

VER. 1.1. 845

INGRESADO AL
SISTEMA

RICEVUTA DA SIDOR
IL 20-10-2003 *Fecini*

Specifications For Design And Use Of Ladles

AISE Technical Report No. 9

August 1991

C.V.G. SIDOR, C.A.
C. R. L.



ASSOCIATION OF IRON AND STEEL ENGINEERS

**C.V.G. SIDOR, C.A.
C. I. T.**

Specifications For Design And Use Of Ladles



AISE Technical Report No. 9

August 1991

Published by

ASSOCIATION OF IRON AND STEEL ENGINEERS

Three Gateway Center, Suite 2350, Pittsburgh, Pennsylvania 15222-1097 U.S.A.

DISCLAIMER

This report has been prepared by a committee of steel company representatives and the Association of Iron and Steel Engineers, and others, who considered the technology available at the time of preparation. This report does not represent either minimum acceptable standards or mandatory specifications. In addition, this report is subject to compatibility with all governmental requirements.

The Association of Iron and Steel Engineers in no way mandates or is responsible for use of this report, whether voluntary or pursuant to a mandate of others. The Association of Iron and Steel Engineers and the committee assume and strongly recommend that parties who intend to use this report will examine it thoroughly and will utilize appropriate professional guidance in adapting this report to each particular project.

The use of language in this report that might be construed as mandatory is intended only to preserve the integrity of the report as the committee views it. It is not intended to require strict compliance where not necessitated by safety or operational needs.

FOREWORD

AISE Subcommittee No. 9 on Specifications for Design of Ladles consists of a balance of representatives from large and small steel companies and ladle manufacturers. Outside consultants were retained to perform theoretical and experimental studies which, together with studies by Subcommittee members' organizations, form the basis for this comprehensive report.

The basic structure of the previous AISE Technical Report No. 9, Specifications for Design of Ladles, published July 1, 1982 has been retained in this new version; however, extensive modifications have been made. This new version:

- Enables designers to minimize underdesign as well as overdesign.
- Allows a broader range of material selection.
- Updates old design data and adds new design sections to cover various ladle components.
- Illustrates step-by-step design procedures for two expanded numerical examples.
- Updates specifications to reflect the impact of clean steel and continuous caster practices.
- Addresses new conditions imposed on ladles by the use of stronger working linings, longer hot metal hold times, ladle preheating, and other operating environments; suggests specific operating practices to minimize the detrimental effects of these conditions.
- Adds new sections on use of ladles which include ladle inspection, repair, alteration and maintenance.

COPYRIGHT 1991

*Association of Iron and Steel Engineers
Pittsburgh, Pennsylvania 15222*

Printed in United States of America

*All rights reserved. This book, or any part thereof,
may not be reproduced in any form
without permission of the publisher.*

AISE TECHNICAL REPORT NO. 9

TABLE OF CONTENTS

PART I: LADLE DESIGN — STEEL SHELL

I-1 Scope	1
I-1.1 General	1
I-1.2 Intended Coverage	1
I-1.3 Specification Assumptions	1
I-2 Workmanship	1
I-3 Materials	1
I-3.1 General	1
I-3.2 Bottom Plate and Adjacent Shell Plate	1
I-3.3 Stiffener Bands, Splash Plate and Upper Sidewall	2
I-3.4 Lip Ring	3
I-3.5 Trunnion Pin	3
I-3.6 Trunnion Block	3
I-3.7 Rivets	3
I-3.8 Miscellaneous Forged Fittings	3
I-3.9 Other Materials	3
I-3.10 Material Testing Procedures	3
I-4 General Requirements	4
I-4.1 General Shape	4
I-4.2 Ladle Bottoms	4
I-4.3 Continuous Caster and Clean Steel Ladles	4
I-4.4 Reinforcement for Nozzle Opening	4
I-4.5 Welded Ladles	6
I-4.6 Stress Relieved Welds	6
I-4.7 Wear Sleeves for Trunnion Pins	6
I-4.8 Safety Flanges	6
I-4.9 Splash Plates	7
I-4.10 Vent Holes	7
I-4.11 Reinforcement of Lip Ring	7
I-4.12 Refractory Retainer	7
I-4.13 Capacity Identification	7

I-5 Design Assumptions and Allowable Stresses	7
I-5.1 General	7
I-5.2 Ladle Volume and Metal Density	7
I-5.3 Location of Trunnion Axis	8
I-5.4 Allowable Stresses in Ladle Components	8
I-5.5 Allowable Stresses in Trunnion Pins	13
I-5.6 Allowable Shear Stresses in Rivets	15
I-5.7 Allowable Shear Stress in Pins of Tilt Mechanisms	15
I-6 Design of Trunnion Block and Pin	15
I-6.1 General	15
I-6.2 Shear and Bearing Stresses	15
I-6.3 Bending Moment in Pins	15
I-6.4 Fillet Radius	16
I-6.5 Fitting in Trunnion Block	16
I-6.6 Sleeves	16
I-6.7 Stiffness in Trunnion Block	16
I-6.8 Attaching Block to Ladle	16
I-6.9 Installation of Pins	16
I-6.10 Bending Stresses in Trunnion Blocks	16
I-6.11 Ribbed Trunnion Block Design	16
I-7 Design of Bottom Plates of Flat-Bottom Ladles	17
I-7.1 General	17
I-7.2 Thickness of Circular Flat Bottoms	17
I-7.3 Reinforcing Plate	17
I-7.4 Thickness of Bottom Plate and Reinforcing Plate	18
I-7.5 Equivalent Diameter for Oval Ladles	18
I-7.6 Stiffener Ribs for Bottom Plates	18
I-8 Design of Bottom Plates of Dished-Bottom Ladles	19
I-8.1 General	19
I-8.2 Thickness of Dished Circular Ladle Bottoms	19
I-8.3 Thickness of Dished Oval Ladle Bottoms	19
I-8.4 Reinforcing Plates	19
I-8.5 Stiffener Ribs for Dished Circular Bottom Plates	19
I-8.6 Stiffener Ribs for Dished Oval Bottom Plates	21
I-9 Design of Stiffener Bands	21
I-9.1 General	21
I-9.2 Effective Band	21
I-9.3 Calculations of Effective Band Width	21
I-9.4 Properties of Bands	23
I-9.5 Calculations of Compressive Forces in Bands	23
I-9.6 Portion of Trunnion Block Included in Effective Band Section	23
I-9.7 Band Bending Moment	24
I-9.8 Calculation of Band Bending Moments	24
I-9.9 Combined Stresses in Bands	24

I-10 Design of Sidewall Plates	25
I-10.1 Sidewall Plate Thickness	25
I-10.2 Sidewall Plate Joint	25
I-10.3 Supplementary Thickness	25
I-10.4 Upper Sidewall Plate Thickness	25
I-11 Inward Deflection Stiffness at Trunnions	25
I-12 Design of Tilt Mechanism	27
I-12.1 General	27
I-12.2 Primary Functional Requirements	27
I-12.3 Loading Conditions	27
I-12.4 Tilt Mechanism Description	27
I-12.5 Design Conditions	28
I-12.6 Maximum Loads and Service Temperatures for the Tilt Mechanism Components	28
I-12.7 Design of Pin-Connected Member	29
I-12.8 Design of Latch Plates and Tilt Bearing Devices	31
I-12.9 Design of Other Style Tilt Mechanisms	31
I-12.10 Non-Structural Appurtenances	31
I-13 Riveted Sidewall Circumferential Connection Joints	31
I-13.1 General	31
I-13.2 Design of the Riveted Sidewall Connection	31
I-13.3 Minimum Rivet Spacing and Edge Distance	32
I-13.4 Allowable Stresses in Rivets	32
I-13.5 Allowable Stress in Sidewall Plate	32
I-13.6 Postweld Heat Treatment	32
I-13.7 Preparation of Plate Edges	32
I-13.8 Buttstrap End Connection	32
I-14 Design of Support Legs for Dished-Bottom Ladles	32
I-14.1 General	32
I-14.2 Loading Conditions	32
I-14.3 Description of Support Legs	33
I-14.4 Design of the Support Legs	33
I-15 Assembling and Welding Ladles in the Shop and Field	34
I-15.1 Fitting	34
I-15.2 Cleaning	34
I-15.3 Welding	34
I-15.4 Weld Defects	34
I-15.5 Inspection and Non-Destructive Tests of Welds	34

PART II: LADLE DESIGN — REFRACTORY LINING

II-1 Scope	35
II-2 Ladle Lining	35
II-2.1 General	35
II-2.2 Lining Insulating Capacity	35
II-2.3 Estimating Wall Working Lining Thermal Expansion Stress	35
II-2.4 Wall Working Lining Expansion Allowance	36
II-2.5 Compressible Expansion Allowance Materials	37
II-2.6 Lining Stabilization	38

PART III: LADLE INSPECTION, REPAIR, ALTERATION AND MAINTENANCE

III-1 Ladle Inspection	39
III-1.1 General	39
III-1.2 Ladle Details for Inspection	39
III-2 Ladles with Riveted Lap Joints	39
III-3 Ladle Repair and Alteration Procedures	40
III-3.1 General	40
III-3.2 Procedure for Ladle Repair	40
III-3.3 Procedure for Ladle Alteration	40
III-4 Repair and Maintenance Details of Structural Components	40
III-4.1 General	40
III-4.2 Sidewall or Bottom Patch	40
III-4.3 Closure of Vent Holes	41
III-4.4 Repair of Welds	41
III-4.5 Crack Repair	41
III-5 Alterations to Ladles	41
III-5.1 General	41
III-5.2 Additional Freeboard	41
III-5.3 Slide Gates	41
III-5.4 Sidewall and Bottom Plate Openings	41

PART IV: USE OF LADLES

IV-1 Recommended Operating Practices for Minimization of Shell Flexing	42
IV-2 Brimful Ladle	42
IV-3 Lip Pouring Considerations	42

Symbols — Part I	43
Symbols — Part II	47
Commentary	49
Codes, Specifications and Standards Cited	55
References	55
Appendix A — Design Examples	56
Appendix B — Method of Determining Ladle Deflection Coefficient	111
Owner's Information Sheet	113

3



PART I: LADLE DESIGN — STEEL SHELL

I-1 SCOPE.

