STRESS ENGINEERING SERVICES INC.

an employee-owned company

Evaluation of Methods of Qualifying Cranes for Offshore Arctic Service

Final Report

Prepared for:

Bureau of Safety and Environmental Enforcement (BSEE)

US Department of the Interior

BSEE Contract No.: E13PC00032

Prepared by:

Stress Engineering Services, Inc.

Houston, Texas

19 December 2014

SES Document No.: 1152237-EN-RP-01 (Rev 0)

Rev	Date	Description	Originator	Checker	Reviewer
0	19-Dec-2014	Issued for use	RAyers	KBrownlee	RLong

Evaluation of Methods of Qualifying Cranes for Offshore Arctic Service

Final Report

SES Document No.: 1152237-EN-RP-01 (Rev 0)

19 December 2014

Prepared for:

Bureau of Safety and Environmental Enforcement (BSEE)

BSEE Contract No.: E13PC00032

Prepared by: ______________________
Ray Ayers, PhD, PE
Staff Consultant (Project Manager)

Prepared by: ______________________
Elliot Brown, PhD, PE
Metallurgical and Materials Consultant

Prepared by: ______________________
J. Kirk Brownlee, PE
Sr. Staff Consultant

Reviewed by: ______________________
J. Randy Long, PE
Vice President

Stress Engineering Services, Inc.

13800 Westfair East Drive

Houston, Texas 77041-1101

Phone: 281-955-2900

Web: www.stress.com

Texas Registered Engineering Firm F-195

Limitations of This Report

This report is prepared for the sole benefit of BSEE, and the scope is limited to matters expressly covered within the text. In preparing this report, SES has relied on information provided by BSEE and, if requested by BSEE, third parties. SES may not have made an independent investigation as to the accuracy or completeness of such information unless specifically requested by BSEE or otherwise required. Any inaccuracy, omission, or change in the information or circumstances on which this report is based may affect the recommendations, findings, and conclusions expressed in this report. SES has prepared this report in accordance with the standard of care appropriate for competent professionals in the relevant discipline and the generally applicable industry standards.

List of Acronyms

AASHTO	American Association of State Highway and Transportation Officials
AISC	American Institute of Steel Construction
ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing and Materials
BAA	Broad Agency Announcement
BASM	Best available and safest methods
BPVC	ASME Boiler and Pressure Vessel Code
BSEE	Bureau of Safety and Environmental Enforcement
CE	Carbon equivalent
CVN	Charpy V-notch (toughness)
DBT	Ductile to brittle transition
FFS	Fitness for service
HSLA	High strength low alloy
K_{IC}	Fracture toughness
LAST	Lowest anticipated service temperature
LEFM	Linear elastic fracture mechanics
MODU	Mobile offshore drilling units
NDE	Nondestructive examination
Q&T	Quenched and tempered
RP	Recommended practice
SES	Stress Engineering Services, Inc. (Contractor)
TMCP	Thermomechanical control processing
UTS	Ultimate tensile strength
YS	Yield strength

Executive Summary

Background

As interest in Arctic oil and gas exploration increases, Bureau of Safety and Environmental Enforcement (BSEE) recognized the growing need to ensure that offshore cranes can withstand extreme low-temperature conditions. This focus is expected to result in additional issues when designing new equipment and likewise when evaluating existing equipment for potential use in Arctic environments.

Stress Engineering Services, Inc. (SES) was contracted by Bureau of Safety and Environmental Enforcement (BSEE) to perform an evaluation of current standards, regulations, and practices as related to the design of cranes for Arctic service conditions. Specifically, unless the design methodology (including design verification and validation) and crane materials of construction are both suitable for Arctic conditions, cranes may be sensitive to brittle fracture initiation at small imperfections, which could lead to unexpected failures.

Objectives of Study

This project was undertaken as an engineering study to provide initial guidance for the safe use of cranes in Arctic offshore oil and gas and other operations. Specific objectives are as follows:

1. Determine the applicability of current standards, regulations, and practices existing domestically and internationally both within and outside the oil and gas industry for use in determining and validating the load ratings for new cranes and for modifying the ratings (possibly de-rating) of existing cranes that will be used during offshore oil and gas activities in the Arctic.

2. If no acceptable methods are available, provide a process based on sound science and good engineering principles for determining the initial rating and derated lifting capacity of cranes to be used in the US Arctic offshore.

Project Tasks

Key tasks performed by the project team to accomplish these objectives include the following:

- Review the current industry specifications, standards, regulations, and practices for applicability as a fundamental basis for rating and de-rating the load capacity of cranes.

- Identify the load-critical components.

- Create a list of typical steel grades for manufacture of critical components. In addition, identify the likely failure modes for these components.

- Review the literature related to strength and toughness for the steels identified with particular emphasis on intrinsic fracture toughness as a function of temperature and loading rate, and correlations of intrinsic fracture toughness with CVN impact energy.

- Utilize fracture-toughness data from the literature to rationally establish a specification for load rating and de-rating of cranes used in Arctic conditions. Establish statistically valid correlations between appropriate intrinsic fracture-toughness parameters and CVN impact energy from the literature to aid in the implementation of the specification.

- Define a rational approach and illustrate this with several types of steels of different classes.

Conclusions and Recommendations

Based on the results of these tasks, the team developed the following primary conclusions and recommendations:

- Current stress-based crane-design methods (such as API 2C and others) appear generally adequate for the task. The specifications provide guidance regarding types of loadings, design factors, and material selection. However, the challenges associated with providing cranes for extreme cold service conditions generate additional problems for material selection due to the difficulty of finding materials that meet the specified CVN material requirements. The guidance provided herein proposes a method to proceed if materials cannot be found to satisfy the CVN requirements for a particular component.

- To enhance the current specifications for extreme cold applications, modifications should be considered including emphasizing the advantages of fine-grain steel for these applications and the importance of minimizing stress concentrations in the design. Inspection criteria should also be enhanced. In addition, a fracture-mechanics-based design approach should be offered as an option to provide consideration of allowable defect size and better design consideration of brittle fracture as a failure mode.

- The crane manufacturers surveyed in this project indicated that they utilize CVN impact tests to qualify materials for low-temperature service. Charpy requirements currently vary from specification to specification. However, the overall intent of providing ductile material at design service temperature is generally being met by each of the various specifications.

- To enable design and FFS evaluation of new/existing cranes for Arctic service using a fracture-mechanics approach, fracture-toughness data are required for common crane materials of construction. Generating the necessary data via typical fracture-mechanics testing will be difficult and expensive.

- K_{IC}-CVN correlations exist that appear to be suitable for converting CVN test results for typical crane steels to fracture-toughness values. In particular, this study investigated three of these correlations.

- All three correlations studied are sufficiently simple to warrant inclusion in existing design standards when Arctic conditions are anticipated. However, in order to be credible, inclusion of fracture-mechanics-based design requirements into existing design standards must be accompanied by suitable NDE acceptance criteria.

Table of Contents

List of Tables

List of Figures

1. Introduction

1.1 Problem Statement

This report was prepared by Stress Engineering Services, Inc. (SES) as a response to the Bureau of Safety and Environmental Enforcement (BSEE) under Broad Agency Announcement (BAA) No. E13PS00017 for proposed research on the Safety of Oil and Gas Operations in the US Outer Continental Shelf, and Request for Proposal No. E13PS00042. Specifically, SES was contracted to perform work addressing **BAA Topic 9: "Evaluate Methods of Qualifying Cranes for Offshore Arctic Service."**

Service conditions for lifting equipment in Arctic regions may include operation at low temperatures. Lifting equipment is typically constructed of steel. Thus, depending on the design basis, materials selection, and in-service inspection and maintenance routines, offshore cranes may be more or less susceptible to a number of degradation mechanisms including brittle fracture, corrosion, and hydrogen embrittlement. For example, if the materials of construction are not specifically selected to exhibit adequate resistance to brittle fracture initiation and/or propagation, the crane may be sensitive to brittle fracture initiation and/or propagation from small crack-like flaws. Furthermore, if such flaws are undetected during fabrication inspections or regular maintenance/inspection while in service, affected cranes may fail unexpectedly. Since cranes are typically not rated for use in Arctic conditions where the combined effects of these (and possibly other) degradation mechanisms may be realized, this study was funded by BSEE to develop a rational approach to address this issue.

1.2 Objectives and Scope of Work

This project is an engineering study to provide initial guidance for the safe use of cranes in Arctic offshore oil and gas and other operations. Specific objectives are as follows:

1. Determine the applicability of current standards, regulations, and practices which exist domestically and internationally both within and outside of the oil and gas industry for use in determining and validating the load ratings for new cranes and for modifying these ratings (possibly de-rating) existing cranes that will be used during offshore oil and gas activities in the Arctic.

2. If no acceptable methods are available, provide a process based on sound science and good engineering principles for determining the initial rating and de-rated lifting capacity of cranes to be used in the US Arctic offshore.

The tasks undertaken to achieve these stated objectives include the following:

Task 1: Plan and conduct a Kick Off Meeting with BSEE via video conference.

Task 2: Review the current industry specifications, standards, regulations, and practices for applicability as a fundamental basis for rating and de-rating the load capacity of cranes. With the assistance of Randy Long, former committee chair, the team will have access to the crane manufacturer members on the API 2C Offshore Crane Committee.

Task 3: Identify the load-critical components.

Task 4: Create a list of typical steel grades for manufacture of critical components in concert with crane manufacturers and likely operating temperature ranges in crane design via stress modeling and the experience of manufacturers and end users. In addition, identify the likely failure modes for these components.

Task 5: Review strength and toughness literature for the steels identified in Task 4 with particular emphasis on intrinsic fracture toughness as a function of temperature and loading rate and correlations of intrinsic fracture toughness with CVN impact energy.

Task 6: Utilize fracture toughness data from the literature to rationally establish a specification for load rating and de-rating of cranes used in Arctic conditions. Establish statistically valid correlations between appropriate intrinsic fracture toughness parameters and CVN impact energy from the literature to aid in the implementation of the specification.

Task 7: Define a rational approach and illustrate this with several types of steels of different classes.

Task 8: Prepare a formal report on study program results, conclusions, and recommendations, focusing on the Best Available and Safest Methods (BASM).

Task 9: Present results to BSEE via a video conference call.

All project tasks were completed as planned. This report represents the primary deliverable of the program as listed in Task 8.

2. Background and Approach

2.1 Background

Regulators, as well as the energy industry and social/environmental groups, are becoming increasingly focused on the risks associated with oil and gas exploration and production in Arctic regions. Previously, the attention of these groups has been centered on the functionality and reliability of well-known pieces of exploration and production "kit" such as drillships, wellheads, christmas trees, etc. Load-carrying equipment, such as offshore cranes, has been largely ignored.

Typically, most cranes, whether intended for onshore or offshore application, are constructed from steel. While steels exist that are suitable for use in Arctic conditions, they are not widely used in crane construction. Thus, depending on the design basis and materials selection, new and existing cranes may or may not be suitable for application in Arctic conditions. Specifically, unless the design methodology (including design verification and validation) and crane materials of construction are both suitable for Arctic conditions, cranes may be sensitive to brittle-fracture initiation at small imperfections, which could lead to unexpected failures.

As interest in the Arctic exploration increases, BSEE has recognized a growing need to ensure that offshore cranes can withstand extreme low-temperature conditions. This focus is expected to result in additional considerations when designing new equipment and likewise when evaluating existing equipment for potential use in Arctic environments.

As further described in Section 1.2, the purpose of this study is to determine the applicability of current standards, regulations, and practices existing domestically and internationally both within and outside the oil and gas industry for use in validating load ratings for newly built cranes and for de-rating existing cranes used during offshore oil and gas activities in the Arctic. If no acceptable methods are available, the next goal will be to provide a process for determining the initial rating and de-rated lifting capacity of a crane used in the US Arctic offshore.

Integrity assessment of structures that contain planar flaws (either real or postulated) necessitates the use of fracture mechanics (see Section 2.2). Thus, one fundamental approach to determining the initial rating of new cranes and the de-rated lifting capacity of existing cranes for Arctic offshore applications could be based on a combination of classical stress analysis and fracture mechanics. Classical stress analysis allows designers/analysts to use the physical and geometric relationships between applied loads, boom orientations, and stresses in crane structural members and to predict the likely behavior of those structural members under various load cases. Fracture mechanics allows the designer/analyst to predict further what might happen if any structural members of a crane contain imperfections, i.e., flaws (metallurgical or manufacturing defects or deficiencies).

Modern crane steels are composed mainly of ferrite, the body-centered-cubic form of iron, which causes these steels to undergo a transition from ductile to brittle behavior with decreasing temperature. Thus, in addition to considering overloading and time-dependent failure modes such as fatigue, in Arctic environments, designers must also consider brittle fracture, which can and often leads to unexpected failures. Moreover, when considering a fracture-mechanics approach to crane design, the nature of the likely failure mode(s) of critical components must be considered. However, the multitude of fracture-toughness definitions often makes it difficult for the designer/analyst to select the proper definition of fracture toughness for their purposes.

To apply a stress-analysis/fracture-mechanics approach to crane design or analysis, one must have knowledge of three primary variables:

1. Prevailing stress field or state of stress
2. Flaw geometry
3. Fracture toughness of the steel

Standard structural design methods and/or finite element analysis (FEA) typically can provide designers with adequate information for designing cranes. Thus, one must be able to either measure or calculate fracture toughness, which is typically identified as K_{IC}. Additionally, if the linear elastic fracture mechanics (LEFM) method of crane design is to have merit, the available methods of non-destructive examination (NDE) of crane components must be adequate for reliably detecting flaws that are smaller than the critical flaw.

On this basis, a portion of the work presented here was directed toward estimating whether existing CVN-to-fracture toughness correlations, specifically CVN to K_{IC}, are valid for modern crane steels, and if not, toward developing an adequate correlation or at least specifying test methods that will yield the required information. More specifically, the prime objective of this study was to produce a set of recommendations that would serve as the basis for a future specification or industry standard for rating or de-rating cranes that will be used at Arctic temperatures. The design methodology espoused here is fundamentally based on fracture mechanics implemented via CVN rather than K_{IC} testing.

SES believes that this approach provides several important benefits:

- The fracture-mechanics approach allows designers to directly address the likely effects of flaws on crane behavior.
- As compared to K_{IC} testing, CVN impact testing is more economical and easier to perform.
- Via correlation with K_{IC} test results, CVN test results can be used to help rate new cranes or theoretically to re-rate existing cranes for use in Arctic conditions.

2.2 Approach to Problem

As described above, the fundamental approach to determining the initial rating and de-rated lifting capacity of cranes for Arctic offshore applications should be based on a combination of classical stress analysis and fracture mechanics. Such an approach will allow the designer to understand the relationships that exist between applied loads, boom orientations, and stresses in crane structural members and further to predict the likely behavior of those structural members that contain metallurgical or manufacturing defects/deficiencies. The stress-analysis/fracture-mechanics approach developed here can also be utilized to perform fitness-for-service (FFS) evaluations on cranes that develop flaws as a result of service.

When considering a fracture-mechanics approach to crane design, the nature of the likely failure mode(s) of a critical component must be considered. One must also understand the limitations of the NDE techniques that will be applied to various crane components. LEFM is typically used to predict and help prevent brittle fracture events from small flaws. Thus, NDE methods applied must be capable of reliably detecting flaws that are near the same size as the critical flaw if this approach is to have merit. On the other hand, flaw detection is somewhat less important when elastic/plastic fracture mechanics methods are used. Elastic/plastic fracture mechanics is typically applied to help predict the margin of safety against structural collapse under "over-yield" conditions. In Arctic applications, a material's resistance to fracture propagation at loads below yielding is paramount.

Fortunately, numerous correlations between fracture and impact (CVN) toughness have been published in the literature for many commonly used materials. These correlations exist because fracture-mechanics testing is expensive and slow, and because the normally ductile nature of constructional steels prevents workers from determining valid fracture-toughness values. The project team directed its efforts toward verifying whether existing correlations between CVN impact toughness and fracture toughness are valid for crane materials of construction. If not, the team was to develop an adequate correlation or specify test methods that will yield the required information.

The ultimate objective of this study is to produce a specification for rating or de-rating cranes for use at Arctic temperatures that is fundamentally based on fracture mechanics, but is implemented via CVN testing. A fracture-mechanics basis provides access to a quantitative interrelationship between applied stress, geometry, and critical defect size for fracture, and fracture toughness (see Section 2.1). However, fracture-mechanics testing is too complicated and expensive for the purpose of specification implementation, even for a quasi-static testing rate. Consequently, the SES team pursued an alternate approach—the CVN impact test.

The CVN impact test is an economical and easy-to-perform test that can be conveniently used to implement a specification. However, the CVN test measures an impact or dynamic energy for fracture at a given test temperature. While measured impact energy as a function of temperature can characterize a ductile-to-brittle transition (DBT) for a steel, providing a means of screening and comparing steels, it does not provide a fundamental basis for the specification. Impact energy cannot be related to applied stress, geometry, or critical defect size, as can fracture toughness. In addition, the CVN test is a measurement of fracture energy at a high rate of load application, whereas most service conditions represent a quasi-static rate of load application.

To be sure, a specification based solely on the CVN impact test would represent a conservative approach since the dynamic fracture conditions of the test are associated with increased constraint and, therefore, greater tendency for brittle fracture at a given temperature. However, without the correlation to fracture toughness, the real extent of that “safety factor” is not known for a given steel. In addition, it would be difficult to perform an FFS analysis on a crane without fracture toughness information on the steel.

In summary, the technical approach adopted to address this problem is to relate the fundamental knowledge associated with fracture toughness to the specification-related testing associated with CVN impact energy via established correlations. CVN impact energy at given temperatures can provide fundamental information for rating or de-rating cranes for Arctic service through the use of fracture toughness.

2.3 Limitations of Study

Consideration of all possible crane designs along with all possible variations in critical crane components was beyond the authorized scope of work for this analysis. Thus, SES selected the lattice-boom designs of Figure 1 (on page 9) to help focus the study. This selection appears reasonable because the performance characteristics of lattice-boom designs are less sensitive to boom weight and because these designs are representative of the “heavy-duty” cranes that are often mounted on mobile offshore drilling units (MODUs).

Although certain critical components of cranes are subject to multiple degradation mechanisms including fatigue, metal loss caused by corrosion, and hydrogen embrittlement; SES’s efforts were primarily focused on brittle fracture of structural components, which are most often manufactured from carbon or high-strength low-alloy (HSLA) steels. Efforts were focused on brittle fracture of these materials for the following reasons:

- Carbon and HSLA steels are the most widely used materials in crane construction.
- Although the resistance of carbon and low-alloy steels to brittle fracture can be improved by the use of modern steelmaking practices, brittle fracture of these materials is primarily a function of temperature. The possibility of operating cranes at temperatures below the ductile to brittle transition (DBT) temperatures of primary load-bearing components is the main feature that separates cranes used in the Arctic from those used in more temperate climates.
- Prevention of brittle fracture of critical crane components manufactured from carbon or HSLA steels can be most effectively addressed at the design stage via materials selection.
- The risk of failure due to other mechanisms such as metal loss of structural components caused by corrosion can be effectively managed by inspection and maintenance activities.

Wire ropes, which are a critical component of most offshore cranes, are mentioned only briefly herein. This is mainly due to the following:

- Unlike most structural components of cranes, wire ropes are, in fact, highly complicated systems. As a result, the toughness of a rope cannot be assessed correctly by considering only the inherent Charpy impact or fracture toughness of the steel. Proper assessment of wire-rope behavior requires consideration of the load sharing between individual strands and wires. While performing such an assessment was beyond the authorized scope of work for this effort, this area could be the subject of a future study.

- Wire-rope manufacturers who responded to the survey all indicated clearly that their standard ropes exhibit acceptable toughness and strength at temperatures as low as -40 °F (-40 °C), a temperature that our research indicates is a likely minimum operating temperature for cranes in Arctic regions.

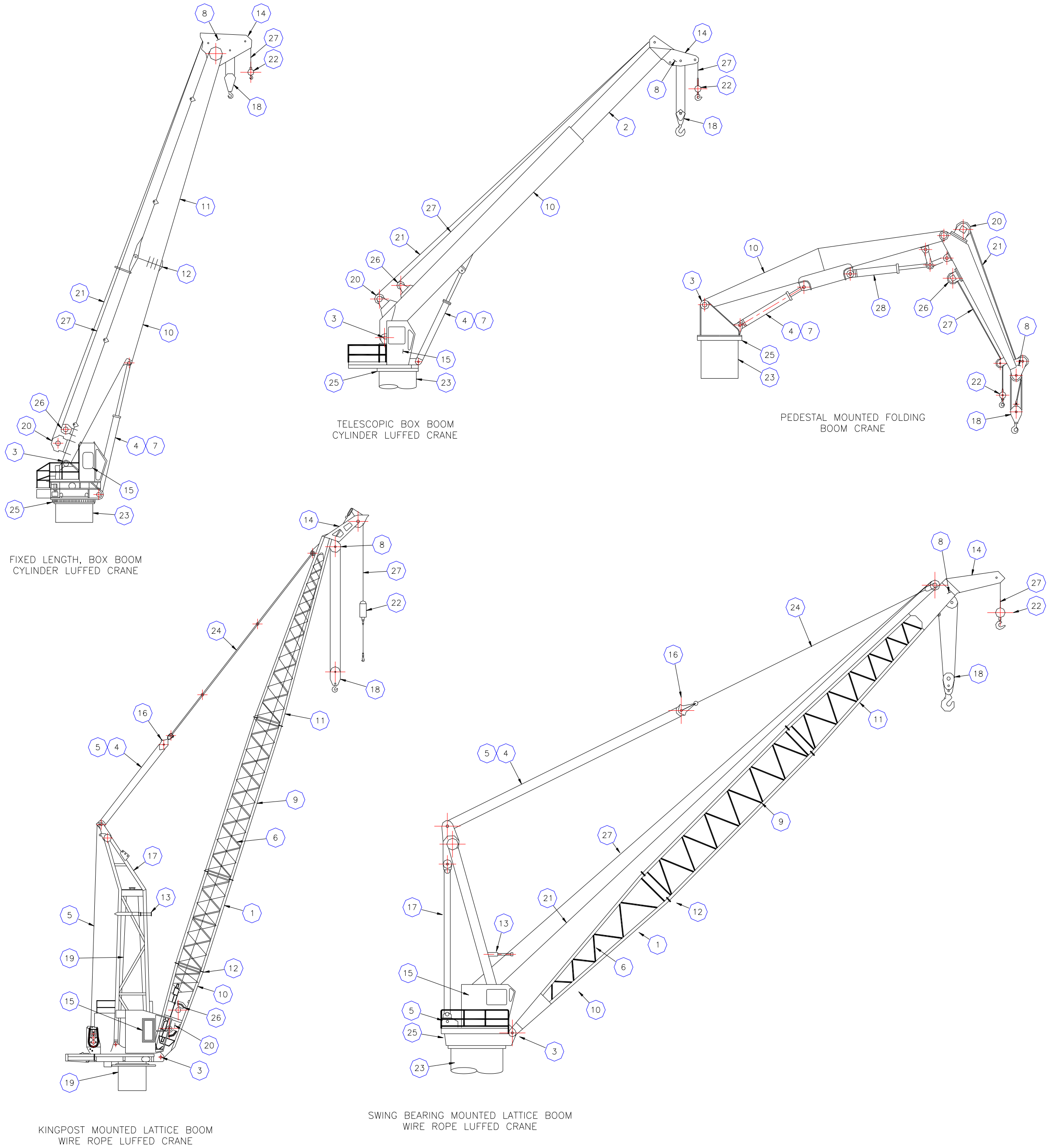
- Wire-rope manufacturers indicated that the main problem observed in cold climates is ensuring that the ropes remain properly lubricated. Thus, as with structural components, ensuring acceptable low-temperature behavior of wire ropes is primarily a maintenance issue.

3. Structural Design Considerations for Cranes and Identification of Critical Crane Components

3.1 Structural Design Considerations

Cranes have been in common use for centuries and have developed into highly specialized pieces of equipment depending on the particular application. In onshore environments, a wide variety of crane types are available including mobile, overhead, tower cranes, and others. For the offshore oil industry, most cranes are fixed pedestals mounted at one location on the fixed offshore platform, movable jack-up rig, or floating rig. The crane rotates around this fixed point, moving people, supplies, and equipment onboard and/or offboard from supply vessels and barges.

Figure 1 shows the basic designs of several typical offshore crane types. All are capable of positioning lifted items (the load) anywhere within their reach around the fixed pedestal.



1	Boom chord	15	Cab
2	Boom extension	16	Bridle
3	Boom heel pin	17	Gantry, mast, or A-frame
4	Boom hoist mechanism	18	Hook block
5	Boom hoist wire rope or boom line	19	King post or center post
6	Boom lacing	20	Main hoist drum
7	Boom luffing cylinder	21	Main hoist rope or load line
8	Boom point sheave assembly or boom head	22	Overhaul ball
9	Boom section, insert	23	Pedestal or base
10	Boom section, lower, base or butt	24	Pendant line
11	Boom section, upper, point or tip	25	Swing-circle assembly
12	Boom splice	26	Whip line or auxiliary hoist drum
13	Boom stop	27	Whip line or auxiliary hoist rope
14	Boom tip extension or jib	28	Folding boom articulating cylinder

Figure 1: Typical Offshore Cranes (from Ref 4).

The loading conditions imposed on the various crane components (boom, boomlines, loadlines, gantry, pedestal, etc.) vary greatly depending on the crane type, load being lifted, working radius, and dynamics of the lift. All cranes (onshore and offshore) are subjected to some dynamics during the load-lifting process. Offshore cranes are subjected to considerably more dynamic loadings than others because many of the lifting operations for offshore cranes are made to and from moving supply boats. Motion of the supply boat induced by waves, wind, and currents cause difficult lifting conditions for offshore cranes that add to the design conditions acting on the cranes. If the crane is mounted on a moving platform, these added motions serve to increase the dynamic forces acting on the crane during lifting operations.

Structural design of offshore cranes, similar to structural design of most structures, must produce a design that is safe, cost-effective, and performs the required functions. To achieve this, engineers develop predictions of load conditions, calculate forces and stresses in the various crane components, and proportion these components such that failure does not occur. The modes of failure typically considered for offshore cranes are as follows:

1. Overloading (as evidenced by general yielding or excessive plastic deformation)
2. Buckling or general instability (either elastic or plastic)
3. Fatigue
4. Brittle fracture

Existing design codes in the industry give detailed guidance on the design of offshore cranes. Most of the design considerations are focused on the first two modes of failure (yielding and buckling). The crane specifications provide specific guidance to the design engineers on defining expected loads and providing adequate design factors to provide adequate strength to prevent general yielding or excessive plastic deformation. Buckling or general instability is also considered in the structural design process (both local and overall instability).

Guidance is also given for considering fatigue failure, although not in as much detail as for the first two failure modes. Most offshore cranes are not used in high-fatigue service applications. They are designed to be able to lift a heavy load at specific operating conditions (working radius, wind, seastate). However, most lifts are performed at 50% of capacity or less and therefore result in a much lower stress level in the crane than design stress conditions. As a result, fatigue has rarely been identified as a factor in offshore crane incidents, with most incidents reportedly caused by overload, operator error, or maintenance issues. However, with the industry moving into deeper water with more floating platforms, the added motion and resulting fatigue loading on cranes may produce added requirements in the future.

