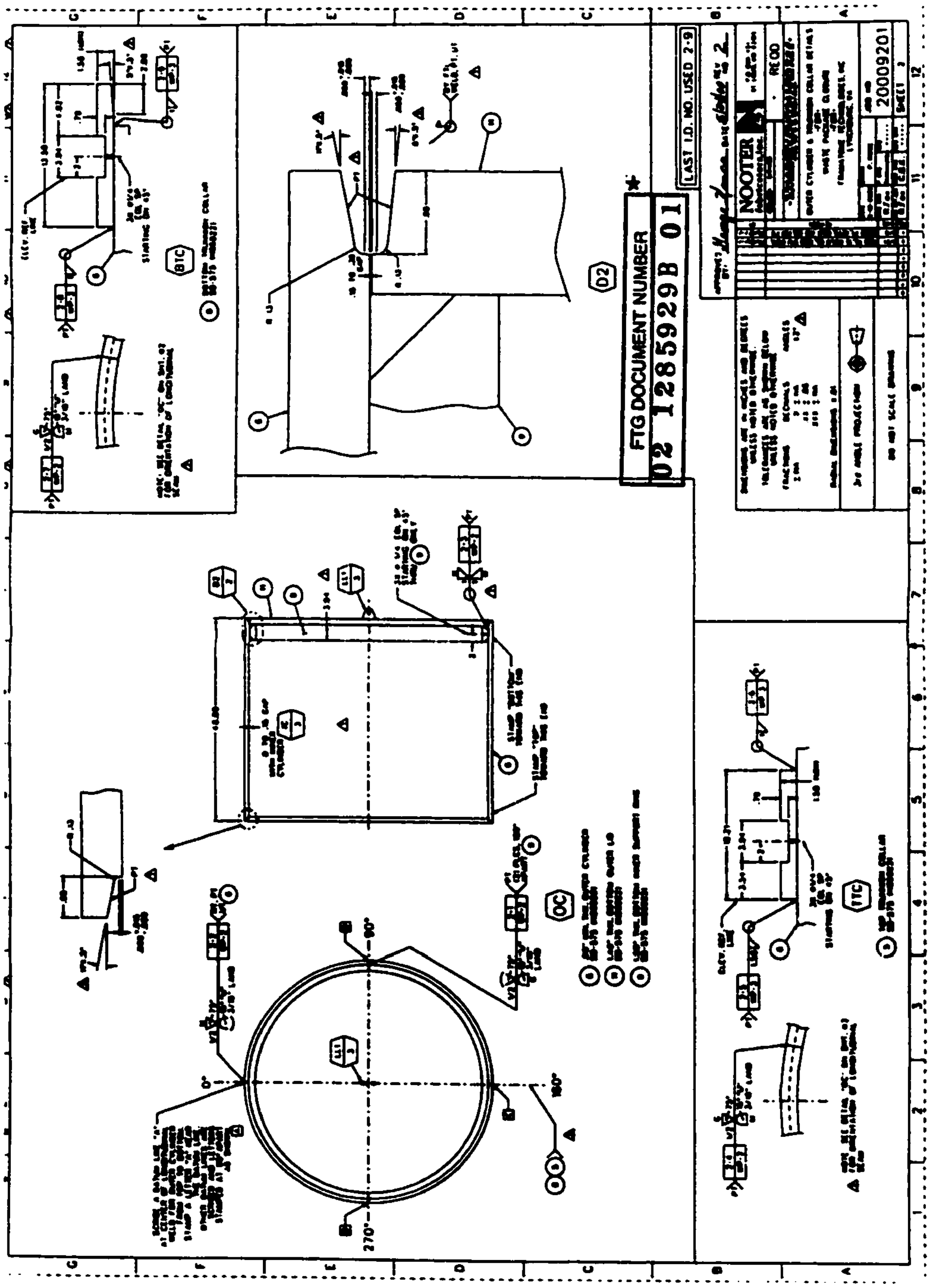
The finite element modeling work on the solution annealing and induction annealing of the spent nuclear fuel (SNF) canister mock-up has been initiated by Zekai Ceylan, who is an engineer of the Framatome Cogema Fuels, Civilian Radioactive Waste Management System, Management and Operating Contractor. Mr. Ceylan has also been a principal participator in experimental studies. Mr. Ceylan organized the design, processed the results, and drew conclusions to give directions to the SNF canister design development.

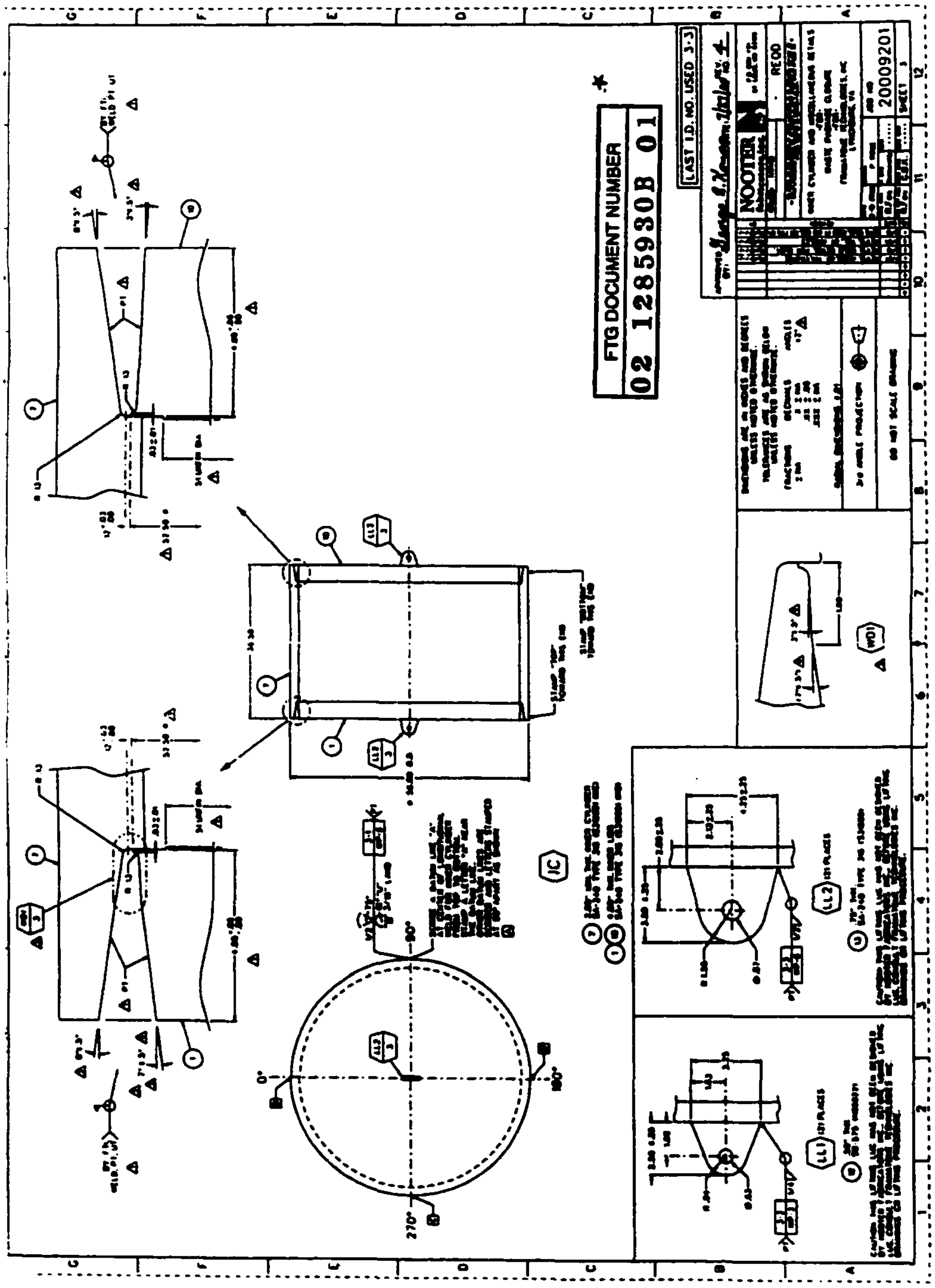
Should there be any questions on this matter, I can be reached at (702) 295-5494.

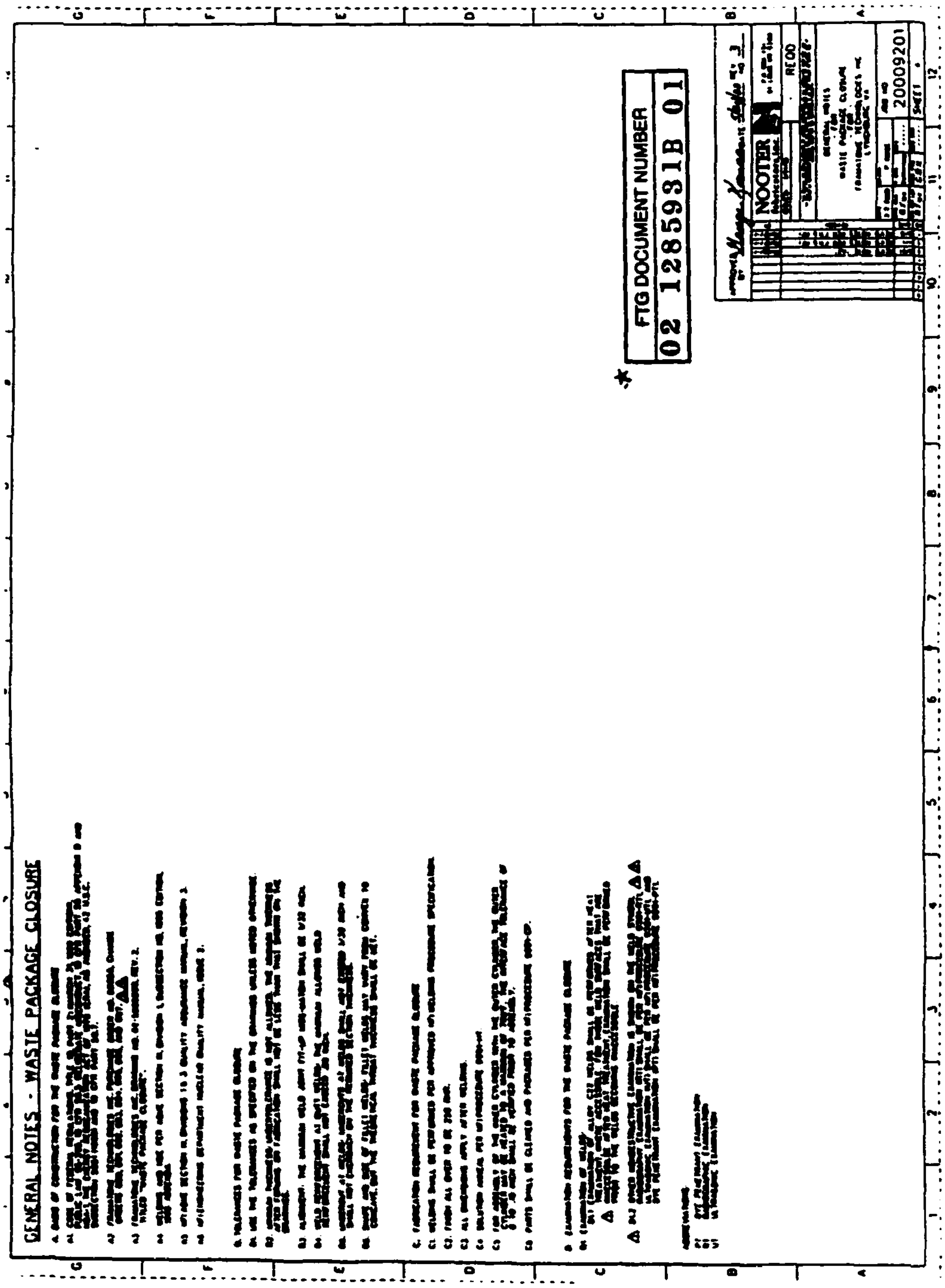
10/30/00
Michael J. Anderson
Manager, Waste Package Design Section

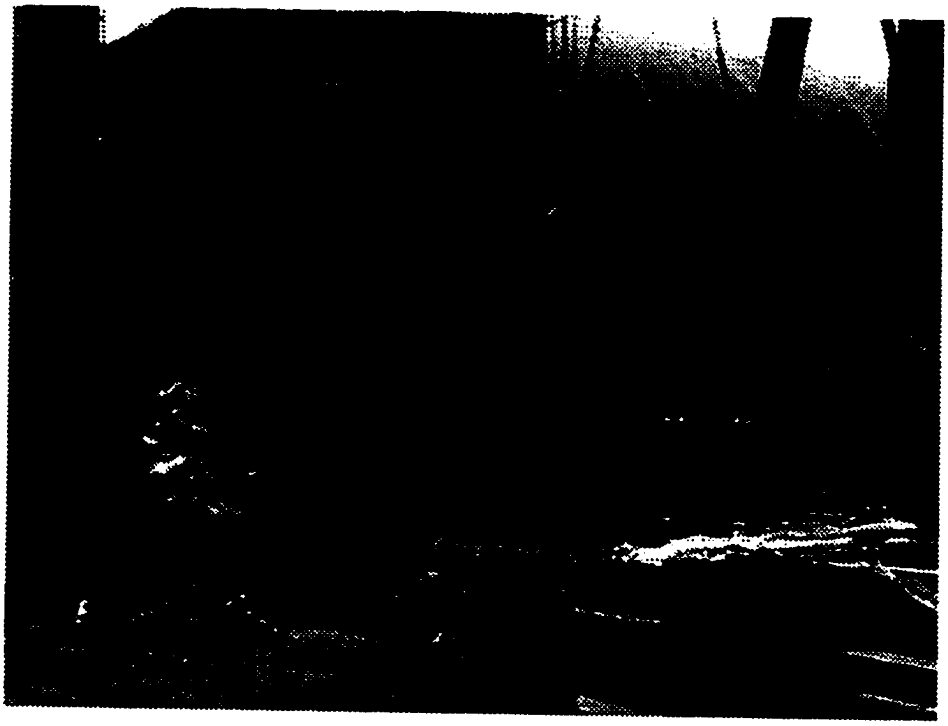
Framatome Cogema Fuels


FTG DOCUMENT NUMBER
02 128592 8B 01
LAST I.D. NO. USED 1-5
NOOTER
20009201
ASSEMBLY VIEW
0°
90°
180°
270°


FTG DOCUMENT NUMBER
02 1285929B 01
LAST I.D. NO. USED 2-9
NOOTER
20009201
D2
OC
0°
90°
180°
270°

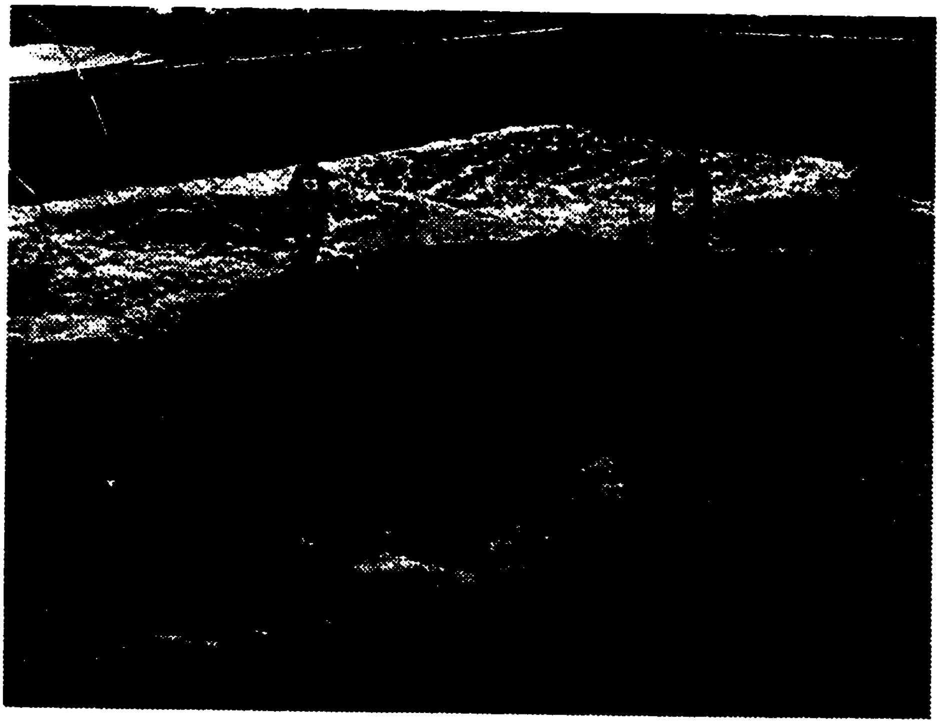

FTG DOCUMENT NUMBER
02 1285930B 01
LAST I.D. NO. USED 3-3
NOOTER
20009201


GENERAL NOTES - WASTE PACKAGE CLOSURE
FTG DOCUMENT NUMBER
02 1285931B 01
NOOTER
20009201



SNF Canister Mock-up Picture (Canister is being removed from the furnace)

SNF Canister Mock-up Picture (Canister is being quenched)



SNF Canister Mock-up Picture (Canister is being quenched)

22176 (3/96)

FRAMATOME TECHNOLOGIES

CERTIFICATE OF CONFORMANCE
(SAFETY-RELATED EQUIPMENT & SERVICES)

Customer/Plant Site: YUCCA MT. Data Pkg. No.: 23-5009877-00

Customer Order No.: NOT ISSUED Customer C.O. No.(s): N/A

FTI Technical Document No.: 50-5007991-00, 50-1182272-00

FTI Contract No.: 3992000 Task No.: N/A

FTI Order No.: N/A FTI C.O. No.(s): N/A

FTI Quality Assurance Program 56-1201212 Rev. 04

Equipment or Service Description:

Quantity Shipped	Description	Part / Mark No.
1	Waste Package Mockup with 4 Welded Lids	N/A
50 LBS	0.045 DIA. SFA 5.14 ERNiCrMo-10	N/A
150 LBS	0.045 DIA. SFA 5.9 ER316L	N/A
		N/A
		N/A

Framatome Technologies, hereby certifies that the items or services listed above are furnished in accordance with the applicable codes, specifications and purchase order requirements unless otherwise noted below.

This QA data package has been reviewed by FTI QA and found acceptable, except as noted below. Nonconformance to referenced requirements may result in equipment being released to ship in a QA hold status by FTI QA.

Nonconformance(s) to requirements:

N/A

Nonconformance(s) will be / was resolved by:

N/A

Revision / Description:

N/A

Woodrow W. Moody Jr. 9/27/2000

FTI Quality Assurance Date

NOOTER
fabricators, inc

CERTIFICATE OF CONFORMANCE

Nooter Fabricators, Inc.
1400 South Third St.
St. Louis, Missouri, 63104

Customer Name: Framatome

Customer P.O. No. 88855 Revision No. 00000010 Line Item No. 1

Component Description:

(1) Waste Package Closure in accordance with Framatome Technologies Inc. Drawing 02-5006890E-01 and the requirements of the Purchase Order.

We certify that the material and workmanship of the above referenced component(s) conform(s) to all the requirements of the above referenced Purchase Order and was controlled in accordance with Nooter Fabricators, Inc. Quality System Manual, Revision 4, dated April 17, 2000.

Name: [illegible]

Position: Q.A. Engineer Date: 09/05/2000

[illegible] South Third Street • [illegible]
Mailing Address [illegible]
Telephone [illegible]

PURCHASE ORDER
for
MATERIAL

REVISION LOG		
Rev. No.	**Description of Revision**	**Date**
0	Initial Submittal of Documents	

NOOTER

'abricators, inc.

PO Box 451
St. Louis, Missouri 63166
Telephone (314) 621-6000
Fax (314) 421-7760
E-mail sales@nooter.com

PURCHASE ORDE

DATE 04/27/2000
P.O NO 9201 REV :
PAGE 1
BUYER

VENDOR CUSTOMER MATERIAL

,

2400

SHIP TO 1500 SOUTH SECOND STREET
ST. LOUIS. MO
63104

FREIGHT	SHIP DATE	DOCUMENTATION	JOB NO.	REQUESTED BY
ALLOWED	04272000	FURNISH MATERIAL TEST REPORTS WITH SHIPMENT	9201	PESKORSE/MINCEMEYER

ITEM	QUANTITY	DESCRIPTION	U M NO	PRICE
		** R E V I S I O N # 1 **		
		REVISION TO ADD ITEMS 3 AND 4 TO THIS ORDER.		
		** THIS ORDER SHOULD NOW READ AS FOLLOWS: **		
		* * NFI SECTION III QUALITY SYSTEM APPLIES * *		
		* CUSTOMER MATERIAL *		
		MILL TEST REPORTS REQUIRED		
		SB-575 UNS N06022 HAST C-22 FURNISHED IN ACCORDANCE WITH ATTACHED FRAMATOME TECHNOLOGIES INC. PURCHASE ORDER 86206. CHANGE ORDER 3, DATED 2/21/00. **		
1	2	1.5" X 96.5" X 200" ITEM #2 ON FRAMATOME PURCHASE ORDER.	2	EA

APPROVED

QUALITY ASSURANCE

BY [signature]

DATE 04/27/2000

* * * C O N T I N U E D * * * * * * * *

INVOICE IN DUPLICATE

NOOTER FABRICATORS, INC.

PER [signature]

NOOTER

Fabricators, inc.

PO Box 451
St Louis, Missouri 63166
Telephone (314) 621-6000
Fax (314) 421-7760
E-mail sales@nooter.com

PURCHASE ORDE

DATE 04/27/2000
PO NO 9201 REV 1
PAGE 2
BUYER

VENDOR CUSTOMER MATERIAL

,

2400

SHIP TO 1500 SOUTH SECOND STREET
ST. LOUIS. MO
63104

FREIGHT	SHIP DATE	DOCUMENTATION	JOB NO.	REQUESTED BY
ALLOWED	04272000	FURNISH MATERIAL TEST REPORTS WITH SHIPMENT	9201	PESKORSE/MINCEMEYER

ITEM	QUANTITY	DESCRIPTION	BTM NO	PRICE
		******** CONTINUED ********		
2	1	2" X 37" X 207" ITEM #6 ON FRAMATOME PURCHASE ORDER.	3	EA
		SA-240-316 STAINLESS STEEL FURNISHED IN ACCORDANCE WITH FRAMATOME TECHNOLOGIES PURCHASE ORDER 86156, CHANGE ORDER 2, DATED 4/26/00. **		
3	1	4.5" X 61" X 180" ITEM #2 ON FRAMATOME PURCHASE ORDER	1	EA
4	1	2.25" X 66" X 210" ITEM #1 ON FRAMATOME PURCHASE ORDER	7	EA
		THIS PURCHASE ORDER IS FOR THE SOLE PURPOSE OF		

INVOICE IN DUPLICATE

******** CONTINUED ********

NOOTER FABRICATORS, INC.

PER [signature]

NOOTER

^ıbricators, inc.

PO Box 451
St. Louis, Missouri 63166
Telephone (314) 621-6000
Fax (314) 421-7760
E-mail sales@nooter.com

PURCHASE ORDE

DATE 04/27/2000
P.O. NO. 9201 REV 1
PAGE 3
BUYER

VENDOR CUSTOMER MATERIAL

,

2400

SHIP TO 1500 SOUTH SECOND STREET
ST. LOUIS. MO
63104

FREIGHT	SHIP DATE	DOCUMENTATION	JOB NO.	REQUESTED BY
ALLOWED	04272000	FURNISH MATERIAL TEST REPORTS WITH SHIPMENT	9201	PESKORSE/MINCEMEYER

ITEM	QUANTITY	DESCRIPTION	B.M. NO	PRICE
		• • • • • • • • C O N T I N U E D • • • • • • • •		
		RECEIVING CUSTOMER FURNISHED MATERIAL. NFI HAS NO DIRECT CONTACT WITH THE MATERIAL SUPPLIER. RESPONSIBILITY FOR MATERIAL QUALITY IS HELD BY THE ISSUER OF THE ATTACHED PURCHASE ORDER.		
		NO SALES TAX APPLICABLE. MISSOURI RESALE NUMBER: 16551435		

INVOICE IN DUPLICATE

NOOTER FABRICATORS, INC.

PER ______

NOOTER FABRICATORS, INC.
Subcontracted On-Site Calibration Services Verification

Supplier of Calibration Services: Honeywell Inc.
Applicable NFI Purchase Order Number(s): P.O. 33389

Description of Measuring and Test Equipment to be Calibrated:

- [ ] Extensometers
- [ ] Hardness Testers
- [x] Heat Treat Temperature Recorders
- [ ] Impact Testers
- [ ] Optical Comparator
- [ ] Tensile Testers
- [ ] Other: ________
- [ ] Other: ________

APPROVED
QUALITY ASSURANCE
BY [signature]
DATE 04/06/2000

The following items are required for subcontracted calibration activities (Check-off when completed and retain verifying documentation):

- [x] Review of Quality Program of Calibration Services Subcontractor
  Program: 917 CalSys dated Sept. 17, 1996 Revision: 1
  Program: Hardware Support Service Program Revision: 12/01/99
- [x] Review of Calibration Procedure(s) of Subcontractor. Identify Procedures:
  Procedure: Calibration Procedure Manual; July 26, 1996
  Procedure: ________
- [x] Review of Qualification Records of Subcontractor Personnel. Identify Personnel:
  Name: Robert Layton, Level III Certified Control Systems Technician (CCST)
  Certificate No. 10478; Expiration Date March 15, 2002
- [x] Review of Calibration Records of Standards. Identify Standards and NIST Trace:
  Standard: 7100909 Model 2020
  Standard: ________
- [x] Sign Calibration Records
- [x] Forward Calibration Records to QA for Review

I certify that the above checked requirements have been met; and I have witnessed the calibration activities and have found them to be carried out in a satisfactory manner.

Signed: [signature] Date: 03/24/2000

QA Review: [signature] Date: 3/24/00

Form 81-108-1

Honeywell

Industrial Automation and Control FIELD SERVICE & MATERIAL REPORT	Project Number 56410		Task Number 820-39374		RID Number 81278	
Persons Contacted: Bill Luther	Page 1 of 4				Check routine or Trouble below	
Location: 917 St. Louis	Call Date: 2/10/00	Car Miles: 137	Expenses:	ST Hours: 16.0	OT Hours:	H/S Hours:	Routine Call: X	Trouble Call:
Service Representative: Bob Layton	Approved By:		Customer Order No.: PO# 33389' Rev. 0		Complete: X	Incomplete:
Time Call Rec. By Dispatch:	Time Tech Called Customer:	Time Tech on Site:	M.T.T.R.:		T.T.T.R.:	

Customer Name and Address	Nooter Fabricators Inc.	1400 S. Second Street St. Louis, MO 63104

Completed Scheduled Preventative Maintenance and Calibration for February per Service Agreement dated 12/01/99.

Equipment is being calibrated per Honeywell Calibration Procedure 917-CalProc July 26, 1996

Customer reports no problems at this time.

Bill Luther requests that instrument #3375, a Honeywell Temperature Recorder with Serial No. Z4723311006 be permanently removed from Calibration Schedule.

Bill Luther requests that instrument #3367, a Honeywell Temperature Recorder with Serial No. 7811-R-05246001 be permanently removed from Calibration Schedule.

APPROVED
QUALITY ASSURANCE
BY [signature]
DATE 02/24/2000

List Model and Serial Number of Test Equipment Used:

Honeywell 2030 Calibrator   Serial No. 7100909   Cal Date Jan 18, 2000   Due Date Jan 18, 2001

Test Equipment being used is certified per Honeywell Procedure 917-CalSys Rev-1 Sept 17, 1996.

Invoice Parts Used:

None Used

The amounts shown below will appear on your invoice for this service call.
The amounts shown below do not include any required governmental taxes which may be added to the invoice.

Total Labor	Total Material	Total Software	Total Other (T&L Expenses, Freight etc.)	Total Invoice Amount (Does not include taxes)

THE SERVICE REQUESTED BY US HAS BEEN HANDLED BY YOUR REPRESENTATIVE IN A SATISFACTORY MANNER

Customer Signature [signature]   Title Q.A. Engineer   Date 02/10/2000

Robert P. Layton

#F3073(5/96)

Honeywell

Industrial Automation and Control FIELD SERVICE & MATERIAL REPORT			Project Number 56410		Task Number 820-39374		RID Number 81278	
Persons Contacted Bill Luther			Page 2 of 4				Check routine or Trouble below	
Location 917 St. Louis	Call Date 2/10/00	Car Miles	Expenses	ST Hours	OT Hours	D/T Hours	Routine Call X	Trouble Call
Service Representative Bob Layton		Approved By			Customer Order No.		Complete X	Incomplete
Time Call Rec. By Dispatch	Time Tech Called Customer		Time Tech on Site		M.T.T.R.		T.T.T.R.	

Customer Name and Address	Nooter Fabricators Inc.	1400 S. Second Street St. Louis, MO 63104

Description	Calibration as Found						Calibration as Left						Tolerance	Out of Tolerance	
	Input	/ Reading	Input	/ Reading	Input	/ Reading	Input	/ Reading	Input	/ Reading	Input	/ Reading	+/-	Found	As Left
#1 Furnace Honeywell Temperature Recorder Instrument No. 6160 Serial No. 9709-72106344-055-16															
Channel #1	100	101	1200	1201	2300	2301	100	101	1200	1201	2300	2301	3		
Channel #5	100	101	1200	1200	2300	2301	100	101	1200	1200	2300	2301	3		
Channel #9	100	101	1200	1201	2300	2302	100	101	1200	1201	2300	2302	3		
Channel #16	100	102	1200	1202	2300	2302	100	102	1200	1202	2300	2302	3		
#2 Furnace Honeywell Temperature Recorder Instrument No. 6161 Serial No. 9709-72106344-055-12															
Channel #1	100	101	1200	1200	2300	2301	100	101	1200	1200	2300	2301	3		
Channel #5	100	101	1200	1200	2300	2300	100	101	1200	1200	2300	2300	3		
4 Furnace Honeywell Temperature Recorder Instrument No. 6162 Serial No. 9709-72106344-055-06															
Channel #1	100	100	1200	1200	2300	2300	100	100	1200	1200	2300	2300	3		
Channel #5	100	100	1200	1201	2300	2300	100	100	1200	1201	2300	2300	3		
1833 Furnace Honeywell Temperature Recorder Instrument No. 3373 Serial No. STL104															
	100	100	1200	1199	2300	2302	100	100	1200	1199	2300	2302	10		
4278 Furnace Honeywell Temperature Recorder Instrument No. 3368 Serial No. G1003049007															
	100	100	1200	1196	2300	2300	100	100	1200	1196	2300	2300	10		

Notes:

1. Units of Measurement: Temperature= Degrees F (All K Thermocouples except Instrument No. 6164 which is a T Thermocouple)
2.
3.

List Model and Serial Number of Test Equipment Used:

Honeywell 2020 Calibrator   Serial No. 7100909   Cal Date Jan 18, 2000   Due Date Jan 18, 2001

Hamlin Parts Used:

None Used

The amounts shown below will appear on your invoice for this service call.
The amounts shown below do not include any required governmental taxes which may be added to the invoice.

