ELECTRIC POWER RESEARCH INSTITUTE

Refining the Probability of Failure for the Risk Management Process

1012742

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Technical Update, March 2007

EPRI Project Manager

D. Gandy

ELECTRIC POWER RESEARCH INSTITUTE
3420 Hillview Avenue, Palo Alto, California 94304-1338 ▪ PO Box 10412, Palo Alto, California 94303-0813 ▪ USA
800.313.3774 ▪ 650.855.2121 ▪ askepri@epri.com ▪ www.epri.com

ORGANIZATION(S) THAT PREPARED THIS DOCUMENT

Structural Integrity Associates

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CITATIONS

This document was prepared by

Structural Integrity Associates, Inc
3500 Massillon Road
Suite 420
Uniontown, OH 44685

Principal Investigator
S. Rau

This document describes research sponsored by the Electric Power Research Institute (EPRI).

This publication is a corporate document that should be cited in the literature in the following manner:

Refining the Probability of Failure for the Risk Management Process. EPRI, Palo Alto, CA: 2007. 1012742.

ABSTRACT

Safe and reliable equipment performance under increasing financial constraints requires the integration and implementation of complex engineering principals and assessment methodologies. Paramount in the process is the application of probabilistic evaluation methods that account for variability in the materials of construction, operating conditions, and financial impact. This report describes work performed under EPRI funding to assemble a knowledge-base relating damage accumulation in high-energy piping and headers that will be instrumental in the evaluation of component probability of failure (PoF), required for safety, reliability, and financial implication assessments.

As a precursor to performing more quantitative probabilistic analyses, a simplified method of "estimating" PoF has been proposed that determines a "damage potential value" for each component (e.g. girth weld) in a system. The methodology identifies those components having the greatest chance of containing damage based on weighted rank values of selected characteristics. The "selected" characteristics and associated weight factors were developed by a group of utility and industry "experts" with considerable experience in high-energy piping and headers. The approach has been incorporated into an Excel spreadsheet for application by utility personnel. Application of the methodology to a series of utility-supplied test cases has been performed to verify its function and predictive capabilities.

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1 INTRODUCTION

In the current marketplace in which power generation companies must operate, engineering-based maintenance/inspection programs designed to ensure safe and reliable equipment operation have succumbed to increased scrutiny caused by deregulation and tighter profit margins. In some cases the programs were only revamped, extending the time between planned inspections but still maintaining a pro-active approach, while others experienced significant downsizing to complete abandonment adopting the run-till-it-breaks approach. Clearly, this latter approach (when it can be applied without safety concerns) has been short-lived given the financial penalties of forced outages. Consequently utilities are forced to achieve a middle ground that meets safety concerns within some financial boundaries. For safety-related "no fail" systems such as high-energy steam piping and headers this is especially difficult to administer because of multiple active damage mechanisms, difficult and costly access, and the required application of advanced technology to detect incipient stages of damage.

As a consequence, utilities are continually faced with the following fundamental question:

> ***"If we only have resources to inspect X number of components, which ones should be examined to minimize the potential for a forced outage?"***

To answer this question and ensure continued compliance with safety requirements, broader application of Financial Risk evaluation is occurring through-out the industry. These evaluation methods, historically applied only by the accounting-side of the house, are now being utilized by engineers to identify those system/components most-critical to "successful" operation (no forced outages). One of the fundamental inputs to evaluation of financial risk is the component's probability of failure (PoF) as a function of service time. With PoF determined and knowledge of costs associated with failure versus maintenance (also versus time), informed decisions can be made that provide the most efficient utilization of resources within the imposed safety limits.

Quantitative evaluation of the PoF for any system and/or component requires an in-depth understanding of potential damage mechanisms, the rate of damage accumulation, operating conditions (stress, temperature and time exposures), and failure criteria. Not only the typical or mean values of each, but definition of the variability in each of these factors. In most instances utilities do not have the resources to perform such evaluations. Consequently, simplified methods of evaluating PoF are currently employed, i.e. application of NERC-GADS data.

To this end, a collaborative program between EPRI, selected utility members and Structural Integrity Associates, Inc was initiated to develop methods to improve the accuracy of Probability of Failure estimates for critical fossil plant components. Thereby benefiting programs involved with maintenance optimization and defining an effective end of life.

1.1 Project Goals and Structure

The overall goal of the project was to provide fossil plant personnel with an evaluation tool and a supportive database for probability of failure estimation of selected high-energy components. More specifically, the deliverables of the project are:

- An 'Experienced Based' method for Risk Ranking and Probability of Failure estimation. The methodology has been incorporated into an Excel spread sheet.
- A database of component records detailing plant, component and operating information as well as recording damage at specific operating times. This data was used to benchmark the estimation methodology.

The project was divided into two Phases. In Phase 1, the experienced-based approach for estimating of Probability of Failure was developed and implemented into an Excel spreadsheet, along with the identification and collection of test cases for the database and benchmarking. This work was performed in 2005 and 2006 and is the primary subject matter contained in this report.

In Phase 2, the spreadsheet was fine-tuned to ensure that the defined requirements were met and worked efficiently <u>without</u> extensive training. Also in this Phase, a users manual was written to accompany the spreadsheet providing further information concerning the spreadsheet inputs and their potential effects on the ranking process. A draft of the users manual is provided in Appendix A.

Section 2 of this report describes the development of an approach for PoF estimation; an Experience-Based ranking methodology and its implementation via a spreadsheet. Section 3 presents the benchmarking studies performed using utility-supplied experience.

Appendices include Appendix A: Spreadsheet User's Guide and Appendix B: Piping Stress Analysis Methodology. The user's guide should be used with the current beta release of the spreadsheet. Additionally, the piping stress analysis methodology has been included due to the importance of stress in the ranking methodology presented herein.

2
EXPERIENCED-BASED RANKING METHODOLOGY

The assessment process, based on calculation of Probability of Failure with time, evolves logically from the well-established three-phase methodology for component assessment to give:

- An engineering output that is directly compatible with models for risk-based decision making.
- An efficient approach to communication.
- A tool to evaluate how changing conditions modify operating risk.

As a first step in the process, developing estimates for a component's "potential" for damage are necessary. Historically, these estimates have been solely stress-based however, recent experience (specifically Type IV cracking) has indicated that other factors warrant consideration.

The authors recognize that approaches associated with risk-ranking and assessment of PoF are relevant to system wide decision-making. However, this project has focused initially on estimates for high energy piping and headers. These components have been selected because:

- They are frequently designated 'No Fail' and therefore are subject to significant maintenance costs, and
- A significant knowledge base exists that facilitates development of the methodology, and
- A number of documented examples exist such that method validation can be performed.

2.1 Methodology Development

Development of an experience-based ranking methodology is predicated on the identification of characteristics categories that can be scored regarding their contribution to, in this application, material damage. It should be noted that this methodology can be applied to *any* component or system for which the life-effecting damage mechanisms are known and those characteristics effecting their formation and rate of accumulation (i.e., design, operation, materials, etc) can be identified. Within each category there are sub-categories that isolate the contribution of specific characteristics to the overall damage susceptibility. The contribution of each category is then determined by summation of sub-category scores.

Rank values within each category and sub-category are assigned on a scale of 0 to 10 (zero being the lowest damage potential and 10 being highest). Recognizing that each characteristic is not equal in its contribution to overall damage susceptibility, each category/sub-category is also assigned a weighting factor. These weighting factors are the core of the experienced-based methodology, since by definition they are the means by which one characteristic has more impact than another. Determining which characteristic(s) are most important is not a trivial task due to the inherent complex nature of the damage mechanisms effecting high-energy components, coupled with the multi-variant conditions under which the components are constructed and operate. Each weighting factor represents the *perceived* level of contribution of that category/sub-category to the entire state of damage susceptibility.

The total potential for damage is then the sum of each category's rank value multiplied by its' respective weight factor. The methodology is structured so that the maximum potential score a component can achieve is 100. Listings of the component categories and their weight factors are presented in Tables 2-1 through 2-4. Development of the category lists and their associated weight factors was performed by the advisory committee.

2.2 Advisory Committee

The project advisory committee consisted of representatives from EPRI, and Structural Integrity Associates, plus invited utility members. Utility members that served on the advisory committee are:

American Electric Power	Ameren	Salt River Project
Tennessee Valley Authority	First Energy	Progress Energy
Pacificorp	Southern Company	

During 2005 the committee met three times. The role of the advisory committee was to select the included components, identification of the categories/sub-categories for each component, and development of weight factors. The components selected by the committee for evaluation in the project were:

- High Energy Piping Girth Welds
- Header Girth Welds
- Header Ligaments
- Header Stub Tubes

It should be noted that piping and header seam welds were discussed by the committee and intentionally not considered in this project due to their high-severity safety implications. It was the judgment of the committee that the application of simplified, approximate methods of analysis are not justifiable for such components.

A brief discussion of the categories identified by the committee is presented in Section 2.3.

2.3 Component Characteristic Categories

To provide a basis on which to perform component ranking, it is necessary to identify those characteristics that effect the initiation of damage and its rate of accumulation. For each component between 9 and 10 primary categories were identified by the advisory committee. A brief description of each category is presented below.

Operation - This category relates component operating conditions. Specifically, operating hours, system starts, the type of operation, temperature and pressure. These characteristics typically will not vary for welds within a given piping system or header (except if repairs or replacements have been made) but are necessary for cross-system ranking is to be performed.

Inspection – This category accounts for the effects of component inspection history to damage potential. This category accounts only for the fact that inspections were performed.

The implications of results obtained from the inspections are addressed in the Damage category. The Inspection category is sub-divided into two sub-categories; the time elapsed since the last inspection, and the type(s) of inspections performed. Elapsed time effects are set to decay over a ten-year period. Ranking of inspection type(s) is performed for surface, volumetric, and metallographic methods with cumulative effects for compound inspections. It is assumed that each surface or volumetric examination covered 100-percent of the component (e.g. the entire girth weld) and was performed in accordance with standard practice.

Damage – In this category the state of **service** damage present in the component is described. Note that only service damage is considered, the presence of fabrication-related defects is not considered detrimental. The damage should be classified as micro or macro, its extent, and causative mechanism. In the current methodology, a component that is known to have macro-service damage automatically has its total rank value set to 100, independent of any other inputs. It is the feeling of the advisory committee that if macro damage is present, other evaluation tools are available for dispositioning.

Repair/Action – This category addresses whether the component has been previously repaired, and if so to what extent. It is assumed that any repairs performed removed all existing damage.

Maintenance – This category accounts for the effects of performing examination and/or maintenance of structural supports (hangers) near the specific component. It is assumed that any malfunctioning supports identified by the examinations have been repaired, with the supports returned to their prescribed design condition.

Stress – This category accounts for the extent to which the operating stresses and temperatures in the component have been determined. This category effects both cross-system and inter-system component ranking. In the absence of a quantitative evaluation (i.e. finite element analysis) component stresses can be relatively ranked from highest to lowest. It should be noted however, that cross-system component rankings **should not** be performed in the absence of a quantitative stress analysis.

Design/Fabrication – For piping girth welds this category incorporates the effect of the component type (wyes, tees, saddle welds). For header ligaments and stub tubes the effect of selected design factors are addressed.

Materials – For piping and header girth welds this category includes effects of the component operating temperature-to-material creep-start temperature, whether the component is cast or forged, and Type IV cracking susceptibility. For header ligaments and stub tubes the effect of the ratio of component operating temperature-to-material creep-start temperature is addressed.

Welds – This category includes the effects of the weld process used during manufacture, aspects of weld geometry (counterbore extent, reinforcement, and backing rings), and whether material transitions are present.

Header General Knowledge - Applicable only to header weld, ligament, or stub tube components this category accounts for knowledge of the specific component geometry.

2.4 Weight Factors

Recognizing that each category identified in Section 2.3 does not contribute equally to the potential for damage, weight factors for each category were developed on a component-by-component basis. Determination of the weight factors was performed by the advisory committee by averaging the voted percent contributions of each. In this process each committee member had equal voting power and the summation of all category contributions equaled 100 percent.

2.4.1 Piping Girth Welds

Ranking of piping girth welds is performed based on the list of characteristics and weight factors presented in Table 2-1.

2.4.2 Header Girth Welds

Ranking of header girth welds parallels that for piping girth welds with the addition of a "General Knowledge" category. The list of list of characteristics and weight factors is presented in Table 2-2.

2.4.3 Header Ligaments

Ranking of header ligaments is performed based on the list of characteristics and weight factors is presented in Table 2-3. Note there is not "Weld" category.

2.4.4 Header Stub Tubes

Ranking of header stub tube attachment welds is performed based on the list of characteristics and weight factors is presented in Table 2-4.

Table 2-1
Piping Girth Weld Categories/Weight Factors

Category		Sub-Category		Sub-Sub Category		Comment
Operation	1.51	Hours	0.3			Operating hrs/max hours, used for cross-system ranking
		Cycles	0.2			Ratio of hot/cold starts to total starts; water/steam hammer?
		Type of Operation	0.1			Base or Load Following
		Temperature	0.3			Under/Over temperature
		Pressure	0.1			Under/Over/Sliding pressure
Inspection	1.23	Last Inspection	0.4	Timing	0.7	Years since last Insp.
				Frequency	0.3	Multiple Insp?
		Method	0.6	Surface	0.4	Visual, Dry Power, WFMT, None
				Volumetric	0.4	RT, Manual, Automated, TOFD, Arrays, None
				Metallographic	0.2	Replicas, Sampling, None
Damage (Service Only)	1.28	Type	0.6			Macro or Micro
		Mechanism	0.4			Creep, Creep/Fatigue, Fatigue, Unknown
Repair/Action	0.62	Extent	1.0			Full, Partial, Blend
Maintenance	1.01	Supports	1.0			Walkdowns, Functionality Checks, Measurements, Nothing
Stress	1.34	Analysis Type	1.0			Elastic, Creep, None
Design/ Fabrication	0.59	Component Type	1.0			Pipe, Tee, Wye, Saddle, Bend/Elbow
Materials	1.35	Grade	0.4			Operating Temp/Creep-Start Temp.
		Cast/Forged	0.2			Cast, Forged, or Austenitic
		Type IV	0.4	Grade	0.25	P11, P22, P91, ½ CrMoV
				Weld Type	0.2	Shop/Submerged Arc, Shop/Unknown, Shop/Other, Field
				OD/Thk Ratio	0.2	>10 no effect
				Neighboring Component	0.15	Thick Section, Pipe
				Weld Profile	0.2	V, J, Narrow Groove
Welds	1.07	Process	0.33			Submerged Arc, Other
		Geometry	0.33	Counterbore	0.7	High, Low
				Reinforcement	0.2	High, Low
				Backing Ring	0.1	Yes, No
		Material Transitions	0.34			New-to-Old, Alloy1 to Alloy 2

Table 2-2
Header Girth Weld Categories/Weight Factors

Category		Sub-Category		Sub-Sub Category		Comment
Operation	1.56	Hours	0.3			Operating hrs/max hours, used for cross-system ranking
		Cycles	0.2			Ratio of hot/cold starts to total starts; soot blowing freq, excursions
		Type of Operation	0.1			Base or Load Following
		Temperature	0.3			Global, Local at welds
		Pressure	0.1			Operating Pres./Design Pres.
Inspection	1.30	Last Inspection	0.4	Timing	0.7	Years since last Insp.
				Frequency	0.3	Multiple Insp?
		Method	0.6	Surface	0.4	Visual OD, Visual ID, Dry Power, WFMT, None
				Volumetric	0.4	RT, Manual, Automated, TOFD, Arrays, None
				Metallographic	0.2	Replicas, Sampling, None
Damage (Service Only)	1.2	Type	0.6			Macro or Micro
		Mechanism	0.4			Creep, Creep/Fatigue, Fatigue, Graphitization, Unknown
Repair/Action	0.71	Extent	1.0			Full, Partial, Blend
Maintenance	0.63	Supports	1.0			Walkdown, Functionality Checks, Measurements, Nothing
Stress	0.85	Analysis Type	1.0			Detailed, Global, Local, None
Design/Fabrication	0.8	Component Type	1.0			Pipe, Tee, End Cap, Saddle Weld
Materials	1.15	Grade	0.5			Operating Temp/Creep-Start Temp.
		Type IV	0.5	Grade	0.25	P11, P22, P91, ½ CrMoV
				Weld Type	0.2	Submerged Arc, Other
				OD/Thk Ratio	0.2	>10 no effect
				Neighboring Component	0.15	Thick Section, Pipe
				Weld Profile	0.2	V, J, Narrow Groove
HDR General Knowledge	0.74	Weld Locations	1.0			Weld locations known?
Welds	1.06	Process	0.33			Submerged Arc, Other
		Geometry	0.33	Counterbore	0.7	High, Low
				Reinforcement	0.2	High, Low
				Backing Ring	0.1	Yes, No
		Material Transitions	0.34			New-to-Old, Alloy1 to Alloy 2