The need to provide ductile material to prevent brittle fracture is recognized in the current codes. Current code guidance typically uses a toughness-based approach. Materials must meet specified minimum Charpy toughness levels at specified test temperatures that are slightly below the specified Lowest Anticipated Service Temperature (LAST). Little or no guidance is given on selection of steels for extreme cold service, the advantages of fine-grain, clean steel for cold service, etc.

3.2 Identification of Critical Crane Components

Identification of critical crane components requires that these components first be defined. Several sections of API 2C, including Section 3.1; Annex A, Section A.1, General; and Annex A, Sections A.2 through A.4, offer assistance in this regard. Note that the 7th edition of API 2C is referred to in this document, although the Code of Federal Regulations currently only recognizes the 6th edition. With regard to the major concerns and principles discussed in this document (e.g., cold service, material properties, ductility), there are no major changes between these two editions of API 2C.

API-2C, Section 3.1, Terms and Definitions, defines a critical component as follows:

> *"Any component of the crane assembly devoid of redundancy and auxiliary restraining devices whose failure shall result in an uncontrolled descent of the load or uncontrolled rotation of the upper structure."*

Based on this definition, Sections A.2 through A.4 of API 2C suggest the following lists of critical mechanical, structural, and rigging components:

1. Critical Mechanical Components (Section A.2):
    a. All linkage between brake control element and the component to be controlled
    b. Hoist and slewing brake systems
    c. Drums, shafts, and gears of hoisting and slewing systems
    d. Swing circle assembly
2. Critical Structural Components (Section A.3):
    a. Fasteners in the critical load path of all critical components
    b. Boom chord members
    c. Boom section connection components
    d. Boom heel pins
    e. Boom jib section and connection components
    f. Primary load members of gantries, masts, and A-frames
    g. Load-transfer members of the rotating upper structure, including fasteners
    h. Kingposts
    i. Pedestals and swing-circle transition pieces

3. Critical Rigging Components (Section A.4):
   a. All running wire ropes in hoist systems
   b. All standing wire ropes in load restraint and support systems
   c. Hook block assembly
   d. Overhaul ball or weight assembly
   e. Wire rope dead-end connection devices
   f. Bridle assemblies
   g. Wireline sheaves and sheave shafts

Ultimately, however, the designer and manufacturer are responsible for developing what is perhaps a fuller list of critical components. API 2C Annex A, Section A.1, General states the following:

> *"…the designer and manufacturer of a crane are responsible for developing a complete list of critical components for each individual design."*

4. Review of Existing Crane Specifications and Standards

4.1 Background

Task 2 of the project was to review specifications, standards, and recommended practices pertinent to the construction of offshore cranes, with an emphasis on steels used. The emphasis on construction steels is derived from an overall program emphasis on the role of steel properties—specifically low-temperature fracture toughness—in rating and de-rating of offshore cranes for use in the Arctic.

An overall review of the specification literature on offshore cranes indicates two major governing specifications:

1. API Specification 2C, "Offshore Pedestal-Mounted Cranes," 7^{th} Edition, March 2012.
2. EN 13852-1:2004, "Offshore Cranes: General-Purpose Offshore Cranes," October 2004.

The first of these is API 2C, a US domestic (American Petroleum Institute) specification. EN 13852 is a European specification. Both specifications are quite general in scope, and identify and refer to other specifications and recommended practices, specifically in the area of construction steel. A review is presented below of the major and associated specifications and recommended practices pertinent to the properties and testing of offshore crane construction steel. Additional offshore-crane specifications are available from ABS, DNV, Bureau Veritas, and others.

4.2 API 2C and Associated Specifications and Recommended Practices

The bulk of API Specification 2C is concerned with design strategies for offshore cranes. Section 5 covers loads and represents a significant portion of the specification. It primarily addresses safe working limits for critical components. Loads that should be considered during design include those resulting from "in-service" and "out of service" conditions, wind, ice, and seismic events.

Section 6, "Structure," deals with application of an allowable stress design strategy to specific crane components. In this regard, reference is made to the applicability of an American Institute of Steel Construction (AISC) specification, AISC 360-10, for structural steel buildings [Ref 6], which describes a list of ASTM specifications for structural steels that are summarized in Table 1.

Table 1: ASTM Structural Steel Specifications from AISC Specification 360-10

1	Hot-Rolled Structural Shapes
	A36, A529, A572, A588, A709, A913, A992, A1043
2	Structural Tubing
	A500, A501, A618, A847
3	Pipe
	A53, Grade B
4	Plate
	A36, A242, A283, A514, A529, A572, A588, A709, A852, A1011, A1043
5	Bar
	A36, A529, A572, A709

By way of reference to the AISC specification, Section 6 of API 2C provides a list of constructional steels that can be used for construction of offshore cranes. However, for the purposes of the present program, it should be noted that AISC 360-10 does not generally consider fracture controlled by notch toughness to be a very important consideration. This is probably the result of two facts: loading in buildings is quasi-static and temperatures are relatively high. Charpy V notch (CVN) impact tests are therefore generally performed at temperatures higher than the minimum anticipated service temperature for Arctic cranes.

Section 8, "Ratings," addresses procedures for crane rating. See Section 5 for more information on this subject.

Section 9, "Gross Overload Conditions," deals with failure-mode calculations and failure mode charts. Essentially, this section considers scenarios whereby a particular crane could fail via service-induced unintentional gross overload (hooking/entanglement with a supply boat) and provides cautionary information for users/consumers.

Section 11, "Manufacturing Requirements," considers material requirements for critical components (Section 11.1). Specifically, Section 11.1.5.1 refers to the "fracture toughness" of critical components, and Table 24 of that specification describes CVN testing requirements with regard to a minimum impact energy that must be achieved at a particular temperature. Requirements are presented as a function of minimum specified yield strength of the steel (Table 2). The temperature is defined as 10 °F below the minimum design service temperature. As yield strength of the steel increases above 44 ksi, the minimum required CVN energy increases due to the increased risk of brittle fracture at higher strength.

Table 2: CVN Energy Requirements of Steels; API-2C, Table 24

Min. Specified Yield Strength (ksi)	Min. Avg Energy Value (three tests) (ft lb)	Max Test Temperature
≤ 44	20	10 °F below lowest design svc temp
> 44 and ≤ 60	25	10 °F below lowest design svc temp
> 60	25	10 °F below lowest design svc temp

Annex B, Section B.11.3, is a commentary on Section 11 that considers fracture toughness. Although the commentary acknowledges the details and importance of a fracture-toughness design approach, the specification embodies facture-toughness measurement in the CVN impact test. This section also acknowledges that the material property of fracture toughness can probably be determined with greater precision than either flaw/defect size or applied stress associated with stress concentration.

Section 2, “Normative References,” cites other specifications pertinent to offshore cranes. In addition to AISC 360-10 [Ref 6] (reviewed above), other specifications pertinent to construction steels were cited:

- API Recommended Practice 2A WSD, “Planning, Designing and Constructing Fixed Offshore Platforms – Working Stress Design,” 21st Edition
- API Specification 2H, “Specification for Carbon Manganese Steel Plate for Offshore Platform Tubular Joints”

API supports a Committee on Standardization of Oilfield Equipment and Materials (CSOEM) that has several subcommittees. Subcommittee 2 (SC2) on Offshore Structures deals with offshore structures, offshore construction materials, and offshore cranes. Specifically, Subcommittee 2 is cognizant of additional API specifications on offshore construction steels:

- API Specification 2B, “Specification for the Fabrication of Structural Steel Pipe”
- API Specification 2MT1, “Specification for Carbon Manganese Steel Plate with Improved Toughness for Offshore Structures”
- API Specification 2MT2, “Rolled Shapes with Improved Notch Toughness”
- API Specification 2SC, “Manufacture of Structural Steel Castings for Primary Offshore Applications”
- API Specification 2W, “Specification for Steel Plates for Offshore Structures Produced by Thermomechanical Control Processing (TMCP)”
- API Specification 2Y, “Specification for Steel Plates, Quenched and Tempered, for Offshore Structures”

- API Recommended Practice (RP) 2Z, "Recommended Practice for Preproduction Qualification for Steel Plates for Offshore Structures"

These API specifications describe chemical composition, tensile properties, and impact toughness (CVN) requirements for structural steels used in offshore cranes. Requirements of these specifications are summarized in the sections that follow.

4.3 API Recommended Practice 2A-WSD

API RP 2A-WSD [Ref 7] defines a general steel-classification system with regard to groups and classes. Steels are grouped by yield strength (YS) and carbon equivalent (CE), with YS and CE increasing with group number. Group I steels comprise mild steels with YS ≤ 40 ksi and CE ≤ 0.4 that may be welded with any weld process, per AWS Specification D1.1 [Ref 45]. Group II includes intermediate-strength steels with 40 ksi ≤ YS ≤ 52 ksi, and Group III steels exhibit minimum specified yield strengths in excess of 52 ksi. The CE of Group II and Group III steels can exceed 0.45. As such, welding of these steels typically involves use of low-hydrogen welding processes and, in some cases, may require preheating and/or post-weld heat treatment to avoid delayed hydrogen cracking (cold cracking) due to their higher hardenability and strength. API 2A-WSD cautions that designers of equipment that use Group III steels must consider fatigue problems that may arise from higher working stresses and notch toughness in relation to other elements of fracture control such as fabrication, inspection procedures, service stresses, and temperature of the environment.

Within the API 2A-WSD steel groups, the term "steel class" refers to notch-toughness requirements, which are determined based on anticipated service conditions. Class C steels are typically used for primary structural members with limited thickness. They may undergo moderate forming and are typically applied in low-restraint conditions, i.e., those associated with moderate stress concentration under quasi-static loading and structural redundancy.

Class C steels are widely used in welded structures at service temperatures above freezing. Typically there are no notch-toughness concerns under such conditions; therefore, CVN testing of Class C steels is generally not required.

As compared to Class C, Class B steels mainly exhibit improved notch toughness, which results in Class B steels being more suitable for applications that require greater thickness or that are characterized by moderate to severe stress concentrations, dynamic loading conditions, and/or lack of structural redundancy. For Class B steels, CVN impact testing is generally required with a minimum CVN energy of 15 ft·lb (20 J) for Group I and 25 ft·lb (34 J) for Group II at the LAST. Class B steels can generally meet these CVN energy requirements at temperatures ranging from 50 to 32 °F (10 to 0 °C).

Class A steels possess greater notch toughness than either Class A or Class B materials, and many times Class A steels are suitable for use at sub-freezing temperatures in critical applications involving adverse combinations of the factors cited above. The extra margin of notch toughness available for Class A steels helps to prevent propagation of brittle fractures from large flaws. Additionally, the improved toughness of Class A steels may make crack arrest possible in components with section thicknesses of up to several inches. CVN impact testing is required at 36 to 54 °F (20 to 30 °C) below the LAST.

The individual steels listed in this specification are described in Table A-1 (see Appendix A).

4.4 API Specification 2H

API-2H [Ref 8] governs fully-killed[1] carbon/manganese (C-Mn) steel plate for offshore structures. The standard specifically covers two grades of intermediate-strength steels for use in welded construction: Grades 42 and 50. Both grades are available in thicknesses of up to 4 inches.

API-2H plates are typically produced in the normalized condition. However, by agreement between the purchaser and manufacturer, Grade 50 plates thicker than 2.5 inches can be provided in the quenched-and-tempered condition. API 2H specifies a minimum service temperature of 14 °F (-10 °C) for all plates, irrespective of heat-treat condition or thickness.

API 2H steels can exhibit two levels of CE. Plates less than 2.5 inches thick may exhibit a maximum CE equal to 0.43. Thicker plates may exhibit CEs up to 0.45. The increased CE for thicker plates is necessary to ensure that the plates meet minimum yield and tensile strength requirements, especially at higher thicknesses. The C content of API 2H plates is typically limited to less than the maximum allowable value to improve weldability.

In steels of this strength level, low sulfur (S) levels are important for maintaining high toughness, and for helping reduce instances of lamellar tearing, especially in thick sections. The use of low-S steel-making practices helps in limiting the S content of these steels to below about 0.006%. Although not required, microalloying with columbium and titanium (Cb and Ti) is apparently allowed. The use of Cb and/or Ti to increase strength and improve toughness (via austenite grain refinement) is common, especially in Grade 50.

The specification recognizes that, due to the low carbon and sulfur contents of 2H steels, the energy of full-size specimens can exceed the limits of typical Charpy test equipment. To avoid this, the producer is allowed the option of testing sub-size specimens. Combinations of specimen size, test temperature, and energy requirements for full- and sub-size specimens are summarized in Table 3 of the standard. This approach, which is widely used in many industry standards, relies on the expected reduction in absorbed energy as specimen size is reduced. The approach also utilizes the compensating effect of temperature to gain equivalence between full- and sub-size specimens.

4.5 API Specification 2W

API-2W [Ref 13] governs two grades of high-strength steel for welded construction: Grade 50 and Grade 60, which are offered in thicknesses up to and including 6 in. and 4 in., respectively. The higher

[1] Fully-killed steels are those that are completely deoxidized in the molten state by the addition of one or more deoxidizing agents (e.g., aluminum, ferrosilicon, or manganese) before casting.

strengths/thicknesses of these plates as compared to plates produced under API-2H are primarily the result of controlled rolling and accelerated cooling after rolling. As a result of using thermomechanical controlled processing (TMCP), post-fabrication heating (i.e., postweld heat treatment) must be minimized or closely controlled. Due to a high YS/UTS ratio, the use of under-matched weld metal should be avoided.

With regard to notch toughness, a minimum service temperature of 14 °F (-10 °C) is specified.

The properties of API-2W steel are summarized in Tables A-2, A-3, and A-4 (see Appendix A).

Controlled thermomechanical processing requires the chemistry of these steels to be closely controlled as well. Like API 2H steels, the steels listed in API 2W are fully killed, and most deoxidation practices for these steels use both aluminum (Al) and ferrosilicon (FeSi). Many are alloyed with nickel (Ni), chromium (Cr), and molybdenum (Mo). Microalloying with Ti and Cb is also used to enhance strength and toughness. The CE is controlled to accommodate welding.

With regard to notch toughness, the same accommodations are made to higher toughness for valid CVN testing as described above for API-2H steels. For equal fracture resistance, the higher strength of Grade 60 requires higher minimum CVN energy.

4.6 API Specification 2Y

API-2Y [Ref 14] governs two grades of high-strength steel for welded construction: Grade 50 and Grade 60, which are offered in thicknesses of up to and including 6 in. for Grade 50 and 4 in. for Grade 60. However, API-2W plate achieves its strength via TMCP; API-2Y achieves similar properties via quenching and tempering. Except for lower carbon (C), the chemical composition, tensile properties, and notch toughness of 2Y plates are nearly identical to plates made under API-2W. The C concentrations of API 2Y plates are held below those for 2H and 2W plates, again to enhance their weldability.

The properties of API-2H, API-2Y and API-2W plates are summarized in Tables A-2, A-3, and A-4, which are attached in Appendix A.

4.7 API Specification 2MT1

API-2MT1 [Ref 10] governs a single grade of plate, generally delivered in the hot-rolled condition with improved toughness for offshore structures. If plates in the hot-rolled condition do not meet specification requirements, then the material may be retreated via normalizing or Q&T heat treatment.

The properties of API-2MT1 steel are also summarized in Tables A-2, A-3, and A-4 (see Appendix A). This steel includes a lower C content and is Al-killed, with the potential for Cb-V microalloying to aid in attaining properties. It is essentially a Grade 50 steel. Oddly, the CVN impact-test requirements do not seem to be consistent with the higher toughness levels of other API steels at the same strength level. Investigation of reasons for this inconsistency was beyond the scope of the present study.

4.8 API Specification 2MT2

API-2MT2 [Ref 11] governs the processing and properties of rolled shapes, specifically wide flanges, angles, etc. The steel is provided in a single grade (Grade 50) and is available in three classes (A, B, and C) as discussed previously for API 2A WSD. The maximum allowable C content increases from Class A to C; however, the allowable levels of Ni, Cr, Mo, and V vary by class. All three classes of this steel are Al-killed and processed with fine-grain practice.

Class A shapes may be provided in the as-hot rolled, controlled-rolled, recrystallization controlled-rolled, normalized, Q&T, or quenched and self-tempered conditions. Class B and C steels are provided in as-hot rolled, controlled-rolled and recrystallization controlled-rolled conditions. Class C is normally used for the least fracture-critical applications.

Minimum CVN energy increases with lower test temperatures moving from Class C to Class A steel, reflecting more fracture critical applications. Lower CVN test temperatures are also suggested.

The properties of API-2MT2 steel are summarized in Tables A-2, A-3, and A-4 (see Appendix A).

4.9 European Standard EN 13852-1 and Associated Standards and Specifications

4.9.1 European Standard EN 13852-1

EN 13852 [Ref 5] is the European counterpart to API-2C and is very similar in form and content. Section 1, "Scope," specifically states that the specification does not cover design temperatures less than -20 °C (-4 °F) or operating temperatures greater than 40 °C (104 °F). This limit appears to bear directly on crane operations in Arctic environments.

- Section 5, "Safety Requirements and/or Protective Measures," covers loading, structures, and mechanisms.
- Section 6, "Verification of the Safety Requirements and/or Protective Measures," describes testing to ensure that the measures of Section 5 are being accomplished.
- Annex D, "Failure Mode Analysis," refers to failure mode analysis and failure mode charts.
- Annex E, "Materials Selection," and specifically Section E.1 cite several criteria for selection of materials: (1) strength and ductility at design temperature, (2) resistance to brittle fracture at specified design temperature, (3) resistance to fatigue loading, (4) consistency and reliability of material processes, (5) suitability of fabrication processes, and (6) resistance to corrosion. Section E.2 refers to verification of material quality of primary components per Specification EN 1024 type 3.1.b.

- Sections E.3 and E.4 refer to forged rings for slewing bearings and slewing bearing fasteners. These specify testing for impact toughness, fatigue properties, and fracture toughness (see Tables E.1 and E.2). The information in these tables is summarized in Table 3.

- Section E.5 refers to welded structures and describes CVN testing as a function of material thickness (Table E.3). Impact test temperatures are specified as a function of material thickness, design temperature, and whether YS is above or below 355 MPa (51.5 ksi). Interestingly, no minimum CVN energy is indicated. The information from this section is summarized in Table 4.

- Section E.6 refers to non-welded components and refers to Table E.4 in the specification.

Table 3: Summary of Notch Toughness (CVN) Requirements for Steels of EN 13852

	ECVN min avg (ft·lb)	ECVN min avg (J)	ECVN min single (ft·lb)	ECVN min single (J)	T (F)	T (C)
Forged rings, EN 13852-1, Table E.1						
	31	42	20	27	-4	-20
Slewing bearing fasteners, EN13852-1, Table E.2						
Grade 8.8	31	42	20	27	-4	-20
Grade 10.9	31	42	20	27	-4	-20
Grade 12.9	31	42	20	27	-4	-20

Table 4: Summary of Notch Toughness Properties for Welded Structures in EN 13852

Material Thickness (mm)	Impact Test T (C), Primary Members	Impact Test T (C), Secondary Members
t < 12	$T = T_d + 10$	*No test required*
12 < t < 25	$T = T_d$	*No test required*
25 < t < 50	$T = T_d – 20$	$T = T_d + 10$
t > 50	$T = T_d – 30$	$T = T_d$

Notes: T_d = design temperature; For C-Mn steels with YS ≤ 355 MPa, T_{min} = -40 °C;
For YS > 355 MPa, -60 °C ≤ T_{min} ≤ 0 °C

4.9.2 European Standard EN 10025

EN 13852 [Ref 5] refers to specific steel specifications that are embodied in the EN 10025 "Structural Steel Standard." EN10025 includes five standards:

1. Part 2: Technical delivery conditions for non-alloy structural steels

2. Part 3: Technical delivery conditions for normalized/normalized and rolled weldable fine grain structural steels

3. Part 4: Technical delivery conditions for thermo-mechanical rolled weldable fine grain structural steels

4. Part 5: Technical delivery conditions for structural steels with improved atmospheric corrosion resistance

5. Part 6: Technical delivery conditions for flat products of high-yield-strength structural steels in the Q&T condition

The main alloying elements for Part 2 steels are C and Mn, with each being added incrementally to increase YS. The steels in Part 2 are designated with regard to minimum YS at 16 mm, and strength varies with thickness. The following definitions are used in Part 2 to identify various grades of steel:

- S = structural steel
- E = engineering steel
- JR = minimum longitudinal CVN energy of 27 J (20 ft·lb) at 20 °C (68 °F)
- J0 = minimum longitudinal CVN energy of 27 J (20 ft·lb) at 0 °C (32 °F)
- J2 = minimum longitudinal CVN energy of 27 J (20 ft·lb) at -20 °C (-4 °F)
- K2 = minimum longitudinal CVN energy of 40 J (29.5 ft·lb) at -20 °C (-4 °F)
- +AR = supplied in as-rolled condition
- +N = supplied in normalized/normalized rolled conditions
- C = grade suitable for cold forming
- Z = grade with improved properties in through-thickness direction

For Part 3 steels, C, Mn, V, N, and Ni are increased incrementally to increase YS. Designations in addition to those found in Part 2 are:

- N = minimum longitudinal CVN energy at not lower than -20 °C (-4 °F)
- NL = minimum longitudinal CVN energy at not lower than -50 °C (-58 °F)

For Part 4 steels, C, Mn, V, N, and Ni are also increased to achieve target YS. However, lower C is required for strength due to the advantages of microalloying and thermomechanical controlled rolling. Designations in addition to those of Part 2 are:

- M = minimum longitudinal CVN energy at not lower than -20 °C (-4 °F)

- ML = minimum longitudinal CVN energy at not lower than -50 °C (-58 °F)

Part 6 deals with Q&T steels that exhibit higher strengths than the steels in previous parts. Despite increased strength, toughness of Part 6 steels is higher than for steels covered in previous parts. In addition to the designations in Part 2, Part 6 steels may exhibit the following quality level markings:

- Q = minimum longitudinal CVN energy at not lower than -20 °C (-4 °F)
- QL = minimum longitudinal CVN energy at not lower than -40 °C (-40 °F)
- QL1 = minimum longitudinal CVN energy at not lower than -60 °C (-76 °F)

The quality designations are similar to the class designations of the API specifications but are more informative in that they specify a minimum CVN energy at a given temperature. In general, maximum P and S levels are decreased as the quality (designation) is increased. A minimum CVN energy at a lower temperature indicates a higher toughness steel at the same strength.

The properties of steels described in the various parts of EN 10025 are summarized in Tables A-5 and A-6 (see Appendix A).

5. Review of Crane Steels

5.1 Choice of Steels for Investigation

Previously, Section 3.2 identified critical crane structural components (Task 3), and Sections 4.3 through 4.9 presented a review of API and EN specifications that cover the steels from which most of the critical components can be fabricated (Task 2). Obviously, a wide range of steels can be selected for crane structural components. However, for the purposes of this study and for Arctic service, it was important that the steels selected in Task 4 (see Section 1.2) exhibit the following characteristics:

- The steels should be representative of a broad range of strength and toughness, i.e., the groups and classes listed in API 2A WSD
- The steels should be representative of all possible processing routes, i.e., hot-rolled, normalized, TMCP, Q&T, etc.
- The steels should be representative of those actually used by crane manufacturers

Plate and pipe steels that satisfy these criteria are described in Table 5 and Table 6.

Table 5: Plate Steels for Crane Fabrication

Group	Class	Specification and Grade	Form	Type of Steel & Processing
I	C	A36	Plate, shapes	C-Mn steel, conventional processing
I	B	A709, Gr 36T2	Plate, shapes	C, HSLA steel, AR, control rolled, TMCP, Q&T (HPS 50W, HPS 70W)
I	A	ASTM A131, Gr CS, E	Plate, shapes	Normalized, TMCP
II	C	A572 Gr 42	Plate, shapes	HSLA, microalloyed
II	C	A572 Gr 50	Plate, shapes	HSLA, microalloyed
II	B	A709, Gr 50T2, 50T3	Plate, shapes	C, HSLA steel, AR, control rolled, TMCP, Q&T (HPS 50W, HPS 70W)
II	A	ASTM A131, Gr DH32, EH32	Plate, shapes	Normalized, TMCP
II	A	ASTM A131, Gr DH36, EH36	Plate, shapes	Normalized, TMCP
II	A	API 2W, Gr 50 (≤ 1 in.)	Plate, shapes	TMCP
II	A	API 2W, Gr 50 (> 1 in.)	Plate, shapes	TMCP
II	A	API 2W, Gr 60 (≤ 1 in.)	Plate, shapes	TMCP
II	A	API 2W, Gr 60 (> 1 in.)	Plate, shapes	TMCP
II	A	API 2Y, Gr 50 (≤ 1 in.)	Plate, shapes	Q&T
II	A	API 2Y, Gr 50 (> 1 in.)	Plate, shapes	Q&T
III	A	API 2W, Gr 60 (≤ 1 in.)	Plate	TMCP
III	A	API 2W, Gr 60 (> 1 in.)	Plate	TMCP
III	A	API 2Y, Gr 60 (≤ 1 in.)	Plate	Q&T
III	A	API 2Y, Gr 60 (> 1 in.)	Plate	Q&T
III	A	ASTM A710, Grade A, Class 3	Plate	Low-alloy steel, heat treated (Q&T).
III	A	A514	Plate	Low-alloy steel, heat treated (Q&T).

Table 6: Structural Steel Pipe and Tubing for Crane Fabrication

Group	Class	Specification and Grade
I	C	A500 Gr A or B
		A53 Gr B
		A501
	B	A106 Gr B
	A	ASTM A333, Gr 6
		ASTM A334, Gr 6
II	C	A500 Gr C
	B	API 5L, Gr X52 (with SR5 or SR6)
		API 2W, Gr 50 (≤ 1 in. & > 1 in.)
		API 2W, Gr 60 (≤ 1 in. & > 1 in.)

Ultimately, a number of steels must be chosen around which to create a database of CVN and fracture-toughness data. To be relevant, it seems reasonable that this population of steels be derived from the steels employed for fabricating critical structural components for cranes.

In this regard, the review of specifications identified the universe of steel grades that are specified for crane fabrication. Specific steels would have to be derived from this population. Identification of cranes and their critical structural components (described previously) combined with association of steel grades with these components, narrows the population of steels for potential investigation. Importantly, it is recognized that within a crane design the steel of a given critical component may vary with crane load rating.

Thus, steels used for critical components as a function of crane load rating are required for a manageable number of cases. Once this more limited population of steels has been identified, the pertinent CVN and fracture-toughness data may be collected to populate the required database. In lieu of specific steels manufactured by specific steelmakers, the general class of steel with a given set of properties may be identified for data collection.

5.2 General Classes of Steels

The specification review in Section 4 herein identified virtually all of the generic steel types used in crane fabrication, as described in API specifications. Those specifications are listed in Table 7. The Group/Class designation system perhaps provides a convenient method of specifying appropriate steels for critical structural components. This system would account for strength (Group) and notch toughness (Class). The next more specific level of description would be via individual specifications. Of course, the most specific level of description would be a particular steel produced by a particular steelmaker.

