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HEAT EXCHANGER STAYBOLT ACCEPTANCE CRITERIA (U) Task Number: 90-058-1

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EXECUTIVE SUMMARY

The structural integrity demonstration of the primary coolant piping system includes evaluating the structural capacity of each component against a large break or equivalent Double-Ended Guillotine Break. A large break at the inlet or outlet heads of the heat exchangers would occur if the restraint members of the heads become inactive. The structural integrity of the heads is demonstrated by showing the redundant capacity of the staybolts to restrain the head at design conditions and under seismic loadings.

The SRS heat exchanger head is attached to the tubesheet by 84 staybolts. Access to the staybolts is limited due to a welded seal cap over the staybolts. An ultrasonic testing (UT) inspection technique to provide an in-situ examination of the staybolts has recently been developed at SRS. Examination of the staybolts will be performed to ensure their service condition and configuration is within acceptance limits.

An acceptance criteria methodology has been developed to disposition flaws reported in the staybolt inspections while ensuring adequate restraint capacity of the staybolts to maintain integrity of the heat exchanger heads against collapse. The methodology includes an approach for the baseline and periodic inspections of the staybolts.

The heat exchanger head is analyzed with a three-dimensional finite element model. The restraint provided by the staybolts is evaluated for several postulated cases of inactive or missing staybolts, i.e., bolts that have a flaw exceeding the UT threshold depth of 25% for the UT inspection technique. A limit of 6 inactive staybolts is reached in the fracture analysis of flawed staybolts; the fracture criterion is the CTOD¹ of 0.032 inches corresponding to the greatest local displacement of the head at the active staybolts. A total of up to 6 staybolts, reported as containing flaws with depths at or exceeding 25%, would therefore be acceptable in the heat exchanger.

Evaluation of specific, inactive staybolt configurations based on the UT results can be performed with the finite element model and fracture methodology in this report.

¹Crack Tip Opening Displacement, an elastic-plastic fracture parameter based on the material toughness, J_{IC}.

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1.0 INTRODUCTION

1.1 Background

The structural integrity analysis of the heat exchangers of the reactor Process Water System had been previously performed as part of the LOCA Definition Project (Task 88-001-1) (Refs.1 and 2). Failure by a large break equivalent to a Double-Ended Guillotine Break was postulated at the inlet/outlet heads if the heads were not adequately restrained. The break time-history was not addressed; however, it was shown that head failure would be preceded by detectable leakage. The analysis in this report is an extension of the previous heat exchanger analysis and is focussed on demonstrating the head restraint capacity of the staybolts.

1.2 Inspection Technique for the Staybolts

The Equipment Engineering Section was requested by Reactor Restart Division to develop a nondestructive test to examine the staybolts for flaws (Ref.3). An ultrasonic, pulse-echo, straight beam transmitted from outside of the staybolt housing through the welded concave sealing cap and water gap to one end of a staybolt, allows an in-place, in-service inspection for the staybolts. Problems involving multiple reflections from the couplant layer, sealing cap, water gap, and the countersinks at the centers of both ends of the staybolts (due to machining) were resolved. A transducer fixture mounted to the staybolt housing was designed (Ref.4), resulting in a successful technique for the inspection with a capability to detect flaws with sizes greater than 25% of the staybolt diameter (Ref.5).

1.3 Acceptance Criteria for Staybolt Flaw Disposition

Acceptance criteria to support the ultrasonic testing (UT) inspection of the staybolts were requested by Reactor Restart Division (Ref.6). This report provides an acceptance criteria methodology with the technical bases to disposition flaws reported in the staybolt inspections. This methodology ensures adequate restraint capacity of the staybolts and provides an approach for the baseline and periodic inspections of the staybolts so that any degradation of the staybolts reducing their load-carrying capacity would be detected and monitored.

The adequacy of head restraint, even with flawed staybolts, is demonstrated by performing stress analysis of the heat exchanger head and staybolts with fracture mechanics analyses of the postulated staybolt flaws. A three-dimensional finite element model was developed for the head and staybolts. The heat exchanger design pressure and piping seismic reaction forces were applied to the model. The critical flaw depths for individual staybolts and various configurations of multiple inactive staybolts were estimated by linear elastic fracture mechanics, upper bound limit load analysis, and lower bound limit load analysis. Acceptance criteria based on flaw sizes are developed for potential future application with advanced UT sizing capability. Acceptance criteria for flaw disposition under present UT capability were developed by applying a crack tip opening displacement (CTOD) fracture criterion to evaluate the results reported as "flawed" or "unflawed" staybolts. A reduced staybolt cross-section, equivalent to a staybolt containing a 25% deep flaw (at the UT limit) is assumed for all "unflawed" staybolts in the development of the acceptance criteria. A finite element model for stress analysis was developed to support any future UT

inspections of the staybolts and would allow evaluation of various customized, inactive staybolt configurations based on the inspection results.

The heat exchanger service history, operating conditions, and material specifications are summarized in Section 2 of this report. Section 3 contains the details of the finite element modeling and fracture analysis of flaw postulates in staybolts. The acceptance criteria methodology for the staybolt inspections is provided in Section 4. Recommendations for in-service inspections of the staybolts and a flowchart for flaw disposition are given in Section 5. Appendix A contains the finite element input for the staybolt analysis with instructions for future customized applications.

2.0 HEAT EXCHANGER STRUCTURAL ANALYSIS OVERVIEW

2.1 Heat Exchanger Service History Summary

The reactor process water heat exchangers have operated successfully without gross rupture or failure of the heads (primary pressure boundary), tubes (primary to secondary pressure boundary), or shells (secondary pressure boundary) throughout service. During the past 36 years of reactor operation, approximately 60 instances of leakage from cracking or wear have occurred through the pressure boundaries which were remedied by repair of, replacement of, or design modifications to the heat exchangers (Ref.7). Many heat exchangers were repaired or replaced because of tube cracking. Most of the tube cracking resulting in leakage of moderator into the secondary coolant was due to corrosion. Corrosion mechanisms have also caused cracking in other parts of the heat exchangers including the head, staybolts, and shell (Ref.8). Additional heat exchangers were procured through the years with design improvements to reduce or eliminate these degradation mechanisms. The newest design fabricated by Nooter Corporation incorporates features that should eliminate all of the significant degradation mechanisms leading to leakage. Crevice corrosion of the head staybolts is the only remaining postulated degradation mechanism in the Nooter design (Ref.8). Sections 2.1.1 to 2.1.3 provide an overview of the leakage failures of the heat exchangers throughout their service history as condensed from Reference 7. A list of the designs of the heat exchangers presently in service, along with years in service, is also contained in Reference 7.

2.1.1 *Vibration of the Heat Exchanger Tubes*

Fatigue and/or wear-induced leaks were encountered during the first 11 years of operation with the original heat exchangers installed. The original design utilized double tubesheets at each end of the shell, with the head attached to the outer tubesheet by staybolts and flange bolts. Vibration of the tubes against baffles or by wear from debris against tubes caused many tube leaks to develop. Only two heat exchangers were replaced because of vibration fatigue of a heat exchanger tube. The first failure occurred in 1961 following a CW flow test (21,000 gpm per heat exchanger versus 14,000 gpm normal flow). The second fatigue failure occurred in 1964 and originated at a point of galling damage on the tube. Fatigue failures have been prevented by maintaining flow rates in the normal operating ranges and by the installation of an improved cooling water flow distributor plate at the inlet in 1964-65. The last confirmed failure due to vibration occurred in 1972.

2.1.2 *Corrosion of the Heat Exchanger*

The SRS heat exchangers had corrosion in five separate areas leading to cracking and/or leaking: 1) Corrosion of tubes within the leak collection spaces of the double tubesheet design, 2) Corrosion of the staybolts at the elastomeric seals, 3) Corrosion of tubes in the river water space under or near the inner tube sheets, 4) Corrosion of the shell adjacent to welds, and 5) Corrosion of the heads at the head flange. Corrosion in the first area occurred in 1960 when tubes in the leak collection spaces between the double tube sheets developed leaks from chloride stress corrosion. Experience with the SRS heat exchangers revealed that the leak collection space was not necessary and an inhibitor solution was circulated through the space. All heat exchangers fabricated after 1980 are single tube sheet design eliminating the leak collection space. Corrosion in the second area occurred because of chloride stress corrosion of the staybolts, O-ring retainers, and the head bosses resulting in leakage past the seals. This problem was solved by eliminating the O-rings and

installing new staybolts, cutting out the boss seat, and installing boss closure sleeves in each boss with a seal-welded boss closure cap. In addition, some of the heads contain stress corrosion cracks in the flange area. This problem has not been completely solved in the original heads and inspections are made periodically to determine if cracks are propagating or forming.

2.1.3 *Seal Leakage, Tube Fouling, and Pluggage of the Heat Exchangers*

Other instances of leakage not caused by cracking included D₂O leakage past O-rings and gaskets. The original head gasket seat was designed for use with asbestos gaskets. The asbestos was replaced with a rubber gasket, which leaked, and later a Buna S rubber gasket which caused pitting of the flange faces. The same problem occurred on the O-rings used to seal the staybolt to the heat exchanger head bosses. The elastomer gasket was then replaced with a seal-welded closure. This consisted of seal-welding plugs in the bolt holes of both the head and tube sheet flanges, welding a half-pipe between the head and tube sheet flanges and replacing the flange bolts with C-clamps.

Loss of heat transfer caused by tube fouling and reduction of cooling water flow from shell side pluggage have also occurred in the heat exchangers. The service history of the heat exchangers, including a compendium of all the service-induced failures, is provided in Reference 7.