Table 2-3
Header Ligament Categories/Weight Factors

<table>
<tr><th colspan="2">Category</th><th colspan="2">Sub-Category</th><th colspan="2">Sub-Sub Category</th><th>Comment</th></tr>
<tr><td rowspan="5">Operation</td><td rowspan="5">2.12</td><td>Hours</td><td>0.2</td><td colspan="2"></td><td>Operating hrs/max hours, used for cross-system ranking</td></tr>
<tr><td>Cycles</td><td>0.4</td><td colspan="2"></td><td>Ratio of hot/cold starts to total starts; soot blowing freq, excursions</td></tr>
<tr><td>Type of Operation</td><td>0.1</td><td colspan="2"></td><td>Base or Load Following</td></tr>
<tr><td>Temperature</td><td>0.2</td><td colspan="2"></td><td>Global, Local at row, tube-to-tube variation</td></tr>
<tr><td>Pressure</td><td>0.1</td><td colspan="2"></td><td>Operating Pres./Design Pres.</td></tr>
<tr><td rowspan="4">Inspection</td><td rowspan="4">1.34</td><td rowspan="2">Last Inspection</td><td rowspan="2">0.4</td><td>Timing</td><td>0.7</td><td>Years since last Insp.</td></tr>
<tr><td>Frequency</td><td>0.3</td><td>Multiple Insp?</td></tr>
<tr><td rowspan="2">Method</td><td rowspan="2">0.6</td><td>Surface</td><td>0.5</td><td>Visual ID (all, random, hot), None</td></tr>
<tr><td>Volumetric</td><td>0.5</td><td>Manual, Automated, TOFD, Arrays, None</td></tr>
<tr><td>Damage (Service Only)</td><td>1.55</td><td>Type</td><td>1.0</td><td colspan="2"></td><td>Yes/No, Repaired?</td></tr>
<tr><td>Repair/Action</td><td>0.05</td><td>Yes/No</td><td>1.0</td><td colspan="2"></td><td></td></tr>
<tr><td>Maintenance</td><td>0.53</td><td>Support Problems</td><td>1.0</td><td colspan="2"></td><td>Yes/No</td></tr>
<tr><td>Stress</td><td>0.95</td><td>Analysis Type</td><td>1.0</td><td colspan="2"></td><td>Must account for Transient Thermal effects</td></tr>
<tr><td rowspan="4">Design/ Fabrication</td><td rowspan="4">1.91</td><td>Dia/Thk Ratio</td><td>0.3</td><td colspan="2"></td><td></td></tr>
<tr><td>Ligament Spacing</td><td>0.4</td><td colspan="2"></td><td></td></tr>
<tr><td>Intersection</td><td>0.2</td><td colspan="2"></td><td>Does Lig intersect a weld or thickness transition?</td></tr>
<tr><td>Penetration Type</td><td>0.1</td><td colspan="2"></td><td>Radial, Trangential</td></tr>
<tr><td rowspan="2">Materials</td><td rowspan="2">0.97</td><td>Oper. Temp/Creep Start Temp</td><td>0.7</td><td colspan="2"></td><td>.</td></tr>
<tr><td>Oxidation or Fatigue</td><td>0.7</td><td colspan="2"></td><td></td></tr>
<tr><td rowspan="2">HDR General Knowledge</td><td rowspan="2">0.68</td><td>Ligament Geometry</td><td>0.5</td><td colspan="2"></td><td>Ligament Geometry known?</td></tr>
<tr><td>Header Type</td><td>0.5</td><td colspan="2"></td><td>Inlet, Intermediate, Outlet/Finishing</td></tr>
</table>

Table 2-4
Header Stub Tube Categories/Weight Factors

Category		Sub-Category		Sub-Sub Category		Comment
Operation	2.23	Hours	0.2			Operating hrs/max hours, used for cross-system ranking
		Cycles	0.3			Ratio of hot/cold starts to total starts; soot blowing freq, excursions
		Type of Operation	0.1			Base or Load Following
		Temperature	0.4			Global, Local at row, tube-to-tube variation
Inspection	1.75	Last Inspection	0.4	Timing	0.7	Years since last Insp.
				Frequency	0.3	Multiple Insp?
		Method	0.6	Surface	0.4	Visual OD, Dry Powder, WFMT, None
				Volumetric	0.3	Manual UT, Arrays, None
				Metallographic	0.1	Replicas?
				Oxide Survey	0.2	Yes/No
Damage (Service Only)	1.69	Type	1.0			Yes/No, Repaired?
Repair/Action	0.2	Yes/No	1.0			
Maintenance	0.25	Support Problems	1.0			Yes/No
Stress	0.05	Analysis Type	1.0			Must account for Transient Thermal effects
Design/ Fabrication	2.03	Gap Present	0.6			Yes/No
		Flexibility	0.4			High, Med, Low
Materials	0.95	Oper. Temp/Creep Start Temp	0.6			.
		Oxidation or Fatigue	0.4			
HDR General Knowledge	0.8	Stub Tube Geometry	1.0			Stub Tube Geometry known?

2.5 Ranking Methodology Implementation

With the component categories and weight factors defined, implementation of the methodology becomes a matter of gathering the category data for each component (girth weld, ligament, stub tube) and determining the rank values. This process has been streamlined through the creation of an Excel spreadsheet that provides tabular inputs for the component data, automatic evaluation of the rank values using the determined weight factors, and results presentation.

The spreadsheet is structured so that one system (piping or header) is handled per file. Each spreadsheet file consists of 5 tabs; two for data entry and three for results presentation. The data entry tabs are labeled "System Data" and "*Component* Data" where *Component* can be Girth Weld, Ligament, or Stub Tube. General help for each input cell is provided through a comment dialog boxes that appear when your pointing device is positioned over the cell. A Users Manual for the spreadsheet is provided with the spreadsheet and is attached in Appendix A. Each file tab is protected to prevent inadvertent changing of the damage index calculations. Where possible, error checks have been installed to capture erroneous inputs as the data is being entered.

2.5.1 "System Data" Tab

The *System Data* tab lists all the system related information required. A screen capture of the sheet tab is provided in Figure 2-1. On this screen the user provides system identification and a reference date. Input cells are color coded to minimize confusion as to where user-provided data is necessary. For non-numeric inputs where a prescribed response is required, drop-down selection lists are provided. Such lists are accessed by selecting the arrow located on the right-side of the cell.

The information provided is used to determine the Operation Effects factor and contributes to other factors found on the *Component* Data tab. Several inputs on this tab relate to cross-system component evaluations.

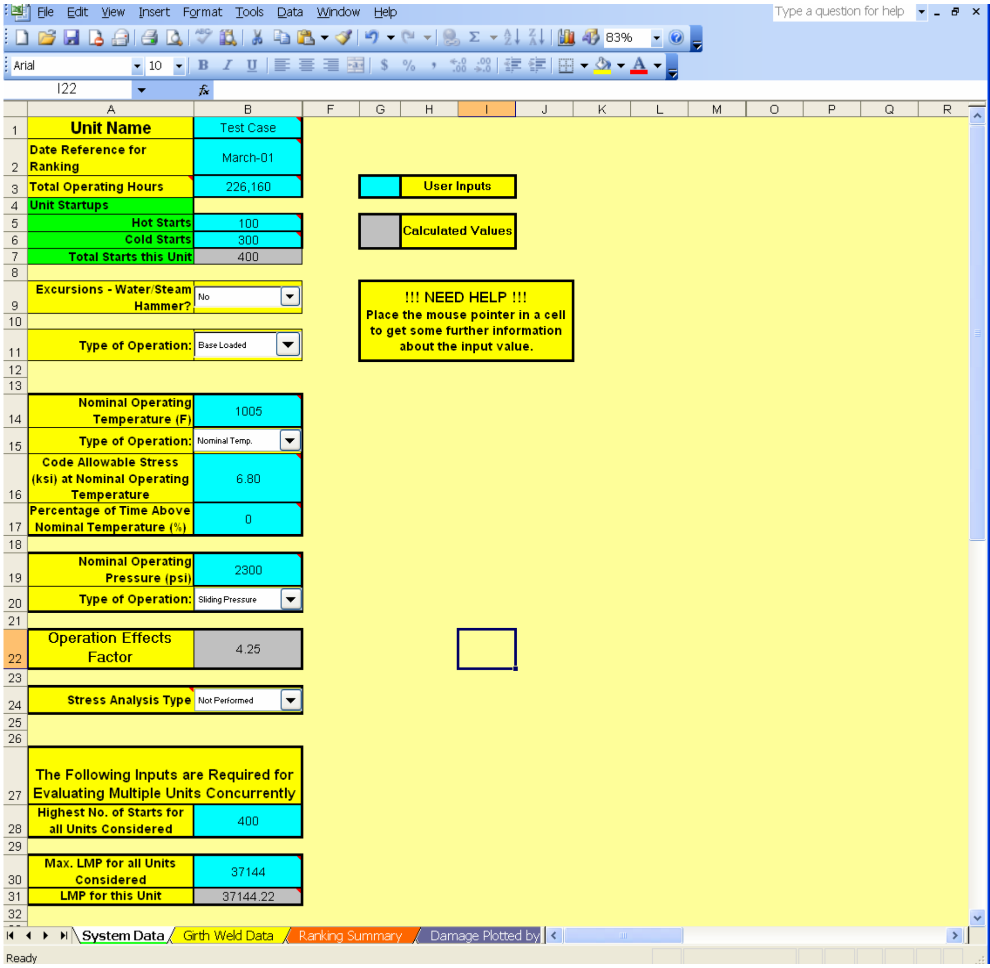


Figure 2-1
The *System Data* input tab.

2.5.2 "Component Data" Tab

The *Component Data* tab is where the bulk of information is input. This tab is laid out in tabular form with each row referencing one component (weld, ligament, or stub tube). Due to the amount of information requested for each component the entire sheet **cannot** be viewed (at reasonable magnification) on a typical computer screen at one time. Therefore, the user should remember to scroll-right to ensure that all data columns have been reviewed.

The columnar structure of the table tracks the categories identified for each component type, as discussed earlier. As on the System Data tab, help on the input required in each column can be found in comment dialog boxes that appear when your pointing device is positioned over the column heading cell. Component identifications are input on the left side of the table (columns A through D). These are text inputs and are for tracking purposes. Column D entries should be unique for each component to facilitate identification on the summary plots. A screen capture showing a portion of this tab is shown in Figure 2-2.

The Component Data tab is currently structured to hold up to 100 components, although that limitation is imposed due limits on results presentation. The damage index value for each component is displayed in Column E. As you proceed across the table, inputting information for the component, this value will change as well as those highlighted in tan, the rank value determined for each category. Selected cells on this tab are protected to prevent alteration of the damage index calculation. Tab rows can be copied to facilitate data entry for large numbers of components.

Test Case

					Spool Information		Inspection Effects						Service Damage Effects				Repair Effects		Support Maintenace	
Item Count	SYSTEM	Weld ID	Comments	*Damage Index*	Pipe Outside Diameter (in.)	Wall Thickness (in.)	Time Since Last Inspection (Years)	Multiple Inspections of this Component? Yes or No	Surface Insp. Type [select]	Volumetric Insp. Type [select]	Metallographic Insp. Type [select]	Inspection Factor	Type of Damage Present [select]	Damage Angular Extent (degrees)	Potential Damage Mechanism [select]	Service Damage Factor	Repairs Made?	Repair Factor	Support Maintenance Performed?	Su Main F
1	MS	MS-1		47.35	18.00	3.20	5.00	n	None	None	None	8.6	None	[illegible]	Creep/Fatigue	4.00	Blend	5.00	Not Checked	
2	MS	MS-2		46.62	18.00	3.20	1.00	n	WFMT	None	Replication	5.6	None	[illegible]	Creep/Fatigue	4.00	None	0.00	Not Checked	
3	MS	MS-3		54.99	18.00	3.20	10.00	n	WFMT	None	None	8.3	None	[illegible]	Creep/Fatigue	4.00	None	0.00	Not Checked	
4	MS	MS-4		56.33	18.00	3.20	10.00	n	WFMT	None	None	8.3	None	[illegible]	Creep/Fatigue	4.00	None	0.00	Not Checked	
5	MS	MS-5		53.91	18.00	3.20	10.00	n	WFMT	Manual UT or RT	Replication	7.6	None	[illegible]	Creep/Fatigue	4.00	None	0.00	Not Checked	
6	MS	MS-6		60.48	18.00	3.20	10.00	n	Visual	None	None	9.5	None	[illegible]	Creep/Fatigue	4.00	None	0.00	Not Checked	
7	MS	MS-7		61.82	18.00	3.20	10.00	n	Visual	None	None	9.5	None	[illegible]	Creep/Fatigue	4.00	None	0.00	Not Checked	
8	MS	MS-8		63.16	18.00	3.20	10.00	n	Visual	None	None	9.5	None	[illegible]	Creep/Fatigue	4.00	None	0.00	Not Checked	
9	MS	MS-9		61.65	18.00	3.20	6.00	y	Visual	None	None	7.2	None	[illegible]	Creep/Fatigue	4.00	None	0.00	Not Checked	
10	MS	MS-10		52.44	18.00	3.20	10.00	n	Visual	None	None	9.5	None	[illegible]	Creep/Fatigue	4.00	None	0.00	Not Checked	
11	MS	MS-11		54.37	18.00	3.20	10.00	n	None	None	None	10.0	None	[illegible]	Creep/Fatigue	4.00	None	0.00	Not Checked	
12	MS	MS-12		55.71	18.00	3.20	10.00	n	None	None	None	10.0	None	[illegible]	Creep/Fatigue	4.00	None	0.00	Not Checked	
13	MS	MS-13		57.05	18.00	3.20	10.00	n	None	None	None	10.0	None	[illegible]	Creep/Fatigue	4.00	None	0.00	Not Checked	
14	MS	MS-14		58.39	18.00	3.20	10.00	n	None	None	None	10.0	None	[illegible]	Creep/Fatigue	4.00	None	0.00	Not Checked	
15	MS	MS-15		59.73	18.00	3.20	10.00	n	None	None	None	10.0	None	[illegible]	Creep/Fatigue	4.00	None	0.00	Not Checked	
16	MS	MS-16		61.07	18.00	3.20	10.00	n	None	None	None	10.0	None	[illegible]	Creep/Fatigue	4.00	None	0.00	Not Checked	
17	MS	MS-17		62.41	18.00	3.20	10.00	n	None	None	None	10.0	None	[illegible]	Creep/Fatigue	4.00	None	0.00	Not Checked	
18	MS	MS-18		63.75	18.00	3.20	10.00	n	None	None	None	10.0	None	[illegible]	Creep/Fatigue	4.00	None	0.00	Not Checked	
19	MS	MS-19		65.09	18.00	3.20	10.00	n	None	None	None	10.0	None	[illegible]	Creep/Fatigue	4.00	None	0.00	Not Checked	
20	MS	MS-20		53.03	18.00	3.20	10.00	n	None	None	None	10.0	None	[illegible]	Creep/Fatigue	4.00	None	0.00	Not Checked	
21	MS	MS-21		51.27	18.00	3.20	10.00	n	None	Linear/Phased Array	Sampling	7.5	None	[illegible]	Creep/Fatigue	4.00	None	0.00	Not Checked	
22	MS	MS-22		55.71	18.00	3.20	10.00	n	None	None	None	10.0	None	[illegible]	Creep/Fatigue	4.00	None	0.00	Not Checked	

System Data | Girth Weld Data | Ranking Summary | Damage Plot by Weld ID | Damage Plot by Rank Value

Figure 2-2
Portion of the *Component* Data tab (this example is for piping girth welds).

2.5.3 “Ranking Summary” Tab

The *Ranking Summary* tab provides two tabular listings of the determined damage index for each component. The first list is ordered according to the input identification (Column C from the *Component Data* tab) with the second list ordered by damage index (highest to lowest). These lists are not created automatically by Excel, but through an embedded macro that must be activated by the user. This is performed by selecting the “List and Sort Damage Indices” button on the tab sheet, as shown in Figure 2-3.

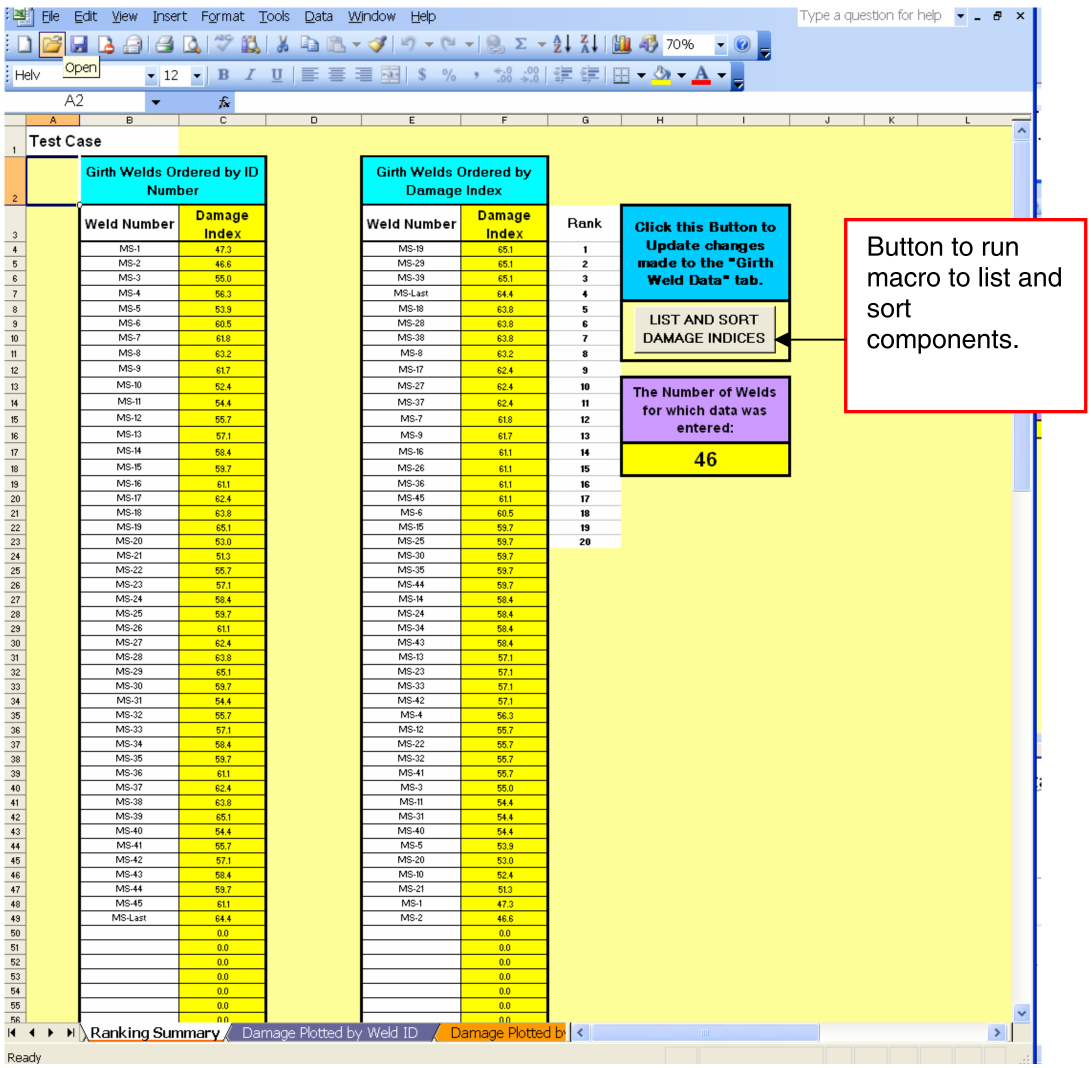


Figure 2-3
Ranking Summary tab, for piping girth welds.