For completeness, a similar list of steels derived from European standards is provided in Table 8. The classification system for these steels benefits from so-called "quality" designations of specified minimum CVN energy at a given temperature as well as strength.

Table 7: API-Related Steel Specifications Identified with Crane Fabrication

	Group	Class	Specification & Grade
Plate (Table 8.1.4-1, API RP 2A-WSD)	I	C	ASTM A36 (≤ 2 in.)
			ASTM A131, Gr A (≤ 0.5 in)
			ASTM A285, Gr C (≤ 0.75 in.)
		B	ASTM A131, Gr B, D
			ASTM A516, Gr 65
			ASTM A573, Gr 65
			ASTM A709, Gr 36T2
		A	ASTM A131, Gr CS, E
	II	C	ASTM A572, Gr 42 (≤ 2 in.)*
			ASTM A572, Gr 50 (≤ 2 in.)
		B	API 2MT1
			ASTM A709, Gr 50T2, 50T3
			ASTM A131, Gr AH32
			ASTM A131, Gr AH36
		A	API 2H, Gr 42
			API 2H, Gr 50 (≤ 2.5 in. & >2.5 in.)
			API 2W, Gr 42 (≤ 1 in. & > 1 in.)
			API 2W, Gr 50 (≤ 1 in. & > 1 in.)
			API 2W, Gr 50T (≤ 1 in. & > 1 in.)
			API 2W, Gr 60 (≤ 1 in. & > 1 in.)
			API 2Y, Gr 42 (≤ 1 in. & > 1 in.)
			API 2Y, Gr 50 (≤ 1 in. & > 1 in.)
			API 2Y, Gr 50T (≤ 1 in. & > 1 in.)
			ASTM A131, Gr DH32, EH32
			ASTM A131, Gr DH36, EH36
			ASTM A537, Class I (≤ 2.5 in.)
			ASTM A633, Gr A
			ASTM A633, Gr C, D
			ASTM A678, Gr A
	III	A	ASTM A537, Class II (≤ 2.5 in.)
			ASTM A678, Gr B
			API 2W, Gr 60 (≤ 1 in. and > 1 in.)
			API 2Y, Gr 60 (≤ 1 in. & > 1 in.)
			ASTM A710, Grade A, Class 3

	Group	Class	Specification & Grade
			(Q+Pptn heat treated) (≤2, 2–4, & >4 in.
Shapes (Table 8.1.4-2, API RP 2A-WSD)	I	C	ASTM A36 (≤ 2 in.)
			ASTM A131, Gr A (≤ 0.5 in)
		B	ASTM A709, Gr 36T2
	II	C	ASTM A572, Gr 42 (≤ 2 in.)*
			ASTM A572, Gr 50 (≤ 2 in.)
		B	ASTM A709, Gr 50T2, 50T3
			ASTM A131, Gr AH32
			ASTM A131, Gr AH36
Pipe (Table 8.2.1-1, API RP 2A-WSD)	I	C	API 5L, Gr B
			ASTM A53, Gr B
			ASTM A135, Gr B
			ASTM A139, Gr B
			ASTM A500, Gr A (round & shaped)
			ASTM A501
		B	ASTM A106, Gr B (normalized)
			ASTM A524, Gr I (≤ 0.375 in. WT)
			ASTM A524, Gr II (>0.375 in. WT)
		A	ASTM A333, Gr 6
			ASTM A334, Gr 6
	II	C	API 5L, Gr X42 (2% max cold exp)
			API 5L, Gr X52 (2% max cold exp)
			ASTM A500, Gr B (round & shaped)
			ASTM A618
		B	API 5L, Gr X52 (with SR5 or SR6)

Table 8: European Standard-Related Steel Specifications

	Specification	Grades	
Non-Alloy Structural Steels	EN 10025-2	S185	S275J2
		S235JR	S355JR
		S235J0	S355J0
		S235J2	S355J2
		S275JR	S355K2
		S275J0	S450J0
Normalized/ Normalized Rolled Steels	EN 10025-3	S275N	S420N
		S275NL	S420NL
		S355N	S460N
		S355NL	S460NL

Thermomechanical Controlled Rolled Steels	En 10025-4	S275M	S420M
		S275ML	S420ML
		S355M	S460M
		S355ML	S460ML
Q&T Steels	EN 10025-6	S460Q	S620QL1
		S460QL	S690Q
		S460QL1	S690QL
		S500Q	S690QL1
		S500QL	S890Q
		S500QL1	S890QL
		S550Q	S990QL1
		S550QL	S960Q
		S550QL1	S960QL
		S620Q	S960QL1
		S620QL	

5.3 Critical Components

The critical component review identified general crane types, of which the king post and slewing bearing lattice-boom types were chosen for consideration. API-2C identified a list of critical structural components:

1. Fasteners in the critical load path of all critical components
2. Boom chord members
3. Boom section connection components
4. Boom heel pins
5. Boom jib section and connection components
6. Primary load members of gantries, masts, and A-frames
7. Load-transfer members of the rotating upper structure, including fasteners
8. Kingposts
9. Pedestals and swing-circle transition pieces

5.4 Information Derived from Crane Manufacturers

In addition to the somewhat arbitrary choices for a population of steels, based on what is possible from specification, the project team sought to utilize information gleaned from crane manufacturers. Ideally, such a body of information would include:

- What crane types do you manufacture?
- What is load or load range?
- What are the critical components, per API-2C?
- For each critical component, at a particular load rating, which steel is specified or used (Group/Class, quality designation, steel specification, particular steel, strength, CVN requirements)?

A review of discussions between SES and crane manufacturers indicated that their choices for crane structural steels for low-temperature service are as follows:

1. API 2H Gr 50
2. A572 Gr 50
3. A131 DH36
4. A588
5. A633 Gr C
6. EN 10113-2 S355NL
7. EN 10025 S355K2G4
8. EN 10028-3 P355NL1/NL/2
9. A514/A517, A514 T1
10. EN 10025-6 S690QL1
11. EN 10028-6 P690QL2
12. A500 Gr B (tubing)
13. EN 10210-1 S355J2H (tubing)
14. A333 (pipe, similar to A106 Gr B, API 5L X52 (normalized)

15. 4820, 9310 (carburized forgings)

16. Modified 4330, 4340H

17. A500 Gr B, C; HSLA 70 (square tubing)

18. API 5L X42, PLS1, PLS2

The steels listed above can be produced via a wide range of steel-making practices. However, modern versions of the listed steels are more likely than older examples to have been produced fully killed and using a fine (austenite) grain practice. Killing using aluminum, ferrosilicon, manganese, or combinations of these produces steel with fewer and smaller inclusions, which in turn results in improved toughness. Limiting austenite grain size results in microstructural refinement following transformation, which provides benefits not only in terms of toughness but also strength.

Unless sufficient manufacturing records exist, it is impossible *a priori* to determine whether an existing crane was manufactured using steels made by older or by more modern processing. This raises the question of whether Charpy impact or fracture toughness data obtained on newer steels are applicable to older versions of the same steel. In other words, using toughness data obtained from or which is representative of newer steels may result in non-conservative predictions of the fracture resistance of older cranes. On the other hand, toughness data obtained from older (less clean and/or refined) steels will almost always produce conservative estimates of the fracture resistance of newer cranes.

At least one of the crane manufacturers who responded to this project's survey emphasized the benefits of using clean steel and fine grain-size processing for the steels used for crane construction. However, the responses from other manufacturers were not as clear. Complete responses received from crane manufactures are provided in Section 9.1 of this report.

5.5 Population of Steels for Project

Based on the responses of the crane manufacturers regarding steel selection, SES narrowed the population of steels that were utilized in this study. The final list of selected materials is shown in Table 9.

Table 9: Steels for Crane Project

Group	Class	Specification and Grade	Form	Type of Steel & Processing
I	C	A36	Plate, shapes	C-Mn steel, conventional processing
II	C	A572 Gr 50	Plate, shapes	HSLA
II	A	ASTM A131, Gr DH36	Plate, shapes	HSLA, TMCP
III	A	A514	Plate	Alloy steel, heat treated (Q&T)
I	B	A106 Gr B	Pipe	C-Mn steel, conventional processing
II	C	A500 Gr B	Pipe	C-Mn steel
II	B	API 5L, Gr X52	Pipe	HSLA, TMCP (typical)

6. Notch (CVN) Toughness Data

6.1 Background

A significant volume of toughness data was collected for this project. Full transition Charpy V-notch (CVN) data and as much pertinent fracture toughness data as possible have been included in the study. These data were collected on the basis of steels identified in work described previously.

Data on several general types of structural steels were consulted: (1) ship steels, (2) bridge steels, (3) building steels, (4) pressure vessel steels, and (5) pipeline steels. Obviously, there is significant overlap in steel composition and processing. In this regard, literature searching benefited from the availability of relatively large compendia of data for ship steels (Ship Structures Committee), bridge steels (AASHTO, FWHA), and pressure vessel steels (Welding Research Council).

Perusal of the steels associated with the references below indicates that data have been obtained for many of the steels identified in earlier task work and through discussions with crane manufacturers. In fact, the population of steels may be further reduced by grouping steels that are virtually equivalent.

An issue was noted above with regard to the age of data. Some of the data cited below are definitely older and may not be very relevant to current steel-processing capabilities. However, as mentioned, the data will need to be critically reviewed, but provide value with regard to FFS analyses.

CVN data are described in the next section.

6.2 CVN Data

The final choices of steels for data collection are summarized in Table 10. These choices were based on a review of specifications, discussions with crane manufacturers, and the availability of coherent data sets.

Table 10: Steels for CVN Data

Group	Class	Specification and Grade	Form	Type of Steel & Processing
I	C	A36	Plate, shapes	C-Mn steel, conventional processing
II	C	A572 Gr 50	Plate, shapes	HSLA
II	A	ASTM A131, Gr EH36	Plate, shapes	HSLA, TMCP
III	A	A514	Plate	Alloy steel, heat treated (Q&T)

6.2.1 A36

A36 steel was included in this investigation because it provides a baseline steel and is, in fact, used in crane construction. A number of plate thicknesses were considered to include the effect of thermomechanical treatment (total roll reduction).

Examination of raw CVN data indicates significant statistical scatter, despite the use of coherent data sets and mean values. It was therefore decided to employ a fitting equation to provide an unambiguous set of smoothed data. A fitting equation based on a hyperbolic tangent function (tanh) was adopted:

$$E_{CVN} = A + B \tanh \frac{T-D}{C} \quad \text{Equation 1}$$

where,

E_{CVN} = CVN energy (ft·lb)

T = temperature (°F)

A, B, C and D are fitting coefficients

The tanh formalism has been utilized by others [Ref 22 through 44]. Statistical fitting to determine the coefficients of the model was accomplished using the Solver tool in MS-Excel. (The criterion for the regression performed is minimization of the total squared error or residual. The error is the algebraic difference between an actual datum and its predicted value, which is squared to eliminate the effect of sign. Solver adjusts the fitting coefficients until the total squared error has been minimized.) The A36 CVN data are summarized in Figure 2 for several plate thicknesses. These data plots indicate variability with plate thickness. The fitting coefficients are summarized in Table 11.

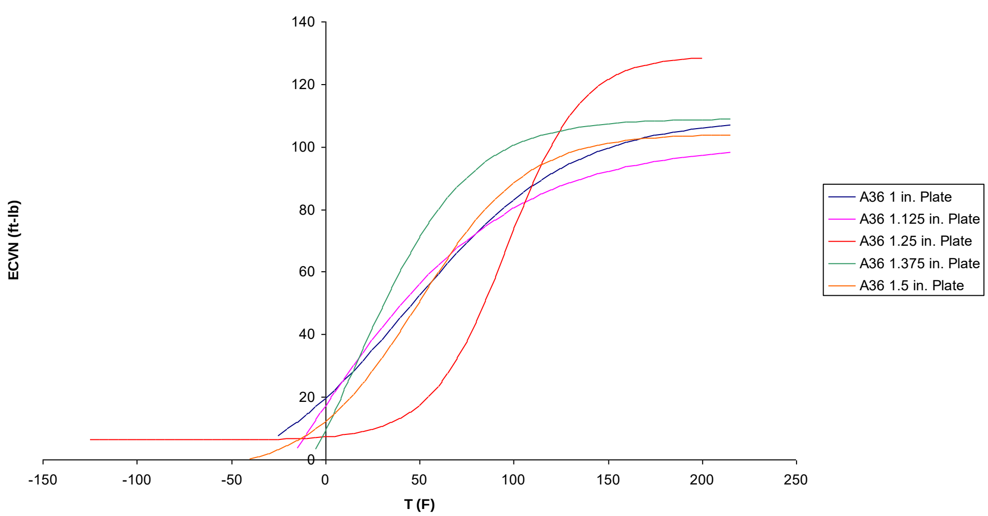


Figure 2: CVN energy data for A36 steel.

Table 11: Summary of Fitting Coefficients for A36 CVN Energy

	A	B	C	D
1 in.	48.44	60.62	85.49	44.16
1.125 in.	3.14	97.68	107.71	-15.68
1.25 in.	67.73	61.39	39.74	95.94
1.375 in.	29.69	79.36	59.25	15.36
1.5 in.	49.89	54.35	57.23	48.94

The tanh plotting allows transition temperatures at various CVN energy levels to be easily determined. A summary of transition temperatures at various CVN energy levels is provided in Table 12. It is evident that A36 steel will not generally possess adequate notch toughness at the lowest Arctic temperatures.

Table 12: Summary of Transition Temperatures (°F) as a Function of CVN Energy and Plate Thickness for A36 Steel.

	15 ft lb	20 ft lb	25 ft lb
1 in.	-9	1	9.5
1.125 in.	-2.5	3	9
1.25 in.	45	55	62
1.375 in.	4	8	12
1.5 in.	5.5	13	21

6.2.2 A572 Grade 50

The CVN energy data for A572 Gr 50 steel are summarized in Figure 3. Plotting coefficients are listed in Table 13 and transition temperatures in Table 14.

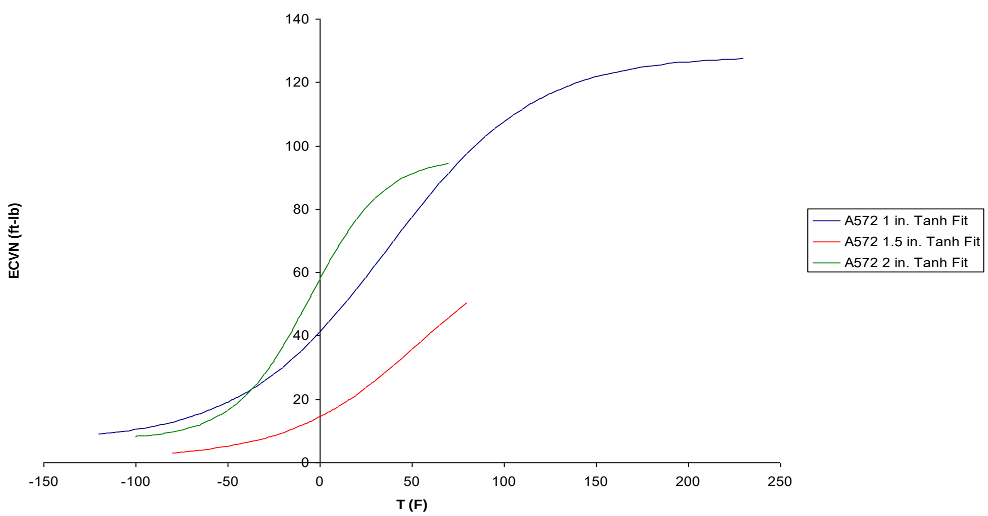


Figure 3: CVN energy data for A572 Gr 50 steel.

Table 13: Summary of Fitting Coefficients for A572 Gr 50 CVN Energy

	A	B	C	D
1 in.	67.57	60.99	79.89	36.78
1.5 in.	37.71	36.17	70.35	53.77
2 in.	52.02	44.58	40.56	-5.76

Table 14: Summary of Transition Temperatures (°F) as a Function of CVN Energy and Plate Thickness for A572 Gr 50 Steel

	15 ft lb	20 ft lb	25 ft lb	ft lb at 40 F
1 in.	-67	-47	-32	22
1.5 in.	2	16	28	6.2
2 in.	-54	-42	-34	21

It is noted that the data for 1.5 in. thick plate seem to be inconsistent. While it is unknown why 1.5 in. thick A572 Gr 50 plate exhibits significantly lower toughness, it is possible that thermomechanical processing to produce the specified yield strength has produced a microstructure and/or state of precipitation that results in lower toughness. However, in general, the A572 Gr 50 steels appear to possess greater notch toughness, which is consistent with microalloying and more sophisticated processing.

6.2.3 A131 EH36

The CVN energy data for A131 EH36 steel are plotted in Figure 4. Plotting coefficients are summarized in Table 15 and transition temperatures in Table 16.

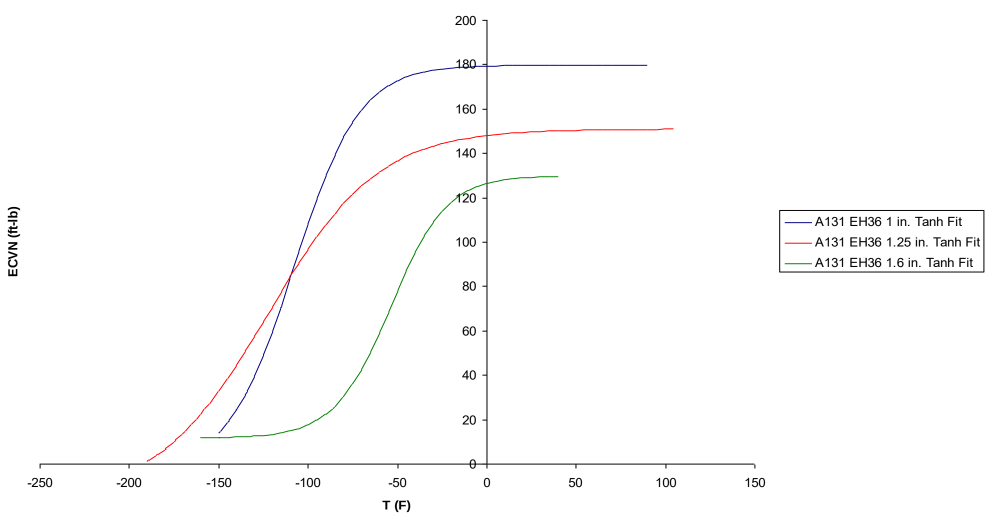


Figure 4: CVN energy data for A131 EH36 steel.

Table 15: Summary of Fitting Coefficients for A131 EH36 CVN Energy

	A	B	C	D
1 in.	88.77	91.11	36.50	-108.01
1.25 in.	67.82	83.20	61.52	-122.41
1.6 in.	70.82	59.07	31.15	-54.00

Table 16: Summary of Transition Temperatures (°F) as a Function of CVN Energy and Plate Thickness for A131 EH36 Steel

	15 ft lb	20 ft lb	25 ft lb	ft lb at 40 F
1 in.	-149	-144	-139.6	175.6
1.25 in.	-168.5	-162.5	-157.5	140
1.6 in.	-110	-95	-86	96

These data appear consistent as a function of plate thickness, with notch toughness decreasing with increasing thickness. In addition, the notch toughness of A131 EH36 steel is generally high and appears quite adequate for Arctic service.

6.2.4 A514

The CVN energy data for A514 steel is summarized in Figure 5. Plotting coefficients are summarized in Table 17 and transition temperatures in Table 18.

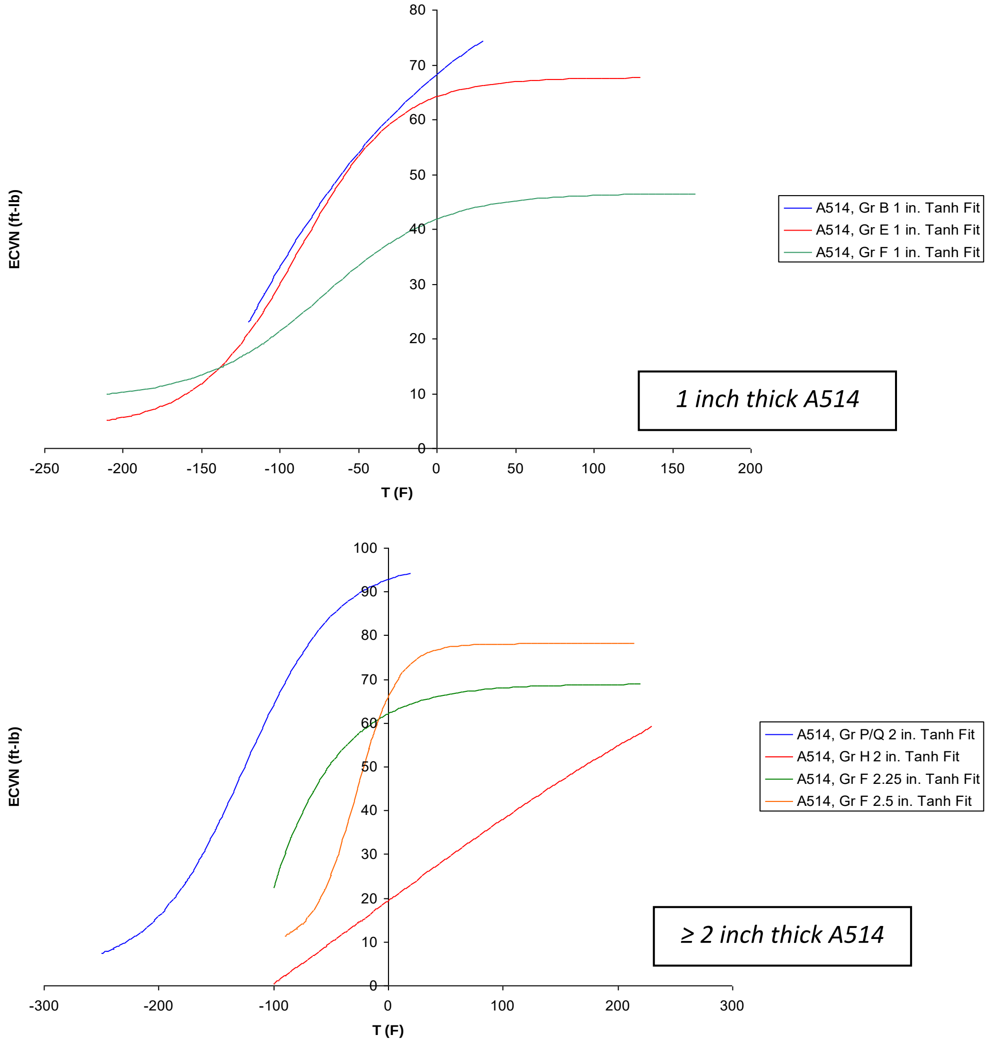


Figure 5: CVN energy data for A514 steel.

Table 17: Summary of Fitting Coefficients for A514 CVN Energy

	A	B	C	D
A514, Gr B, 1 in.	-35.64	127.92	187.68	-213.07
A514, Gr E, 1 in.	35.79	31.90	62.62	-88.78
A514, Gr F, 1 in.	27.74	18.83	75.98	-73.53
A514, Gr P or Q, 2 in.	50.06	46.64	79.92	-125.41
A514, Gr H, 2 in.	16.43	84.87	443.05	-15.56
A514, Gr F, 2.25 in.	-189.64	258.61	99.93	-215.64
A514, Gr F, 2.5 in.	43.65	34.51	36.54	-28.62

Table 18: Summary of Transition Temperatures (°F) as a Function of CVN Energy and Plate Thickness for A514 Steel

	15 ft lb	20 ft lb	25 ft lb	ft lb at 40 F
A514, Gr B, 1 in.	—	—	-116	57
A514, Gr E, 1 in.	-135	-122.5	-111	56.6
A514, Gr F, 1 in.	-135	-107	-85	35.6
A514, Gr P or Q, 2 in.	-203.5	-187	-173.5	86.9
A514, Gr H, 2 in.	-22.5	3	30	11.75
A514, Gr F, 2.25 in.	—	—	-97	54
A514, Gr F, 2.5 in.	-72	-59	-50.5	33.24

The CVN data vary with grade and thickness but are generally quite high, consistent with higher alloying and a Q&T process. Note that there are no CVN energy values for the 2.25 inch thick A514 plate because the data set does not include data for lower temperatures.

6.3 Summary

Steels for which CVN data have been collected and analyzed represent a fairly wide range of strength and toughness (group and class, per specifications). CVN data were reduced via application of a hyperbolic tangent-fitting routine. Data-fitting is beneficial for unambiguously determining transition temperatures.

As expected, the notch toughness of A36 steel is generally not adequate for the lowest temperatures anticipated in Arctic service. However, other steels considered in the investigation possess notch toughness values that could prove useful in Arctic service.

7. Challenges for Developing New Cranes and for Qualifying Existing Cranes

7.1 Developing New Cranes

Developing new cranes for Arctic service requires adherence to the same design practices and specifications used for all offshore cranes plus added focus on the effects of extreme cold service conditions. The same design guidelines are required to provide a crane with adequate strength and design capacity to resist yielding and buckling/instability. The same concerns are required for fatigue design as for cranes in more temperate regions. However, the extreme cold service conditions result in greatly increased propensity for brittle fracture.

For new cranes, the codified option available to the manufacturer is to select materials that satisfy the code-specified Charpy toughness requirements. If this can be accomplished for a test temperature below the LAST, this represents an excellent start in preventing brittle fracture. However, improvements could be made to the existing crane codes to provide additional guidance on steel selection and guidance on methods to ensure that welding, bolting, wire ropes, etc. will perform adequately. For example, weld deposits and heat-affected zones should be required to exhibit toughness that is at least equal to the base metal. Design of crane connections and other details to minimize stress concentrations due to design configuration or weld profiles and to reduce residual stresses caused by welding should be considered for limiting local stresses than can lead to fatigue cracking that may later result in brittle fracture.

Added guidance could also be given by the codes on various subjects such as providing warming and shielding for the mechanical/hydraulic equipment, slew ring, and slew ring bolting to shield them from extreme temperatures. Designing these items to function properly in extreme service temperatures may be very difficult.

Also, guidance should be given on what to do when the environmental temperature falls below the design temperature. Typically this guidance would be to cease crane operations and park the crane in the stowed condition (in the boom rest or other arrangement) until temperatures increase above the LAST.

7.2 Inspection Requirements/Guidelines

Two basic types of inspection requirements are applicable to cranes (as well as other kinds of engineered equipment and systems). The first of these is typically referred to as "workmanship standards." The second type (which many codes and industry standards have adopted as an alternative to workmanship standards) is based on the concept of fitness-for-purpose, which equates quality with the fulfillment of a specification, a set of specifications, or stated outcomes. The notion derives from the idea that manufacturers and end-users purportedly assess a product against its stated purpose. Although API 579/ASME FFS-1, "Fitness for Purpose," has been developed over the years for assessment of pressure-containing equipment, to SES's knowledge, a similar standard for assessment of structural application has not yet been developed. Joint development of such a standard by industry, code-writing bodies, and regulators would represent a significant advance in this area.