2.2 Materials of Construction and Service Conditions

The present arrangement of heat exchangers in K and L reactors contains head and shell material of either Type 304 or 304L stainless steel and staybolt material of Type 303 stainless steel. When new heat exchangers were procured, modifications were made to the design to eliminate problems that were encountered with the original heat exchangers. Significant changes were made to the design of the heat exchangers procured from Mitsui and Hitachi in 1983. The leak collection spaces were eliminated; the tube and tube sheets were made of 316L; and the shell nozzles, distributor plates, baffles and heads were made of 304L SS. These parts in the original heat exchangers were made of 304 SS. All of the modifications made to the Mitsui and Hitachi heat exchangers were also incorporated in the Nooter heat exchangers. However, Sea Cure tubes (ferritic SS) were used in the Nooter design rather than 316L SS. All twelve heat exchangers in L Area are Mitsui with new heat exchanger heads of 304L SS, all 12 in P Area are Foster Wheeler, and K Area has 5 Nooter, 1 Mitsui, 2 American Locomotive Company, and 4 Foster Wheeler units. Tensile properties (yield, tensile, and flow strengths and Young's modulus) are provided in Table 4 for each of Types 304, 304L, and 303 stainless steel.

2.3 Temperatures and Pressures

The heat exchanger operating and design conditions are summarized in Table 1:

TABLE 1. Heat Exchanger Operating and Design Conditions

		PW Inlet	PW Outlet	CW Inlet	CW Outlet
Temperature (°F)	Operating	203	104	68	194
	Design	250	250	200	200
Pressure (psig)	Operating	218†	163†	50	20
	Design	300	300	150	150

(References 1, 2 and 9)

† Typical for Mark VI Charge. Note that a maximum pressure of 267 ± 4 psig occurs during startup of the pump's AC motor before opening the rotovalves for approximately 6 ± 3 seconds (Reference NES-ETH-920039, "HX Inlet Pressure with Bingham Pump Dead-Headed", J. Whitehouse, dated 1/23/92.).

2.4 Mechanical Properties for Engineering Analysis

A value of 0.3 is nominal for Poisson's Ratio for the 303 SS, 304 SS and 304L SS materials. A single, lower bound fracture toughness property is given as J_{IC} (Ref.10) or the equivalent linear elastic parameter K_{IC} for fracture analyses in the staybolt, head, or shell materials. Full tensile curves and J-R curves are available in tabular form (See MEA Report #2345 Appendices D and F in RMP Task Files, 89-023-1).

2.4.1 Heat Exchanger Staybolt

The heat exchanger staybolt material is Type 303 stainless steel. The tensile strength and yield strength of Type 303 stainless steel at room temperature, 100 °F, and 200 °F are shown below:

TABLE 2. Tensile Strength and Yield Strength for Type 303 SS

Material	Temperature (°F)	Tensile Strength (ksi)	Yield Strength (ksi)
Type 303 SS	70	75	30
	100	74†	30†
	200	71†	30†

(References 11 and 12)

† Linear interpolation from other Reference 12 values

Type 303 SS mechanical properties are similar to Type 304 SS at room temperature as shown in Tables 2 and 4. The ASME B31.1 & B31.3 piping construction codes and the ASME BPV code do not specify fracture toughness properties for austenitic stainless steels. Therefore, the fracture toughness data shown in Table 3, obtained from the Reactor Materials Program (RMP) baseline testing for Type 304 SS at 257 °F, is the recommended fracture toughness parameter for Type 304 SS and Type 304L SS. No significant difference in toughness between Type 304 SS and Type 303 SS is expected since the compositions and product forms are similar. Therefore, the properties in Table 3 are recommended for the fracture toughness of the Type 303 SS staybolt material:

TABLE 3. Fracture Toughness for Types 304, 304L and 303 SS

Material	Test Temperature (°F)	Sample ASTM Orientation	J _{Ic} -Deformation (kJ/m ²)	K _{Ic} -Deformation (MPa√m)
304 SS Base	257	C-L	338	258

(Reference 10, Table 5-4).

2.4.2 Heat Exchanger Head and Shell

The heat exchanger head and shell material is either 304 SS or 304L SS (Ref.7). Since the computer model of the heat exchanger head assembly is designed to support any future UT inspections of the staybolts, the mechanical properties for 304L SS were used in the analysis as the tensile strength of Type 304L SS is most limiting. Mechanical properties for Type 304 SS and Type 304L SS at various temperatures are provided in Table 4:

TABLE 4. Material Properties for Type 304 and 304L SS

Material	Temp. (°F)	Design Stress Intensity S _m (ksi)	Yield Strength S _y (ksi)	Tensile Strength S _u (ksi)	Young's Modulus E (psi)	Flow Stress (ksi) ††
Type 304	70	20†	30	75	28.3 x 10 ⁶	60
	100	20	30	75	28.1 x 10 ⁶ †	60
	200	20	25	71	27.6 x 10 ⁶	60
Type 304L	70	16.7†	25	70	28.3 x 10 ⁶	50.1
	100	16.7	25	70	28.1 x 10 ⁶ †	50.1
	200	16.7	21.3	66.2	27.6 x 10 ⁶	50.1

(Reference 12 and Reference 13, Table I-1.2, Table I-2.2, Table I-6.0 and Table I-3.2)

† Linear interpolation from other Table 4 values

†† The flow stress is given as 3 S_m as suggested in Reference 14.

3.0 FINITE ELEMENT MODEL AND FRACTURE ANALYSIS OF HEAT EXCHANGER HEAD

3.1 Overview

A finite element model of the heat exchanger head is constructed for analyzing the loads acting on the staybolts and the elongation of the staybolts due to process water pressure and piping reaction forces including seismic loadings. The three-dimensional model can accommodate the asymmetric geometry if some of the staybolts become inactive when a fracture criterion is exceeded. Several criteria for staybolt fracture include Linear Elastic Fracture Mechanics (LEFM), Upper Bound Plastic Limit Load, Lower Bound Plastic Limit Load, and Crack Tip Opening Displacement (CTOD) methods. Staybolt loads are treated as remote loading in the analyses to determine flaw instability. As will be discussed in Section 3.4, staybolt flaw disposition is governed by CTOD criterion, while the individual staybolt instability flaw sizes can be conservatively obtained by a lower bound limit load for various configurations of inactive staybolts.

3.2 Introduction

The SRS heat exchanger head is a funnel-shaped structure attached to the tubesheet by 84 staybolts (Ref.15). The other end of the head is attached to the process water piping system at the pipe flange. In addition to the staybolts, the head is also supported by secondary load-carrying components such as the C-clamps and the half-pipe seals across the head flange and the tubesheet flange. These components are primarily used for leakage prevention.

In a previous study (Ref.1), the load-carrying capacity of the C-clamps and the half-pipe seals were demonstrated under the assumption that all the 84 staybolts were inactive. The purpose of the present work is to develop acceptance criteria for staybolts should flaws be detected in the UT inspection (see Section 5). The load-carrying capacity of those secondary components is ignored in the stress analysis for the development of staybolt acceptance criteria. The finite element model, thus, does not include the half-pipe seals. However, the model is capable of activating the C-clamp elements.

The forces acting on staybolts (Section 3.4.3) and the displacements of heat exchanger head flange were obtained by increasing the process water pressure in the head plenum space (the volume bounded by the head and the tubesheet) to 300 psi, the design pressure, and above in the head collapse load analysis (Section 3.4.2). Similarly, for the staybolt displacement analysis (Section 3.4.4), the head is "pressurized" to increasing levels until a critical displacement is achieved at a staybolt. The piping reaction forces were applied to the pipe flange in the center of the head. Both the head and the staybolt materials were assumed to follow elastic-perfectly plastic behavior. Flow stresses (see Section 2.4.2) were chosen for the effective yield stresses in this material idealization.

The calculation was first performed for the Teledyne case (Section 3.4.1) in which all staybolts were considered inactive (Ref.1). The revisit of the Teledyne case served to establish the adequacy of the present model through comparison of the results from both numerical models which used different finite element approaches. Collapse load analysis (3.4.2) of the heat exchanger head showed that pressure over 900 psi or 3X the design pressure would not lead to head collapse for an intact head-staybolt configuration. Collapse analysis also showed that, even if all 84 staybolts contain 25% deep flaws (implied by the UT resolution limit), the head is structurally stable up to 2.7X design

pressure or 3.7X normal operating pressure (218 psi). Collapse load analysis indicated that 10 inactive staybolts would be a limiting configuration for the heat exchanger head structural integrity at 290 psi.

Fracture analysis was performed for both staybolt load and displacement. The instability flaw sizes are characterized by applying LEFM, upper bound plastic limit load, and lower bound plastic limit load for cases of inactive staybolts. The use of CTOD fracture criterion establishes how many inactive staybolts are allowed. Up to 6 staybolts may be inactive without fracturing additional staybolts at a pressure of 280 psi. In this case, all active staybolts may already contain 25% deep flaws.

3.3 Finite Element Model

The heat exchanger head is an axisymmetric structure and the staybolt arrangement is octagonally symmetric. However, some of the staybolts are deactivated in the analysis of the head with flawed staybolts. Therefore, this limited symmetry is lost and a full three-dimensional finite element model must be considered. To reduce the model size, three-dimensional shell elements were adopted to model the head, rather than the more accurate continuum solid elements. In the current versions (4-8 and 4-9) of ABAQUS code, beam elements and the regular shell elements (except the axisymmetric shells) do not have finite strain capability (Ref.16); therefore, any solution with large strains may contain erroneous information. However, unless there are numerous inactive staybolts, the engineering strain would be applicable and would not violate the restrictions of infinitesimal strain. Cases from zero to 10 grouped, inactive staybolts were analyzed and the large strain constraint of the model was satisfied. In addition, large rotations (which can be handled by the ABAQUS shell elements) were expected to occur in the cases of several staybolt failures in a grouped arrangement. The nonlinear geometry option, NLGEOM, was therefore specified.