Total Labor	Total Material	Total Software	Total Other (T&L Expenses, Freight etc.)	Total Invoice Amount (Does not include taxes)

THE SERVICE REQUESTED BY US HAS BEEN HANDLED BY YOUR REPRESENTATIVE IN A SATISFACTORY MANNER

Customer Signature: [signature]   Title: Q.A. Engineer   Date: 02/10/2000

[illegible]

Honeywell

Industrial Automation and Control FIELD SERVICE & MATERIAL REPORT	Project Number 56410	Task Number 820-39374	RID Number 81278
Persons Contacted Bill Luther	Page 3 of 4		Check routine or Trouble Below

Location	Call Date	Car Miles	Expenses	ST Hours	OT Hours	H/S Hours	Routine Call	Trouble Call
917 St. Louis	2/10/00						X	

Service Representative	Approved By	Customer Order No.	Complete	Incomplete
Bob Layton			X	

Time Call Rec. By Dispatch	Time Tech Called Customer	Time Tech on Site	M.T.T.R.	T.T.T.R.

Customer Name and Address		
	Nooter Fabricators Inc.	1400 S. Second Street St. Louis, MO 63104

Description	Calibration as Found						Calibration as Left						Tolerance	Out of Tolerance	
	Input	/ Reading	Input	/ Reading	Input	/ Reading	Input	/ Reading	Input	/ Reading	Input	/ Reading	+/-	Found	As Left
Lab Electronics Controls Data Logger Instrument No. 6163 Serial No. 008-1269															
	100	100.5	1200	1199.7	2200	2200.5	100	100.5	1200	1199.7	2200	2200.5	3		
Lab Omega Digital Indicator Instrument No. 6164 Serial No. 702625															
	-200	-199.4	100	100.2	500	500	-200	-199.4	100	100.2	500	500	2		
Lab Yokogawa Temperature Recorder Instrument No. 6165 Serial No. 4370DB107															
	100	101	1200	1201	2300	2301	100	101	1200	1201	2300	2301	3		
Portable Honeywell Temperature Recorder Instrument No. 5999 Serial No. PR231001001															
	100	112	1200	1214	2300	2316	100	100	1200	1198	2300	2299	10	X	
Portable Honeywell Temperature Recorder Instrument No. 3377 Serial No. R7118805001															
	100	100	1200	1199	2300	2300	100	100	1200	1199	2300	2300	10		
Portable Honeywell Temperature Recorder Instrument No. 3372 Serial No. Q4619071002															
	100	100	1200	1199	2300	2300	100	100	1200	1199	2300	2300	10		

Notes:

1. Units of Measurement : Temperature- Degrees F (All K Thermocouples except Instrument No. 6164 which is a T Thermocouple)
2. Instrument No. 3374 has been changed to Instrument No. 5999 because Customer replaced broken door that had number affixed.
3.
4.

List Model and Serial Number of Test Equipment Used:

Honeywell 2020 Calibrator Serial No. 7100909 Cal Date Jan 18, 2000 Due Date Jan 18, 2001

Service Parts Used:

None Used

The amounts shown below will appear on your invoice for this service call.
The amounts shown below do not include any required governmental taxes which may be added to the invoice.

Total Labor	Total Material	Total Software	Total Other (T&L Expenses, Freight etc.)	Total Invoice Amount (Does not include taxes)

THE SERVICE REQUESTED BY US HAS BEEN HANDLED BY YOUR REPRESENTATIVE IN A SATISFACTORY MANNER

Customer Signature [illegible signature] Title Q.A. Engineer Date 02/10/2000

#F3973(8/96)

Honeywell

Industrial Automation and Control FIELD SERVICE & MATERIAL REPORT	Project Number 56410	Task Number 020-39374	RID Number 81278
Persons Contacted: Bill Luther	Page 4 of 4		Check routine or Trouble below

Location	Call Date	Car Miles	Expenses	ST Hours	OT Hours	H/S Hours	Routine Call	Trouble Call
917 St. Louis	2/10/00						X	

Service Representative	Approved By	Customer Order No.	Complete	Incomplete
Bob Layton			X	

Time Call Rec. By Dispatch	Time Tech Called Customer	Time Tech on Site	M.T.T.R.	T.T.T.R.

Customer Name and Address		
	Nester Fabricators Inc.	1400 S. Second Street St. Louis, MO 63104

Description	Calibration as Found						Calibration as Left						Tolerance	Out of Tolerance	
	Input	/ Reading	Input	/ Reading	Input	/ Reading	Input	/ Reading	Input	/ Reading	Input	/ Reading	+/-	Found	As Left
Portable Honeywell Temperature Recorder Instrument No. 3378 Serial No. Q4619071001															
	100	99	1200	1195	2300	2301	100	99	1200	1195	2300	2301	10		
Portable Honeywell Temperature Recorder Instrument No. 3376 Serial No. 854959															
	100	100	1000	1002	1900	1900	100	100	1000	1002	1900	1900	10		
Portable Honeywell Temperature Recorder Instrument No. 6033 Serial No. 9050805761-0001															
Channel #1	100	100	1200	1199	2300	2300	100	100	1200	1199	2300	2300	3		
Channel #5	100	100	1200	1200	2300	2300	100	100	1200	1200	2300	2300	3		
Channel #9	100	100	1200	1199	2300	2300	100	100	1200	1199	2300	2300	3		
Channel #13	100	101	1200	1200	2300	2301	100	101	1200	1200	2300	2301	3		
Channel #17	100	100	1200	1200	2300	2300	100	100	1200	1200	2300	2300	3		
Channel #21	100	100	1200	1200	2300	2300	100	100	1200	1200	2300	2300	3		
Portable Honeywell Temperature Recorder Instrument No. 6034 Serial No. 07794979014															
Channel #1	100	100	1200	1199	2300	2300	100	100	1200	1199	2300	2300	3		
Channel #5	100	100	1200	1199	2300	2300	100	100	1200	1199	2300	2300	3		
Channel #9	100	100	1200	1200	2300	2300	100	100	1200	1200	2300	2300	3		

Notes:

1. Units of Measurement: Temperature- Degrees F (All K Thermocouples except Instrument No. 6164 which is a T Thermocouple)
2.
3.
4.

List Model and Serial Number of Test Equipment Used:

Honeywell 2020 Calibrator Serial No. 7100909 Cal Date Jan 18, 2000 Due Date Jan 18, 2001

Standard Parts Used:

None Used

The amounts shown below will appear on your invoice for this service call.
The amounts shown below do not include any required governmental taxes which may be added to the invoice.

Total Labor	Total Material	Total Software	Total Other (T&L Expenses, Freight etc.)	Total Invoice Amount (Does not include taxes)

THE SERVICE REQUESTED BY US HAS BEEN HANDLED BY YOUR REPRESENTATIVE IN A SATISFACTORY MANNER

Customer Signature [signature] Title Q.A. Engineer Date 02/10/2000

(F3977X(8/96))

NOOTER FABRICATORS, INC.
Subcontracted On-Site Calibration Services Verification

Supplier of Calibration Services: HONEYWELL, INC.
Applicable NFI Purchase Order Number(s): P.O. 33389

Description of Measuring and Test Equipment to be Calibrated:

- [ ] Extensometers
- [ ] Hardness Testers
- [x] Heat Treat Temperature Recorders
- [ ] Impact Testers
- [ ] Optical Comparator
- [ ] Tensile Testers
- [ ] Other: ______
- [ ] Other: ______

APPROVED
QUALITY ASSURANCE
BY [signature]
DATE 09/06/2000

The following items are required for subcontracted calibration activities (Check-off when completed and retain verifying documentation):

- [x] Review of Quality Program of Calibration Services Subcontractor
  Program: 917 CalSys dated Sept. 17, 1996 Revision: 1
  Program: Hardware Support Service Program Revision: 12/01/99
- [x] Review of Calibration Procedure(s) of Subcontractor. Identify Procedures:
  Procedure: Calibration Procedure Manual; July 26, 1996
- [x] Review of Qualification Records of Subcontractor Personnel. Identify Personnel:
  Name: Robert Layton, Level III Certified Control Systems Technician (CCST)
  Certificate No. 10478; Expiration Date: March 15, 2002
- [x] Review of Calibration Records of Standards. Identify Standards and NIST Trace:
  Standard: 7100909 Model 2020
- [x] Sign Calibration Records
- [x] Forward Calibration Records to QA for Review

I certify that the above checked requirements have been met; and I have witnessed the calibration activities and have found them to be carried out in a satisfactory manner.

Signed: [signature] Date: 06/07/2000
QA Review: [signature] Date: 06/08/2000

Form 51-108-1

Honeywell

Industrial Automation and Control FIELD SERVICE & MATERIAL REPORT			Project Number 56410		Task Number 820-39374		RID Number 113249	
Persons Contacted Bill Luther			Page 1 of 5				Check routine or Trouble Below	
Location 917 St. Louis	Call Date 5/31/00	Car Miles	Expenses	ST Hours	OT Hours	H/S Hours	Routine Call X	Trouble Call
Service Representative Bob Layton (314)-569-5403		Approved By			Customer Order No. PO# 33389 Rev. 0		Complete X	Incomplete
Time Call Rec. By Dispatch	Time Tech Called Customer		Time Tech on Site		M.T.T.R.		T.T.T.R.	

Customer Name and Address	Nooter Fabricators Inc.	1400 S. Second Street St. Louis, MO 63104

Completed Scheduled Preventative Maintenance and Calibration for May per Service Agreement dated 12/01/99.

Equipment is being calibrated per Honeywell Calibration Procedure 917-CalProc July 26, 1996

Customer reports no problems at this time.

APPROVED
QUALITY ASSURANCE
BY
DATE 09/06/2000

List Model and Serial Number of Test Equipment Used:

Honeywell 2020 Calibrator Serial No. 7100909 Cal Date Jan 18, 2000 Due Date Jan 18, 2001

Test Equipment being used is certified per Honeywell Procedure 917-CalSys Rev-1 Sept 17, 1996.

Itemize Parts Used:

None Used

The amounts shown below will appear on your invoice for this service call.
The amounts shown below do not include any required governmental taxes which may be added to the invoice.

Total Labor	Total Material	Total Software	Total Other (T&L Expenses, Freight etc.)	Total Invoice Amount (Does not include taxes)

THE SERVICE REQUESTED BY US HAS BEEN HANDLED BY YOUR REPRESENTATIVE IN A SATISFACTORY MANNER

31 5/31/00

Customer Signature ______ Title Q.A. Engineer Date 05/31/00

Honeywell

Industrial Automation and Control FIELD SERVICE & MATERIAL REPORT	Project Number 56410	Task Number 820-39374	RID Number 113249
Persons Contacted: Bill Larther	Page 2 of 5		Check routine or Trouble Below

Location	Call Date	Car Miles	Expenses	ST Hours	OT Hours	H/S Hours	Routine Call	Trouble Call
917 St. Louis	5/8/00						X	

Service Representative	Approved By	Customer Order No.	Complete	Incomplete
Bob Layton (314)-569-5403			X	

Time Call Rec. By Dispatch	Time Tech Called Customer	Time Tech on Site	M.T.T.R.	T.T.T.R.

Customer Name and Address	Nooter Fabricators Inc.	1400 S. Second Street St. Louis, MO 63104

Description	Calibration as Found						Calibration as Left						Tolerance	Out of Tolerance	
	Input	Reading	Input	Reading	Input	Reading	Input	Reading	Input	Reading	Input	Reading	+/-	As Found	As Left
#1 Furnace Honeywell Temperature Recorder Instrument No. 6160 Serial No. 9709-72106344-055-16															
Channel #1	100	101	1200	1200	2300	2301	100	101	1200	1200	2300	2301	3°F		
Channel #5	100	101	1200	1200	2300	2301	100	101	1200	1200	2300	2301	3°F		
Channel #9	100	101	1200	1201	2300	2301	100	101	1200	1201	2300	2301	3°F		
Channel #16	100	102	1200	1201	2300	2302	100	102	1200	1201	2300	2302	3°F		
#2 Furnace Honeywell Temperature Recorder Instrument No. 6161 Serial No. 9709-72106344-055-12															
Channel #1	100	101	1200	1202	2300	2303	100	101	1200	1202	2300	2303	3°F		
Channel #5	100	101	1200	1201	2300	2302	100	101	1200	1201	2300	2302	3°F		
#4 Furnace Honeywell Temperature Recorder Instrument No. 6162 Serial No. 9709-72106344-055-06															
Channel #1	100	100	1200	1200	2300	2300	100	100	1200	1200	2300	2300	3°F		
Channel #5	100	100	1200	1200	2300	2300	100	100	1200	1200	2300	2300	3°F		
1833 Furnace Honeywell Temperature Recorder Instrument No. 3373 Serial No. STL104															
	100	100	1200	1200	2300	2301	100	100	1200	1200	2300	2301	10°F		
4278 Furnace Honeywell Temperature Recorder Instrument No. 3368 Serial No. G1003049007															
	100	100	1200	1198	2300	2300	100	100	1200	1100	2300	2300	10°F		

Notes:

1. Units of Measurement: Temperature= Degrees F (All K Thermocouples except Instrument No. 6164 which is a T Thermocouple)
2.
3.

List Model and Serial Number of Test Equipment Used:

Honeywell 2020 Calibrator Serial No. 7100909 Cal Date Jan 18, 2000 Due Date Jan 18, 2001

Test Equipment being used is certified per Honeywell Procedure 917-CalSys Rev-1 Sept 17, 1996.

Service Parts Used:

None Used

The amounts shown below will appear on your invoice for this service call.
The amounts shown below do not include any required governmental taxes which may be added to the invoice.

Total Labor	Total Material	Total Software	Total Other (T&L Expenses, Freight etc.)	Total Invoice Amount (Does not include taxes)

THE SERVICE REQUESTED BY US HAS BEEN HANDLED BY YOUR REPRESENTATIVE IN A SATISFACTORY MANNER.

Customer Signature: [signature] Title: Q.A. Engineer Date: 05/31/00

Honeywell

Industrial Automation and Control	Project Number	Task Number	RID Number
FIELD SERVICE & MATERIAL REPORT	56410	820-39374	113249

Persons Contacted	Page	Check routine or Trouble Below
Bill Luther	3 of 5	

Location	Call Date	Car Miles	Expenses	ST Hours	OT Hours	H/S Hours	Routine Call	Trouble Call
917 St. Louis	5/31/00						X	

Service Representative	Approved By	Customer Order No.	Complete	Incomplete
Bob Layton (314)-569-5403			X	

Time Call Rec. By Dispatch	Time Tech Called Customer	Time Tech on Site	M.T.T.R.	T.T.T.R.

Customer Name and Address		
	Nooter Fabricators Inc.	1400 S. Second Street St. Louis, MO 63104

Description	Calibration as Found			Calibration as Left			Tolerance	Out of Tolerance	
	Input / Reading	Input / Reading	Input / Reading	Input / Reading	Input / Reading	Input / Reading	+/-	As Found	As Left
Lab Electronics Controls Data Logger . Instrument No. 6163 Serial No. 008-1269									
	100.0 / 98.5	1200.0 / 1198.5	2200.0 / 2198.4	100.0 / 98.5	1200.0 / 1198.5	2200.0 / 2198.4	3°F		
Lab Omega Digital Indicator Instrument No. 6164 Serial No. 702625									
	-200 / -199	100 / 100	500 / 500	-200 / -199	100 / 100	500 / 500	2°F		
Lab Yokogawa Temperature Recorder Instrument No. 6165 Serial No. 4370DB107									
	100 / 101	1200 / 1200	2300 / 2300	100 / 101	1200 / 1200	2300 / 2300	3°F		
Portable Honeywell Temperature Recorder Instrument No. 5999 Serial No. FB231001001									
	100 / 90	1200 / 1190	2300 / 2288	100 / 101	1200 / 1199	2300 / 2300	10°F	X	
Portable Honeywell Temperature Recorder Instrument No. 3377 Serial No. R7118805001									
	100 / 100	1200 / 1200	2300 / 2300	100 / 100	1200 / 1200	2300 / 2300	10°F		
Portable Honeywell Temperature Recorder Instrument No. 3372 Serial No. Q4619071002									
	100 / 100	1200 / 1199	2300 / 2300	100 / 100	1200 / 1199	2300 / 2300	10°F		

Notes :

1. Units of Measurement : Temperature= Degrees F (All K Thermocouples except Instrument No. 6164 which is a T Thermocouple)
2. Instrument No. 3374 has been changed to Instrument No. 5999 because Customer replaced broken door that had number affixed.
3.

List Model and Serial Number of Test Equipment Used:

Honeywell 2020 Calibrator Serial No. 7100909 Cal Date Jan 18, 2000 Due Date Jan 18, 2001

Test Equipment being used is certified per Honeywell Procedure 917-CalSys Rev-1 Sept 17, 1996.

Number Parts Used:

None Used

The amounts shown below will appear on your invoice for this service call.
The amounts shown below do not include any required governmental taxes which may be added to the invoice.

Total Labor	Total Material	Total Software	Total Other (T&L Expenses, Freight etc.)	Total Invoice Amount (Does not include taxes)

THE SERVICE REQUESTED BY US HAS BEEN HANDLED BY YOUR REPRESENTATIVE IN A SATISFACTORY MANNER

Customer Signature [illegible] Title Q.A. Engineer Date 05/31/00

Honeywell

Industrial Automation and Control	Project Number	Task Number	RID Number
FIELD SERVICE & MATERIAL REPORT	56410	820-39374	113249

Persons Contacted: Bill Lather

Page 4 of 5

Check routine or Trouble Below

Location	Call Date	Car Miles	Expenses	ST Hours	OT Hours	H/S Hours	Routine Call	Trouble Call
917 St. Louis	5/31/00						X	

Service Representative	Approved By	Customer Order No.	Complete	Incomplete
Bob Layton (314)-569-5403			X	

Time Call Rec. By Dispatch	Time Tech Called Customer	Time Tech on Site	M.T.T.R.	T.T.T.R.

Customer Name and Address: Nooter Fabricators Inc., 1400 S. Second Street, St. Louis, MO 63104

Description	Calibration as Found						Calibration as Left						Tolerance	Out of Tolerance	
	Input	Reading	Input	Reading	Input	Reading	Input	Reading	Input	Reading	Input	Reading	+/-	As Found	As Left
Portable Honeywell Temperature Recorder Instrument No. 3378 Serial No. Q4619071001															
	100	99	1200	1195	2300	2300	100	99	1200	1195	2300	2300	10°F		
Portable Honeywell Temperature Recorder Instrument No. 3376 Serial No. 854959															
	100	100	1000	999	1900	1899	100	100	1000	999	1900	1899	10°F		
Portable Honeywell Temperature Recorder Instrument No. 6033 Serial No. 9050805761-0001															
Channel #1	100	99	1200	1199	2300	2299	100	99	1200	1199	2300	2299	3°F		
Channel #5	100	100	1200	1199	2300	2300	100	100	1200	1199	2300	2300	3°F		
Channel #9	100	100	1200	1199	2300	2300	100	100	1200	1199	2300	2300	3°F		
Channel #13	100	100	1200	1200	2300	2300	100	100	1200	1200	2300	2300	3°F		
Channel #17	100	100	1200	1200	2300	2300	100	100	1200	1200	2300	2300	3°F		
Channel #21	100	100	1200	1199	2300	2300	100	100	1200	1199	2300	2300	3°F		
Portable Honeywell Temperature Recorder Instrument No. 6034 Serial No. O77949790014															
Channel #1	100	99	1200	1199	2300	2299	100	99	1200	1199	2300	2299	3°F		
Channel #5	100	99	1200	1200	2300	2300	100	99	1200	1200	2300	2300	3°F		
Channel #9	100	101	1200	1200	2300	2300	100	101	1200	1200	2300	2300	3°F		

Notes:

1. Units of Measurement: Temperature= Degrees F (All K Thermocouples except Instrument No. 6164 which is a T Thermocouple)
2.
3.

List Model and Serial Number of Test Equipment Used:

Honeywell 2020 Calibrator Serial No. 7100909 Cal Date Jan 18, 2000 Due Date Jan 18, 2001

Test Equipment being used is certified per Honeywell Procedure 917-CalSys Rev-1 Sept 17, 1996.

Number Parts Used:

None Used

The amounts shown below will appear on your invoice for this service call.
The amounts shown below do not include any required governmental taxes which may be added to the invoice.

Total Labor	Total Material	Total Software	Total Other (T&L Expenses, Freight etc.)	Total Invoice Amount (Does not include taxes)

THE SERVICE REQUESTED BY US HAS BEEN HANDLED BY YOUR REPRESENTATIVE IN A SATISFACTORY MANNER

Customer Signature: [illegible] Title: Q.A. Engineer Date: 05/31/00

6F0073(3/00)

Honeywell

Industrial Automation and Control	Project Number	Task Number	RID Number
FIELD SERVICE & MATERIAL REPORT	56410	820-39374	113249

Persons Contacted		Check routine or Trouble Below
Bill Luther	Page 5 of 5	

Location	Call Date	Car Miles	Expenses	ST Hours	OT Hours	H/S Hours	Routine Call	Trouble Call
917 St. Louis	5/8/00						X	

Service Representative	Approved By	Customer Order No.	Complete	Incomplete
Bob Layton (314)-569-5403			X	

Time Call Rec. By Dispatch	Time Tech Called Customer	Time Tech on Site	M.T.T.R.	T.T.T.R.

Customer Name and Address		
	Nooter Fabricators Inc.	1400 S. Second Street St. Louis, MO 63104

Description	Calibration as Found: Input / Reading	Input / Reading	Input / Reading	Calibration as Left: Input / Reading	Input / Reading	Input / Reading	Tolerance +/-	Out of Tolerance: As Found	As Left
Portable Omega Handheld Temperature Indicator Model No. HH21 Serial No. T-116317 (NC5513)									
	100.0 100.0	1200.0 1200.1	2300.0 2299.3	100.0 100.0	1200.0 1200.1	2300.0 2299.3	6°F		
Portable Omega Handheld Temperature Indicator Model No. HH200A Serial No. 20022 (NC 5555)									
	100.0 100.7	1200 1200	2300 2302	100.0 100.7	1200 1200	2300 2302	6°F		
Portable Omega Handheld Temperature Indicator Model No. HH200A Serial No. 20025 (NC 5556)									
	100.0 101.3	1200 1201	2300 2302	100.0 101.3	1200 1201	2300 2302	6°F		

Notes:

1. Units of Measurement: Temperature= Degrees F (All K Thermocouples except Instrument No. 6164 which is a T Thermocouple)
2. Instrument No. 3374 has been changed to Instrument No. 5999 because Customer replaced broken door that had number affixed.
3.

List Model and Serial Number of Test Equipment Used:

Honeywell 2020 Calibrator Serial No. 7100909 Cal Date Jan 18, 2000 Due Date Jan 18, 2001

Test Equipment being used is certified per Honeywell Procedure 917-CalSys Rev-1 Sept 17, 1996.

Number Parts Used:

None Used

The amounts shown below will appear on your invoice for this service call.
The amounts shown below do not include any required governmental taxes which may be added to the invoice.

Total Labor	Total Material	Total Software	Total Other (T&L Expenses, Freight etc.)	Total Invoice Amount (Does not include taxes)

THE SERVICE REQUESTED BY US HAS BEEN HANDLED BY YOUR REPRESENTATIVE IN A SATISFACTORY MANNER

Customer Signature: [illegible signature] Title Q.A. Engineer Date 05/31/00

FORMING PROCEDURE FOR CYLINDERS		
	PROCEDURE:	9201FRM1
	PAGE:	1 OF 2
	REVISION:	0
	DOCUMENT PUBLISHER:	TDT
	APPROVED.	EIM
	QA APPROVED:	
	EFFECTIVE DATE:	03/16/2000

NOOTER fabricators, inc.

1.0 SCOPE:

This procedure describes the process utilized to form cylinders from plate for job 20009201

2.0 REFERENCE: ASME Section III Divisions 1 & 3 Quality Assurance Manual
Section 9 "Control of Special Processes"
Framatome's Purchase Order 88855 dated 02/14/00

3.0 Definition: None

4.0 Procedure:

4.1 All items shall be cold formed.

4.2 Material being formed is SB-575-UNS N06022 and SA 240 Type 316 (S31600)(NG)

4.3 Forming procedure qualification tests per paragraph NB-4213 are not required since the material is exempt from impact testing per paragraph NB-4213.1 (c).

4.4 Minimum material thickness shall be as shown on the fabrication drawings.

4.5 The machine operator shall visually examine plate edges prior to forming, checking for potential stress risers. Questionable areas must be blend ground with adjacent material to eliminate the risk of material failure during forming. The operator shall form the cylinder to the size shown on the departmental requisition.

4.6 When tacks are used to secure the plate edges they shall be made on the outside surface at the bottom of the bevel by qualified welders using approved job specific weld procedures.

Use of temporary attachments is not permitted; however, if temporary attachments must be used, permission must be obtained from the Quality Assurance Department before their use.

4.7 The machine operator shall perform a preliminary examination of the formed material for diameter variation and thickness to assure the formed material can be released for further processing.

The maximum acceptable limits for diameter variation at all cross sections except those with openings, shall be determined as follows. The difference in inches between the maximum and minimum diameters at any cross section shall not exceed the smaller of

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(D+50)/200 and D/100, where D is the nominal inside diameter, in inches, at the cross section under consideration. If measured on the outside, the diameters shall be corrected for plate thickness at the cross section under consideration.

4.8 After welding the longitudinal seam, the cylinder shall be examined to verify it satisfies the job requirements. If required, rework the cylinder until it meets the acceptable limits for diameter variation. Cylinders meeting the acceptance criteria shall be forwarded to the next operation.

4.9 Training

Machine operators shall be trained to use standard forming skills common to the pressure vessel industry through on the job training.

5.0 Attachments

None

Procedure 9201HT

NOOTER Fabricators, Inc.	1103 PROCEDURE FOR 103 20000301	PROCEDURE: 9201HT
		PAGE: 1 OF [illegible]
		REVISION: [illegible]
		DOCUMENT PUBLISHER: [illegible]
		APPROVED: [illegible]
		QA APPROVED: [illegible]
		EFFECTIVE DATE: 03/18/2000

N... extract
DSS
9/15/00

1.0 SCOPE

This procedure describes the equipment and defines the requirements for:

A. Full solution annealing of a Hastelloy C-22 waste package closure.

B. Intermediate quench annealing of parts following forming or welding operations as specified in the fabrication procedure.

2.0 REFERENCES: ASME SB-575 UNS N06022

3.0 DEFINITIONS: None

4.0 PROCEDURE

4.1 Preparation for Heat Treatment

Prior to heat treatment, all surfaces (both inside and outside) shall be thoroughly cleaned to remove oil, paint, grease, etc. Local areas may be cleaned, as needed, with a chloride and sulphur free solvent which will not leave a residue.

4.2 Equipment

The parts will be heat treated in an enclosed furnace of the car bottom, over-firing type, operating at a slight positive pressure.

4.3 Burners

4.3.1 Burners are natural gas fired and operate on the excess air side of the stoichiometric ratio.

4.3.2 The burners are baffled so as to avoid direct flame impingement on the furnace charge.

4.4 Fuel

The fuel shall be natural gas. Maximum sulfur limit is 0.200 gr/mcf.

FTG DOCUMENT NUMBER
03 1289763 00

4.5 Temperature Recording

4.5.1 The furnace is equipped with a multipoint strip chart recorder (Honeywell Electronik Model 15), which prints out thermocouple temperatures of the item being heat treated.

4.5.2 The strip chart recorder and furnace controls are maintained and calibrated on a regular basis by an outside contractor. Copies of the calibration certificates will be furnished.

4.6 Thermocouples

4.6.1 Temperatures are measured by Chromel-Alumel (Type K) thermocouples. The hot junction, as well as all leads, are Chromel-Alumel.

4.6.2 Thermocouples will be placed directly on the work so that the temperature recorded will be actual work temperatures, not furnace temperatures. One thermocouple will be welded on the part to monitor cooling temperature during the quench.

4.7 Quenching

4.7.1 Immersion quenching

4.7.1.1 Parts shall be quenched by immersion in water in a quench tank. Compressed air is forced through spargers built into the bottom of the tank. The rising air creates turbulence to break up steam envelopes sometimes encountered in quench annealing.

4.7.1.2 Using an overhead crane, the items to be quenched are immersed. The maximum elapsed time from 2050° F to 700° F shall be 13 minutes.

4.8 Furnace Loading

4.8.1 The parts will be supported on bolsters for the heat treatment. These bolsters support approximately 120° of circumference and are 9" wide. A row of soft, insulating firebrick is used to line the bolster and isolate the Hastelloy C-22 shell from the steel bolsters.

4.8.2 Subassemblies and parts will be loaded on bolsters or supports with firebrick spacers and in no case will the Hastelloy C-22 material contact any carbon steel during heat treatment.

4.9 Temperature Control

4.9.1 Thermocouple locations are as shown on the loading diagrams.

4.9.2 A heat treat coupon will be heat treated with each furnace load.

4.9.3 The furnace will be at ambient temperature at the start of the cycle.

4.9.4 The rate of heating will not be restricted and will be as rapid as possible.

4.9.5 The soak temperature shall be 2050 ± 50°F.

4.9.6 The hold time shall be 1/2 hour for the outer cylinder and 1 hour for the completed outer cylinder and the completed top cover assembly.

4.9.7 The parts will be water quenched as described in paragraph 4.7.

4.10 Sample Examination

The test coupon will be sent to the Metallurgical Laboratory for examination after solution annealing.

4.11 Reports

Subsequent to the solution anneal and quench, the following will be provided:

A. Copies of the heat treating charts, as printed by the multipoint recorder
B. Furnace loading diagrams
C. Copies of the calibration records for the equipment being used
D. A report on the heat treat coupon microstructure

5.0 ATTACHMENTS

5.1 Attachment 1 (20009201-1) "Preliminary Outer Cylinder"

5.2 Attachment 2 (20009201-2) "Completed Outer Cylinder"

5.3 Attachment 3 (20009201-3) "Completed Top Cover Assembly"

NOOTER Fabricators, Inc.		PROCEDURE: 9201-HT-AD
		PAGE: 1 of 2
		REVISION: 0
		DOCUMENT PUBLISHER: BSH
	ADDENDUM TO	APPROVED: BSH
	HEAT TREAT PROCEDURE	QA APPROVED: 6/20/00
	JOB 20009201	EFFECTIVE DATE: 6/20/2000

1.0 SCOPE

A. This procedure is an addendum to NFI Procedure 9201-HT, Revision 1. It is to be applied to the Heat Treatment and Cooling of the Top Outer Lid assembly for the Waste Package Closure.

B. This Heat treatment procedure is being used for experimental purposes to determine cooling rate based on forced air cooling.

C. Heat treatment & cooling is to be performed as described in NFI procedure 9201HT, revision 1, except as noted below.

2.0 PREPARATION FOR HEAT TREATMENT

Per Procedure 9201HT.

3.0 EQUIPMENT

3.1 3.3 Per Procedure 9201HT.

3.4 Thermocouples

3.4.1 Per Procedure 9201HT.

3.4.2 Thermocouples will be placed directly on the work so that the temperature recorded will be actual work temperatures, not furnace temperatures. Two thermocouples will be welded on the part to monitor cooling temperature during the forced air cooling that will be attached to a Data Logger to record the cooling curve. One thermocouple will be located on the OD of the shell, mid height. One thermocouple located on the weld build up on the ID of the shell, mid height.