7.2.1 Workmanship Standards

First and foremost, workmanship standards reflect what experience indicates that "the average journeyman workman can reasonably be expected to produce using average equipment on an average day." However, workmanship standards also reflect industry experience related to typical uses and design margins for equipment as well as reported failures. While workmanship standards were historically set based on the concept of what could reasonably be expected of an experienced and qualified worker, most sets of acceptance criteria have evolved to reflect changes in equipment usage, increases or decreases in design margins, and failure histories. Workmanship standards also evolve based on improvements in nondestructive examination (NDE) technology.

7.2.2 Fitness-for-Purpose Standards

Fitness-for-purpose standards are increasingly applied by quality agencies, mainly because these allow a more direct assessment of serviceability than do workmanship-based standards. Direct assessment is made possible via development of the science of fracture mechanics, which relates a material's inherent resistance to crack propagation to the available driving force in a component or structure for flaw growth or propagation.

As fracture mechanics was originally conceived, it was assumed that a given material exhibits a single, lower-bound fracture toughness value when it experiences a plane-strain stress state. It was further assumed that this fracture toughness value, referred to as K_{IC} or the linear elastic fracture toughness, would be independent of flaw geometry, flaw size, and structural details. Deviations from plane-strain would, therefore, result in an increase in resistance to crack growth or propagation. This is the continuum-mechanics view adopted in most fracture-mechanics texts in use today. However, improved understanding of materials behavior has revealed that the continuum-mechanics description of fracture criteria is insufficient and may lead to major misconceptions about the failure process. Thus, one problem with the application of fracture-mechanics principles to development of inspection requirements for cranes is that, while the application of fracture-mechanics principles in design is well understood by some, these same principles are misunderstood and therefore inappropriately applied by others. Misapplication of these principles can lead to a false sense of security related to a crane's fitness for service (FFS). When applying FFS standards to cranes, one must be extremely careful to not overestimate either a material's or a structure's resistance to fracture or to underestimate the effects of applied stress, flaw geometry, and structural details with respect to how they contribute to crack driving forces. ASME VNV10-2006, "Guide for Verification and Validation in Computational Solid Mechanics," provides information on verification and validation of both classical and fracture-mechanics-based design methodologies.

Another problem with setting inspection standards based on FFS requirements, is that the purpose for a component may be determined based on potentially competing ideas; that is, the purpose of a component (such as a crane) may be determined based on the manufacturer's needs or the needs of the end user. The needs of manufacturers, end users, and regulators must be effectively reconciled if fitness-for-purpose inspection standards are to be applied to cranes.

7.2.3 API 2C

API 2C requirements for NDE of critical crane components (found in Section 11.3 of that document) are essentially workmanship standards. This standard requires the use of written NDE procedures (para. 11.3.1) and qualified NDE personnel (para. 11.3.2). Paragraph 11.3.3. specifies the minimum extent of NDE, which shall include all critical components of a crane, as identified by the manufacturer.

Unlike other standards such as API 1104 (pipeline welding), API 2C requirements do not specify actual acceptance criteria, that is, limits on the size and distribution of discontinuities allowed to exist in either base materials or welds. Table 28 in the latest edition of API 2C (7^{th} edition, dated March 2012) does, however, provide examples of some recognized procedures for conducting NDE as well as acceptance criteria for welds and base materials that are based mainly on AWS D1.1 (welds) [Ref 45] and ASTM A578 (base materials) [Ref 46].

API 2C also allows for development of acceptance criteria that are based on fitness-for-purpose evaluations. When these criteria are used, they shall consider applied and residual stresses, materials properties, environmental exposure, and limitations of the selected NDE method for detection and evaluation (sizing) of imperfections. The document provides no further guidance on how to ensure that these considerations are given proper weight in the overall analysis.

7.2.4 Suggested Inspection Guidelines

The workmanship-based inspection requirements included in AWS D1.1 [Ref 45], which is widely used in crane construction, are generally more stringent than those resulting from a fitness-for-purpose analysis. This should not be surprising since most FFS assessments are performed to "clear" a component or structure that contains flaws in excess of what is allowed under the workmanship rules. Thus, if fitness-for-purpose inspection standards are to be applied to new cranes, an engineering assessment should be conducted (at least for critical components) to determine the increased level of risk that will be experienced if a less stringent set of inspection criteria is applied. This assessment should consider technical as well as economic issues, i.e., a cost/benefit study.

When fitness-for-purpose inspection requirements are applied to cranes, the limitations of selected NDE methods for detection and sizing of imperfections should be formally evaluated. For each type of flaw being considered, the evaluation should determine and report the following characteristics for each NDE method:

- Probability of detection
- Expected sizing error
- Probabilities of Type I and Type II inspection errors

In the routine (or non-routine) inspection of components or structures, there are only four possible results:

1. A defect is indicated where one exists
2. No defect is indicated where one exists
3. A defect is indicated where none exists
4. No defect is indicated where none exists

Only outcomes 1 and 4 result in correct acceptance/rejection decisions. Outcome 2 is referred to as a "miss," and results in false acceptance (Type I inspection error). Outcome 3 is a false indication and results in false rejection of an otherwise acceptable component (Type II inspection error).

For any NDE method, the frequency of false acceptance errors can be reduced by lowering the specified value for the maximum acceptable response. Unfortunately, this approach often increases the frequency of false rejections to an unacceptable level. An effective and practical inspection program must achieve a reasonable balance between Type I and Type II inspection errors. Such a balance can be achieved only if the probability of detection and the expected sizing error are both known and handled effectively. For additional information on this subject, readers are referred to treatises and texts on quality and the application of statistical methods to inspection problems.

7.3 Qualifying Existing Cranes

Qualifying existing cranes for colder service conditions than specified during their design and fabrication is difficult at best. Material selection for the base metal and weld metal is not possible. Improving design details of welds and attachments is difficult (if not impossible). Unless detailed information related to welding and fabrication, material properties, and past inspection history for a particular crane is available, it is probably not practical to determine the adequacy of an existing crane for service in colder conditions than those specified at the time of fabrication. On the other hand, if the current condition of the crane can be determined (based on inspections such as those described in Section 7.2.4), and detailed information exists related to the crane's welding and fabrication, inspection history, and materials properties, and the industry can agree on a document similar to API 579 for determining a crane's FFS; then it may be possible to de-rate a crane to the point where it is considered safe to use at somewhat reduced temperatures. However, the de-rating is likely to be significant, which may render the crane unsuitable for the required tasks.

8. Selection of Design Temperatures for Arctic Service

Selection of lowest anticipated service temperature (LAST) to be used for the design of an offshore crane must consider the possible environments in which a crane might be used. For a mobile offshore drilling unit (MODU), this task is complicated by the transportability of the unit. Depending on where oil and gas exploration is planned, these MODUs may operate all over the world. This is also true for "transportable" production systems such as FPSO's (floating production, storage, and offloading units). For relatively fixed production installations (jackets, man-built islands, gravity-based platforms), the selection of a design temperature can be more site-specific.

ISO Standard 19906:11 (Canadian CSA standard [Ref 1]) provided a great deal of information on temperature conditions in the Arctic and near-Arctic regions of the northern hemisphere. Annex B in that document provides average annual minimum temperatures and their range for many regions. Table 19 presents a compilation of this information for a few locations.

Table 19: Annual Minimum Temperatures [Ref 1]

Location	Average Annual Min Temp, °F (°C)	Range of Annual Min Values, F (°C)
Baffin Bay and Davis Strait	-38 (-39))	-36 to -42 (-38 to -41)
Labrador	-15 (-26)	-13 to -40 (-25 to -40)
Canadian Arctic Archipelago	-40 (-40)	-31 to -49 (-35 to -45)
Beaufort Sea	-22 (-30)	-4 to -40 (-20 to -40)
Chukchi Sea (Northeastern)	-47 (-44)	-40 to -58 (-40 to -50)
East Siberian Sea (Cape Billings)	-58 (-50)	-60 (-51)

Also, an article [Ref 2] was recently published by the American Bureau of Shipping (ABS) that provided information for the Barrow, Alaska area. The ABS article provides information on exposure times at minimum temperature, as well as probability of occurrence. Their findings indicate a 5% probability (approximately) that up to 100 hours of exposure is possible at this location at -40 °C (-40 °F). The worst-case temperature for a brief (1 hour) exposure is -46 °C (-51 °F). Figure 6 shows a graph from their article showing extreme temperature versus time of exposure and probability of occurrence. This type of data for other locations would be extremely valuable for designers in selecting LASTs and in predicting the probable lowest actual temperature to be encountered at possible rig locations.

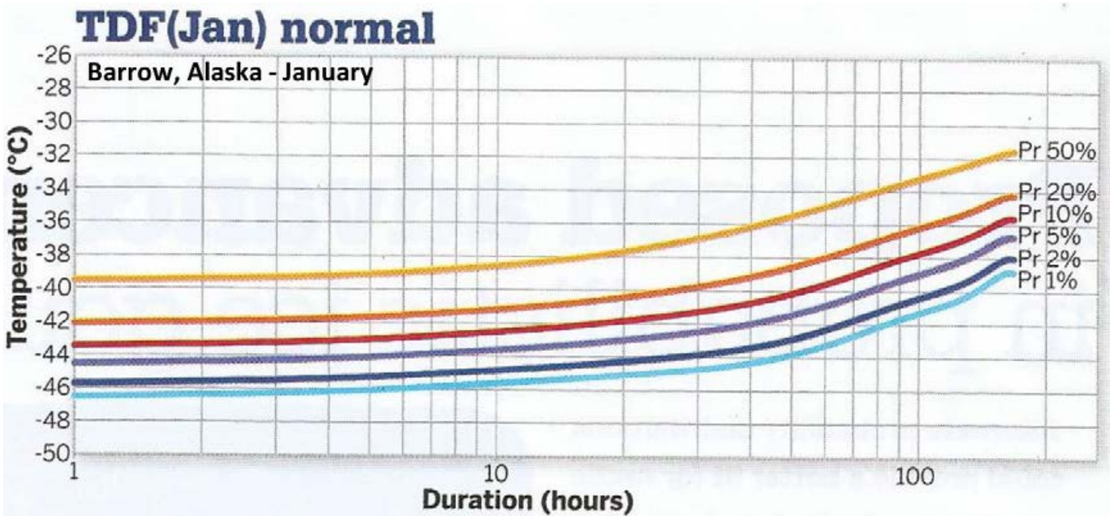


Figure 6: Annual minimum temperatures for Barrow, Alaska [from Ref 2]

Based on the above information, selection of -40 °C (-40 °F) seems reasonable for a LAST value for this study. It should be noted that, if the temperature is occasionally lower than this limit, the crane can be placed in its rest position until the temperature returns to above LAST levels. This approach is similar to current practice regarding lifting operations and sea/wind conditions. Cranes are not used in high wind/sea-state conditions. Lifting operations are ceased until conditions become more favorable.

No matter how low the LAST is specified for the crane, other factors may limit actual crane operations in cold weather. Whenever the crane is in use, riggers must be working in the same environment. Human factors, visibility, and other considerations may limit actual operation minimum temperature before the crane limitations are reached.

9. Survey of Industry

9.1 Crane Manufacturers

The project team performed a survey of a number of offshore crane manufacturers regarding their experience and gathered their comments on crane design for extreme cold service. The survey results are listed in detail in Table 20.

In general, these manufacturers have designed cranes with LASTs specified in the range of -4 °F (-20 °C), with a few designs down to about -40 °F (-40 °C). For structural design, they follow the crane design code specified by the purchaser (API 2C for USA typically). The crane code specifies the required minimum Charpy test results at some temperature slightly below LAST (10 °F or 6 °C below LAST in API 2C). Steels are chosen to satisfy those requirements, and weld metals are chosen to be strength-compatible or slightly overmatched to the base metal. Typically, no special considerations (beyond the manufacturer's normal design efforts) are taken on the structural components to minimize stress concentrations and no added material analyses (fracture-toughness/fracture-mechanics calculations) are performed.

For mechanical components, most manufacturers consider similar Charpy toughness requirements as for the structural items. Most of their concerns for mechanical components are focused on keeping the mechanical item operational. These include selection of fluids, heaters, pre-warm up prior to operation, etc. to ensure that the equipment will function mechanically.

Table 20: Survey Responses from Selected Offshore Crane Manufacturers

Questions posed to Crane Manufacturers:

1. Have you had any cold temperature service cranes (or looked at the design / material selection for such cranes)? If so, what is the lowest temperature that was considered?
2. What materials would / did you consider for use for critical structural members?
3. What materials would / did you consider for use for cold weather cranes for the critical mechanical components?
4. For the materials you mentioned above, are the material properties such that ductile behavior would be expected at these cold temperatures?
5. Are there typically any special operating precautions, particularly design factors, considerations for those components?

Manufacturer "B" Response

We typically don't change the actual material specifications (yield strength), but we do ensure that the steel we get passes a Charpy impact test at a specific temperature. A case in point is when we would normally specify A572 Gr 50 we would change that to API 2H Gr 50 because the API plate comes with Charpy tests already done. I don't know the temperature on those tests, though, and I think the "service temp" will dictate the temperature you need for the Charpy tests. In this case, the API plate may not be done at a cold enough temperature for your needs – negative 40 is COLD!!! As you noted, this could lead to a situation where we would select the next model size larger from the data-sheet to make up some of the difference. Another aspect you'd have to look at is all of the purchased parts – hoists, pumps, motors, bearings, gearboxes, etc. – to make sure all of them are capable of operating in extreme cold service conditions. Heck, even bolts and wire ropes and wedge sockets come into question when you get that cold.

Table 20 (Cont'd): Survey Responses from Selected Offshore Crane Manufacturers

acturer "C"

Manuf Response	
	1. We have never designed a crane for a Design Service Temperature (DST) = -40°C. However, we have designed many cranes for DST = -20°C. -20°C tends to be a common service temperature required by many of our customers. Typically, this is dictated by the DST of the rig or vessel that the crane is to be installed on.
	2. We have developed over the years several material specifications for critical structural members. These specifications define the material description, chemistry requirements (if anything beyond a referenced standard), mechanical requirements, material toughness (Charpy) requirements, traceability requirements, and various reports or documentation required with the material. Some may have additional requirements such as Ultrasonic Testing, Through Thickness Testing, Heat Treatment requirements, etc. Some specific critical member materials that we typically use as an example would include: Bars, Plates, Shapes, High-Strength Low-Alloy Structural Steel (50 ksi Yield) would conform to standards such as ASTM A131 Grade DH-36, ASTM A572 Grade 50, ASTM A588, ASTM A633 Grade C, API 2H Grade 50, EN 10113-2-S355NL, EN 10025-S355K2G4 or EN 10028-3-P355NL1/NL2. Plates, High Strength Alloy Structural Steel (100 ksi Yield) would conform to ASTM A514, EN 10025-6 – S690QL1 or EN 10028-6 – P690QL2. Tubing, Carbon Steel, Cold-Formed, Welded, Rounds and Shapes (46 ksi Yield) would conform to ASTM A500 Grade B or EN 10210-1-S355J2H. Stainless Steel Forging or Bars (100 to 125 ksi Yield range) would conform to ASTM A705, ASTM A564 UNS designation S17400 Type 630-H1150D or EN 10088-3 – 1.4542.
	3. Any or all the above mentioned would be recommended.
	4. Yes, we would typically be required to meet the toughness (Charpy V-notch) requirements of say the ABS Guide for Lifting Appliances, Lloyds Code, Bureau Veritas or such.
	5. I would think that for an operating service temperature of -40°C one would need to pay close attention to the lubricates and fluids used, using fluid heaters or pre-heat warm-up procedures for any machinery.
Manufacturer "D" Response	
	At the end it's all about rules and regulations and what they specify in regards to design and material test-temperatures. There is a design temperature and then you need to source the material which perform the tests (impact tests) at deeper temperatures and it needs to pass.
	Test of materials at minus 40°C is a normal range for S355/S690 steel, even -60°C tested material can be purchased. However, if the design temperature is specified below -30°C it is always recommended to contact the classification society as sometimes they specify the test temperature based on plate thickness and then you wouldn't get the material purchased to what the standards mention (as simply no more available) and then a "special consideration" would have to be agreed upon up front.
Manufacturer "E" Response	
	1. We've designed and manufactured cranes with a service temperature of -50F and have made many others at service temperatures approaching that low.
	2. We used A514 for the critical structural members.
	3. If by critical mechanical components you mean cylinder stem and barrel material then I will only say that those are the toughest items by far to find. (R. Long note - he is referring to the main boom lift cylinder on a cylinder lift crane)
	4. Material properties are such that ductile behavior is expected at the cold temperatures.
	5. Other than using API and/or ABS requirements we don't use any special design factors or deratings. We do warn that hydraulic systems must be warmed for proper operation.

Table 20 (Cont'd): Survey Responses from Selected Offshore Crane Manufacturers

Manufacturer "F" Response	
	1. On recent considerations of cranes, we had considered some -50C applications. However, we did not progress to construction due to project cancellation due to other reasons.
	2. For critical structure, we considered AB/FQ type material for both tubing and for plate. However, since the normal -20C below service temp is beyond the FQ range we were focused instead on brittle transition curves based on CVN testing at various temps down to -60C and -70C. Historically we used 15 ft-lbs minimum L-CVN as being proof that structural material exhibited ductile failure. While manufacturing processes need to be controlled a little more, a number of now common grades can meet this at those low temps, including A514 (especially when manufactured for consideration of A517) for plate. A333 is a pipe spec (lower strength) that is designed for the cold temps. For higher strength pipe / tubing, we had some proprietary materials, plus there are some offerings from Vallourec and SumiSTRONG that work.
	3. For machinery components, we generally have had very good success with controlled chemistries (extra clean, etc) of 4820 and 9310 for carburized forgings. We have some modifications of 4330 that can achieve very high thru-hardness with ductile behavior below -60C. To a lesser extent, 4340H as well. As far as standards go, however, we strongly push back against CVN requirements on machined/ground parts (gears) and instead would prove resilience of the finished component based on a destructive (impact) test on a sacrificial part. We consider the testing and the acceptance criteria based on how the part could be impact loaded in service.
	4. Yes, but we have found that extra specifications are needed to guarantee extra clean material, fine grain structure, and good grain flow. Using premium material (sometimes difficult to get for forgings and castings, though…) we have successfully gotten "ductile" behavior at lower than usual temperatures.
	5. Caution on startup (ensuring all machinery/electrical systems are operational), synthetic lubricants, and sometimes special seals are the main things that seem to crop up. We have used space heaters on some electronics, depending on whether the specific components were designed to MIL spec or not.
Manufacturer "G" Response	
Following answers are for service temperature of -20C. They have not looked at colder than that	
	Slew Bearing
	- Standard API 2C bearing material is acceptable for this service temperature.
	- Standard bearing grease should be acceptable, but may want to verify.
	Winches
	-Ductile iron side plates of winch are NOT good for this service temperature. Would require fabricated side plates from material with increased notch toughness, such as API 2H Gr. 50.
	- Brake valves may stick or have slow response due to viscosity of hydraulic oil at this temperature.
	- Would probably need a different type of synthetic oil for this temperature service.
	- Hydraulic signal pilot lines may "freeze up" or have bad response due to viscosity of the oil at this temperature.
	- Even with heaters for hydraulic oil, some pilot lines with little or no flow may give problems.
	- Winch drum would need to be fabricated from a material with suitable notch toughness at this temperature.
	- Would have to verify notch toughness of gearbox gears.
	Swing Drive Gearboxes
	- Eskridge 252 series gearboxes are suitable for use at this temperature. They don't become concerned with temperature until about -20°F.
	- We may want to consider using a 65 wt or synthetic gear oil for sustained operation at -4°F.
	Sheaves
	- Material for polymer sheaves is suitable for use at this service temperature. Material strength, "brittleness", and water absorption should be ok.
	- However, would need to order different sheaves because the bearings would need to be changed and the sheave bore would have to be machined to a different tolerance.
	- Would need to use different sheave grease.
	Major Structural Materials

Table 20 (Cont'd): Survey Responses from Selected Offshore Crane Manufacturers

Manufacturer "G" Response, continued	
Following answers are for service temperature of -20C. They have not looked at colder than that	
	Major Structural Materials
	- ALL plate on the crane would be API 2H Gr. 50 with 100% grid UT, though thickness, and Charpy impact test supplements.
	- Front and rear gantry legs would be made from API 2H Gr. 50 fabricated into shapes. These fabricated shapes would require 100% full penetration welds between the webs and flanges with 100% x-ray or other suitable NDE inspection of all welds.
	- Gantry horizontal members may be made from API 2H Gr. 50 plate fabricated into suitable shapes or possibly A333 pipe or A500GrB "R.O.P.S." square tubing Charpy impact tested in accordance with A370. Final design will depend on further research into these last two material types. Discussion of these materials follows:
	- A333 is a pipe specification that comes with Charpy impact testing. Physical / mechanical properties for A333 are similar to A106 Gr. B (35 ksi yield). Sizes are fairly readily available up to 24" OD. A possible work around would be to order API 5L Gr. X52 pipe, normalize using a proprietary process (USX?) and be certified to A333 with required Charpy toughness (probably). The pipe will only be guaranteed to A333 (A106 Gr. B) strength requirements. However, the pipe will probably have strength characteristics better than or equal to API 5L Gr. X42, and with the good impact strength required by the A333 specification. The big problem here is all the times you see the word "probably", and not being able to order to a standard, straight forward specification.
	- "R.O.P.S." square tubing gets its name from "Roll Over Protective Structure" and is a type of tubing developed for use in roll cages on heavy machinery. Basically, it is produced from coils of future ERW A500 Gr. B or C tubing that have very low carbon content, and high manganese to carbon ratios (about 5.5:1) which usually provides very good notch toughness at low temperature. Here again, it can only be produced from specific heats that have certain chemical ratios, not all A500 Gr. B or C will work. The documentation on ROPS tubing seems to vary depending on the particular mill that produced it. Some MTR's will certify the material to A500 Gr. B or C, and show the Charpy tests, but NOT state that the heats were tested in accordance with the Charpy impact testing requirements of ASTM Specification A370. MTR's from other mills may not certify to an A500 Grade spec, but instead just show "ROPS Tubing" with the associated data and Charpy tests performed to A370. Here again, we will have a problem with there not being a real standard for this type of material. There may be some issues with weldability, although at this point, more research would be needed and some weld tests would certainly be required.
	- From a material standpoint, the preferred option for the boom chords and lacings would be to press brake API 2H Gr. 50 plate into angle shapes. While angle chord booms are generally not as resistant to damage from impacting objects, they are certainly used frequently worldwide and may be the lesser evil in this situation. Weld procedures and material characteristics for API 2H Gr. 50 chords and lacings would not be a problem.
	- There may be some other material options out there that may warrant further investigation. They include API 5L Gr. X42 pipe with "PLS1" or "PSL2" supplements, A514 (T1) plate, and "HSLA" 70 ksi yield square tube. All of these have Charpy impact testing supplements that may make them suitable for certain situations. However, weldability especially for field repairs may discourage their use.

9.2 Wire-Rope Manufacturers

A brief survey was also completed of several wire-rope manufacturers. Wire rope is critical in offshore crane operations. These wire ropes provide the means to lift the loads and move the boom to the desired radius (lifting or "luffing" the boom).

Three wire-rope manufacturers responded to the e-mail survey. Table 21 lists the questions asked and the responses of the manufacturers. In summary, all three vendors indicated that their standard ropes were acceptable down to -40 °C design temperatures and that no reduction in design strength was required.

They also indicated that the main problem observed in cold temperatures down to the -40 °C level is to ensure that the ropes remain lubricated. Providing the rope with the appropriate lubrication initially, and field dressing for re-lubrication that is compatible for the low temperatures, is important to ensure the proper operation and life of wire ropes.

Table 21: Survey Responses from Selected Wire Rope Manufacturers

Vendor Survey – Wire Ropes for Cranes & Drilling Systems

Three wire rope vendors were asked for input on design temperatures for wire rope that is used on cranes and drilling systems. The responses are summarized in the following for Vendor A, B, & C:

1. Are the wire rope types typically used on offshore cranes acceptable for extreme cold service down to -40°C?
   A. Our ropes are acceptable to -40°C
   B. Ditto
   C. Ditto
2. Do they still behave normally (not prone to brittle fracture at normal operating load levels)?
   A. Down to the -40°C it will have normal behavior
   B. Normal behavior.
   C. Behavior is normal
3. Are the same materials acceptable as are used for warmer applications?
   A. Standard ropes with standard materials
   B. Ditto
   C. Ditto
4. Are there any special operating precautions or increased design factors?
   A. There is nothing to consider. The same breaking load is guaranteed.
   B. No increased design factors. Use field dressing for re-lubrication that is compatible for the low temperatures.
   C. No increased design factors. Use field dressing for re-lubrication that is compatible for the low temperatures.

10. Proposed Additional Design Procedures

The design procedures in the existing offshore crane specifications should be followed with regard to strength, buckling/instability, and fatigue. The same material factors of safety, load factors, and design approach should be used to address these failure modes. Additional design procedures discussed here should be used to address the increased propensity for brittle fracture during extreme cold weather service conditions.

All critical crane components (and their connections and subcomponents) should be reviewed/revised as necessary to satisfy this cold-weather design approach. Different methods may be used for various crane components as needed, but the designer should ensure that all critical crane components will not be subjected to brittle fracture during operations within the LAST and the specified crane design operating conditions.

Possible methods to consider to improve/provide cold-weather performance for the various crane components are as follows:

- Selection of materials that satisfy required Charpy levels at test temperatures below LAST
- Selection of fine-grain, enhanced toughness steels to improved cold temperature ductility
- Modification of welds, connections, and other details to reduce peak stresses
- Use of fracture mechanics with material constants based on tests of materials and weld procedures to evaluate flaw tolerance
- Rigorous inspection of the crane during fabrication to ensure actual details are less than the critical defect sizes established by fracture-mechanics analysis
- Shielding/heating of mechanical/hydraulic components to provide higher temperatures for these items

11. Correlations Between Charpy and Fracture Toughness

11.1 Background

As mentioned previously in Section 2.1, most steels used for crane construction are ductile at room temperature and slightly below. Additionally, most crane components are not very thick. As a result, it is typically difficult (expensive and slow) to measure valid linear elastic fracture toughness values, i.e., K_{Ic} values, for most crane materials of construction directly using existing industry standards such as ASTM E399. Alternative fracture toughness testing methods (e.g., J_{Ic} and CTOD testing per ASTM E1820) exist that are potentially better suited for testing ductile crane materials. However, even when valid alternative measurements of fracture toughness values can be obtained, designers must ensure that those fracture toughness values are relevant to the failure mode(s) of interest.

On the other hand, impact toughness (CVN) testing is an economical, easy-to-perform test that is widely used for ranking steels that undergo a ductile-to-brittle transition (DBT) with decreasing temperature. However, the dynamic nature of CVN testing does not represent all the service conditions under which brittle fracture can occur. More specifically, CVN testing is not representative of service conditions associated with quasi-static loading of crack-like defects to produce unstable fracture. CVN testing does not afford any opportunity for fundamental consideration of the interrelationship of applied stress and defect size. The interrelationship of applied stress and defect size, with regard to unstable fracture, is embodied in fracture mechanics, specifically fracture toughness.