The model was generated with PATRAN (Ref.17) finite element pre/post-processor according to engineering drawings (Refs. 15 and 18) for the shape of the head and the locations of 84 staybolts and 72 C-clamps. Note that the C-clamp elements were removed for the development of acceptance criteria providing a conservative approach for the staybolt analysis without having to consider the integrity of the C-clamps or half-pipe seal weld. The PATRAN model was transformed to a finite element mesh for the ABAQUS code (Ref.19) on the SRS Cray X-MP EA Supercomputer.

3.3.1 Finite Element Mesh

The finite element mesh (Fig.1) contains 1008 thin shell elements (S4R5) for the majority of the heat exchanger head, 216 thick shell elements (S4R) for the pipe flange and the head flange, 300 beam elements (B31, including 84 dummy elements representing the bosses above the head to identify the staybolt locations - see Ref.15, TYPICAL BOSS DETAILS, length "S") for 84 staybolts which have 5 different lengths (Ref.20), and 72 spring elements (SPRING1) for the 72 C-clamps on the circumference of the head flange. The spring elements representing the C-clamps were not included in the ABAQUS input deck for the analysis of staybolts and the development of acceptance criteria. They were included only in revisiting the Teledyne case of postulated inactivity of all 84 staybolts (Section 3.4.1). The finite element mesh design for the heat exchanger head accommodates the exact locations of the 84 staybolts described in Reference 15.

Two to seven beam elements were used to represent the partial length of a staybolt between the head and the tubesheet. According to Reference 20, the shortest staybolt is 8.875". However, the shortest distance between the centerline of the head and the tubesheet is approximately 2.5" (estimated from Refs.15 and 18). Based on the load transfer mechanism of the staybolt assembly (Ref.21), the centerline distances between the head and tubesheet were considered to be the effective lengths of the staybolts.

A total of 1596 nodes were used for the model. An additional node was created so that the Multi-Point Constraint (MPC) option in ABAQUS provides rigid beam connections between this extra node and the pipe flange nodes. This ensures that all the nodes connected to the process water piping system will deform in a consistent manner. This additional node and MPC were not used in the Teledyne case.

The thickness of the heat exchanger head is 1.25" for the design minimum and is 1.625" near the head flange (Ref.18). For simplicity, a thickness of 1.5" was input as the head thickness in the finite element model. The thicknesses for the pipe flange and the head flange were estimated to be 4.5" and 2.875", respectively. These thicknesses were specified in the SHELL SECTION option of the ABAQUS input deck (Appendix A). The nominal shaft diameter of the staybolts is 2" (Ref.20); however, the narrowest diameter of the staybolts is 1.567" near the threaded ends and was used in the model as specified in the BEAM SECTION option in the input deck. [The induced staybolt crack prepared for the development of UT technique was included in the narrowest part of a staybolt.]

The finite element model, constructed with the pre/post-processor PATRAN, was converted to an ABAQUS input deck by using an interfacing program (Ref.22). The calculations were carried out on the SRS Cray X-MP EA Supercomputer.

3.3.2 *Material Idealizations*

As discussed in Section 2, tensile properties for 304L and 304 are chosen for bounding analyses for the heat exchanger head and the staybolt materials, respectively. At 200°F,

Young's modulus is identical for these two stainless steels, 27.6×10^6 psi. Both materials are assumed to behave with elastic-perfectly plastic response (nonhardening) with effective yield stresses taken to be three times the ASME stress intensities, S_m . This is consistent with the approach in the Teledyne analysis (Ref.1) and the General Electric piping analysis scheme (Ref.14). The effective yield stresses are thus 50.1 ksi for the head, and 60 ksi for the staybolts. Poisson's ratios are 0.3 for both stainless steels.

For revisiting the Teledyne case (Section 3.4.1), the effective yield stress for the head material is taken as 60 ksi. In addition, the load-deflection curve for the spring elements representing C-clamps is chosen as the "Armstrong Test 3" in Figure 4 of the Teledyne Report (Ref.1).

For the collapse load analysis of the heat exchanger head in Section 3.4.2, the effective yield stresses for the head were 2.3 times S_m , i.e., 38.41 ksi. The multiplier of 2.3 is given in the ASME Boiler and Pressure Vessel Code Section III, Division 1, Appendix F, Article F-1341.3 for limit load analysis. The effective yield stress for the staybolts was not reduced because this collapse load analysis applies to the structural integrity of the head itself.

3.3.3 *Boundary Conditions*

The PWS pressure is maintained at 300 psi (or at higher pressures in collapse load or staybolt displacement analyses) in the head plenum space, even when some staybolts are inactive resulting in a separation of the head flange from the tubesheet flange. [Note that the C-clamp elements are deactivated in this case.] This pressure is the heat exchanger head design pressure reported in Reference 23 and in Section 2.3. The tubesheet was not modeled in this analysis and the tubesheet ends of the staybolts were fixed in space at their original locations.

A set of piping seismic reaction forces, calculated by URS/John A. Blume & Associates, Engineers (Ref.24), and an axial tension due to the pressure in a 12-inch PWS pipe ($300\pi r^2$, $r = 6"$) were applied to an extra node to which all pipe flange nodes were tied by MPC. These multiple-point constraints force the pipe flange nodes to deform coincidentally because the flange is physically bolted to the process water piping system. The piping seismic reaction forces had insignificant impact on the cases examined. For example, the maximum reaction force in the axial direction of the heat exchanger was 4,137 lbs (Ref.24, page 6-10, System 2 - Area 105-C, Node 32, Design Load = Gravity $\pm$ Seismic). On the other hand, the axial resultant force due to the 300 psi pressure loading in the head was about 2 million lbs from the finite element results. As long as the majority of the staybolts are intact, the piping seismic reaction forces are insignificant. Similar observations are obtained for the piping moments calculated by the same source. The piping seismic reaction forces applied to this model for all calculations (except the Teledyne case) correspond to the Design Loads of System 1 - Area 105-C, in Blume Report (Ref.24) page 6-5, Node 31: The axial force was 3,106 lbs; the lateral forces were 624 and 1,192 lbs; the axial moment was 43,143 in-lb; and the lateral moments were 106,393 and 40,209 in-lb. Note that the total axial force applied to the heat exchanger pipe flange was $(300\pi 6^2 + 3106)$ lbs.

3.3.4 *Element Removal*

Elements can be removed to render staybolts inactive in one of the two separate sequences with the use of ABAQUS option MODEL CHANGE. Both sequences lead to almost identical solutions if the numerical procedures converge. The staybolts could be removed first followed by load application, or the loads could be applied to the intact model first and followed by removal of the staybolts. The second sequence may be more similar to the actual staybolt failure process and was proven to be computationally economic for deactivating small numbers of staybolts. Numerically, this is equivalent to replacing reaction forces to the structure where elements are removed and then gradually reducing these forces to zero. If, however, too many staybolts were deactivated by the removal of elements, the convergence of the nonlinear analysis was extremely slow, resulting in a less efficient method than the first sequence. The second sequence failed to reach a convergent solution when large numbers of staybolts (e.g., 6) were removed, and the first sequence was adopted.

3.4 *Results*

The finite element model with the spring elements representing the C-clamps was used to revisit the Teledyne case (Ref.1) in which none of the staybolts were active. In the

development of staybolt acceptance criteria, the C-clamps were removed from the model and the staybolt elements were activated. For the structural integrity of the heat exchanger head with or without inactive staybolts, collapse load analyses (Section 3.4.2) were performed according to ASME Boiler and Pressure Vessel Code Section III, Division 1, Appendix F, Article F-1341.3. In the staybolt loading analysis (3.4.3), the highest stressed staybolt was postulated to contain a flaw. The critical flaw depth was calculated using LEFM, upper bound limit load, or lower bound limit load (3.5.1 to 3.5.3). The highest stressed staybolts were then postulated to be inactive and the critical flaw depth for the new highest stressed staybolts of the resulting configuration were calculated. In a similar staybolt deactivating sequence, staybolt displacement analysis (3.4.4) was carried out in which the critical staybolt elongation was identified as the crack tip opening displacement ($CTOD = J_{IC} / \sigma_y$, where J_{IC} is the fracture parameter in Section 2.4, and σ_y is the effective yield stress). The staybolt fracture analysis based on CTOD is described in Section 3.5.4.

3.4.1 *Teledyne Case*

Reference 1 (Attachment No.1) contains an analysis by Teledyne Engineering Services of a special case of heat exchanger head in which all the 84 heat exchanger staybolts were inactive. The head was supported by C-clamps alone. This configuration allows a much simpler axisymmetric model, and Teledyne applied continuum elements which are more accurate than shell elements. It was concluded (Ref.1) that the Armstrong C-clamps provide adequate restraint without any active staybolts, but the weaker Williams C-clamps would have to be replaced to maintain this same capability. A limit load analysis for the half-pipe seal weld as a load-carrying component was also performed by Teledyne.

The Teledyne case was reanalyzed to demonstrate the adequacy of both finite element approaches, i.e., axisymmetric continuum elements in Teledyne analysis and shell/beam elements for the current three-dimensional model. All the staybolt elements were temporarily removed from the model. Instead, 72 nonlinear springs were installed on the head flange to simulate the C-clamps. The water pressure was increased up to 230 psi, exceeding the maximum pressure achieved by Teledyne (223 psi).

For comparison purposes, the load deflection curves for the pipe flange (labeled by SRL[1] in Fig.2) and for the C-clamp locations on the head (labeled by SRL[2]) were constructed. The Teledyne data were transferred to this figure and labeled by Teledyne [1] and Teledyne [2]. It can be seen that these two solutions, obtained from two completely different finite element formulations, were nearly equivalent to each other. Therefore, the current model effectively reproduced the Teledyne solution and it can be applied to the configurations involving staybolts and more general loadings.