3.5 ~~Quenching~~ Forced Air Cooling

3.5.1 Forced Air Cooling

3.5.1.1 Part will be removed from the furnace, suspended by a crane and cooled by blowing forced air on the part.

3.5.1.2 Target cooling rate is a drop from 2050° F to 930° F in 8 minutes.

FTG DOCUMENT NUMBER		
03	1289764	00

NOOTER fabricators, Inc.	ADDENDUM TO HEAT TREAT PROCEDURE JOB 20009201	PROCEDURE:	9201-HT-AD
		PAGE:	2 of 2
		REVISION:	0

4.0 FURNACE LOADING
Per Procedure 9201HT.

5.0 THERMOCOUPLE LOCATIONS
Per Procedure 9201HT.

6.0 PROCEDURE

6.1 6.5 Per Procedure 9201HT.

6.6 The parts will be forced air cooled as described in paragraph 3.5

7.0 SAMPLE EXAMINATION
Per Procedure 9201HT.

8.0 REPORTS
Per Procedure 9201HT.

NOOTER fabricators, inc.	CLEANING AND PACKAGING PROCEDURE FOR WASTE PACKAGE CLOSURE	PROCEDURE:	9201-CP
		PAGE:	1 OF 2
		REVISION:	0
		DOCUMENT PUBLISHER:	KTL
		APPROVED:	FJ
		QA APPROVED:	[illegible] / FT
		EFFECTIVE DATE:	5/1/00

1 SCOPE

This procedure provides the details for cleaning and packaging of the Waste Package Closure.

2 REFERENCE

Section III Quality Assurance Manual
Quality Assurance Department Manual Procedure #52-006 "Final Inspection"
SSPC-SP6 (NACE -3)

3 DEFINITIONS

None

4 PROCEDURE

4.1 **Cleaning Requirements for the Waste Package Closure**

4.1.1 All alloy surfaces of the completed Waste Package Closure, including the Inner Shell Assembly, and Top Outer Lid shall be free of grease, oil, paint, weld spatter, crayon marks and all other gross contaminants.

4.1.2 All components shall be solvent cleaned with "Turko Remover #3" to remove all contaminants. Hastelloy C-22 components shall be cleaned prior to solution anneal per NFI procedure #9201-HT.

4.1.3 After solvent cleaning, rinse with potable water and a mild detergent such as "Sweetheart" or "Joy" dishwashing detergent to remove all solvent residue.

4.1.4 Visually examine all components after cleaning to ensure that they are in compliance with step #4.1.1.

4.1.5 After solution annealing the Hastelloy C-22 components, sandblast to remove oxide using DuPont "Starblast" media to SSPC-SP6 (commercial blast).

FTG DOCUMENT NUMBER
03 1289766 00

NOOTER fabricators, Inc.	CLEANING PROCEDURE FOR WASTE PACKAGE CLOSURE	PROCEDURE:	9201-CP
		PAGE:	2 OF 2
		REVISION:	0

4.2 **Packaging Requirements for the Waste Package Closure**

4.2.1 The completed Waste Package Closure/Inner Shell, Top Inner Lid and Top Outer Lid Assemblies shall be wrapped in plastic to protect from environmental contaminants. The components shall be placed on skids and tied down to the trailer for shipment.

4.2.2 The completed Closure shall be identified with a waterproof tag attached for shipment. The tag shall be marked with the purchase order number and a description of the components. The tag shall be securely attached with corrosion resistant wire at the Closure lift lug.

4.3 Personnel implementing this procedure shall be trained in accordance with the Quality Assurance Department Manual Procedure #51-019 "Indoctrination and Training".

4.4 Upon completion of the Waste Package Closure, Inner Shell Assembly, Top Inner Lid and Top Outer Lid Assemblies, the assigned Q.A. personnel shall final inspect for cleanliness per Procedure #52-006 of the Qualiity Assurance Department Manual. After acceptance, the assigned Q.A. personnel shall sign and date the applicable sign off step(s) in the NIS Router. This information will be included in the final data package.

NOOTER fabricators, inc.	VISUAL INSPECTION	PROCEDURE	9201-VE1
		PAGE:	1 OF 1
		REVISION:	0
		DOCUMENT PUBLISHER:	DLF
		APPROVED:	FT
		QA APPROVED:	
		EFFECTIVE DATE:	04/11/2000

All visual weld examination shall be performed in accordance with NFI Procedure 54-611, Rev 0, with the following additions·

Add to 2.0, Reference·

Applicable edition of the ASME Code is the 1995 Edition with 1996 Addenda

FTG DOCUMENT NUMBER		
54	1289768	00

NOOTER fabricators, inc.	NDE DEPARTMENT QUALITY MANUAL VISUAL INSPECTION	PROCEDURE:	54-611
		PAGE:	1 OF 5
		REVISION:	0
		DOCUMENT PUBLISHER:	DLF
		APPROVED:	FT
		QA APPROVED:	
		EFFECTIVE DATE:	04/11/2000

1.0 SCOPE

This document defines the procedure and acceptance criteria for performing visual examination of welds. The techniques described herein meet the requirements of the ASME Code Section III.

2.0 REFERENCES

ASME Code Section V, Article 9
ASME Code Section NB4000

3.0 DEFINITIONS

None

FTG DOCUMENT NUMBER
54 1027099 00

4.0 PROCEDURE

4.1 **Requirements**

4.1.1 **The requirements of this procedure shall be implemented when visual weld examination is called for by the referencing documents**

4.1.2 **When performing visual inspection, a drop light or hand held light shall be used to assure adequate interpretation**

4.1.3 **Prior to examination, the surfaces to be inspected shall be free of any extraneous matter that would obscure surface openings or otherwise interfere with the examination.**

4.2 **Examination**

4.2.1 **Direct visual examination shall be performed in such a manner as to place the eye within twenty-four inches of the surface being examined and at an angle not less than 30 degrees to the surface being examined. The minimum light level shall be 50 foot candles**

4.2.2 **Examination of surfaces where the direct method is not feasible or access is limited shall be performed only when specifically delineated in the fabrication or erection procedure In such cases, mirrors may be utilized**

NOOTER Fabricators, Inc.	VISUAL INSPECTION	PROCEDURE: 54-611
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4.2.3 Weld size and weld reinforcement shall be measured using suitable weld gages or straight edges and scales, as applicable

4.3 Acceptance Criteria

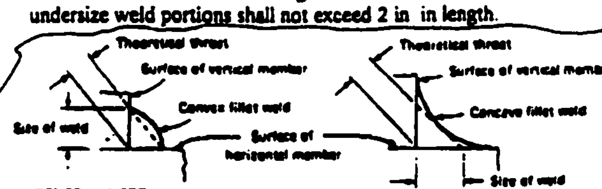
4.3.1 General

4.3.1.1 As-welded surfaces are permitted; however, the surface of welds shall be sufficiently free from coarse ripples, grooves, overlaps, and abrupt ridges and valleys to permit proper interpretation of radiographic and other required nondestructive examinations. If there is a question regarding the surface condition of the weld when interpreting a radiographic film, the film shall be compared to the actual weld surface for determination of acceptability.

4.3.2 Fillet Welds

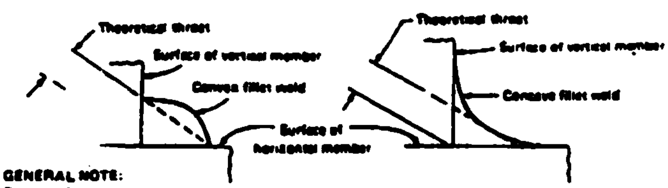
4.3.2.1 Fillet welds may vary from convex to concave. The shape and size of the weld shall be in accordance with the requirements of Fig. 1. A fillet weld in any single continuous weld may be less than the specified fillet weld dimension by not more than 1/16 in (1.6mm), provided that the total undersize portion of the weld does not exceed 10% of the length of the weld. Individual undersize weld portions shall not exceed 2 in. in length.

Not Pertinent DJS 9/1/00



GENERAL NOTE:
The size of an equal leg fillet weld is the leg length of the largest inscribed right isosceles triangle.
Theoretical throat = 0.7 x size of weld.

(a) Equal Leg Fillet Weld



GENERAL NOTE:
The size of an unequal leg fillet weld is the shorter leg length of the largest right triangle which can be inscribed within the fillet weld cross section.

(b) Unequal Leg Fillet Weld

NOOTER fabricators, inc.	VISUAL INSPECTION	PROCEDURE:	54-611
		PAGE:	2 OF 5
		REVISION:	0

4.2.3 Weld size and weld reinforcement shall be measured using suitable weld gages or straight edges and scales, as applicable

4.3 **Acceptance Criteria**

4.3.1 General

4.3.1.1 As-welded surfaces are permitted; however, the surface of welds shall be sufficiently free from coarse ripples, grooves, overlaps, and abrupt ridges and valleys to permit proper interpretation of radiographic and other required nondestructive examinations. If there is a question regarding the surface condition of the weld when interpreting a radiographic film, the film shall be compared to the actual weld surface for determination of acceptability

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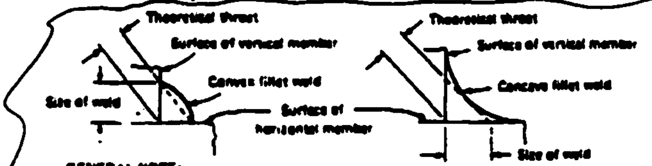
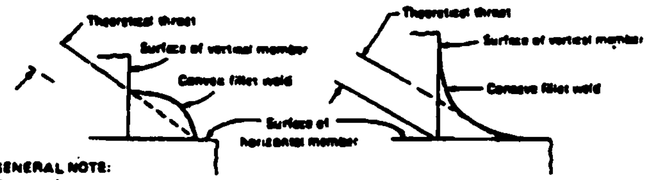
Not Pertinent D.J.S. 9/1/00



GENERAL NOTE:
The size of an equal leg fillet weld is the leg length of the largest inscribed right isosceles triangle.
Theoretical throat = 0.7 x size of weld.

(a) Equal Leg Fillet Weld



GENERAL NOTE:
The size of an unequal leg fillet weld is the shorter leg length of the largest right triangle which can be inscribed within the fillet weld cross section.

NOOTER fabricators, inc.	VISUAL INSPECTION	PROCEDURE: 54-611
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4 3 3 Butt Welds

A weld shall be acceptable by visual examination if the examination shows that:

4.3.3 1 The weld has no cracks

4.3.3 2 The weld has complete fusion and penetration

4 3 3 3 All craters are filled to the full cross section of the weld

4 3 3.4 Undercuts shall not exceed 1/32 in. and shall not encroach on the required section thickness.

4.3 3.5 The weld shall be free of porosity

4 3 3 6 Reinforcement of Welds

4 3 3 6 1 Thickness of Weld Reinforcement for Vessels
The surface of the reinforcement of all butt welded joints in vessels, pumps and valves may be flush with the base material or may have uniform crowns. The height of reinforcement on each face of the weld shall not exceed the thickness in the following tabulation

Nominal Thickness, in	Maximum Reinforcement, in
Up to 1, incl.	3/32
Over 1 to 2, incl.	1/8
Over 2 to 3, incl	5/32
Over 3 to 4, incl	7/32
Over 4 to 5, incl.	1/4
Over 5	5/16

4.3.3 6.2 Thickness of Weld Reinforcement for Piping

For double-welded butt joints, the limitation on the reinforcement given in Column 1 of the following tabulation shall apply separately to both inside and outside surfaces of the joint. For single-welded butt joints, the reinforcement given in Column 2 shall apply to the inside surface and the reinforcement given in Column 1 shall be determined from the higher of the abutting surfaces involved

NOOTER Fabricators Inc.	VISUAL INSPECTION	PROCEDURE: 54-611
		PAGE: 4 OF 5
		REVISION: 0

Material Nominal Thickness, in.	Maximum Reinforcement Thickness, in Column 1	Column 2
Up to 1/8, incl.	3/32	3/32
Over 1/8 to 3/16, incl.	1/8	3/32
Over 3/16 to 1/2, incl.	5/32	1/8
Over 1/2 to 1, incl.	3/16	5/32
Over 1 to 2, incl.	1/4	5/32
Over 2	Greater of 1/4 in. or 1/8 times the width of the weld, in inches	5/32

4.4 **Rejectable Indications**

4.4.1 Surface indications and weld defects may be conditioned for further evaluation by grinding or filing. Additional rework shall be performed if such conditioning renders the part to be outside the specified characteristics.

4.4.2 After conditioning, the part shall be re-examined in accordance with this procedure. If the indication still appears relevant, it shall be repaired. If no relevant indications remain, the part shall be considered acceptable.

4.5 **Repairs**

4.5.1 Repairs shall be visually re-examined in accordance with this procedure.

4.6 **Physical Qualifications**

4.6.1 All personnel performing visual inspection shall have an annual eye examination to assure that the candidate has natural or corrected near field visual acuity capable of reading Jaeger number 1 letters (or equivalent) at a distance of not less than twelve inches.

4.7 **Procedure Qualifications**

4.7.1 This procedure has been qualified in the report Visual Examination Procedure Qualification dated 2/21/00.

NOOTER Fabricators Inc.	VISUAL INSPECTION	PROCEDURE:	54-611
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4 8 **Personnel Qualifications**

4 9 1 Personnel performing visual examinations shall be qualified as required by NFI Procedure 52-017

4 9 **Reports**

4 9 1 Upon completion of each visual examination, the appropriate router step shall be signed off by the individual performing the examination and Inspection Log Form 250 will have the appropriate entry made

5 0 ATTACHMENTS

None

LAMBDA RESEARCH

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DATE:	May 24, 2000
TO:	Mr. Daniel Smith
AFFILIATION:	Framatome Technologies, Inc.
FAX NO.:	(804) 832-3177
PHONE NO.:	(804) 832-2960
FROM:	Melissa Bowen, Customer Service \ Cathleen Bowen
REFERENCE:	Lambda Research Report No. 824-9312

Dear Mr. Smith:

Enclosed please find a copy of the final report for Lambda Research Project No. 824-9312. Three copies of the final report will follow shortly via U.S. Mail.

Please don't hesitate to contact us should you require additional information or have any questions.

Sincerely,

Melissa Bowen
Customer Service

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ON-SITE HOLE DRILLING DETERMINATION OF THE PRINCIPAL RESIDUAL STRESSES IN ONE C22-HASTELLOY CANISTER MOCKUP

REPORT:	824-9312	ATTN:	Mr. Daniel Smith
DATE:	May 24, 2000	AUTHORIZATION:	91616

INTRODUCTION

On-site center hole-drilling measurements were made on a canister mockup at Nooter Fabrication for the purpose of determining the principal residual stresses resulting from welding before and after heat treatment. The cylinder was reportedly manufactured from C22-Hastelloy. The cylinder was nominally 88 in. (O.D.) x 48 in. (height).

Douglas J. Hornbach
Supervisor
Residual Stress Laboratory

Quality Assurance

TECHNIQUE

The near-surface principal residual stresses were determined using the center hole drilling method per the ASTM E837 procedure. The residual stress measurements were made at three positions on the outside diameter along the weld and at four locations at each position both before and after heat treatment for a total of 24 locations, as shown in Figure 4. The three positions were near the top, centered through the wall of the reinforcement band, at mid-length of the weld, and nominally 5 in. from the bottom. The four locations per position were at the weld center, adjacent to the fusion line, 0.2 in. from the fusion line, and 0.3 in. from the fusion line. The measurements after heat treatment were made at an axial distance of 0.2 in. from the original measurements.

Rectangular electrical resistance strain gages (Micro-Measurements type CEA-06-062UM-120), were installed at the locations adjacent to the fusion line. Rectangular electrical resistance strain gages (Micro-Measurements type EA-06-062RE-120) were installed at all other measurement locations. A hole was machined at the geometric center of the strain gage rosette to a depth of nominally 40 percent of the grid centerline diameter. The hole was machined with a high speed air turbine assembly employing a carbide cutter. The strain relaxation was recorded and the principal residual stresses were computed per ASTM E 837 at the full depth of cut.

RESULTS AND DISCUSSION

The principal residual stresses obtained by hole drilling on the canister mockup are listed in Tables I, II, and III and shown graphically as a function of distance from the weld centerline in Figures 1, 2, and 3. It should be noted that the actual measurement locations for any given position do not lie on a single circumferential ring but are, in fact, staggered laterally as shown in Figure 4.

The maximum stress direction is defined by the angle phi, which is taken to be a positive angle counterclockwise from the hoop direction. The number one gage direction was the hoop direction for this analysis. Compressive stresses are shown as negative values, tensile as positive, in units of ksi (10^3 psi).

The residual stresses calculated using the hole drilling method that exceed 50% of the yield stress of the material may be overestimated (Reference: ASTM E 837-95 Determining Residual Stresses by the Hole-Drilling Strain-Gage Method). Because the stress intensity factor for a hole in a plate is nominally 2, introduction of a hole into a stress field higher than nominally one-half the yield stress will cause yielding at the edge of the hole. The underlying equations for stress calculation are based upon linear elasticity and will be increased in error as the zone of yielding increases. The calculated residual stresses will tend to be exaggerated if yielding does occur.

CONCLUSIONS

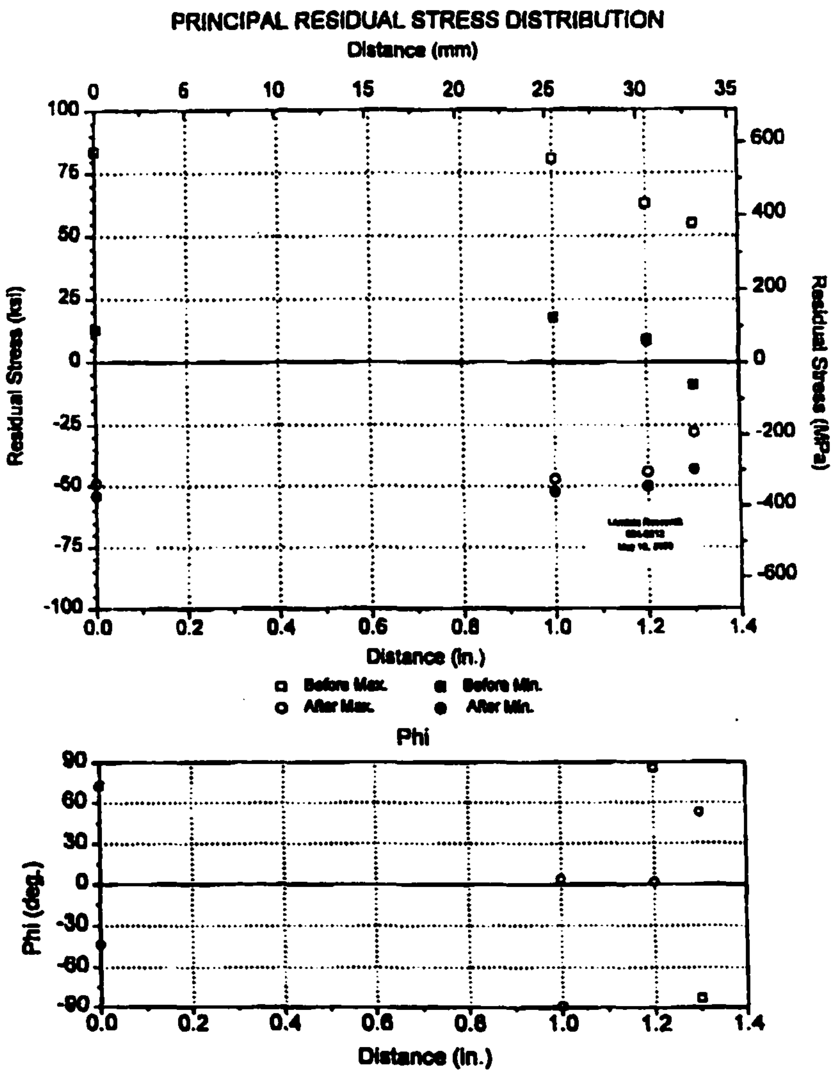
The principal residual stresses are presented in Tables I, II, and III and Figures 1, 2, and 3. Before the heat treatment and quench, the results indicate that the highest tensile stresses are found at the Top position. The maximum residual stresses at the four locations at the Top position range from +65 to +84 ksi, and the minimum residual stresses range from -9 to +18 ksi. The maximum residual stresses for the Mid-Weld and Bottom positions range from +31 to +7 ksi, and the minimum residual stresses range from -57 to +16 ksi. The fact that there is a welded reinforcement band on the inside diameter of the Top position locations may be the reason for the higher tensile stresses at these locations.

The data after the heat treatment and quench show that all of the locations are in compression in all directions. The maximum principal residual stresses range from -28 to -72 ksi and the minimum residual stresses range from -39 to -86 ksi. At each position the most compressive residual stresses are found at the weld center location. Of all the locations, the Mid Weld Center location is the most compressive.

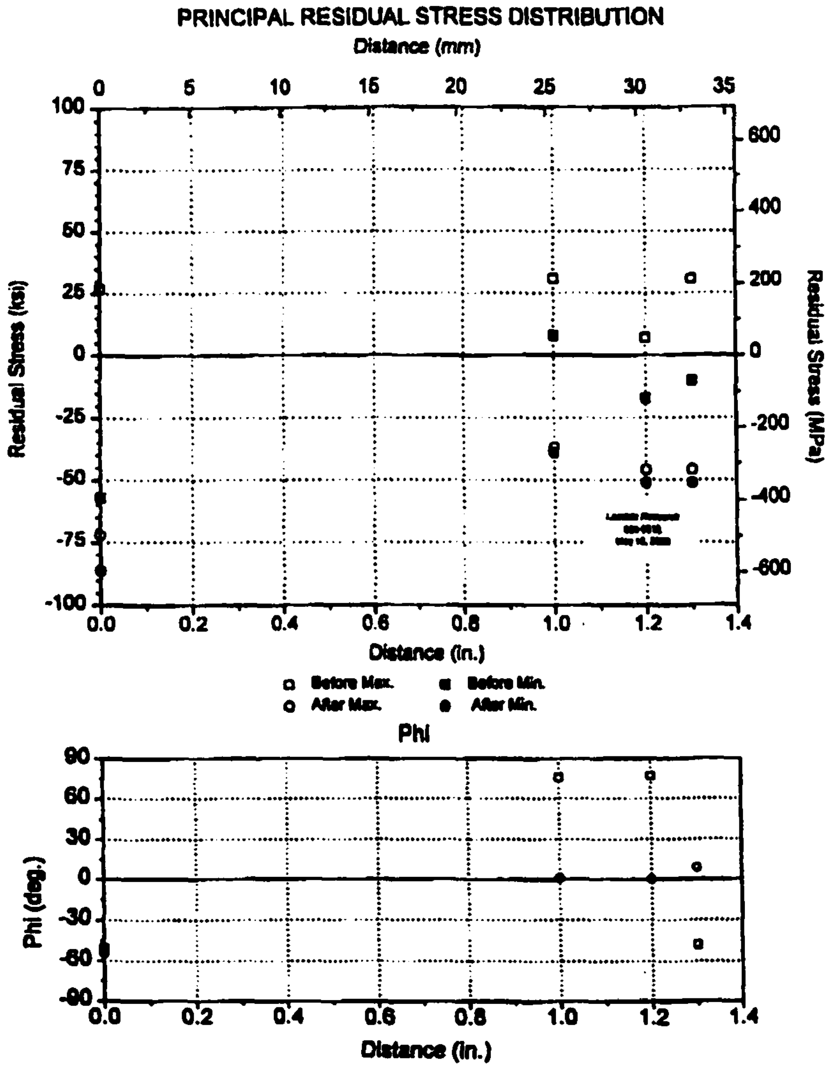
The right hand columns of Tables I, II, and III list the directions of the maximum principal residual stresses. These data are also plotted at the bottoms of Figures 1, 2, and 3. Before the heat treatment and quench, for the Top position the maximum principal stresses are fairly close to the axial direction. The direction of the maximum residual stresses at the other two positions range from 1 to 77 deg. from the axial direction.

After the heat treatment and quench, the maximum and minimum principal residual stresses for a given location tend to be very similar. Therefore, the direction of the maximum principal residual stress is not well defined.

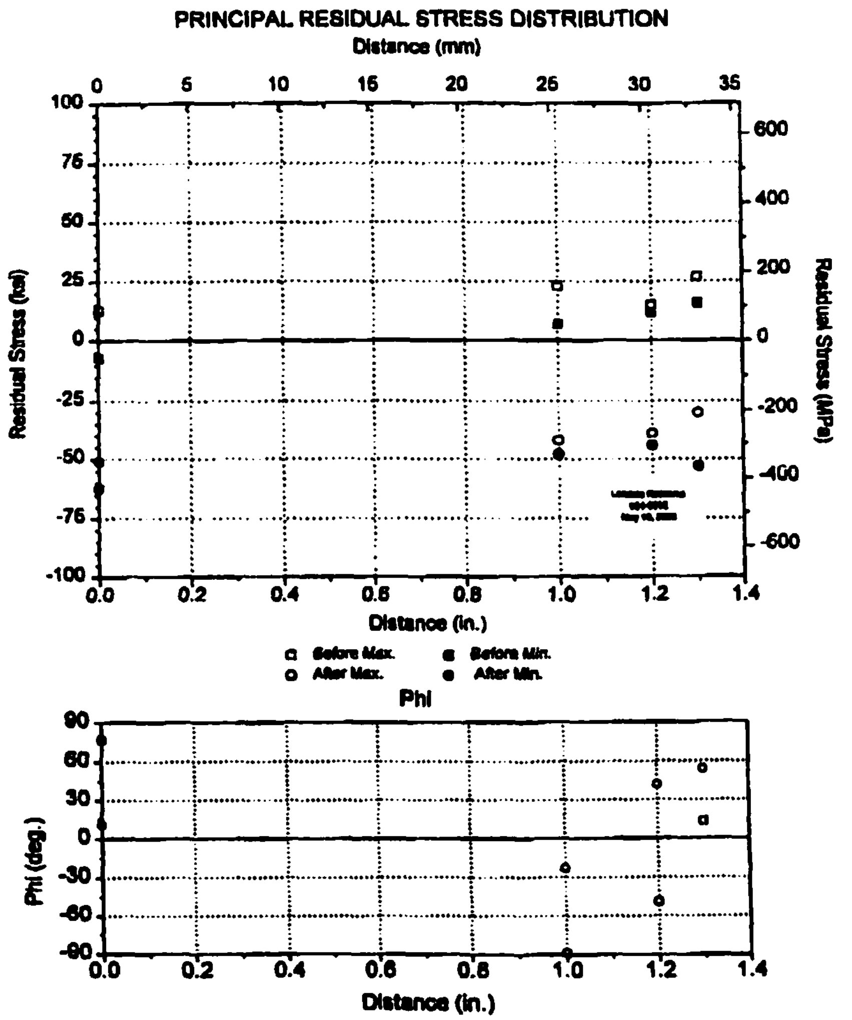
[holedril.fm 10.97]



C-22 HASTELLOY CANISTER MOCKUP
Bottom ~~Top~~ Locations
Number 1 Direction = Hoop

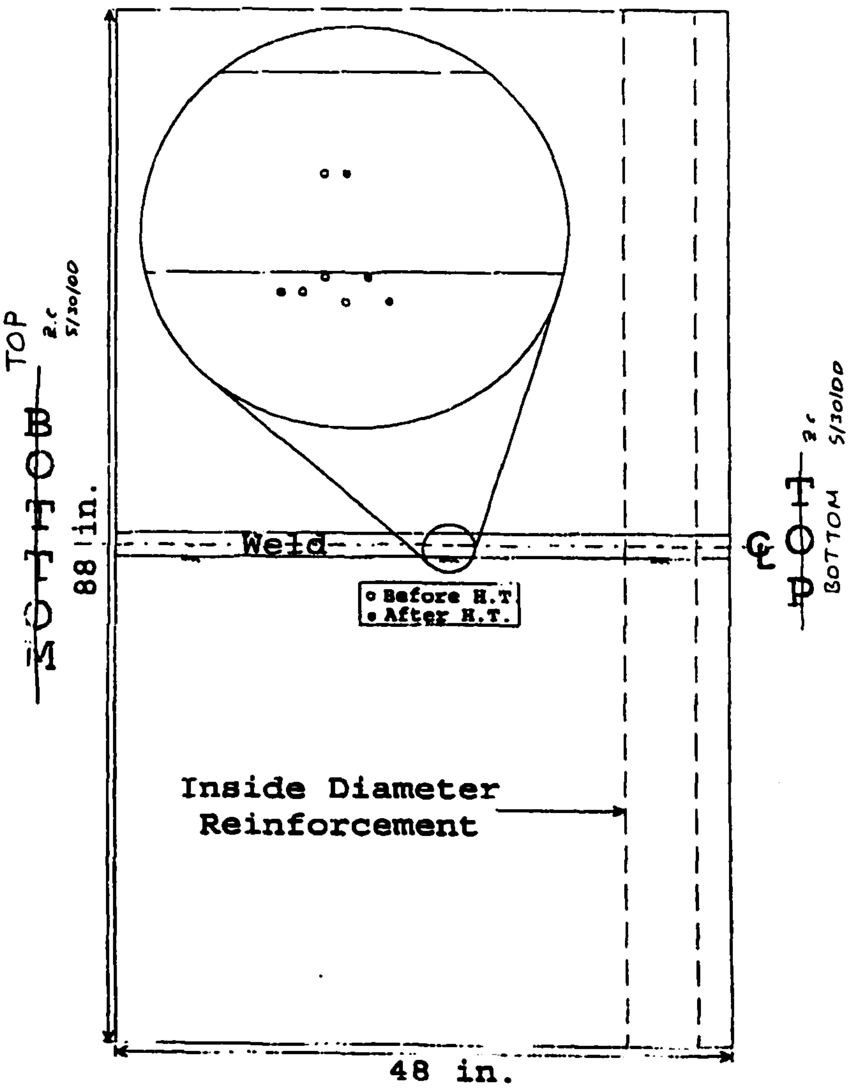


C-22 HASTELLOY CANISTER MOCKUP
Mid-Weld Locations
Number 1 Direction = Hoop



C-22 HASTELLOY CANISTER MOCKUP
Top -Bottom Locations
Number 1 Direction = Hoop

Lambda Research — Figure 3 — 824-9312



Lambda Research

Figure 4

824-9312

PRINCIPAL RESIDUAL STRESSES
C-22 HASTELLOY CANISTER MOCKUP
Bottom ~~Top~~ Locations
No. 1 Direction = Hoop
5/30/00

Distance from Weld	Residual Stress (ksi)				Phi (deg.)[a]	
	Maximum		Minimum			
	Before Heat Treat	After Heat Treat	Before Heat Treat	After Heat Treat	Before Heat Treat	After Heat Treat
Center	+84	-49	+13	-54	+73	-43
Adjacent	+81	-47	+18	-52	-89	+4
0.2 in.	+83	-44	+9	-50	+86	+2
0.3 in.	+55	-28	-9	-43	-83	+53

(a) Phi is taken as the angle positive counterclockwise from the hoop direction.

PRINCIPAL RESIDUAL STRESSES
C-22 HASTELLOY CANISTER MOCKUP
Mid-Weld Locations
No. 1 Direction = Hoop

Distance from Weld	Residual Stress (ksi)				Phi (deg.)[a]	
	Maximum		Minimum			
	Before Heat Treat	After Heat Treat	Before Heat Treat	After Heat Treat	Before Heat Treat	After Heat Treat
Center	+27	-72	-57	-86	-60	-54
Adjacent	+31	-37	+8	-39	+78	+1
0.2 in.	+7	-48	-17	-51	+77	0
0.3 in.	+31	-48	-10	-51	-48	+9

(a) Phi is taken as the angle positive counterclockwise from the hoop direction.