2.5.4 Results Plotting

The remaining two tabs in the spreadsheet provide bar graphs showing damage index plotted versus input order (as on the *Component Data* tab) and ordered by damage index value. The plots are selectable and can be copied to other documents for reporting purposes. Sample plots provided by the spreadsheet are shown in Figures 2-4 and 2-5.

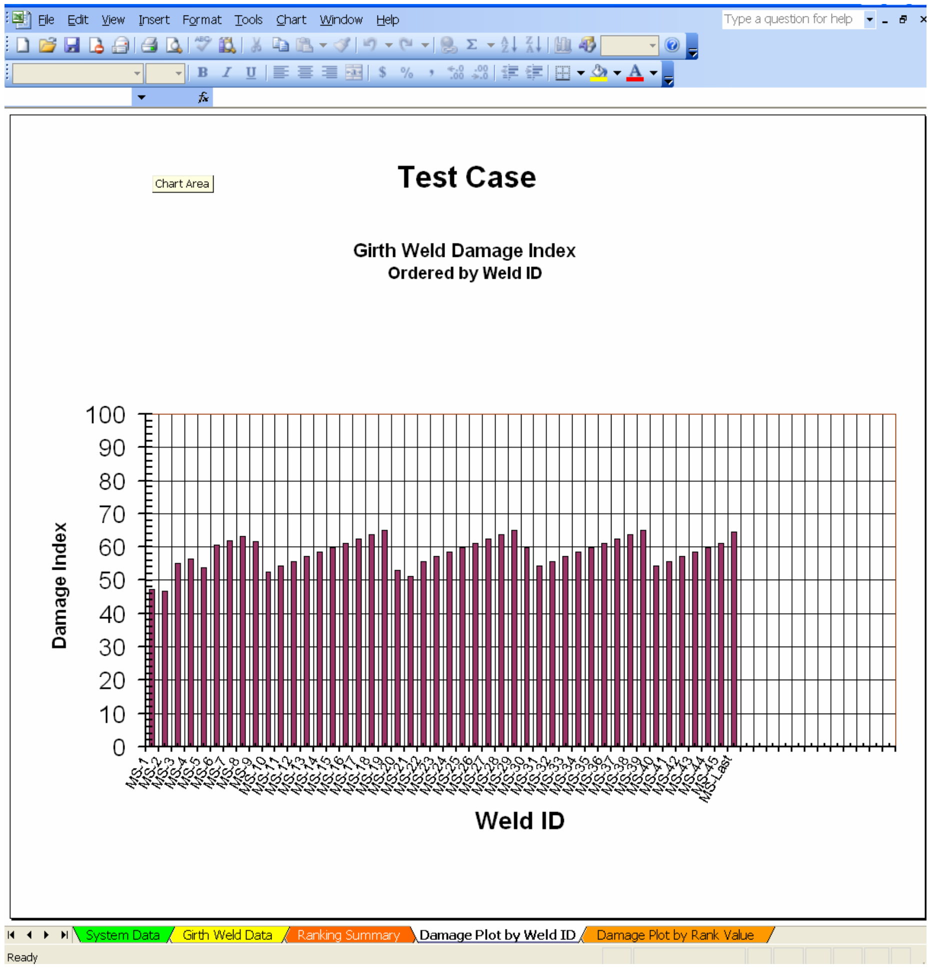


Figure 2-4
Results summary bar chart ordered by Component ID. Example shown for piping girth welds.

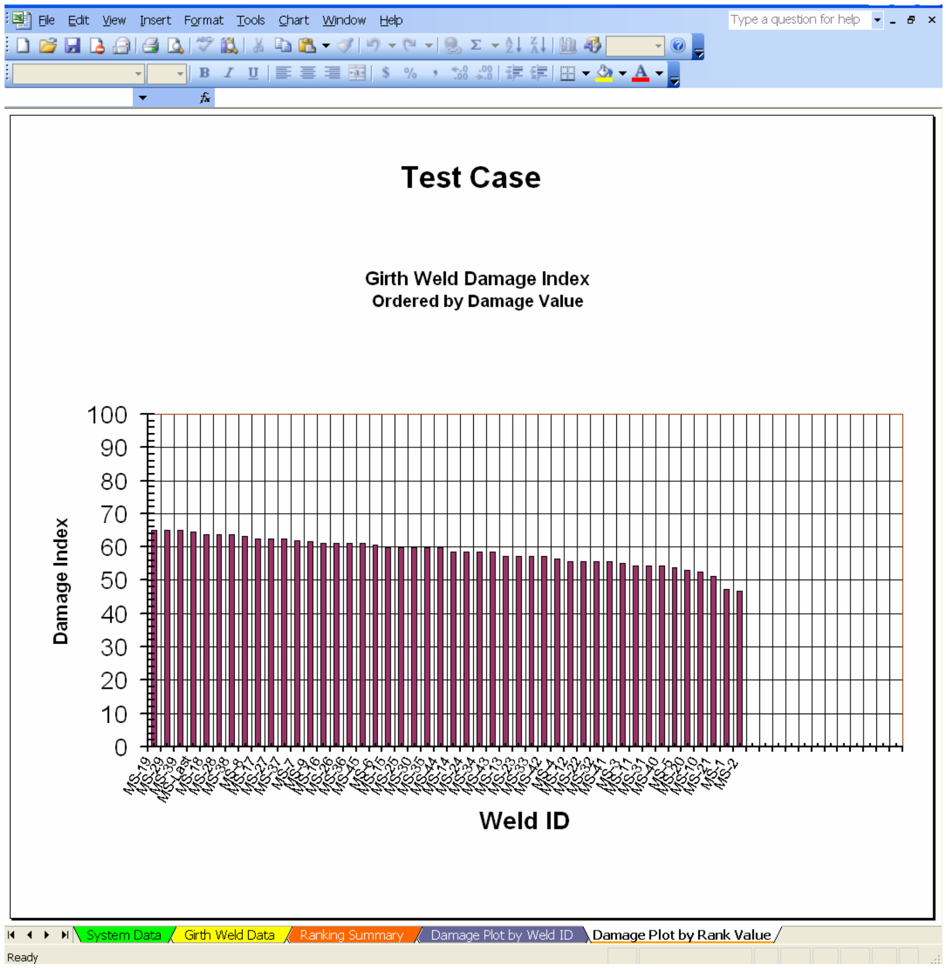


Figure 2-5
Results summary bar chart ordered by Damage Index. Example shown for piping girth welds.

3
METHODOLOGY BENCHMARKING

To demonstrate the effectiveness of the methodology at identifying components most likely to experience damage, members of the Advisory Committee were asked to provide component information from systems that had experienced through-wall failure (leaks) or significant service damage (cracking). For this initial demonstration of the methodology, test cases for piping girth welds were requested. Selection of girth welds was made since there was a broader range of documented system service histories available.

At first the criteria used to select a test case for consideration were:

- System drawings were available.
- The locations of all welds in the system were known.
- The system had been subjected to previous inspection(s) for which specifics were available.
- Weld(s) in the system had failed or inspection results showed the presence of service damage.

During review of the first sets of cases obtained, it became apparent that the performance of some form of quantitative stress analysis was influential in the identification of damaged welds. Consequently, the performance of a system stress analysis was added to the criteria list along with a “piping stress analysis methodology,” which is provided in Appendix B.

The strong dependence of stress on weld rank is reflected in the comparatively high weighting given to this category by the advisory committee (see Table 2-1). Consequently, any errors introduced whether they be by relative ranking or incorrect analyses are amplified accordingly. Therefore, it is important that such analyses be implemented as accurately as possible. Further, it is recommended that when warranted by operating temperatures and construction materials, the analysis account for the redistribution of stress by creep.

In total, committee members provided information for fourteen cases. Of these systems, six meet all the cited criteria. Descriptions of these six systems and the results of their evaluation using the experienced-based methodology are provided in the following sub-sections.

3.1 Test Cases

3.1.1 Case 1

This was a P22 main steam system composed of 13.75 and 18.75 inch diameter pipe. The system had accumulated approximately 188,000 hours when weld S5 failed, shown circled in Figure 3-1. An elastic stress analysis of the system was provided. Results of the damage ranking using the program methodology are shown in Figure 3-2. Of the total of 20 girth welds included in the ranking process, the damaged weld was ranked 5th.

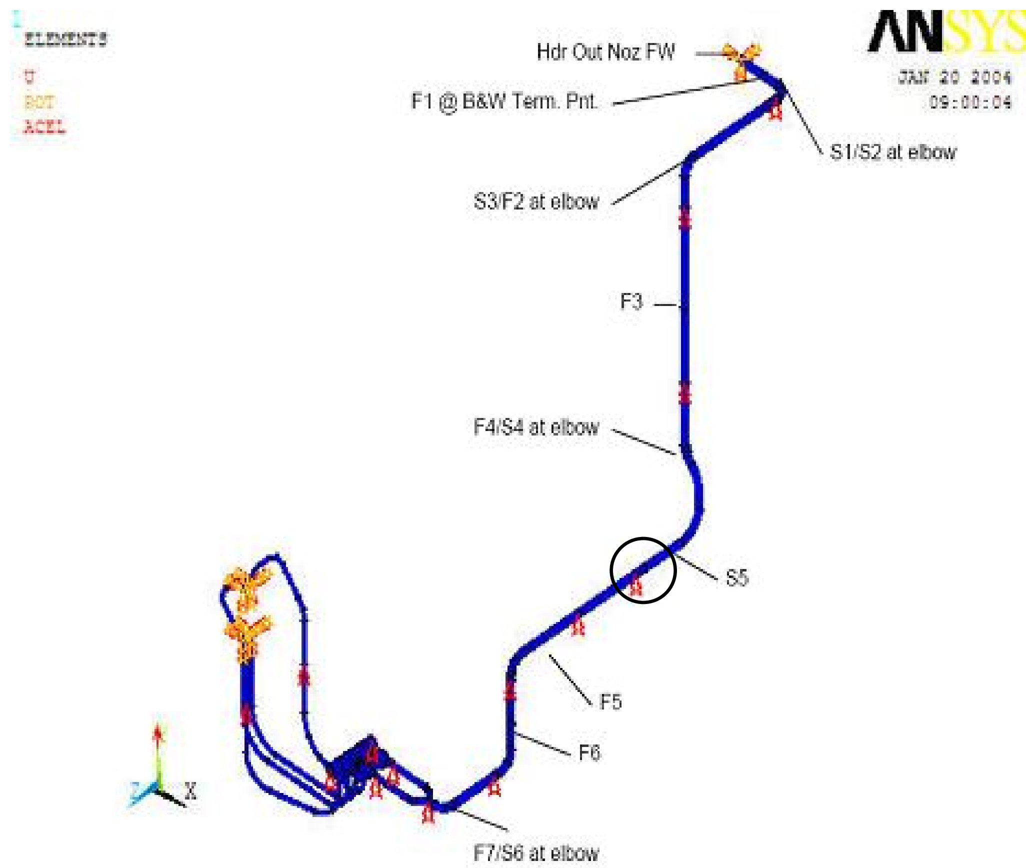


Figure 3-1
Plot of Test Case 1 piping system.

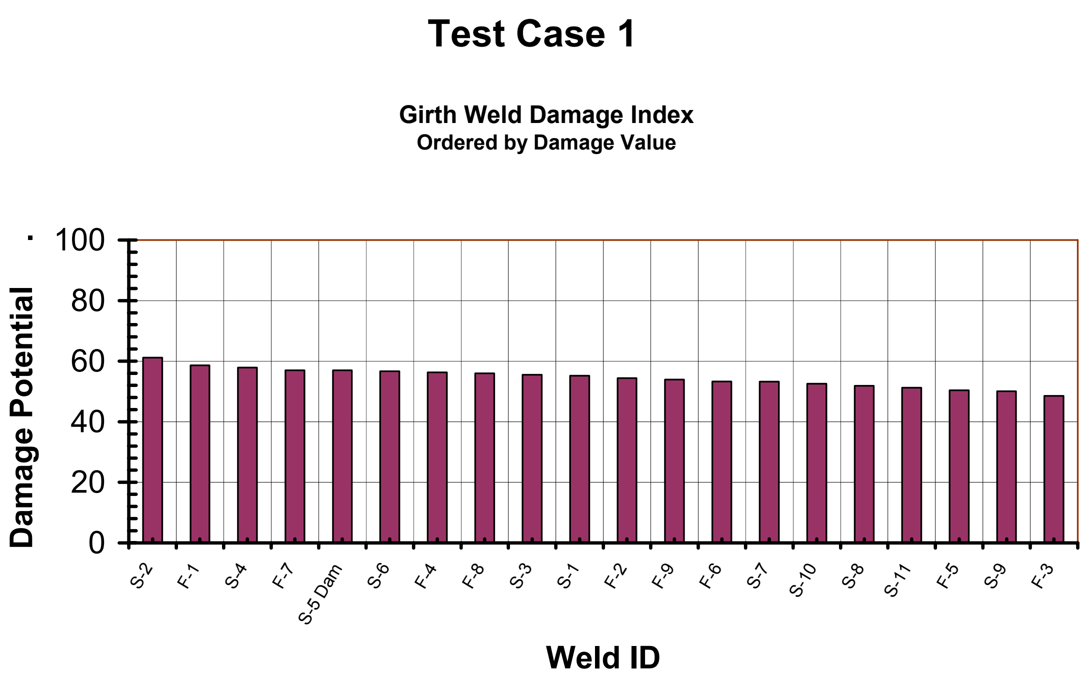


Figure 3-2

Results plot from Test Case #1 plotted in order of predicted damage index.

3.1.2 Case 2

This case is for a P-11 main steam piping system with 14.5 and 18.75 inch OD pipe. The system experienced a girth weld steam leak following approximately 220,000 hours of operation. Subsequent, inspections following the leak detected near through-wall cracking in another girth weld and service damage in two other welds, Figure 3-3. A creep redistribution stress analysis of the system was performed. Results of the damage ranking are shown in Figure 3-4. Of the twenty-six welds included in the ranking, the damaged welds were ranked at the top of the list with the failed welds falling in the top 30-percent.

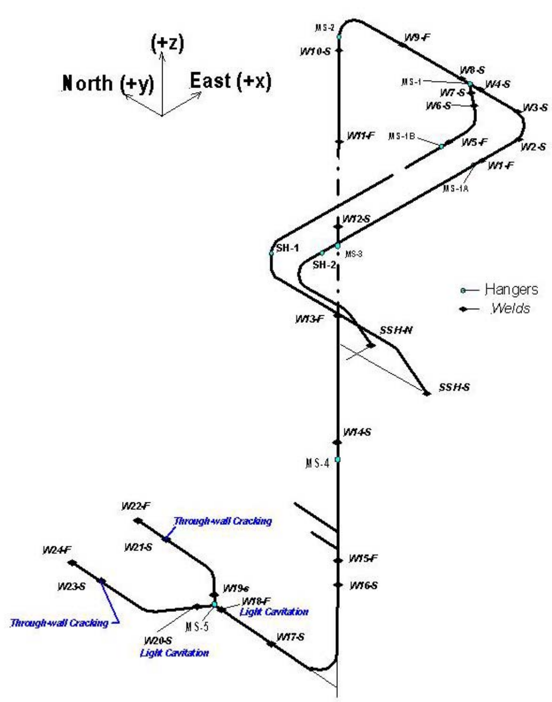


Figure 3-3
Plot of Test Case 2 piping system.

Test Case 2

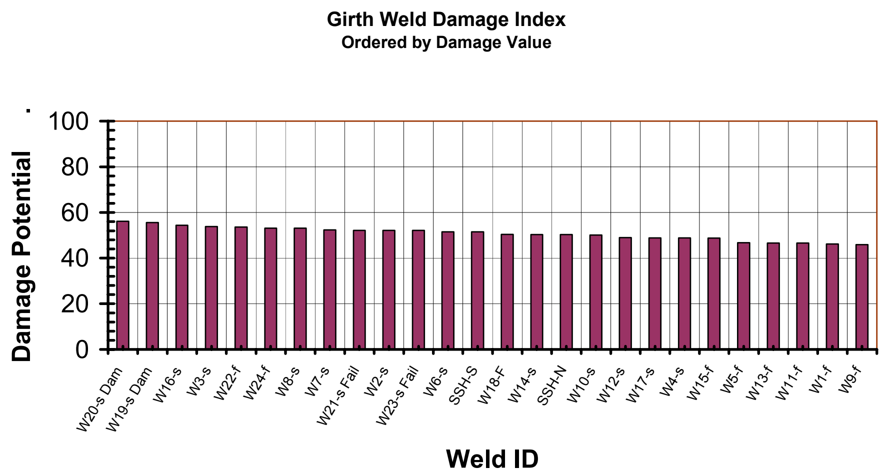


Figure 3-4
Results plot from Test Case 2 plotted in order of predicted damage index.

3.1.3 Case 3

This case is for a P-22 main steam piping system with 16, 20 and 25 inch OD pipe (Figure 3-5). The system experienced a girth weld leak at a stop valve following approximately 188,000 hours of operation. Inspections of the system had been performed 3 and 5 years previously. Results of the damage ranking are shown in Figure 3-6. The cracked weld was ranked 8th out of 46 welds included in the ranking.