3.4.2 *Heat Exchanger Head Collapse Load Analysis*

The collapse loads for heat exchanger head with various inactive staybolt configurations were analyzed according to ASME Boiler and Pressure Vessel Code Section III, Division 1, Appendix F, Article F-1341.3. The calculated load-deflection curves, plotted as the head flange axial displacement versus the process water pressure, are shown in Figure 3 for an intact head and a head with 10 inactive staybolts. Note that the maximum displacement of the deformed heat exchanger head would occur at the head flange (no C-

clamps), especially when some staybolts have already been deactivated starting with the highest stressed corner ones (Section 3.4.3).

As mentioned earlier, the ASME Code requires that the equivalent yield stress for the head material be reduced to $2.3 S_m$. The same piping reaction forces were applied to the pipe flange as in Section 3.3.3. The numerical procedure was stable when the pressure was increased to 900 psi (3 times the design pressure) for an intact head. For a head with 10 inactive staybolts, the ABAQUS program had a convergence problem at 324 psi. However, by applying ASME II-1430 and reference figure II-1430-1 to the load deflection curve for 10 inactive staybolts (Fig.3), the collapse load point is about 290 psi which is beyond the recorded maximum pressure for start-up and steady-state operation (Section 2.3). Therefore, even with 10 inactive staybolts, the head is structurally acceptable.

The load-deflection curve for a heat exchanger head with all 84 staybolts of reduced area equivalent to a staybolt with a 25% deep flaw is also plotted in Figure 3. This flaw size reflects the present UT detection (resolution) limit. In this case the staybolt cross-section remains circular, with area corresponding to the remaining ligament of a staybolt with a 25% deep crack. It can be seen that the load-deflection curve with the 25% deep flawed staybolts are indistinguishable from the intact head curve up to about 650 psi. The collapse load point for the head with flawed staybolts will be above 800 psi. The full effective yield stresses, $3S_m$, were employed for both head and staybolt materials. Therefore, the heat exchanger head is unconditionally stable up to 2.7X design pressure, even if UT can not detect any staybolt flaws which may already exist but are below the UT resolution limit. The Mises stress distribution for the head with flawed staybolts pressurized to 813 psi is shown in Figure 4 (generated by the ABAQUS Postprocessor, Ref.27). Note that the maximum Mises stress is 32.5 ksi and the effective yield stress for the head material is 50.1 ksi. In other words, the head is not yielded by this high pressure.

3.4.3 Staybolt Loading Analysis

The staybolt loads due to the pressure in the head (primary loading) and piping reaction forces (boundary conditions - including seismic forces and PWS piping pressure, about 1.8% of the total pressure resultant in the head at 300 psi) were calculated as input to the fracture analysis to determine flaw instability lengths for individual staybolts (Section 3.5.1 to 3.5.3). The axial tension (the tensile force along the staybolt axis) was the dominant force component in the cases considered (i.e., majority of the staybolts were still active). Therefore, the bending effects will be neglected in the fracture analysis. The axial force was used as a screening criterion for the subsequent removal of staybolts with flaws exceeding instability lengths, a_{cr} , resulting in worst case configurations of grouped inactive staybolts (Sections 3.5.1 through 3.5.3).

The staybolt identification numbering system is similar to those in Metallurgical Reports (for example, Ref.25). In Figure 5, the numbers inside the parentheses are the finite element node numbers from which the staybolt reaction forces can be read off in the ABAQUS output. These reaction forces are the staybolt loads with their signs changed (or the directions of the forces reversed). Note that Figure 5 is the staybolt arrangement viewing from the tubesheet, i.e., the axial direction of the heat exchanger head is the +Y-direction (see Figure 1 for the coordinate system; in Figure 5 the +Y-direction is perpendicular to the paper and pointing downward). The algorithm of removing the highest stressed staybolts for the intact head and for the subsequent configurations is as follows:

1. Load the 300 psi process water pressure and piping reaction forces (Section 3.3.3) to the heat exchanger head model with all 84 staybolts active. Without the piping reaction forces, the highest stressed staybolts would occur equally at 12 remote corners of the staybolt arrangement map (see Figure 5, Staybolt Numbers A01, A04, A05, A38, A56, A74, A84, A81, A80, A47, A29 and A11). [The head curvature is nearly flat in those areas so the resultant force due to pressure is almost completely acting along the staybolts.] The perturbation due to the seismic piping reaction forces is minor, but gives a preferential failure direction initiating at one of the corner staybolts. For a particular set of piping reaction forces (Section 3.3.3), staybolt A29 is the highest stressed.
2. The maximum staybolt axial tension, $(P_{max})_0$ (denoted by RF2 in the ABAQUS output for nodal reactions in the Y-direction), and the node number are determined from the ABAQUS output file. The corresponding staybolt number can be located by using Figure 5 as a guide. In the present case, the maximum tension is 46,125 lbs at staybolt A29. This axial tensile force is used to calculate $(a_{cr})_0$, the critical flaw size or instability length for the case of zero inactive staybolts (Sections 3.5.1 to 3.5.3).
3. Staybolt A29 is removed from the model and the applied loads (pressure and piping reaction forces) remain unchanged. The staybolt loads are calculated for the remaining staybolts.
4. Find the maximum staybolt tensile load, $(P_{max})_i$ for the configuration of Step 3. The corresponding critical flaw size, $(a_{cr})_i$, is calculated by fracture analysis (Sections 3.5.1 to 3.5.3).
5. Remove all staybolts with axial tensile forces exceeding $(P_{max})_0$, the maximum tensile force acting on the staybolts in the intact head configuration (obtained in Step 2).
6. With the new configuration, recalculate the staybolt loads with the applied loads fixed.
7. Repeat steps 4 to 6, until a_{cr} is below UT resolution or the number of the inactive staybolts becomes unacceptable according to the collapse load analysis in Section 3.4.2.

Table 5 summarizes the calculated maximum staybolt loads for various staybolt configurations under the applied loads described in Section 3.3.3.

TABLE 5 Maximum Axial Loads on the Staybolts

No. of Inactive Staybolts	Configurations	Max.Axial Loads & Locations
0	All 84 Staybolts are Active	46,125 lbs at Staybolt A29
1	Staybolt A29 is Inactive	62,399 lbs at Staybolt A28
3	Staybolts A29, A28, A47 are Inactive	87,299 lbs at Staybolt A46
6	Staybolts A29, A28, A47, A46, A12, A65 are Inactive	113,910 lbs at Staybolt A30
10	Staybolts A29, A28, A47, A46, A12, A65, A30, A48, A11, A66 are Inactive	Not Available

Note that the use of ABAQUS nodal reaction forces may be slightly inaccurate from the true staybolt axial forces read from the element output. This could have been caused by the numerical errors in calculating nodal reactions, which is the product of the finite element stiffness matrix and the displacement vector. For the analyses involving highly nonlinear materials (elastic-perfectly plastic idealization), it is not unusual that the local constitutive relationship is not satisfied. On the other hand, using the ABAQUS nodal reaction output is more convenient than searching through the element quantities (see Appendix A). In the present calculations of up to 6 inactive staybolts, the deviation is insignificant.

As a demonstration of the conservative approach to identify flaw instability depths for active staybolts based on the removal of the highest stressed staybolt (Steps 3 and 4 above), the following exercise is performed: The highest stressed staybolt was not removed but rather was assumed active, and the load acting on it was recalculated when its adjacent staybolt was deactivated. In other words, the load originally acting on a less stressed staybolt (now inactive) will be redistributed to the already highest stressed staybolt (still active). It was found that whenever the inactive staybolts involve one of the original highest stressed corner staybolts (numbers A01, A04, A05, A38, A56, A74, A84, A81, A80, A47, A29 and A11 in Fig.5), the load transfer (to the adjacent staybolts) will be the most severe.

The Mises stress distribution for a heat exchanger head with 6 inactive staybolts and under 300 psi design pressure was generated with the ABAQUS Postprocessor (Ref.27) and is plotted in Figure 6. The inactive staybolts are grouped according to Table 5 and their location can be found from Figure 5. The head is opened up from the tubesheet by the pressure due to the lack of staybolt and C-clamp constraints. The maximum Mises stress in the head (46.8 ksi) is below the effective yield stress of the material (50.1 psi).

3.4.4 Staybolt Displacement Analysis

To facilitate a crack tip opening displacement controlled fracture criterion (Section 3.5.4), the displacements or the elongations of the staybolts were calculated. Similar to Figure 5,

Figure 7 has the same staybolt identification numbers, but the numbers inside the parentheses are the finite element node numbers for the staybolts on the heat exchanger head side. The corresponding nodal displacements can be read from the ABAQUS output and they are the total elongations of the staybolts (the tubesheet ends of the staybolts are fixed and have zero displacements). The maximum displacement for these nodes will be used in the CTOD fracture criterion (Section 3.5.4). The acceptance criteria obtained relate the maximum number of inactive staybolts to a maximum operating pressure. An additional initial condition was imposed based on the 25% UT detectability limit: All active staybolts may contain 25% deep flaws. Therefore, the cross-sectional area of staybolts were reduced to that of the uncracked ligament resulting from a 25% deep crack. The calculation of the remaining area is described in Section 3.5.2.

Several configurations of inactive staybolts were examined. As in Section 3.4.3, the grouped inactive staybolts will bound the deformations for any other combinations of the same number of inactive staybolts. The staybolt deactivating sequence is similar to that in Section 3.4.3. The criterion to determine the individual inactive staybolt is a critical staybolt displacement. In the present analysis, the CTOD of the material, 0.032 inches (Section 3.5.4) is the fracture criterion. Therefore, any staybolt displacements above or close to the CTOD will be subject to removal for the next calculation. To be consistent with Section 3.4.2, cases of the same number of grouped inactive staybolts were chosen for calculations.

Once an inactive staybolt configuration is determined, the PWS pressure is increased to produce load-deflection curves (Fig.8). Acceptance criteria based on the displacement analysis are developed in Section 3.5.4.