I-1.1 General. Part I of this technical report shall cover the specifications for design of new ladles with circular, oval or obround cross-sections and with welded or riveted construction as are used for transporting and processing molten metal ¹⁻¹⁰. Insofar as applicable these specifications may be used in the design of other types of ladles. The user shall provide the ladle manufacturer with necessary information, including that shown on the Owner's Information Sheet (OIS).

I-1.2 Intended Coverage. Part I of these specifications is intended to cover a selection of materials and structural design methods for primary ladle components. Supplementary specifications covering special features may be added by the purchaser. No change in the intended use of a ladle, increase in its rated capacity, or modification of the ladle as designed initially in accordance with the OIS, shall be made without verifying that the criteria for strength, stability, deflection and other design criteria mentioned in this report have been met.

I-1.3 Specification Assumptions. These specifications are based on the assumption that while the ladle is in service, adequate maintenance will be carried out and that frequent periodic inspections shall be made for cracks, thermal distortion, loss of section or other damage. Ladles designed to these specifications shall be repaired, reinforced or retired whenever necessary for continued conformity to this report. Suggested practices are discussed in the Commentary.

I-2 WORKMANSHIP.

Workmanship shall be first class in every respect. The workmanship shall be in accordance with the requirements of the ASME Boiler and Pressure Vessel Code (hereafter referred to as the ASME Code), Section VIII, Division I.

I-3 MATERIALS.

I-3.1 General. This section lists materials that may be used for construction of ladle components. The materials covered by this report shall be in accordance with the latest standards of the American Society for Testing and Materials (ASTM) as outlined below.

In addition to recognizing the service temperature of the components through the selection of appropriate materials, a temperature derating factor shall be employed in the design of ladle components. The application of temperature derating factors is also discussed in the sections on design assumptions and allowable stresses (Sections I-5.4 and I-5.5).

Welding materials such as welding rods, electrodes and filler materials shall be in accordance with appropriate specifications of the American Welding Society (AWS), Filler Metal Specification.

I-3.2 Bottom Plate and Adjacent Shell Plate. Materials that may be used for the construction of the bottom plate and adjacent lower shell plate operating under the maximum service temperatures listed are:

650°F or less: A 36 Structural Steel

- Use only for flatbottom ladles with stiffener ribs
- May be used for stiffener ribs

A 441 High Strength Low-Alloy Structural Manganese Vanadium Steel

700°F or less: A 285 Pressure Vessel Plates, Carbon Steel, Low- and Intermediate-Tensile Strength

- Grade C
- Use for thickness of 2 in. or less

A 516 Pressure Vessel Plates, Carbon Steel, for Moderate- and Lower-Temperature Service

- Grades 55, 60, 65 and 70

750°F or less: A 515 Pressure Vessel Plates, Carbon Steel, for Intermediate- and Higher-Temperature Service

- Grades 55, 60, 65 and 70

800°F or less: A 204 Pressure Vessel Plates, Alloy Steel, Molybdenum

- Grades A, B and C

A 387 Pressure Vessel Plates, Alloy Steel, Chromium-Molybdenum

- Class 2, Grades 11, 12, 21 and 22

The maximum service temperature is considered to be the maximum operating temperature in the bottom plate and adjacent shell plate. In addition to selecting appropriate grades of steel for the maximum service temperature, the appropriate temperature derating factors discussed in Section I-5.4, and summarized in Table I-1 must be applied.

The design of other components subject to increased temperature conditions such as stiffener ribs for bottom plates are also discussed in Section I-5.4.

I-3.3 Stiffener Bands, Splash Plate and Upper Sidewall.

Moderate- and Lower-Temperature Service

- Grades 55, 60, 65 and 70

I-3.3.1 Carbon Steel.

A 36 Structural Steel

A 283 Low and Intermediate Tensile Strength Carbon Steel Plates, Shapes, and Bars

- Grade C

A 285 Pressure Vessel Plates, Carbon Steel, Low- and Intermediate Tensile Strength

- Grade C
- This material shall be used if specified by the purchaser on the OIS for thicknesses up to and including 2 in. only

A 515 Pressure Vessel Plates, Carbon Steel, for Intermediate- and Higher-Temperature Service

- Grades 55, 60, 65 and 70

A 516 Pressure Vessel Plates, Carbon Steel, for

I-3.3.2 Low-Alloy Steel. The following material shall be used for thicknesses over 2 in. if specified by the purchaser on the OIS.

A 204 Pressure Vessel Plates, Alloy Steel, Molybdenum

- Grades A, B and C normalized

A 387 Pressure Vessel Plates, Alloy Steel, Chromium-Molybdenum

- Class 1, Grades 2, 5, 11, 12, 21 and 22
- Class 2, Grades 11, 12, 21 and 22

A 441 High Strength Low-Alloy Structural Manganese Vanadium Steel

Temperature derating factors are shown in Table I-1.

Table I-1 — Temperature Derating Factor, F_t , for Ladle Components*

Materials (ASTM Designations)	Maximum Design Temperature, °F						
	600	650	700	750	800	850	900
Group I	0.739	0.729	0.720	0.693	0.666	0.650	0.634
A 285, Gr C							
A 284, Gr C, D							
A 515, Gr 55, 60, 65, 70							
A 516, Gr 55, 60, 65, 70							
Group II	0.813	0.790	0.766	0.740	0.713	0.684	0.654
A 242							
A 441							
A 440							
Group III	0.833	0.807	0.782	0.765	0.748	0.723	0.697
A 204, Gr A, B, C							
A 387, Class 1, Gr 2, 5, 11 12, 21, 22							
Group IV	0.733	0.712	0.690	0.674	0.658	0.619	0.580
A 387, Class 2, Gr 11, 12							
A 36							
A 283, Gr C							
Group V	0.776	0.774	0.771	0.764	0.756	0.737	0.722
A 387, Class 2, Gr 21, 22							
Group VI**	0.740	0.730	0.720	0.693	0.665	0.650	0.635
A 216, Gr WCA, WCB, WCC							
A 27, Gr 60-30							

Materials listed in Table I-1 that are not otherwise mentioned have been added as a guide to implement Section I-3.

* Based on the ASME Code, Section VIII, Division 2 and Reference 17

** This group is applicable to trunnion blocks only and not for trunnion pins or miscellaneous forged fittings.

I-3.4 Lip Ring. The material of construction of the lip ring, if not specified by the purchaser on the OIS, shall be selected from materials listed in Section I-3.3. Alternate materials of construction such as gray iron, ductile iron or steel castings may be used if specified by the purchaser on the OIS.

I-3.5 Trunnion Pin.

A 668 Steel Forgings, Carbon and Alloy, for General Industrial Use

- Classes B, C and D normalized or annealed
- Classes G and H

In addition, carbon and alloy steel chemical compositions should be specified to suit the requirements of the applications.

Temperature derating factors for trunnion pins are shown in Table I-2. When ordering replacement pins, the purchaser may specify a higher grade material to take advantage of improved material properties; however, the minimum pin size supplied shall be the same as the original pin.

I-3.6 Trunnion Block

I-3.6.1 Castings.

A 27 Mild-to-Medium-Strength Carbon-Steel-Castings for General Application

- Grades 60-30, 65-35

A 216 Carbon-Steel Castings Suitable for Fusion Welding for High-Temperature Service

- Grades WCA, WCB and WCC

I-3.6.2. Plate

A 36 Structural Steel

A 283 Low and Intermediate Tensile Strength Carbon Steel Plates, Shapes, and Bars

- Grade C

A 285 Pressure Vessel Plates, Carbon Steel, Low- and Intermediate-Tensile Strength

- Grade C

A 515 Pressure Vessel Plates, Carbon Steel, for Intermediate- and Higher-Temperature Service

- Grades 55, 60, 65 and 70

A 516 Pressure Vessel Plates, Carbon Steel, for Moderate- and Lower-Temperature Service

- Grades 55, 60, 65 and 70

I-3.7 Rivets.