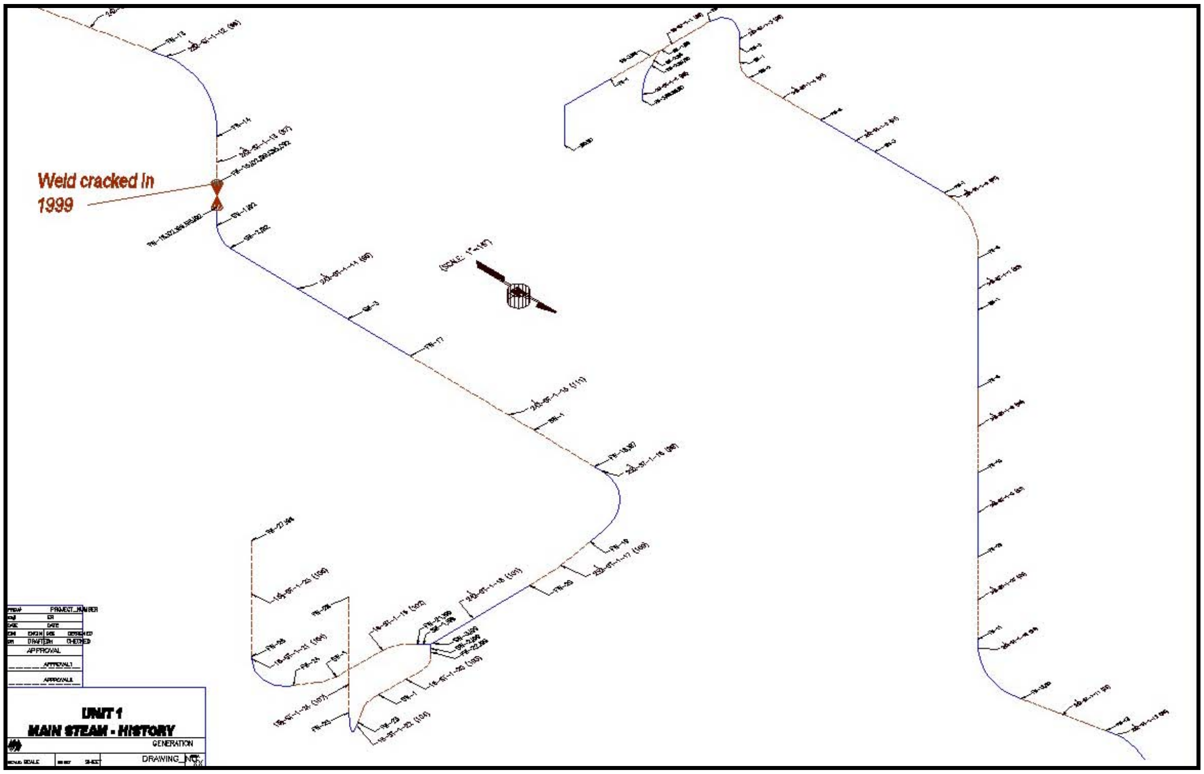


Figure 3-5
System layout for Test Case 3 piping.

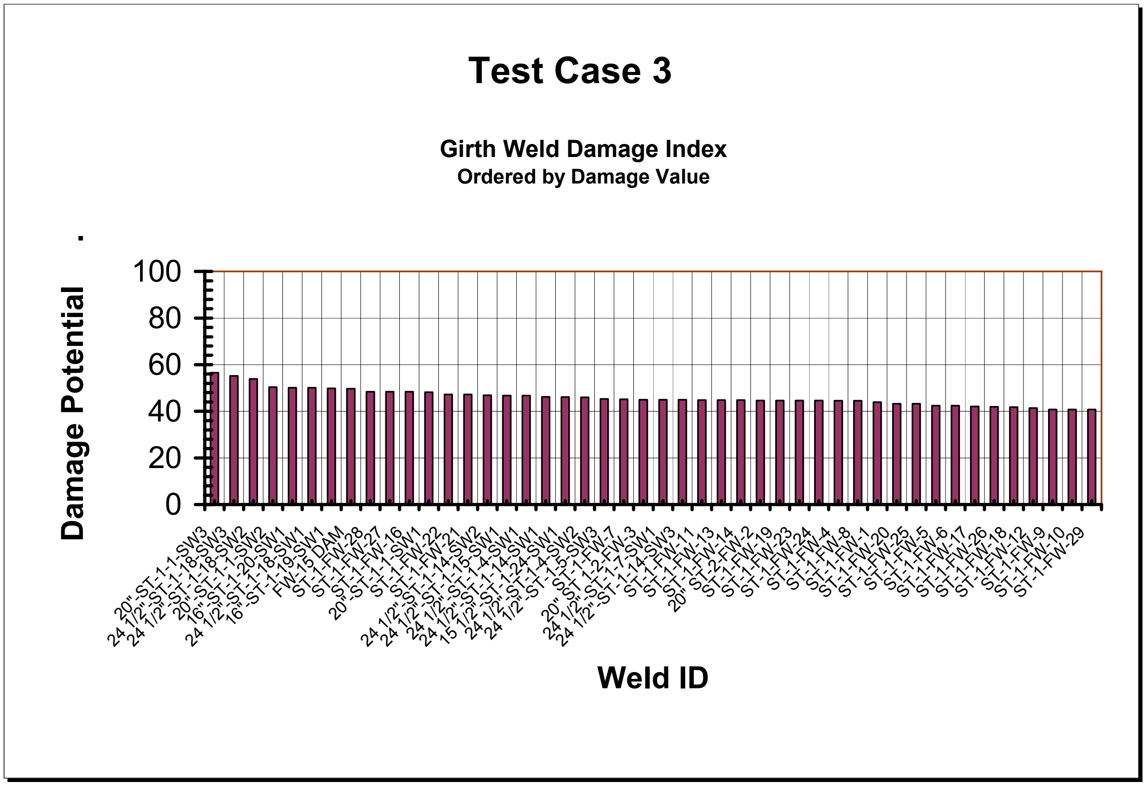


Figure 3-6
Results plot from Test Case 3 plotted in order of predicted damage index.

3.1.4 Case 4

This case is for a P-22 hot reheat piping system with 24 and 32 inch OD pipe (Figure 3-7). An inspection performed in 1999 revealed two welds with macro cracking after approximately 188,000 hours of operation. Prior inspections of the system had been performed 3 and 5 years previously. Results of the damage ranking are shown in Figure 3-8. The cracked welds were ranked 1st and 7th out of 56 welds included in the ranking.

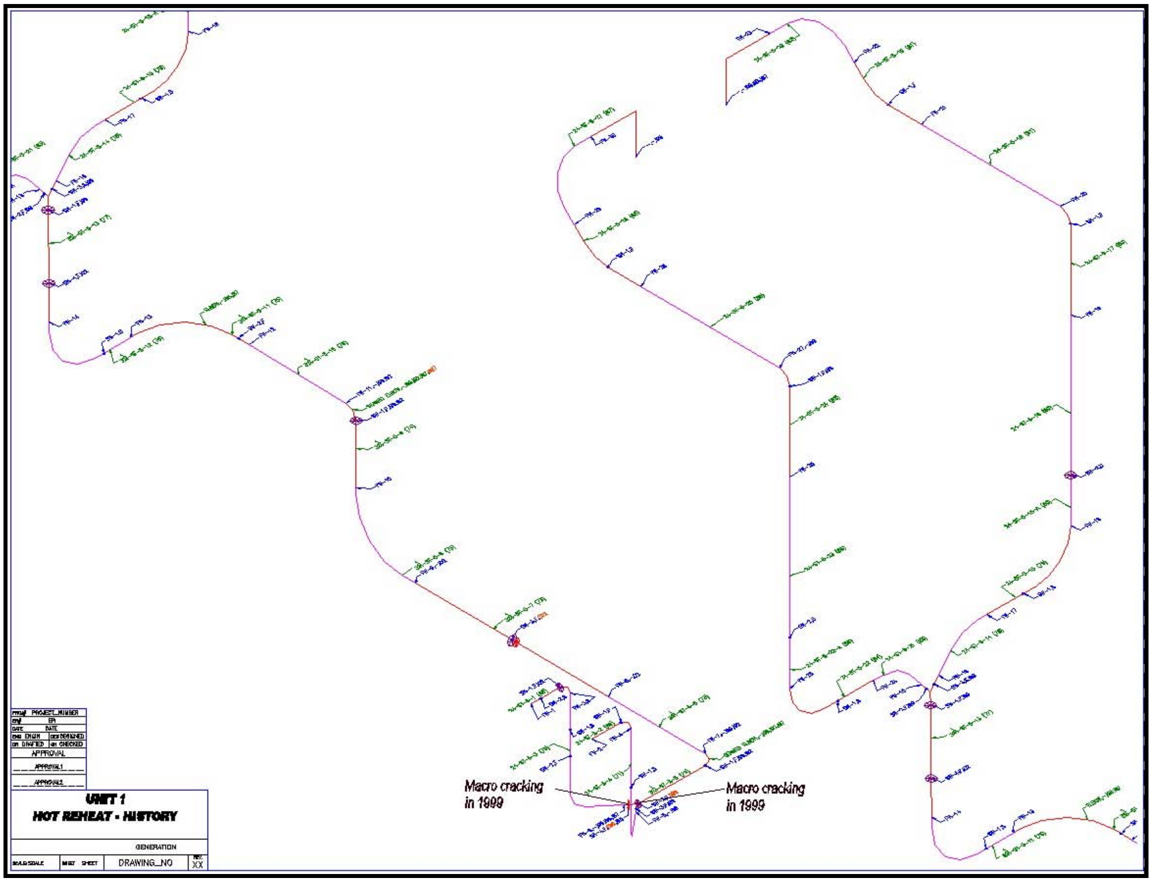


Figure 3-7
System layout for Test Case 4 piping.

Test Case 4

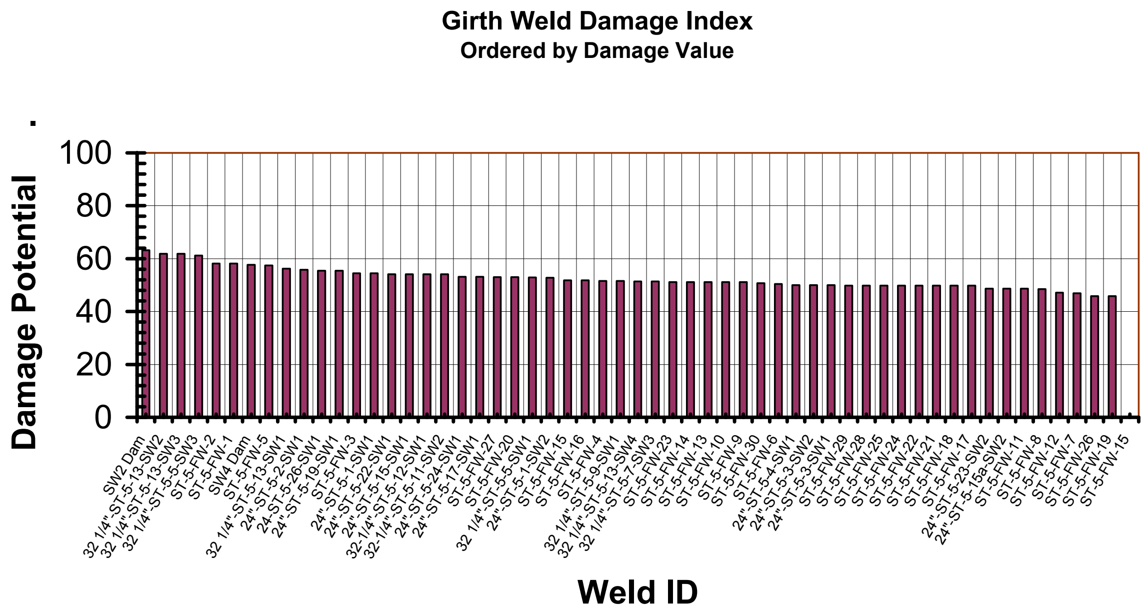


Figure 3-8
Results plot from Test Case 4 plotted in order of predicted damage index.

3.1.5 Case 5

This case is for a P-22 main steam piping system with 17, 24 and 30 inch OD pipe (Figure 3-9). The system experienced a girth weld leak in a shop weld following approximately 195,000 hours of operation. Prior inspections of the system including this weld had been performed 4-years previously with some surface MT indications noted. Results of the damage ranking are shown in Figure 3-10. The cracked weld was ranked 7th out of 60 welds included in the ranking.

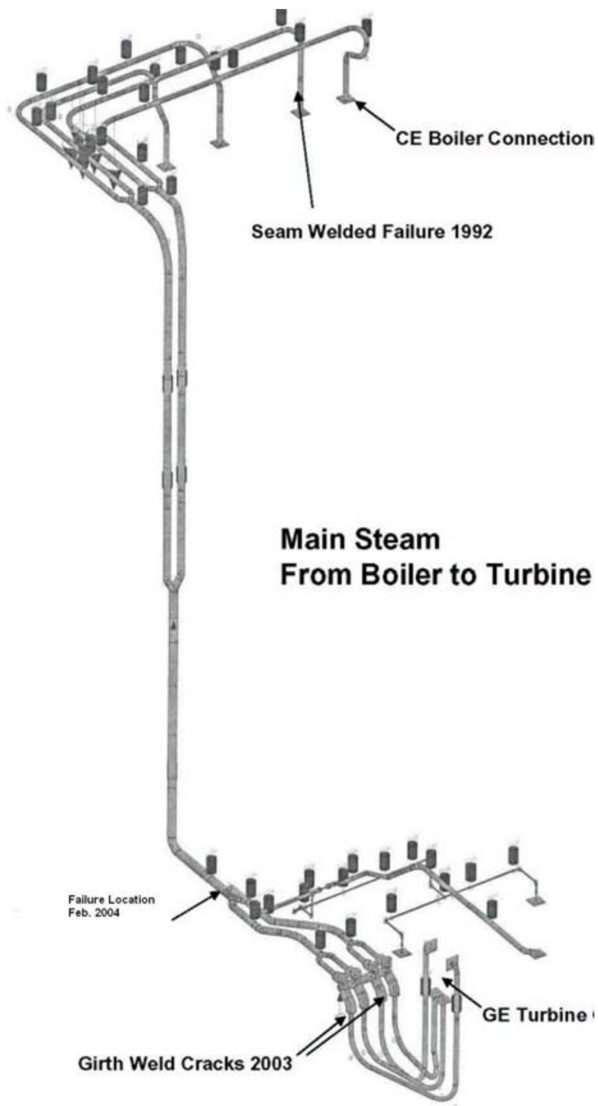


Figure 3-9
System layout for Test Case 5 piping.

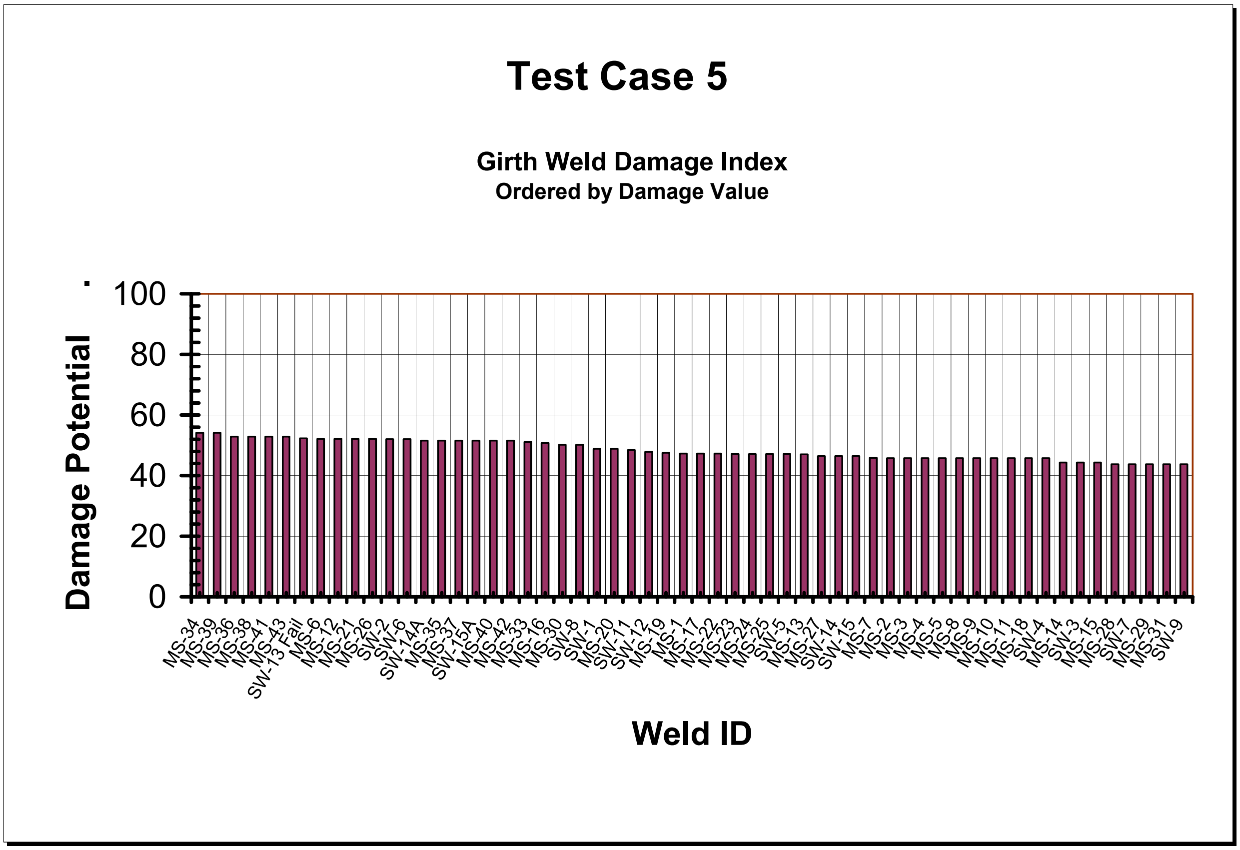


Figure 3-10
Results plot from Test Case 5 plotted in order of predicted damage index.

3.1.6 Case 6

This case is for a P-22 main steam piping system with 14, 16 and 21 inch OD pipe (Figure 3-10). The system experienced near through-wall girth weld cracking in two shop welds following approximately 237,000 hours of operation. Prior inspections of the system including this weld had been performed 4-years previously with some surface MT indications noted. Results of the damage ranking are shown in Figure 3-11. The cracked welds were ranked 2nd and 29th out of 121 welds included in the ranking.