The relationship between fracture toughness, defect size, and applied stress can perhaps best be understood by considering a through-thickness crack in a plate of infinite dimensions. The stress intensity factor, K, for such a plate subjected to uniform stress, σ, and containing a through-crack of length 2a is:

$$K = \sigma\sqrt{\pi a} \qquad \text{Equation 2}$$

Orowan and Irwin [Ref 47] demonstrated the equivalence between stress intensity and energy-release rate at the tip of a propagating crack. Thus, the term on the left side of Equation 2 represents resistance to crack propagation (fracture toughness) while the terms on the right side represent crack driving force. Thus, given a value of fracture toughness, if Equation 2 is solved for a, the result is the critical crack size, a_c, for that fracture toughness. Moreover, Equation 2, which essentially represents an energy balance, indicates that, as long as the available fracture toughness is greater than or equal to the crack driving force, the crack will not propagate.

Since crane performance is more easily predicted using a fracture-mechanics approach while existing specifications for crane materials of construction feature the use of CVN compliance testing, a large incentive exists to correlate the results of simpler and less expensive CVN impact tests with fracture toughness values obtained at quasi-static or intermediate loading rates. These are far more useful for crane design purposes and for evaluating the FFS of existing (and perhaps damaged or degraded) cranes. Furthermore, since the cracks in fracture-toughness test specimens tend to produce brittle behavior (via constraint) as do the higher loading rates of CVN testing, it should not be surprising that correlations exist between the two test methods. There are numerous examples where engineering organizations such as the American Association of State Highway and Transportation Officials (AASHTO) and the American Society of Mechanical Engineers (ASME) have taken this approach. However, since there are significant differences between fracture mechanics and notch-toughness testing, both experience and engineering judgment must be applied if a similar approach is eventually adopted for evaluation of cranes for Arctic service.

One of the principal reasons why engineering judgment is required is that WRC Bulletin 299 [Ref 48] along with certain classic textbooks contain numerous examples of such correlations between CVN and K_{IC} values. It is left to the end user to determine the applicability of a specific correlation to a given design problem.

11.2 K_{IC}-CVN Correlations

Numerous K_{IC}-CVN correlations have been developed over the years. Figure 7 lists several of these correlations and shows a graphical comparison of their predictions. Most of the correlations were developed for specific materials or specific sets of conditions; this is the main reason that engineering judgment must be applied when using them. More specifically, many of the steels used in modern crane construction were not widely available when many of the existing CVN-to-fracture-toughness (K_{IC}) correlations were developed. Additionally, most of these correlations are purely empirical; few have been developed from a fundamental basis. In addition, no single correlation has been developed for the entire toughness transition curve; that is, many of the existing correlations were developed for specific regions of the transition curve: (1) the lower shelf transition region, (2) the transition region and (3) the upper shelf region. The end user must determine the applicability of a specific correlation to their situation.

- Barsom-Rolfe-Novak $\left(\frac{K_{IC}}{\sigma_Y}\right)^2 = 5\left(\frac{CVN}{\sigma_Y} - 0.05\right)$
- Sailors-Cortens $K_{IC} = 15.5\sqrt{CVN}$
- Thorby-Ferguson $K_{IC} = 43.6\sqrt{\frac{CVN}{A}}$
- Logan-Crossland $K_{IC}^2\left(\frac{1-\nu}{E}\right) = CVN$
- Lower-Bound $K_{IC} = 9.35(CVN)^{0.63}$

Units for these correlations are K_{IC} in (ksi√in), CVN in (ft·lb), σ and E in (ksi), and A in (in^2).

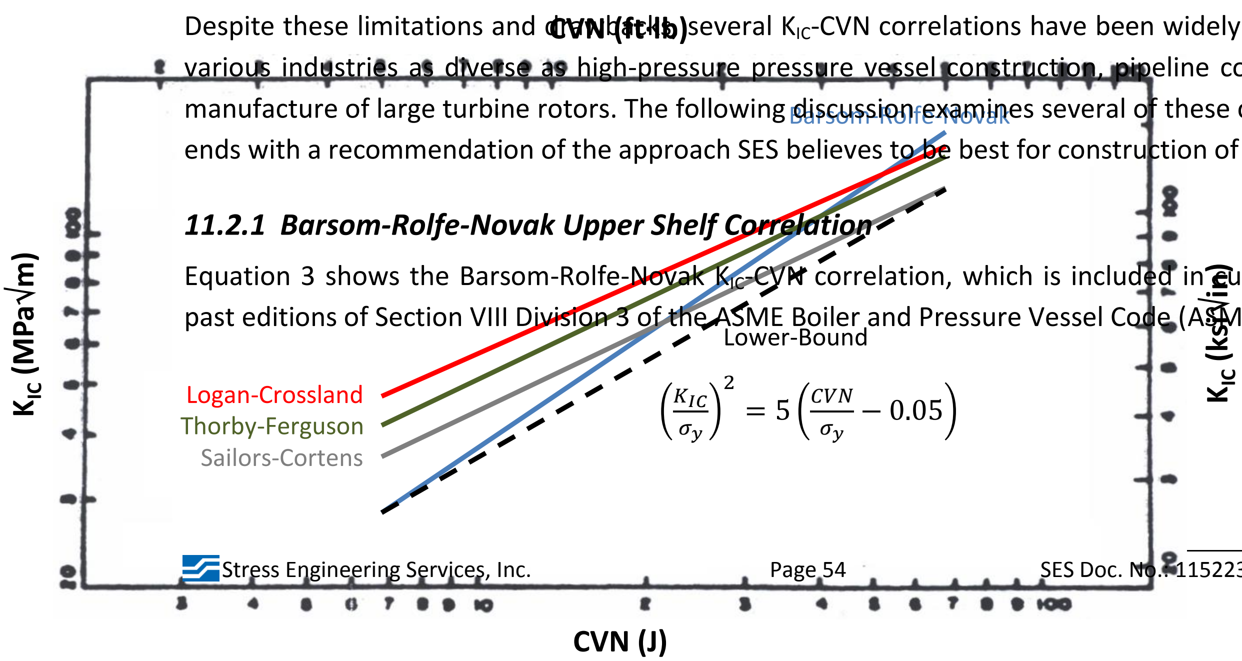
Figure 7: K_{IC}-CVN correlations

Despite these limitations and drawbacks, several K_{IC}-CVN correlations have been widely adopted across various industries as diverse as high-pressure pressure vessel construction, pipeline construction, and manufacture of large turbine rotors. The following discussion examines several of these correlations and ends with a recommendation of the approach SES believes to be best for construction of Arctic cranes.

11.2.1 Barsom-Rolfe-Novak Upper Shelf Correlation

Equation 3 shows the Barsom-Rolfe-Novak K_{IC}-CVN correlation, which is included in current as well as past editions of Section VIII Division 3 of the ASME Boiler and Pressure Vessel Code (ASME BPVC).

$$\left(\frac{K_{IC}}{\sigma_y}\right)^2 = 5\left(\frac{CVN}{\sigma_y} - 0.05\right) \quad \text{Equation 3}$$



As mentioned, units for this correlation as presented here are ksi√in, ksi, and ft·lb. Additional formulations in SI units can be found in ASME BPVC.

As indicated, this correlation is only to be used when converting upper-shelf CVN values to K_{IC}. Since the steels used in the construction of Arctic cranes are unlikely to exhibit upper-shelf behavior at a minimum-use temperature of -40 °F, this correlation, while useful in some applications, is unlikely to find much application in the venue of cold-weather cranes.

11.2.2 Barsom-Rolfe Two-Step Method

Based on data such as that shown in Figure 7, early workers in this field tended to believe (or make the simplifying assumption) that the K and CVN transition curves were of similar shape (i.e., they were parallel) and that the significant differences in, for example, loading rate and notch acuity between the two test methods could be effectively accounted for by a simple temperature shift. For example, in [Ref 47], Barsom and Rolfe propose a two-step method for predicting K_{IC} values from lower-shelf and transition-region CVN test results:

- Calculate "equivalent" K_{ID} (dynamic fracture toughness) from CVN data using:

$$\mathrm{K_{ID}} = 15\sqrt{\mathrm{CVN}} \quad \text{Equation 4}$$

- Estimate the temperature shift between K_{ID} and K_{IC} curves using the following equation:

$$\Delta T = 215 - 1.5\sigma y \quad \text{Equation 5}$$

where CVN = impact toughness in ft·lb, K_{ID} = fracture toughness in ksi√in, σ_y = yield strength in ksi, and ΔT = expected temperature shift in °F.

In Step 1 (Equation 4), it is assumed that the DBT for the CVN is effectively equivalent to that of the dynamic fracture toughness and that the constant is sufficient to account for differences in notch acuity between CVN and fracture-toughness specimens. The temperature shift associated with Step 2 presumes that the shape of the fracture-toughness transition curve is unchanged and that decreasing temperature results in an increase in constraint at the crack tip, justifying the temperature shift.

The Materials Properties Council (MPC) proposed an even simpler version where the temperature shift is equal to a constant of 75 °F (42 °C).

11.2.3 Roberts-Newton Lower-Bound Correlation

Roberts and Newton [Refs 48 and 49] developed an alternative correlation for the lower transition region, which is sometimes referred to as the "lower-bound" K-CVN correlation:

$$\mathrm{K}_{IC} = 9.35(CVN)^{0.63} \quad \text{Equation 6}$$

where K_{IC} = fracture toughness (ksi√in) and CVN = CVN energy (ft·lb).

As will be shown, this correlation typically produces very conservative estimates of fracture toughness. Owing to this conservatism, the Roberts-Newton correlation was at one time included in the ASME BPVC. (Use of this correlation was discontinued by the Code in about 2001.)

The Barsom-Rolfe as well as the MPC methods are included in API 579/ASME FFS-1. As a result, both are widely used. However, recent work by Wallin and Anderson [Ref 52] has cast doubt on both methods. Moreover, it has been demonstrated that the simple temperature-shift method is incorrect. Since the use of simple temperature-shift methods may lead to non-conservative predictions of K_{IC}, Anderson recommended that all such conversions be withdrawn from API 579/ASME FFS-1.

11.2.4 K-CVN Correlations based on Master Curve

The Master Curve method is based on the following observations and conclusions regarding ferritic steels in the ductile/brittle transition region:

1. Scatter in fracture toughness data in the transition region follows a characteristic three-parameter Weibull distribution with a slope of approximately 4.0.

2. Statistical distribution of fracture-toughness data in the transition region is similar for all ferritic steels.

3. The shape of the fracture toughness versus temperature curve in the transition range is virtually identical for all ferritic steels. The only difference between steels is the absolute position of this curve on the temperature axis.

Based on the above, it has been possible to develop "indexing procedures" that provide a conservative lower-bound estimate of fracture toughness for many ferritic steels based on a reference temperature. Once the reference temperature is derived from experimental data, the temperature dependence of median toughness in the ductile/brittle transition region can be defined.

Early efforts in this regard were undertaken by Bannister [Ref 50] and Marandet and Sanz [Ref 51], each of whom developed a type of "master curve" approach in which a K_{IC}-T curve is generated by a K_{IC}-CVN relation that they proposed:

$$K_{IC} = 20\sqrt{CVN} \qquad \text{Equation 7}$$

where K_{IC} = fracture toughness (ksi√in) and CVN = CVN energy (ft·lb).

They developed a correlation between the temperature for which CVN energy is 21 ft·lb (T_{21}) and for which K_{IC} = 91 ksi√in (T_{91}):

$$T_{91} = 1.37 \cdot T_{21} + 4 \qquad \text{Equation 8}$$

where T_{91}, T_{21} = temperatures (°F).

The K_{IC}-T curve generated from CVN data by Equation 5 is then shifted so that K_{IC} = 91 ksi√in which coincides with T_{91}.

More recently Wallin proposed a correlation between CVN and K_{IC} based on the master-curve approach [need Ref??]. In this method, one determines experimentally the temperature at which the CVN energy is 28 J (20 ft·lb), T_{28J}. Then, one calculates the reference temperature, T_o, using the following equation (from Wallin):

$$\mathrm{T_{28J}} - T_0 = 77°\mathrm{C} - \frac{\sigma_y}{12\ MPa} - \frac{1000\ J}{CVN_{US}}$$ Equation 9

Here, σ_y equals the yield strength of the steel, and CVN_{US} is the Charpy upper-shelf energy in J.

Once T_o has been determined, equivalent fracture toughness, K_{median}, is calculated as a function of temperature using the master-curve equation:

$$\mathrm{K_{median}} = 30 + 70\mathrm{e}^{C_{MC}(\mathrm{T} - T_0)}$$ Equation 10

where $C_{MC} = 0.019°C^{-1}$.

11.2.5 Comparison of K_{IC}-CVN Approaches

According to Anderson, the Wallin approach is preferable to either the Barsom and Rolfe (Two-Step) or the MPC approach because Equation 9 is based on a very large database of toughness test results (reportedly over 20,000 CVN and fracture toughness data points). Also, unlike other correlations, Wallin reports the statistical variance in his results, which can be incorporated if necessary into a probabilistic analysis. Anderson also states that use of the Wallin method for predicting K_{IC} from CVN values should yield more consistent estimates of fracture toughness by precluding the analyst from "cherry-picking" between alternative CVN to K_{IC} conversion schemes, i.e., schemes that are either more or less favorable to the analyst's situation.

11.3 Fracture Toughness Data

Fracture toughness (K_{IC}) was calculated for all steel conditions, utilizing the Barsom Two-Step correlation, the Roberts-Newton lower-bound correlation, and the Wallin master-curve approach. Fitted data, as described above in Section 11.2 were used for the calculations.

Where actual fracture-toughness data were available, a comparison with calculated fracture toughness was possible. To use actual fracture-toughness data for comparison to correlations, it was necessary to couch all fracture toughness data in terms of a common type of toughness, K_{IC}. This necessitated applying established correlations between K, CTOD (δ) and J [Ref 47].

11.3.1 A36

Fracture-toughness conversions for A36 steel are summarized in Figure 8 through Figure 12. As seen, the Roberts-Newton lower-bound correlation typically predicts a significantly higher transition temperature range for this steel than either the Barsom Two-Step or the Wallin Master Curve correlation. The Wallin correlation typically matches the Two-Step correlation closely, especially in the lower transition region.

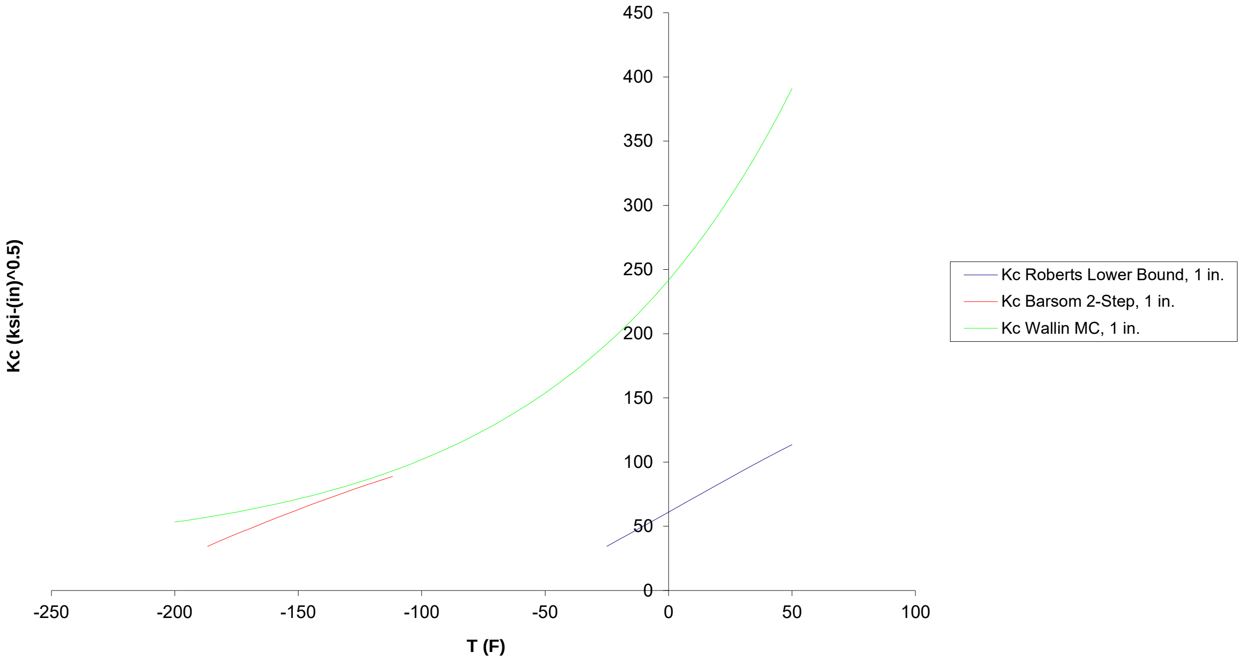


Figure 8: Wallin, Two-Step, and Lower-Bound correlations for 1” thick A36 plate.

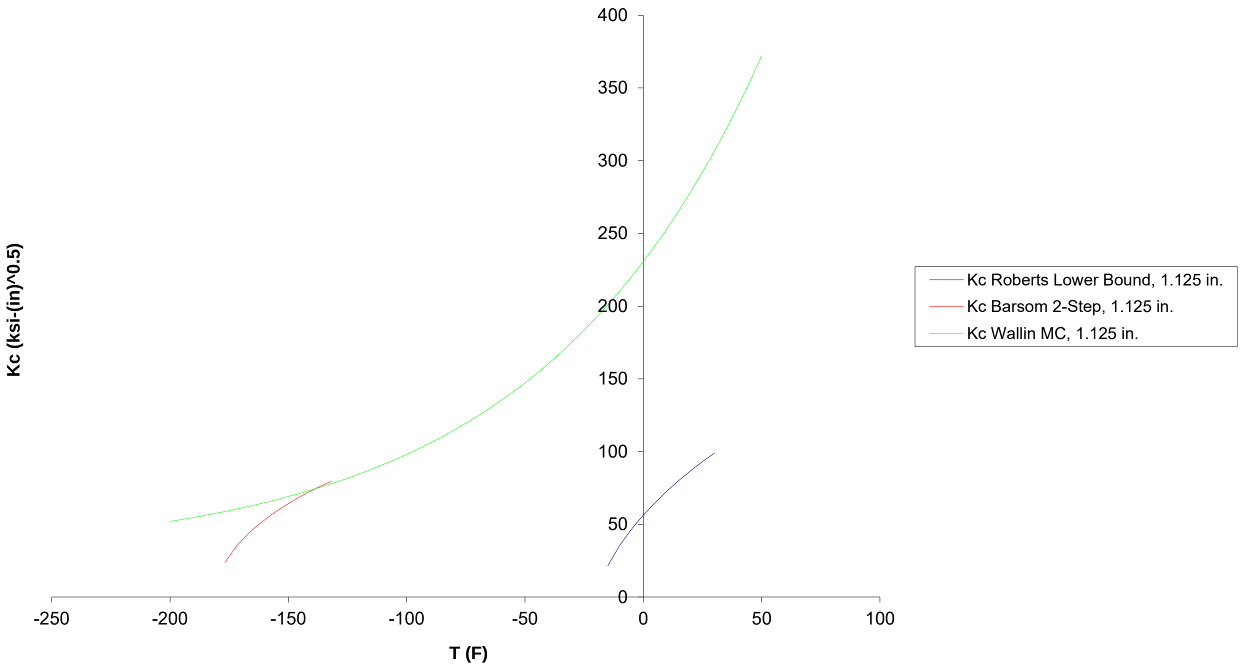


Figure 9: Wallin, Two-Step, and Lower-Bound correlations for 1.125” thick A36 plate.

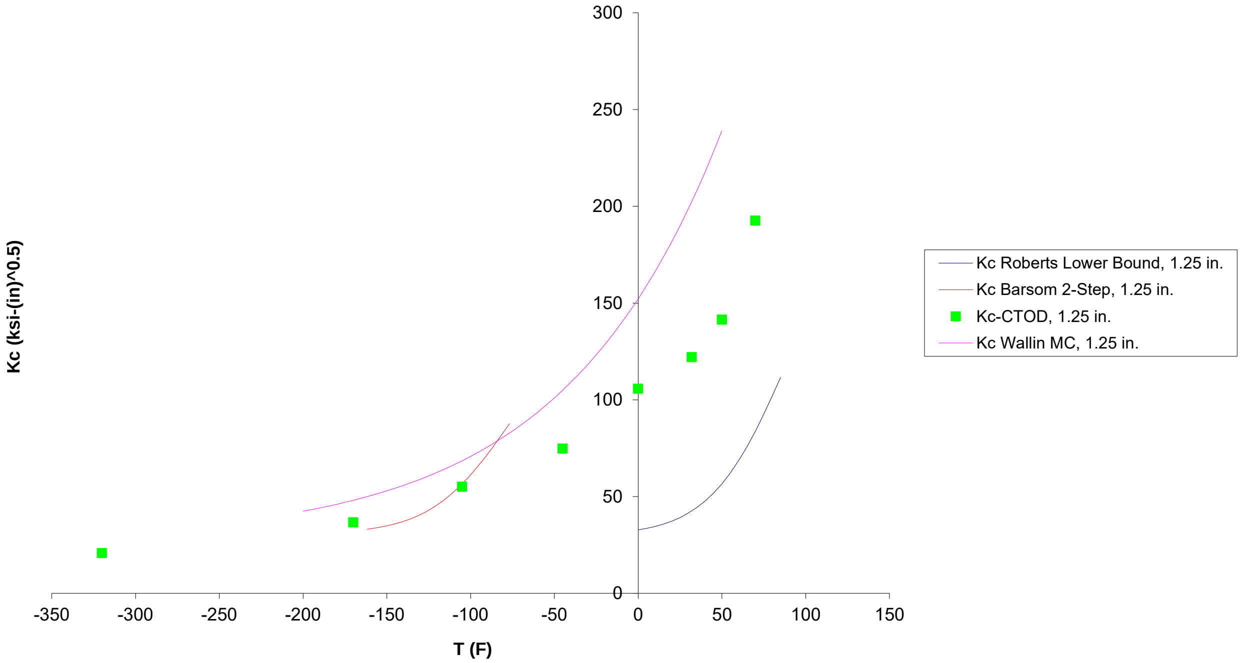


Figure 10: Wallin, Two-Step, and Lower-Bound correlations for 1.25" thick A36 plate.

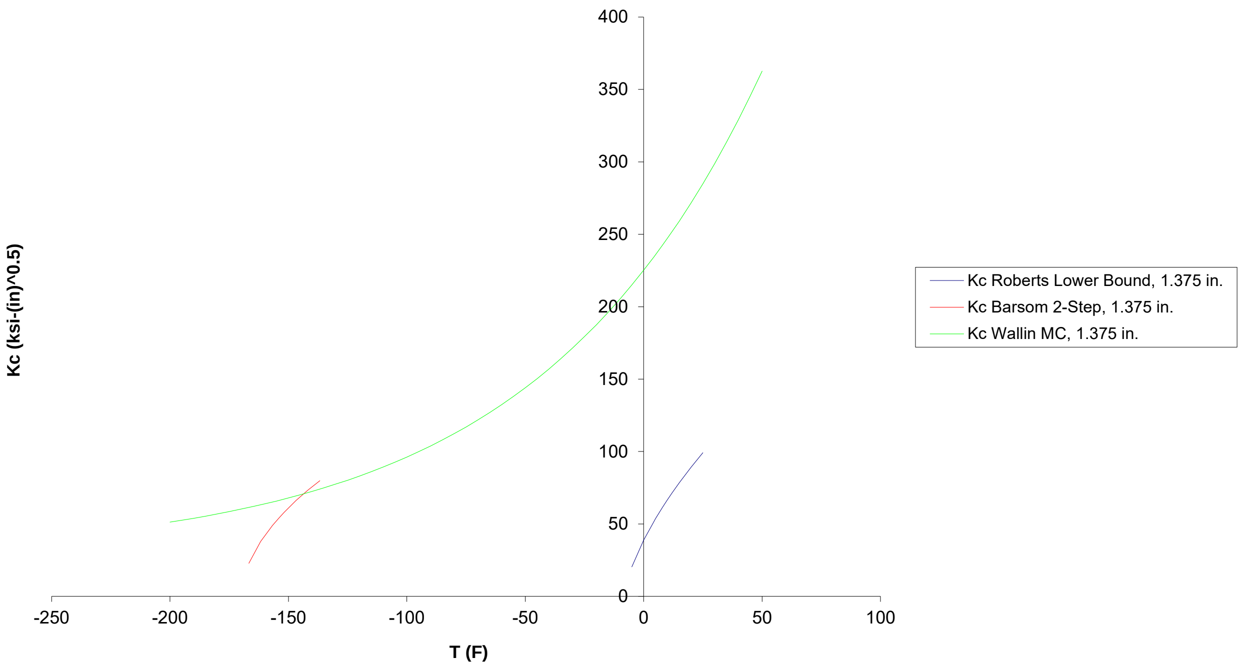


Figure 11: Wallin, Two-Step, and Lower-Bound correlations for 1.375" thick A36 plate.

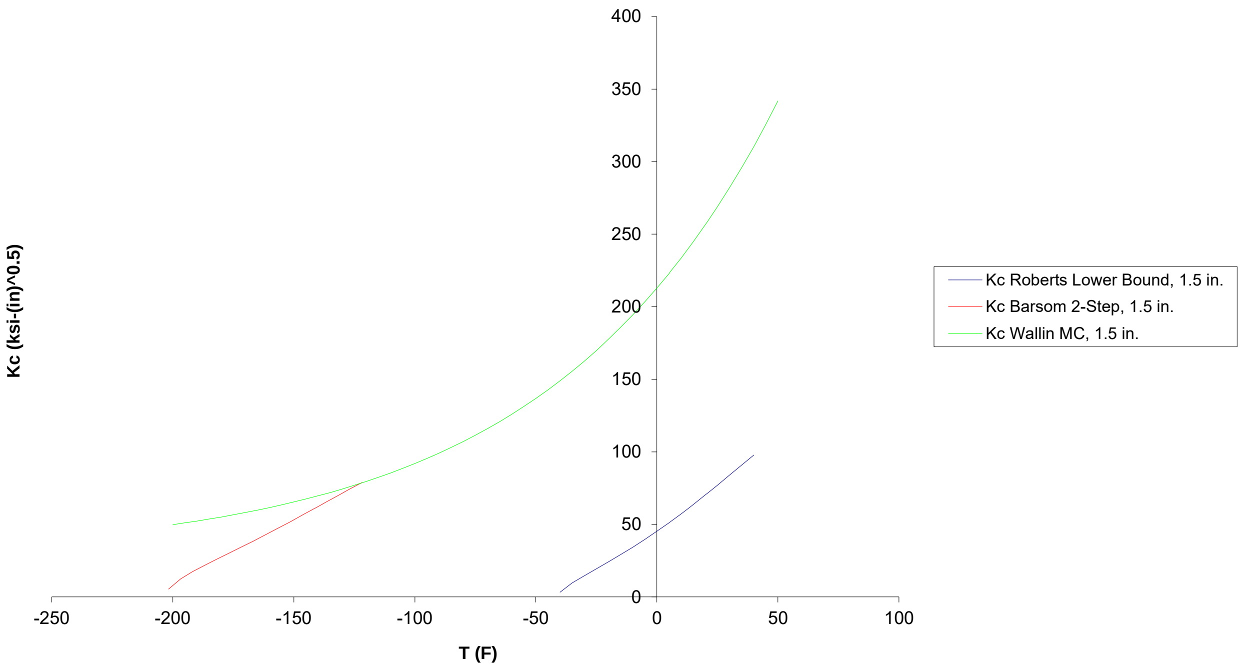


Figure 12: Wallin, Two-Step, and Lower-Bound correlations for 1.5" thick A36 plate.