A 31 Boiler Rivet Steel and Rivets

- Grades A and B (Grade A is recommended for attaching reinforcing plate to a flat bottom ladle)

A 502 Steel Structural Rivets

- Grades 1 and 2

I-3.8 Miscellaneous Forged Fittings.

A 668 Steel Forging, Carbon and Alloy, for General Industrial Use

- Class B normalized or annealed

I-3.9 Other Materials. Other materials may be used for ladle components provided that the mechanical properties, including impact properties, aging and work hardening characteristics are the same or superior to the minimum values of the materials listed in Sections I-3.2 through I-3.8 inclusive and are approved by the purchaser.

I-3.10 Material Testing Procedures. The chemical composition and physical properties quoted in the materials specifications shown in Sections I-3.2 through I-3.9 should be determined in accordance with ASTM testing standards.

The purchaser may specify on the OIS additional inspection procedures to confirm the suitability of the material for the components covered in this report. Typical ASTM inspection and testing standards may include, but are not limited to, the following:

A 573 Structural Carbon-Steel Plates of Improved Toughness

- Proof testing for improved toughness

A 435 Straight Beam Ultrasonic Examination of Steel Plates for Pressure Vessels

- Ultrasonic inspection of plate

A 388 Ultrasonic Examination of Heavy Steel Forgings

- Ultrasonic inspection of forgings

Table I-2 — Temperature Derating Factor, F_t , for Trunnion Pins and Miscellaneous Forged Fittings*

Materials (ASTM Designations)	Maximum Design Temperature, °F		
	300	400	500
Group I	0.885	0.857	0.808
A 668, Class B, C, D, G, H			

*Based on ASME Code, Section VIII, Division 2 and Reference 22.

I-4 GENERAL REQUIREMENTS

I-4.1 General Shape. Ladles may be circular or oval. If oval, flat plate sidewall segments may be used in the simulation of oval ladles (called obround) if blended with a smooth junction to the curved end sections.

I-4.2 Ladle Bottoms. One of the following designs^{11, 12, 13} shall be used for ladle bottoms, excepting continuous caster ladles and ladles used in a variety of clean steel or similar hot metal processing environments (Section I-4.3):

- (1) Flat bottom with flanged sides. The inside corner radius (knuckle radius) between the sidewall and the flat bottom shall be hot formed with a radius of not less than three times the thickness.
- (2) Flat bottom with stiffener ribs. Flat bottoms with stiffener ribs welded to the shell and bottom may be used as an alternate, in which case the bottom plate need not be flanged.
- (3) Flanged and dished bottoms with or without stiffener ribs. The knuckle between the sidewall and the dished bottom shall be hot-formed with an inside radius of not less than three times the thickness.
- (4) Torispherical and ellipsoidal heads. Torispherical and ellipsoidal bottom heads designed in accordance with the ASME Code, Section VIII, Divisions 1 and 2 are acceptable.
- (5) Knuckle radius. The knuckle radius shall be not less than 6% of the inside diameter of the sidewalls at the bottom for all types of bottom flanged heads for those ladles subjected to high thermal stresses as a result of special operating conditions.

I-4.3 Continuous Caster and Clean Steel Ladles. For continuous caster ladles and ladles used in a variety of clean steel metallurgy processing and other similar environments, sustained operating temperatures on the working lining result in high steady-state lining and shell temperatures. These practices, combined with the use of high strength working linings, result in more severe structural environments. For these conditions, the following practices for ladle bottoms are recommended:

- (1) For all types of flanged bottom ladles, the stress in the knuckle may reach critical levels due to thermal expansion of the bottom. The purchaser may elect to increase the hot formed knuckle radius to four times the plate thickness, or not less than 6% of the inside diameter of the sidewall at the bottom. Cold formed knuckle radii are not acceptable.
- (2) If specified by the purchaser on the OIS, ladles shall be provided with heat protection shields around the teeming nozzle.

(3) Torispherical or ellipsoidal bottoms designed in accordance with the ASME Code, Section VIII, Divisions 1 and 2 are recommended where possible.

(4) Shrouds for teeming stream should be provided and properly maintained.

(5) Designing both the ladle sidewall and bottom for temperatures of 800°F or more and using creep resistant steels (higher strength) should be considered due to the nature of continuous caster and clean steel practices.

(6) For flat bottoms with ribs, special attention should be paid to the nozzle area where ribs cannot be placed in order to clear the slide gate. Either the bottom plate is reinforced, or the surrounding ribs are upgraded, or a combination of both is provided.

(7) In the case where the sidewall plate and dished-bottom plate differ in thickness (Fig. I-1), the connection shall be a tapered transition having a length not less than three times the offset between the adjacent surfaces of abutting sections, as described in the ASME Code Section VIII, Divisions 1 and 2. The offset (y) can be made on either the inside or outside of the ladle.

I-4.4 Reinforcement for Nozzle Opening. Nozzle reinforcing plates and their welds shall be designed to meet the mechanical and thermal loads imposed by the operating conditions.

The openings in the wall or bottom shall preferably be circular, elliptical or obround. Rectangular or square openings are not encouraged, however the ASME Code Section VIII, Divisions 1 and 2 shall be used for guidance in the design of these type openings.

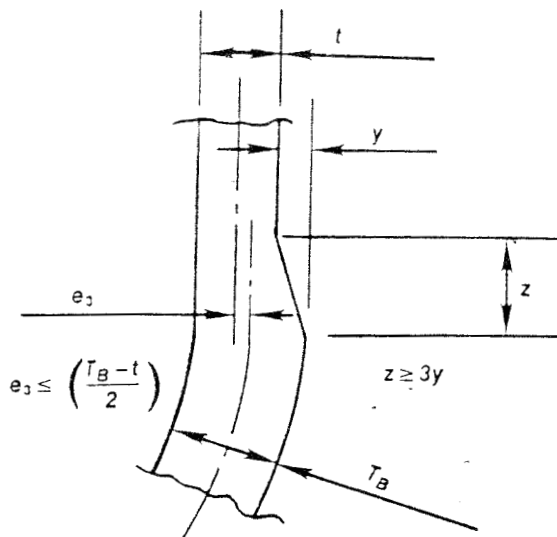
I-4.4.1 Design of Nozzle Opening Reinforcing Plates.

The dimensions of reinforcing plates are not limited; however, for calculation purposes, the dimensions shall not exceed twice the diameter of the opening. Variations of this configuration will be acceptable if the design is in conformity with the latest edition of the ASME Code, Section VIII, Division 1. The inner edge of the reinforcement shall be placed at edge of the nozzle hole.

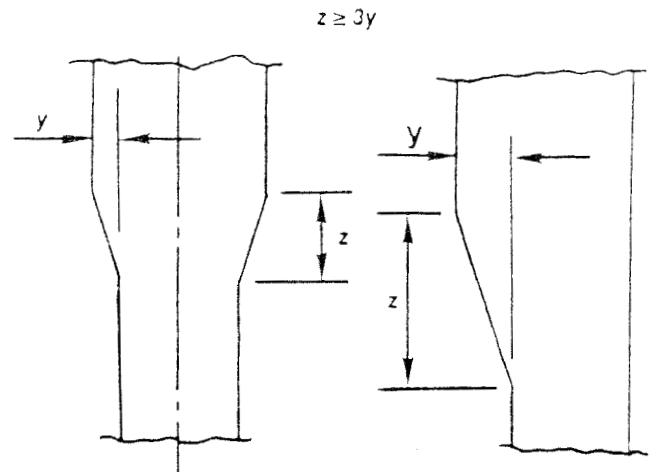
The total cross-sectional area of reinforcement through the center line shall not be less than the net cross-sectional area of the metal removed. The plate thickness of the reinforcing element or welded adapter shall not be less than the original required thickness of the ladle bottom (Fig. I-2a). This thickness would include the thickness of any reinforcing plate, T_R , when used.

A reinforcing plate can be highly stressed where high heat flow or high transient temperatures exist. A considerable temperature differential and corresponding stresses can exist between the ladle bottom and the reinforcing plate. Heat flow is restricted because of the limited fastener or weld area and by the insulating effect of:

- (1) Mill scale or surface rust



(a) Sidewall plate to bottom plate connection transition.



(b) Sidewall plate connection transition.