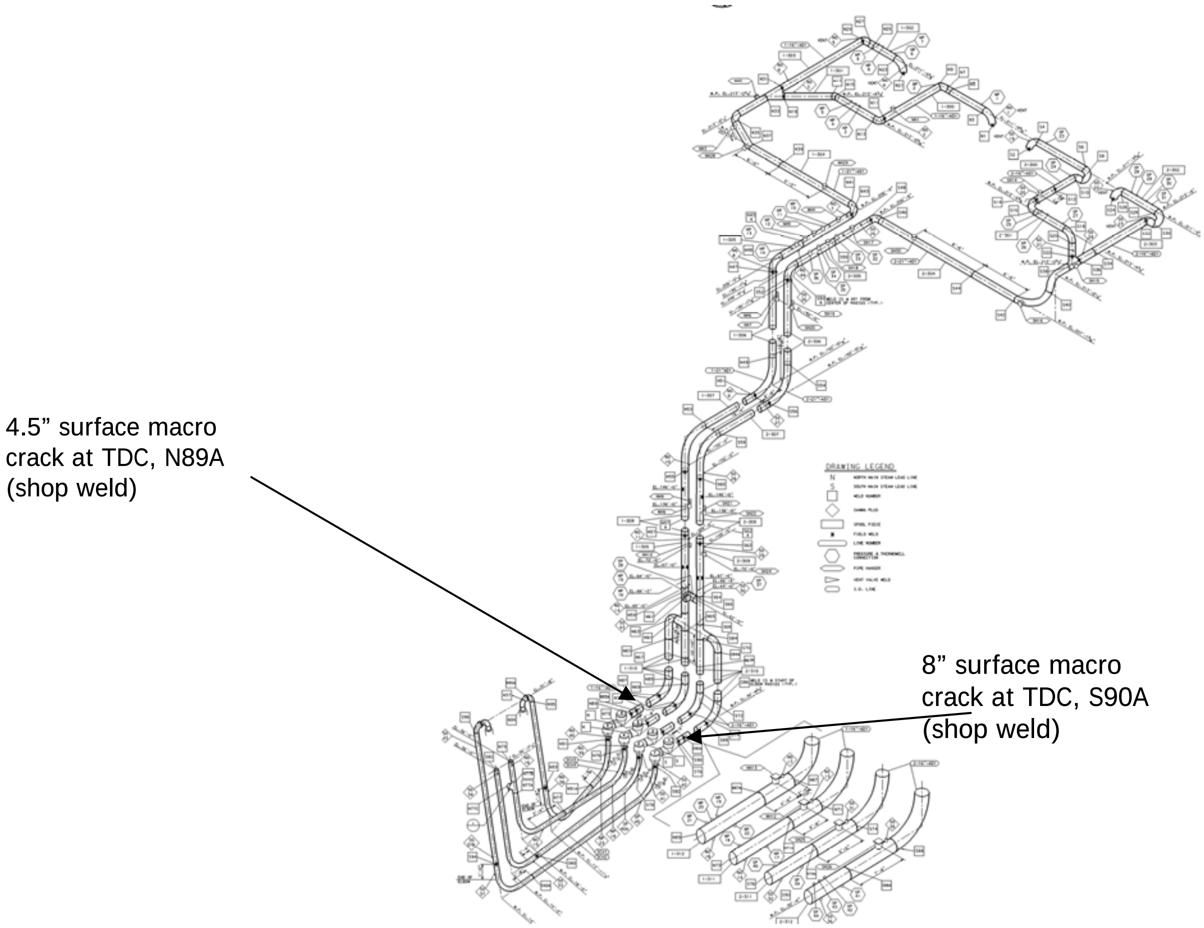


Figure 3-11
System layout for Test Case 6 piping.

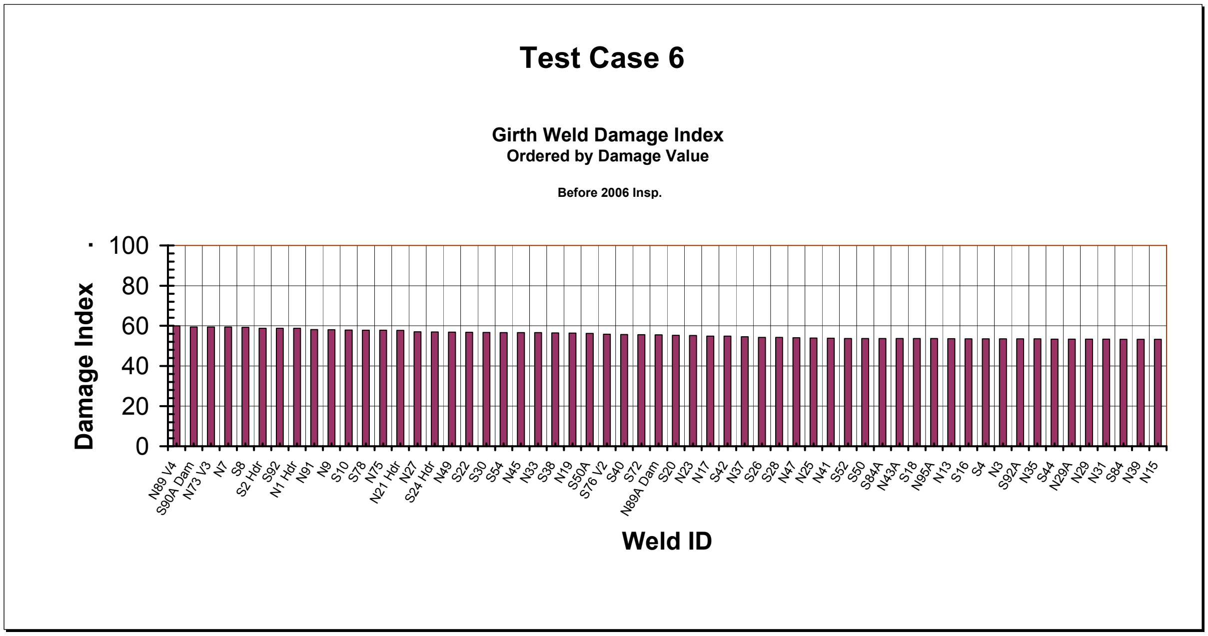


Figure 3-12
Results plot from Test Case 6 plotted in order of predicted damage index.

3.2 Test Case Summary

To track the ability of the methodology to predict the occurrence of damage, the ranking results of all 14 test cases were evaluated on a ‘predictability basis’. Specifically, the percentile of the highest-ranked damaged weld with respect to the total number of welds in the system.

For this predictability assessment, the six cases meeting the information criteria (listed below) were included in one group and the remaining 8 cases in another group. Recall that the established criteria for system information is:

- System drawings were available.
- The locations of all welds in the system were known.
- The system had been subjected to previous inspection for which specifics were available.
- Weld(s) in the system had failed or inspection results showed the presence of service damage.
- A quantitative stress analysis of the piping system had been performed.

The six test cases meeting these criteria are listed in Table 3-1 and result in an average predictability percentage of 81.6 percent. The remaining 8 cases not meeting the criteria are listed in Table 3-2. In each of these cases some information was lacking or in question. In several of these cases stress analyses were not available or if performed unverified. In one case the damage identified in an earlier inspection turn out to not be service-related. The average predictability percentage of these 8 cases is approximately 67 percent.

Considering all 14 cases available there were a total of 686 girth welds in which 33 were reported to contain damage (4.8 percent). Of those 33 damaged welds the spreadsheet was found to have an overall average prediction rate of approximately 73 percent.

Table 3-1
Summary of System Data Provided

Data Set Number	Utility	Total Operating Hours	Material Spec.	Operating Temp (F)	Pipe OD's (in.)	Stress Analysis	Damage Description	Total Number of Welds	Damaged-Weld Rank	Percentile
1	A	188,000	P22	1000	18.75 & 13.75	Elastic & Creep	Weld Failure at S5	20	9	55.00
2	B	220,000	P11	1005	14.5 & 18.75	Elastic & Creep	2 shop welds with through thickness, Type IV cracking. 2-welds with light damage	26	Cracked Welds 8 & 10, Damaged Welds 6 & 11	76.9
3	D	188,000	P22	1005	16, 20, & 25	None	Field Weld at block valve cracked	46	8	82.61
4	D	188,000	P22	?	24 & 32	None	Macro cracking found in two welds (24 & 32" OD)	61	1 & 7	93.44
5	F	195,600	P22	1000	17, 24, & 30	Limited, not verified	30" OD girth weld cracking	60+	13	78.33
6	G	237,000	P22	1005	14, 16, & 21	Elastic & Creep	2 valve inlet girth welds cracked	122	2 & 29	87.30

Table 3-2
Summary of System Data (continued)

Data Set Number	Utility	Total Operating Hours	Material Spec.	Operating Temp (F)	Pipe OD's (in.)	Stress Analysis	Damage Description	Total Number of Welds	Damaged-Weld Rank	Percentile
7	A	125,000	P22	1050	36 & 46	Elastic	Damage discovered in 5 welds	48	1, 12, 24, 38, 46	50.00
8	B	220,000	P11	1005	19.5, 23, & 26.5	Elastic & Creep	3 welds with light cavitation	36	15, 17, & 26	46.30
9	C	363,000	P22	1050	5, 10, & 14	Elastic, not verified	Cracking in branch connection saddle welds	43	1 & 2	96.51
10	E	?	P11	?	15 & 18	None	Block valve inlet welds (2) cracked, (18" OD)	40	12 & 18	62.50
11	E	174,300	P22	1005	16, 18, 24, & 32	None	5 Cracked welds in 2003	83	2, 3, 4, 11, 20	90.36
12	G	220,000	P22	1005	14, 16, & 20	None	360-degree micro damage at 2 turbine casing connections (CrMoV)	109	13 & 17	86.24
13	H	209,000	P22	1050	8 & 17	Elastic, not verified	1987 360-degree macro damage in 1 weld	26	11	57.69

4
SUMMARY AND CONCLUSIONS

A set of semi-quantitative ranking methodologies has been developed for high energy piping girth welds, header girth welds, stub tube welds, and ligaments. Each methodology identifies characteristics that through experience and/or investigation have been found to impact the occurrence and growth of component service damage. For piping girth welds the methodology has been implemented for use by utility personnel in an Excel spreadsheet, allowing the ranking of up to 100 welds at one time.

A group of piping girth weld test cases have been reviewed and evaluated using the spreadsheet to rank the potential for each failure or significant service damage in the sample welds. Considering those test cases that met an established information criteria (six cases) the average ‘predictability’ of the methodology was determined to be <u>81.6 percent</u>. The average predictability of the cases without complete information was 67 percent.

The results obtained to-date for piping-girth welds are encouraging and it is concluded that the spreadsheet can be used for relative rankings of system welds. However, evaluation of additional test cases are required to ensure the ability of the methodology to capture damage accumulation associated with Type IV cracking and to tune the category weight factors.

Test cases for each of the other component ranking methodologies (header girth welds, stub tubes, and ligaments) need to be collected and evaluated to assess each method.

5
REFERENCES

1. "Spreadsheet Users Guide and Technical Reference", February 2007, by Structual Integrity Associates.

A
APPENDIX: SPREADSHEET USERS GUIDE

Section 1
Introduction

This document provides background and insight into the development and application of an Excel spreadsheet **tool** developed under EPRI project "Refining the Probability of Failure for the Risk Management Process". The function of the spreadsheet is to provide utility personnel with a means to ***qualitatively*** rank the potential for service damage development in high-temperature piping girth welds based on weld characteristics and service experience, thereby providing guidance for inspection planning.

There are two keys to performing a valid damage ranking. The first is determination of those characteristics that effect damage development, and second application of the characteristic effects in a consistent manner. As you will encounter when performing the process for the first time some of the requested inputs are not necessarily distinct values that you can look up or calculate. Instead they will require some level of interpretation. Before becoming disillusioned keep in mind that this is a ranking, not a life analysis. Regardless of your level of 'expertise', as long as you are consistent in your application of the process used to select the inputs, then the relative effect(s) will be captured.

The spreadsheet will run on any personal computer (PC) with a functioning version of Microsoft Excel. The spreadsheet was developed on an IBM-compatible platform, running Windows XP. It has **not** been tested in other environments, however, it is anticipated that porting to other systems/environments running Excel will not encounter problems. Further information concerning the development of the ranking methodology and benchmarking of the process can be found in Reference [1].

Section 2
Ranking Methodology Background

A.2.1 Methodology Development

Development of an experience-based ranking methodology is predicated on the identification of characteristics that can be scored regarding their contribution to material damage. The methodology can be applied to *any* component or system for which the life-effecting damage mechanisms are known and those characteristics effecting their formation and rate of accumulation (i.e., design, operation, materials, etc) can be identified. Within each category there are sub-categories that isolate the contribution of specific characteristics to the overall damage susceptibility. The contribution of each category is then determined by summation of sub-category scores.

Rank values within each category and sub-category are assigned on a scale of 0 to 10 (zero being the lowest damage potential and 10 being highest). Recognizing that each characteristic is not equal in its contribution to overall damage susceptibility, each category/sub-category is also assigned a weighting factor. These weighting factors are the core of the experienced-based methodology, since by definition they are the means by which one characteristic has more impact than another. Identifying which characteristic(s) are most important is not straight-forward due to the inherent complex nature of the damage mechanisms effecting high-energy components, coupled with the multi-variant conditions under which the components are constructed and operate. Therefore, each weighting factor represents the *perceived* level of contribution of that category/sub-category to the entire state of damage susceptibility.

The total potential for damage is the sum of each category's rank value multiplied by its' respective weight factor. The ranking methodology is structured so that the maximum potential score a component can achieve is 100. Listings of the component categories and their assigned weight factors are presented in Table A-1. Category lists and weight factors were developed by the project advisory committee. Further information regarding the advisory committee and project details can be found in Reference [1].

A.2.2 Component Characteristic Categories

To provide a basis on which to perform component ranking, it is necessary to identify those characteristics that effect the initiation of damage and its rate of accumulation. For high-temperature girth welds 9 primary categories have been identified. A brief description of each category is presented below.

Operation - This category relates component operating conditions. Specifically, operating hours, system starts, the type of operation, temperature and pressure. These characteristics typically will not vary for welds within a given piping system (except if repairs or replacements have been made) but are necessary for cross-system rankings.

Inspection – This category accounts for the effects of inspection history on damage potential. It should be noted that this category accounts only for the fact that inspections were performed, implications of results obtained from the inspections are addressed in the Damage category. The Inspection category is sub-divided into two sub-categories; the time elapsed since the last inspection, and the type(s) of inspections performed. Elapsed time effects are set to decay over a ten-year period. Ranking of inspection type(s) is performed for surface, volumetric, and metallographic methods with cumulative effects for compound inspections. It is assumed that each surface or volumetric examination covered 100-percent of the component (e.g. the entire girth weld) and was performed in accordance with standard practice.

Damage – In this category the state of **service** damage present in the component is described. Note, only service damage is considered, the presence of fabrication-related defects is not considered detrimental. Damage is classified as micro or macro, its extent, and causative mechanism. In the methodology implemented, ***a component that is known to have macro-service damage automatically has its total rank value set to 100, independent of any other inputs***. This automatically puts the effected weld at the top of the rank list. The advisory committee believes that welds with known service-related macro damage should be given the highest priority and evaluated using quantitative lifing methods.

Repair/Action – This category addresses whether the component has been previously repaired, and if so to what extent. It is assumed that any repairs performed removed all existing damage.

Maintenance – This category accounts for the effects of performing examination and/or maintenance of structural supports (hangers) near the specific component. It is assumed that any malfunctioning supports identified by the examinations have been repaired, with the supports returned to their prescribed design condition.

Stress – This category accounts for the extent to which the operating stresses and temperatures in the component have been determined. This category effects both cross-system and inter-system component ranking. In the absence of a quantitative evaluation (i.e. finite element analysis) component stresses can be relatively ranked from highest to lowest. It should be noted however, that cross-system component rankings **should not** be performed in the absence of a quantitative stress analysis.

Design/Fabrication –This category incorporates the effect of component type (wyes, tees, saddle welds).

Materials –This category includes effects of the component operating temperature-to-material creep-start temperature, whether the component is cast or forged, and Type IV cracking susceptibility.

Welds – This category includes the effects of the weld process used during manufacture, aspects of weld geometry (counterbore extent, reinforcement, and backing rings), and whether material transitions are present.

A.2.3 Weight Factors

Recognizing that each category identified in Section A.3 does not contribute equally to the potential for damage, weight factors for each category were developed by the project advisory committee based on its collective experience. The assigned weight factors represent the perceived relative contribution of each sub-category/category to the overall damage development potential for a girth weld. A listing of characteristics and weight factors is presented in Table A-1.

Table A-1

Piping Girth Weld Categories/Weight Factors

Category		Sub-Category		Sub-Sub Category		Comment
Operation	1.51	Hours	0.3			Operating hrs/max hours, used for cross-system ranking
		Cycles	0.2			Ratio of hot/cold starts to total starts; water/steam hammer?
		Type of Operation	0.1			Base or Load Following
		Temperature	0.3			Under/Over temperature
		Pressure	0.1			Under/Over/Sliding pressure
Inspection	1.23	Last Inspection	0.4	Timing	0.7	Years since last Insp.
				Frequency	0.3	Multiple Insp?
		Method	0.6	Surface	0.4	Visual, Dry Power, WFMT, None
				Volumetric	0.4	RT, Manual, Automated, TOFD, Arrays, None
				Metallographic	0.2	Replicas, Sampling, None
Damage (Service Only)	1.28	Type	0.6			Macro or Micro
		Mechanism	0.4			Creep, Creep/Fatigue, Fatigue, Unknown
Repair/Action	0.62	Extent	1.0			Full, Partial, Blend
Maintenance	1.01	Supports	1.0			Walkdowns, Functionality Checks, Measurements, Nothing
Stress	1.34	Analysis Type	1.0			Elastic, Creep, None
Design/ Fabrication	0.59	Component Type	1.0			Pipe, Tee, Wye, Saddle, Bend/Elbow
Materials	1.35	Grade	0.4			Operating Temp/Creep-Start Temp.
		Cast/Forged	0.2			Cast, Forged, or Austenitic
		Type IV	0.4	Grade	0.25	P11, P22, P91, ½ CrMoV
				Weld Type	0.2	Shop/Submerged Arc, Shop/Unknown, Shop/Other, Field
				OD/Thk Ratio	0.2	>10 no effect
				Neighboring Component	0.15	Thick Section, Pipe
				Weld Profile	0.2	V, J, Narrow Groove
Welds	1.07	Process	0.33			Submerged Arc, Other
		Geometry	0.33	Counterbore	0.7	High, Low
				Reinforcement	0.2	High, Low
				Backing Ring	0.1	Yes, No
		Material Transitions	0.34			New-to-Old, Alloy1 to Alloy 2

Section 3
Spreadsheet Operation

A.3.1 Ranking Methodology Implementation

With the categories identified and weight factors defined, implementation of the methodology becomes a matter of gathering the category data for each weld and determining the rank values. The process has been streamlined through the creation of an Excel spreadsheet that provides tabular inputs for the component data, automatic evaluation of the rank values using the determined weight factors, and results presentation.