PRINCIPAL RESIDUAL STRESSES
C-22 HASTELLOY CANISTER MOCKUP
Top ~~Bottom~~ Locations
No. 1 Direction = Hoop
BC 5/30/00

Distance from Weld	Residual Stress (ksi)				Phi (deg.)[a]	
	Maximum		Minimum			
	Before Heat Treat	After Heat Treat	Before Heat Treat	After Heat Treat	Before Heat Treat	After Heat Treat
Center	+13	-51	-7	-62	+77	+11
Adjacent	+23	-42	+7	-48	-89	-23
0.2 in.	+15	-39	+12	-44	-49	+42
0.3 in.	+27	-30	+16	-53	+13	+54

(a) *Phi is taken as the angle positive counterclockwise from the hoop direction.*

APPENDIX VI

MATHCAD CALCULATION FILE FOR TRANSFORMATION OF PRINCIPAL STRESSES INTO HOOP STRESS

Transformation of Principal Stresses into Hoop Stress

All principal stresses and their corresponding directions in terms of angles are obtained from the documents given in Appendix V

Hoop stresses at the top locations in the canister mock-up:

$i := 0..3$

$$\sigma 1top := \begin{pmatrix} -51 \\ -42 \\ -39 \\ -30 \end{pmatrix}$$

Maximum principal stresses at four different locations: 1, 2, 3, and 4, respectively

$$\sigma 2top := \begin{pmatrix} -62 \\ -48 \\ -44 \\ -53 \end{pmatrix}$$

Minimum principal stresses at four different locations: 1, 2, 3, and 4, respectively

$$\theta top := \begin{pmatrix} 11 \\ -23 \\ 42 \\ 54 \end{pmatrix}$$

Maximum principal stress directions (angles) measured from the direction of the hoop stress (circumference) at four different locations: 1, 2, 3, and 4, respectively

The magnitudes of the hoop stresses are obtained using the following relation from the Mohr's circle for biaxial stress state:

$$\sigma hoop_i := \left[\frac{(\sigma 1top_i + \sigma 2top_i)}{2}\right] + \left[\frac{(\sigma 1top_i - \sigma 2top_i)}{2}\right] \cdot \cos\left(2 \cdot \theta top_i \cdot \frac{\pi}{180}\right)$$

Therefore:

$$\sigma hoop_i = \begin{array}{|c|} \hline -51 \\ \hline -43 \\ \hline -41 \\ \hline -45 \\ \hline \end{array} \quad \text{ksi}$$

Hoop stresses at the middle locations in the canister mock-up:

$i := 0..3$

$$\sigma 1mid := \begin{pmatrix} -72 \\ -37 \\ -46 \\ -46 \end{pmatrix}$$

Maximum principal stresses at four different locations: 1, 2, 3, and 4, respectively

$$\sigma 2mid := \begin{pmatrix} -86 \\ -39 \\ -51 \\ -51 \end{pmatrix}$$

Minimum principal stresses at four different locations: 1, 2, 3, and 4, respectively

$$\theta mid := \begin{pmatrix} -54 \\ 1 \\ 0 \\ 9 \end{pmatrix}$$

Maximum principal stress directions (angles) measured from the direction of the hoop stress (circumference) at four different locations: 1, 2, 3, and 4, respectively

The magnitudes of the hoop stresses are obtained using the following relation from the Mohr's circle for biaxial stress state:

$$\sigma hoop_i := \left[\frac{(\sigma 1mid_i + \sigma 2mid_i)}{2}\right] + \left[\frac{(\sigma 1mid_i - \sigma 2mid_i)}{2}\right] \cdot \cos\left(2 \cdot \theta mid_i \cdot \frac{\pi}{180}\right)$$

Therefore: $\sigma hoop_i =$

$$\begin{array}{|c|} \hline -81 \\ \hline -37 \\ \hline -46 \\ \hline -46 \\ \hline \end{array} \quad \text{ksi}$$

Hoop stresses at the bottom locations in the canister mock-up:

$i := 0..3$

$$\sigma 1bot := \begin{pmatrix} -49 \\ -47 \\ -44 \\ -28 \end{pmatrix}$$

Maximum principal stresses at four different locations: 1, 2, 3, and 4, respectively

$$\sigma 2bot := \begin{pmatrix} -54 \\ -52 \\ -50 \\ -43 \end{pmatrix}$$

Minimum principal stresses at four different locations: 1, 2, 3, and 4, respectively

$$\theta bot := \begin{pmatrix} -43 \\ 4 \\ 2 \\ 53 \end{pmatrix}$$

Maximum principal stress directions (angles) measured from the direction of the hoop stress (circumference) at four different locations: 1, 2, 3, and 4, respectively

The magnitudes of the hoop stresses are obtained using the following relation from the Mohr's circle for biaxial stress state:

$$\sigma hoop_i := \left[\frac{(\sigma 1bot_i + \sigma 2bot_i)}{2}\right] + \left[\frac{(\sigma 1bot_i - \sigma 2bot_i)}{2}\right] \cdot \cos\left(2 \cdot \theta bot_i \cdot \frac{\pi}{180}\right)$$

Therefore: $\sigma hoop_i =$

$$\begin{array}{|c|} \hline -51 \\ \hline -47 \\ \hline -44 \\ \hline -38 \\ \hline \end{array} \text{ ksi}$$

APPENDIX VII

TWO DIMENSIONAL AXISYMMETRIC FINITE ELEMENT MODEL INPUT FILE FOR OPTIMIZATION USING ANSYS SOFTWARE

```
!
!     Coarse mesh 2-D axisymmetric model for induction aneealing
!     Obective function: Maximum compression on the outer surface
!     State variable: None
!     Design variables: Defined below
!
/config,nres,2000
/units,si
!
!                         SET INITIAL VALUE OF DESIGN VARIABLES
var1=0.09           ! Trunnion collar upper section length (variable #1)
var2=0.025          ! Outer lid closure weld length (variable #2)
var3=0.05           ! Extended lid outer fillet weld base length
(variable #3)
var4=0.05           ! Extended lid inner fillet weld base length
(variable #4)
var5=0.025          ! Extended outer shell lid thickness (variable #5)
var6=0.05           ! Reinforcement ring (variable #6)
var7=0.05           ! Ring weld section - inner (variable #7)
!
!
/prep7
/title, FEA to determine residual stresses due to induction coil
heating of closure welds
/vcon,,0
et,1,plane13,4,,1   ! Axisymmetric model for the outer shell
!
mptemp,1,20,1120
mpdata,ex,1,1,206e9,134e9 ! Alloy 22 Elastic Modulus
mpdata,nuxy,1,1,0.278,0.46   ! Alloy 22 Poisson's ratio
! Material properties of outer shell
tb,biso,1
tbtemp,20
tbdata,,310e6,0.847e9  ! Alloy 22
tbtemp,1120
tbdata,,85e6,0.173e9   ! Alloy 22
!
mp,dens,1,8690.0    ! Alloy 22
mpdata,alpx,1,1,12.4e-6,16.2e-6   ! Alloy 22
! Thermal properties of Alloy 22
/COM,    Define conductivity
MPTEMP,   1,  48,   100,  200,   300,  400,  500,
MPTEMP,   7,  600,
MPDATA, KXX, 1, 1,  10.1,  11.1,  13.4,  15.5,  17.5,  19.5,
MPDATA, KXX, 1, 7,  21.3,
/COM,    Define specific heat
MPTEMP,   1,  52,   100,  200,   300,  400,  500,
MPTEMP,   7,  600,
MPDATA, C, 1, 1,  414,  423,  444,  460,  476,  485,
MPDATA, C, 1, 7,  514,
/com, Define Parameters
!
! Parameters along x-axis
osir=0.762       ! Outer shell inner radius
osip=0.004       ! Outer shell inner part
osop=0.016       ! Outer shell outer part
tcti=0.02         ! Trunnion collar thickness - inner
```

```
tctm=0.005       ! Trunnion collar thickness - middle
tcto=0.015       ! Trunnion collar thickness - outer
gap=0.004      ! Gap between extended outer shell lid and outer shell
!
! Parameters along y-axis
cav=4.775+0.03+0.01+0.03+0.07   ! Distance between outer shell lid
inner surfaces
hcav=cav/2     ! Half distance between outer shell lid inner surfaces
trl=0.1          ! Trunnion ring length
tcl=0.14         ! Trunnion collar length
tcbi=0.005       ! Trunnion collar bottom - innner region
tcbo=0.02        ! Trunnion collar bottom - outer region
clth=0.01      ! Closure lid thickness
clw=0.01       ! Closure lid weld
tcui=0.02        ! Trunnion collar upper section - inner part of the
fillet weld
tcuo=0.02        ! Trunnion collar upper section - outer part of the
fillet weld
olid=0.025     ! Extended lid base
!
/com, Define keypoints
csys,0
k,1,osir,
k,2,osir+osip,
k,3,osir+osip+osop,
k,4,osir,hcav-trl-tcl-tcbi-tcbo
k,5,osir+osip,hcav-trl-tcl-tcbi-tcbo
k,6,osir+osip+osop,hcav-trl-tcl-tcbi-tcbo
k,7,osir,hcav-trl-tcl-tcbi
k,8,osir+osip,hcav-trl-tcl-tcbi
k,9,osir+osip+osop,hcav-trl-tcl-tcbi
k,10,osir+osip+osop+tcti,hcav-trl-tcl-tcbi
k,11,osir,hcav-trl-tcl
k,12,osir+osip,hcav-trl-tcl
k,13,osir+osip+osop,hcav-trl-tcl
k,14,osir+osip+osop+tcti,hcav-trl-tcl
k,15,osir+osip+osop+tcti+tctm,hcav-trl-tcl
k,16,osir+osip+osop+tcti+tctm+tcto,hcav-trl-tcl
k,17,osir,hcav-trl
k,18,osir+osip,hcav-trl
k,19,osir+osip+osop,hcav-trl
k,20,osir+osip+osop+tcti,hcav-trl
k,21,osir+osip+osop+tcti+tctm,hcav-trl
k,22,osir+osip+osop+tcti+tctm+tcto,hcav-trl
k,23,0,hcav
k,24,osir,hcav
k,25,osir+osip,hcav
k,26,osir+osip+osop,hcav
k,27,osir+osip+osop+tcti,hcav
k,28,osir+osip+osop+tcti+tctm+tcto,hcav
k,29,0,hcav+clth
k,30,osir+osip-clw,hcav+clth
k,31,osir+osip,hcav+clth
k,32,osir+osip+osop,hcav+clth
k,33,osir+osip+osop+tcti,hcav+clth
k,34,osir+osip+osop+tcti+tctm+tcto,hcav+clth
k,35,osir+osip,hcav+clth+clw
```

```
k,36,osir+osip+osop,hcav+clth+clw
k,37,osir+osip+osop+tcti,hcav+clth+clw
k,38,osir+osip+osop+tcti+tctm+tcto,hcav+clth+clw
k,39,osir+osip,hcav+clth+clw+var1
k,40,osir+osip+osop,hcav+clth+clw+var1
k,41,osir+osip+osop+tcti,hcav+clth+clw+var1
k,42,osir+osip+osop+tcti+tctm+tcto,hcav+clth+clw+var1
k,43,osir+osip,hcav+clth+clw+var1+tcui
k,44,osir+osip+osop,hcav+clth+clw+var1+tcui
k,45,osir+osip+osop+tcti,hcav+clth+clw+var1+tcui
k,46,osir+osip,hcav+clth+clw+var1+tcui+tcuo
k,47,osir+osip+osop,hcav+clth+clw+var1+tcui+tcuo
k,48,osir+osip-gap-var5,hcav+clth+clw+var1+tcui+tcuo+var2
k,49,osir+osip-gap,hcav+clth+clw+var1+tcui+tcuo+var2
k,50,osir+osip,hcav+clth+clw+var1+tcui+tcuo+var2
k,51,osir+osip+osop,hcav+clth+clw+var1+tcui+tcuo+var2
k,52,osir+osip-gap,hcav+clth+clw+var1+tcui+tcuo
k,53,osir+osip-gap-var5-var6,hcav+clth+clw+var1+tcui+tcuo+var2-var3
k,54,osir+osip-gap-var5,hcav+clth+clw+var1+tcui+tcuo+var2-var3
k,55,osir+osip-gap,hcav+clth+clw+var1+tcui+tcuo+var2-var3
k,56,0,hcav+clth+clw+var1+tcui+tcuo+var2-var3-var4
k,57,osir+osip-gap-var5-var6-var7,hcav+clth+clw+var1+tcui+tcuo+var2-
var3-var4
k,58,osir+osip-gap-var5-var6,hcav+clth+clw+var1+tcui+tcuo+var2-var3-
var4
k,59,osir+osip-gap-var5,hcav+clth+clw+var1+tcui+tcuo+var2-var3-var4
k,60,osir+osip-gap,hcav+clth+clw+var1+tcui+tcuo+var2-var3-var4
k,61,0,hcav+clth+clw+var1+tcui+tcuo+var2-var3-var4-olid
k,62,osir+osip-gap-var5-var6-var7,hcav+clth+clw+var1+tcui+tcuo+var2-
var3-var4-olid
k,63,osir+osip-gap-var5-var6,hcav+clth+clw+var1+tcui+tcuo+var2-var3-
var4-olid
k,64,osir+osip-gap-var5,hcav+clth+clw+var1+tcui+tcuo+var2-var3-var4-
olid
k,65,osir+osip-gap,hcav+clth+clw+var1+tcui+tcuo+var2-var3-var4-olid
/com, Horizontal lines in inner (first) part of the outer shell
l,1,2
l,4,5
l,7,8
l,11,12
l,17,18
l,24,25
l,30,31
l,30,35
l,31,35
l,32,36
l,33,37
l,34,38
lesize,all,,,2,1,1
lsel,none
/com, Horizontal lines in second part of the outer shell
l,2,3
l,5,6
l,8,9
l,12,13
l,18,19
l,25,26
```

```
l,31,32
l,35,36
l,39,40
l,43,44
l,46,47
l,50,51
lesize,all,,,2,1,1
lsel,none
/com, Horizontal lines in inner part of the trunnion collar
l,7,4
l,8,5
l,9,6
l,10,6
l,9,10
l,13,14
l,19,20
l,26,27
l,32,33
l,36,37
l,40,41
l,44,45
l,47,45
l,44,47
l,43,46
lesize,all,,,2,1,1
lsel,none
/com, Horizontal lines in the thin section of the lower trunnion collar
l,11,7
l,12,8
l,13,9
l,14,10
l,15,10
l,14,15
l,20,21
lesize,all,,,2,1,1
lsel,none
/com, Horizontal lines in the thick section of the lower trunnion
collar
l,15,16
l,21,22
lesize,all,,,1,1,1
lsel,none
/com, Horizontal lines in the outer part of the upper trunnion collar
l,27,28
l,33,34
l,37,38
l,41,42
l,45,42
l,41,45
l,40,44
l,39,43
lesize,all,,,2,1,1
lsel,none
/com, Horizontal lines in the gap
l,52,46
l,49,50
lesize,all,,,1,1,1
```

```
lsel,none
/com, Horizontal lines in the extended outer shell lid
l,64,65
l,59,60
l,54,55
l,48,52
l,48,49
l,49,52
l,50,46
l,51,47
lesize,all,,,4,1,1
lsel,none
/com, Horizontal lines in the extended lid reinforcement ring
l,63,64
l,58,59
l,53,54
l,53,48
l,48,54
l,52,55
lesize,all,,,4,1,1
lsel,none
/com, Horizontal lines in the extended lid reinforcement ring - left
side section
l,62,63
l,57,58
l,57,53
l,53,58
l,54,59
l,55,60
lesize,all,,,4,1,1
lsel,none
/com, Horizontal lines in the outer lid
l,61,62
l,56,57
lesize,all,,,6,.0625,1
lsel,none
/com, Horizontal lines in the closure lid
l,23,24
l,29,30
lesize,all,,,6,.0625,1
lsel,none
/com, Vertical lines above the symmetry line
l,1,4
l,2,5
l,3,6
lesize,all,,,6,.06,1
lsel,none
/com, Vertical lines in the lower part of the trunnion collar
l,11,17
l,12,18
l,13,19
l,14,20
l,15,21
l,16,22
lesize,all,,,2,1,1
lsel,none
/com, Vertical lines in the middle part of the trunnion collar
```

```
l,17,24
l,18,25
l,19,26
l,20,27
lesize,all,,,2,1,1
lsel,none
/com, Vertical lines in the closure lid
l,23,29
l,24,30
l,25,31
l,26,32
l,27,33
l,28,34
lesize,all,,,1,1,1
lsel,none
/com, Vertical lines in the upper part of the trunnion collar
l,35,39
l,36,40
l,37,41
l,38,42
lesize,all,,,6,.2,1
lsel,none
/com, Vertical lines in the outer lid
l,61,56
l,62,57
l,63,58
l,64,59
l,65,60
lesize,all,,,2,1,1
lsel,none
/com, Define areas starting from the region close to bottom symmetry
plane
allsel
al,1,84,2,83
al,13,85,14,84
al,2,26,3,25
al,14,27,15,26
al,27,28,29
al,3,41,4,40
al,15,42,16,41
al,29,43,30,42
al,43,44,45
al,4,87,5,86
al,16,88,17,87
al,30,89,31,88
al,45,90,46,89
al,47,91,48,90
al,5,93,6,92
al,17,94,18,93
al,31,95,32,94
al,81,97,82,96
al,6,98,7,97
al,18,99,19,98
al,32,100,33,99
al,49,101,50,100
al,7,9,8
al,19,10,20,9
```

```
al,33,11,34,10
al,50,12,51,11
al,20,103,21,102
al,34,104,35,103
al,51,105,52,104
al,21,55,22,56
al,35,54,36,55
al,52,53,54
al,22,38,23,39
al,36,37,38
al,23,66,24,65
al,57,65,58,64
al,62,64,63
al,69,71,70
al,61,72,62,71
al,74,76,75
al,68,77,69,76
al,60,78,61,77
al,79,107,80,106
al,73,108,74,107
al,67,109,68,108
al,59,110,60,109
/com, Outer shell and lid mesh
alls
type,1   ! plane13
mat,1    ! Alloy 22
smrt,off
mshkey,1
amesh,all
/com, Apply displacement/symmetry constraints
nsel,s,loc,y,0
d,all,uy,0
nsel,s,loc,x,-.001,.001
d,all,ux,0
allsel
save
/nerr,,100000
/SOLU
ANTYPE,TRAN,NEW,
NROPT,FULL,,ON,
TRNOPT,FULL,
ALLS
TIME,35
/COM,          Thermal initial boundary condition for the WP at 20
degrees C
TUNIF,20
/COM,          Apply loads and solve for 0 to 35 seconds
nsel,s,loc,y,hcav+clth+clw+var1+tcui+tcuo+(var2/2),hcav+clth+clw+var1+t
cui+tcuo+var2   ! Select volume of first HAZ from coil induction
D,ALL,TEMP,1120
nsel,s,loc,y,hcav+clth+clw+var1+tcui+tcuo,hcav+clth+clw+var1+tcui+tcuo+
(var2/2)-0.0001    ! Select volume of second HAZ from coil induction
D,ALL,TEMP,750
nsel,s,loc,y,hcav+clth+clw+var1,hcav+clth+clw+var1+tcui+tcuo-0.0001
! Select volume of third HAZ from coil induction
D,ALL,TEMP,500
```

```
nsel,s,loc,y,hcav+clth+clw+var1+tcui+tcuo+var2-var3-
var4+0.0001,hcav+clth+clw+var1-0.00001   ! Select volume of fourth HAZ
from coil induction
D,ALL,TEMP,250
/COM,           Set time integration parameters for the first time
interval
ALLS
NSUBST,5,10,4,ON,
KBC,0
AUTOTS,ON
OUTRES,ALL,ALL
SOLVE
!
!
/COM,           Solve from 35 to 45 seconds
TIME,45
nsel,s,loc,y,hcav+clth+clw+var1+tcui+tcuo+(var2/2),hcav+clth+clw+var1+t
cui+tcuo+var2   ! Select volume of first HAZ from coil induction
D,ALL,TEMP,1120
nsel,s,loc,y,hcav+clth+clw+var1+tcui+tcuo,hcav+clth+clw+var1+tcui+tcuo+
(var2/2)-0.0001    ! Select volume of second HAZ from coil induction
D,ALL,TEMP,750
nsel,s,loc,y,hcav+clth+clw+var1,hcav+clth+clw+var1+tcui+tcuo-0.0001
! Select volume of third HAZ from coil induction
D,ALL,TEMP,500
nsel,s,loc,y,hcav+clth+clw+var1+tcui+tcuo+var2-var3-
var4+0.0001,hcav+clth+clw+var1-0.00001   ! Select volume of fourth HAZ
from coil induction
D,ALL,TEMP,250
ALLS
OUTRES,ALL,ALL
SOLVE
!
!
/COM,           Solve from 45 to 75 seconds
nsel,all
DDELE,ALL,TEMP                      ! Delete previously set boundary
conditions
TM_START=46
TM_END=75
TM_INC=1
ALLS
*DO,TM,TM_START,TM_END,TM_INC
        TIME,TM,
! Identify and group all surface nodes for quenching
lsel,s,,,75
lsel,a,,,70
lsel,a,,,63
lsel,a,,,58
lsel,a,,,24
lsel,a,,,66
lsel,a,,,37
lsel,a,,,53
lsel,a,,,105
nsll,s,1
cm,s_nodes,node
alls
```

```
! Select first set of surface nodes for quenching
nsel,s,,,s_nodes
nsel,r,loc,y,hcav+clth+clw+var1+tcui+tcuo+(var2/2),hcav+clth+clw+var1+t
cui+tcuo+var2
cm,surf1,node
D,ALL,TEMP,1120-((1000/29)*(TM-46))
! Select second surface area for quenching
nsel,s,,,s_nodes
nsel,r,loc,y,hcav+clth+clw+var1+tcui+tcuo,hcav+clth+clw+var1+tcui+tcuo+
(var2/2)-0.0001
cm,surf2,node
D,ALL,TEMP,750-((730/29)*(TM-46))
! Select third surface area for quenching
nsel,s,,,s_nodes
nsel,r,loc,y,hcav+clth+clw+var1,hcav+clth+clw+var1+tcui+tcuo-0.0001
cm,surf3,node
D,ALL,TEMP,500-((480/29)*(TM-46))
! Select fourth surface area for quenching
nsel,s,,,s_nodes
nsel,r,loc,y,hcav+clth+clw+var1+tcui+tcuo+var2-var3-
var4+0.0001,hcav+clth+clw+var1-0.00001
cm,surf4,node
D,ALL,TEMP,250-((230/29)*(TM-46))
        ALLS
        NSUBST,2,4,1,ON,
        OUTRES,ALL,ALL
        SOLVE
*ENDDO
!
!
/COM,           Solve from 75 to 1800 seconds
nsel,s,,,surf1
nsel,a,,,surf2
nsel,a,,,surf3
nsel,a,,,surf4
D,ALL,TEMP,20
TM_START=80
TM_END=1800
TM_INC=5
ALLS
*DO,TM,TM_START,TM_END,TM_INC
        TIME,TM,
        NSUBST,2,4,1,ON,
        OUTRES,ALL,ALL
        SOLVE
*ENDDO
!
FINISH
/POST1
SET,LAST
alls
! Select first surface area for quenching
nsel,s,,,s_nodes
nsel,r,loc,y,hcav+clth+clw+var1+tcui+tcuo+(var2/2),hcav+clth+clw+var1+t
cui+tcuo+var2
cm,surf1,node
! Select second surface area for quenching
```

```
nsel,s,,,s_nodes
nsel,r,loc,y,hcav+clth+clw+var1+tcui+tcuo,hcav+clth+clw+var1+tcui+tcuo+
(var2/2)-0.0001
cm,surf2,node
! Select third surface area for quenching
nsel,s,,,s_nodes
nsel,r,loc,y,hcav+clth+clw+var1,hcav+clth+clw+var1+tcui+tcuo-0.0001
cm,surf3,node
! Select fourth surface area for quenching
nsel,s,,,s_nodes
nsel,r,loc,y,hcav+clth+clw+var1+tcui+tcuo+var2-var3-
var4+0.0001,hcav+clth+clw+var1-0.00001
cm,surf4,node
nsel,s,,,surf1
nsel,a,,,surf2
nsel,a,,,surf3
nsel,a,,,surf4
nsort,s,z,0,0,1
*get,sz_max,sort,,max               ! Z-STRESS (COMPRESSION) MAXIMUM REAL
VALUE
comp_mx=200e6+sz_max                ! OBJECTIVE FUNCTION: MAXIMUM
COMPRESSION
!                                     POSITIVE NUMBER FOR MINIMIZATION
OBTAINED
!                                     USING 200 MPa OFFSET
FINISH
/OPT
OPVAR,comp_mx,OBJ,,,.01               ! OBJECTIVE FUNCTION
OPVAR,var1,DV,0.085,0.15,.002          ! DESIGN VARIABLE #1
OPVAR,var2,DV,0.01,0.025,.002          ! DESIGN VARIABLE #2
OPVAR,var3,DV,0.03,0.06,.002           ! DESIGN VARIABLE #3
OPVAR,var4,DV,0.01,0.06,.002           ! DESIGN VARIABLE #4
OPVAR,var5,DV,0.01,0.05,.002           ! DESIGN VARIABLE #5
OPVAR,var6,DV,0.01,0.08,.002           ! DESIGN VARIABLE #6
OPVAR,var7,DV,0.01,0.08,.002           ! DESIGN VARIABLE #7
OPSAVE,INITIAL,OPT                  ! SAVE INITIAL DESIGN
OPTYPE,SUBP                         ! OPT METHOD IS SUBPROBLEM APPROX.
OPSUBP,30                           ! OPTIMIZE FOR 30 ITERATIONS (MAX)
OPEXE                               ! PERFORM SUB-PROBLEM APPROX.
OPTIMIZATION
OPLIST,ALL,,1                       ! LIST DESIGN SETS
FINISH
/EXIT,NOSA
/EOF
```

APPENDIX VIII

MATHCAD CALCULATION FILES FOR OPTIMIZATION USING SUCCESSIVE QUADRATIC APPROXIMATION

37 data points: Mxy gives the values of 7 variables;
vz gives the corresponding hoop stresses from ANSYS

Mxy =

0.085	0.016	0.042	0.03	0.026	0.038	0.038
0.098	0.016	0.042	0.03	0.026	0.038	0.038
0.111	0.016	0.042	0.03	0.026	0.038	0.038
0.124	0.016	0.042	0.03	0.026	0.038	0.038
0.137	0.016	0.042	0.03	0.026	0.038	0.038
0.15	0.016	0.042	0.03	0.026	0.038	0.038
0.111	0.01	0.042	0.03	0.026	0.038	0.038
0.111	0.013	0.042	0.03	0.026	0.038	0.038
0.111	0.019	0.042	0.03	0.026	0.038	0.038
0.111	0.022	0.042	0.03	0.026	0.038	0.038
0.111	0.025	0.042	0.03	0.026	0.038	0.038
0.111	0.016	0.03	0.03	0.026	0.038	0.038
0.111	0.016	0.036	0.03	0.026	0.038	0.038
0.111	0.016	0.048	0.03	0.026	0.038	0.038
0.111	0.016	0.054	0.03	0.026	0.038	0.038
0.111	0.016	0.06	0.03	0.026	0.038	0.038
0.111	0.016	0.042	0.01	0.026	0.038	0.038
0.111	0.016	0.042	0.02	0.026	0.038	0.038
0.111	0.016	0.042	0.04	0.026	0.038	0.038
0.111	0.016	0.042	0.05	0.026	0.038	0.038
0.111	0.016	0.042	0.06	0.026	0.038	0.038
0.111	0.016	0.042	0.03	0.01	0.038	0.038
0.111	0.016	0.042	0.03	0.018	0.038	0.038
0.111	0.016	0.042	0.03	0.034	0.038	0.038
0.111	0.016	0.042	0.03	0.042	0.038	0.038
0.111	0.016	0.042	0.03	0.05	0.038	0.038
0.111	0.016	0.042	0.03	0.026	0.01	0.038
0.111	0.016	0.042	0.03	0.026	0.024	0.038
0.111	0.016	0.042	0.03	0.026	0.052	0.038
0.111	0.016	0.042	0.03	0.026	0.066	0.038
0.111	0.016	0.042	0.03	0.026	0.08	0.038
0.111	0.016	0.042	0.03	0.026	0.038	0.01
0.111	0.016	0.042	0.03	0.026	0.038	0.024
0.111	0.016	0.042	0.03	0.026	0.038	0.052
0.111	0.016	0.042	0.03	0.026	0.038	0.066
0.111	0.016	0.042	0.03	0.026	0.038	0.08
0.107	0.021	0.031	0.059	0.039	0.053	0.01

Minimum	0.085	0.010	0.030	0.010	0.010	0.010	0.010
Maximum	0.150	0.025	0.060	0.060	0.050	0.080	0.080

vz :=

36616568
22200656
37097322
31736332
28339273
26399543
36493172
23698965
40064955
17111637
134211136
93672103
36448620
16928727
45893010
50971165
140489329
68229458
860031
-23459964
6217825
64502322
50194254
24701456
12184933
-741879
72349661
53812611
21389186
6461343
-7376020
14713633
34878853
36262139
37176709
38547459
-129570000

D:\unlv2\data The values in "coeff" are written out to the file "data" in the D:\unlv2 directory

coeff

The objective function given above as polynomial "p" is minimized using "Monte Carlo Programming": Approximate minimum hoop stress = -299,382,000 Pa

Corresponding design variables:
x1 = 92 mm
x2 = 15 mm
x3 = 41 mm
x4 = 60 mm
x5 = 49 mm
x6 = 77 mm
x7 = 12 mm

Next, ANSYS solution for the values of design variables given above (x1 through x7) are obtained: Actual minimized hoop stress = -23,409,699 Pa

37 data points: Mxy gives the values of 7 variables;
vz gives the corresponding hoop stresses from ANSYS

Mxy =

0.085	0.016	0.042	0.03	0.026	0.038	0.038
0.098	0.016	0.042	0.03	0.026	0.038	0.038
0.111	0.016	0.042	0.03	0.026	0.038	0.038
0.124	0.016	0.042	0.03	0.026	0.038	0.038
0.137	0.016	0.042	0.03	0.026	0.038	0.038
0.15	0.016	0.042	0.03	0.026	0.038	0.038
0.111	0.01	0.042	0.03	0.026	0.038	0.038
0.111	0.013	0.042	0.03	0.026	0.038	0.038
0.111	0.019	0.042	0.03	0.026	0.038	0.038
0.111	0.022	0.042	0.03	0.026	0.038	0.038
0.111	0.025	0.042	0.03	0.026	0.038	0.038
0.111	0.016	0.03	0.03	0.026	0.038	0.038
0.111	0.016	0.036	0.03	0.026	0.038	0.038
0.111	0.016	0.048	0.03	0.026	0.038	0.038
0.111	0.016	0.054	0.03	0.026	0.038	0.038
0.111	0.016	0.06	0.03	0.026	0.038	0.038
0.092	0.015	0.041	0.06	0.049	0.077	0.012
0.111	0.016	0.042	0.02	0.026	0.038	0.038
0.111	0.016	0.042	0.04	0.026	0.038	0.038
0.111	0.016	0.042	0.05	0.026	0.038	0.038
0.111	0.016	0.042	0.06	0.026	0.038	0.038
0.111	0.016	0.042	0.03	0.01	0.038	0.038
0.111	0.016	0.042	0.03	0.018	0.038	0.038
0.111	0.016	0.042	0.03	0.034	0.038	0.038
0.111	0.016	0.042	0.03	0.042	0.038	0.038
0.111	0.016	0.042	0.03	0.05	0.038	0.038
0.111	0.016	0.042	0.03	0.026	0.01	0.038
0.111	0.016	0.042	0.03	0.026	0.024	0.038
0.111	0.016	0.042	0.03	0.026	0.052	0.038
0.111	0.016	0.042	0.03	0.026	0.066	0.038
0.111	0.016	0.042	0.03	0.026	0.08	0.038
0.111	0.016	0.042	0.03	0.026	0.038	0.01
0.111	0.016	0.042	0.03	0.026	0.038	0.024
0.111	0.016	0.042	0.03	0.026	0.038	0.052
0.111	0.016	0.042	0.03	0.026	0.038	0.066
0.111	0.016	0.042	0.03	0.026	0.038	0.08
0.107	0.021	0.031	0.059	0.039	0.053	0.01