3.5. Staybolt Fracture Analysis

Based on the finite element results (Sections 3.4.3 and 3.4.4), fracture criteria are developed for heat exchanger staybolts. The approaches of LEFM (Section 3.5.1), upper bound limit load (Section 3.5.2), and lower bound limit load (Section 3.5.3) determine the individual staybolt acceptance criteria for configurations of zero to 6 inactive staybolts. These criteria require that UT flaw sizing techniques be developed to allow application of flaw-size-based criteria. Therefore, staybolt acceptance criteria based on CTOD (Section 3.5.4) are developed. With a predetermined maximum operating pressure, the number of allowable inactive staybolts is established.

3.5.1 Linear Elastic Fracture Mechanics (LEFM)

The forces on the staybolts (Section 3.4.3) are applied to estimate the critical flaw length (or depth, with respect to the staybolt diameter). The axial tension was the dominant force component in our case. This force component was used as the remote axial load acting on a flawed sample (Fig.9). In the center of the three-dimensional crack front, plane strain condition prevails. Based on these assumptions, the instability flaw size was calculated with linear elastic fracture mechanics. The stress intensity factor, K_I , for a plane strain finite plate under remote tension (Fig.3) is given in Reference 26:

$$K_I = \sigma \sqrt{\pi a} F\left(\frac{a}{b}\right),$$

where

$$F\left(\frac{a}{b}\right) = \sqrt{\frac{2b \tan \frac{\pi a}{2b}}{\pi a}} \frac{0.752 + 2.02 \frac{a}{b} + 0.37 \left(1 - \sin \frac{\pi a}{2b}\right)^3}{\cos \frac{\pi a}{2b}}$$

and

$$\sigma = \frac{4}{\pi D^2} \times (\text{Axial Tension Load})$$

In the above expressions, a is the length (depth) of the flaw, b is the width of the plane strain plate or the diameter ($D = 1.567''$) of the staybolt. The flaw is assumed to reach its critical or instability length ($a = a_{cr}$) when $K_I = K_{IC}$, where K_I is the applied stress intensity factor and K_{IC} is the fracture toughness of the material. The fracture toughness for staybolt material, 303 Stainless Steel, is selected from the Reactor Materials Program baseline testing of archive Type 304 Stainless Steel (Ref.23, also Section 2.4). The fracture toughness for this calculation was $258 \text{ Mpa}\sqrt{\text{m}}$, or $235 \text{ ksi}\sqrt{\text{in}}$.

For this given fracture toughness and the finite element calculated axial tensile forces on the staybolts, the critical flaw lengths can be obtained by solving the above set of nonlinear equations. The results are included in Table 6.

3.5.2 Upper Bound Plastic Limit Load

In the application of limit load analysis, it is necessary to assume rigid plastic material behavior and small geometry changes up to plastic collapse. For the upper bound analysis, a kinematically admissible velocity field ($\dot{u}$) satisfying boundary conditions exists along a slip line (plane) emanating from crack tip at an angle θ with respect to the crack line (Fig.9). Except on this slip plane, the upper and lower parts of the staybolt remain rigid. The cracked staybolt has a total velocity of ($\dot{q}$) at the load point where load P is applied. Equating the work rates of the system, we have

$$P\dot{q} = \tau_y A_r \dot{u} / \cos\theta,$$

where $\dot{q} = \dot{u} \sin\theta$, $\tau_y = \frac{\sigma_y}{\sqrt{3}} = \frac{60 \text{ ksi}}{\sqrt{3}}$ is the yield stress in shear for a Mises material, and

$A_r = R^2 (\pi - \cos^{-1} \frac{R-a}{R}) + (R-a)\sqrt{R^2 - (R-a)^2}$ is the remaining area of the staybolt cross-

section (R is the radius of staybolt). Therefore, $P = \frac{2}{\sqrt{3}} \frac{\sigma_y A_r}{\sin 2\theta}$ so that the upper bound limit load is

$$P_{ub} = \frac{2}{\sqrt{3}} \sigma_y A_r$$

The instability flaw size is calculated from these equations with P_{ub} set equal to the staybolt load. The results are listed in Table 6.

3.5.3 Lower Bound Plastic Limit Load

In the lower bound limit load analysis, a statically admissible stress field satisfying equilibrium is assumed for the flawed staybolt. In this case, a stress equal to the yield stress in tension (σ_y) is acting on the uncracked ligament of the staybolt (Fig.9). Therefore, the lower bound limit load is

$$P_{lb} = \sigma_y A_r$$

The instability flaw size can be obtained by equating the staybolt load to the lower bound limit load and solving for the crack length (a). The results are summarized in Table 6.

TABLE 6 Instability Flaw Lengths (Depths) for Various Staybolt Configurations (Staybolt Diameter = 1.567 inches)

No. of Inactive Staybolts	Staybolt Load (lbs)	Instability Flaw Length (% of Staybolt Diameter)		
		Lower Bound Limit Load $\sigma_y = 60$ ksi	Upper Bound Limit Load $\sigma_y = 60$ ksi	LEFM $K_{IC} = 235$ ksi $\sqrt{\text{in}}$
0	46,125	58	62	67
1	62,399	47	53	61
3	87,299	29	38	54
6	113,910	No Solution	21	47

When plane strain condition prevails in the center of the staybolt crack (as was justified in Section 3.5.1), the admissible stress field can be modified as

$\sigma_{11} = 0$, $\sigma_{22} = \sigma$, $\sigma_{33} = \frac{1}{2}(\sigma_{11} + \sigma_{22}) = \frac{1}{2}\sigma$, and all shear stress components are zero. For these stress components, direction 11 is along the crack plane, 22 is the staybolt axial direction and 33 is perpendicular to the paper. This stress field also satisfies equilibrium.

The Mises yield condition leads to $\sigma = \frac{2}{\sqrt{3}} \sigma_y$. Therefore, the modified lower bound limit load becomes

$$P_{lb} = \sigma_{22} A_r = \frac{2}{\sqrt{3}} \sigma_y A_r$$

This expression coincides with the upper bound limit load in Section 3.5.2. According to the limit load theory, this is the exact limit load for the flawed staybolt. However, it is valid only when the plane strain condition is dominant.

3.5.4 Crack Tip Opening Displacement (CTOD) Criterion

A "strip yield model" or Dugdale crack model leads to $J = \sigma_y \delta_t$, where J is the fracture parameter J-integral, δ_t is the crack tip opening displacement. The fracture condition $J = J_{IC}$ is met when $\delta_t = \delta_t^{\text{critical}} = \text{CTOD}$. In Section 2.4.1, J_{IC} is given as 338 kJ/m² or

1930 lb/in. Therefore, the critical crack tip opening displacement (CTOD) is $\frac{J_{IC}}{\sigma_y} = 0.032"$.

Again, assume that the staybolt is rigid up to plastic collapse, the critical staybolt displacement will be equal to CTOD. From the load-deflection curves in Figure 8 (all staybolts may contain 25% deep flaws), it can be seen that the critical pressure levels corresponding to this critical displacement, CTOD, are 740, 590, 410, and 280 psi for head configurations with zero, one, three and six inactive staybolts, respectively. Conversely, when all active staybolts contain 25% deep flaws, the heat exchanger head can be safely operated at maximum pressures of 740, 590, 410, or 280 psi for the head with 0, 1, 3, or 6 nonfunctional staybolts, respectively (without fracturing additional staybolts).

4.0 HEAT EXCHANGER STAYBOLT ACCEPTANCE CRITERIA

4.1 Overview

An Acceptance Criteria Methodology is produced to ensure the structural integrity of the heat exchanger head by demonstrating adequate restraint throughout the service. The methodology includes inspections, degradation assessment, and structural analyses of the head staybolts as shown schematically in Figure 10. Criteria for the disposition of UT inspection of the heat exchanger staybolts are also provided. Acceptance criteria can be developed based on staybolt loads (Section 3.5.1 to 3.5.3) for Instability Flaw Size Criteria (Section 4.2), or based on crack tip opening displacement (Section 3.5.4) for Maximum Flaw Number Criteria (Section 4.3). The former criteria require UT flaw sizing techniques and, therefore, they could not be applied with the present UT technique. However, the size criteria are documented in this report since the technology and personnel qualifications could be advanced in the future. The Maximum Flaw Number Criteria will determine the maximum number of flawed staybolts, with a very conservative assumption that all active staybolts have already contained 25% deep flaws. In addition, an ASME collapse load analysis (Section 3.4.2) showed that the heat exchanger head will maintain structural integrity up to 10 grouped inactive staybolts.

Note that in the numerical procedure, all the inactive staybolts were grouped together according to the algorithms described in Sections 3.4.3 and 3.4.4. This grouped pattern will represent the most severe condition compared to that of an equivalent number of inactive staybolts distributed throughout the head. In addition, no pressure drops due to leakage was assumed in the staybolt deactivation, even though a displacement of the head flange from the tubesheet flange occurs in the analysis (Fig.3). The C-clamps and the half-pipe seals around the heat exchanger head and the tubesheet flanges were not considered in the present model for developing the staybolt acceptance criteria, but would presumably limit the opening and resultant leakage. Teledyne Engineering Services (Ref.1) has demonstrated that those components could be effective load-carrying members with missing staybolts. As a result, the acceptance criteria, based on the staybolts as the only load-carrying members, are conservative.