The spreadsheet is structured so that one group of welds (maximum of 100) is handled per file. The definition of a group of welds is at the discretion of the user, however, typically it would consist of all girth welds in a main steam or hot reheat piping system. Remember that each file (or copy of the spreadsheet) represents a ranking of the given set of welds at one specific point in time (or the operating history of the unit).

A.3.2 Spreadsheet Protection and General Help

The spreadsheet and selected cells within it are protected to prevent inadvertent changing of the damage index calculations or modification of the weight factors. As a consequence of this protection copying of entire rows in the '*System Data'* and '*Girth Weld Data*' tabs is prevented. In general, copying the contents of non-colored cells is possible. If you attempt to copy/delete/or modify a protected cell you will receive a warning message (Figure A-1) preventing any action. Selecting "OK" in the Warning dialog will return you to the spreadsheet with no changes made.

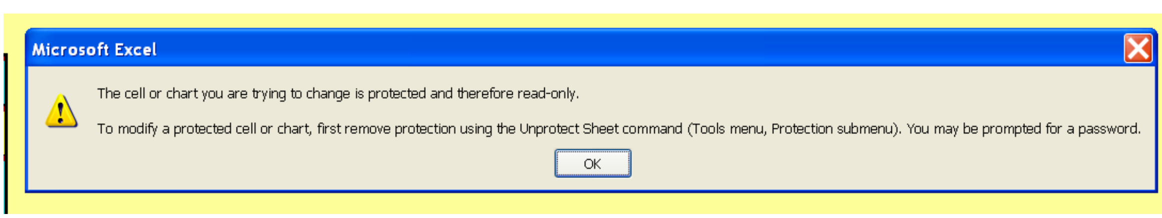


Figure A-1. Warning message issued when attempting to copy, delete, or modify a protected cell. Selecting 'OK' will return you to the spreadsheet with no changes.

There is no on-line Help file for the spreadsheet. Instead, help for each input cell is provided through comment boxes that appear when your pointing device is positioned over the cell or column heading. A cell that contains a help dialog can be identified through the presence of an indicator flag in the upper right-hand corner of the cell (see Figure A-2a). An example of a comment box used to provide guidance is shown in Figure A-2b.

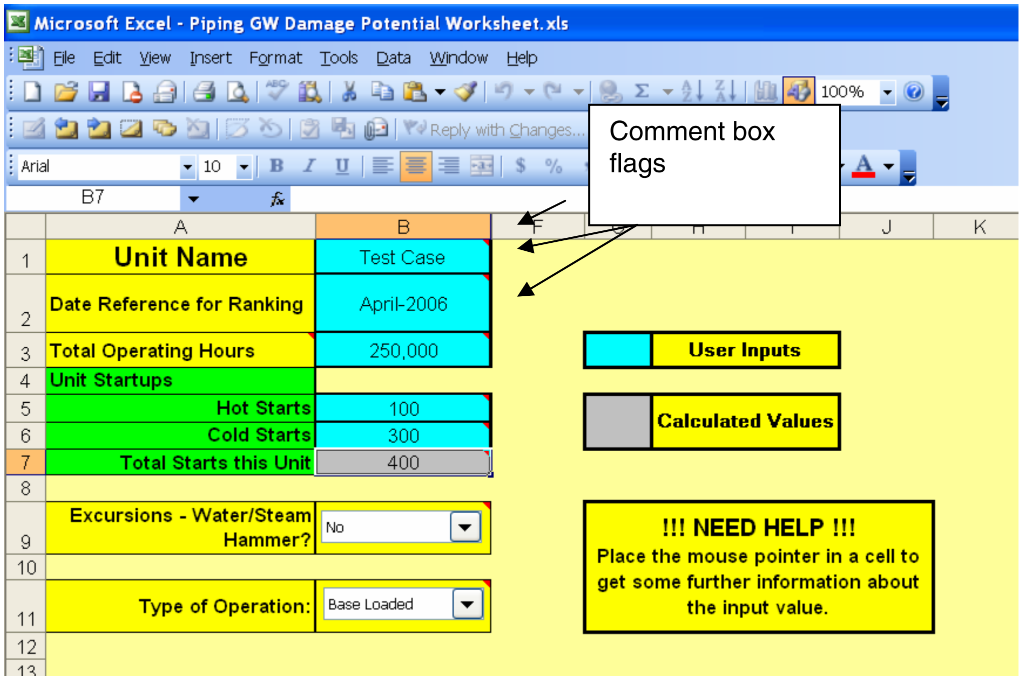


Figure A-2a. Spreadsheet cells showing the comment box flags in the upper right-hand corner of several cells.

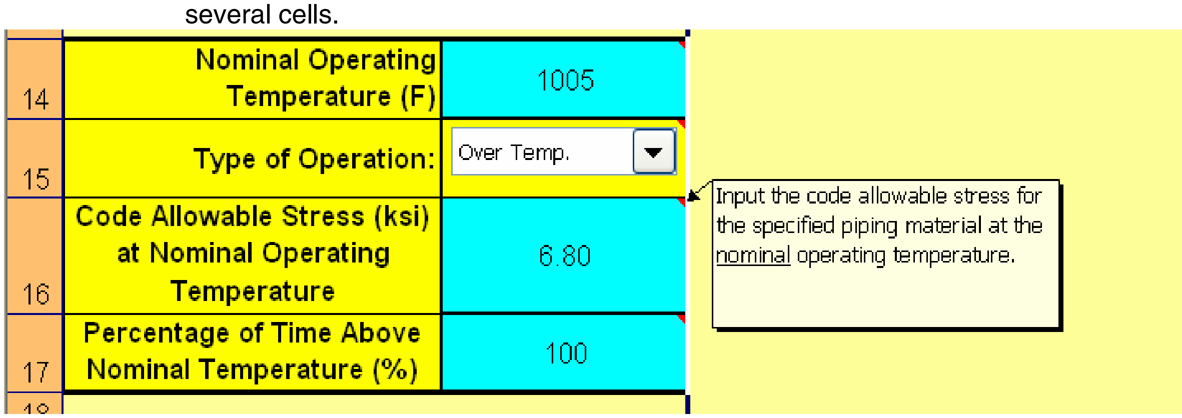


Figure A-2b. Comment dialog box that will appear when setting your pointing device over a cell with a comment flag.

In some instances when first opening a spreadsheet the comment box indicators may not be visible. If this happens, the user will need to turn-on the indicators. To accomplish this from the Excel top menu bar select Tools and from the drop-down menu Options... On the View tab under Comments select the button for "Comments Indicator Only" and select OK. The comments indicators should now be visible.

A.3.3 Spreadsheet Layout

The spreadsheet consists of 5 tabs; two for data entry and three for results presentation. The data entry tabs are labeled "*System Data*" and "*Girth Weld Data*" which indicate the nature of the data to be entered on each tab. The results presentations tabs are entitled: '*Ranking Summary*', '*Damage Plotted by Weld ID*', and '*Damage Plotted by Value*'. Descriptions of each tab are provided in the following sections.

A.3.3.1 "System Data" Tab

The *System Data* tab contains system-related information required for the damage potential assessment. By default the data on this tab applies equally to each weld listed on the *Girth Weld Data* tab. A view of the tab is provided in Figure A-3. Input cells are color coded to minimize confusion as to where user-provided data is necessary. For non-numeric inputs where a prescribed response is required, drop-down selection lists are provided. Such lists are accessed by selecting the arrow located on the right-side of the cell. Following selection you will be provided with a list of possible selections.

The information provided on this tab is used to determine the Operation Effects factor and contributes to other factors found on the *Component Data* tab. A cell by cell description of the inputs found on this tab is provided below. In general all numeric entries should be positive integers. Error traps are included where possible to detect erroneous data entry provide guidance for correct values.

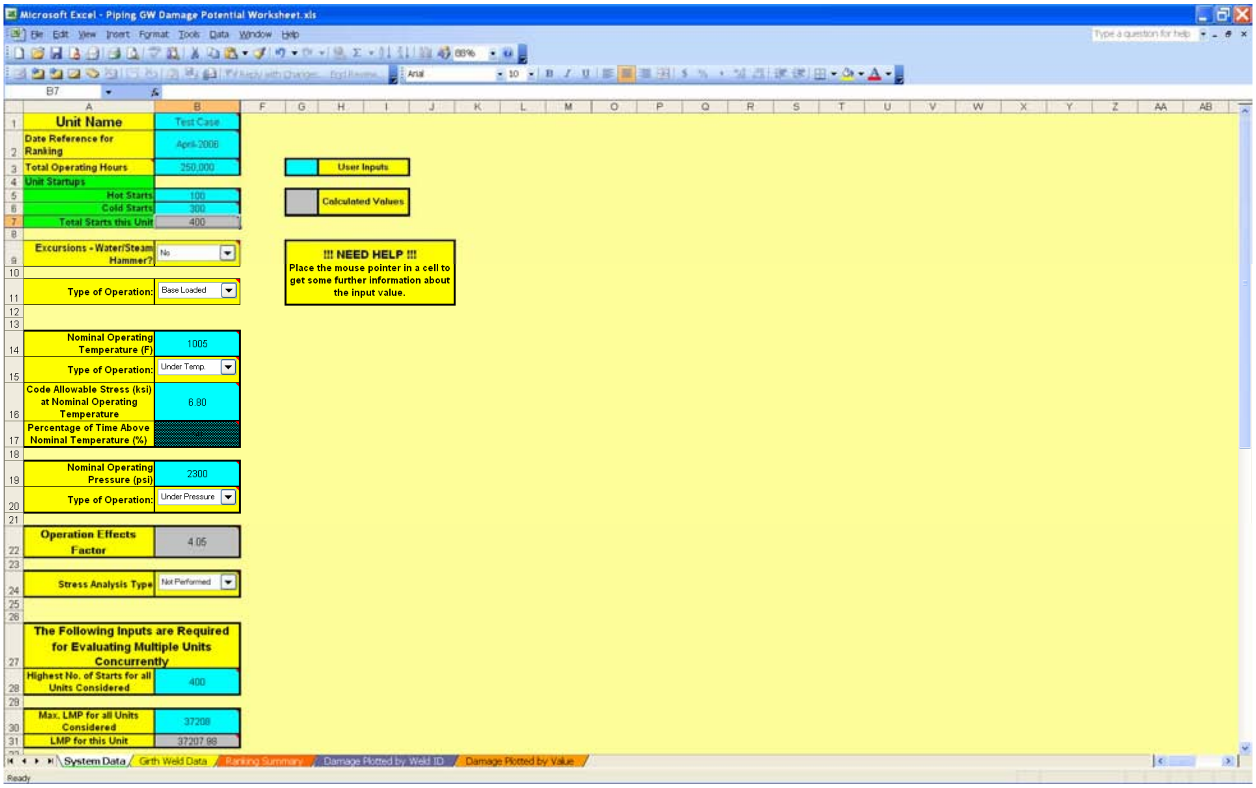


Figure A-3. The *System Data* input tab.

Cell B1, Unit Name – An alpha-numeric title for the weld group. What is entered here appears in the title bar of the Girth Weld Data tab and in the titles of the bar charts appearing in the results tabs.

Cell B2, Date Reference for Ranking – Enter the date that corresponds to the data that will be entered on the Girth Weld Data tab. This date is not used specifically in performing the ranking but is provided as a means of record keeping. Note that it is possible to track a weld group through time, monitoring damage potential as a function of elapsed time, inspection, and service history using multiple spreadsheet files.

Cell B3, Total Operating Hours – The total accumulated operating time (hours) for this unit. This entry is important for cross-system evaluations since exposure time is directly related to the potential for damage development.

Cells B5 and B6, Starts –The number of cold and hot starts the unit has experienced since the start of operation. Cold starts provide more damage potential than hot starts in the ratio of 8-to 5.

Cell B7, Total Starts – This cell is the sum of cold and hot starts entered in cells B5 and B6. It is protected and automatically calculated by the spreadsheet. The quotient of this cell and B28 determine a scale factor for the relative effect of unit starts.

Cell B9, Excursions – Select 'Yes' or 'No' from the drop-down to indicate whether or not the unit experiences water/steam hammer events. Clearly, this is a subjective judgement in regards to frequency and severity.

Cell B11, Type of Operation – From the drop-down list select the type of operation for the unit. Load following units will have a higher damage potential than base-loaded units.

Cell B14, Nominal Operation Temperature – The nominal steam temperature for the system from which the welds are being ranked, in degrees F. This value is used in combination with the material designations specified for each weld on the Girth Weld Data tab to determine the potential for creep damage development.

Cell B15, Type of Operation – From the drop-down list select whether the unit "typically" runs at normal temperature, over-temperature, or under-temperature. This judgment should be made based on average operating characteristics. Unit operation is always complex and dynamic and the intent here is not the quantitatively dissect the unit, but to compare its operation to that of other units.

Cell B16, Code Allowable Stress – Enter the applicable allowable stress for the specified system material at the nominal temperature entered in Cell B14. This value is used to determine the Stress factor for each weld and normalize the result for cross-system comparisons.

Cell B17, Percentage of Time Above Nominal Temperature – Enter the value of the percentage of operating time spent above the temperature entered in Cell B14. For Example, 20.5% would be entered as "20.5". This cell will be grayed-out and have no effect if under-temperature is selected in Cell B15.

Cell B19, Nominal Operating Pressure – The nominal operating pressure of the system in psi.

Cell B20, Type of Operation – From the drop-down list indicate the type of pressure operation for the unit. Under pressure and overpressure selections refer to the nominal operating pressure entered in Cell B19.

Cell B22, Operation Effects Factor – This is a protected cell that is calculated by the spreadsheet. The value shown represents the weighted contribution of unit operation to the potential for damage development in each system weld. The maximum value that can be calculated is 8.50.

Cell B24, Stress Analysis Type – From the drop-down list select the type of quantitative stress analysis that has been performed for the system. The selection chosen here effects the information requested on the Girth Weld Data tab under Stresses.

Cell B28, Starts – Entries in this cell are used to normalize the effects of the number of starts on damage potential between different units. The value entered here should be the highest number of starts experienced by any unit for which the welds are being ranked. If you are only ranking welds in one unit the value in this cell should equal that of Cell B7.

Cell B30, Maximum LMP - Entries in this cell are used to normalize the effects of the creep exposure on damage potential between different units. The value entered here should be the highest LMP of the units for which the welds are being ranked. If you are only ranking welds in one unit the value in this cell should equal that of Cell B31.

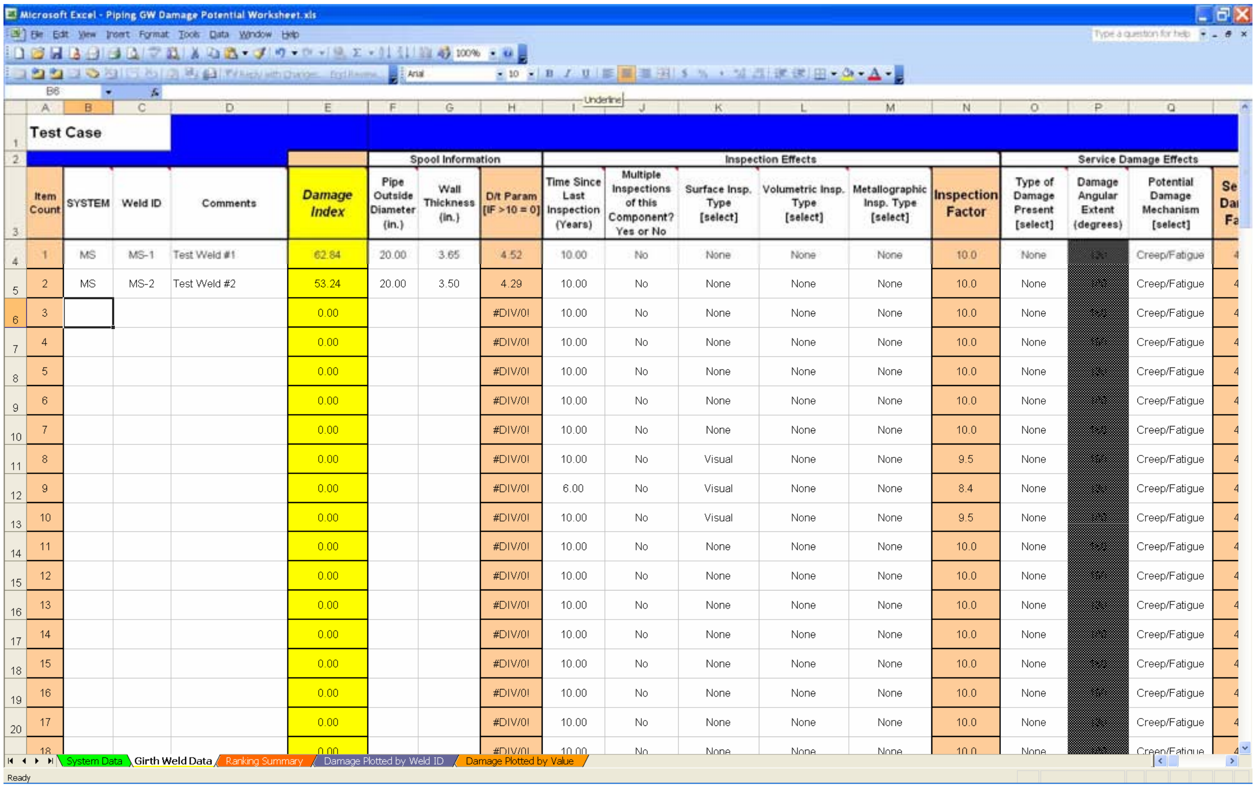
Cell B31, Larson-Miller Parameter (LMP) - This is a protected cell that is calculated by the spreadsheet. The LMP value for the unit is determined using Equation A-11

$$LMP = [Log_{10}(OperatingHours) + 20] \times OP\_Temp \qquad \text{Eq. A-1}$$

for OP_Temp in degrees Rankine.