Minimum	0.085	0.010	0.030	0.010	0.010	0.010	0.010
Maximum	0.150	0.025	0.060	0.060	0.050	0.080	0.080

$$vz := \begin{pmatrix} 36616568 \\ 22200656 \\ 37097322 \\ 31736332 \\ 28339273 \\ 26399543 \\ 36493172 \\ 23698965 \\ 40064955 \\ 17111637 \\ 134211136 \\ 93672103 \\ 36448620 \\ 16928727 \\ 45893010 \\ 50971165 \\ -23409699 \\ 68229458 \\ 860031 \\ -23459964 \\ 6217825 \\ 64502322 \\ 50194254 \\ 24701456 \\ 12184933 \\ -741879 \\ 72349661 \\ 53812611 \\ 21389186 \\ 6461343 \\ -7376020 \\ 14713633 \\ 34878853 \\ 36262139 \\ 37176709 \\ 38547459 \\ -129570000 \end{pmatrix}$$

D:\unlv2\data The values in "coeff" are written out to the file "data" in the D:\unlv2 directory

coeff

First, the objective function given above as polynomial "p" is minimized using "Monte Carlo Programming":
Approximate minimum hoop stress = -337,154,000 Pa

Corresponding design variables:
x1 = 150 mm
x2 = 17 mm
x3 = 39 mm
x4 = 58 mm
x5 = 48 mm
x6 = 77 mm
x7 = 10 mm

Next, ANSYS solution for the values of design variables given above (x1 through x7) are obtained:
Actual minimized hoop stress = -76,166,379 Pa

37 data points: Mxy gives the values of 7 variables;
vz gives the corresponding hoop stresses from ANSYS

Mxy =

0.085	0.016	0.042	0.03	0.026	0.038	0.038
0.098	0.016	0.042	0.03	0.026	0.038	0.038
0.111	0.016	0.042	0.03	0.026	0.038	0.038
0.124	0.016	0.042	0.03	0.026	0.038	0.038
0.137	0.016	0.042	0.03	0.026	0.038	0.038
0.15	0.016	0.042	0.03	0.026	0.038	0.038
0.111	0.01	0.042	0.03	0.026	0.038	0.038
0.111	0.013	0.042	0.03	0.026	0.038	0.038
0.111	0.019	0.042	0.03	0.026	0.038	0.038
0.111	0.022	0.042	0.03	0.026	0.038	0.038
0.15	0.017	0.039	0.058	0.048	0.077	0.01
0.111	0.016	0.03	0.03	0.026	0.038	0.038
0.111	0.016	0.036	0.03	0.026	0.038	0.038
0.111	0.016	0.048	0.03	0.026	0.038	0.038
0.111	0.016	0.054	0.03	0.026	0.038	0.038
0.111	0.016	0.06	0.03	0.026	0.038	0.038
0.092	0.015	0.041	0.06	0.049	0.077	0.012
0.111	0.016	0.042	0.02	0.026	0.038	0.038
0.111	0.016	0.042	0.04	0.026	0.038	0.038
0.111	0.016	0.042	0.05	0.026	0.038	0.038
0.111	0.016	0.042	0.06	0.026	0.038	0.038
0.111	0.016	0.042	0.03	0.01	0.038	0.038
0.111	0.016	0.042	0.03	0.018	0.038	0.038
0.111	0.016	0.042	0.03	0.034	0.038	0.038
0.111	0.016	0.042	0.03	0.042	0.038	0.038
0.111	0.016	0.042	0.03	0.05	0.038	0.038
0.111	0.016	0.042	0.03	0.026	0.01	0.038
0.111	0.016	0.042	0.03	0.026	0.024	0.038
0.111	0.016	0.042	0.03	0.026	0.052	0.038
0.111	0.016	0.042	0.03	0.026	0.066	0.038
0.111	0.016	0.042	0.03	0.026	0.08	0.038
0.111	0.016	0.042	0.03	0.026	0.038	0.01
0.111	0.016	0.042	0.03	0.026	0.038	0.024
0.111	0.016	0.042	0.03	0.026	0.038	0.052
0.111	0.016	0.042	0.03	0.026	0.038	0.066
0.111	0.016	0.042	0.03	0.026	0.038	0.08
0.107	0.021	0.031	0.059	0.039	0.053	0.01

Minimum	0.085	0.010	0.030	0.010	0.010	0.010	0.010
Maximum	0.150	0.025	0.060	0.060	0.050	0.080	0.080

vz :=

$$\begin{pmatrix} 36616568 \\ 22200656 \\ 37097322 \\ 31736332 \\ 28339273 \\ 26399543 \\ 36493172 \\ 23698965 \\ 40064955 \\ 17111637 \\ -76166379 \\ 93672103 \\ 36448620 \\ 16928727 \\ 45893010 \\ 50971165 \\ -23409699 \\ 68229458 \\ 860031 \\ -23459964 \\ 6217825 \\ 64502322 \\ 50194254 \\ 24701456 \\ 12184933 \\ -741879 \\ 72349661 \\ 53812611 \\ 21389186 \\ 6461343 \\ -7376020 \\ 14713633 \\ 34878853 \\ 36262139 \\ 37176709 \\ 38547459 \\ -129570000 \end{pmatrix}$$

D:\unlv2\data The values in "coeff" are written out to the file "data" in the D:\unlv2 directory

coeff

First, the objective function given above as polynomial "p" is minimized using "Monte Carlo Programming":
Approximate minimum hoop stress = -236,905,000 Pa

Corresponding design variables:
x1 = 95 mm
x2 = 24 mm
x3 = 38 mm
x4 = 58 mm
x5 = 49 mm
x6 = 14 mm
x7 = 10 mm

Next, ANSYS solution for the values of desigr. variables given above (x1 through x7) are obtained:
Actual minimized hoop stress = -83,654,169 Pa

37 data points: Mxy gives the values of 7 variables;
vz gives the corresponding hoop stresses from ANSYS

Mxy =

0.085	0.016	0.042	0.03	0.026	0.038	0.038
0.098	0.016	0.042	0.03	0.026	0.038	0.038
0.111	0.016	0.042	0.03	0.026	0.038	0.038
0.124	0.016	0.042	0.03	0.026	0.038	0.038
0.137	0.016	0.042	0.03	0.026	0.038	0.038
0.15	0.016	0.042	0.03	0.026	0.038	0.038
0.111	0.01	0.042	0.03	0.026	0.038	0.038
0.111	0.013	0.042	0.03	0.026	0.038	0.038
0.111	0.019	0.042	0.03	0.026	0.038	0.038
0.111	0.022	0.042	0.03	0.026	0.038	0.038
0.15	0.017	0.039	0.058	0.048	0.077	0.01
0.095	0.024	0.038	0.058	0.049	0.014	0.01
0.111	0.016	0.036	0.03	0.026	0.038	0.038
0.111	0.016	0.048	0.03	0.026	0.038	0.038
0.111	0.016	0.054	0.03	0.026	0.038	0.038
0.111	0.016	0.06	0.03	0.026	0.038	0.038
0.092	0.015	0.041	0.06	0.049	0.077	0.012
0.111	0.016	0.042	0.02	0.026	0.038	0.038
0.111	0.016	0.042	0.04	0.026	0.038	0.038
0.111	0.016	0.042	0.05	0.026	0.038	0.038
0.111	0.016	0.042	0.06	0.026	0.038	0.038
0.111	0.016	0.042	0.03	0.01	0.038	0.038
0.111	0.016	0.042	0.03	0.018	0.038	0.038
0.111	0.016	0.042	0.03	0.034	0.038	0.038
0.111	0.016	0.042	0.03	0.042	0.038	0.038
0.111	0.016	0.042	0.03	0.05	0.038	0.038
0.111	0.016	0.042	0.03	0.026	0.01	0.038
0.111	0.016	0.042	0.03	0.026	0.024	0.038
0.111	0.016	0.042	0.03	0.026	0.052	0.038
0.111	0.016	0.042	0.03	0.026	0.066	0.038
0.111	0.016	0.042	0.03	0.026	0.08	0.038
0.111	0.016	0.042	0.03	0.026	0.038	0.01
0.111	0.016	0.042	0.03	0.026	0.038	0.024
0.111	0.016	0.042	0.03	0.026	0.038	0.052
0.111	0.016	0.042	0.03	0.026	0.038	0.066
0.111	0.016	0.042	0.03	0.026	0.038	0.08
0.107	0.021	0.031	0.059	0.039	0.053	0.01

Minimum	0.085	0.010	0.030	0.010	0.010	0.010	0.010
Maximum	0.150	0.025	0.060	0.060	0.050	0.080	0.080

$$vz := \begin{pmatrix} 36616568 \\ 22200656 \\ 37097322 \\ 31736332 \\ 28339273 \\ 26399543 \\ 36493172 \\ 23698965 \\ 40064955 \\ 17111637 \\ -76166379 \\ -83654169 \\ 36448620 \\ 16928727 \\ 45893010 \\ 50971165 \\ -23409699 \\ 68229458 \\ 860031 \\ -23459964 \\ 6217825 \\ 64502322 \\ 50194254 \\ 24701456 \\ 12184933 \\ -741879 \\ 72349661 \\ 53812611 \\ 21389186 \\ 6461343 \\ -7376020 \\ 14713633 \\ 34878853 \\ 36262139 \\ 37176709 \\ 38547459 \\ -129570000 \end{pmatrix}$$

D:\unlv2\data	The values in "coeff" are written out to the file "data" in the D:\unlv2 directory

coeff

First, the objective function given above as polynomial "p" is minimized using "Monte Carlo Programming":
Approximate minimum hoop stress = -196,155,000 Pa

Corresponding design variables:
x1 = 97 mm
x2 = 24 mm
x3 = 31 mm
x4 = 58 mm
x5 = 14 mm
x6 = 79 mm
x7 = 12 mm

Next, ANSYS solution for the values of design variables given above (x1 through x7) are obtained:
Actual minimized hoop stress = -135,790,023 Pa

37 data points: Mxy gives the values of 7 variables;
vz gives the corresponding hoop stresses from ANSYS

Mxy =

0.085	0.016	0.042	0.03	0.026	0.038	0.038
0.098	0.016	0.042	0.03	0.026	0.038	0.038
0.111	0.016	0.042	0.03	0.026	0.038	0.038
0.124	0.016	0.042	0.03	0.026	0.038	0.038
0.137	0.016	0.042	0.03	0.026	0.038	0.038
0.15	0.016	0.042	0.03	0.026	0.038	0.038
0.111	0.01	0.042	0.03	0.026	0.038	0.038
0.111	0.013	0.042	0.03	0.026	0.038	0.038
0.111	0.019	0.042	0.03	0.026	0.038	0.038
0.111	0.022	0.042	0.03	0.026	0.038	0.038
0.15	0.017	0.039	0.058	0.048	0.077	0.01
0.095	0.024	0.038	0.058	0.049	0.014	0.01
0.111	0.016	0.036	0.03	0.026	0.038	0.038
0.111	0.016	0.048	0.03	0.026	0.038	0.038
0.111	0.016	0.054	0.03	0.026	0.038	0.038
0.111	0.016	0.06	0.03	0.026	0.038	0.038
0.092	0.015	0.041	0.06	0.049	0.077	0.012
0.111	0.016	0.042	0.02	0.026	0.038	0.038
0.111	0.016	0.042	0.04	0.026	0.038	0.038
0.111	0.016	0.042	0.05	0.026	0.038	0.038
0.111	0.016	0.042	0.06	0.026	0.038	0.038
0.111	0.016	0.042	0.03	0.01	0.038	0.038
0.111	0.016	0.042	0.03	0.018	0.038	0.038
0.111	0.016	0.042	0.03	0.034	0.038	0.038
0.111	0.016	0.042	0.03	0.042	0.038	0.038
0.111	0.016	0.042	0.03	0.05	0.038	0.038
0.097	0.024	0.031	0.058	0.014	0.079	0.012
0.111	0.016	0.042	0.03	0.026	0.024	0.038
0.111	0.016	0.042	0.03	0.026	0.052	0.038
0.111	0.016	0.042	0.03	0.026	0.066	0.038
0.111	0.016	0.042	0.03	0.026	0.08	0.038
0.111	0.016	0.042	0.03	0.026	0.038	0.01
0.111	0.016	0.042	0.03	0.026	0.038	0.024
0.111	0.016	0.042	0.03	0.026	0.038	0.052
0.111	0.016	0.042	0.03	0.026	0.038	0.066
0.111	0.016	0.042	0.03	0.026	0.038	0.08
0.107	0.021	0.031	0.059	0.039	0.053	0.01

Minimum	0.085	0.010	0.030	0.010	0.010	0.010	0.010
Maximum	0.150	0.025	0.060	0.060	0.050	0.080	0.080

vz :=

$$\begin{pmatrix} 36616568 \\ 22200656 \\ 37097322 \\ 31736332 \\ 28339273 \\ 26399543 \\ 36493172 \\ 23698965 \\ 40064955 \\ 17111637 \\ -76166379 \\ -83654169 \\ 36448620 \\ 16928727 \\ 45893010 \\ 50971165 \\ -23409699 \\ 68229458 \\ 860031 \\ -23459964 \\ 6217825 \\ 64502322 \\ 50194254 \\ 24701456 \\ 12184933 \\ -741879 \\ -135790023 \\ 53812611 \\ 21389186 \\ 6461343 \\ -7376020 \\ 14713633 \\ 34878853 \\ 36262139 \\ 37176709 \\ 38547459 \\ -129570000 \end{pmatrix}$$

D:\unlv2\data The values in "coeff" are written out to the file "data" in the D:\unlv2 directory

coeff

First, the objective function given above as polynomial "p" is minimized using "Monte Carlo Programming":
Approximate minimum hoop stress = -199,218,000 Pa

Corresponding design variables:
x1 = 145 mm
x2 = 24 mm
x3 = 32 mm
x4 = 56 mm
x5 = 50 mm
x6 = 12 mm
x7 = 11 mm

Next, ANSYS solution for the values of design variables given above (x1 through x7) are obtained:
Actual minimized hoop stress = -87,555,938 Pa

37 data points: Mxy gives the values of 7 variables;
vz gives the corresponding hoop stresses from ANSYS

Mxy =

0.085	0.016	0.042	0.03	0.026	0.038	0.038
0.098	0.016	0.042	0.03	0.026	0.038	0.038
0.111	0.016	0.042	0.03	0.026	0.038	0.038
0.124	0.016	0.042	0.03	0.026	0.038	0.038
0.137	0.016	0.042	0.03	0.026	0.038	0.038
0.15	0.016	0.042	0.03	0.026	0.038	0.038
0.111	0.01	0.042	0.03	0.026	0.038	0.038
0.111	0.013	0.042	0.03	0.026	0.038	0.038
0.111	0.019	0.042	0.03	0.026	0.038	0.038
0.111	0.022	0.042	0.03	0.026	0.038	0.038
0.15	0.017	0.039	0.058	0.048	0.077	0.01
0.095	0.024	0.038	0.058	0.049	0.014	0.01
0.111	0.016	0.036	0.03	0.026	0.038	0.038
0.111	0.016	0.048	0.03	0.026	0.038	0.038
0.111	0.016	0.054	0.03	0.026	0.038	0.038
0.111	0.016	0.06	0.03	0.026	0.038	0.038
0.092	0.015	0.041	0.06	0.049	0.077	0.012
0.145	0.024	0.032	0.056	0.05	0.012	0.011
0.111	0.016	0.042	0.04	0.026	0.038	0.038
0.111	0.016	0.042	0.05	0.026	0.038	0.038
0.111	0.016	0.042	0.06	0.026	0.038	0.038
0.111	0.016	0.042	0.03	0.01	0.038	0.038
0.111	0.016	0.042	0.03	0.018	0.038	0.038
0.111	0.016	0.042	0.03	0.034	0.038	0.038
0.111	0.016	0.042	0.03	0.042	0.038	0.038
0.111	0.016	0.042	0.03	0.05	0.038	0.038
0.097	0.024	0.031	0.058	0.014	0.079	0.012
0.111	0.016	0.042	0.03	0.026	0.024	0.038
0.111	0.016	0.042	0.03	0.026	0.052	0.038
0.111	0.016	0.042	0.03	0.026	0.066	0.038
0.111	0.016	0.042	0.03	0.026	0.08	0.038
0.111	0.016	0.042	0.03	0.026	0.038	0.01
0.111	0.016	0.042	0.03	0.026	0.038	0.024
0.111	0.016	0.042	0.03	0.026	0.038	0.052
0.111	0.016	0.042	0.03	0.026	0.038	0.066
0.111	0.016	0.042	0.03	0.026	0.038	0.08
0.107	0.021	0.031	0.059	0.039	0.053	0.01

Minimum	0.085	0.010	0.030	0.010	0.010	0.010	0.010
Maximum	0.150	0.025	0.060	0.060	0.050	0.080	0.080

$$
vz := \begin{pmatrix} 36616568 \\ 22200656 \\ 37097322 \\ 31736332 \\ 28339273 \\ 26399543 \\ 36493172 \\ 23698965 \\ 40064955 \\ 17111637 \\ -76166379 \\ -83654169 \\ 36448620 \\ 16928727 \\ 45893010 \\ 50971165 \\ -23409699 \\ -87555938 \\ 860031 \\ -23459964 \\ 6217825 \\ 64502322 \\ 50194254 \\ 24701456 \\ 12184933 \\ -741879 \\ -135790023 \\ 53812611 \\ 21389186 \\ 6461343 \\ -7376020 \\ 14713633 \\ 34878853 \\ 36262139 \\ 37176709 \\ 38547459 \\ -129570000 \end{pmatrix}
$$

D:\unlv2\data	The values in "coeff" are written out to the file "data" in the D:\unlv2 directory

coeff

First, the objective function given above as polynomial "p" is minimized using "Monte Carlo Programming":
Approximate minimum hoop stress = -177,281,000 Pa

Corresponding design variables:
x1 = 132 mm
x2 = 25 mm
x3 = 30 mm
x4 = 54 mm
x5 = 35 mm
x6 = 79 mm
x7 = 11 mm

Next, ANSYS solution for the values of design variables given above (x1 through x7) are obtained:
Actual minimized hoop stress = -113,421,927 Pa

37 data points: Mxy gives the values of 7 variables; vz gives the corresponding hoop stresses from ANSYS

Mxy =

0.085	0.016	0.042	0.03	0.026	0.038	0.038
0.098	0.016	0.042	0.03	0.026	0.038	0.038
0.111	0.016	0.042	0.03	0.026	0.038	0.038
0.124	0.016	0.042	0.03	0.026	0.038	0.038
0.137	0.016	0.042	0.03	0.026	0.038	0.038
0.15	0.016	0.042	0.03	0.026	0.038	0.038
0.111	0.01	0.042	0.03	0.026	0.038	0.038
0.111	0.013	0.042	0.03	0.026	0.038	0.038
0.111	0.019	0.042	0.03	0.026	0.038	0.038
0.111	0.022	0.042	0.03	0.026	0.038	0.038
0.15	0.017	0.039	0.058	0.048	0.077	0.01
0.095	0.024	0.038	0.058	0.049	0.014	0.01
0.111	0.016	0.036	0.03	0.026	0.038	0.038
0.111	0.016	0.048	0.03	0.026	0.038	0.038
0.111	0.016	0.054	0.03	0.026	0.038	0.038
0.111	0.016	0.06	0.03	0.026	0.038	0.038
0.092	0.015	0.041	0.06	0.049	0.077	0.012
0.145	0.024	0.032	0.056	0.05	0.012	0.011
0.111	0.016	0.042	0.04	0.026	0.038	0.038
0.111	0.016	0.042	0.05	0.026	0.038	0.038
0.111	0.016	0.042	0.06	0.026	0.038	0.038
0.132	0.025	0.03	0.054	0.035	0.079	0.011
0.111	0.016	0.042	0.03	0.018	0.038	0.038
0.111	0.016	0.042	0.03	0.034	0.038	0.038
0.111	0.016	0.042	0.03	0.042	0.038	0.038
0.111	0.016	0.042	0.03	0.05	0.038	0.038
0.097	0.024	0.031	0.058	0.014	0.079	0.012
0.111	0.016	0.042	0.03	0.026	0.024	0.038
0.111	0.016	0.042	0.03	0.026	0.052	0.038
0.111	0.016	0.042	0.03	0.026	0.066	0.038
0.111	0.016	0.042	0.03	0.026	0.08	0.038
0.111	0.016	0.042	0.03	0.026	0.038	0.01
0.111	0.016	0.042	0.03	0.026	0.038	0.024
0.111	0.016	0.042	0.03	0.026	0.038	0.052
0.111	0.016	0.042	0.03	0.026	0.038	0.066
0.111	0.016	0.042	0.03	0.026	0.038	0.08
0.107	0.021	0.031	0.059	0.039	0.053	0.01

Minimum	0.085	0.010	0.030	0.010	0.010	0.010	0.010
Maximum	0.150	0.025	0.060	0.060	0.050	0.080	0.080

$$vz := \begin{pmatrix} 36616568 \\ 22200656 \\ 37097322 \\ 31736332 \\ 28339273 \\ 26399543 \\ 36493172 \\ 23698965 \\ 40064955 \\ 17111637 \\ -76166379 \\ -83654169 \\ 36448620 \\ 16928727 \\ 45893010 \\ 50971165 \\ -23409699 \\ -87555938 \\ 860031 \\ -23459964 \\ 6217825 \\ -113421927 \\ 50194254 \\ 24701456 \\ 12184933 \\ -741879 \\ -135790023 \\ 53812611 \\ 21389186 \\ 6461343 \\ -7376020 \\ 14713633 \\ 34878853 \\ 36262139 \\ 37176709 \\ 38547459 \\ -129570000 \end{pmatrix}$$

D:\unlv2\data — The values in "coeff" are written out to the file "data" in the D:\unlv2 directory

coeff

First, the objective function given above as polynomial "p" is minimized using "Monte Carlo Programming":
Approximate minimum hoop stress = -312,935,000 Pa

Corresponding design variables:
x1 = 149 mm
x2 = 23 mm
x3 = 59 mm
x4 = 29 mm
x5 = 49 mm
x6 = 79 mm
x7 = 79 mm

Next, ANSYS solution for the values of design variables given above (x1 through x7) are obtained:
Actual minimized hoop stress = -23,960,716 Pa

37 data points: Mxy gives the values of 7 variables;
vz gives the corresponding hoop stresses from ANSYS

Mxy =

0.085	0.016	0.042	0.03	0.026	0.038	0.038
0.098	0.016	0.042	0.03	0.026	0.038	0.038
0.111	0.016	0.042	0.03	0.026	0.038	0.038
0.124	0.016	0.042	0.03	0.026	0.038	0.038
0.137	0.016	0.042	0.03	0.026	0.038	0.038
0.15	0.016	0.042	0.03	0.026	0.038	0.038
0.111	0.01	0.042	0.03	0.026	0.038	0.038
0.111	0.013	0.042	0.03	0.026	0.038	0.038
0.111	0.019	0.042	0.03	0.026	0.038	0.038
0.111	0.022	0.042	0.03	0.026	0.038	0.038
0.15	0.017	0.039	0.058	0.048	0.077	0.01
0.095	0.024	0.038	0.058	0.049	0.014	0.01
0.111	0.016	0.036	0.03	0.026	0.038	0.038
0.111	0.016	0.048	0.03	0.026	0.038	0.038
0.111	0.016	0.054	0.03	0.026	0.038	0.038
0.111	0.016	0.06	0.03	0.026	0.038	0.038
0.092	0.015	0.041	0.06	0.049	0.077	0.012
0.145	0.024	0.032	0.056	0.05	0.012	0.011
0.111	0.016	0.042	0.04	0.026	0.038	0.038
0.111	0.016	0.042	0.05	0.026	0.038	0.038
0.111	0.016	0.042	0.06	0.026	0.038	0.038
0.132	0.025	0.03	0.054	0.035	0.079	0.011
0.111	0.016	0.042	0.03	0.018	0.038	0.038
0.111	0.016	0.042	0.03	0.034	0.038	0.038
0.111	0.016	0.042	0.03	0.042	0.038	0.038
0.111	0.016	0.042	0.03	0.05	0.038	0.038
0.097	0.024	0.031	0.058	0.014	0.079	0.012
0.149	0.023	0.059	0.029	0.049	0.079	0.079
0.111	0.016	0.042	0.03	0.026	0.052	0.038
0.111	0.016	0.042	0.03	0.026	0.066	0.038
0.111	0.016	0.042	0.03	0.026	0.08	0.038
0.111	0.016	0.042	0.03	0.026	0.038	0.01
0.111	0.016	0.042	0.03	0.026	0.038	0.024
0.111	0.016	0.042	0.03	0.026	0.038	0.052
0.111	0.016	0.042	0.03	0.026	0.038	0.066
0.111	0.016	0.042	0.03	0.026	0.038	0.08
0.107	0.021	0.031	0.059	0.039	0.053	0.01

Minimum	0.085	0.010	0.030	0.010	0.010	0.010	0.010
Maximum	0.150	0.025	0.060	0.060	0.050	0.080	0.080

$$vz := \begin{pmatrix} 36616568 \\ 22200656 \\ 37097322 \\ 31736332 \\ 28339273 \\ 26399543 \\ 36493172 \\ 23698965 \\ 40064955 \\ 17111637 \\ -76166379 \\ -83654169 \\ 36448620 \\ 16928727 \\ 45893010 \\ 50971165 \\ -23409699 \\ -87555938 \\ 860031 \\ -23459964 \\ 6217825 \\ -113421927 \\ 50194254 \\ 24701456 \\ 12184933 \\ -741879 \\ -135790023 \\ -23960716 \\ 21389186 \\ 6461343 \\ -7376020 \\ 14713633 \\ 34878853 \\ 36262139 \\ 37176709 \\ 38547459 \\ -129570000 \end{pmatrix}$$

D:\unlv2\data   The values in "coeff" are written out to the file "data" in the D:\unlv2 directory

coeff

First, the objective function given above as polynomial "p" is minimized using "Monte Carlo Programming":
Approximate minimum hoop stress = -199,748,000 Pa

Corresponding design variables:
x1 = 87 mm
x2 = 25 mm
x3 = 30 mm
x4 = 37 mm
x5 = 48 mm
x6 = 80 mm
x7 = 17 mm

Next, ANSYS solution for the values of design variables given above (x1 through x7) are obtained:
Actual minimized hoop stress = -110,954,614 Pa

37 data points: Mxy gives the values of 7 variables;
vz gives the corresponding hoop stresses from ANSYS

Mxy =

0.085	0.016	0.042	0.03	0.026	0.038	0.038
0.098	0.016	0.042	0.03	0.026	0.038	0.038
0.111	0.016	0.042	0.03	0.026	0.038	0.038
0.124	0.016	0.042	0.03	0.026	0.038	0.038
0.137	0.016	0.042	0.03	0.026	0.038	0.038
0.15	0.016	0.042	0.03	0.026	0.038	0.038
0.111	0.01	0.042	0.03	0.026	0.038	0.038
0.111	0.013	0.042	0.03	0.026	0.038	0.038
0.111	0.019	0.042	0.03	0.026	0.038	0.038
0.111	0.022	0.042	0.03	0.026	0.038	0.038
0.15	0.017	0.039	0.058	0.048	0.077	0.01
0.095	0.024	0.038	0.058	0.049	0.014	0.01
0.111	0.016	0.036	0.03	0.026	0.038	0.038
0.111	0.016	0.048	0.03	0.026	0.038	0.038
0.111	0.016	0.054	0.03	0.026	0.038	0.038
0.087	0.025	0.03	0.037	0.048	0.08	0.017
0.092	0.015	0.041	0.06	0.049	0.077	0.012
0.145	0.024	0.032	0.056	0.05	0.012	0.011
0.111	0.016	0.042	0.04	0.026	0.038	0.038
0.111	0.016	0.042	0.05	0.026	0.038	0.038
0.111	0.016	0.042	0.06	0.026	0.038	0.038
0.132	0.025	0.03	0.054	0.035	0.079	0.011
0.111	0.016	0.042	0.03	0.018	0.038	0.038
0.111	0.016	0.042	0.03	0.034	0.038	0.038
0.111	0.016	0.042	0.03	0.042	0.038	0.038
0.111	0.016	0.042	0.03	0.05	0.038	0.038
0.097	0.024	0.031	0.058	0.014	0.079	0.012
0.149	0.023	0.059	0.029	0.049	0.079	0.079
0.111	0.016	0.042	0.03	0.026	0.052	0.038
0.111	0.016	0.042	0.03	0.026	0.066	0.038
0.111	0.016	0.042	0.03	0.026	0.08	0.038
0.111	0.016	0.042	0.03	0.026	0.038	0.01
0.111	0.016	0.042	0.03	0.026	0.038	0.024
0.111	0.016	0.042	0.03	0.026	0.038	0.052
0.111	0.016	0.042	0.03	0.026	0.038	0.066
0.111	0.016	0.042	0.03	0.026	0.038	0.08
0.107	0.021	0.031	0.059	0.039	0.053	0.01

Minimum	0.085	0.010	0.030	0.010	0.010	0.010	0.010
Maximum	0.150	0.025	0.060	0.060	0.050	0.080	0.080

$$vz := \begin{pmatrix} 36616568 \\ 22200656 \\ 37097322 \\ 31736332 \\ 28339273 \\ 26399543 \\ 36493172 \\ 23698965 \\ 40064955 \\ 17111637 \\ -76166379 \\ -83654169 \\ 36448620 \\ 16928727 \\ 45893010 \\ -110954614 \\ -23409699 \\ -87555938 \\ 860031 \\ -23459964 \\ 6217825 \\ -113421927 \\ 50194254 \\ 24701456 \\ 12184933 \\ -741879 \\ -135790023 \\ -23960716 \\ 21389186 \\ 6461343 \\ -7376020 \\ 14713633 \\ 34878853 \\ 36262139 \\ 37176709 \\ 38547459 \\ -129570000 \end{pmatrix}$$

D:\unlv2\data	The values in "coeff" are written out to the file "data" in the D:\unlv2 directory

coeff

First, the objective function given above as polynomial "p" is minimized using "Monte Carlo Programming":
Approximate minimum hoop stress = -201,030,000 Pa

Corresponding design variables:
x1 = 85 mm
x2 = 24 mm
x3 = 31 mm
x4 = 60 mm
x5 = 14 mm
x6 = 14 mm
x7 = 12 mm

Next, ANSYS solution for the values of design variables given above (x1 through x7) are obtained:
Actual minimized hoop stress = -4,347,296 Pa

37 data points: Mxy gives the values of 7 variables;
vz gives the corresponding hoop stresses from ANSYS