The data set for 1.25 in. thick A36 plate (Figure 10) is particularly noteworthy. This data set includes K_{IC} data derived from CTOD (δ_c) from the same heat of steel via an established correlation. The K_{IC}-CTOD is very close to the Barsom Two-Step and Wallin correlations, especially at lower temperatures in the transition region, where they are deemed to work best. The Roberts-Newton lower-bound correlation definitely represents a more conservative estimate of fracture toughness (at least for this steel).

Given that the CVN energy data of this data set are consistent with other A36 steel CVN data, this suggests that toughness correlations for other thicknesses of A36 steel plates will be adequate. Importantly, a comparison of the K_{IC}-CTOD data to K_{IC}-CVN data seems favorable, given the correlations and data conversion employed. Thus, for A36 steel, K_{IC} data can be predicted from CVN energy data in the lower transition regime.

In addition, examination of the data associated with the temperature shift between K_d and K_{IC} data illustrates the conservative nature of K_d and K_{IC}-CVN data due to the effect of dynamic or impact loading. That is, fracture toughness at quasi-static loading rates is greater at lower temperatures. This would seem important when considering FFS analysis.

11.3.2 A131 EH36

The correlations between CVN or CTOD and K_{IC} for the A131 EH36 steels were also studied (Figure 13 through Figure 15). The K_{IC}-CTOD data for 1 in. plate lies between the Roberts-Newton lower bound and Barsom Two-Step correlations (Figure 13). Again, the Lower-Bound prediction was the most conservative of the three, and the Wallin correlation matched the Two-Step method well in the lower transition region.

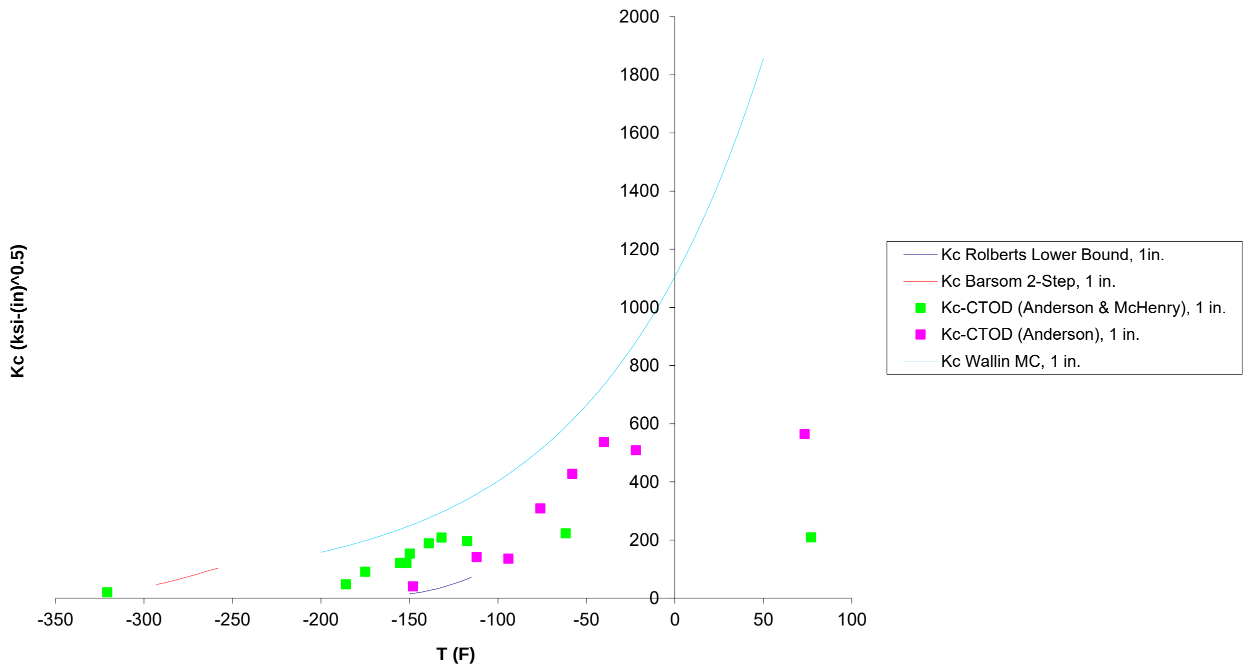


Figure 13: Wallin, Two-Step, and Lower-Bound correlations for 1” thick A131 EH36 plate.

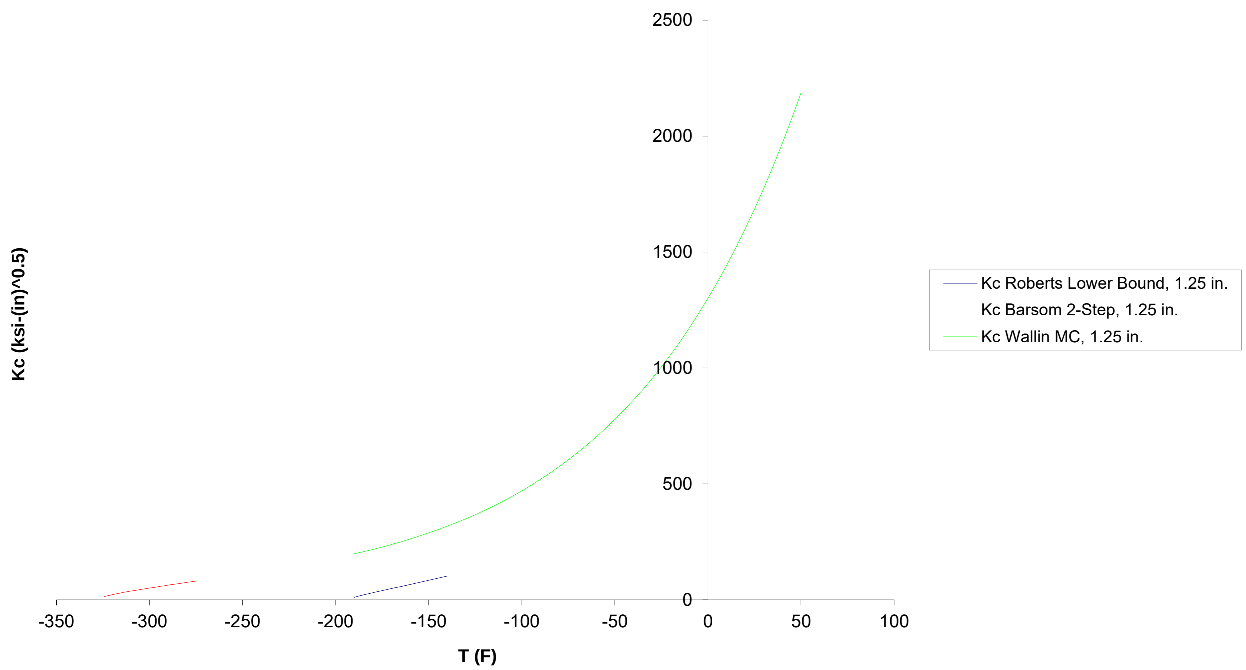


Figure 14: Wallin, Two-Step, and Lower-Bound correlations for 1.25” thick A131 EH36 plate.

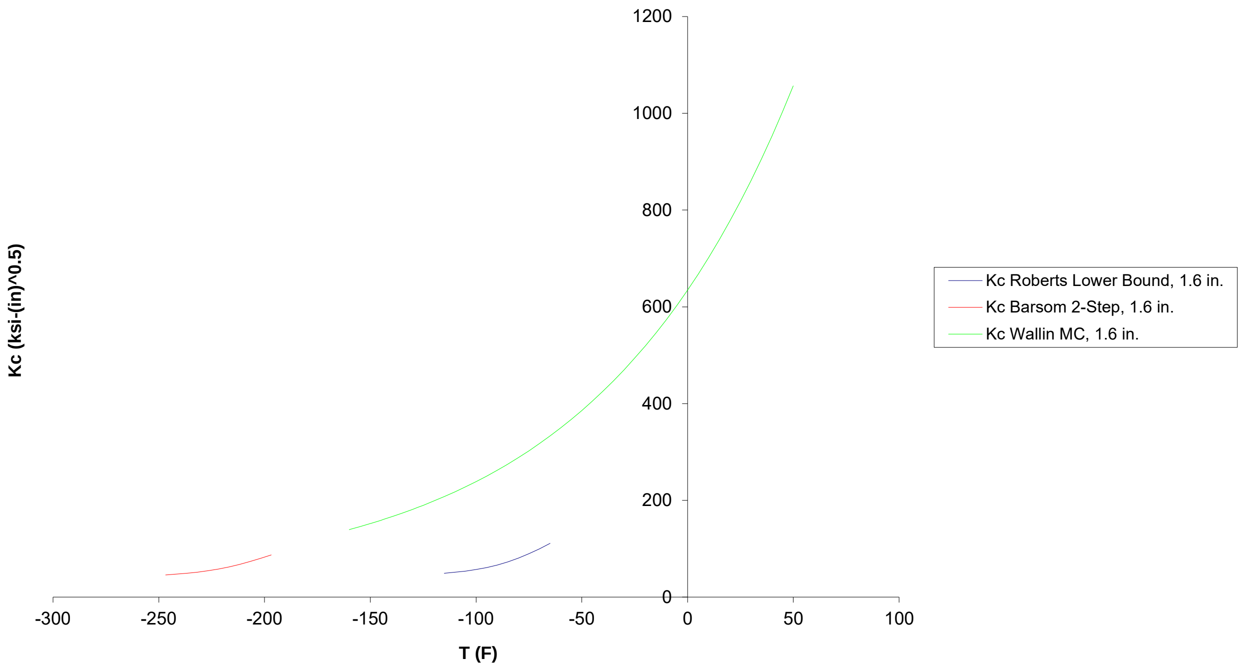


Figure 15: Wallin, Two-Step, and Lower-Bound correlations for 1.6" thick A131 EH36 plate.

11.3.3 A572 Gr 50

Fracture-toughness data for A572 Gr 50 steel are summarized in Figure 16 through Figure 18. In most cases, measured fracture toughness data falls between the three correlations; however, the Wallin correlation provided the least conservative estimate of fracture toughness, followed by the Two-Step and Lower-Bound methods.

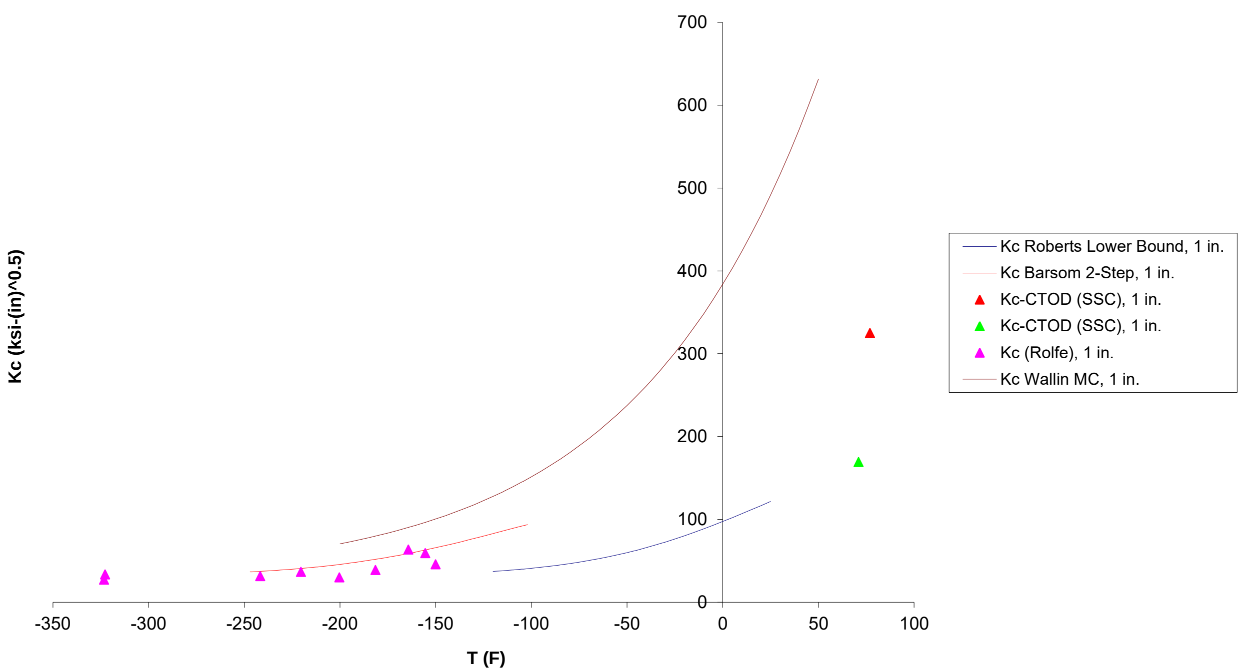


Figure 16: Wallin, Two-Step, and Lower-Bound correlations for 1" thick A572 Gr 50 plate.

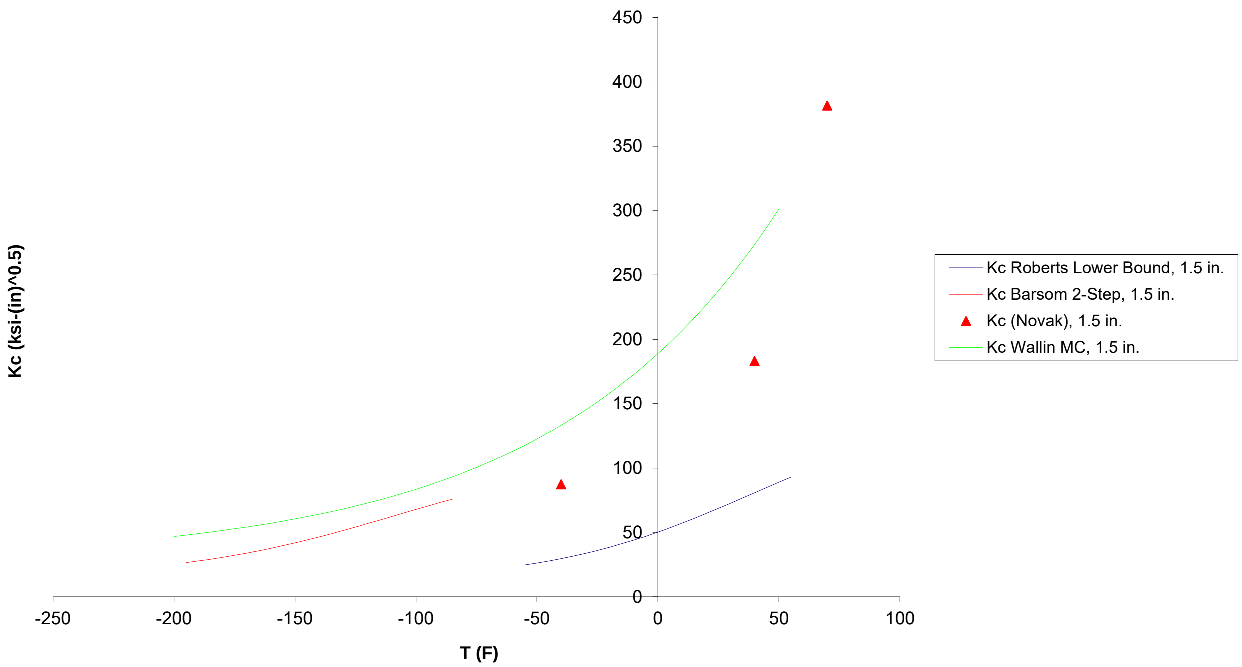


Figure 17: Wallin, Two-Step, and Lower-Bound correlations for 1.5" thick A572 Gr 50 plate.

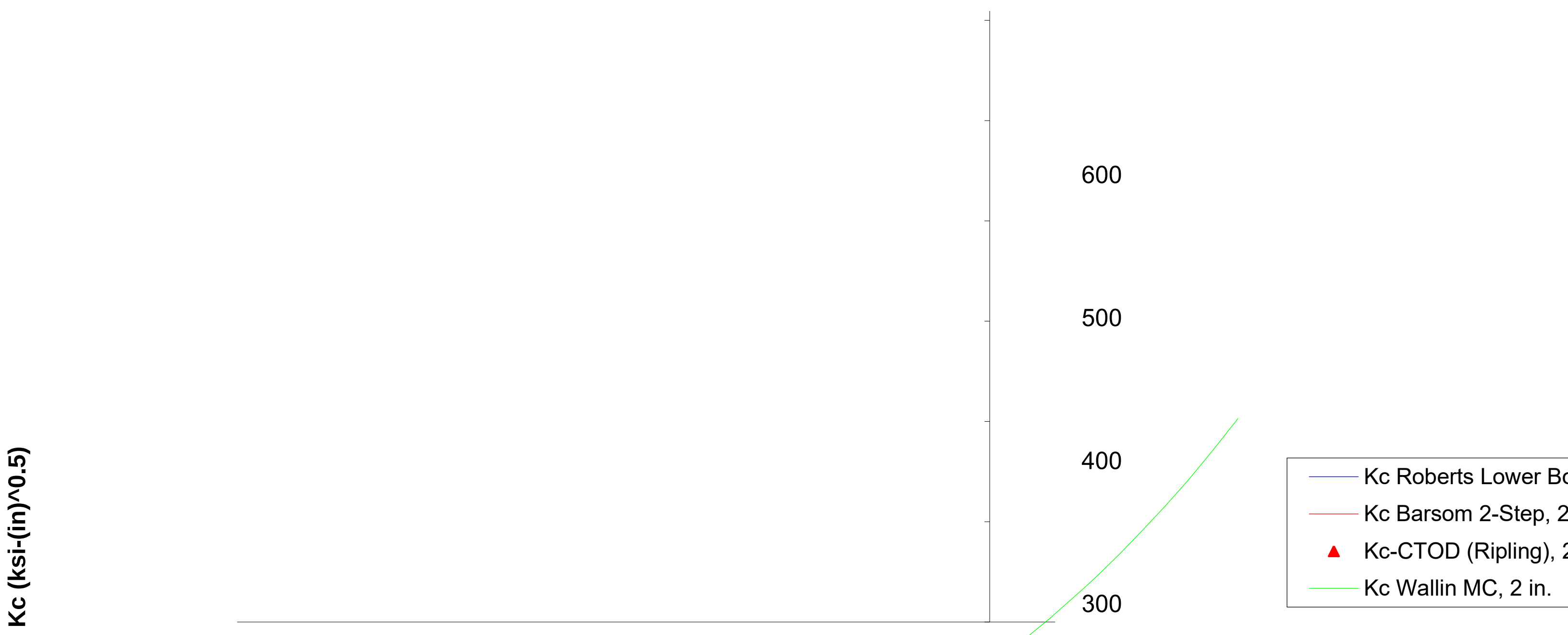


Figure 18: Wallin, Two-Step, and Lower-Bound correlations for 2" thick A572 Gr 50 plate.

11.3.4 A514

Fracture toughness data for A514 steel are summarized in Figure 19 through Figure 25. Data were acquired for a number of grades.

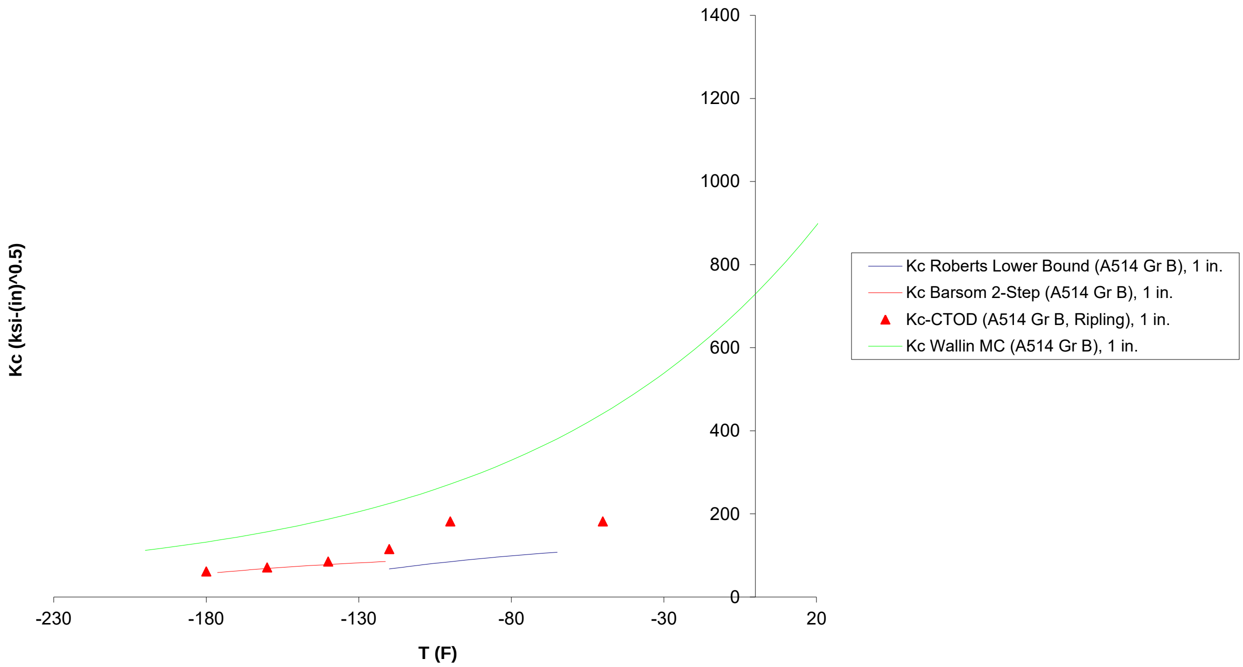


Figure 19: Wallin, Two-Step, and Lower-Bound correlations for 1" thick A514 Gr B plate.

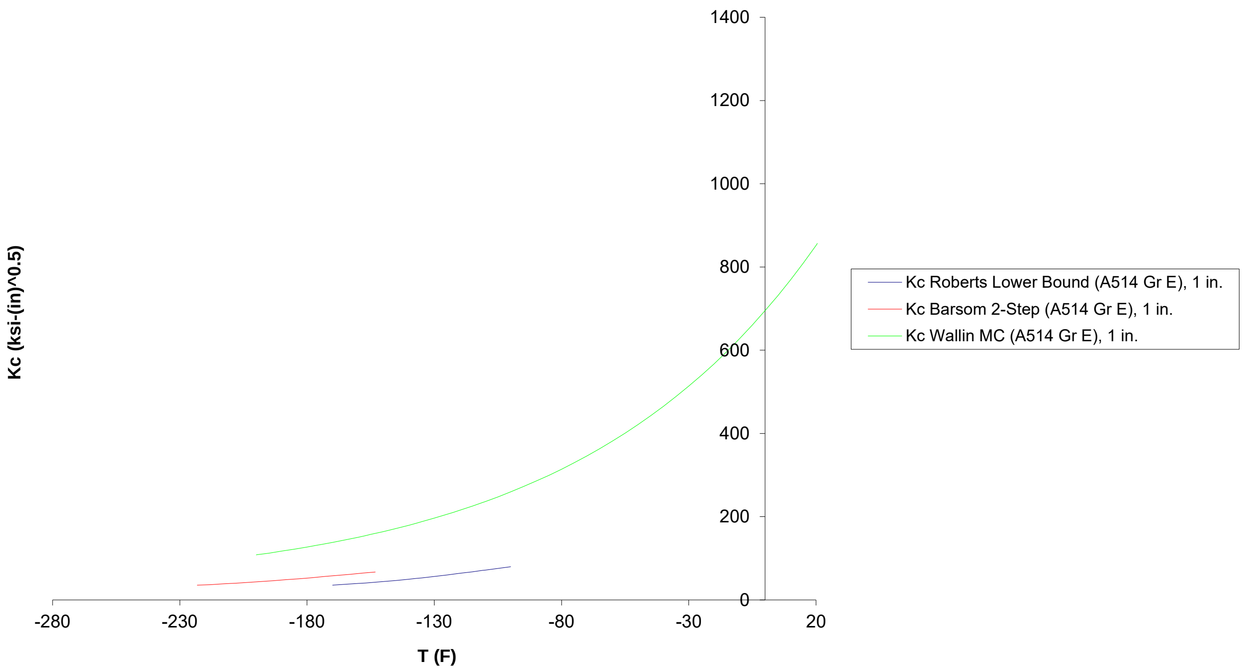


Figure 20: Wallin, Two-Step, and Lower-Bound correlations for 1" thick A514 Gr E plate.

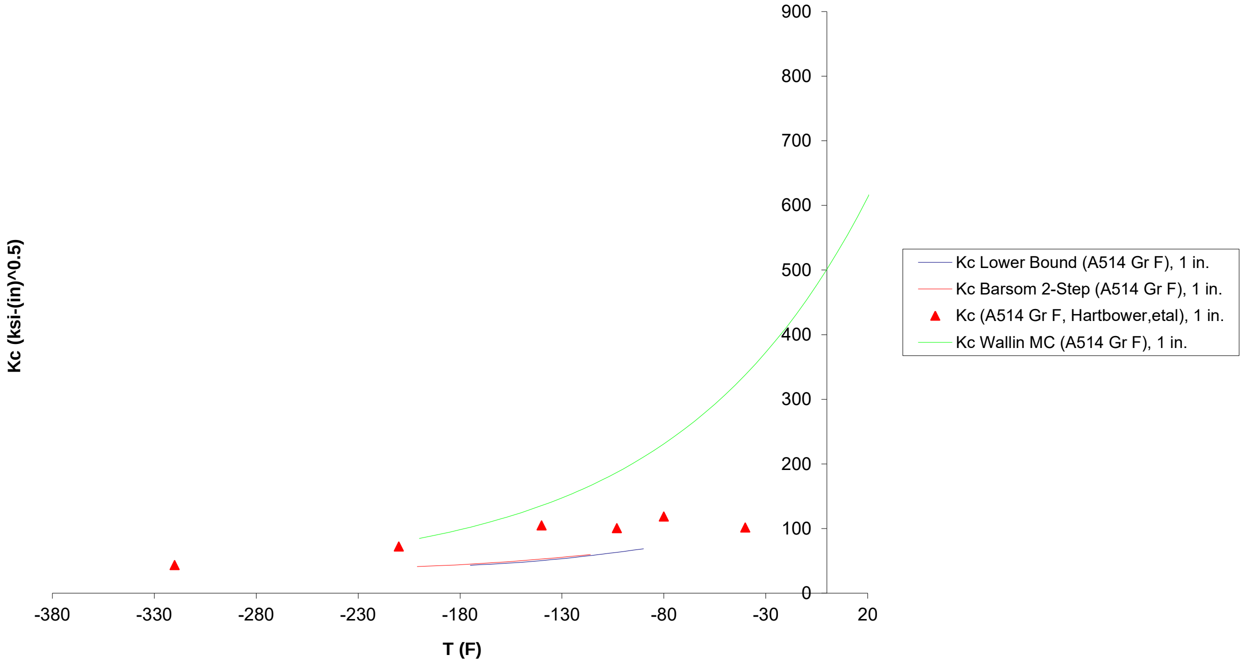


Figure 21: Wallin, Two-Step, and Lower-Bound correlations for 1" thick A514 Gr F plate.