*A.3.3.2 "***Girth Weld Data***" Tab*

The Girth Weld Data tab is where the bulk of information is input. This tab is laid out in tabular form with each row referencing one weld. Due to the amount of information requested for each weld the entire sheet cannot be viewed (at reasonable magnification) on a typical computer screen at one time. Therefore, the user should remember to scroll-right to ensure that all data columns have been reviewed for each weld. Figure A-4 shows a view of the Girth Weld Data tab.



Item Count	SYSTEM	Weld ID	Comments	Damage Index	Pipe Outside Diameter (in.)	Wall Thickness (in.)	D/t Param [IF >10 = 0]	Time Since Last Inspection (Years)	Multiple Inspections of this Component? Yes or No	Surface Insp. Type [select]	Volumetric Insp. Type [select]	Metallographic Insp. Type [select]	Inspection Factor	Type of Damage Present [select]	Damage Angular Extent (degrees)	Potential Damage Mechanism [select]	Se Da Fa
					Spool Information			Inspection Effects						Service Damage Effects			
1	MS	MS-1	Test Weld #1	62.84	20.00	3.65	4.52	10.00	No	None	None	None	10.0	None	[illegible]	Creep/Fatigue	4
2	MS	MS-2	Test Weld #2	53.24	20.00	3.50	4.29	10.00	No	None	None	None	10.0	None	[illegible]	Creep/Fatigue	4
3				0.00			#DIV/0!	10.00	No	None	None	None	10.0	None	[illegible]	Creep/Fatigue	4
4				0.00			#DIV/0!	10.00	No	None	None	None	10.0	None	[illegible]	Creep/Fatigue	4
5				0.00			#DIV/0!	10.00	No	None	None	None	10.0	None	[illegible]	Creep/Fatigue	4
6				0.00			#DIV/0!	10.00	No	None	None	None	10.0	None	[illegible]	Creep/Fatigue	4
7				0.00			#DIV/0!	10.00	No	None	None	None	10.0	None	[illegible]	Creep/Fatigue	4
8				0.00			#DIV/0!	10.00	No	Visual	None	None	9.5	None	[illegible]	Creep/Fatigue	4
9				0.00			#DIV/0!	6.00	No	Visual	None	None	8.4	None	[illegible]	Creep/Fatigue	4
10				0.00			#DIV/0!	10.00	No	Visual	None	None	9.5	None	[illegible]	Creep/Fatigue	4
11				0.00			#DIV/0!	10.00	No	None	None	None	10.0	None	[illegible]	Creep/Fatigue	4
12				0.00			#DIV/0!	10.00	No	None	None	None	10.0	None	[illegible]	Creep/Fatigue	4
13				0.00			#DIV/0!	10.00	No	None	None	None	10.0	None	[illegible]	Creep/Fatigue	4
14				0.00			#DIV/0!	10.00	No	None	None	None	10.0	None	[illegible]	Creep/Fatigue	4
15				0.00			#DIV/0!	10.00	No	None	None	None	10.0	None	[illegible]	Creep/Fatigue	4
16				0.00			#DIV/0!	10.00	No	None	None	None	10.0	None	[illegible]	Creep/Fatigue	4
17				0.00			#DIV/0!	10.00	No	None	None	None	10.0	None	[illegible]	Creep/Fatigue	4
18				0.00			#DIV/0!	10.00	No	None	None	None	10.0	None	[illegible]	Creep/Fatigue	4

Figure A-4. Portion of the *Girth Weld Data* tab showing columnar structure. Colored cells are protected; white cells are for input data.

The columnar structure of the table tracks the categories identified in Section A.2 and Table A-1. As on the System Data tab, help on the input required in each column can be found in comment dialog boxes that appear when your pointing device is positioned over the column heading cell. Weld identifications are input on the left side of the table in columns A through D. Inputs in these cells can be alpha/numeric and are used for tracking purposes only. Column D entries should be unique for each weld to facilitate identification on the summary plots.

The Girth Weld Data tab is sized to hold up to 100 welds. That limitation is imposed due limits on results presentation. The damage index for each weld displayed in Column E. This is the value that is used to rank the damage potential for each weld and is affected by entries in each of the columns to the right.

As you proceed across the table, inputting information for a specific weld the Damage Index will change, as well as those cells colored tan. The tan cells represent the unweighted contributions of each category. Selected cells on this tab are protected to prevent alteration of the damage index calculation. As a result of the protection, copying of entire rows of data are not possible. However, copying of non-colored cells is allowed and can be used to facilitate populating of the cell inputs for each weld. A description of the entries in each column is presented below.

Column A, Item Count – This is a protected cell and represents a counter for the number of welds being considered.

Column B, System – This is a cell for weld identification. Any entry is allowed and does not enter into the Damage Index calculation.

Column C, Weld ID – This should be a unique alpha-numeric identifier for each weld. This entry is used as a label on the ordered results bar charts provided in the Results tabs. The entry does not enter into the Damage Index calculation.

Column D, Comments – Space for any other information regarding the weld. This entry does not enter into the Damage Index calculation.

Column E, Damage Index – This is a protected cell, calculated by the spreadsheet and is the value used to rank the damage potential for each weld. It is the combination of the category factors (tan-colored cells to the right) multiplied by their respective weight factors.

Column F, Pipe Outside Diameter – Enter the pipe outside diameter in inches. This value in combination with the wall thickness specified in Column G is used to determine the D/t ratio for the weld which affects the potential for Type IV cracking. This cell value is also used as an indicator flag for the spreadsheet. A zero entry for pipe diameter will automatically result in a Damage Index of 0.0, regardless of other data entered. This allows easy removal and re-insertion of a weld or welds from the ranking evaluation without having to re-enter data.

Column G, Wall Thickness – Enter the wall thickness of the pipe at the weld location. If you know it put in the actual wall thickness at the weld. If you don't, enter the specified minimum wall for the pipe from design calculations. This value in combination with the outside diameter specified in Column F is used to determine the D/t ratio for the weld which affects the potential for Type IV cracking.

Column H, D/t Parameter – This is a protected cell, calculated by the spreadsheet and is the ratio of the weld outside diameter to the wall thickness. Industry experience to date has shown that welds with D/t ratios < 10 have a potential for Type IV cracking, therefore in this methodology the D/t parameter increases as D/t ratios become smaller.

Column I, Time Since Last Inspection – Enter a real number from 0.0 to 10.0 that is the time (in years) since the last inspection of the weld. The damage index calculation incorporates the benefit of performing inspections on welds by weighting the time since the last inspection over a 10-year maximum period. The 10-year period was agreed to by the advisory committee as representative of the length of time over which uncertainties regarding unit operation, stresses, and time-dependent material property effects nullify the inspection results where no service damage was noted. The assumption made herein is that the inspections were performed ‘properly’ and would have found damage if it were present.

Column J, Multiple Inspections of This Component – Indicate Yes or No from the drop-down menu if multiple inspections of this weld have been performed over the last 10-year period. This information is included to account for the benefit of more frequent inspections performed on some welds over others.

Column K, Surface Inspection Type – Select from the drop-down menu the highest level of surface inspection last performed on this weld. The applicable methods are “visual, dry-powder or PT, or wet fluorescent MT listed in their order of sophistication. Entries in this column are used in the Damage Index calculation only if the value entered in Column I is < 10.

Column L, Volumetric Inspection Type - Select from the drop-down menu the highest level of volumetric inspection last performed on this weld. The applicable methods are “manual UT, automated UT such as TOFD, and Linear phased array or similar high-resolution scan, listed in their order of sophistication. Entries in this column are used in the Damage Index calculation only if the value entered in Column I is < 10.

Column M, Metallographic Inspection Type - Select from the drop-down menu the highest level of metallographic inspection last performed on this weld. The applicable methods are “replication” or “material sampling’, listed in the order of sophistication. Entries in this column are used in the Damage Index calculation only if the value entered in Column I is < 10.

Column N, Inspection Factor – This is a protected cell, calculated by the spreadsheet based on the inputs provided in Columns I, J, K, L, and M. It represents the unweighted contribution of Inspection to the total damage index of a weld. The maximum value is 10.0.

Column O, Type of Damage Present – Indicate the type of damage detected during the last inspection from the drop-down menu. The allowed entries are 'none', 'micro' and 'macro'. If macro is selected all input cells for the weld will be grayed out and the Damage Index (Column E) will be set at 100. The advisory committee believes that welds known to contain macro, service-related defects should be dispositioned using more quantitative methods that this ranking procedure and therefore, peg the Damage Index value to ensure that such welds are always ranked highest.

Column P, Damage Angular Extent – This column is only active if the entry in Column O is 'micro'. For that condition, enter the angular extent of damage in the weld. A typical problem with this entry is that in many instances replication will reveal the presence of creep damage. However, replication is performed over a very small angular extent. Recall that maintaining consistency is paramount in the process, therefore, it is recommended that you decide on a default angular extent (e.g 30-degrees) for replica-detected damage.

Column Q, Potential Damage Mechanism – Select from the drop-down menu the most likely damage mechanism for the service damage noted during an inspection. The damage potential increases for Creep/Fatigue (combined) and Unknown, over selection of just Creep or Fatigue.

Column R, Service Damage Factor - This is a protected cell, calculated by the spreadsheet based on the inputs provided in Columns O, P, and Q. It represents the unweighted contribution of Service Damage to the total damage index of a weld. The maximum value is 10.0.

Column S, Repairs Made – In this column you indicate if any repairs have been made to this weld in the past. Valid entries are provided in the drop-down menu.

Column T, Years Since Repair – Unless the entry in Column S is "Full Repair" this column will be grayed out. If a full repair has been made, indicate the number of years from the repair date to the time corresponding to the data being entered on the spreadsheet (Cell B2 from the System Data tab).

Column U, Repair Factor - This is a protected cell, calculated by the spreadsheet based on the inputs provided in Column S. It represents the unweighted contribution of Repair to the total damage index of a weld. The maximum value is 10.0.

Column V, Support Maintenance – From the drop-down list select the entry that best describes the level of maintenance performed on the piping system supports. The available selections are: Not checked, Inspection performed, Functionality Checked, Load and Stroke measurements. These are listed in the order of highest contribution to damage potential to lowest.

Column W, Support Maintenance Factor - This is a protected cell, calculated by the spreadsheet based on the input provided in Column V. It represents the unweighted contribution of support maintenance to the total damage index of a weld. The maximum value is 10.0.

Column X, Stress Calculated by Analysis – In this column the stress acting at the weld, as determined from quantitative analysis, is specified. This column may be grayed out depending on the entry in Cell B24 of the System Data tab. If an elastic or creep redistribution stress analysis has been performed for the piping system, the column will be open and you should enter the stress determined at the weld location (in ksi.). It is suggested that the entered stress include the combination of primary and secondary components. The entered value will be normalized by the code allowable stress for the specified piping material (Cell B16 of the System Data tab).

Column Y, Relative Stress Rank – If you performed a quantitative analysis of the piping system (Cell B24 of the System Data tab is elastic or creep redistributed) then this column will be grayed out. If no quantitative analysis has been performed Column X will be grayed and this column will be open for data input. Specifically, in the absence of a quantitative system stress analysis, the perceived stresses (primary + secondary) at the welds in the system need to ranked on a scale from 0-to-10, with 0 being the lowest stressed and 10 being the highest stressed. Entry must be a real number between 0 and 10. The implication of using this relative ranking method (instead of quantitative analysis results) is that it prevents performing cross-system evaluations, since there is no basis on which to stress rank a weld from one system against the weld of another system. It is clear that stress plays a major role in the development of damage. Therefore it is highly recommended that quantitative stress analysis of high-energy piping systems be performed in support of inspection activities. A brief guide to performing piping stress analysis is provided in Appendix A.

Column Z, Stress Factor - This is a protected cell, calculated by the spreadsheet based on the input provided in Column X or Y, Cells B16 and B24 of the System Data tab . It represents the unweighted contribution of stress to the total damage index of a weld. The maximum value is 10.0.

Column AA, Component Type – From the drop-down list select the types of components the weld is joining. Allowed entries are: Pipe-to-Pipe, Pipe-to-Tee, Pipe-to-Wye, Saddle Weld, Bend or Elbow with thickness transition, and Pipe-to-Valve.

Column AB, Design/Fabrication Factor - This is a protected cell, calculated by the spreadsheet based on the input provided in Column AA. It represents the unweighted contribution of Design to the total damage index of a weld. The maximum value is 10.0.

Column AC, Material Grade – From the drop-down list select the base material for the piping system. Allowed entries are: P11, P22, P91, and ½CrMoV.

Column AD, Component Form – Select from the drop-down list the form of the component where the weld is located. Allowable entries are: Cast, Forged, or Austenitic.

Column AE, Welding Process – From the drop-down list select the weld process used to make the weld. Allowed entries are: Shop/Submerged Arc, Shop/Other, Shop/Unknown, and Field. The entry in this column is used to indicate whether Type IV cracking is a potential contributor for this weld. To date Type IV cracking has been observed only in Shop welds.

Column AF, Neighboring Component – From the drop-down list select either Pipe or Thk Section. This entry effects the damage potential from a design viewpoint. Experience has shown a higher potential for damage at a thickness transition in comparison to a pipe-to-pipe joint.

Column AG, Weld Profile – From the drop-down list identify the type of weld geometry used. Allowed entries are: V, J, and Narrow groove. On hot reheat systems the typical weld profile is V, on main steam and other heavy-walled systems J and Narrow groove are frequently used.

Column AH, Material Factor - This is a protected cell, calculated by the spreadsheet based on the inputs provided in Columns AD, AE, AF, AG, and Cell B14 from the System Data tab. It represents the unweighted contribution of Materials to the total damage index of a weld. The maximum value is 10.0.

Column AI, Weld Counterbore – Enter a real number from 0 to 10 inclusive that represents the degree of counterbore present in the weld. Zero is no counterbore and 10 is a severe one. Remember since this is a subjective entry, be consistent in assigning values.

Column AJ, Weld Reinforcement – As with Column AI enter a real number from 0 to 10 inclusive that represents the degree of reinforcement present at the weld. Zero is no reinforcement and 10 is a lot of it. Remember since this is a subjective entry, be consistent in assigning values. The more reinforcement present the higher the damage index will be.

Column AK, Backing Ring – Identify whether or not a backing ring is present at the weld. If unsure, it is recommended that you select Yes from the drop-down list. The presence of a backing ring increases the potential for damage and increases the damage index.

Column AL, Material Transitions – From the drop-down list select the type of material transition present (if any). Allowed selections are: None, New-to-Old, Alloy 1 to Alloy 2, P91 to Other, CrMoV to Other, Austenitic to Other. Most welds will be None, if a weld has been repaired select New-to-Old. Dis-similar metal welds have the highest potential for damage.

Column AM, Weld Factor - This is a protected cell, calculated by the spreadsheet based on the inputs provided in Columns AI, AJ, AK, AL, and AE. It represents the unweighted contribution of Weld factors to the total damage index of a weld. The maximum value is 10.0.

A.3.3.3 "Ranking Summary" Tab

The Ranking Summary tab provides two tabular listings of the damage index for the input group of welds. The first list is ordered according to the input identification (Column C from the Girth Weld Data tab) with the second list ordered by damage index value(Column E from the Girth Weld Data tab, highest to lowest). These lists are created by an embedded macro that must be activated by the user. This is performed by selecting the "List and Sort Damage Indices" button on the tab sheet, as shown in Figure A-5.

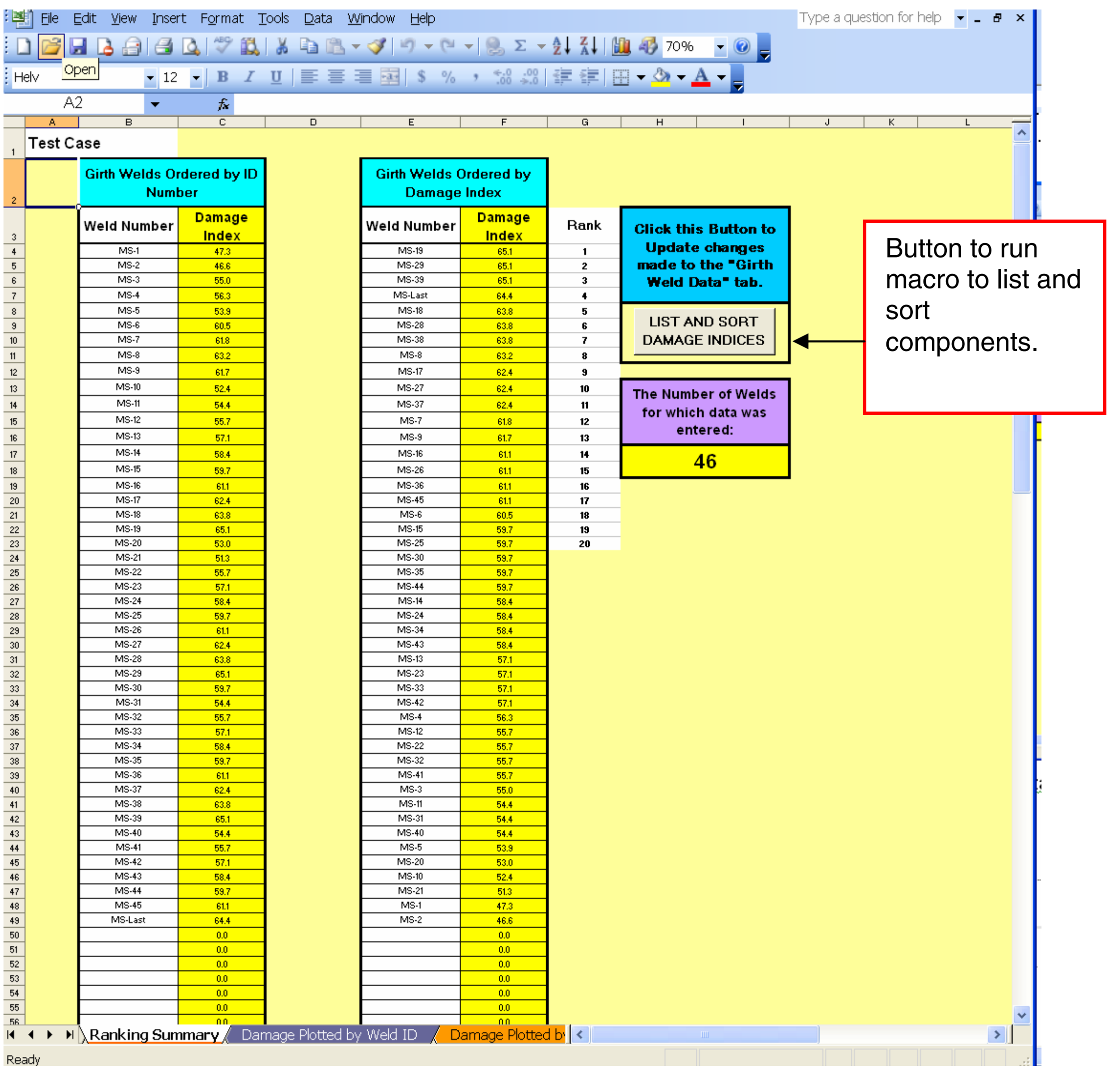


Figure A-5. *Ranking Summary* tab indicating active button that executes a macro that sorts the weld damage index results and creates the results plots.