Fig. I-1 — Transition Requirements in Sidewall Plate Connection and Sidewall Plate to Bottom Connection

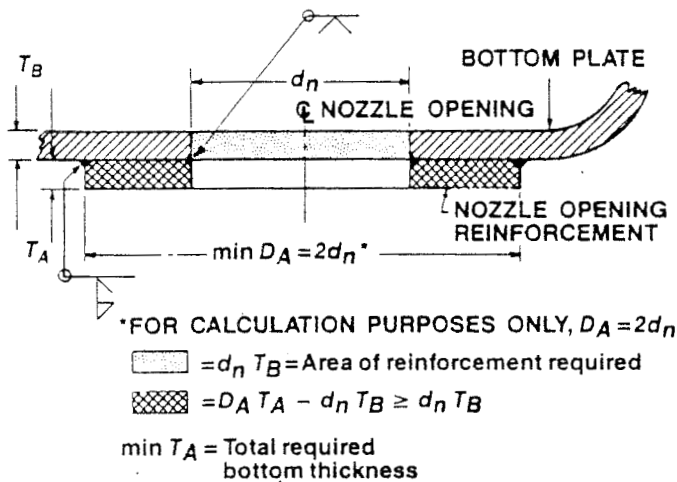


Fig. I-2a — Nozzle Opening Reinforcement Plate Design

- (2) Scale formed in service
- (3) Limited surface contact due to normal plate irregularities
- (4) Possible air gaps formed by warping of either plate during construction or service.

Where high thermal stresses may be encountered, the alternate designs described in Section I-4.4.2 should be considered.

I-4.4.2 Alternate Design of Reinforcing Plate. For continuous caster ladles and ladles used in a variety of clean steel/molten metal processing and other similar environ-

ments, an alternate method of reinforcement for nozzle openings is recommended. This alternate method of reinforcement for nozzle openings which can be used for wall, flat bottom and dished bottoms is to install a thick circular plate with an opening in the plate center to replace the wall or bottom plate nozzle region. The thickness of this plate shall not be less than the minimum combined thickness of the bottom plate and the doubler plate, as discussed in Section I-4.4.1. The diameter of the plate shall not be less than twice the diameter of the opening, as shown in Fig. I-2b. The material selection for this plate shall be in accordance with Section I-3.2.

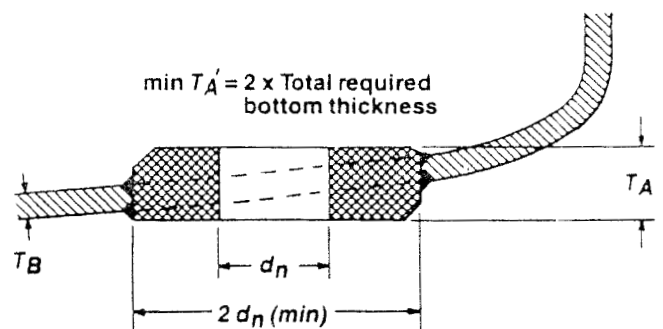


Fig. I-2b — Nozzle Opening Reinforcement—Alternate Design

I-4.4.3 Design of Plates for Slide Valves or Gate Valves. For ladles equipped with slide valves or gate valves, the mounting plate, adapter plate or leveling plate shall not be thinner than the bottom head plate thickness. Such plates must be full-strength welded, riveted or bolted to the bottom head plate. The riveting or bolting must be adequate to limit the horizontal shearing stress in accordance with Section I-7.3.2 of this Report.

I-4.4.4 Nozzle Openings. The centers of nozzle openings in the bottom plate shall be located within a horizontal angle of ± 60 degrees from the ladle cross axis plane. The opening shall be placed as close as possible to the ladle cross axis plane.

I-4.5 Welded Ladles. Details of welded ladles or subassemblies and welding symbols shown on drawings shall conform with the latest recommended practice of the AWS Structural Welding Code D1.1. Welding procedures are covered in Section I-15 of this Report.

Intermittent fillet welds are not permitted for connecting a stiffener plate or any appurtenance to the ladle shell, ladle bottom, stiffener bands or any primary structural member.

Joints in the ladle shell, joints in the ladle bottom and joints between the ladle shell and ladle bottom shall be either full penetration butt welds or lap riveted connections.

I-4.5.1 Lap Riveted Connections. Only circumferential lap riveted joints shall be used in connecting the sidewall plates or in connecting the sidewall plate to the ladle bottom. The lap riveted joint shall be designed according to the requirements of Section I-13.

I-4.6 Stress Relieved Welds.

I-4.6.1 General. Welded ladles shall be stress relieved by uniform heating in a furnace in accordance with the ASME Code, Section VIII, Division 1 except that the furnace temperature shall not exceed 500°F at the time the welded assembly is placed in the furnace. 260°C

Field welds on new ladles (except those conditions listed in Section I-4.6.2), shall be thermally stress relieved in accordance with the heating, holding and cooling cycle specified by the ASME Code, Section VIII, Division 1. The ladle shall be properly braced and supported to avoid structural damage due to the effects of temperature when the ladle is stress relieved. Other stress relieving methods agreeable to the purchaser may be specified on the OIS.

Preheat and interpass temperatures for welding shall be in accordance with ASME Code, Section VIII, Division 1.

Welds shall be normalized for grain refinement when the welding procedure used makes it necessary.

I-4.6.2 Postweld Heat Treatment of Field Welds.

Postweld heat treatment (thermal stress relief) of field welds is to be performed in accordance with the ASME Code, Section VIII, Division 1.

(1) Postweld heat treatment is not mandatory for carbon steels (P-No. 1 materials) up to and including $1\frac{1}{2}$ in. thick provided that material over $1\frac{1}{4}$ in. thick is preheated to a minimum temperature of 200°F prior to and during welding.

(2) For material over $1\frac{1}{2}$ in. thick and for material of any thickness when the purchaser specifies postweld heat treatment on the OIS, all welded connections and attachments shall be postweld heat treated with the following exceptions:

(a) Groove welds $\frac{1}{2}$ in. or less in size and fillet welds with a throat $\frac{1}{2}$ in. or less which attach nozzle connections having a finished inside diameter 2 in. or less, provided the connections do not form ligaments requiring an increase in shell or head thickness and provided that a minimum preheat temperature of 200°F is applied.

(b) Fillet welds having a throat thickness of $\frac{1}{2}$ in. or less which are used for attaching nonpressure parts to pressure parts, and provided that a minimum preheat temperature of 200°F is applied when the thickness of the pressure part exceeds $1\frac{1}{4}$ in.

(c) Studs welded to pressure parts provided that a minimum preheat temperature of 200°F is applied when the thickness of the pressure part exceeds $1\frac{1}{4}$ in.

$$F = \frac{9 \times C^2}{8} + 32 =$$
$$C = \frac{8(F - 32)}{9}$$

Modification of the foregoing shall be made in accordance with the latest issue of the ASME Code, Section VIII, Division 1.

I-4.6.3 Peening. Peening of the field weld metal is recommended for control of shrinkage stresses where thermal stress relief is not required. When this practice is implemented, a pneumatic chisel with a blunt, rounded edge should be used. This is in accordance with the ASME Code, Section IX. In such cases, the first (root) pass and the last (cover) pass shall not be peened. Caution: excessive peening may set up new residual stresses. Care should be taken to prevent overlapping or cracking of the weld or base metal (See AWS D1.1).

I-4.7 Wear Sleeves for Trunnion Pins. If specified by the purchaser on the OIS, trunnion pins for ladles shall be provided with steel sleeves to avoid wear on the trunnion pin.

I-4.8 Safety Flanges. Safety flanges shall be provided on the end of the trunnion pin to facilitate the engagement of the ladle hook.

I-4.9 Splash Plates. Ladles which may be exposed to splashing shall be provided with a splash plate around the circumference of the ladle to prevent metal and slag from sticking to side plates of the ladle and building up on the stiffener bands. The plate shall be arranged so as not to prohibit removal for inspection of the ladle.

I-4.10 Vent Holes. Vent or weep holes shall be provided in accordance with the request of the purchaser on the OIS.

Vent or weep holes if requested by the purchaser shall be provided in the bottom and walls using established practices. An example of good practice would be 1/2 in. holes on 9 in. centers.

I-4.11 Reinforcement of Lip Ring. Openings in the lip or top stiffener ring shall be reinforced to meet operating conditions.

I-4.12 Refractory Retainer. A refractory retaining plate or angle shall be attached by welding, riveting or bolting to the lip of the ladle wall. Stress risers at the top edge of the ladle walls shall be avoided. The stiffness of the top of the ladle wall edge, enhanced by the addition of the brick retainer, shall be maintained as uniform as possible.

I-4.13 Capacity Identification. The manufacturer of each new ladle shall provide visible information on the ladle concerning its rated capacity in tons of molten metal.

I-5 DESIGN ASSUMPTIONS AND ALLOWABLE STRESSES.

I-5.1 General. The design procedures used in this report are based on a specified ladle capacity in short tons (one short ton = 2000 pounds), the type or composition of metal to be transported, the ladle refractory lining, the freeboard requirements, the ladle lid requirements, the type of refractory in the ladle lid, the weight of the ladle lid, and other load environments imposed on the ladle. The refractory lining and lid information shall include the types of material, thickness, profile and densities. This information shall be specified by the purchaser on the OIS, together with other necessary design parameters.

The purchaser of the ladle shall specify on the OIS the ladle rated operating capacity and the freeboard requirements. The proliferation of the ladle refining stations and other clean steel practices has led to the use of ladles with a large amount of freeboard as compared to what has been traditionally held as normal. Therefore, the following three-step method has been developed for designing and/or checking the design of large freeboard ladles.