4.2 Instability Flaw Size Criteria

The axial force in tension dominated the failure process of the flawed staybolts. The calculated axial forces acting on the staybolts were used to estimate the critical (or instability) flaw depth (with respect to the diameter of staybolts) based on a linear elastic fracture mechanics (Section 3.5.1), a upper bound plastic limit load (Section 3.5.2), and a lower bound plastic limit load (Section 3.5.3). The resulting instability flaw sizes are summarized in Table 6 for various configurations of grouped inactive staybolts. It shows that the LEFM gives an overestimate for the flaw size because the plasticity effects are totally ignored. On the other hand, lower bound limit load would underestimate the actual instability flaw size. However, it provides the most conservative flaw size criteria even though the upper bound limit load, or the modified lower bound limit load could lead to an exact limit load solution if plane strain condition is invoked (Section 3.5.3).

A customized analysis can be performed for an actual inactive staybolt distribution pattern. Appendix A contains a typical ABAQUS input deck. The forces acting on the staybolts can be obtained in the ABAQUS output, either from the SECTION FORCE under each of the staybolt element sets, or from the nodal reaction forces for the staybolt fixed ends (the

tubesheet ends). The latter usually contained numerical inaccuracy so that local constitutive relationship may not be preserved (Section 3.4.2). However, the nodal reaction forces were relatively easy to look up in the output and generally gave slightly higher values than the SECTION FORCE. The fracture analysis can be performed (Sections 3.5.1 to 3.5.3) to solve for the instability flaw size according to the maximum reaction force in Y-direction (RF2, see Appendix A).

As mentioned in Section 4.1, the Instability Flaw Size Criteria are more aggressive than the Maximum Flaw Number Criteria and were developed for potential advanced UT applications. For example, using the lower bound limit load solution in Table 6, for a heat exchanger head with no failed (inactive) staybolts, all 84 staybolts may contain flaw depths less than 58% of its diameter, and all of them are still active. For a head already known to have failed 3 staybolts, the remaining 81 staybolts could contain flaws less than 29% deep without being inactive. The lower bound limit load ceases to have a solution when 6 staybolts are inactive, although head stability requires only 74 staybolts (ASME collapse load analysis, Section 3.4.2).

4.3 Maximum Flaw Number Criteria

An assumption for the criteria is that all active staybolts may contain 25% deep flaws. These flaws would be at the UT detection limit for staybolt inspection (Ref.5). The load-deflection curves for maximum staybolt displacement (Fig.8) are used to determine the maximum number of inactive staybolts for several heat exchanger head pressures in conjunction with the CTOD fracture criterion (Section 3.5.4). The critical crack tip opening displacement (CTOD) has been determined as 0.032" for the staybolt material in Section 3.5.4. The flawed staybolts are considered to have failed if their axial displacements exceed that value. From Figure 8 it can be seen that the maximum operating pressure is 280 psi for a heat exchanger head with 6 inactive staybolts. In other words, under heat exchanger normal and start-up operations, and with the boundary conditions including seismic piping forces (Section 3.3.3), 6 staybolts can be lost without causing additional fracture, even if all the active staybolts contain 25% deep flaws. Therefore, for a UT inspection method based on determining "flawed" or "unflawed" staybolts, it is recommended that the number of flawed staybolts shall not exceed 6.

A customized analysis can be performed for the actual inspection results of inactive staybolts distributed throughout the heat exchanger head. The staybolt displacements can be obtained from an ABAQUS output file. Appendix A also provides this feature to print out nodal displacements for the staybolt nodes on the head side.

5.0 RECOMMENDATION FOR IN-SERVICE INSPECTION OF HEAT EXCHANGER STAYBOLTS

5.1 Background

The previous structural analysis of the SRS PWS heat exchanger heads (Ref.1) provided an analysis of the heat exchanger heads for the case of no active staybolts. This bounding case was considered (Refs.1 and 2) since corrosion degradation of the staybolts was postulated (Refs.1 and 8) and no in-service inspections or examinations of staybolts had been performed to determine whether active degradation of the staybolts is occurring. High strength C-clamps (Ref.1, Attachment No.1) would be required along with monitoring of the half-pipe seal to demonstrate the structural integrity of the heat exchanger heads in lieu of considering the staybolts as load-carrying members.

An in-service inspection technique for the staybolts was requested by Reactor Restart Division (Ref.3). No considerations of C-clamps would then be necessary to ensure adequate restraint of the heads.

An inspection technique for the staybolts has been developed (Ref.4). This report provides acceptance criteria based on maintaining adequate restraint capacity of the heat exchanger heads for various configurations of active staybolts. In addition, an approach for the baseline and periodic inspections of the staybolts is recommended (Section 5.2) ensuring that any degradation to the staybolts reducing their load-carrying capacity would be detected and monitored.

5.2 Initial and Successive Examinations

Crevice corrosion of the PWS heat exchanger staybolts is postulated as a degradation mechanism (Refs.1 and 8) which may lead to a crack and fracture of the staybolts under load (Section 3). Therefore, to demonstrate the integrity of the heat exchanger head, in-situ inspections of the staybolts have been proposed (Section 5.1).

The inspections are based on the evaluation of corrosion degradation and would be performed on a periodic basis if degradation is occurring. That is, an initial or baseline inspection of all staybolts should be performed at the next long outage for the SRS K reactor. Inspections of all accessible staybolts in K would provide a large data base (>4,000 samples) for evaluation of staybolt degradation. Based on the results of the initial inspection, the scope and frequency for periodic inspections would be developed by Reactor Engineering. The acceptance criteria methodology (Fig.10) shows the inspection→evaluation→inspection sequence recommended for the staybolts. If no degradation is occurring as determined from the results of the inspections, the inspections could be reduced or eliminated without impact to the demonstration of head restraint.

5.3 Disposition of Reported Flaws

In the field, the ultrasonic inspection technique will provide information that the staybolt is either "flawed" or "unflawed". The UT detectability limit is 25% with respect to the 1.567" staybolt diameter (the narrowest portion). Therefore, an assumption that all 84 staybolts contain undetectable 25% deep flaws was made in the Maximum Flaw Number Criteria for the staybolts (Section 4.3). If a flaw greater than 25% deep is detected, the staybolt is "flawed" and considered inactive. A total of up to 6 staybolts may be inactive per heat exchanger head with adequate structural stability for the head. Therefore, configurations of zero to 6 inactive staybolts are acceptable for continued operation. If the number of inactive staybolts per heat exchanger head exceeds 6, additional evaluation, flaw specific analysis, and/or additional examination is required to determine if the head restraint provided by the staybolts is acceptable, or if the staybolts require replacement (Figure 11).

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Figure 1 Finite Element Mesh for SRS Heat Exchanger Head

Figure 2 Heat Exchanger Head Load-Deflection Curves (Teledyne Case)

Figure 3 Load Deflection Curves and Collapse Load Analysis for Various Staybolt Configurations

Figure 4 Mises Stress Distribution on Heat Exchanger Head at 813 psi
with All 84 Staybolts Containing 25% Deep Cracks

Figure 5 Staybolt Identification Numbers and Corresponding Finite Element Node Numbers on the Tubesheet End

Figure 6 Mises Stress Distribution on Heat Exchanger Head with 6 Inactive staybolts at 300 psi Design Pressure

Figure 7 Staybolt Identification Numbers and Corresponding Finite Element Node Numbers on the Heat Exchanger Head End

Figure 8 Maximum Pressure Based on Crack Tip Opening Displacement (CTOD) Fracture Criterion

Figure 9 Fracture Analysis: Flawed Staybolt

Figure 10 Heat Exchanger Staybolt Acceptance Criteria Methodology

Figure 11 Flowchart For Disposition Of Staybolt Inspection Results

APPENDIX A

A typical ABAQUS finite element program input deck for the heat exchanger staybolt loading analysis is listed in Section A.1. This input deck and other essential input files have been stored in 90-058-1 Task File and in SRS Common File System (CFS) with file name /L0200/HX_INPUT/ABAQUS.INP. The calculated staybolt loads can be obtained from either the element output or from the nodal reaction output. Their relationship is discussed in Section A.2. For staybolt displacement analysis, the treatment of a particular finite element node set is discussed in Section A.3.

A.1 Program Listing

(Beginning On Next Page)

NOTE:
Some ABAQUS functions (options) were commented out by beginning the line with ** (comment card).

Input nodal coordinates from a separate file (Unit 15).
This file is stored in 90-058-1 Task File and in
SRS Common File System (CFS),
File Name: /L0200/HX_INPUT/ABAQUS.015