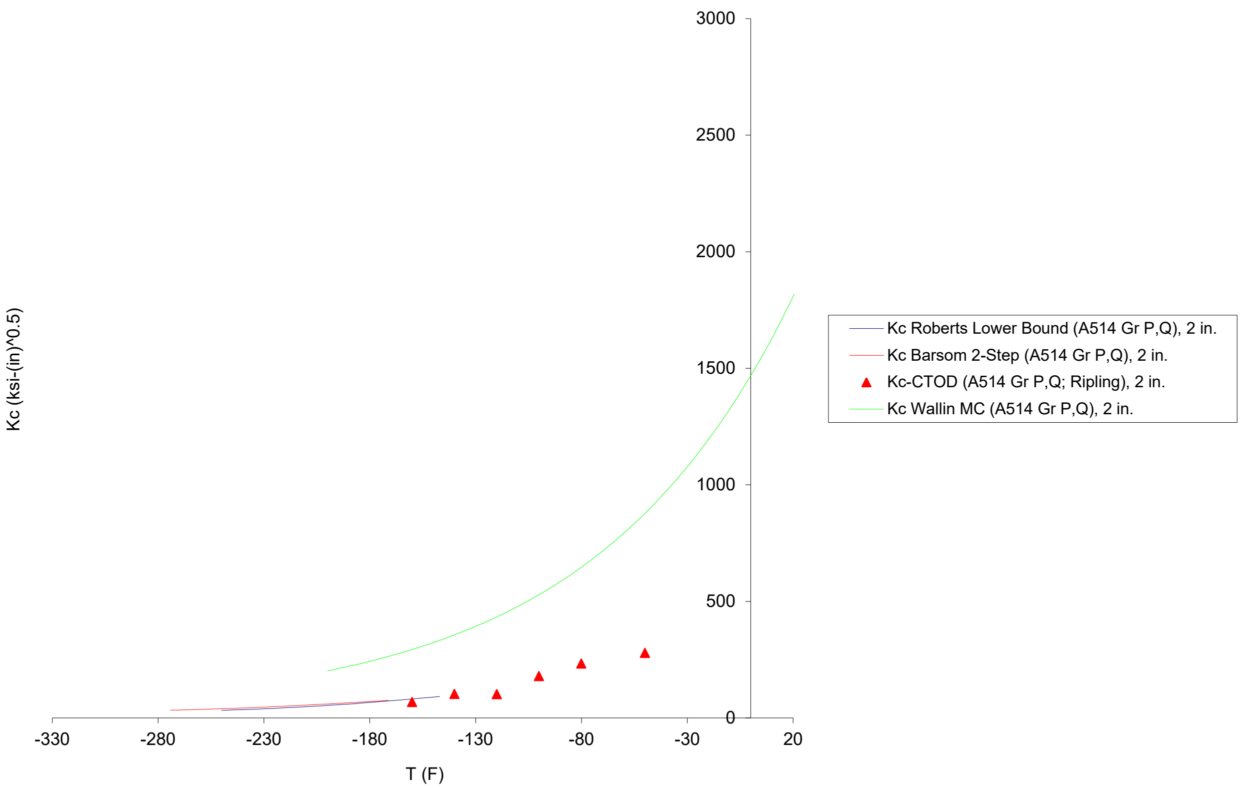


Figure 22: Wallin, Two-Step, and Lower-Bound correlations for 2" thick A514 Gr P, Q plate.

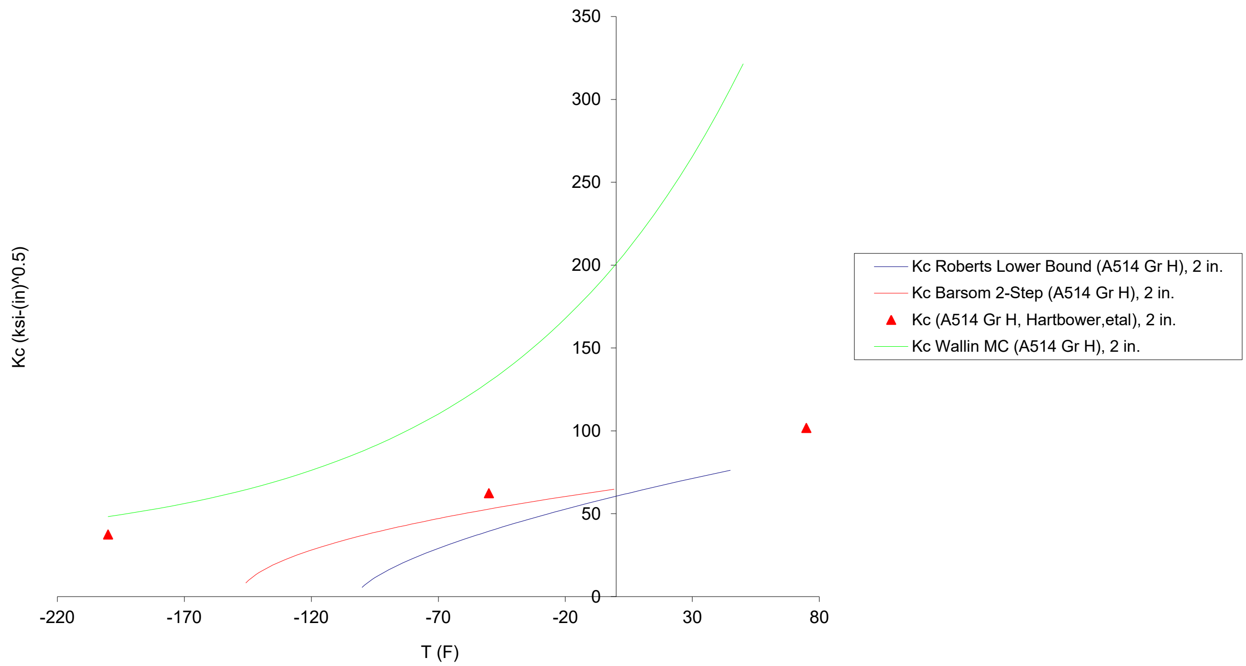


Figure 23: Wallin, Two-Step, and Lower-Bound correlations for 2" thick A514 Gr H plate.

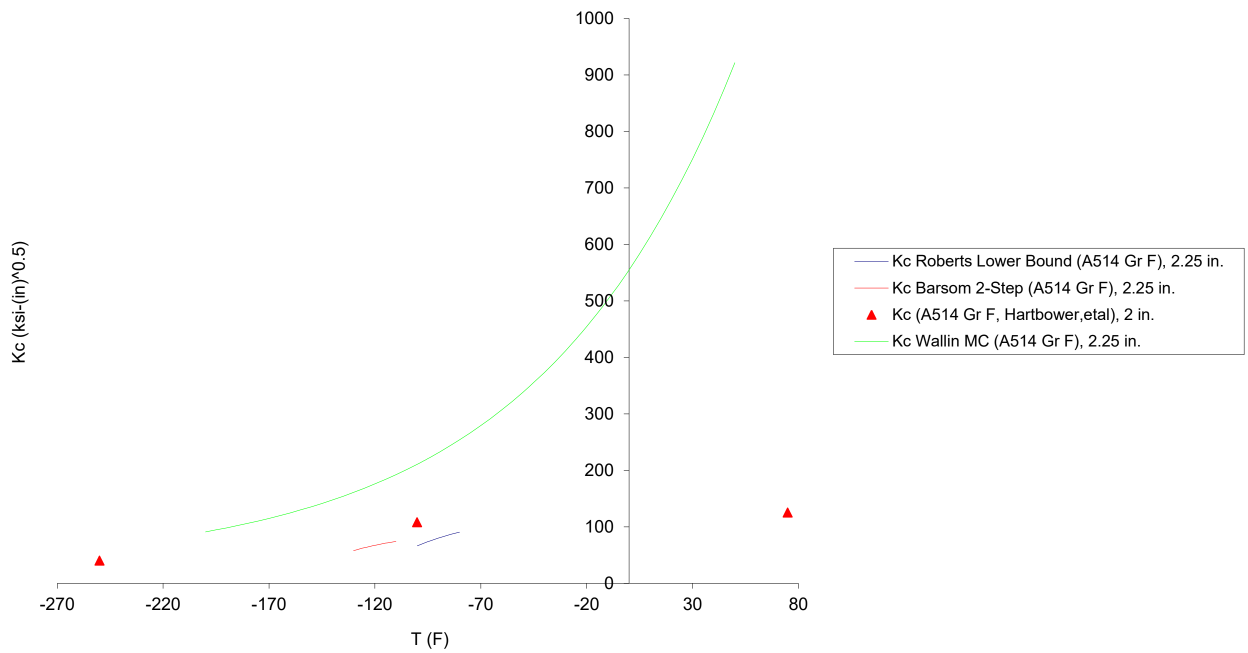


Figure 24: Wallin, Two-Step, and Lower-Bound correlations for 2.25" thick A514 Gr F plate.

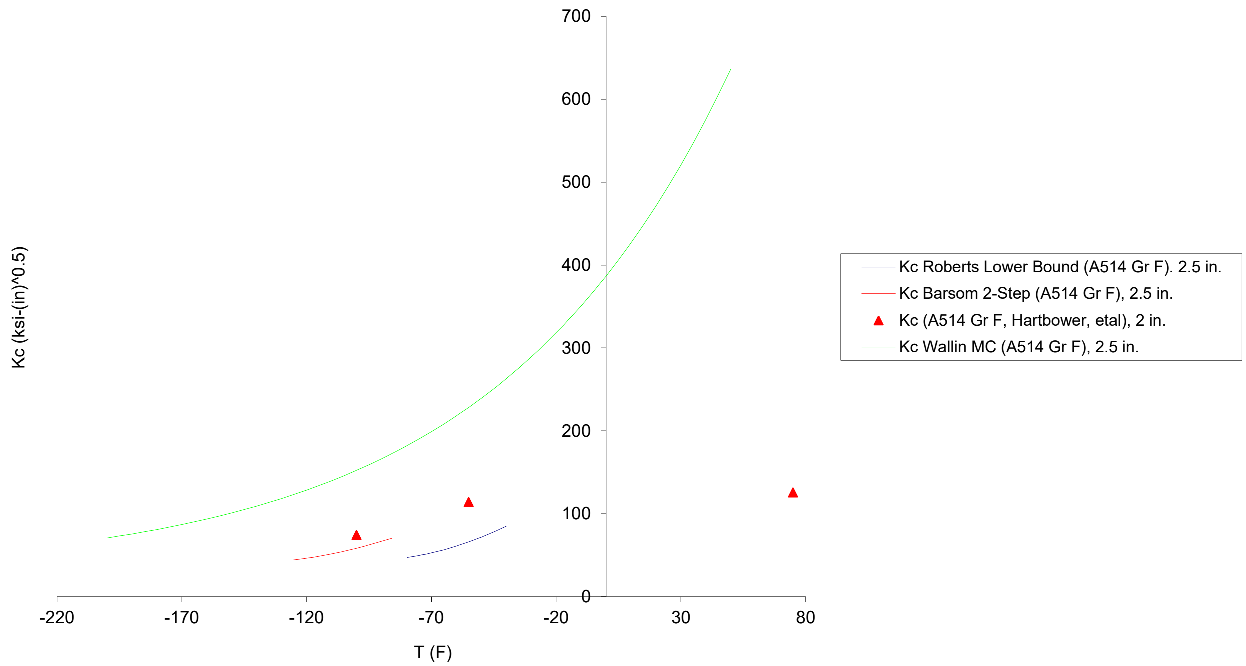


Figure 25: Wallin, Two-Step, and Lower-Bound correlations for 2.5" thick A514 Gr F plate.

It is evident that, for these higher-strength Q&T steels, the Wallin correlation provided the least conservative estimates of fracture toughness. The Lower-Bound and Barsom Two-Step correlations did not generally differ as much for this A514 steel. This is due in part to the fact that the temperature shift of the latter correlation decreases with increasing yield strength (as shown in Equation 5).

Estimated fracture toughness values from correlations as a function of temperature are summarized below for A36 (Table 22), A131 EH36 (Table 23), A572 Gr 50 (Table 24), and A514 steels (Table 25).

Table 22: Fracture Toughness Data for A36 Steel [K_{IC} (ksi√in)]

Thickness	Correlation	Temperature	
		40 F	20 F
1 in.	Roberts Lower-Bound		40
	Barsom Two-Step	117	121
1.125 in.	Roberts Lower-Bound		20
	Barsom Two-Step	114	117
1.25 in.	Roberts Lower-Bound	30	31
	Barsom Two-Step	123	133
1.375 in.	Roberts Lower-Bound		
	Barsom Two-Step	125	127
1.5 in.	Roberts Lower-Bound	3	24
	Barsom Two-Step	120	122

Table 23: Fracture Toughness Data for A131 EH36 Steel [K_{IC} (ksi√in)]

Thickness	Correlation	Temperature	
		40 F	20 F
1 in.	Roberts Lower-Bound	243	245
	Barsom Two-Step	164	164
1.25 in.	Roberts Lower-Bound	211	215
	Barsom Two-Step	150	150
1.6 in.	Roberts Lower-Bound	166	189
	Barsom Two-Step	140	140

Table 24: Fracture Toughness Data for A572 Gr 50 Steel [K_{IC} (ksi√in)]

Thickness	Correlation	Temperature	
		40 F	20 F
1 in.	Roberts Lower-Bound	66	80
	Barsom Two-Step	123	128
1.5 in.	Roberts Lower-Bound	30	36
	Barsom Two-Step	94	98
2 in.	Roberts Lower-Bound	64	91
	Barsom Two-Step	120	120

Table 25: Fracture Toughness Data for A514 Steel [K_{IC} (ksi√in)]

Grade/Thickness	Correlation	Temperature	
		40 F	20 F
Gr B, 1 in.	Roberts Lower-Bound	120	128
	Barsom Two-Step	104	106
Gr E, 1 in.	Roberts Lower-Bound	119	125
	Barsom Two-Step	99	100
Gr F, 1 in.	Roberts Lower-Bound	89	94
	Barsom Two-Step	77	80
Gr P/Q, 2 in.	Roberts Lower-Bound	156	160
	Barsom Two-Step	117	118
Gr H, 2 in.	Roberts Lower-Bound	44	53
	Barsom Two-Step	55	60
Gr F, 2.25 in.	Roberts Lower-Bound	115	122
	Barsom Two-Step	95	98
Gr F, 2.5 in.	Roberts Lower-Bound	85	112
	Barsom Two-Step	102	106

11.3.5 Summary

In general, the Roberts-Newton Lower-Bound correlation, due to its similarity to the dynamic fracture toughness (K_d) correlation with CVN energy (see Equation 3), provides the most conservative estimates of fracture toughness and transition temperature range. The Barsom Two-Step and Wallin Master Curve correlations match each other closely in the lower transition region, especially for lower-strength steels. However, for Q&T low-alloy steels (for example, A514), the Wallin correlation predicts higher toughness and a lower transition temperature range than either the Two-Step or Lower-Bound correlations.

Based on the size of the Master-Curve database (see Section 11.2.4), the ease with which the 28 J (20 ft·lb) transition temperature can be determined for most constructional steels, and the wide acceptance of the Master-Curve method by the nuclear power and other industries; some might recommend it over the other two methods for crane construction steels. However, comparisons of the K_{IC}-CVN correlations performed during this project indicate that the Master Curve may not be the best correlation for crane design/rating in all instances. Whenever possible, users of any of the K_{IC}-CVN correlations presented herein should try to verify the applicability of the correlation to the steel and the temperature range in question.

12. Conclusions and Recommendations

Current stress-based crane design methods such as API 2C and EN13852 appear generally adequate for the stated task. These specifications provide guidance regarding types of loadings, design factors, and material selection. However, the challenges associated with providing cranes for extreme cold service conditions generate additional problems for material selection due to the difficulty of finding materials that meet the specified CVN material requirements. To enhance the current specifications for extreme cold applications, modifications should be considered including emphasizing the advantages of fine-grain steel for these applications and the importance of minimizing stress concentrations in the design. Inspection criteria should also be enhanced for this equipment. In addition, a fracture-mechanics-based design approach should be offered as an option to provide consideration of allowable defect size and better design consideration of brittle fracture as a failure mode.

The crane manufacturers surveyed in this project indicated that they utilize CVN impact tests to qualify materials for low-temperature service. Charpy requirements currently vary from manufacturer to manufacturer and from specification to specification.

To enable design and FFS evaluation of new/existing cranes for Arctic service using a fracture-mechanics approach, fracture-toughness data are required for common crane materials of construction. Generating the necessary data via typical fracture-mechanics testing will be difficult and expensive.

K_{IC}-CVN correlations exist that appear to be suitable for converting CVN test results for typical crane steels to fracture-toughness values. In particular, this study investigated three of these correlations (listed here in no particular order of preference): Barsom Two-Step method, Roberts-Newton Lower-Bound correlation, and Wallin Master-Curve method.

In general, the Lower-Bound correlation appears to produce more conservative estimates of fracture toughness (lower values) and of DBT temperature range (higher values) than the other two correlations. The Wallin and Two-Step correlations match closely for lower strength steels, especially in the lower transition region. The Lower-Bound and Two-Step correlations match each other closely for higher-strength Q&T low-alloy steels. Overall comparison of these three K_{IC}-CVN correlations indicates that it is probably best to verify the applicability of the selected correlation to the steel and temperature range in question.

All three correlations studied are sufficiently simple to warrant inclusion in existing design standards when Arctic conditions are anticipated. However, in order to be credible, inclusion of fracture-mechanics-based design requirements into existing design standards must be accompanied by suitable NDE acceptance criteria.

13. References

1. CAN/CSA-ISO 19906:11: "Petroleum and Natural Gas Industries – Arctic Offshore Structures," adopted from ISO 19906:2010, first edition, 15 December 2010.
2. Bond, James, and Dan Olford (American Bureau of Shipping (ABS)): "Arctic Operations at What Temperature?" *Offshore Engineer* magazine, December 2013. (http://www.oedigital.com/regions/arctic/item/4518-arctic-operations-at-what-temperature).
3. Barsom, John and Rolfe, Stanley, *Fracture and Fatigue Control in Structures,* American Society for Testing and Materials, 1999.
4. API Specification 2C, "Offshore Pedestal-Mounted Cranes," 7th Edition, March 2012.
5. EN 13852-1: 2004, "Offshore Cranes: General-Purpose Offshore Cranes," October 2004.
6. AISC 360-10, "Specification for Structural Steel Buildings," 22 June 2010.
7. API Recommended Practice 2A WSD, "Planning, Designing and Constructing Fixed Offshore Platforms- Working Stress Design," 21st Edition, December 2009.
8. API Specification 2H, "Specification for Carbon Manganese Steel Plate for Offshore Platform Tubular Joints," 8th Edition, 1 August 1999.
9. API Specification 2B, "Specification for the Fabrication of Structural Steel Pipe," 6th Edition, 1 July 2001.
10. API Specification 2MT1, "Specification for Carbon Manganese Steel Plate with Improved Toughness for Offshore Structures," 2nd Edition, 1 September 2001.
11. API Specification 2MT2, "Rolled Shapes with Improved Notch Toughness," 1st Edition, 1 June 2002.
12. API Specification 2SC, "Manufacture of Structural Steel Castings for Primary Offshore Applications," 1st Edition, 1 September 2009.
13. API Specification 2W, "Specification for Steel Plates for Offshore Structures Produced by Thermomechanical Control Processing (TMCP)," 5th Edition, 1 January 2006.
14. API Specification 2Y, "Specification for Steel Plates, Quenched and Tempered, for Offshore Structures," 5th Edition, 1 December 2006.
15. API Recommended Practice (RP) 2Z, "Recommended Practice for Preproduction Qualification for Steel Plates for Offshore Structures," 4th Edition, 1 September 2005.

16. EN 10025, "Hot Rolled Products of Structural Steels," 2004.

17. Rolfe, S.T.: *AISC Eng. J*, 1st Quarter, 1977, 2.

18. Shank, M.E.: "A Critical Survey of Brittle Failure in Carbon Plate Steel Structures other than Ships," Ship Structures Committee, SSC-65, 1 December 1953.

19. Puzak, P.P., M.E. Schuster, and W.S. Pellini: "Part I: Crack Starter Test of Ship Fracture and Project Steels," Ship Structures Committee, SSC-77, 18 June 1954.

20. Pellini, W.S., and E.W. Eschbacher: "Part II: Investigation of Performance of Weldments and Prime Plate of ABS-B Steel," Ship Structures Committee, SSC-78, 18 June 1954.

21. Owen, W.S. et al.: "The Relation of Microstructure to the Charpy Impact and Low Temperature Tensile Properties of Two Ship Steels," Ship Structures Committee, SSC-102, 18 June 1956.

22. Owen, W.S., M. Cohen, and B.L. Averbach: "The Influence of Ferrite Banding on the Impact Properties of Mild Steel," Ship Structures Committee, SSC-114, 6 October 1958.

23. Staugaitis, C.L.: "Mill Sampling Techniques for Quality Determination of Ship Steel Plate," Ship Structures Committee, SSC-141, 28 February 1962.

24. Vanderbeck, R.W.: "Mechanical Properties of High Mn Semi-killed Steel Plate," Ship Structures Committee, SSC-144, 2 January 1963.

25. Boulger, F.W. and W.R. Hansen: "The Effect of Metallurgical Variables in Ship Plate Steels on the Transition Temperatures in the DWT and Charpy V Notch Tests," Ship Structures Committee, SSC-145, 3 December 1962.

26. Kapadia, B.M. and W.A. Backofen: "Rolling History in Relation to the Toughness of Ship Plate," Ship Structures Committee, SSC-168, May 1965.

27. Rolfe, S.T. et al.: "Fracture Control Guidelines for Welded Steel Ship Hulls," Ship Structures Committee, SSC-244, 4 November 1974.

28. Hawthorne, J.P. and F.J. Loss: "Fracture Toughness Characterization of Ship Building Steels," Ship Structures Committee, SSC-248, 1975.

29. Francis, P.H. et al.: "Fracture Behavior Characterization of Ship Steels and Weldments," Ship Structures Committee, SSC-276, 1970.

30. Anderson, T.L.: "Elastic-Plastic Fracture Mechanics: Marine Structural Applications, Part 2," Ship Structures Committee, SSC-345, 17 December 1990.

31. Kaufman, J.G. and M. Prager: "Marine Structural Steel Toughness Data Bank, Vols. 1 to 4," Ship Structures Committee, SSC-352, 352B, 352C, 352D; 1991.

32. Kaufman, J.G. and M. Prager: "Marine Structural Steel Toughness Data Bank, Abridged Edition," Ship Structures Committee, 1991.

33. Barsom, J.M., Fisher, J.W., Frank, K.H., and Irwin, G.R., "Fracture Control Considerations for Steel Bridges, March 1980," Fritz Laboratory Reports, Paper 471, 1980.

34. Dalder, E.N.C.: "Results of Fracture Mechanics Analyses of the Ederer Cranes in the Device Assembly Facility Using Reduced Static Fracture-Toughness Values," USDOE Report UCRL-ID-125068-Rev-1 ON: DE97051354, 1 November 1996.

35. Iskander, S.K. and R.E. Stoller: "Results of Charpy V-Notch Impact Testing of Structural Steel Specimens Irradiated at Approximately 30 °C to 1 x 10^{16} neutrons/cm^2 in a Commercial Reactor Cavity," NUREG/CR-6399; ORNL-6886, 1997.

36. Ripling, E.J. et al.: "Brittle-Ductile Transition of Bridge Steels, Vol. 1, Final Report," FHWA-RD-90-008, May 1990.

37. Malitz, L. et al.: "Optimized Design Parameters for Welded TMCP Steels," Ship Structures Committee, SSC-396, 1997.

38. Roberts, R. et al.: in *Flaw Growth and Fracture*, ASTM STP 631, 1977, page 267.

39. Whorley, R.A. and S.T. Rolfe: "The Significance of the A/W Ratio on Fracture Toughness of A36 Steel," WRC Bulletin 375, 1 September 1992.

40. Barsom, J.M. and S.R. Novak: "Subcritical Crack Growth and Fracture of Bridge Steels," National Cooperative Highway Research Program, Report 181, 1977.

41. Novak, S.R.: "Resistance to Plane Stress Fracture (R-Curve Behavior) of A572 Structural Steel," ASTM STP 591, 1974.

42. Hartbower, C.E. and R.D. Sunbury: "Variability of Fracture Toughness in A514/A517 Plate," FHWA Report, 1975.

43. Prager, M. et al.: "Development of Material Fracture Toughness Rules for the ASME B&PV Code, Section VIII, Div 2," WRC Bulletin 528, 30 November 2009.

44. Erickson-Kirk, M.A., M.T. Erickson-Kirk, S. Rosinski, and J. Spanner: *Journal of Pressure Vessel Technology*, 131, 031404-1, 2009.

45. AWS D1.1: "Structural Welding Code – Steel," 30 June 2004.

46. ASTM A578: "Standard Specification for Straight-Beam Ultrasonic Examination of Rolled Steel Plates for Special Applications," July 2012.

47. Barsom, J.M, and S.T. Rolfe: *Fracture and Fatigue Control in Structures, Applications of Fracture Mechanics*, 3rd Ed., ASTM MNL141, 1999.

48. Wellman, G.W., and S.T. Rolfe: "Engineering Aspects of CTOD Fracture Toughness Testing," WRC Bulletin 299, December 1984.

49. Roberts, R. and C. Newton: "Interpretive Report on Small Scale Test Correlations with KIc Data," WRC Bulletin 265, February 1981.

50. Bannister, A.C.: "Determination of Fracture Toughness from Charpy Impact Energy: Procedure and Validation," SINTAP/BS/17, 1998.

51. Marandet, B. and G. Sanz: Tenth National Symposium on Fracture Mechanics, 1976.

52. Anderson, T.L.: "Elastic/Plastic Fracture Mechanics-Marine Structural Applications," Ship Structures Committee Report SSC-345B, April 1990.