(1) Locate the trunnion pins and check the stability of the ladle using the procedures as set forth in this Technical Report.

(2) Design or verify the design as specified in this Technical Report but with the following factors considered:

(a) For the total weight (W_2), use the design hot metal capacity plus the weight of the refractories plus ladle.

(b) For the purpose of this initial set of calculations, develop an artificial ladle height (h) such that the freeboard above the hot metal is only 5% of the total ladle height (H). This artificial height is not to be used to adjust the weight (W_2) developed in step 2-a.

(3) After step 2 has yielded an acceptable design, verify the design again but with the following factors considered:

(a) Use the actual height of the ladle for H .

(b) For the total weight (W), increase the amount of hot metal until the ladle is brimful.

(c) Increase the allowable stresses by 30%.

This procedure should be followed only if the freeboard exceeds 10% of the ladle height (H). Note that for step 3-b, W is defined in Eq I-1 using half of the total new refractory lining thickness. Careful consideration of all operating conditions and potential emergency situations should be taken into account by both the ladle user and the ladle supplier.

I-5.2 Ladle Volume and Metal Density. The total ladle volume can be determined from the sum of the volume of metal, refractory lining and the freeboard. The metal volumes can be calculated using the density from Fig. I-3^{14, 15} for plain carbon iron and steel or from data supplied by the purchaser on the OIS for alloy steels. Different types or compositions of metal are recognized in the design equations by a molten metal term, q , kips/cu ft (1 kip = 1000 lb).

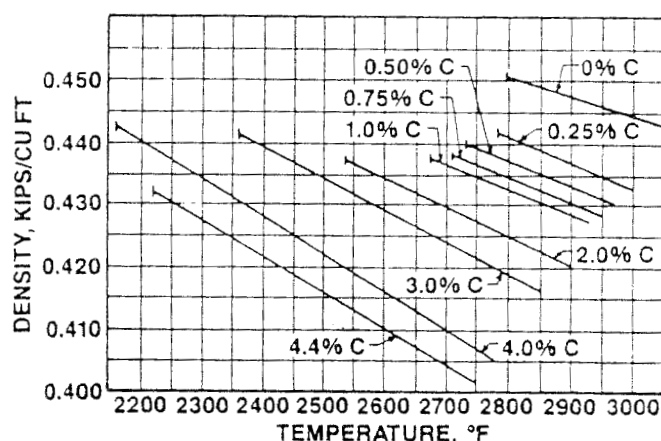


Fig. I-3 — Density of Plain Carbon Iron and Steel of Various Carbon Content as a Function of Temperature

I-5.3 Location of Trunnion Axis. The trunnion axis shall be located a distance j above the combined center of gravity of the ladle, worn lining (defined as the condition at which half the total new wall refractory thickness has eroded and the full bottom thickness is intact), the molten metal which fills the ladle to the brim, and the ladle lid if applicable, as calculated by Eq I-1.

$$j = 3.236 (10)^{-6} \left[\frac{q}{W} \right] [D_{wr(min)}] [D_{wr(max)}]^3 \quad (\text{Eq I-1})$$

Where:

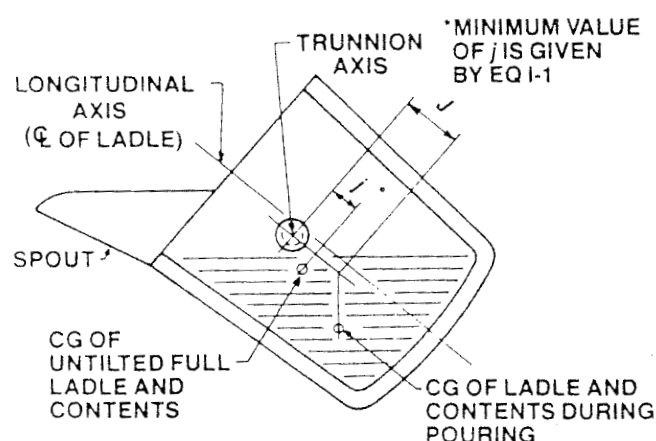
j = Minimum distance between the trunnion axis and the center of gravity of the full untilted ladle such as to provide static and dynamic stability in all positions, ft (Fig. I-4)

q = Density of molten metal, kips/cu ft

W = Total weight of a brimful ladle including molten metal, worn lining (defined as the condition at which half the total new wall refractory thickness has eroded and the full bottom thickness is intact), ladle steelwork, and ladle lid if applicable, kips

$D_{wr(min)}$ = Inside diameter of the worn lining at the top of a ladle as defined by the diameter of the mid-total thickness center line of a new ladle lining of a circular ladle, or the length between the mid-total thickness center lines of the new ladle lining measured at the short axis at the top of an oval or obround ladle, in.

$D_{wr(max)}$ = Inside diameter of worn lining at top of an oval or obround ladle as defined by the length between the mid-total thickness center lines of its new refractory measured at the long axis at the top of the ladle, in.



g. I-4 — Notations Used in Determining Location of Trunnion Axis with Respect to Center of Gravity

Charging ladles and teeming ladles, when pouring over the top, shall be checked for stability in a sequence of rotational positions which can occur, for example, during the pouring operation, with worn lining and new lining, with skull and without skull. The user shall specify on the OIS the maximum weight and location of skull as well as the maximum metal level in the pouring spout during pouring.

An additional unbalanced weight shall be introduced to allow for the effect of skulling. The value J (Fig. I-4) shall be made to become greater than j (calculated by Eq I-1) at a relatively small tilt angle (usually less than 10 degrees) and thereafter shall remain greater than the calculated value of j or all subsequent angles of tilt until the ladle is emptied. The quantity j (minimum acceptable value as defined) is the distance between the trunnion axis and the center of gravity of the full ladle, so as to provide static and dynamic stability in the vertical position. The value J is the distance from the trunnion axis along a line parallel to the longitudinal axis through the trunnion pin of the ladle (vertical when untilted) to the point of intersection with the vertical line through the center of gravity of the tilted ladle and its contents.

The ladle trunnions shall be located horizontally after calculating the center of gravity of the empty, partially filled and completely filled ladles. In teeming ladles with sloped bottoms, the combined ladle center of gravity changes its horizontal location (as well as its vertical location) while the molten metal is being discharged from the ladle. The designer shall specify the optimum location of the trunnion pins; that is, the position which will minimize the possibility of a sudden rotational shift of the ladle on the ladle hooks during normal teeming operations.

I-5.4 Allowable Stresses in Ladle Components.

The following stresses in various categories shall not be exceeded in the design as calculated by the method of elastic analysis of the ladle components, except for trunnion pins (see Section I-5.5 for trunnion pins). These stresses are based on the use of materials that meet the requirements of this report.

The equations in the following sections define the allowable stresses. For σ_a , σ_d , and σ_{dl} , the allowable stresses are calculated for the permitted materials in Tables I-3, I-4 and I-5, respectively. However, the allowable stress values do not include the effect of the fabrication derating factor F_f .

Table I-3 — Allowable Normal Design Stress, $\sigma_a^\dagger$ for Ladle Components, ksi

Materials (ASTM Designations)	Maximum Design Temperature, °F							
	70	600	650	700	750	800	850	900
Group I								
A 285, Gr C	10.96	8.10	7.99	7.89	7.60	7.30	7.13	6.95
A 284, Gr C	10.96	8.10	7.99	7.89	7.60	7.30	7.13	6.95
Gr D	12.06	8.91	8.79	8.68	8.36	8.03	7.84	7.65
A 515, Gr 55	10.96	8.10	7.99	7.89	7.60	7.30	7.13	6.95
Gr 60	11.70	8.64	8.53	8.42	8.11	7.79	7.60	7.42
Gr 65	12.79	9.45	9.33	9.21	8.87	8.52	8.31	8.11
Gr 70	13.89	10.26	10.13	10.00	9.63	9.25	9.03	8.81
A 516, Gr 55	10.96	8.10	7.99	7.89	7.60	7.30	7.13	6.95
Gr 60	11.70	8.64	8.53	8.42	8.11	7.79	7.60	7.42
Gr 65	12.79	9.45	9.33	9.21	8.87	8.52	8.31	8.11
Gr 70	13.89	10.26	10.13	10.00	9.63	9.25	9.03	8.81
Group II *								
A 242, < 3/4	15.35	12.48	12.13	11.76	11.36	10.95	10.50	10.04
3/4 to < 1 1/2	14.69	11.95	11.61	11.25	10.87	10.48	10.05	9.61
1 1/2 to < 4	13.82	11.23	10.91	10.58	10.22	9.85	9.45	9.04
A 441, < 3/4	15.35	12.48	12.13	11.76	11.36	10.95	10.50	10.04
3/4 to < 1 1/2	14.69	11.95	11.61	11.25	10.87	10.48	10.05	9.61
1 1/2 to < 4	13.82	11.23	10.91	10.58	10.22	9.85	9.45	9.04
4 to < 8	13.16	10.70	10.39	10.08	9.74	9.38	9.00	8.61
Group III								
A 204, Gr A	13.52	11.27	10.91	10.58	10.35	10.12	9.78	9.43
Gr B	14.62	12.18	11.80	11.43	11.18	10.94	10.57	10.19
Gr C	15.72	13.09	12.68	12.29	12.02	11.76	11.36	10.95
A 387, Gr 2, C1	12.06	10.05	9.73	9.43	9.22	9.02	8.72	8.41
Gr 5, C1	10.96	9.13	8.85	8.57	8.39	8.20	7.93	7.64
Gr 11, C1	12.79	10.66	10.32	10.00	9.79	9.57	9.25	8.92
Gr 12, C1	12.06	10.05	9.73	9.43	9.22	9.02	8.72	8.41
Gr 21, C1	10.96	9.13	8.85	8.57	8.39	8.20	7.93	7.64
Gr 22, C1	10.96	9.13	8.85	8.57	8.39	8.20	7.93	7.64
Group IV								
A 387, Gr 11, C2	16.45	12.06	11.71	11.35	11.09	10.82	10.18	9.54
Gr 12, C2	14.25	10.45	10.15	9.84	9.61	9.38	8.82	8.27
A 36	12.72	9.32	9.06	8.78	8.57	8.37	7.87	7.38
A 283, Gr C	10.96	8.04	7.81	7.57	7.39	7.21	6.79	6.36
Group V								
A 387, Gr 21, C2	16.45	12.76	12.73	12.68	12.57	12.43	12.12	11.88
A 387, Gr 22, C2	16.45	12.76	12.73	12.68	12.57	12.43	12.12	11.88
Group IV								
A 216, Gr WCA	10.96	8.11	8.00	7.89	7.60	7.29	7.13	6.96
Gr WCB	13.16	9.74	9.61	9.47	9.12	8.75	8.55	8.36
Gr WCC	14.62	10.82	10.67	10.53	10.13	9.72	9.50	9.28
A 27, Gr 60-30	10.96	8.11	8.00	7.89	7.60	7.29	7.13	6.96