Mxy =

0.085	0.016	0.042	0.03	0.026	0.038	0.038
0.098	0.016	0.042	0.03	0.026	0.038	0.038
0.111	0.016	0.042	0.03	0.026	0.038	0.038
0.124	0.016	0.042	0.03	0.026	0.038	0.038
0.137	0.016	0.042	0.03	0.026	0.038	0.038
0.15	0.016	0.042	0.03	0.026	0.038	0.038
0.111	0.01	0.042	0.03	0.026	0.038	0.038
0.111	0.013	0.042	0.03	0.026	0.038	0.038
0.111	0.019	0.042	0.03	0.026	0.038	0.038
0.111	0.022	0.042	0.03	0.026	0.038	0.038
0.15	0.017	0.039	0.058	0.048	0.077	0.01
0.095	0.024	0.038	0.058	0.049	0.014	0.01
0.111	0.016	0.036	0.03	0.026	0.038	0.038
0.111	0.016	0.048	0.03	0.026	0.038	0.038
0.111	0.016	0.054	0.03	0.026	0.038	0.038
0.087	0.025	0.03	0.037	0.048	0.08	0.017
0.092	0.015	0.041	0.06	0.049	0.077	0.012
0.145	0.024	0.032	0.056	0.05	0.012	0.011
0.111	0.016	0.042	0.04	0.026	0.038	0.038
0.111	0.016	0.042	0.05	0.026	0.038	0.038
0.111	0.016	0.042	0.06	0.026	0.038	0.038
0.132	0.025	0.03	0.054	0.035	0.079	0.011
0.085	0.024	0.031	0.06	0.014	0.014	0.012
0.111	0.016	0.042	0.03	0.034	0.038	0.038
0.111	0.016	0.042	0.03	0.042	0.038	0.038
0.111	0.016	0.042	0.03	0.05	0.038	0.038
0.097	0.024	0.031	0.058	0.014	0.079	0.012
0.149	0.023	0.059	0.029	0.049	0.079	0.079
0.111	0.016	0.042	0.03	0.026	0.052	0.038
0.111	0.016	0.042	0.03	0.026	0.066	0.038
0.111	0.016	0.042	0.03	0.026	0.08	0.038
0.111	0.016	0.042	0.03	0.026	0.038	0.01
0.111	0.016	0.042	0.03	0.026	0.038	0.024
0.111	0.016	0.042	0.03	0.026	0.038	0.052
0.111	0.016	0.042	0.03	0.026	0.038	0.066
0.111	0.016	0.042	0.03	0.026	0.038	0.08
0.107	0.021	0.031	0.059	0.039	0.053	0.01

Minimum	0.085	0.010	0.030	0.010	0.010	0.010	0.010
Maximum	0.150	0.025	0.060	0.060	0.050	0.080	0.080

$$
vz := \begin{pmatrix} 36616568 \\ 22200656 \\ 37097322 \\ 31736332 \\ 28339273 \\ 26399543 \\ 36493172 \\ 23698965 \\ 40064955 \\ 17111637 \\ -76166379 \\ -83654169 \\ 36448620 \\ 16928727 \\ 45893010 \\ -110954614 \\ -23409699 \\ -87555938 \\ 860031 \\ -23459964 \\ 6217825 \\ -113421927 \\ -4347296 \\ 24701456 \\ 12184933 \\ -741879 \\ -135790023 \\ -23960716 \\ 21389186 \\ 6461343 \\ -7376020 \\ 14713633 \\ 34878853 \\ 36262139 \\ 37176709 \\ 38547459 \\ -129570000 \end{pmatrix}
$$

D:\unlv2\data — The values in "coeff" are written out to the file "data" in the D:\unlv2 directory

coeff

First, the objective function given above as polynomial "p" is minimized using "Monte Carlo Programming":
Approximate minimum hoop stress = -329,016,000 Pa

Corresponding design variables:
x1 = 147 mm
x2 = 10 mm
x3 = 30 mm
x4 = 60 mm
x5 = 10 mm
x6 = 71 mm
x7 = 13 mm

Next, ANSYS solution for the values of design variables given above (x1 through x7) are obtained:
Actual minimized hoop stress = -63,177,822 Pa

37 data points: Mxy gives the values of 7 variables; vz gives the corresponding hoop stresses from ANSYS

Mxy =

0.085	0.016	0.042	0.03	0.026	0.038	0.038
0.098	0.016	0.042	0.03	0.026	0.038	0.038
0.111	0.016	0.042	0.03	0.026	0.038	0.038
0.124	0.016	0.042	0.03	0.026	0.038	0.038
0.137	0.016	0.042	0.03	0.026	0.038	0.038
0.15	0.016	0.042	0.03	0.026	0.038	0.038
0.111	0.01	0.042	0.03	0.026	0.038	0.038
0.111	0.013	0.042	0.03	0.026	0.038	0.038
0.111	0.019	0.042	0.03	0.026	0.038	0.038
0.111	0.022	0.042	0.03	0.026	0.038	0.038
0.15	0.017	0.039	0.058	0.048	0.077	0.01
0.095	0.024	0.038	0.058	0.049	0.014	0.01
0.111	0.016	0.036	0.03	0.026	0.038	0.038
0.111	0.016	0.048	0.03	0.026	0.038	0.038
0.147	0.01	0.03	0.06	0.01	0.071	0.013
0.087	0.025	0.03	0.037	0.048	0.08	0.017
0.092	0.015	0.041	0.06	0.049	0.077	0.012
0.145	0.024	0.032	0.056	0.05	0.012	0.011
0.111	0.016	0.042	0.04	0.026	0.038	0.038
0.111	0.016	0.042	0.05	0.026	0.038	0.038
0.111	0.016	0.042	0.06	0.026	0.038	0.038
0.132	0.025	0.03	0.054	0.035	0.079	0.011
0.085	0.024	0.031	0.06	0.014	0.014	0.012
0.111	0.016	0.042	0.03	0.034	0.038	0.038
0.111	0.016	0.042	0.03	0.042	0.038	0.038
0.111	0.016	0.042	0.03	0.05	0.038	0.038
0.097	0.024	0.031	0.058	0.014	0.079	0.012
0.149	0.023	0.059	0.029	0.049	0.079	0.079
0.111	0.016	0.042	0.03	0.026	0.052	0.038
0.111	0.016	0.042	0.03	0.026	0.066	0.038
0.111	0.016	0.042	0.03	0.026	0.08	0.038
0.111	0.016	0.042	0.03	0.026	0.038	0.01
0.111	0.016	0.042	0.03	0.026	0.038	0.024
0.111	0.016	0.042	0.03	0.026	0.038	0.052
0.111	0.016	0.042	0.03	0.026	0.038	0.066
0.111	0.016	0.042	0.03	0.026	0.038	0.08
0.107	0.021	0.031	0.059	0.039	0.053	0.01

Minimum	0.085	0.010	0.030	0.010	0.010	0.010	0.010
Maximum	0.150	0.025	0.060	0.060	0.050	0.080	0.080

$$vz := \begin{pmatrix} 36616568 \\ 22200656 \\ 37097322 \\ 31736332 \\ 28339273 \\ 26399543 \\ 36493172 \\ 23698965 \\ 40064955 \\ 17111637 \\ -76166379 \\ -83654169 \\ 36448620 \\ 16928727 \\ -63177822 \\ -110954614 \\ -23409699 \\ -87555938 \\ 860031 \\ -23459964 \\ 6217825 \\ -113421927 \\ -4347296 \\ 24701456 \\ 12184933 \\ -741879 \\ -135790023 \\ -23960716 \\ 21389186 \\ 6461343 \\ -7376020 \\ 14713633 \\ 34878853 \\ 36262139 \\ 37176709 \\ 38547459 \\ -129570000 \end{pmatrix}$$

D:\unlv2\data   The values in "coeff" are written out to the file "data" in the D:\unlv2 directory

coeff

First, the objective function given above as polynomial "p" is minimized using "Monte Carlo Programming":
Approximate minimum hoop stress = -481,532,000 Pa

Corresponding design variables:
x1 = 87 mm
x2 = 25 mm
x3 = 30 mm
x4 = 58 mm
x5 = 42 mm
x6 = 57 mm
x7 = 80 mm

Next, ANSYS solution for the values of design variables given above (x1 through x7) are obtained:
Actual minimized hoop stress = -95,536,865 Pa

37 data points: Mxy gives the values of 7 variables;
vz gives the corresponding hoop stresses from ANSYS

Mxy =

	0.085	0.016	0.042	0.03	0.026	0.038	0.038
	0.098	0.016	0.042	0.03	0.026	0.038	0.038
	0.111	0.016	0.042	0.03	0.026	0.038	0.038
	0.124	0.016	0.042	0.03	0.026	0.038	0.038
	0.137	0.016	0.042	0.03	0.026	0.038	0.038
	0.15	0.016	0.042	0.03	0.026	0.038	0.038
	0.111	0.01	0.042	0.03	0.026	0.038	0.038
	0.111	0.013	0.042	0.03	0.026	0.038	0.038
	0.087	0.025	0.03	0.058	0.042	0.057	0.08
	0.111	0.022	0.042	0.03	0.026	0.038	0.038
	0.15	0.017	0.039	0.058	0.048	0.077	0.01
	0.095	0.024	0.038	0.058	0.049	0.014	0.01
	0.111	0.016	0.036	0.03	0.026	0.038	0.038
	0.111	0.016	0.048	0.03	0.026	0.038	0.038
	0.147	0.01	0.03	0.06	0.01	0.071	0.013
	0.087	0.025	0.03	0.037	0.048	0.08	0.017
	0.092	0.015	0.041	0.06	0.049	0.077	0.012
	0.145	0.024	0.032	0.056	0.05	0.012	0.011
	0.111	0.016	0.042	0.04	0.026	0.038	0.038
	0.111	0.016	0.042	0.05	0.026	0.038	0.038
	0.111	0.016	0.042	0.06	0.026	0.038	0.038
	0.132	0.025	0.03	0.054	0.035	0.079	0.011
	0.085	0.024	0.031	0.06	0.014	0.014	0.012
	0.111	0.016	0.042	0.03	0.034	0.038	0.038
	0.111	0.016	0.042	0.03	0.042	0.038	0.038
	0.111	0.016	0.042	0.03	0.05	0.038	0.038
	0.097	0.024	0.031	0.058	0.014	0.079	0.012
	0.149	0.023	0.059	0.029	0.049	0.079	0.079
	0.111	0.016	0.042	0.03	0.026	0.052	0.038
	0.111	0.016	0.042	0.03	0.026	0.066	0.038
	0.111	0.016	0.042	0.03	0.026	0.08	0.038
	0.111	0.016	0.042	0.03	0.026	0.038	0.01
	0.111	0.016	0.042	0.03	0.026	0.038	0.024
	0.111	0.016	0.042	0.03	0.026	0.038	0.052
	0.111	0.016	0.042	0.03	0.026	0.038	0.066
	0.111	0.016	0.042	0.03	0.026	0.038	0.08
	0.107	0.021	0.031	0.059	0.039	0.053	0.01
Minimum	0.085	0.010	0.030	0.010	0.010	0.010	0.010
Maximum	0.150	0.025	0.060	0.060	0.050	0.080	0.080

vz :=

36616568
22200656
37097322
31736332
28339273
26399543
36493172
23698965
−95536865
17111637
−76166379
−83654169
36448620
16928727
−63177822
−110954614
−23409699
−87555938
860031
−23459964
6217825
−113421927
−4347296
24701456
12184933
−741879
−135790023
−23960716
21389186
6461343
−7376020
14713633
34878853
36262139
37176709
38547459
−129570000

D:\unlv2\data	The values in "coeff" are written out to the file "data" in the D:\unlv2 directory

coeff

First, the objective function given above as polynomial "p" is minimized using "Monte Carlo Programming":
Approximate minimum hoop stress = -459,349,000 Pa

Corresponding design variables:
x1 = 150 mm
x2 = 24 mm
x3 = 59 mm
x4 = 33 mm
x5 = 11 mm
x6 = 78 mm
x7 = 73 mm

Next, ANSYS solution for the values of design variables given above (x1 through x7) are obtained:
Actual minimized hoop stress = -3,646,239 Pa

37 data points: Mxy gives the values of 7 variables; vz gives the corresponding hoop stresses from ANSYS

Mxy =

0.085	0.016	0.042	0.03	0.026	0.038	0.038
0.098	0.016	0.042	0.03	0.026	0.038	0.038
0.111	0.016	0.042	0.03	0.026	0.038	0.038
0.124	0.016	0.042	0.03	0.026	0.038	0.038
0.137	0.016	0.042	0.03	0.026	0.038	0.038
0.15	0.016	0.042	0.03	0.026	0.038	0.038
0.111	0.01	0.042	0.03	0.026	0.038	0.038
0.111	0.013	0.042	0.03	0.026	0.038	0.038
0.087	0.025	0.03	0.058	0.042	0.057	0.08
0.111	0.022	0.042	0.03	0.026	0.038	0.038
0.15	0.017	0.039	0.058	0.048	0.077	0.01
0.095	0.024	0.038	0.058	0.049	0.014	0.01
0.111	0.016	0.036	0.03	0.026	0.038	0.038
0.111	0.016	0.048	0.03	0.026	0.038	0.038
0.147	0.01	0.03	0.06	0.01	0.071	0.013
0.087	0.025	0.03	0.037	0.048	0.08	0.017
0.092	0.015	0.041	0.06	0.049	0.077	0.012
0.145	0.024	0.032	0.056	0.05	0.012	0.011
0.111	0.016	0.042	0.04	0.026	0.038	0.038
0.111	0.016	0.042	0.05	0.026	0.038	0.038
0.111	0.016	0.042	0.06	0.026	0.038	0.038
0.132	0.025	0.03	0.054	0.035	0.079	0.011
0.085	0.024	0.031	0.06	0.014	0.014	0.012
0.111	0.016	0.042	0.03	0.034	0.038	0.038
0.111	0.016	0.042	0.03	0.042	0.038	0.038
0.111	0.016	0.042	0.03	0.05	0.038	0.038
0.097	0.024	0.031	0.058	0.014	0.079	0.012
0.149	0.023	0.059	0.029	0.049	0.079	0.079
0.111	0.016	0.042	0.03	0.026	0.052	0.038
0.111	0.016	0.042	0.03	0.026	0.066	0.038
0.111	0.016	0.042	0.03	0.026	0.08	0.038
0.111	0.016	0.042	0.03	0.026	0.038	0.01
0.111	0.016	0.042	0.03	0.026	0.038	0.024
0.111	0.016	0.042	0.03	0.026	0.038	0.052
0.111	0.016	0.042	0.03	0.026	0.038	0.066
0.15	0.024	0.059	0.033	0.011	0.078	0.073
0.107	0.021	0.031	0.059	0.039	0.053	0.01

Minimum	0.085	0.010	0.030	0.010	0.010	0.010	0.010
Maximum	0.150	0.025	0.060	0.060	0.050	0.080	0.080

$$
vz := \begin{pmatrix} 36616568 \\ 22200656 \\ 37097322 \\ 31736332 \\ 28339273 \\ 26399543 \\ 36493172 \\ 23698965 \\ -95536865 \\ 17111637 \\ -76166379 \\ -83654169 \\ 36448620 \\ 16928727 \\ -63177822 \\ -110954614 \\ -23409699 \\ -87555938 \\ 860031 \\ -23459964 \\ 6217825 \\ -113421927 \\ -4347296 \\ 24701456 \\ 12184933 \\ -741879 \\ -135790023 \\ -23960716 \\ 21389186 \\ 6461343 \\ -7376020 \\ 14713633 \\ 34878853 \\ 36262139 \\ 37176709 \\ -3646239 \\ -129570000 \end{pmatrix}
$$

D:\univ2\data	The values in "coeff" are written out to the file "data" in the D:\univ2 directory

coeff

First, the objective function given above as polynomial "p" is minimized using "Monte Carlo Programming":
Approximate minimum hoop stress = -817,799,000 Pa

Corresponding design variables:
x1 = 139 mm
x2 = 15 mm
x3 = 34 mm
x4 = 60 mm
x5 = 50 mm
x6 = 10 mm
x7 = 78 mm

Next, ANSYS solution for the values of design variables given above (x1 through x7) are obtained:
Actual minimized hoop stress = -32,639,757 Pa

37 data points: Mxy gives the values of 7 variables;
vz gives the corresponding hoop stresses from ANSYS

Mxy =

0.085	0.016	0.042	0.03	0.026	0.038	0.038
0.098	0.016	0.042	0.03	0.026	0.038	0.038
0.111	0.016	0.042	0.03	0.026	0.038	0.038
0.124	0.016	0.042	0.03	0.026	0.038	0.038
0.137	0.016	0.042	0.03	0.026	0.038	0.038
0.15	0.016	0.042	0.03	0.026	0.038	0.038
0.111	0.01	0.042	0.03	0.026	0.038	0.038
0.111	0.013	0.042	0.03	0.026	0.038	0.038
0.087	0.025	0.03	0.058	0.042	0.057	0.08
0.111	0.022	0.042	0.03	0.026	0.038	0.038
0.15	0.017	0.039	0.058	0.048	0.077	0.01
0.095	0.024	0.038	0.058	0.049	0.014	0.01
0.111	0.016	0.036	0.03	0.026	0.038	0.038
0.111	0.016	0.048	0.03	0.026	0.038	0.038
0.147	0.01	0.03	0.06	0.01	0.071	0.013
0.087	0.025	0.03	0.037	0.048	0.08	0.017
0.092	0.015	0.041	0.06	0.049	0.077	0.012
0.145	0.024	0.032	0.056	0.05	0.012	0.011
0.111	0.016	0.042	0.04	0.026	0.038	0.038
0.111	0.016	0.042	0.05	0.026	0.038	0.038
0.111	0.016	0.042	0.06	0.026	0.038	0.038
0.132	0.025	0.03	0.054	0.035	0.079	0.011
0.085	0.024	0.031	0.06	0.014	0.014	0.012
0.111	0.016	0.042	0.03	0.034	0.038	0.038
0.111	0.016	0.042	0.03	0.042	0.038	0.038
0.111	0.016	0.042	0.03	0.05	0.038	0.038
0.097	0.024	0.031	0.058	0.014	0.079	0.012
0.149	0.023	0.059	0.029	0.049	0.079	0.079
0.111	0.016	0.042	0.03	0.026	0.052	0.038
0.111	0.016	0.042	0.03	0.026	0.066	0.038
0.111	0.016	0.042	0.03	0.026	0.08	0.038
0.111	0.016	0.042	0.03	0.026	0.038	0.01
0.111	0.016	0.042	0.03	0.026	0.038	0.024
0.111	0.016	0.042	0.03	0.026	0.038	0.052
0.139	0.015	0.034	0.06	0.05	0.01	0.078
0.15	0.024	0.059	0.033	0.011	0.078	0.073
0.107	0.021	0.031	0.059	0.039	0.053	0.01

Minimum	0.085	0.010	0.030	0.010	0.010	0.010	0.010
Maximum	0.150	0.025	0.060	0.060	0.050	0.080	0.080

$$vz := \begin{pmatrix} 36616568 \\ 22200656 \\ 37097322 \\ 31736332 \\ 28339273 \\ 26399543 \\ 36493172 \\ 23698965 \\ -95536865 \\ 17111637 \\ -76166379 \\ -83654169 \\ 36448620 \\ 16928727 \\ -63177822 \\ -110954614 \\ -23409699 \\ -87555938 \\ 860031 \\ -23459964 \\ 6217825 \\ -113421927 \\ -4347296 \\ 24701456 \\ 12184933 \\ -741879 \\ -135790023 \\ -23960716 \\ 21389186 \\ 6461343 \\ -7376020 \\ 14713633 \\ 34878853 \\ 36262139 \\ -32639757 \\ -3646239 \\ -129570000 \end{pmatrix}$$

D:\unlv2\data The values in "coeff" are written out to the file "data" in the D:\unlv2 directory

coeff

First, the objective function given above as polynomial "p" is minimized using "Monte Carlo Programming":
Approximate minimum hoop stress = -649,567,000 Pa

Corresponding design variables:
x1 = 87 mm
x2 = 24 mm
x3 = 59 mm
x4 = 57 mm
x5 = 25 mm
x6 = 11 mm
x7 = 79 mm

Next, ANSYS solution for the values of design variables given above (x1 through x7) are obtained:
Actual minimized hoop stress = 40,284,471 Pa

APPENDIX IX

FORTRAN 90 FILES USED TO DETERMINE THE MINIMUM POINT OF A QUADRATIC SURFACE BY MONTE CARLO PROGRAMMING TECHNIQUE

```
!
!     Monte Carlo Programming
!
!     Read coefficients from data file
!
      dimension c(36),xi(7),y(7),x(7),Z(7),R(7)
      open(10,file='data')
      do i=1,36
      read(10,'(f25.5)') c(i)
      end do
      close(10)
!
!     Read lower limits of all design variables
!
      open(11,file='lower')
      do i=1,7
      read(11,'(f5.3)') Z(i)
      end do
      close(11)
!
!     Read range of all design variables
!
      open(12,file='range')
      do i=1,7
      read(12,'(f5.3)') R(i)
      end do
      close(12)
!
!     7 design variables defined
!
      pmin=9999999.0
      do 1 i=1,10000000
!
!     define minimum and maximum values of design variables
!
!     set design variable values; generate random dimensions where
applicable
!
      do j=1,7
      x(j)=(R(j)*rand())+Z(j)
      end do
!
!     define objective function for minimization
!
      p=c(1)*x(1)*x(7)+c(2)*x(2)*x(7)+c(3)*x(3)*x(7)+c(4)*x(4)*x(7)  &

+c(5)*x(5)*x(7)+c(6)*x(6)*x(7)+c(7)*x(7)*x(7)+c(8)*x(7)+c(9)*x(1)*x(6)
&
      +c(10)*x(2)*x(6)+c(11)*x(3)*x(6)+c(12)*x(4)*x(6)+c(13)*x(5)*x(6)
&
      +c(14)*x(6)*x(6)+c(15)*x(6)+c(16)*x(1)*x(5)+c(17)*x(2)*x(5)  &
      +c(18)*x(3)*x(5)+c(19)*x(4)*x(5)+c(20)*x(5)*x(5)+c(21)*x(5)  &
      +c(22)*x(1)*x(4)+c(23)*x(2)*x(4)+c(24)*x(3)*x(4)+c(25)*x(4)*x(4)
&

+c(26)*x(4)+c(27)*x(1)*x(3)+c(28)*x(2)*x(3)+c(29)*x(3)*x(3)+c(30)*x(3)
&
```

```
      +c(31)*x(1)*x(2)+c(32)*x(2)*x(2)+c(33)*x(2)+c(34)+c(35)*x(1)  &
      +c(36)*x(1)*x(1)
      if(p.lt.pmin) go to 2
      go to 1
 2    continue
      do 6 m=1,7
 6    xi(m)=x(m)
      pmin=p
 1    continue
      open(8,file='results.out')
      write(8,*)'Optimized values for the design variables:'
      write(8,*)'x1= ',xi(1),' m'
      write(8,*)'x2= ',xi(2),' m'
      write(8,*)'x3= ',xi(3),' m'
      write(8,*)'x4= ',xi(4),' m'
      write(8,*)'x5= ',xi(5),' m'
      write(8,*)'x6= ',xi(6),' m'
      write(8,*)'x7= ',xi(7),' m'
      write(8,*)'Minimum hoop stress value (pmin)= ',pmin,' Pa'
      close(8)
      stop
      end
```

```
! Input file "data" that contains the coefficients "c(i)"
-11357899923.136808
12969185152.092247
-31376155986.570736
79883454388.56168
35839288778.38199
41388842723.27731
-999522962.6249875
-2139550492.8222687
5572905159.830531
-8334057497.072403
15421267715.515356
-43618645775.58822
-19535055607.283867
11873910577.68694
-3042531400.4525332
4700517963.664221
-7085553309.342083
13457992852.888754
-37756320685.95624
31104311072.908985
-3852048353.274278
10137651892.921741
-15226659389.14586
30462734893.138264
93676314855.89244
-11931257968.203974
-6689377714.943879
4165108680.611187
219706386886.0258
-20711393665.17791
-539769083.9075795
776076173307.2313
-22588362570.563152
1143742756.019714
-673910654.7738097
2956202642.474992
```

```
! Input file "lower" that contains the lower limits "Z(i)"
0.085
0.01
0.03
0.01
0.01
0.01
0.01
```

```
! Input file "range" that contains the range "R(i)"
0.065
0.015
0.03
0.05
0.04
0.07
0.07
```

```
! Output file "results.out" that contains the results
 Optimized values for the design variables:
 x1=  9.16534E-02  m
 x2=  1.51475E-02  m
 x3=  4.05489E-02  m
 x4=  5.97101E-02  m
 x5=  4.87860E-02  m
 x6=  7.69588E-02  m
 x7=  1.17495E-02  m
 Minimum hoop stress value (pmin)=  -2.99382E+08  Pa
```

APPENDIX X

MATHCAD CALCULATION FILES FOR OPTIMIZATION USING SUCCESSIVE HEURISTIC QUADRATIC APPROXIMATION

Extracting Coefficients from Multi-Variate Regression (#1)

Multi-variable second degree polynomial regression is used to fit a function to 37 data points.
The regression function is used to solve the coefficients of the polynomial.

Define matrices that include the values of 7 independent variables:

$$
\mathbf{Axy} := \begin{pmatrix}
0.085 & 0.016 & 0.042 & 0.03 & 0.026 & 0.038 & 0.038 \\
0.098 & 0.016 & 0.042 & 0.03 & 0.026 & 0.038 & 0.038 \\
0.111 & 0.016 & 0.042 & 0.03 & 0.026 & 0.038 & 0.038 \\
0.124 & 0.016 & 0.042 & 0.03 & 0.026 & 0.038 & 0.038 \\
0.137 & 0.016 & 0.042 & 0.03 & 0.026 & 0.038 & 0.038 \\
0.15 & 0.016 & 0.042 & 0.03 & 0.026 & 0.038 & 0.038 \\
0.111 & 0.01 & 0.042 & 0.03 & 0.026 & 0.038 & 0.038 \\
0.111 & 0.013 & 0.042 & 0.03 & 0.026 & 0.038 & 0.038 \\
0.111 & 0.019 & 0.042 & 0.03 & 0.026 & 0.038 & 0.038 \\
0.111 & 0.022 & 0.042 & 0.03 & 0.026 & 0.038 & 0.038 \\
0.111 & 0.025 & 0.042 & 0.03 & 0.026 & 0.038 & 0.038 \\
0.111 & 0.016 & 0.03 & 0.03 & 0.026 & 0.038 & 0.038
\end{pmatrix}
$$

$$
\mathbf{Bxy} := \begin{pmatrix}
0.111 & 0.016 & 0.036 & 0.03 & 0.026 & 0.038 & 0.038 \\
0.111 & 0.016 & 0.048 & 0.03 & 0.026 & 0.038 & 0.038 \\
0.111 & 0.016 & 0.054 & 0.03 & 0.026 & 0.038 & 0.038 \\
0.111 & 0.016 & 0.06 & 0.03 & 0.026 & 0.038 & 0.038 \\
0.111 & 0.016 & 0.042 & 0.01 & 0.026 & 0.038 & 0.038 \\
0.111 & 0.016 & 0.042 & 0.02 & 0.026 & 0.038 & 0.038 \\
0.111 & 0.016 & 0.042 & 0.04 & 0.026 & 0.038 & 0.038 \\
0.111 & 0.016 & 0.042 & 0.05 & 0.026 & 0.038 & 0.038 \\
0.111 & 0.016 & 0.042 & 0.06 & 0.026 & 0.038 & 0.038 \\
0.111 & 0.016 & 0.042 & 0.03 & 0.01 & 0.038 & 0.038 \\
0.111 & 0.016 & 0.042 & 0.03 & 0.018 & 0.038 & 0.038 \\
0.111 & 0.016 & 0.042 & 0.03 & 0.034 & 0.038 & 0.038
\end{pmatrix}
$$

$$\mathbf{Cxy} := \begin{pmatrix} 0.111 & 0.016 & 0.042 & 0.03 & 0.042 & 0.038 & 0.038 \\ 0.111 & 0.016 & 0.042 & 0.03 & 0.05 & 0.038 & 0.038 \\ 0.111 & 0.016 & 0.042 & 0.03 & 0.026 & 0.01 & 0.038 \\ 0.111 & 0.016 & 0.042 & 0.03 & 0.026 & 0.024 & 0.038 \\ 0.111 & 0.016 & 0.042 & 0.03 & 0.026 & 0.052 & 0.038 \\ 0.111 & 0.016 & 0.042 & 0.03 & 0.026 & 0.066 & 0.038 \\ 0.111 & 0.016 & 0.042 & 0.03 & 0.026 & 0.08 & 0.038 \\ 0.111 & 0.016 & 0.042 & 0.03 & 0.026 & 0.038 & 0.01 \\ 0.111 & 0.016 & 0.042 & 0.03 & 0.026 & 0.038 & 0.024 \\ 0.111 & 0.016 & 0.042 & 0.03 & 0.026 & 0.038 & 0.052 \\ 0.111 & 0.016 & 0.042 & 0.03 & 0.026 & 0.038 & 0.066 \\ 0.111 & 0.016 & 0.042 & 0.03 & 0.026 & 0.038 & 0.08 \\ 0.107 & 0.021 & 0.031 & 0.059 & 0.039 & 0.053 & 0.01 \end{pmatrix}$$

Stack A, B, and C matrices to obtain Mxy:

ABxy := stack(Axy ,Bxy)

Mxy := stack(ABxy ,Cxy)

37 data points: Mxy gives the values of 7 variables;
vz gives the corresponding hoop stresses from ANSYS

Mxy =

0.085	0.016	0.042	0.03	0.026	0.038	0.038
0.098	0.016	0.042	0.03	0.026	0.038	0.038
0.111	0.016	0.042	0.03	0.026	0.038	0.038
0.124	0.016	0.042	0.03	0.026	0.038	0.038
0.137	0.016	0.042	0.03	0.026	0.038	0.038
0.15	0.016	0.042	0.03	0.026	0.038	0.038
0.111	0.01	0.042	0.03	0.026	0.038	0.038
0.111	0.013	0.042	0.03	0.026	0.038	0.038
0.111	0.019	0.042	0.03	0.026	0.038	0.038
0.111	0.022	0.042	0.03	0.026	0.038	0.038
0.111	0.025	0.042	0.03	0.026	0.038	0.038
0.111	0.016	0.03	0.03	0.026	0.038	0.038
0.111	0.016	0.036	0.03	0.026	0.038	0.038
0.111	0.016	0.048	0.03	0.026	0.038	0.038
0.111	0.016	0.054	0.03	0.026	0.038	0.038
0.111	0.016	0.06	0.03	0.026	0.038	0.038
0.111	0.016	0.042	0.01	0.026	0.038	0.038
0.111	0.016	0.042	0.02	0.026	0.038	0.038
0.111	0.016	0.042	0.04	0.026	0.038	0.038
0.111	0.016	0.042	0.05	0.026	0.038	0.038
0.111	0.016	0.042	0.06	0.026	0.038	0.038
0.111	0.016	0.042	0.03	0.01	0.038	0.038
0.111	0.016	0.042	0.03	0.018	0.038	0.038
0.111	0.016	0.042	0.03	0.034	0.038	0.038
0.111	0.016	0.042	0.03	0.042	0.038	0.038
0.111	0.016	0.042	0.03	0.05	0.038	0.038
0.111	0.016	0.042	0.03	0.026	0.01	0.038
0.111	0.016	0.042	0.03	0.026	0.024	0.038
0.111	0.016	0.042	0.03	0.026	0.052	0.038
0.111	0.016	0.042	0.03	0.026	0.066	0.038
0.111	0.016	0.042	0.03	0.026	0.08	0.038
0.111	0.016	0.042	0.03	0.026	0.038	0.01
0.111	0.016	0.042	0.03	0.026	0.038	0.024
0.111	0.016	0.042	0.03	0.026	0.038	0.052
0.111	0.016	0.042	0.03	0.026	0.038	0.066
0.111	0.016	0.042	0.03	0.026	0.038	0.08
0.107	0.021	0.031	0.059	0.039	0.053	0.01

Minimum	0.085	0.010	0.030	0.010	0.010	0.010	0.010
Maximum	0.150	0.025	0.060	0.060	0.050	0.080	0.080
Difference	0.065	0.015	0.030	0.050	0.040	0.070	0.070

$$
vz := \begin{pmatrix} 36616568 \\ 22200656 \\ 37097322 \\ 31736332 \\ 28339273 \\ 26399543 \\ 36493172 \\ 23698965 \\ 40064955 \\ 17111637 \\ 134211136 \\ 93672103 \\ 36448620 \\ 16928727 \\ 45893010 \\ 50971165 \\ 140489329 \\ 68229458 \\ 860031 \\ -23459964 \\ 6217825 \\ 64502322 \\ 50194254 \\ 24701456 \\ 12184933 \\ -741879 \\ 72349661 \\ 53812611 \\ 21389186 \\ 6461343 \\ -7376020 \\ 14713633 \\ 34878853 \\ 36262139 \\ 37176709 \\ 38547459 \\ -129570000 \end{pmatrix}
$$

The 'Mxy' matrix holds the independent variables and the 'z' matrix holds the depenedent variables. The degree of the polynomal is 'n'.

n := 2 **vs := regress(Mxy, vz, n)**

$$
vs = \begin{pmatrix} 3 \\ 3 \\ 2 \\ -1.136\cdot10^{10} \\ 1.297\cdot10^{10} \\ -3.138\cdot10^{10} \\ 7.988\cdot10^{10} \\ 3.584\cdot10^{10} \\ 4.139\cdot10^{10} \\ -9.995\cdot10^{8} \\ -2.14\cdot10^{9} \\ 5.573\cdot10^{9} \\ -8.334\cdot10^{9} \\ 1.542\cdot10^{10} \\ -4.362\cdot10^{10} \\ -1.954\cdot10^{10} \\ 1.187\cdot10^{10} \\ -3.043\cdot10^{9} \\ 4.701\cdot10^{9} \\ -7.086\cdot10^{9} \\ 1.346\cdot10^{10} \\ -3.776\cdot10^{10} \\ 3.11\cdot10^{10} \\ -3.852\cdot10^{9} \\ 1.014\cdot10^{10} \\ -1.523\cdot10^{10} \\ 3.046\cdot10^{10} \\ 9.368\cdot10^{10} \\ -1.193\cdot10^{10} \\ -6.689\cdot10^{9} \\ 4.165\cdot10^{9} \\ 2.197\cdot10^{11} \\ -2.071\cdot10^{10} \\ -5.398\cdot10^{8} \\ 7.761\cdot10^{11} \\ -2.259\cdot10^{10} \\ 1.144\cdot10^{9} \\ -6.739\cdot10^{8} \\ 2.956\cdot10^{9} \end{pmatrix}
$$

The first three elements of the output vector contain information for the interp function. The values after that are the coefficients of the fitting polynomial. For multi-dimensional fitting, the program below is used to match the coefficients with the terms.