Input beam element connectivities for staybolts and
bosses from a separate file (Unit 17).
This file is stored in 90-058-1 Task File and in
SRS Common File System (CFS),
File Name: /L0200/HX_INPUT/ABAQUS.017

```

**HEADING
HX HEAD(PRESSURE+PIPING REACTIONS+PRESSURE REACTION) REMOVE:29,28,27,26,25,24,23,22,21,20,19,18,17,16,15,14,13,12,11,10,9,8,7,6,5,4,3,2,1
TASK NO.90-058-1 (STAYBOLT DIA.=1.567, EL-PERF.PL SHELLS & BOLTS, NO C-CLAMPS)
STEP 1: REMOVE BOSS; 29,28,27,26,25,24,23,22,21,20,19,18,17,16,15,14,13,12,11,10,9,8,7,6,5
STEP 2: ADD PRESSURE-300 PSI AND PIPING REACTIONS
PIPING REACTIONS WILL BE APPLIED TO PIPE FLANGE, *MPC 7 IS USED*****
**
**PREPRINT, MODEL=NO, HISTORY=NO
**
**NODE, INPUT=15
**
**NSET, NSET=BOLTTEND
343 350 357 360 364 367 371 373 375 377 379 381 383 385 387 389
391 393 395 397 399 401 403 405 755 762 769 772 776 779 781 783
785 787 789 791 793 795 797 799 801 803 805 807 809 811 1159 1166
1170 1173 1177 1179 1181 1183 1185 1187 1189 1191 1193 1195 1197 1199 1201 1203
1205 1207 1535 1542 1546 1549 1551 1553 1555 1557 1559 1561 1563 1565 1567 1569
1571 1573 1575 1577
**NSET, NSET=NCLAMP
229 230 231 232 233 234 235 236 237 238 239 240 241 242 243 244
245 246 247 647 648 649 650 651 652 653 654 655 656 657 658 659
660 661 662 663 664 1051 1052 1053 1054 1055 1056 1057 1058 1059 1060 1061
1062 1063 1064 1065 1066 1067 1068 1433 1434 1435 1436 1437 1438 1439 1440 1441
1442 1443 1444 1445 1446 1447 1448 1449
**NSET, NSET=INFLANGE
324 325 326 327 328 329 330 331 332 333 334 335 336 337 338 339
340 341 342 737 738 739 740 741 742 743 744 745 746 747 748 749
750 751 752 753 754 1141 1142 1143 1144 1145 1146 1147 1148 1149 1150 1151
1152 1153 1154 1155 1156 1157 1158 1518 1519 1520 1521 1522 1523 1524 1525 1526
1527 1528 1529 1530 1531 1532 1533 1534
**NSET, NSET=NOZNOD
248 249 250 251 252 253 254 255 256 257 258 259 260 261 262 263
264 265 266 665 666 667 668 669 670 671 672 673 674 675 676 677
678 679 680 681 682 1069 1070 1071 1072 1073 1074 1075 1076 1077 1078 1079
1080 1081 1082 1083 1084 1085 1086 1450 1451 1452 1453 1454 1455 1456 1457 1458
1459 1460 1461 1462 1463 1464 1465 1466
**NSET, NSET=NOZGOV
5000, NOZNOD
**NSET, NSET=BOLTTOP
643 628 208 224 220 203 187 190 608 623 639 618 602 587 573 150
165 181 198 196 178 142 108 114 533 565 599 616 631 596 561 509
479 51 83 138 175 212 191 153 96 39 467 521 575 611 1034 999
964 912 882 1274 1302 1351 1384 1417 1403 1387 1355 1325 942 936 968 1002
1019 1021 1005 990 976 1363 1376 1390 1405 1425 1410 1396 1014 1011 1026 1042
1046 1031 1415 1429
**
** ELEMENT DEFINITIONS
**
**ELEMENT, TYPE=B31, INPUT=17

```

```
*ELSET, ELSET-A21
211 249
*ELSET, ELSET-A22
295 335
*ELSET, ELSET-A23
419 458 498
*ELSET, ELSET-A24
631 672 715 758
*ELSET, ELSET-A25
1034 1076 1116
*ELSET, ELSET-A26
1144 1185
*ELSET, ELSET-A27
1285 1324
*ELSET, ELSET-A28
1326 1367
*ELSET, ELSET-A29
1447 1486
*ELSET, ELSET-A30
1405 1444
*ELSET, ELSET-A31
1363 1402
*ELSET, ELSET-A32
1143 1184 1226 1267
*ELSET, ELSET-A33
762 805 848 891 934 976 1015
*ELSET, ELSET-A34
512 556 599 643 688 731 778
*ELSET, ELSET-A35
263 307 349 392
*ELSET, ELSET-A36
131 169
*ELSET, ELSET-A37
91 129
*ELSET, ELSET-A38
53 89
*ELSET, ELSET-A39
10 14
*ELSET, ELSET-A40
9 13
*ELSET, ELSET-A41
6 8 12
*ELSET, ELSET-A42
1 2 3 4 5 7 11
*ELSET, ELSET-A43
1507 1515 1519 1521 1522 1523 1524
*ELSET, ELSET-A44
1510 1516 1520
*ELSET, ELSET-A45
1511 1517

*ELSET, ELSET-A46
1514 1518
*ELSET, ELSET-A47
1466 1504
*ELSET, ELSET-A48
1424 1464
*ELSET, ELSET-A49
1382 1422
*ELSET, ELSET-A50
1145 1186 1227
1268
*ELSET, ELSET-A51
763 806 849 892
935 977 1016
*ELSET, ELSET-A52
532 575 618 664
708 752 800
*ELSET, ELSET-A53
275 320 365 408
*ELSET, ELSET-A54
133 170
*ELSET, ELSET-A55
93 130
*ELSET, ELSET-A56
54 90
*ELSET, ELSET-A57
173 210
*ELSET, ELSET-A58
213 250
*ELSET, ELSET-A59
297 336
*ELSET, ELSET-A60
421 459 499
*ELSET, ELSET-A61
795 838 883 926
*ELSET, ELSET-A62
939 978 1017
*ELSET, ELSET-A63
1217 1258
*ELSET, ELSET-A64
1303 1344
*ELSET, ELSET-A65
1345 1387
*ELSET, ELSET-A66
1261 1307
*ELSET, ELSET-A67
1179 1221
*ELSET, ELSET-A68
1058 1098
*ELSET, ELSET-A69
810 851
*ELSET, ELSET-A70
633 674

*ELSET, ELSET-A71
461 501
*ELSET, ELSET-A72
338 378
*ELSET, ELSET-A73
254 294
*ELSET, ELSET-A74
380 418
*ELSET, ELSET-A75
462 502
*ELSET, ELSET-A76
591 630
*ELSET, ELSET-A77
719 760
*ELSET, ELSET-A78
852 893
*ELSET, ELSET-A79
980 1019
*ELSET, ELSET-A80
1066 1105
*ELSET, ELSET-A81
896 937
*ELSET, ELSET-A82
764 807
*ELSET, ELSET-A83
677 717
*ELSET, ELSET-A84
549 588
*ELSET, ELSET-A85
15 16 17 18 92 94 132 134 172 174 212 214 252 253 255 276
296 298 339 352 379 381 420 422 503 504 505 506 507 521 537 544
590 625 634 648 676 678 720 736 761 765 766 780 809 843 853 864
895 928 938 940 1020 1021 1022 1023 1028 1037 1050 1057 1122 1140 1159 1178
1187 1188 1241 1263 1269 1270 1284 1305 1327 1346 1362 1381 1404 1426 1448 1467
1508 1509 1512 1513
*ELSET, ELSET-A86
45 46 49 50 81 82 85 86 120 122 125 126 163 164 165 166
203 206 207 208 244 245 247 248 289 290 291 292 329 332 333 334
372 373 375 376 414 415 416 417 439 455 456 457 479 480 496 497
526 527 546 547 567 568 585 586 608 609 627 628 652 653 670 671
695 696 713 714 738 739 756 757 784 785 803 804 827 828 846 847
871 872 889 890 913 914 932 933 957 958 974 975 996 997 1013 1014
1043 1044 1063 1064 1084 1085 1102 1103 1123 1124 1141 1142 1163 1164 1182 1183
1205 1206 1224 1225 1245 1246 1265 1266 1289 1290 1309 1310 1329 1330 1349 1350
1369 1370 1389 1390 1409 1410 1429 1430 1449 1450 1469 1470 1487 1488 1505 1506
*ELSET, ELSET-A87
**THIS SET IS THE TOP RING OF THE MODEL, USE S4R ELEMENTS TO REPRESENT NOZZLE FLANGE.
51 52 87 88 127 128 167 168 180 193 220 234 261 279 304 322
345 364 387 406 428 448 468 489 514 538 555 578 597 619 640 660
684 703 726 746 772 792 816 835 859 879 902 920 946 964 986 1003
1030 1051 1072 1091 1111 1130 1151 1170 1194 1212 1233 1252 1276 1296 1316 1336
1356 1376 1396 1416 1436 1456 1476 1494
*ELSET, ELSET-A88
**THIS SET IS USED TO IMPOSE HEAVY WATER PRESSURE.
HEAD, FLANGE, NOZZLE
```

**If C-clamps are activated, insert nonlinear spring properties here.
The property block can be found in 90-058-1 Task File and in
SRS Common File System (CFS),
File Name: /L0200/HX INPUT/ABAUQUS.CLAMP**

[illegible]

Apply PWS piping reaction forces to Node No.5000, to which all pipe flange nodes are tied with rigid links.