This table is based on the ASME Code, Section VIII, Division 2, and Reference 17.

† Allowable design stress is based on a fabrication derating factor, F_b , of 1.0. Designer should adjust according to the actual factor.

* Range of thickness, in.

Table I-4 — Allowable Total Stress, $\sigma_d^\dagger$ for Ladle Components, ksi

Materials (ASTM Designations)		Maximum Design Temperature, °F							
		70	600	650	700	750	800	850	900
Group I									
A 285,	Gr C	41.25	30.48	30.07	29.70	28.59	27.47	26.81	26.15
A 284,	Gr C	45.00	33.26	32.80	32.4	31.18	29.97	29.25	28.53
	Gr D	45.00	33.26	32.80	32.4	31.18	29.97	29.25	28.53
A 515,	Gr 55	41.25	30.48	30.07	29.70	28.59	27.47	26.81	26.15
	Gr 60	45.00	33.26	32.81	32.40	31.18	29.97	29.25	28.53
	Gr 65	48.75	36.03	35.54	35.10	33.78	32.47	31.69	30.91
	Gr 70	52.50	38.80	38.27	37.80	36.38	34.96	34.12	33.28
A 516,	Gr 55	41.25	30.48	30.07	29.70	28.59	27.47	26.81	26.15
	Gr 60	45.00	33.26	32.81	32.40	31.18	29.97	29.25	28.53
	Gr 65	48.95	36.03	35.54	35.10	33.78	32.47	31.69	30.91
	Gr 70	52.50	38.80	38.27	37.80	36.38	34.96	34.12	33.28
Group II*									
A 242,	< 3/4	52.50	42.68	41.48	40.22	38.85	37.43	35.91	34.33
	3/4 to < 1 1/2	50.25	40.85	39.70	38.49	37.18	35.83	34.37	32.86
	1 1/2 to < 4	47.25	38.41	37.33	36.19	34.96	33.69	32.32	30.90
A 441,	< 3/4	52.50	42.68	41.48	40.22	38.85	37.43	35.91	34.33
	3/4 to < 1 1/2	50.25	40.85	39.70	38.49	37.18	35.83	34.37	32.86
	1 1/2 to < 4	47.25	38.41	37.33	36.19	34.96	33.69	32.32	30.90
	4 to < 8	45.00	36.58	35.55	34.47	33.30	32.08	30.78	29.43
Group III									
A 204,	Gr A	48.75	40.61	39.34	38.12	37.29	36.46	35.25	33.98
	Gr B	52.50	43.73	42.37	41.06	40.16	39.27	37.96	36.59
	Gr C	56.25	46.86	45.39	43.99	43.03	42.08	40.67	39.21
A 387,	Gr 2, C1	41.25	34.36	33.29	32.26	31.56	30.86	29.82	28.75
	Gr 5, C1	45.00	37.48	36.32	35.19	34.42	33.66	32.54	31.36
	Gr 11, C1	45.00	37.48	36.32	35.19	34.42	33.66	32.54	31.36
	Gr 12, C1	41.25	34.36	33.29	32.26	31.56	30.86	29.82	28.75
	Gr 21, C1	45.00	37.48	36.32	35.19	34.42	33.66	32.54	31.36
	Gr 22, C1	45.00	37.48	36.32	35.19	34.42	33.66	32.54	31.36
Group IV									
A 387,	Gr 11, C2	56.25	41.23	40.05	38.81	37.91	37.01	34.82	32.62
	Gr 12, C2	48.75	35.73	34.71	33.64	32.86	32.08	30.18	28.28
A 36		43.50	31.89	30.97	30.02	29.32	28.62	26.93	25.23
A 283,	Gr C	41.25	30.24	29.37	28.46	27.80	27.14	25.53	23.92
Group V									
A 387,	Gr 21, C2	56.25	43.65	43.54	43.37	42.98	42.52	41.46	40.61
A 387,	Gr 22, C2	56.25	43.65	43.54	43.37	42.98	42.52	41.46	40.61
Group VI									
A 216,	Gr WCA	45.00	33.30	32.85	32.40	31.18	29.92	29.25	28.58
	Gr WCB	52.50	38.85	38.32	37.80	36.38	34.91	34.12	33.34
	Gr WCC	52.50	38.85	38.32	37.80	36.38	34.91	34.12	33.34
A 27,	Gr 60-30	45.00	33.30	32.85	32.40	31.18	29.92	29.25	28.58

This table is based on the ASME Code, Section VIII, Division 2, and Reference 17.

† Allowable design stress is based on a fabrication derating factor, F_t , of 1.0. Designer should adjust according to the actual factor.

* Range of thickness, in.

Table I-5 — Allowable Total Stress, σ_{dt} [†] for Ladle Components, ksi

Materials (ASTM Designations)	Maximum Design Temperature, °F							
	70	600	650	700	750	800	850	900
Group I								
A 285, Gr C	30.00	22.17	21.87	21.60	20.79	19.98	19.50	19.02
A 284, Gr C	30.00	22.17	21.87	21.60	20.79	19.98	19.50	19.02
Gr D	33.00	24.39	24.06	23.76	22.87	21.98	21.45	20.92
A 515, Gr 55	30.00	22.17	21.87	21.60	20.79	19.98	19.50	19.02
Gr 60	32.00	23.65	23.33	23.04	22.18	21.31	20.80	20.29
Gr 65	35.00	25.86	25.52	25.20	24.26	23.31	22.75	22.19
Gr 70	38.00	28.08	27.70	27.36	26.33	25.31	24.70	24.09
A 516, Gr 55	30.00	22.17	21.87	21.60	20.79	19.98	19.50	19.02
Gr 60	32.00	23.65	23.33	23.04	22.18	21.31	20.80	20.29
Gr 65	35.00	25.86	25.52	25.20	24.26	23.31	22.75	22.19
Gr 70	38.00	28.08	27.70	27.36	26.33	25.31	24.70	24.09
Group II *								
A 242, < ¾	50.00	40.65	39.50	38.30	37.00	35.65	34.20	32.70
¾ to < 1½	46.00	37.40	36.34	35.24	34.04	32.80	31.46	30.08
1½ to < 4	42.00	34.15	33.18	32.17	31.08	29.95	28.73	27.47
A 441, < ¾	50.00	40.65	39.50	38.30	37.00	35.65	34.20	32.70
¾ to < 1½	46.00	37.40	36.34	35.24	34.04	32.80	31.46	30.08
1½ to < 4	42.00	34.15	33.18	32.17	31.08	29.95	28.73	27.47
4 to < 8	40.00	32.52	31.60	30.64	29.60	28.52	27.36	26.16
Group III								
A 204, Gr A	37.00	30.82	29.86	28.93	28.31	27.68	26.75	25.79
Gr B	40.00	33.32	32.28	31.28	30.60	29.92	28.92	27.88
Gr C	43.00	35.82	34.70	33.63	32.90	32.16	31.09	29.97
A 387, Gr 2, C1	33.00	27.49	26.63	25.81	25.24	24.68	23.86	23.00
Gr 5, C1	30.00	24.99	24.21	23.46	22.95	22.44	21.69	20.91
Gr 11, C1	35.00	29.16	28.24	27.37	26.78	26.18	25.31	24.40
Gr 12, C1	33.00	27.49	26.63	25.81	25.24	24.68	23.86	23.00
Gr 21, C1	30.00	24.99	24.21	23.46	22.95	22.44	21.69	20.91
Gr 22, C1	30.00	24.99	24.21	23.46	22.95	22.44	21.69	20.91
Group IV								
A 387, Gr 11, C2	45.00	32.98	32.04	31.05	30.33	29.61	27.86	26.10
Gr 12, C2	40.00	29.32	28.48	27.60	26.96	26.32	24.76	23.20
A 36	36.00	26.39	25.63	24.84	24.26	23.69	22.28	20.88
A 283, Gr C	30.00	21.99	21.36	20.70	20.22	19.74	18.57	17.40
Group V								
A 387, Gr 21, C2	45.00	34.92	34.83	34.70	34.38	34.02	33.16	32.49
A 387, Gr 22, C2	45.00	34.92	34.83	34.70	34.38	34.02	33.16	32.49
Group VI								
A 216, Gr WCA	30.00	22.20	21.90	21.60	20.79	19.95	19.50	19.05
Gr WCB	36.00	26.64	26.28	25.92	24.95	23.94	23.40	22.86
Gr WCC	40.00	29.60	29.20	28.80	27.72	26.60	26.00	25.40
A 27, Gr 60-30	30.00	22.20	21.90	21.60	20.79	19.95	19.50	19.05