The coefficients can be extracted from the vector "vs"

The coefficients are: $\mathbf{coeff := submatrix\left(vs, 3, last\left(vs^{\langle 0 \rangle}\right), 0, 0\right)}$

Program for Coefficients

A polynomial in nvar variables of degree deg has a number of terms given by the function Nterms:

$$\mathrm{Nterms}(\mathrm{nvar},\mathrm{deg}) := \frac{\mathrm{nvar}+\mathrm{deg}!}{\mathrm{deg}!\cdot\mathrm{nvar}!}$$

The number of variables of the polynomial is: $\mathrm{Nvars} := \mathrm{cols}(\mathrm{Mxy})$

The number of data points is: $\mathrm{Ndata} := \mathrm{rows}(\mathrm{Mxy})$

$\mathrm{Nterms}(\mathrm{Nvars},\mathrm{n}) \le \mathrm{Ndata}$ $\qquad$ $\mathrm{Nterms}(\mathrm{Nvars},\mathrm{n}) = 36$

The ordering of the coefficients employed by regress for a given number of variables and degree can be determined by using the programs below.

```
Step(v,Nvar,deg) := | for i ∈ 0..deg    if Nvar = 1
                    |   v[i,0] ← v[i,0] + i
                    | for i ∈ 0..Nvar − 1  if deg = 1
                    |   v[i,i] ← v[i,i] + 1
                    | otherwise
                    |   | inc ← Nterms(Nvar,deg − 1)
                    |   | for i ∈ 0..inc − 1
                    |   |   v[i,Nvar−1] ← v[i,Nvar−1] + 1
                    |   | v ← stack(Step(submatrix(v,0,inc − 1,0,cols(v) − 1),Nvar,deg − 1),Step(sub
                    | v
```

```
COrder(Nvar,deg) := | v[Nterms(Nvar,deg)−1,Nvar−1] ← 0
                    | Step(v,Nvar,deg)
```

Program for Coefficients

For the data above:

Nvar := cols(Mxy) **deg := n**

Compute the "identity" matrix for the coefficients:

I := COrder(Nvar ,deg) **rows(I) = 36**

coeff =

$-1.136\cdot10^{10}$
$1.297\cdot10^{10}$
$-3.138\cdot10^{10}$
$7.988\cdot10^{10}$
$3.584\cdot10^{10}$
$4.139\cdot10^{10}$
$-9.995\cdot10^{8}$
$-2.14\cdot10^{9}$
$5.573\cdot10^{9}$
$-8.334\cdot10^{9}$
$1.542\cdot10^{10}$
$-4.362\cdot10^{10}$
$-1.954\cdot10^{10}$
$1.187\cdot10^{10}$
$-3.043\cdot10^{9}$
$4.701\cdot10^{9}$
$-7.086\cdot10^{9}$
$1.346\cdot10^{10}$
$-3.776\cdot10^{10}$
$3.11\cdot10^{10}$
$-3.852\cdot10^{9}$
$1.014\cdot10^{10}$
$-1.523\cdot10^{10}$
$3.046\cdot10^{10}$
$9.368\cdot10^{10}$
$-1.193\cdot10^{10}$
$-6.689\cdot10^{9}$
$4.165\cdot10^{9}$
$2.197\cdot10^{11}$
$-2.071\cdot10^{10}$
$-5.398\cdot10^{8}$
$7.761\cdot10^{11}$
$-2.259\cdot10^{10}$
$1.144\cdot10^{9}$
$-6.739\cdot10^{8}$
$2.956\cdot10^{9}$

Independent variables

I =

x1	x2	x3	x4	x5	x6	x7
1	0	0	0	0	0	1
0	1	0	0	0	0	1
0	0	1	0	0	0	1
0	0	0	1	0	0	1
0	0	0	0	1	0	1
0	0	0	0	0	1	1
0	0	0	0	0	0	2
0	0	0	0	0	0	1
1	0	0	0	0	1	0
0	1	0	0	0	1	0
0	0	1	0	0	1	0
0	0	0	1	0	1	0
0	0	0	0	1	1	0
0	0	0	0	0	2	0
0	0	0	0	0	1	0
1	0	0	0	1	0	0
0	1	0	0	1	0	0
0	0	1	0	1	0	0
0	0	0	1	1	0	0
0	0	0	0	2	0	0
0	0	0	0	1	0	0
1	0	0	1	0	0	0
0	1	0	1	0	0	0
0	0	1	1	0	0	0
0	0	0	2	0	0	0
0	0	0	1	0	0	0
1	0	1	0	0	0	0
0	1	1	0	0	0	0
0	0	2	0	0	0	0
0	0	1	0	0	0	0
1	1	0	0	0	0	0
0	2	0	0	0	0	0
0	1	0	0	0	0	0
0	0	0	0	0	0	0
1	0	0	0	0	0	0
2	0	0	0	0	0	0

The polynomial definition can be automated by using a summation:

$$p(x1,x2,x3,x4,x5,x6,x7) := \sum_{i=0}^{last(coeff)} coeff_i \cdot x1^{I_{i,0}} \cdot x2^{I_{i,1}} \cdot x3^{I_{i,2}} \cdot x4^{I_{i,3}} \cdot x5^{I_{i,4}} \cdot x6^{I_{i,5}} \cdot x7^{I_{i,6}}$$

The following best solution from ANSYS will be used as an example to test the function value:

$$p(0.107,0.021,0.031,0.059,0.039,0.053,0.01) = -1.2957 \times 10^8$$

(consistent with actual point value)

Next, objective function given above as polynomial "p" is minimized using "Monte Carlo Programming":
minimum hoop stress = -299,382,000 Pa

Corresponding design variables:
x1 = 92 mm
x2 = 15 mm
x3 = 41 mm
x4 = 60 mm
x5 = 49 mm
x6 = 77 mm
x7 = 12 mm

ANSYS solution for the values of design variables given above (x1 through x7) = -23,409,699 Pa

D:\unlv2\data

The values in "coeff" are written out to the file "data" in the D:\unlv2 directory

coeff

The customized stand-alone optimization algorithm steps are applied below to determine the range
of hoop stress considering all data points:
Stress range : From -129,570,000 Pa to 140,489,329 Pa

Then, the lower half of the stress range is selected:
Lower half: From -129,570,000 Pa to 5,459,665 Pa

The minimum and maximum values of the corresponding design variables and the same range after expansion are determined below (all dimensions are in meters):

	V1	V2	V3	V4	V5	V6	V7
Minimum	0.107	0.016	0.031	0.030	0.026	0.038	0.010
Maximum	0.111	0.021	0.042	0.059	0.050	0.080	0.038
Difference	0.004	0.005	0.011	0.029	0.024	0.042	0.028
Expanded minimum	0.107	0.015	0.030	0.027	0.024	0.034	0.010
Expanded maximum	0.111	0.022	0.043	0.060	0.050	0.080	0.041

37 data points: Mxy gives the values of 7 variables;
vz gives the corresponding hoop stresses from ANSYS

Mxy =

0.107	0.015	0.03	0.027	0.024	0.034	0.01
0.111	0.022	0.043	0.06	0.05	0.08	0.041
0.108	0.016	0.03	0.028	0.024	0.035	0.013
0.109	0.022	0.035	0.03	0.026	0.038	0.038
0.111	0.02	0.036	0.035	0.03	0.04	0.015
0.11	0.021	0.037	0.037	0.031	0.041	0.02
0.11	0.017	0.031	0.055	0.048	0.05	0.025
0.107	0.016	0.034	0.057	0.035	0.06	0.03
0.108	0.021	0.038	0.059	0.04	0.065	0.035
0.11	0.022	0.032	0.031	0.042	0.07	0.04
0.107	0.016	0.041	0.035	0.049	0.08	0.041
0.111	0.018	0.034	0.036	0.034	0.051	0.016
0.107	0.021	0.031	0.058	0.046	0.076	0.01
0.109	0.02	0.032	0.042	0.045	0.075	0.011
0.111	0.019	0.029	0.056	0.044	0.077	0.012
0.107	0.017	0.04	0.038	0.029	0.042	0.017
0.108	0.018	0.028	0.034	0.032	0.052	0.014
0.11	0.018	0.042	0.057	0.028	0.039	0.031
0.111	0.016	0.042	0.04	0.026	0.038	0.038
0.111	0.016	0.042	0.05	0.026	0.038	0.038
0.107	0.015	0.033	0.029	0.025	0.053	0.014
0.107	0.021	0.031	0.058	0.041	0.054	0.016
0.107	0.017	0.039	0.03	0.032	0.066	0.032
0.107	0.015	0.043	0.034	0.037	0.071	0.022
0.107	0.021	0.031	0.056	0.048	0.073	0.01
0.111	0.016	0.042	0.03	0.05	0.038	0.038
0.108	0.018	0.032	0.028	0.033	0.071	0.013
0.108	0.02	0.033	0.031	0.037	0.072	0.014
0.109	0.022	0.035	0.035	0.036	0.074	0.017
0.109	0.021	0.034	0.037	0.034	0.073	0.014
0.111	0.016	0.042	0.03	0.026	0.08	0.038
0.107	0.017	0.041	0.051	0.048	0.08	0.01
0.107	0.019	0.04	0.053	0.05	0.078	0.011
0.108	0.021	0.039	0.057	0.049	0.079	0.011
0.108	0.015	0.037	0.059	0.047	0.076	0.012
0.092	0.015	0.041	0.06	0.049	0.077	0.012
0.107	0.021	0.031	0.059	0.039	0.053	0.01

Minimum	0.092	0.015	0.030	0.027	0.024	0.034	0.010
Maximum	0.111	0.022	0.043	0.060	0.050	0.080	0.041
Difference	0.019	0.007	0.013	0.033	0.026	0.046	0.031

$$vz := \begin{pmatrix} 68663056 \\ -18623241 \\ 53275572 \\ 76842884 \\ 41493887 \\ 26171269 \\ -82747934 \\ -58488139 \\ -48558463 \\ 18599673 \\ -58836042 \\ 26066154 \\ -154626854 \\ -68405480 \\ -153782728 \\ -30743855 \\ -25406901 \\ -39074544 \\ 860031 \\ -23459964 \\ 9494100 \\ -127380157 \\ 2834275 \\ -31573362 \\ -156817999 \\ -741879 \\ -44348423 \\ -78384532 \\ -56857964 \\ -28219569 \\ -7376020 \\ -82445815 \\ -82845264 \\ -83927901 \\ -67138974 \\ -23409699 \\ -129570000 \end{pmatrix}$$

The polynomial definition can be automated by using a summation:

$$p(x1,x2,x3,x4,x5,x6,x7) := \sum_{i=0}^{last(coeff)} coeff_i \cdot x1^{I_{i,0}} \cdot x2^{I_{i,1}} \cdot x3^{I_{i,2}} \cdot x4^{I_{i,3}} \cdot x5^{I_{i,4}} \cdot x6^{I_{i,5}} \cdot x7^{I_{i,6}}$$

The following best solution from ANSYS will be used as an example to test the function value:

$p(0.107, 0.021, 0.031, 0.059, 0.039, 0.053, 0.01) = -1.279553064 \times 10^{8}$ (consistent with actual point value)

Next, objective function given above as polynomial "p" is minimized using "Monte Carlo Programming":
minimum hoop stress = -1,540,010,000 Pa

Corresponding design variables:
x1 = 107 mm
x2 = 22 mm
x3 = 43 mm
x4 = 28 mm
x5 = 49 mm
x6 = 35 mm
x7 = 39 mm

ANSYS solution for the values of design variables given above (x1 through x7) = - 5,472,892 Pa

D:\unlv2\data — The values in "coeff" are written out to the file "data" in the D:\unlv2 directory

coeff

The customized stand-alone optimization algorithm steps are applied below to determine the range
of hoop stress considering all data points:
Stress range : From -156,817,999 Pa to 76,842,884 Pa

Then, the lower half of the stress range is selected:
Lower half: From -156,817,999 Pa to -39,987,558 Pa

The minimum and maximum values of the corresponding design variables and the same range after expansion are determined below (all dimensions are in meters):

	V1	V2	V3	V4	V5	V6	V7
Minimum	0.107	0.015	0.030	0.028	0.033	0.050	0.010
Maximum	0.111	0.022	0.041	0.059	0.050	0.080	0.041
Difference	0.004	0.007	0.011	0.031	0.017	0.030	0.031
Expanded minimum	0.107	0.015	0.030	0.025	0.031	0.047	0.010
Expanded maximum	0.111	0.022	0.042	0.060	0.050	0.080	0.044

37 data points: Mxy gives the values of 7 variables;
vz gives the corresponding hoop stresses from ANSYS

Mxy =

	0.108	0.015	0.036	0.03	0.049	0.073	0.015
	0.111	0.022	0.042	0.06	0.05	0.08	0.044
	0.11	0.02	0.031	0.055	0.043	0.049	0.04
	0.11	0.02	0.032	0.054	0.033	0.052	0.038
	0.109	0.022	0.031	0.052	0.034	0.055	0.03
	0.109	0.02	0.033	0.053	0.036	0.059	0.02
	0.11	0.017	0.031	0.055	0.048	0.05	0.025
	0.107	0.016	0.034	0.057	0.035	0.06	0.03
	0.108	0.021	0.038	0.059	0.04	0.065	0.035
	0.108	0.019	0.031	0.057	0.044	0.065	0.015
	0.107	0.016	0.041	0.035	0.049	0.08	0.041
	0.107	0.021	0.031	0.056	0.045	0.076	0.01
	0.107	0.021	0.031	0.058	0.046	0.076	0.01
	0.109	0.02	0.032	0.042	0.045	0.075	0.011
	0.111	0.019	0.029	0.056	0.044	0.077	0.012
	0.108	0.019	0.033	0.058	0.047	0.075	0.011
	0.107	0.019	0.032	0.059	0.046	0.077	0.012
	0.107	0.019	0.041	0.06	0.048	0.078	0.01
	0.107	0.019	0.037	0.059	0.049	0.075	0.01
	0.108	0.016	0.036	0.03	0.049	0.073	0.016
	0.107	0.021	0.031	0.059	0.048	0.074	0.01
	0.107	0.021	0.031	0.058	0.041	0.054	0.016
	0.111	0.016	0.035	0.035	0.039	0.072	0.013
	0.111	0.017	0.031	0.04	0.046	0.073	0.014
	0.107	0.021	0.031	0.056	0.048	0.073	0.01
	0.107	0.021	0.031	0.057	0.047	0.075	0.01
	0.108	0.018	0.032	0.028	0.033	0.071	0.013
	0.108	0.02	0.033	0.031	0.037	0.072	0.014
	0.109	0.022	0.035	0.035	0.036	0.074	0.017
	0.11	0.018	0.034	0.045	0.041	0.071	0.015
	0.11	0.021	0.03	0.055	0.042	0.053	0.01
	0.107	0.017	0.041	0.051	0.048	0.08	0.01
	0.107	0.019	0.04	0.053	0.05	0.078	0.011
	0.108	0.021	0.039	0.057	0.049	0.079	0.011
	0.108	0.015	0.037	0.059	0.047	0.076	0.012
	0.107	0.022	0.043	0.028	0.049	0.035	0.039
	0.107	0.021	0.031	0.059	0.039	0.053	0.01
Minimum	0.107	0.015	0.030	0.025	0.031	0.047	0.010
Maximum	0.111	0.022	0.042	0.060	0.050	0.080	0.044
Difference	0.004	0.007	0.012	0.035	0.019	0.033	0.034

$$
vz := \begin{pmatrix} -2997440 \\ -18490060 \\ -82057416 \\ -70185365 \\ -66814434 \\ -94661249 \\ -82747934 \\ -58488139 \\ -48558463 \\ -103952383 \\ -58836042 \\ -156679548 \\ -154626854 \\ -68405480 \\ -153782728 \\ -95010402 \\ -93180318 \\ -68870157 \\ -83526732 \\ -6678775 \\ -151712231 \\ -127380157 \\ -11565982 \\ -37259671 \\ -156817999 \\ -158272820 \\ -44348423 \\ -78384532 \\ -56857964 \\ -94068927 \\ -128998472 \\ -82445815 \\ -82845264 \\ -83927901 \\ -67138974 \\ -5472892 \\ -129570000 \end{pmatrix}
$$

The polynomial definition can be automated by using a summation:

$$p(x1,x2,x3,x4,x5,x6,x7) := \sum_{i=0}^{last(coeff)} coeff_i \cdot x1^{I_{i,0}} \cdot x2^{I_{i,1}} \cdot x3^{I_{i,2}} \cdot x4^{I_{i,3}} \cdot x5^{I_{i,4}} \cdot x6^{I_{i,5}} \cdot x7^{I_{i,6}}$$

The following best solution from ANSYS will be used as an example to test the function value:

$p(0.107,0.021,0.031,0.059,0.039,0.053,0.01) = -1.2975886773 \times 10^{8}$ (consistent with actual point value)

Next, objective function given above as polynomial "p" is minimized using "Monte Carlo Programming":
minimum hoop stress = -846,447,000 Pa

Corresponding design variables:
x1 = 111 mm
x2 = 15 mm
x3 = 31 mm
x4 = 50 mm
x5 = 32 mm
x6 = 80 mm
x7 = 44 mm

ANSYS solution for the values of design variables given above (x1 through x7) = - 59,527,399 Pa

D:\unlv2\data — The values in "coeff" are written out to the file "data" in the D:\unlv2 directory

coeff

The customized stand-alone optimization algorithm steps are applied below to determine the range
of hoop stress considering all data points:
Stress range : From -158,272,820 Pa to -2,997,440 Pa

Then, the lower half of the stress range is selected:
Lower half: From -158,272,820 Pa to -80,635,130 Pa

The minimum and maximum values of the corresponding design variables and the same range after expansion are determined below (all dimensions are in meters):

	V1	V2	V3	V4	V5	V6	V7
Minimum	0.107	0.017	0.030	0.045	0.036	0.049	0.010
Maximum	0.111	0.021	0.041	0.059	0.050	0.080	0.040
Difference	0.004	0.004	0.011	0.014	0.014	0.031	0.030
Expanded minimum	0.107	0.017	0.030	0.044	0.035	0.046	0.010
Expanded maximum	0.111	0.021	0.042	0.060	0.050	0.080	0.043

37 data points: Mxy gives the values of 7 variables;
vz gives the corresponding hoop stresses from ANSYS

Mxy =

0.107	0.017	0.031	0.056	0.044	0.07	0.01
0.107	0.018	0.03	0.044	0.045	0.071	0.011
0.11	0.02	0.031	0.055	0.043	0.049	0.04
0.107	0.019	0.031	0.046	0.046	0.072	0.012
0.107	0.02	0.031	0.048	0.047	0.073	0.015
0.109	0.02	0.033	0.053	0.036	0.059	0.02
0.11	0.017	0.031	0.055	0.048	0.05	0.025
0.107	0.021	0.033	0.053	0.048	0.046	0.016
0.108	0.021	0.035	0.056	0.049	0.049	0.02
0.108	0.019	0.031	0.057	0.044	0.065	0.015
0.108	0.02	0.034	0.057	0.05	0.055	0.033
0.107	0.021	0.031	0.056	0.045	0.076	0.01
0.107	0.021	0.031	0.058	0.046	0.076	0.01
0.109	0.021	0.032	0.058	0.035	0.06	0.039
0.111	0.019	0.029	0.056	0.044	0.077	0.012
0.108	0.019	0.033	0.058	0.047	0.075	0.011
0.107	0.019	0.032	0.059	0.046	0.077	0.012
0.109	0.021	0.031	0.059	0.037	0.063	0.043
0.107	0.019	0.037	0.059	0.049	0.075	0.01
0.107	0.021	0.036	0.06	0.042	0.073	0.04
0.107	0.021	0.031	0.059	0.048	0.074	0.01
0.107	0.021	0.031	0.058	0.041	0.054	0.016
0.107	0.021	0.042	0.06	0.043	0.076	0.01
0.11	0.017	0.039	0.059	0.044	0.077	0.01
0.107	0.021	0.031	0.056	0.048	0.073	0.01
0.107	0.021	0.031	0.057	0.047	0.075	0.01
0.111	0.017	0.038	0.058	0.045	0.078	0.012
0.11	0.021	0.037	0.057	0.046	0.079	0.013
0.111	0.02	0.031	0.056	0.046	0.08	0.014
0.11	0.018	0.034	0.045	0.041	0.071	0.015
0.11	0.021	0.03	0.055	0.042	0.053	0.01
0.107	0.017	0.041	0.051	0.048	0.08	0.01
0.107	0.019	0.04	0.053	0.05	0.078	0.011
0.108	0.021	0.039	0.057	0.049	0.079	0.011
0.11	0.019	0.031	0.055	0.046	0.075	0.01
0.111	0.015	0.031	0.05	0.032	0.08	0.044
0.107	0.021	0.031	0.059	0.039	0.053	0.01

Minimum	0.107	0.017	0.030	0.044	0.035	0.046	0.010
Maximum	0.111	0.021	0.042	0.060	0.050	0.080	0.043
Difference	0.004	0.004	0.012	0.016	0.015	0.034	0.033

$$vz := \begin{pmatrix} -102618374 \\ -59791608 \\ -82057416 \\ -82283207 \\ -85856049 \\ -94661249 \\ -82747934 \\ -107500227 \\ -87846516 \\ -103952383 \\ -65656479 \\ -156679548 \\ -154626854 \\ -89164536 \\ -153782728 \\ -95010402 \\ -93180318 \\ -94865311 \\ -83526732 \\ -44584059 \\ -151712231 \\ -127380157 \\ -79295732 \\ -75127038 \\ -156817999 \\ -158272820 \\ -73550472 \\ -84364636 \\ -149281963 \\ -94068927 \\ -128998472 \\ -82445815 \\ -82845264 \\ -83927901 \\ -147940978 \\ -59527399 \\ -129570000 \end{pmatrix}$$

The polynomial definition can be automated by using a summation:

$$p(x1, x2, x3, x4, x5, x6, x7) := \sum_{i=0}^{last(coeff)} coeff_i \cdot x1^{l_{i,0}} \cdot x2^{l_{i,1}} \cdot x3^{l_{i,2}} \cdot x4^{l_{i,3}} \cdot x5^{l_{i,4}} \cdot x6^{l_{i,5}} \cdot x7^{l_{i,6}}$$

The following best solution from ANSYS will be used as an example to test the function value:

$$p(0.107, 0.021, 0.031, 0.059, 0.039, 0.053, 0.01) = -1.29480206 \times 10^8$$ (consistent with actual point value)

Next, objective function given above as polynomial "p" is minimized using "Monte Carlo Programming":
minimum hoop stress = -1,623,110,000 Pa

Corresponding design variables:
x1 = 107 mm
x2 = 17 mm
x3 = 42 mm
x4 = 46 mm
x5 = 40 mm
x6 = 46 mm
x7 = 42 mm

ANSYS solution for the values of design variables given above (x1 through x7) = - 46,531,710 Pa

D:\unlv2\data — The values in "coeff" are written out to the file "data" in the D:\unlv2 directory

coeff

The customized stand-alone optimization algorithm steps are applied below to determine the range
of hoop stress considering all data points:
Stress range : From -158,272,820 Pa to -44,584,059 Pa

Then, the lower half of the stress range is selected:
Lower half: From -158,272,820 Pa to -101,428,440 Pa

The minimum and maximum values of the corresponding design variables and the same range after expansion are determined below (all dimensions are in meters):

	V1	V2	V3	V4	V5	V6	V7
Minimum	0.107	0.017	0.030	0.053	0.039	0.046	0.010
Maximum	0.111	0.021	0.033	0.059	0.048	0.080	0.016
Difference	0.004	0.004	0.003	0.006	0.009	0.034	0.006
Expanded minimum	0.107	0.017	0.030	0.052	0.038	0.043	0.010
Expanded maximum	0.111	0.021	0.033	0.060	0.049	0.080	0.017

37 data points: Mxy gives the values of 7 variables;
vz gives the corresponding hoop stresses from ANSYS

Mxy =

0.107	0.017	0.031	0.056	0.044	0.07	0.01
0.107	0.017	0.03	0.052	0.038	0.043	0.01
0.107	0.017	0.03	0.053	0.039	0.045	0.011
0.108	0.017	0.031	0.054	0.039	0.049	0.011
0.108	0.018	0.031	0.055	0.04	0.053	0.012
0.108	0.018	0.031	0.055	0.041	0.056	0.013
0.109	0.019	0.032	0.055	0.042	0.059	0.013
0.107	0.021	0.033	0.053	0.048	0.046	0.016
0.11	0.02	0.032	0.056	0.043	0.063	0.01
0.108	0.019	0.031	0.057	0.044	0.065	0.015
0.111	0.021	0.033	0.057	0.046	0.067	0.014
0.107	0.021	0.031	0.056	0.045	0.076	0.01
0.107	0.021	0.031	0.058	0.046	0.076	0.01
0.111	0.02	0.033	0.058	0.045	0.075	0.015
0.111	0.019	0.029	0.056	0.044	0.077	0.012
0.107	0.017	0.03	0.058	0.044	0.076	0.016
0.107	0.017	0.031	0.058	0.046	0.077	0.016
0.107	0.017	0.031	0.058	0.046	0.078	0.017
0.107	0.018	0.031	0.059	0.047	0.079	0.01
0.11	0.018	0.032	0.06	0.048	0.08	0.01
0.107	0.021	0.031	0.059	0.048	0.074	0.01
0.107	0.021	0.031	0.058	0.041	0.054	0.016
0.11	0.019	0.031	0.06	0.049	0.074	0.01
0.108	0.02	0.032	0.058	0.048	0.073	0.011
0.107	0.021	0.031	0.056	0.048	0.073	0.01
0.107	0.021	0.031	0.057	0.047	0.075	0.01
0.107	0.021	0.032	0.059	0.048	0.072	0.011
0.109	0.017	0.031	0.058	0.047	0.071	0.013
0.111	0.02	0.031	0.056	0.046	0.08	0.014
0.107	0.017	0.033	0.059	0.046	0.07	0.014
0.11	0.021	0.03	0.055	0.042	0.053	0.01
0.107	0.017	0.031	0.052	0.046	0.069	0.01
0.109	0.017	0.031	0.054	0.045	0.068	0.01
0.109	0.017	0.031	0.055	0.048	0.066	0.01
0.11	0.019	0.031	0.055	0.046	0.075	0.01
0.107	0.017	0.042	0.046	0.04	0.046	0.042
0.107	0.021	0.031	0.059	0.039	0.053	0.01

Minimum	0.107	0.017	0.030	0.046	0.038	0.043	0.010
Maximum	0.111	0.021	0.042	0.060	0.049	0.080	0.042
Difference	0.004	0.004	0.012	0.014	0.011	0.037	0.032

$$\mathbf{vz} := \begin{pmatrix} -102618374 \\ -80490163 \\ -88024012 \\ -93954191 \\ -101580312 \\ -102816185 \\ -109114420 \\ -107500227 \\ -136812565 \\ -103952383 \\ -101631971 \\ -156679548 \\ -154626854 \\ -91933278 \\ -153782728 \\ -85157929 \\ -81999183 \\ -79598642 \\ -94440811 \\ -88554076 \\ -151712231 \\ -127380157 \\ -98053739 \\ -101351077 \\ -156817999 \\ -158272820 \\ -101667129 \\ -91253783 \\ -149281963 \\ -79919850 \\ -128998472 \\ -127703683 \\ -113013381 \\ -111084660 \\ -147940978 \\ -46531710 \\ -129570000 \end{pmatrix}$$

Difference between the minimum and maximum values of design variables (second termination criterion, approximately half the value of the initial DV intervals):

D1 = 4 mm < 30 mm
D2 = 4 mm < 10 mm
D3 = 12 mm < 15 mm
D4 = 14 mm < 25 mm
D5 = 11 mm < 20 mm
D6 = 37 mm ~ 35 mm
D7 = 32 mm < 35 mm

Total number of iterations = 124

124 > maximum number of iterations (I_{max} =100) (third termination criterion)

Calculate standard deviation of data points:

$\mathbf{num} := 36$ Number of data points after final iteration

$$\mathbf{vsum} := \sum_{i=0}^{35} vz_i \qquad \mathbf{vavg} := \frac{\mathbf{vsum}}{\mathbf{num}}$$

$\mathbf{vavg} = -1.1128476344 \times 10^{8}$ Average value of "num" data points

$$\mathbf{sdev} := \left[\left(\frac{1}{\mathbf{num}-1}\right)\cdot\sum_{i=0}^{35}(vz_i - \mathbf{vavg})^2\right]^{\frac{1}{2}}$$

$\mathbf{sdev} = 2.81858836294 \times 10^{7}$ Standard deviation of data points

$\mathbf{pdev} := \left(\frac{\mathbf{sdev}}{\mathbf{vavg}}\right)\cdot(-1)$ Standard deviation devided by the average value of data points

$\mathbf{pdev} = 0.2532766879$ pdev < 0.3 (fourth termination criterion, ratio of standard deviation to average hoop stress)

The minimum hoop stress is the same as the one obtained in the previous loop (-158,272,820 Pa). Therefore, the first termination criterion, as outlined in the program algorithm, has been satisfied.