Appendix A: Select Steel Specifications and Properties

Table A-1: Summary of Steel Classification of API 2A-WSD

Group	Class	Specification & Grade	YS (ksi)	YS (MPa)	UTS (ksi)	UTS (MPa)	ECVN (ft lb)	ECVN (J)	TCVN (F)
Plate (Table 8.1.4-1, API RP 2A-WSD)									
I	C	ASTM A36 (≤ 2in.)	36	250	58–80	400–550			
		ASTM A131, Gr A (≤ 0.5 in)	34	235	58–71	400–490			
		ASTM A285, Gr C (≤ 0.75 in.)	30	205	55–75	380–515			
	B	ASTM A131, Gr B,D	34	235	58–71	400–490	15	20	LAST
		ASTM A516, Gr 65	35	240	65–85	450–585			
		ASTM A573, Gr 65	35	240	65–77	450–530			
		ASTM A709, Gr 36T2	36	250	58–80	400–550			
	A	ASTM A131, Gr CS, E	34	235	58–71	400–490	15	20	
II	C	ASTM A572, Gr 42 (≤ 2 in.)*	42	290	60 min	415 min			
		ASTM A572, Gr 50 (≤ 2 in.)	50	345	65 min	450 min			
	B	API 2MT1	50	345	70–90	483–620	25	34	LAST
		ASTM A709, Gr 50T2, 50T3	50	345	65 min	450 min			
		ASTM A131, Gr AH32	45.5	315	68–85	470–585			
		ASTM A131, Gr AH36	51	350	71–90	490–620			
	A	API 2H, Gr 42	42	290	62–80	430–550			
		API 2H, Gr 50 (≤ 2.5 in.)	50	345	70–90	483–620			
		API 2H, Gr 50 (>2.5 in.)	47	325	70–90	483–620			
		API 2W, Gr 42 (≤ 1 in.)	42-67	290-462	62 min	427 min			
		API 2W, Gr 42 (> 1 in.)	42-62	290-427	62 min	427 min			
		API 2W, Gr 50 (≤ 1 in.)	50-75	345-517	65 min	448 min			
		API 2W, Gr 50 (> 1 in.)	50-70	345-483	65 min	448 min			
		API 2W, Gr 50T (≤ 1 in.)	50-80	345-522	70 min	483 min			
		API 2W, Gr 50T (> 1 in.)	50-75	345-517	70 min	483 min			

Group	Class	Specification & Grade	YS (ksi)	YS (MPa)	UTS (ksi)	UTS (MPa)	ECVN (ft lb)	ECVN (J)	TCVN (F)
		API 2W, Gr 60 (≤ 1 in.)	60-90	414-621	75 min	517 min			
		API 2W, Gr 60 (> 1 in.)	60-85	414-586	75 min	517 min			
		API 2Y, Gr 42 (≤ 1 in.)	42-67	290-462	62 min	427 min			
		API 2Y, Gr 42 (> 1 in.)	42-62	290-427	62 min	427 min			
		API 2Y, Gr 50 (≤ 1 in.)	50-75	345-517	65 min	448 min			
		API 2Y, Gr 50 (> 1 in.)	50-70	345-483	65 min	448 min			
		API 2Y, Gr 50T (≤ 1 in.)	50-80	345-572	70 min	483 min			
		API 2Y, Gr 50T (> 1 in.)	50-75	345-517	70 min	483 min			
		ASTM A131, Gr DH32, EH32	45.5	315	68–85	470–585			
		ASTM A131, Gr DH36, EH36	51	350	71–90	490–620			
		ASTM A537, Class I (≤ 2.5 in.)	50	345	70–90	485–620			
		ASTM A633, Gr A	42	290	63–83	435–570			
		ASTM A633, Gr C, D	50	345	70–90	485–620			
		ASTM A678, Gr A	50	345	70–90	485–620			
III	A	ASTM A537, Class II (≤ 2.5 in.)	60	415	80–100	550–690			
		ASTM A678, Gr B	60	415	80–100	550–690			
		API 2W, Gr 60 (≤ 1 in.)	60-90	414-621	75 min	517 min			
		API 2W, Gr 60 (> 1 in.)	60-85	414-586	75 min	517 min			
		API 2Y, Gr 60 (≤ 1 in.)	60-90	414-621	75 min	517 min			
		API 2Y, Gr 60 (> 1 in.)	60-85	414-586	75 min	517 min			
		ASTM A710, Grade A, Class 3 (Q+Pptn heat treated)							
		(≤ 2 in.)	75	515	85	585			
		(2–4 in.)	65	450	75	515			
		(> 4 in.)	60	415	70	485			

Group	Class	Specification & Grade	YS (ksi)	YS (MPa)	UTS (ksi)	UTS (MPa)	ECVN (ft lb)	ECVN (J)	TCVN (F)
Shapes (Table 8.1.4-2, API RP 2A-WSD)									
I	C	ASTM A36 (≤ 2in.)	36	250	58–80	400–550			
		ASTM A131, Gr A (≤ 0.5 in)	34	235	58–80	400–550			
	B	ASTM A709, Gr 36T2	36	250	58–80	400–550	15	20	LAST
II	C	ASTM A572, Gr 42 (≤ 2 in.)*	42	290	60 min	415 min			
		ASTM A572, Gr 50 (≤ 2 in.)	50	345	65 min	450 min			
	B	ASTM A709, Gr 50T2, 50T3	50	345	65 min	450 min	25	34	LAST
		ASTM A131, Gr AH32	45.5	315	68–85	470–585			
		ASTM A131, Gr AH36	51	350	71–90	490–620			

Group	Class	Specification & Grade	YS (ksi)	YS (MPa)	UTS (ksi)	UTS (MPa)	ECVN (ft lb)	ECVN (J)	TCVN (F)
Pipe (Table 8.2.1-1, API RP 2A-WSD)									
I	C	API 5L, Gr B	35	240	60 min	415 min			
		ASTM A53, Gr B	35	240	60 min	415 min			
		ASTM A135, Gr B	35	240	60 min	415 min			
		ASTM A139, Gr B	35	240	60 min	415 min			
		ASTM A500, Gr A (round)	33	230	45 min	310 min			
		ASTM A500, Gr A (shaped)	39	270	45 min	310 min			
		ASTM A501	36	250	58 min	400 min			
	B	ASTM A106, Gr B (normalized)	35	240	60 min	415 min	15	20	LAST
		ASTM A524, Gr I (≤ 0.375 wt)	35	240	60 min	415 min			
		ASTM A524, Gr II (> 0.375 wt)	30	205	55–80	380–550			
	A	ASTM A333, Gr 6	35	240	60 min	415 min			
		ASTM A334, Gr 6	35	240	60 min	415 min			
II	C	API 5L, Gr X42 (2% max cold expansion)	42	290	60 min	415 min			
		API 5L, Gr X52 (2% max cold expansion)	52	360	66 min	455 min			
		ASTM A500, Gr B (round)	42	290	58 min	400 min			
		ASTM A500, Gr B (shaped)	46	320	58 min	400 min			
		ASTM A618	50	345	70 min	485 min			
	B	API 5L, Gr X52 (with SR5 or SR6)	52	360	66 min	455 min	25	34	LAST

Table A-2: Summary of Chemical Compositions of Steels of API-2H, 2W, 2Y, and 2MT

		C	Mn	P	S	Si	Cb	Ti	Al	N	V	Ni	Cr	Mo	Cu	B	CE max
API-2H, Gr 42	Heat Anal.	0.18	0.90-1.35	0.03	0.01	0.05-0.40	0.04	0.02	0.02-0.06	0.012, NAI	NAI						0.43 (≤2.5 in.)
	Prod. Anal.	0.22			0.015	0.05-0.45											0.45 (>2.5 in.)
API-2H, Gr 50	Heat Anal.	0.18	1.15-1.60	0.03	0.01	0.05-0.40	0.01-0.04	0.02	0.02-0.06	0.012, NAI	NAI						0.43 (≤2 in.)
	Prod. Anal.	0.22			0.015	0.05-0.45											0.45 (>2 in.)
API-2W, Gr 50		0.16	1.15-1.60	0.03	0.01	0.05-0.50	0.03	0.003-0.02 (N≤0.005)	0.015-0.055 (acid sol)	0.012, NAI		0.75	0.25	0.08	0.35	0.0005, NAI	0.39 (≤1.5 in.)
								0.007-0.02 (N>0.005)	0.020-0.060 (total)								0.41 (1.5-3.5 in.)
																	0.43 (3.5-6 in.)
API-2W, Gr 60		0.16	1.15-1.60	0.03	0.01	0.05-0.50	0.03	0.003-0.02 (N≤0.005)	0.015-0.055 (acid sol)	0.012, NAI		1	0.25	0.15	0.35	0.0005, NAI	0.42 (≤1.5 in.)
								0.007-0.02 (N>0.005)	0.020-0.060 (total)								0.45 (>1.5 in.)
API-2Y, Gr 50		0.12	1.15-1.60	0.03	0.01	0.05-0.50	0.03	0.003-0.02 (N≤0.005)	0.015-0.055 (acid sol)	0.012, NAI		0.75	0.25	0.08	0.35	0.0005, NAI	0.39 (≤1.5 in.)
								0.007-0.02 (N>0.005)	0.020-0.060 (total)								0.41 (1.5-3.5 in.)
																	0.43 (3.5-6 in.)
API-2Y, Gr 60		0.16	1.15-1.60	0.03	0.01	0.05-0.50	0.03	0.003-0.02 (N≤0.005)	0.015-0.055 (acid sol)	0.012, NAI		1	0.25	0.15	0.35	0.0005, NAI	0.42 (≤1.5 in.)
								0.007-0.02 (N>0.005)	0.020-0.060 (total)								0.45 (>1.5 in.)
API-2MT1		0.12	1.15-1.60	0.03	0.01	0.10-0.40	0.01-0.04	0.02	0.015-0.055 (acid sol)	0.012, NAI	0.08					0.0005, NAI	0.43 (≤2 in.)
									0.020-0.060 (total)								0.45 (>2 in.)
API-2MT2, Class A		0.14	1.6	0.025	0.025	0.5	0.05	0.025		0.012	0.05	0.5	0.25	0.05	0.35	0.0005	0.38

		C	Mn	P	S	Si	Cb	Ti	Al	N	V	Ni	Cr	Mo	Cu	B	CE max
API-2MT2, Class B		0.16	1.6	0.025	0.025	0.5	0.05	0.025		0.012	0.08	0.5	0.3	0.1	0.35	0.0005	0.42
API-2MT2, Class C		0.23	0.50-1.50	0.035	0.045	0.5	0.05	NAI		0.015	0.11	0.45	0.35	0.15	0.6	NAI	0.45

Table A-3: Summary of Mechanical Properties of Steels of API-2H, 2W, 2Y and 2MT

	YS min (ksi)	YS min (MPa)	UTS (ksi)	UTS (MPa)	e (% in 2 in.)
API-2H, Gr 42	42	289	62–82	427–565	22
API-2H, Gr 50	50 (≤ 2.5 in.)	345	70–90	483–620	21
	47 (> 2.5 in.)	324	70–90	483–620	21
API-2W, Gr 50	50–75 (≤ 1 in.)	345–517	65	448	23
	50–70 (>1 in.)	345–483	65	448	23
API-2W, Gr 60	60–90 (≤ 1 in.)	414–621	75	517	22
	60–85 (> 1 in.)	414–586	75	517	22
API-2Y, Gr 50	50–75 (≤ 1in.)	345–517	65	448	23
	50–70 (> 1 in.)	345–483	65	448	23
API-2Y, Gr 60	60–90 (≤ 1 in.)	414–621	75	517	22
	60–85 (> 1 in.)	414–586	75	517	22
API-2MT1	50 (≤ 2.5 in.)	345	65–90	448–620	23
API-2MT2, Class A	50 min	345 min	65–90	448–620	21
API-2MT2, Class B	50 min	345 min	65–90	448–620	21
API-2MT2, Class C	50 min	345 min	65–90	448–620	21

Table A-4: Summary of Notch Toughness (CVN) of Steels for API 2H, 2W, 2Y, and 2MT

	Option	Specimen Size (mm)	ECVN min, average (ft lb)	ECVN min, average (J)	ECVN min, single (ft lb)	ECVN min, single (J)	T (F)	T (C)
API-2H, Gr 42	A	10x10	25	34	20	27	-40	-40
	B	7.5x10	25	34	20	27	-40	-40
	C	5x10	25	34	20	27	-40	-40
	D	7.5x10	19	26	15	20	-50	-46
	E	5x10	13	18	10	14	-80	-62
	Lower T	10x10	25	34	20	27	-76	-60
API-2H, Gr 50	A	10x10	30	41	25	34	-40	-40
	B	7.5x10	30	41	25	34	-40	-40
	C	5x10	30	41	25	34	-40	-40
	D	7.5x10	23	31	19	26	-50	-46
	E	5x10	15	20	13	18	-80	-62
	Lower T	10x10	35	48	30	41	-76	-60
API-2W, Gr 50	A	10x10	30	41	25	34	-40	-40
	B	7.5x10	30	41	25	34	-40	-40
	C	5x10	30	41	25	34	-40	-40
	D	7.5x10	23	31	19	26	-50	-46
	E	5x10	15	20	13	18	-80	-62
	Lower T	10x10	30	41	25	34	-76	-60
API-2W, Gr 60	A	10x10	35	48	30	41	-40	-40
	B	7.5x10	35	48	30	41	-40	-40
	C	5x10	35	48	30	41	-40	-40
	D	7.5x10	26	35	23	31	-50	-46
	E	5x10	18	24	15	20	-80	-62
	Lower T	10x10	35	48	30	41	-76	-60

	Option	Specimen Size (mm)	ECVN min, average (ft lb)	ECVN min, average (J)	ECVN min, single (ft lb)	ECVN min, single (J)	T (F)	T (C)
API-2Y, Gr 50	A	10x10	30	41	25	34	-40	-40
	B	7.5x10	30	41	25	34	-40	-40
	C	5x10	30	41	25	34	-40	-40
	D	7.5x10	23	31	19	26	-50	-46
	E	5x10	15	20	13	18	-80	-62
	Lower T	10x10	30	41	25	34	-76	-60
API-2Y, Gr 60	A	10x10	35	48	30	41	-40	-40
	B	7.5x10	35	48	30	41	-40	-40
	C	5x10	35	48	30	41	-40	-40
	D	7.5x10	26	35	23	31	-50	-46
	E	5x10	18	24	15	20	-80	-62
	Lower T	10x10	35	48	30	41	-76	-60
API-2MT1		10x10	30	41	25	34	9	-18
API-2MT2, Class A		10x10	30	41			-4	-20
API-2MT2, Class B		10x10	20	27			32	0
API-2MT2, Class C		10x10	20	27			70	21
	Suggested lower T	10x10	30	41			-40	-40
	Suggested lower T	10x10	20	27			-4	-20
	Suggested lower T	10x10	20	27			32	0

Table A-5(A): Summary of Chemical Composition for Steels of EN 10025-2

Grade	C (≤16 mm)	C (16 40 mm)	C (>40mm)	Si	Mn	P	S	N	Cu	Other	CE max (<30 mm)	CE max (30 40 mm)	CE max (40 150 mm)	CE max (150 250 mm)	CE max (250 400 mm)
S235JR	0.17	0.17	0.20		1.4	0.035	0.035	0.012	0.55	If sufficient Al Nmax does not apply.	0.35	0.35	0.38	0.40	
S235J0	0.17	0.17	0.17		1.4	0.03	0.03	0.012	0.55		0.35	0.35	0.38	0.40	
S235J2	0.17	0.17	0.17		1.4	0.025	0.025	0.012	0.55		0.35	0.35	0.38	0.40	0.40
S275JR	0.21	0.21	0.22		1.5	0.035	0.035	0.012	0.55		0.40	0.4	0.42	0.44	
S275J0	0.18	0.18	0.18		1.5	0.03	0.03	0.012	0.55		0.40	0.4	0.42	0.44	
S275J2	0.18	0.18	0.18		1.5	0.025	0.025	0.012	0.55		0.40	0.4	0.42	0.44	0.44
S355JR	0.24	0.24	0.24	0.55	1.6	0.035	0.035	0.012	0.55		0.45	0.47	0.47	0.49	
S355J0	0.2	0.2	0.22	0.55	1.6	0.03	0.03	0.012	0.55		0.45	0.47	0.47	0.49	
S355J2	0.2	0.2	0.22	0.55	1.6	0.025	0.025	0.012	0.55		0.45	0.47	0.47	0.49	0.49
S355K2	0.2	0.2	0.22	0.55	1.6	0.025	0.025	0.012	0.55		0.45	0.47	0.47	0.49	0.49
S450J0	0.2	0.2	0.22	0.55	1.7	0.03	0.03	0.025	0.55	0.05Cb, 0.13V, 0.05Ti	0.47	0.49	0.49		

Table A-5(B): Summary of Chemical Composition for Steels of EN 10025-3

Grade	C	Si	Mn	P	S	N	Cu	Other	CE max (<63 mm)	CE max (63 100 mm)	CE max (100 250 mm)
S275N	0.18	0.4	0.5-1.50	0.03	0.025	0.015	0.55	0.05Cb, 0.05V, 0.05Ti, 0.30Cr, 0.30Ni,0.10Mo, 0.02Al(min)	0.40	0.40	0.42
S275NL	0.16	0.4	0.5-1.50	0.025	0.02	0.015	0.55	0.05Cb, 0.05V, 0.05Ti, 0.30Cr, 0.30Ni,0.10Mo, 0.02Al(min)			
S355N	0.2	0.5	0.90-1.65	0.03	0.025	0.015	0.55	0.05Cb, 0.12V, 0.05Ti, 0.30Cr, 0.50Ni, 0.10Mo, 0.02Al(min)	0.43	0.45	0.45
S355NL	0.18	0.5	0.90-1.65	0.025	0.02	0.015	0.55	0.05Cb, 0.12V, 0.05Ti, 0.30Cr, 0.50Ni, 0.10Mo, 0.02Al(min)			
S420N	0.2	0.6	1.00-1.70	0.03	0.025	0.025	0.55	0.05Cb, 0.20V, 0.05Ti, 0.30Cr, 0.80Ni, 0.10Mo, 0.02Al(min)	0.48	0.5	0.52
S420NL	0.2	0.6	1.00-1.70	0.025	0.02	0.025	0.55	0.05Cb, 0.20V, 0.05Ti, 0.30Cr, 0.80Ni, 0.10Mo, 0.02Al(min)			
S460N	0.2	0.6	1.00-1.70	0.03	0.025	0.025	0.55	0.05Cb, 0.20V, 0.05Ti, 0.30Cr, 0.80Ni, 0.10Mo, 0.02Al(min)	0.53	0.54	0.55
S460NL	0.2	0.6	1.00-1.70	0.025	0.02	0.025	0.55	0.05Cb, 0.20V, 0.05Ti, 0.30Cr, 0.80Ni, 0.10Mo, 0.02Al(min)			

Table A-5(C): Summary of Chemical Composition for Steels of EN 10025-4

Grade	C	Si	Mn	P	S	N	Cu	Other	CE max (≤16 mm)	CE max (16 40 mm)	CE max (40 63 mm)	CE max (63 120 mm)	CE max (120 150 mm)
S275M	0.13	0.5	1.5	0.03	0.025	0.015	0.55	0.05Cb, 0.08V, 0.05Ti, 0.30Cr, 0.30Ni,0.10Mo, 0.02Al(min)	0.34	0.34	0.35	0.38	0.38
S275ML				0.025	0.02								
S355M	0.14	0.5	1.6	0.03	0.025	0.015	0.55	0.05Cb, 0.10V, 0.05Ti, 0.30Cr, 0.50Ni,0.10Mo, 0.02Al(min)	0.39	0.39	0.40	0.45	0.45
S355ML				0.025	0.02								
S420M	0.16	0.5	1.7	0.03	0.025	0.025	0.55	0.05Cb, 0.12V, 0.05Ti, 0.30Cr, 0.80Ni,0.20Mo, 0.02Al(min)	0.43	0.45	0.46	0.47	0.47
S420ML				0.025	0.02								
S460M	0.16	0.6	1.7	0.03	0.025	0.025	0.55	0.05Cb, 0.12V, 0.05Ti, 0.30Cr, 0.80Ni,0.20Mo, 0.02Al(min)	0.45	0.46	0.47	0.48	0.48
S460ML				0.025	0.02								

Table A-5(D): Summary of Chemical Composition for Steels of EN 10025-6

Grade	C	Si	Mn	P	S	N	Cu	Other	CE max (<50 mm)	CE max (50 100 mm)	CE max (100 150 mm)
S460Q	0.20	0.80	1.7	0.025	0.015	0.015	0.50	0.06Cb, 0.12V, 0.05Ti, 1.50Cr, 2.0Ni,0.70Mo	0.47	0.48	0.50
S460QL	0.20	0.80	1.7	0.02	0.01	0.015	0.50	0.06Cb, 0.12V, 0.05Ti, 1.50Cr, 2.0Ni, 0.70Mo	0.47	0.48	0.50
S460QL1	0.20	0.80	1.7	0.02	0.01	0.015	0.50	0.06Cb, 0.12V, 0.05Ti, 1.50Cr, 2.0Ni, 0.70Mo	0.47	0.48	0.50
S500Q	0.20	0.80	1.7	0.025	0.015	0.015	0.50	0.06Cb, 0.12V, 0.05Ti, 1.50Cr, 2.0Ni, 0.70Mo	0.47	0.70	0.70
S500QL	0.20	0.80	1.7	0.02	0.01	0.015	0.50	0.06Cb, 0.12V, 0.05Ti, 1.50Cr, 2.0Ni, 0.70Mo	0.47	0.70	0.70
S500QL1	0.20	0.80	1.7	0.02	0.01	0.015	0.50	0.06Cb, 0.12V, 0.05Ti, 1.50Cr, 2.0Ni, 0.70Mo	0.47	0.70	0.70
S550Q	0.20	0.80	1.7	0.025	0.015	0.015	0.50	0.06Cb, 0.12V, 0.05Ti, 1.50Cr, 2.0Ni,0.70Mo	0.65	0.77	0.83
S550QL	0.20	0.80	1.7	0.02	0.01	0.015	0.50	0.06Cb, 0.12V, 0.05Ti, 1.50Cr, 2.0Ni, 0.70Mo	0.65	0.77	0.83
S550QL1	0.20	0.80	1.7	0.02	0.01	0.015	0.50	0.06Cb, 0.12V, 0.05Ti, 1.50Cr, 2.0Ni, 0.70Mo	0.65	0.77	0.83
S620Q	0.20	0.80	1.7	0.025	0.015	0.015	0.50	0.06Cb, 0.12V, 0.05Ti, 1.50Cr, 2.0Ni,0.70Mo	0.65	0.77	0.83
S620QL	0.20	0.80	1.7	0.02	0.01	0.015	0.50	0.06Cb, 0.12V, 0.05Ti, 1.50Cr, 2.0Ni, 0.70Mo	0.65	0.77	0.83
S620QL1	0.20	0.80	1.7	0.02	0.01	0.015	0.50	0.06Cb, 0.12V, 0.05Ti, 1.50Cr, 2.0Ni, 0.70Mo	0.65	0.77	0.83
S690Q	0.20	0.80	1.7	0.025	0.015	0.015	0.50	0.06Cb, 0.12V, 0.05Ti, 1.50Cr, 2.0Ni,0.70Mo	0.65	0.77	0.83
S690QL	0.20	0.80	1.7	0.02	0.01	0.015	0.50	0.06Cb, 0.12V, 0.05Ti, 1.50Cr, 2.0Ni, 0.70Mo	0.65	0.77	0.83

Grade	C	Si	Mn	P	S	N	Cu	Other	CE max (<50 mm)	CE max (50 100 mm)	CE max (100 150 mm)
S690QL1	0.20	0.80	1.7	0.02	0.01	0.015	0.50	0.06Cb, 0.12V, 0.05Ti, 1.50Cr, 2.0Ni, 0.70Mo	0.65	0.77	0.83
S890Q	0.20	0.80	1.7	0.025	0.015	0.015	0.50	0.06Cb, 0.12V, 0.05Ti, 1.50Cr, 2.0Ni,0.70Mo	0.72	0.82	
S890QL	0.20	0.80	1.7	0.02	0.01	0.015	0.50	0.06Cb, 0.12V, 0.05Ti, 1.50Cr, 2.0Ni, 0.70Mo	0.72	0.82	
S990QL1	0.20	0.80	1.7	0.02	0.01	0.015	0.50	0.06Cb, 0.12V, 0.05Ti, 1.50Cr, 2.0Ni, 0.70Mo	0.72	0.82	
S960Q	0.20	0.80	1.7	0.025	0.015	0.015	0.50	0.06Cb, 0.12V, 0.05Ti, 1.50Cr, 2.0Ni,0.70Mo	0.82		
S960QL	0.20	0.80	1.7	0.02	0.01	0.015	0.50	0.06Cb, 0.12V, 0.05Ti, 1.50Cr, 2.0Ni, 0.70Mo	0.72	0.82	
S960QL1	0.20	0.80	1.7	0.02	0.01	0.015	0.50	0.06Cb, 0.12V, 0.05Ti, 1.50Cr, 2.0Ni, 0.70Mo			

Table A-6: Summary of Tensile and Notch Toughness Requirements for Steels of EN 10025

Specification	Grade	YS (MPa) (16 mm)	YS (ksi)	UTS (MPa)	UTS (ksi)	e (%)	ECVN (J)	ECVN (ft lb)	T (C)	T (F)
EN 10025-2	S185	185	27	290–510	42–74					
	S235JR	235	34	360–510	52–74	24–26	27	20	20	68
	S235J0						27	20	0	32
	S235J2						27	20	-20	-4
	S275JR	275	40	410–560	59.5–81	21–23	27	20	20	68
	S275J0						27	20	0	32
	S275J2						27	20	-20	-4
	S355JR	355	51.5	470–630	68–91	20–22	27	20	20	68
	S355J0						27	20	0	32
	S355J2						27	20	-20	-4
	S355K2						40	29.5	-20	-4
	S450J0	450	65	550–720	78–104	17	27	20	0	32

Specification	Grade	YS (MPa) (16 mm)	YS (ksi)	UTS (MPa)	UTS (ksi)	e (%)	ECVN (J)	ECVN (ft lb)	T (C)	T (F)
EN 10025-3	S275N	275	40	370–510	59.5–74	24	40	29.5	-20	-4
	S275NL						27	20	-50	-58
	S355N	355	51.5	470–630	68–91	22	40	29.5	-20	-4
	S355NL						27	20	-50	-58
	S420N	420	61	520–680	75–99	19	40	29.5	-20	-4
	S420NL						27	20	-50	-58
	S460N	460	67	540–720	78–104	17	40	29.5	-20	-4
	S460NL						27	20	-50	-58
En 10025-4	S275M	275	40	370–530	68–77	24	40	29.5	-20	-4
	S275ML						27	20	-50	-58
	S355M	355	51.5	470–630	68–91	22	40	29.5	-20	-4
	S355ML						27	20	-50	-58
	S420M	420	61	520–680	75–99	19	40	29.5	-20	-4
	S420ML						27	20	-50	-58
	S460M	460	67	540–720	78–104	17	40	29.5	-20	-4
	S460ML						27	20	-50	-58

Specification	Grade	YS (MPa) (16 mm)	YS (ksi)	UTS (MPa)	UTS (ksi)	e (%)	ECVN (J)	ECVN (ft lb)	T (C)	T (F)
EN 10025-6	S460Q	460	67	550–720	80–104		30	22	-20	-4
	S460QL						30	22	-40	-40
	S460QL1						30	22	-60	-76
	S500Q	500	72.5	590–770	85–112		30	22	-20	-4
	S500QL						30	22	-40	-40
	S500QL1						30	22	-60	-76
	S550Q	550	80	640–820	93–119		30	22	-20	-4
	S550QL						30	22	-40	-40
	S550QL1						30	22	-60	-76
	S620Q	620	90	700–890	102–129		30	22	-20	-4
	S620QL						30	22	-40	-40
	S620QL1						30	22	-60	-76
	S690Q	690	100	770-940	112–136		30	22	-20	-4
	S690QL						30	22	-40	-40
	S690QL1						30	22	-60	-76
	S890Q	890	129	940-1100	136–160		30	22	-20	-4
	S890QL						30	22	-40	-40
	S990QL1						30	22	-60	-76
	S960Q	960	139	980-1150	142–167		30	22	-20	-4
	S960QL						30	22	-40	-40