Note also that the number of welds included in the ranking is listed. Recall that you can remove a weld from consideration by entering an outside diameter of 0.0. This allows you to keep all other information you have already entered.

A.3.3.4 Results Plotting

The remaining two tabs of the spreadsheet provide bar graphs of Damage Index plotted versus weld input order (as on the *Girth Weld Data* tab) and ordered by the index value. The plots are selectable and can be copied to other documents for reporting purposes. Sample plots provided by the spreadsheet are shown in Figures A-6 and A-7.

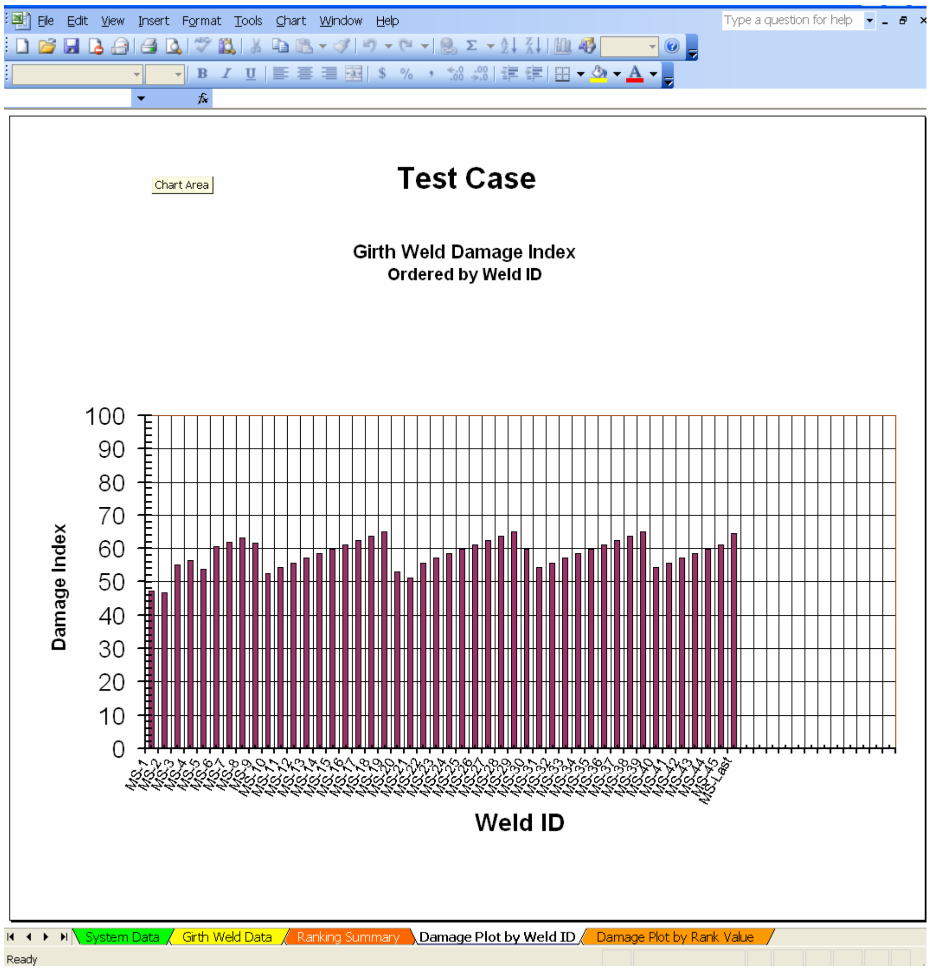


Figure A-6. Results summary bar chart ordered by Weld ID.

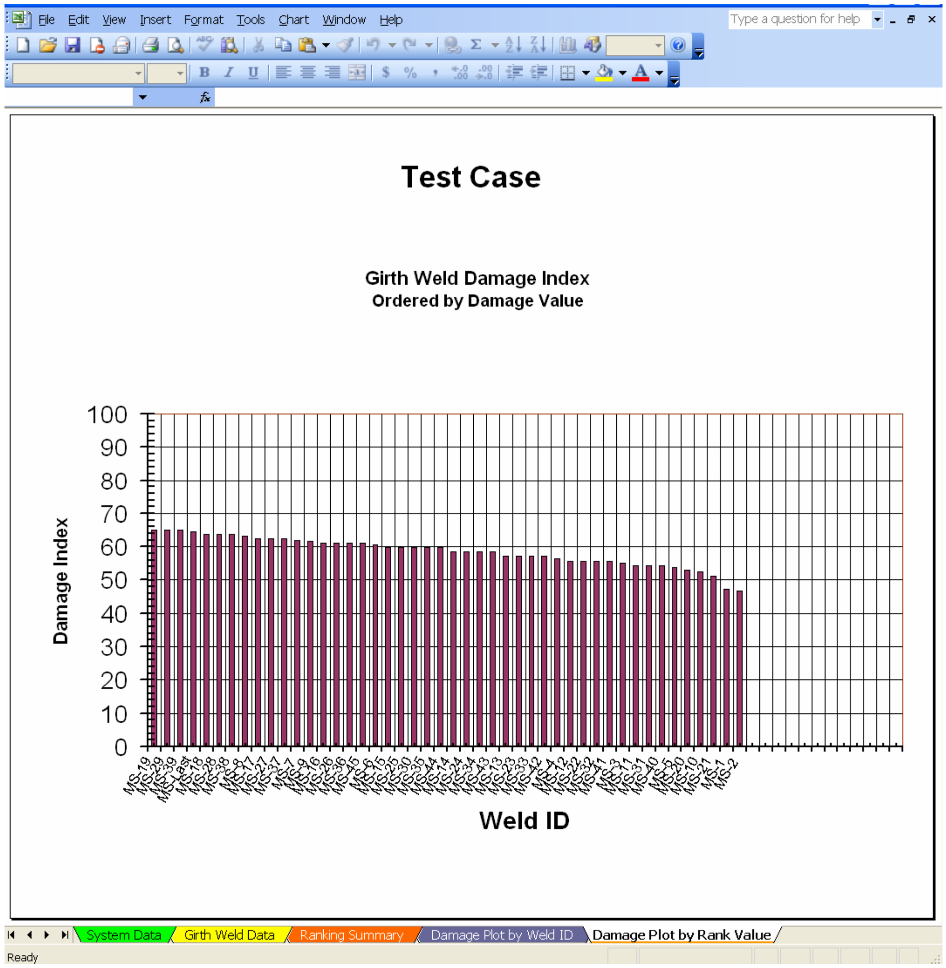


Figure A-7. Results summary bar chart ordered by Damage Index value.

Section 4
References

1. Refining the Probability of Failure for the Risk Management Process" EPRI Project 1010494, Final Report, February 2007.

B

APPENDIX B: PIPING STRESS ANALYSIS METHODOLOGY

Piping Stress Analysis Methodology,
A Brief Review

Application of the weld ranking methodology developed under EPRI Project 1010494 “Refining the Probability of Failure for the Risk Management Process” has identified weld operating stress to be a key element. The flexibility of the ranking methodology allows users to provide quantitative or relative inputs concerning weld stresses. The purpose of this document is to provide the user with guidelines for:

- collection of necessary system information,
- conducting a quantitative stress analysis, and
- methods to verify an analysis

Why Quantitative Stress Analysis?

For application in the PoF spreadsheet, one of the entries on the *System* Data tab indicates the type of stress analysis available for the system. Based on that response operating stresses can be specified quantitatively at each weld (if known) or on a relative basis (i.e. weld ‘A’ higher than ‘B’, higher than ‘C’, etc). Relative stress rankings are performed by assigning a rating value to the stress state at a weld on a scale of 0 to 10. Since the ranking spreadsheet does not perform quantitative lifing it is only necessary to identify the relative difference in stress from weld to weld, e.g. 0 (a low stress) versus 10 (the highest stress). In many instances relative stress rankings can be performed with few errors, by engineers with experience in HEP systems. However, the creep deformation discussed earlier can introduce significant uncertainty for welds located in the middle of the pack. This inaccuracy for welds other than the typical heavy hitters (terminal points, wyes, etc.) can be minimized by performing a quantitative stress analysis. In addition, the performance of quantitative stress analysis allows the ranking methodology to be applied between welds of different systems.

Collecting the Data

The key aspect of any structural analysis is the ability of the analytical model(s) to mimic the response of the physical equipment under operating loads. In the case of high-energy piping, this requires the accumulation of geometric and materials data concerning the spool pieces used to construct the system, support sizes and locations. Typically this information is obtained from drawings provided by the AE. It is important to obtain as-constructed drawings since these will most closely describe the geometry and constraint conditions present at the start of operation. In the absence of such drawings, surveys of the system are required to establish the global geometry.

To verify the correctness of the as-constructed geometric information and assist in identifying the operability of supports, walkdowns of the system being evaluated are strongly recommended. Since one of the primary damage mechanisms is creep and system stresses are highest during operation, it is essential that the analyst know the conditions of the system while in operation. This is accomplished by performing a hot walkdown of the system during which time observations are made and recorded for inclusion in the system analytical model. Through and consistent examinations both the hot and cold conditions valuable information regarding the overall condition and performance of the piping system is obtained.

System walkdowns should be performed on a periodic basis (twice per year minimum) and the results compared with previous data to establish trends. Trending of support readings and observations will in many instances provide a first indication of developing problems within a system. When possible, walkdowns should be performed by the same personnel and according to a set procedure that identifies specifics concerning data recording and interpretation of support scales and direction of movement. A list of information that should be collected during a walkdown is provided below:

- Verify the type of support present agrees with the design specifications.
- Verify that the support locks are <u>not</u> engaged.
- Record the scale reading of the support indicator (photograph if possible). Be sure to apply a consistent interpretation of scale readings.
- Visually examine the support hardware and document any missing/damaged components.
- Examine the structure-side and pipe-side attachments for damage.
- View the piping insulation exterior and document locations of interference with surrounding structure and/or other service piping.
- View along pipe horizontal and vertical runs to assess the presence of sags or other unanticipated deformations. Check horizontal runs for correct slope to drains.
- For hydraulic snubbers check that the reservoir contains fluid. Record the cylinder extension for comparison with alternate (hot/cold) condition reading.

- For hot walkdowns, record the system temperature and pressure at the beginning and end of the walkdown. Cold walkdowns should be performed when piping metal temperatures are below $150^{o}F$ ($65.5^{o}C$).

Data from alternate condition walkdowns should be compared with the currently collected readings to verify the supports are functioning (free to move) and their direction of movement in going from cold to hot conditions.

Quantitative Stress Analysis

Quantitative analysis of piping systems today is performed utilizing commercially available computer codes. There are many codes used for piping design, i.e. Caesar, K-Pipe, and AutoPipe to name a few. The initial design of high-energy piping systems, as performed by the architect engineers, may have been performed using a computer code or via hand calculations, however in either case the analysis assumed the piping material behaved elastically. The system geometry, supports and materials were then sized and selected to ensure that the maximum stresses and deflections fell within established code limits. Such analyses also determined the initial cold spring and hanger loads for the system.

After extended service at elevated temperatures, the elastic stresses in main steam and hot reheat lines are redistributed by creep relaxation. This is an in-elastic, permanent deformation of the component piping that results in reduced stresses at initially high-stress locations and increases in stress at others. *These redistributed stresses are most representative of the long-term stress state of the system, and therefore, it is more accurate to utilize inelastic analysis results when evaluating a high-energy piping system*.

Piping analyses require hanger specifications and hanger, header, and turbine/intercept valve settings and displacements from hot and cold walk-downs. The <u>range</u> of system deflections and moments should be nearly elastic and conform to the initial design calculations. However, because of redistribution by creep, part of the initial cold spring will be lost, and the <u>mean values</u> of deflections and moments will differ from the initial design conditions. The design positions of the system headers, hangers, and turbine/intercept valve connections in the hot and cold conditions should be provided. Significant deviations between measured and design positions indicates excessive stress, malfunctioning hangers and potentially the need for modifications to reduce the rate of accumulation of creep damage. For evaluation of high energy piping systems EPRI recommends a series of analyses be performed to verify the basic design of the system and assess the elastic and creep redistributed stresses.

The first analysis evaluates the *balance between system dead weight (piping, insulation, valves, etc.) and the support loads*. The primary function of the piping supports is to carry the weight of the system while providing minimal resistance to pipe movement from thermal expansion. For a system that is perfectly balanced, this analysis would predict no displacement at hanger locations. When significant displacements are predicted, it indicates either an error in the specified hanger loads and/or component weights. Since no system is perfectly balanced it is not uncommon that several dead weight analyses be performed to adjust hanger loads or component thickness to minimize predicted displacements. The final predicted displacements are used to adjust the hanger travel gaps so that the simulated support travel ranges determined from system walkdown data are maintained.

The second analysis performed addresses the *effects of system cold springing*. Most high-energy piping systems are erected with either 50 or 100 percent cold spring. Cold spring is the shortening of the as-manufactured pipe runs equal to the anticipated thermal expansion at operating temperature. Through this design shortening, the system is 'pre-stressed' in the cold condition and expands during operation to the stress-neutral position.

Analytically, cold spring can be simulated by specification of a gap in the line at specified final field weld location(s) which is then pulled together through application of displacement constraint equations, or by imposition of displacements equal to the cold spring at the piping terminal points. The displacements predicted at hanger locations are used to adjust the travel gap sizes for each hanger during the thermal displacement analyses.

The third analysis performed *simulates the effect of system dead weight, cold spring (if present), and system temperature/pressure operation*. This analysis is performed assuming elastic material response and is used to compare system stresses versus code standards. Support travel gaps are specified based on the system walkdown data and adjusted by the results of the dead weight and cold spring results.

The final analysis performed is the *creep redistribution analysis*. In this analysis the same load and travel gap data used in the elastic analysis are input. Material properties data is input to simulate the time/temperature dependent strain-rate properties for the piping material(s) and an iterative solution performed simulating 50,000 hours of system operation at temperature.

Checking Your Analysis

One of the most important aspects of being a good analyst is the ability to be objective in reviewing your work. This is especially important in piping analysis where a significant amount of detailed information has been reviewed to construct the piping geometry, describe materials properties, simulate supports, and apply operating loads. Listed below are several checks that are relatively easy to perform and should provide valuable insight into how well your model simulates the real system.

System Displacement Evaluation

To assess the reliability of the stress analyses, comparisons of predicted displacements with those measured during field inspections should be performed. Due to the number of uncertainties associated with data used to perform piping assessments, 100 percent agreement is unlikely. Consequently, engineering judgment in association with parametric evaluations can be used to assess the effect of data uncertainties on predicted results. Specifically, if the measured hanger displacement at a particular location is found to be significantly different from that indicated in the original design analysis, a series of review and assessment steps can be performed to verify the correctness of the displacement and address the implication of the difference to continued system operation. The review process followed by EPRI is:

1. As an overall check, review the predicted deformed shape of the system. You should have some idea of how the piping is expected to move from cold to hot conditions. Excessive or unexpected displacements should be an indicator that something is not right and further checks should be performed.
2. At the effected support locations, quantify the magnitude of the displacement difference in conjunction with the available displacement in the support.
3. Review the displacement of neighboring supports to determine if a pattern is apparent. Starting at the location of maximum displacement work away from the support in each direction. Gradual decreases in displacement differences are indicative of errors in thermal expansion or possibly header displacements.
4. Assess the effect of header/turbine displacements and constraints imposed during the analysis. Review header supports and stiffness to determine if additional displacements and/or rotations could occur.

5. Check the forces and moments at the analysis model terminal points. These values should be within (or near) limits specified by the boiler/turbine manufacturer. Excessive values may indicate an error in the specified thermal movements and/or displacement constraints imposed at these locations.
6. If supports are predicted to exceed their specified travel ranges (bottoming or topping out) examine the reaction force due to this prediction. Excessive reaction forces are an indication that predicted system displacements are incorrect.

To track down the cause of an anomaly in the results or predict the effect of hanger malfunction on system stresses, parametric evaluations may be required. In the case of malfunctioning (bottomed out) supports, the stiffness of the support and its structural attachment may need to be included.

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Electric Power Research Institute
3420 Hillview Avenue, Palo Alto, California 94304-1338 • PO Box 10412, Palo Alto, California 94303-0813 • USA
800.313.3774 • 650.855.2121 • askepri@epri.com • www.epri.com