 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40 41 42 43 44 45 46 47 48 49 50 51 52 53 54 55 56 57 58 59 60 61 62 63 64 65 66 67 68 69 70 71 72 73 74 75 76 77 78 79 80 81 82 83 84 85 86 87 88 89 90 91 92 93 94 95 96 97 98 99 100 101 102 103 104 105 106 107 108 109 110 111 112 113 114 115 116 117 118 119 120 121 122 123 124 125 126 127 128 129 130 131 132 133 134 135 136 137 138 139 140 141 142 143 144 145 146 147 148 149 150 151 152 153 154 155 156 157 158 159 160 161 162 163 164 165 166 167 168 169 170 171 172 173 174 175 176 177 178 179 180 181 182 183 184 185 186 187 188 189 190 191 192 193 194 195 196 197 198 199 200 201 202 203 204 205 206 207 208 209 210 211 212 213 214 215 216 217 218 219 220 221 222 223 224 225 226 227 228 229 230 231 232 233 234 235 236 237 238 239 240 241 242 243 244 245 246 247 248 249 250 251 252 253 254 255 256 257 258 259 260 261 262 263 264 265 266 267 268 269 270 271 272 273 274 275 276 277 278 279 280 281 282 283 284 285 286 287 288 289 290 291 292 293 294 295 296 297 298 299 300 301 302 303 304 305 306 307 308 309 310 311 312 313 314 315 316 317 318 319 320 321 322 323 324 325 326 327 328 329 330 331 332 333 334 335 336 337 338 339 340 341 342 343 344 345 346 347 348 349 350 351 352 353 354 355 356 357 358 359 360 361 362 363 364 365 366 367 368 369 370 371 372 373 374 375 376 377 378 379 380 381 382 383 384 385 386 387 388 389 390 391 392 393 394 395 396 397 398 399 400 401 402 403 404 405 406 407 408 409 410 411 412 413 414 415 416 417 418 419 420 421 422 423 424 425 426 427 428 429 430 431 432 433 434 435 436 437 438 439 440 441 442 443 444 445 446 447 448 449 450 451 452 453 454 455 456 457 458 459 460 461 462 463 464 465 466 467 468 469 470 471 472 473 474 475 476 477 478 479 480 481 482 483 484 485 486 487 488 489 490 491 492 493 494 495 496 497 498 499 500 501 502 503 504 505 506 507 508 509 510 511 512 513 514 515 516 517 518 519 520 521 522 523 524 525 526 527 528 529 530 531 532 533 534 535 536 537 538 539 540 541 542 543 544 545 546 547 548 549 550 551 552 553 554 555 556 557 558 559 560 561 562 563 564 565 566 567 568 569 570 571 572 573 574 575 576 577 578 579 580 581 582 583 584 585 586 587 588 589 590 591 592 593 594 595 596 597 598 599 600 601 602 603 604 605 606 607 608 609 610 611 612 613 614 615 616 617 618 619 620 621 622 623 624 625 626 627 628 629 630 631 632 633 634 635 636 637 638 639 640 641 642 643 644 645 646 647 648 649 650 651 652 653 654 655 656 657 658 659 660 661 662 663 664 665 666 667 668 669 670 671 672 673 674 675 676 677 678 679 680 681 682 683 684 685 686 687 688 689 690 691 692 693 694 695 696 697 698 699 700 701 702 703 704 705 706 707 708 709 710 711 712 713 714 715 716 717 718 719 720 721 722 723 724 725 726 727 728 729 730 731 732 733 734 735 736 737 738 739 740 741 742 743 744 745 746 747 748 749 750 751 752 753 754 755 756 757 758 759 760 761 762 763 764 765 766 767 768 769 770 771 772 773 774 775 776 777 778 779 780 781 782 783 784 785 786 787 788 789 790 791 792 793 794 795 796 797 798 799 800 801 802 803 804 805 806 807 808 809 810 811 812 813 814 815 816 817 818 819 820 821 822 823 824 825 826 827 828 829 830 831 832 833 834 835 836 837 838 839 840 841 842 843 844 845 846 847 848 849 850 851 852 853 854 855 856 857 858 859 860 861 862 863 864 865 866 867 868 869 870 871 872 873 874 875 876 877 878 879 880 881 882 883 884 885 886 887 888 889 890 891 892 893 894 895 896 897 898 899 900 901 902 903 904 905 906 907 908 909 910 911 912 913 914 915 916 917 918 919 920 921 922 923 924 925 926 927 928 929 930 931 932 933 934 935 936 937 938 939 940 941 942 943 944 945 946 947 948 949 950 951 952 953 954 955 956 957 958 959 960 961 962 963 964 965 966 967 968 969 970 971 972 973 974 975 976 977 978 979 980 981 982 983 984 985 986 987 988 989 990 991 992 993 994 995 996 997 998 999 1000 1001 1002 1003 1004 1005 1006 1007 1008 1009 1010 1011 1012 1013 1014 1015 1016 1017 1018 1019 1020 1021 1022 1023 1024 1025 1026 1027 1028 1029 1030 1031 1032 1033 1034 1035 1036 1037 1038 1039

SF
S11, S12, E11, E12
MODEL PRINT, SUMMARY-NO, FREQUENCY-20, ELSET-A02
1,3,7,11,15

SF
S11, S12, E11, E12
MODEL PRINT, SUMMARY-NO, FREQUENCY-20, ELSET-A03
1,3,7,11,15

SF
S11, S12, E11, E12
MODEL PRINT, SUMMARY-NO, FREQUENCY-20, ELSET-A04
1,3,7,11,15

SF
 S11, S12, E11, E12
 MEL PRINT, SUMMARY=NO, FREQUENCY=20, ELSET=A03
 1,3,7,11,15

1,3,7,11,15
SF
S11, S12, E11, E12
REF PRINT, SUMMARY=NO, FREQUENCY=20, ELSET=A04

MODEL PRINT, SUMMARY=NO, FREQUENCY=20, ELSET=A04
1,3,7,11,15
SF
S11, S12, E11, E12

S11, S12, E11, E12
 *EL PRINT, SUMMARY=NO, FREQUENCY=20, ELSET=A05
 1,3,7,11,15
 SF

SF
 S11, S12, E11, E12
 MEL PRINT, SUMMARY=NO, FREQUENCY=20, ELSET=A06
 1,3,7,11,15

SF
1,3,7,11,15
S11, S12, E11, E12
MODEL PRINT, SUMMARY-NO, FREQUENCY-20, ELSET-A07
1,3,7,11,15

Version 4.8/4.9, See the sketch below

011, 012, 011, 012
 *EL PRINT, SUMMARY=NO, FREQUENCY=20, ELSET=A08
 1,3,7,11,15
 SF
 \$11, \$12, \$11, \$12

S11, S12, E11, E12
 *EL PRINT, SUMMARY=NO, FREQUENCY=20, ELSET=A09
 1,3,7,11,15
 SF

SF
S11, S12, E11, E12
*EL PRINT, SUMMARY=NO, FREQUENCY=20, ELSET=A10
1,3,7,11,15

1,3,7,11,15
SF
S11, S12, E11, E12

1

Output staybolt element quantities:

SF= Section Forces and Moments;
S11 and E11 = Axial Stress and Strain;
S12 and E12 = Torsional Stress and Strain.

SS11 and S12 are output at the integration points (1, 3, 7, 11, 15) on the circular cross-section. See the sketch below (ABAQUS Users' Manual, Version 4.8/4.9, Section 3.3.2 Beam Section Data):

[illegible]

[illegible]

SIDE VIEW OF HEAT EXCHANGER HEAD

A.2 Staybolt Load Output

The calculated staybolt axial forces can be found in the element output (e.g., *EL PRINT, SUMMARY=N0, FREQUENCY=20, ELSET=A29). Equivalently, this quantity can be obtained from the nodal output for Node Set BOLDEND, (i.e., *NODE PRINT, GLOBAL=YES, SUMMARY=YES, NSET=BOLTEND, TOTAL=YES, FREQUENCY=20). The nodal reactions are less accurate, because they are obtained by multiplying the finite element stiffness matrix to the calculated displacement vector, rather than directly obtained at numerical integration stations where the element output forces are based on. However, the nodal reaction forces can be conveniently located from the ABAQUS output, especially when the option SUMMARY=YES was specified in the input deck. With this option, the maximum/minimum values and their locations (node numbers) are reported. From Figure 3 the corresponding staybolt numbers/locations can be identified. It should be mentioned that, in the fracture analysis only the staybolt tensile loads are relevant (the staybolt flaw can only be opened by tension). This tensile force, when viewed as a nodal reaction at the tubesheet end, is a compressive force. Therefore, the maximum tensile force for the staybolt is the minimum nodal reaction force (negative quantity) in the ABAQUS nodal output list for BOLTEND.

The relationship between the element output for Section Forces (SF1, SF2 and SF3) and the nodal output for reaction forces (RF1, RF2 and RF3) is as followed:

Element Variable	Definition (Element Output Forces)		Nodal Variable	Definition (Nodal Reaction Forces)
SF1	Beam Axial Direction (Global +Y-direction)	=	-RF2	Positive: Global Y-direction
SF2	Beam Local 2-direction (Global -Z-direction)	=	RF3	Positive: Global Z-direction
SF3	Beam Local 1-direction (Global +X-direction)	=	-RF1	Positive: Global X-direction

Note that the option GLOBAL=YES has been specified in the nodal output (*NODE PRINT), the quantities reported are in the global directions. However, the element output (*EL PRINT) is always in the local directions according to ABAQUS User's Manual, Version 4.8, Section 3.3.1, Beam Type Stress/Displacement Elements. It can be seen from the ABAQUS element output for bending moments (SM1 and SM2), lateral forces (SF2 and SF3) may vary from element to element for a staybolt. The axial force (SF1), axial stress at centroid of the cross-section (S11 at Point 1), twist moment about the staybolt axis (SM3), and the torsional shear (S12 at Points 3, 7, 11 and 15) are usually uniform through the staybolt length. As mentioned earlier, with an assumption of axial force dominance for a heat exchanger with low number of inactive staybolts, the relevant quantities for the staybolt fracture analysis are SF1 (or equivalently, -RF2) and/or S11 at centroid of the staybolt cross-section.

A.3 Staybolt Displacement Output

To apply the CTOD fracture criterion for developing staybolt acceptance standards, staybolt displacements must be output for analysis. This was achieved by forming a finite element node set BOLTTOP (see Section A.1 for a typical input deck). These nodes are the intersections of staybolts and the heat exchanger head in the finite element model (mesh). The complete set of BOLTTOP contains 84 nodes:

*NSET, NSET=BOLTTOP

643	628	208	224	220	203	187	190	608	623	639	618	602	587	573	150
165	181	198	196	178	142	108	114	533	565	599	616	631	596	561	509
479	51	83	138	175	212	191	153	96	39	467	521	575	611	1034	999
964	912	882	1274	1302	1351	1384	1417	1403	1387	1355	1325	942	936	968	1002
1019	1021	1005	990	976	1363	1376	1390	1405	1425	1410	1396	1014	1011	1026	1042
1046	1031	1415	1429												

The corresponding staybolt numbers and locations can be found in Figure 7. If a customized analysis is required for a particular pattern or distribution of inactive staybolts, the corresponding node number must be removed from the BOLTTOP list. Again, these node numbers can be found in Figure 7. If these node numbers remain in the list while the staybolts are deactivated, the finite element result file will report those nodal displacements as well. However, these displacements relate to the heat exchanger head, rather than the staybolts. Therefore, for the convenience of applying the CTOD criterion, these node numbers are advised to be removed from BOLTTOP. The input deck in A.1 has already exercised this practice.

END

**DATE
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9/29/93