This table is based on the ASME Code, Section VIII, Division 2, and Reference 17.

† Allowable design stress is based on a fabrication derating factor, F_0 , of 1.0. Designer should adjust according to the actual factor.

* Range of thickness, in.

Table I-6 — Allowable Design Bending Stress, $\sigma_b^\dagger$ (ksi) for Trunnion Pins Without Protective Bushings

Materials (ASTM Designations)		Maximum Design Temperature, °F			
		70	300	400	500
A 668.	Class B	5.48	4.85	4.70	4.43
	Class C	6.03	5.34	5.17	4.87
	Class D	6.76	5.98	5.79	5.46
	Class G	7.31	6.47	6.26	5.91
	Class H	8.22	7.27	7.04	6.64

This table is based on the AMSE Code, Section VIII, Division 2, and Reference 22.

[†] Allowable design stress is based on a fabrication derating factor, F_f , of 1.0. Designer should adjust according to the actual factor.

5.4.1 Normal Stress. The average normal stress through the thickness in the sidewall and bottom plates shall not exceed the allowable stress as determined by Eq I-2 or Eq I-3, whichever yields the lower value¹⁶.

$$\sigma_{au} = \frac{F_f F_t \sigma_u}{F_i (SF)_u} \quad (\text{Eq I-2})$$

$$\sigma_{ay} = \frac{F_f F_t \sigma_y}{F_i (SF)_y} \quad (\text{Eq I-3})$$

Where:

- F_f = Fabrication derating factor
- F_t = Temperature derating factor
- F_i = Impact factor
- $(SF)_u$ = Safety factor against ultimate strength
- $(SF)_y$ = Safety factor against yielding
- σ_a = Allowable normal stress; lower value of σ_{au} or σ_{ay} , ksi
- σ_{au} = Allowable normal stress, based on minimum ultimate strength, ksi
- σ_{ay} = Allowable normal stress; based on minimum yield strength, ksi
- σ_u = Minimum ultimate strength at room temperature, ksi
- σ_y = Minimum yield strength at room temperature, ksi

In this report the following values shall be used:

Impact factor $F_i = 1.2$

Temperature derating factor, F_t , is given in Table I-1 as a function of design temperature and material specified.

Safety factor against ultimate strength $(SF)_u = 3.80$

Safety factor against yielding $(SF)_y = 2.28$

Fabrication derating factor,^{18, 19, 20} $F_f = f_1 f_2 f_3 f_4 f_5$

= 1.0 for welded construction

0.95 for riveted or bolted construction

- f_2 = 1.0 for cold forming
1.05 for hot forming
1.0 if not applicable
- f_3 = 1.0 for thermally cut surface
1.10 for machined or plasma cut surface
0.90 for sheared surface
1.0 if not applicable
- f_4 = 1.0 for straightening by cutting and rewelding
1.05 for flame straightening
1.0 if not applicable
- f_5 = 1.0 for circular ladle
0.95 for noncircular ladle

I-5.4.2 Bending Stress.

I-5.4.2.1 General.

For members which are subjected primarily to bending (except trunnion block members and tee sections of flat bottoms which are covered in the subsections below), the allowable bending stress shall be determined by Eq I-4:

$$\sigma_b = 2\sigma_a \quad (\text{Eq I-4})$$

Where:

- σ_a = Allowable normal stress, ksi
- σ_b = Allowable bending stress, ksi

I-5.4.2.2 Bending and Bearing Stresses in Trunnion Block.

For trunnion block members, the allowable bending stress shall be determined by Eq I-5a:

$$\sigma_b = 1.38 \sigma_a \quad (\text{Eq I-5a})$$

The allowable bearing stress in trunnion block members shall be determined by Eq I-5b:

$$\sigma_{br} = 1.36 \sigma_b \quad (\text{Eq I-5b})$$

Where:

- σ_{br} = Allowable average bearing stress in trunnion block, ksi

I-5.4.2.3 Bending Stress in Tee Section of Ladle Bottoms.

For the tee section of the ladle bottom, the allowable bending stress in tension shall be determined by Eq I-6 and the allowable bending stress in compression shall be determined by Eq I-7:

$$\sigma_{bt} = 2\sigma_a \quad (\text{Eq I-6})$$

$$\sigma_{bc} = 1.25\sigma_a \quad (\text{Eq I-7})$$

Where:

σ_{bt} = Allowable bending stress in tension, ksi

σ_{bc} = Allowable bending stress in compression, ksi

I-5.4.3 Combined Normal and Bending Stresses.

When axial force and bending moment occur simultaneously in members other than the stiffener bands (Section I-9) the following interaction equation shall govern the design²¹:

$$\frac{f_a}{\sigma_a} + \frac{f_b}{\sigma_b} \leq 1.0 \quad (\text{Eq I-8})$$

Where:

f_a = Actual normal stress, ksi

f_b = Actual bending stress, ksi

For stiffener bands, the combined stresses are not to exceed $2\sigma_a$.

I-5.4.4 Total Stress. The allowable total stress is used when the total weight loads (W_2) are being considered in combination with the thermal stresses, other secondary stresses and stresses due to geometric discontinuities (excluding notches such as holes). The thermal stresses are defined here as thermal stresses developed by temperature gradients in the various stiffener plates (bottom stiffener plates) and do not include thermal stresses resulting from the thermal expansion of the wall lining. The allowable total stress, as defined, shall be determined by Eq I-9a or Eq I-9b, whichever is less:

$$\sigma_{du} = 0.75 F_f F_t \sigma_u \quad (\text{Eq I-9a})$$

$$\sigma_{dy} = 1.88 F_f F_t \sigma_y \quad (\text{Eq I-9b})$$

Where:

σ_d = Allowable total stress (lower value of either σ_{du} or σ_{dy}) when working lining expansion stresses are excluded, ksi

σ_{du} = Allowable total stress based on minimum ultimate strength, ksi

σ_{dy} = Allowable total stress based on minimum yield strength, ksi

The allowable total stress used when the thermal expansion stresses include the thermal expansion of the wall lining, other secondary stresses and stresses due to geometric discontinuities (excluding notches such as holes) shall be determined by Eq I-10.

$$\sigma_{dl} = 1.0 F_f F_t \sigma_y \quad (\text{Eq I-10})$$

Where:

σ_{dl} = Allowable total stress when the working lining expansion forces are included, ksi

I-5.4.5 Shear Stress. The allowable shear stress in the structural elements (excluding welds and rivets) shall be determined by Eq I-11:

$$\sigma_s = 0.6 \sigma_a \quad (\text{Eq I-11})$$

Where:

σ_s = Allowable shear stress (excluding welds and rivets), ksi

I-5.4.6 Fatigue Stress. The fatigue stress provisions of the AWS Structural Welding Code D1.1 shall be the minimum weld requirements except that the allowable weld stress in fillet or partial penetration butt welds shall not exceed $1.38 \sigma_a$ in tension or $1.2 \sigma_a$ in shear for the type of loadings (W_2) considered. For full penetration butt welds, the allowable weld stresses shall not exceed the corresponding stress limits in the base metal.

I-5.4.7 Stresses in Used Components. In used ladles where corrosion, wear or other damage has occurred, the calculated stresses in ladle components (other than trunnion pins) may exceed the original allowable stresses, but not by more than 30%, for the type of loadings (W_2) considered. The 30% increase in these stresses is to be based on actual measured dimensions. Higher stresses than the foregoing are reason for replacement or repair. In the case of the ladle sidewall plate below the trunnions, the measured thickness of the sidewall plate shall not be less than the original required thickness (as defined by Table I-7 or design formulae, whichever is maximum) divided by 1.3.