The best solution is given below:

x1 = 107 mm
x2 = 21 mm
x3 = 31 mm
x4 = 57 mm
x5 = 47 mm
x6 = 75 mm
x7 = 10 mm

Minimum hoop stress = -158,272,820 Pa

APPENDIX XI

TWO DIMENSIONAL AXISYMMETRIC ANSYS SOFTWARE MULTIPLE DESIGN VARIABLE INPUT FILE FOR SUCCESSIVE HEURISTIC QUADRATIC APPROXIMATION

```
/BATCH,LIST
!
!      2-D axisymmetric model for induction aneealing
!      Obective function: Maximum compression on the outer surface
!      State variable: None
!      7 design variables
!
/config,nres,10000
/units,si
!
!
*do,nit,1,10,1
n=10                     ! Number of iterations = array size
*dim,vx1,array,n,1
*dim,vx2,array,n,1
*dim,vx3,array,n,1
*dim,vx4,array,n,1
*dim,vx5,array,n,1
*dim,vx6,array,n,1
*dim,vx7,array,n,1
vx1(1)=0.107,0.111,0.108,0.109,0.111,0.11,0.11,0.107,0.108,0.11
vx2(1)=0.015,0.022,0.016,0.022,0.02,0.021,0.017,0.016,0.021,0.022
vx3(1)=0.03,0.043,0.03,0.035,0.036,0.037,0.031,0.034,0.038,0.032
vx4(1)=0.027,0.06,0.028,0.03,0.035,0.037,0.055,0.057,0.059,0.031
vx5(1)=0.024,0.05,0.024,0.026,0.03,0.031,0.048,0.035,0.04,0.042
vx6(1)=0.034,0.08,0.035,0.038,0.04,0.041,0.05,0.06,0.065,0.07
vx7(1)=0.01,0.041,0.013,0.038,0.015,0.02,0.025,0.03,0.035,0.04
!
!                SET INITIAL VALUE OF DESIGN VARIABLES
var1=vx1(nit)            ! Trunnion collar upper section length (variable
#1)
var2=vx2(nit)            ! Outer lid closure weld length (variable #2)
var3=vx3(nit)            ! Extended lid outer fillet weld base length
(variable #3)
var4=vx4(nit)            ! Extended lid inner fillet weld base length
(variable #4)
var5=vx5(nit)            ! Extended outer shell lid thickness (variable
#5)
var6=vx6(nit)            ! Reinforcement ring (variable #6)
var7=vx7(nit)            ! Ring weld section - inner (variable #7)
!
!
/prep7
/title, FEA to determine residual stresses due to induction coil
heating of closure welds
/vcon,,0
et,1,plane13,4,,1   ! Axisymmetric model for the outer shell
!
mptemp,1,20,1120
mpdata,ex,1,1,206e9,134e9 ! Alloy 22 Elastic Modulus
mpdata,nuxy,1,1,0.278,0.46   ! Alloy 22 Poisson's ratio
! Material properties of outer shell
tb,biso,1
tbtemp,20
tbdata,,310e6,0.847e9   ! Alloy 22
tbtemp,1120
tbdata,,85e6,0.173e9    ! Alloy 22
```

```
!
mp,dens,1,8690.0    ! Alloy 22
mpdata,alpx,1,1,12.4e-6,16.2e-6   ! Alloy 22
! Thermal properties of Alloy 22
/COM,    Define conductivity
MPTEMP,   1,  48,   100,  200,   300,  400,  500,
MPTEMP,   7,  600,
MPDATA, KXX, 1, 1,  10.1,  11.1,  13.4,  15.5,  17.5,  19.5,
MPDATA, KXX, 1, 7,  21.3,
/COM,    Define specific heat
MPTEMP,   1,  52,   100,  200,   300,  400,  500,
MPTEMP,   7,  600,
MPDATA, C, 1, 1,  414,  423,  444,  460,  476,  485,
MPDATA, C, 1, 7,  514,
/com, Define Parameters
!
! Parameters along x-axis
osir=0.762      ! Outer shell inner radius
osip=0.004      ! Outer shell inner part
osop=0.016      ! Outer shell outer part
tcti=0.02        ! Trunnion collar thickness - inner
tctm=0.005       ! Trunnion collar thickness - middle
tcto=0.015       ! Trunnion collar thickness - outer
gap=0.004       ! Gap between extended outer shell lid and outer shell
!
! Parameters along y-axis
cav=4.775+0.03+0.01+0.03+0.07   ! Distance between outer shell lid
inner surfaces
hcav=cav/2      ! Half distance between outer shell lid inner surfaces
trl=0.1          ! Trunnion ring length
tcl=0.14         ! Trunnion collar length
tcbi=0.005       ! Trunnion collar bottom - innner region
tcbo=0.02        ! Trunnion collar bottom - outer region
clth=0.01       ! Closure lid thickness
clw=0.01        ! Closure lid weld
tcui=0.02        ! Trunnion collar upper section - inner part of the
fillet weld
tcuo=0.02        ! Trunnion collar upper section - outer part of the
fillet weld
olid=0.025      ! Extended lid base
!
/com, Define keypoints
csys,0
k,1,osir,
k,2,osir+osip,
k,3,osir+osip+osop,
k,4,osir,hcav-trl-tcl-tcbi-tcbo
k,5,osir+osip,hcav-trl-tcl-tcbi-tcbo
k,6,osir+osip+osop,hcav-trl-tcl-tcbi-tcbo
k,7,osir,hcav-trl-tcl-tcbi
k,8,osir+osip,hcav-trl-tcl-tcbi
k,9,osir+osip+osop,hcav-trl-tcl-tcbi
k,10,osir+osip+osop+tcti,hcav-trl-tcl-tcbi
k,11,osir,hcav-trl-tcl
k,12,osir+osip,hcav-trl-tcl
k,13,osir+osip+osop,hcav-trl-tcl
k,14,osir+osip+osop+tcti,hcav-trl-tcl
```

```
k,15,osir+osip+osop+tcti+tctm,hcav-trl-tcl
k,16,osir+osip+osop+tcti+tctm+tcto,hcav-trl-tcl
k,17,osir,hcav-trl
k,18,osir+osip,hcav-trl
k,19,osir+osip+osop,hcav-trl
k,20,osir+osip+osop+tcti,hcav-trl
k,21,osir+osip+osop+tcti+tctm,hcav-trl
k,22,osir+osip+osop+tcti+tctm+tcto,hcav-trl
k,23,0,hcav
k,24,osir,hcav
k,25,osir+osip,hcav
k,26,osir+osip+osop,hcav
k,27,osir+osip+osop+tcti,hcav
k,28,osir+osip+osop+tcti+tctm+tcto,hcav
k,29,0,hcav+clth
k,30,osir+osip-clw,hcav+clth
k,31,osir+osip,hcav+clth
k,32,osir+osip+osop,hcav+clth
k,33,osir+osip+osop+tcti,hcav+clth
k,34,osir+osip+osop+tcti+tctm+tcto,hcav+clth
k,35,osir+osip,hcav+clth+clw
k,36,osir+osip+osop,hcav+clth+clw
k,37,osir+osip+osop+tcti,hcav+clth+clw
k,38,osir+osip+osop+tcti+tctm+tcto,hcav+clth+clw
k,39,osir+osip,hcav+clth+clw+var1
k,40,osir+osip+osop,hcav+clth+clw+var1
k,41,osir+osip+osop+tcti,hcav+clth+clw+var1
k,42,osir+osip+osop+tcti+tctm+tcto,hcav+clth+clw+var1
k,43,osir+osip,hcav+clth+clw+var1+tcui
k,44,osir+osip+osop,hcav+clth+clw+var1+tcui
k,45,osir+osip+osop+tcti,hcav+clth+clw+var1+tcui
k,46,osir+osip,hcav+clth+clw+var1+tcui+tcuo
k,47,osir+osip+osop,hcav+clth+clw+var1+tcui+tcuo
k,48,osir+osip-gap-var5,hcav+clth+clw+var1+tcui+tcuo+var2
k,49,osir+osip-gap,hcav+clth+clw+var1+tcui+tcuo+var2
k,50,osir+osip,hcav+clth+clw+var1+tcui+tcuo+var2
k,51,osir+osip+osop,hcav+clth+clw+var1+tcui+tcuo+var2
k,52,osir+osip-gap,hcav+clth+clw+var1+tcui+tcuo
k,53,osir+osip-gap-var5-var6,hcav+clth+clw+var1+tcui+tcuo+var2-var3
k,54,osir+osip-gap-var5,hcav+clth+clw+var1+tcui+tcuo+var2-var3
k,55,osir+osip-gap,hcav+clth+clw+var1+tcui+tcuo+var2-var3
k,56,0,hcav+clth+clw+var1+tcui+tcuo+var2-var3-var4
k,57,osir+osip-gap-var5-var6-var7,hcav+clth+clw+var1+tcui+tcuo+var2-
var3-var4
k,58,osir+osip-gap-var5-var6,hcav+clth+clw+var1+tcui+tcuo+var2-var3-
var4
k,59,osir+osip-gap-var5,hcav+clth+clw+var1+tcui+tcuo+var2-var3-var4
k,60,osir+osip-gap,hcav+clth+clw+var1+tcui+tcuo+var2-var3-var4
k,61,0,hcav+clth+clw+var1+tcui+tcuo+var2-var3-var4-olid
k,62,osir+osip-gap-var5-var6-var7,hcav+clth+clw+var1+tcui+tcuo+var2-
var3-var4-olid
k,63,osir+osip-gap-var5-var6,hcav+clth+clw+var1+tcui+tcuo+var2-var3-
var4-olid
k,64,osir+osip-gap-var5,hcav+clth+clw+var1+tcui+tcuo+var2-var3-var4-
olid
k,65,osir+osip-gap,hcav+clth+clw+var1+tcui+tcuo+var2-var3-var4-olid
/com, Horizontal lines in inner (first) part of the outer shell
```

```
l,1,2
l,4,5
l,7,8
l,11,12
l,17,18
l,24,25
l,30,31
l,30,35
l,31,35
l,32,36
l,33,37
l,34,38
lesize,all,,,2,1,1
lsel,none
/com, Horizontal lines in second part of the outer shell
l,2,3
l,5,6
l,8,9
l,12,13
l,18,19
l,25,26
l,31,32
l,35,36
l,39,40
l,43,44
l,46,47
l,50,51
lesize,all,,,2,1,1
lsel,none
/com, Horizontal lines in inner part of the trunnion collar
l,7,4
l,8,5
l,9,6
l,10,6
l,9,10
l,13,14
l,19,20
l,26,27
l,32,33
l,36,37
l,40,41
l,44,45
l,47,45
l,44,47
l,43,46
lesize,all,,,2,1,1
lsel,none
/com, Horizontal lines in the thin section of the lower trunnion collar
l,11,7
l,12,8
l,13,9
l,14,10
l,15,10
l,14,15
l,20,21
lesize,all,,,2,1,1
lsel,none
```

```
/com, Horizontal lines in the thick section of the lower trunnion
collar
l,15,16
l,21,22
lesize,all,,,1,1,1
lsel,none
/com, Horizontal lines in the outer part of the upper trunnion collar
l,27,28
l,33,34
l,37,38
l,41,42
l,45,42
l,41,45
l,40,44
l,39,43
lesize,all,,,2,1,1
lsel,none
/com, Horizontal lines in the gap
l,52,46
l,49,50
lesize,all,,,1,1,1
lsel,none
/com, Horizontal lines in the extended outer shell lid
l,64,65
l,59,60
l,54,55
l,48,52
l,48,49
l,49,52
l,50,46
l,51,47
lesize,all,,,4,1,1
lsel,none
/com, Horizontal lines in the extended lid reinforcement ring
l,63,64
l,58,59
l,53,54
l,53,48
l,48,54
l,52,55
lesize,all,,,4,1,1
lsel,none
/com, Horizontal lines in the extended lid reinforcement ring - left
side section
l,62,63
l,57,58
l,57,53
l,53,58
l,54,59
l,55,60
lesize,all,,,4,1,1
lsel,none
/com, Horizontal lines in the outer lid
l,61,62
l,56,57
lesize,all,,,6,.0625,1
lsel,none
```

```
/com, Horizontal lines in the closure lid
l,23,24
l,29,30
lesize,all,,,6,.0625,1
lsel,none
/com, Vertical lines above the symmetry line
l,1,4
l,2,5
l,3,6
lesize,all,,,6,.06,1
lsel,none
/com, Vertical lines in the lower part of the trunnion collar
l,11,17
l,12,18
l,13,19
l,14,20
l,15,21
l,16,22
lesize,all,,,2,1,1
lsel,none
/com, Vertical lines in the middle part of the trunnion collar
l,17,24
l,18,25
l,19,26
l,20,27
lesize,all,,,2,1,1
lsel,none
/com, Vertical lines in the closure lid
l,23,29
l,24,30
l,25,31
l,26,32
l,27,33
l,28,34
lesize,all,,,1,1,1
lsel,none
/com, Vertical lines in the upper part of the trunnion collar
l,35,39
l,36,40
l,37,41
l,38,42
lesize,all,,,6,.2,1
lsel,none
/com, Vertical lines in the outer lid
l,61,56
l,62,57
l,63,58
l,64,59
l,65,60
lesize,all,,,2,1,1
lsel,none
/com, Define areas starting from the region close to bottom symmetry
plane
allsel
al,1,84,2,83
al,13,85,14,84
al,2,26,3,25
```

```
al,14,27,15,26
al,27,28,29
al,3,41,4,40
al,15,42,16,41
al,29,43,30,42
al,43,44,45
al,4,87,5,86
al,16,88,17,87
al,30,89,31,88
al,45,90,46,89
al,47,91,48,90
al,5,93,6,92
al,17,94,18,93
al,31,95,32,94
al,81,97,82,96
al,6,98,7,97
al,18,99,19,98
al,32,100,33,99
al,49,101,50,100
al,7,9,8
al,19,10,20,9
al,33,11,34,10
al,50,12,51,11
al,20,103,21,102
al,34,104,35,103
al,51,105,52,104
al,21,55,22,56
al,35,54,36,55
al,52,53,54
al,22,38,23,39
al,36,37,38
al,23,66,24,65
al,57,65,58,64
al,62,64,63
al,69,71,70
al,61,72,62,71
al,74,76,75
al,68,77,69,76
al,60,78,61,77
al,79,107,80,106
al,73,108,74,107
al,67,109,68,108
al,59,110,60,109
/com, Outer shell and lid mesh
alls
type,1   ! plane13
mat,1    ! Alloy 22
smrt,off
mshkey,1
amesh,all
/com, Apply displacement/symmetry constraints
nsel,s,loc,y,0
d,all,uy,0
nsel,s,loc,x,-.001,.001
d,all,ux,0
allsel
/nerr,,100000
```

```
finish
/SOLU
ANTYPE,TRAN,NEW,
NROPT,FULL,,ON,
TRNOPT,FULL,
neqit,100
ALLS
TIME,35
/COM,          Thermal initial boundary condition for the WP at 20
degrees C
TUNIF,20
/COM,          Apply loads and solve for 0 to 35 seconds
nsel,s,loc,y,hcav+clth+clw+var1+tcui+tcuo+(var2/2),hcav+clth+clw+var1+t
cui+tcuo+var2   ! Select volume of first HAZ from coil induction
D,ALL,TEMP,1120
nsel,s,loc,y,hcav+clth+clw+var1+tcui+tcuo,hcav+clth+clw+var1+tcui+tcuo+
(var2/2)-0.0001    ! Select volume of second HAZ from coil induction
D,ALL,TEMP,750
nsel,s,loc,y,hcav+clth+clw+var1,hcav+clth+clw+var1+tcui+tcuo-0.0001
! Select volume of third HAZ from coil induction
D,ALL,TEMP,500
nsel,s,loc,y,hcav+clth+clw+var1+tcui+tcuo+var2-var3-
var4+0.0001,hcav+clth+clw+var1-0.00001   ! Select volume of fourth HAZ
from coil induction
D,ALL,TEMP,250
/COM,          Set time integration parameters for the first time
interval
ALLS
NSUBST,5,10,4,ON,
KBC,0
AUTOTS,ON
OUTRES,ALL,ALL
SOLVE
!
!
/COM,          Solve from 35 to 45 seconds
TIME,45
nsel,s,loc,y,hcav+clth+clw+var1+tcui+tcuo+(var2/2),hcav+clth+clw+var1+t
cui+tcuo+var2   ! Select volume of first HAZ from coil induction
D,ALL,TEMP,1120
nsel,s,loc,y,hcav+clth+clw+var1+tcui+tcuo,hcav+clth+clw+var1+tcui+tcuo+
(var2/2)-0.0001    ! Select volume of second HAZ from coil induction
D,ALL,TEMP,750
nsel,s,loc,y,hcav+clth+clw+var1,hcav+clth+clw+var1+tcui+tcuo-0.0001
! Select volume of third HAZ from coil induction
D,ALL,TEMP,500
nsel,s,loc,y,hcav+clth+clw+var1+tcui+tcuo+var2-var3-
var4+0.0001,hcav+clth+clw+var1-0.00001   ! Select volume of fourth HAZ
from coil induction
D,ALL,TEMP,250
ALLS
OUTRES,ALL,ALL
SOLVE
!
!
/COM,          Solve from 45 to 75 seconds
nsel,all
```

```
DDELE,ALL,TEMP                          ! Delete previously set boundary
conditions
TM_START=46
TM_END=75
TM_INC=1
ALLS
*DO,TM,TM_START,TM_END,TM_INC
        TIME,TM,
! Identify and group all surface nodes for quenching
lsel,s,,,75
lsel,a,,,70
lsel,a,,,63
lsel,a,,,58
lsel,a,,,24
lsel,a,,,66
lsel,a,,,37
lsel,a,,,53
lsel,a,,,105
nsll,s,1
cm,s_nodes,node
alls
! Select first set of surface nodes for quenching
nsel,s,,,s_nodes
nsel,r,loc,y,hcav+clth+clw+var1+tcui+tcuo+(var2/2),hcav+clth+clw+var1+t
cui+tcuo+var2
cm,surf1,node
D,ALL,TEMP,1120-((1000/29)*(TM-46))
! Select second surface area for quenching
nsel,s,,,s_nodes
nsel,r,loc,y,hcav+clth+clw+var1+tcui+tcuo,hcav+clth+clw+var1+tcui+tcuo+
(var2/2)-0.0001
cm,surf2,node
D,ALL,TEMP,750-((730/29)*(TM-46))
! Select third surface area for quenching
nsel,s,,,s_nodes
nsel,r,loc,y,hcav+clth+clw+var1,hcav+clth+clw+var1+tcui+tcuo-0.0001
cm,surf3,node
D,ALL,TEMP,500-((480/29)*(TM-46))
! Select fourth surface area for quenching
nsel,s,,,s_nodes
nsel,r,loc,y,hcav+clth+clw+var1+tcui+tcuo+var2-var3-
var4+0.0001,hcav+clth+clw+var1-0.00001
cm,surf4,node
D,ALL,TEMP,250-((230/29)*(TM-46))
        ALLS
        NSUBST,2,4,1,ON,
        OUTRES,ALL,ALL
        SOLVE
*ENDDO
!
!
/COM,           Solve from 75 to 1800 seconds
nsel,s,,,surf1
nsel,a,,,surf2
nsel,a,,,surf3
nsel,a,,,surf4
D,ALL,TEMP,20
```

```
TM_START=80
TM_END=1800
TM_INC=5
ALLS
*DO,TM,TM_START,TM_END,TM_INC
        TIME,TM,
        NSUBST,2,4,1,ON,
        OUTRES,ALL,ALL
        SOLVE
*ENDDO
finish
!
/POST1
SET,LAST
alls
! Select first surface area for quenching
nsel,s,,,s_nodes
nsel,r,loc,y,hcav+clth+clw+var1+tcui+tcuo+(var2/2),hcav+clth+clw+var1+t
cui+tcuo+var2
cm,surf1,node
! Select second surface area for quenching
nsel,s,,,s_nodes
nsel,r,loc,y,hcav+clth+clw+var1+tcui+tcuo,hcav+clth+clw+var1+tcui+tcuo+
(var2/2)-0.0001
cm,surf2,node
! Select third surface area for quenching
nsel,s,,,s_nodes
nsel,r,loc,y,hcav+clth+clw+var1,hcav+clth+clw+var1+tcui+tcuo-0.0001
cm,surf3,node
! Select fourth surface area for quenching
nsel,s,,,s_nodes
nsel,r,loc,y,hcav+clth+clw+var1+tcui+tcuo+var2-var3-
var4+0.0001,hcav+clth+clw+var1-0.00001
cm,surf4,node
nsel,s,,,surf1
nsel,a,,,surf2
nsel,a,,,surf3
nsel,a,,,surf4
nsort,s,z,0,0,1
*get,sz_max,sort,,max          ! Z-STRESS (COMPRESSION) MAXIMUM REAL
VALUE
!
! ***********  PRINT STATUS OF ALL DVs and MAXIMUM COMPRESSIVE STRESS
************
!
*status,var1
*status,var2
*status,var3
*status,var4
*status,var5
*status,var6
*status,var7
*status,sz_max
!
! ***********   Clear database for next iteration   **********
!
finish
```

```
/clear
!
*ENDDO
!
/EXIT,NOSA
```

APPENDIX XII

MATHCAD CALCULATION FILE FOR SENSITIVITY ANALYSIS OF THE BEST SOLUTION OBTAINED FROM THE SUCCESSIVE HEURISTIC QUADRATIC APPROXIMATION

Sensitivity Analysis of the Best Solution Obtained from the Customized Stand-Alone Optimization Algorithm

The following previously obtained sets of optimization solutions are used for sensitivity analysis of the best solution. Six different sets are used for this analysis:

Solution set #1:
V1 = 107 mm, V2 = 21 mm, V3 = 31 mm, V4 = 56 mm, V5 = 45 mm, V6 = 76 mm, V7 = 10 mm
Minimum hoop stress = -156,679,548 Pa

Solution set #2:
V1 = 107 mm, V2 = 21 mm, V3 = 31 mm, V4 = 58 mm, V5 = 46 mm, V6 = 76 mm, V7 = 10 mm
Minimum hoop stress = -154,626,854 Pa

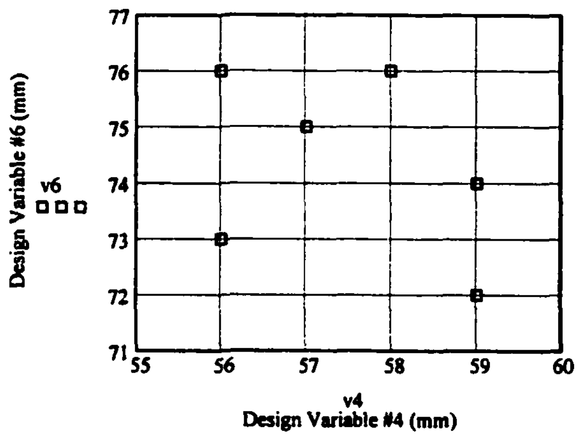
Solution set #3:
V1 = 107 mm, V2 = 21 mm, V3 = 31 mm, V4 = 59 mm, V5 = 48 mm, V6 = 74 mm, V7 = 10 mm
Minimum hoop stress = -151,712,231 Pa

Solution set #4:
V1 = 107 mm, V2 = 21 mm, V3 = 31 mm, V4 = 56 mm, V5 = 48 mm, V6 = 73 mm, V7 = 10 mm
Minimum hoop stress = -156,817,999 Pa

Solution set #5:
V1 = 107 mm, V2 = 21 mm, V3 = 31 mm, V4 = 57 mm, V5 = 47 mm, V6 = 75 mm, V7 = 10 mm
Minimum hoop stress = -158,272,820 Pa

Solution set #6:
V1 = 107 mm, V2 = 21 mm, V3 = 32 mm, V4 = 59 mm, V5 = 48 mm, V6 = 72 mm, V7 = 11 mm
Minimum hoop stress = -101,667,129 Pa
Two design variables are selected for the sensitivity analysis: V4 and V6. The rest of the variables do not significantly change among the six different sets of solutions given above. A graphical representation of the function evaluations for V4 and V6 is determined below:

$$v4 := \begin{pmatrix} 56.0 \\ 58.0 \\ 59.0 \\ 56.0 \\ 57.0 \\ 59.0 \end{pmatrix} \text{mm} \qquad v6 := \begin{pmatrix} 76.0 \\ 76.0 \\ 74.0 \\ 73.0 \\ 75.0 \\ 72.0 \end{pmatrix} \text{mm}$$



The design variable plot given above indicates that the minimum stress value (-158,272,820 Pa corresponding to V4 = 57 mm, V6 = 75 mm), is surrounded by higher stress values. Therefore, the minimum stress value (-158,272,820 Pa) is an optimum solution.

APPENDIX XIII

MATHCAD FILE FOR THE COMPRESSIVE STRESS PENETRATION DEPTH CALCULATIONS

Compressive Stress Penetration Depth Calculations

The hoop stress results that are given in Appendix II are used below to determine the compressive hoop stress penetration depth by linear interpolation.

Original Design:

Calculation of the penetration depth from the induction annealing surface:

$depth1 := 5.65$ mm $\quad$ $stress1 := 58.1$ MPa

$depth2 := 5.95$ mm $\quad$ $stress2 := 68.6$ MPa

$stress := 0.2 \cdot 310$ MPa $\quad$ 20% of Alloy 22 yield strength (310 MPa) is the threshold stress, see Chapters 3 and 7

$$depth := depth1 + \left[(stress - stress1) \cdot \frac{(depth2 - depth1)}{(stress2 - stress1)} \right]$$

$depth = 5.8$ mm

Calculation of the penetration depth from the closure-weld surface:

$depth1 := 9.5$ mm $\quad$ $stress1 := 51.1$ MPa

$depth2 := 9.75$ mm $\quad$ $stress2 := 68.8$ MPa

$$depth := depth1 + \left[(stress - stress1) \cdot \frac{(depth2 - depth1)}{(stress2 - stress1)} \right]$$

$depth = 9.7$ mm

Optimization Problem #1:

Calculation of the penetration depth from the induction annealing surface:

$\text{depth1} := 5.66$ mm $\text{stress1} := 36.6$ MPa

$\text{depth2} := 6.36$ mm $\text{stress2} := 63.8$ MPa

$\text{stress} := 0.2 \cdot 310$ MPa **20% of Alloy 22 yield strength (310 MPa) is the threshold stress, see Chapters 3 and 7**

$$\text{depth} := \text{depth1} + \left[(\text{stress} - \text{stress1}) \cdot \frac{(\text{depth2} - \text{depth1})}{(\text{stress2} - \text{stress1})} \right]$$

$\text{depth} = 6.3$ mm

Calculation of the penetration depth from the closure-weld surface:

$\text{depth1} := 7.75$ mm $\text{stress1} := 58.5$ MPa

$\text{depth2} := 8.0$ mm $\text{stress2} := 68.6$ MPa

$$\text{depth} := \text{depth1} + \left[(\text{stress} - \text{stress1}) \cdot \frac{(\text{depth2} - \text{depth1})}{(\text{stress2} - \text{stress1})} \right]$$

$\text{depth} = 7.8$ mm

Optimization Problem #2:

Calculation of the penetration depth from the induction annealing surface:

$depth1 := 3.8$ mm $stress1 := 56.3$ MPa

$depth2 := 4.02$ mm $stress2 := 69.3$ MPa

$stress := 0.2 \cdot 310$ MPa **20% of Alloy 22 yield strength (310 MPa) is the threshold stress, see Chapters 3 and 7**

$$depth := depth1 + \left[(stress - stress1) \cdot \frac{(depth2 - depth1)}{(stress2 - stress1)} \right]$$

$depth = 3.9$ mm

Calculation of the penetration depth from the closure-weld surface:

$depth1 := 11.44$ mm $stress1 := 52.9$ MPa

$depth2 := 11.88$ mm $stress2 := 66.1$ MPa

$$depth := depth1 + \left[(stress - stress1) \cdot \frac{(depth2 - depth1)}{(stress2 - stress1)} \right]$$

$depth = 11.7$ mm

Optimization Problem #3:

Calculation of the penetration depth from the induction annealing surface:

$depth1 := 4.42$ mm $\quad$ $stress1 := 43.3$ MPa

$depth2 := 4.72$ mm $\quad$ $stress2 := 65.5$ MPa

$stress := 0.2 \cdot 310$ MPa $\quad$ 20% of Alloy 22 yield strength (310 MPa) is the threshold stress, see Chapters 3 and 7

$$depth := depth1 + \left[(stress - stress1) \cdot \frac{(depth2 - depth1)}{(stress2 - stress1)} \right]$$

$depth = 4.7$ mm

Calculation of the penetration depth from the closure-weld surface:

$depth1 := 8.4$ mm $\quad$ $stress1 := 58.6$ MPa

$depth2 := 8.61$ mm $\quad$ $stress2 := 72.1$ MPa

$$depth := depth1 + \left[(stress - stress1) \cdot \frac{(depth2 - depth1)}{(stress2 - stress1)} \right]$$

$depth = 8.5$ mm

Customized Stand-Alone Optimization:

Calculation of the penetration depth from the induction annealing surface:

$\text{depth1} := 4.4$ mm $\quad$ $\text{stress1} := 46.2$ MPa

$\text{depth2} := 4.61$ mm $\quad$ $\text{stress2} := 66.6$ MPa

$\text{stress} := 0.2 \cdot 310$ MPa $\quad$ 20% of Alloy 22 yield strength (310 MPa) is the threshold stress, see Chapters 3 and 7

$$\text{depth} := \text{depth1} + \left[(\text{stress} - \text{stress1}) \cdot \frac{(\text{depth2} - \text{depth1})}{(\text{stress2} - \text{stress1})} \right]$$

$\text{depth} = 4.6$ mm

Calculation of the penetration depth from the closure-weld surface:

$\text{depth1} := 9.24$ mm $\quad$ $\text{stress1} := 50.9$ MPa

$\text{depth2} := 9.45$ mm $\quad$ $\text{stress2} := 63.6$ MPa

$$\text{depth} := \text{depth1} + \left[(\text{stress} - \text{stress1}) \cdot \frac{(\text{depth2} - \text{depth1})}{(\text{stress2} - \text{stress1})} \right]$$

$\text{depth} = 9.4$ mm

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Dissertation Title: Minimization of Residual Stresses in the Closure-Weld Region of the Spent Nuclear Fuel Canisters Using Induction Annealing Process

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