I-5.5 Allowable Stresses in Trunnion Pins. For design of trunnion pins by the method of elastic analysis, the following stresses in various categories shall not be exceeded. These allowable stresses are based on the use of materials conforming with this report.

The equations in the following sections define the allowable stresses in trunnion pins. For σ_b (allowable trunnion pin bending stress), the allowable stresses are calculated for the permitted materials in Table I-6. However, the allowable

Table I-7 — Minimum Sidewall Plate Thicknesses, in.

Ladle capacity, short tons	Operating Temperatures			
	up to 650°F	up to 750°F	up to 800°F	up to 900°F
20	5/8	1 1/16	9/16	1 1/16
60	3/4	1 3/16	1 1/16	1 3/16
110	7/8	1	3/4	1 5/16
175	1	1 1/8	7/8	1 1/8
240	1 1/8	1 1/4	1	1 1/4
320	1 1/4	1 7/16	1 1/8	1 3/8
400	1 3/8	1 9/16	1 1/4	1 1/2
480	1 1/2	1 1 1/16	1 5/16	1 5/8
Acceptable ASTM Material Specifications	A 36	A 283	A 204	A 387
	A 283	A 285	A 387	
	A 285	A 515		
	A 515	A 516		
	A 516	A 242		
	A 242	A 440		
	A 440	A 441		
	A 441			

stress values do not include the effect of the fabrication derating factor F_f .

I-5.5.1 Bending Stresses.

I-5.5.1.1 Trunnion Pins Without Protective Bushings.

In trunnion pins which are subjected to wear without protective bushings, the maximum bending stress, excluding stress concentrations, shall be less than the allowable bending stress determined by Eq I-12 or Eq I-13, whichever is less:

$$\sigma_{bu} = \frac{F_f F_t \sigma_u}{F_i (SF)_u} \quad (\text{Eq I-12})$$

$$\sigma_{by} = \frac{F_f F_t \sigma_y}{F_i (SF)_y} \quad (\text{Eq I-13})$$

Where:

- F_f = Fabrication derating factor = 1.0
- F_t = Temperature derating factor as given in Table I-2
- F_i = Impact factor = 1.2
- $(SF)_u$ = Safety factor against ultimate strength = 9.12 (includes geometry stress riser ≤ 2.0)
- $(SF)_y$ = Safety factor against yielding = 4.56 (includes geometry stress riser ≤ 2.0)
- σ_b = Allowable bending stress; lower value of either σ_{bu} or σ_{by} , ksi
- σ_{bu} = Allowable bending stress based on minimum ultimate strength, ksi
- σ_{by} = Allowable bending stress based on minimum yield strength, ksi

σ_y = Minimum yield strength at room temperature, ksi

σ_u = Minimum ultimate strength at room temperature, ksi

I-5.5.1.2 Trunnion Pins with Protective Bushings.

For trunnion pins supplied with protective bushings, the maximum bending stress, excluding stress concentrations, shall be less than the allowable bending stress determined by Eq I-14:

$$\sigma_p = 1.44 \sigma_b \quad (\text{Eq I-14})$$

Where:

σ_p = Allowable bending stress with protective bushings, ksi

I-5.5.2 Shear Stress. The allowable shear stress shall be determined by Eq I-15:

$$\sigma_s = 0.533 \sigma_b \quad (\text{Eq I-15})$$

Where:

σ_s = Allowable shear stress, ksi

I-5.5.3 Bearing Stress in Trunnion Pin. The allowable bearing stress between the trunnion pin and trunnion block at the outside edge of the block (averaged across the pin diameter as calculated by Eq I-17), shall be determined by Eq I-16a:

$$\sigma_{br} = 3.33 \sigma_b \quad (\text{Eq I-16a})$$

Where:

σ_{br} = Allowable average bearing stress in trunnion pin, ksi

I-5.5.4 Stresses in Used Trunnion Pins. In used ladles, the trunnion pins without bushings should be replaced when calculated stresses, based on actual measured dimensions of the pins, exceed the corresponding allowable stresses by 45% or more because of wear or other causes. Trunnion pins with bushings should have the bushings replaced prior to any wear on the trunnion pin. Replacement should be made with the same material or material with superior physical properties. Repair of the trunnion pin by build-up welding is not permitted.

I-5.6 Allowable Shear Stresses in Rivets. The allowable shear stresses in rivets are dependent on the rivet materials used and are given as follows:

Rivet Material	Allowable Shear Stress †
ASTM A 31 Grade A	12.3 ksi
ASTM A 31 Grade B	15.5 ksi
ASTM A 502 Grade 1	15.0 ksi
ASTM A 502 Grade 2	20.0 ksi

† Based on ASME Code, Section I (1971 edition only) and Reference 21

I-5.7 Allowable Shear Stress in Pins of Tilt Mechanisms. The pins used in the tilt mechanism shall be designed basically for shear rather than for bending and shear as in trunnion pins. The allowable shear stress shall be determined by Eq I-16b:

$$\sigma_s = 0.4 \sigma_y \quad (\text{Eq I-16b})$$

Where:

- σ_s = Allowable shear stress, ksi
 σ_y = Minimum yield strength at room temperature, ksi

I-6 DESIGN OF TRUNNION BLOCK AND PIN

I-6.1 General. The trunnion pin is typically supported by a solid plate trunnion block (see Figs. I-10c and I-10d) and is of sufficient size to connect directly to the sidewall plate and the stiffener bands. A small solid plate trunnion block may require the use of ribs (see Fig. I-10b) to connect the trunnion block to the stiffener bands and surrounding structure. The allowable bending stress (σ_b) in the trunnion block and in the ribs shall be determined by Eq I-5a.

I-6.2 Shear and Bearing Stresses. The average shear and bearing stress may be used for comparison with the allowable stresses. The average shear stress in the trunnion pins shall be computed by dividing the total shear force by the area of the pin (the maximum shear stress will be approximately 33% greater than the average shear stress in a solid circular section).

The average bearing stress between the trunnion pin and trunnion block in the ladle shell shall be calculated by Eq I-17, and shall be less than the minimum value calculated by Eqs I-5b and I-16a.

$$f_B = \frac{W_2}{2 D_B t_T} \left(1 + \frac{6 e_2}{t_T} \right) \quad (\text{Eq I-17})$$

Where:

- D_B = Bearing diameter of trunnion pin, in.
 e_2 = Distance from the centerline of the ladle hook to the centerline of the trunnion block on the trunnion axis, in.
 f_B = Average bearing stress between the trunnion pin and trunnion block, ksi
 t_T = Combined thickness of trunnion block and sidewall, in.
 W_2 = Total weight of ladle (design weight of molten metal, slag, ladle steelwork, refractory lining and ladle lid), kips

(See Fig. I-5a for notations used.)

I-6.3 Bending Moment in Pins. In calculating the bending moment in the trunnion pins, the lifting force shall be assumed to act at the centerline of the ladle hook as positioned for lifting, as far from the body of the ladle as permitted by the geometry of the trunnion pin.

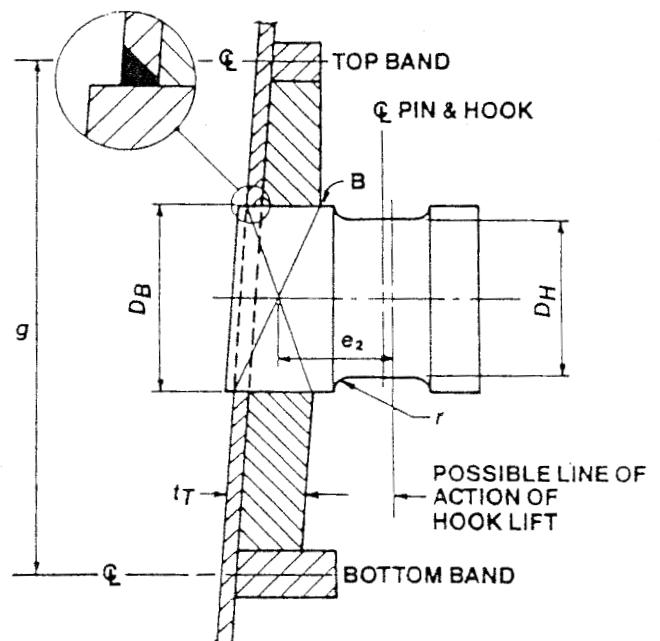


Fig. I-5a — Notations Applicable to the Trunnion Pin

I-6.4 Fillet Radius. The radius between the trunnion pin and trunnion housing shall be large enough so that the stress concentration factor is less than 2. The requirement will be met if the fillet radius, r , is greater than $0.04 D_B$ (Fig. I-5a).

I-6.5 Fitting in Trunnion Block. The diameter of the trunnion pin proper shall not be reduced to fit into the desired trunnion block. It can be increased if desired, as long as the integrity of the block design is retained.

I-6.6 Sleeves. If sleeves are used they shall be nonrotating, to minimize wear between the sleeve and the trunnion pin.

I-6.7 Stiffness in Trunnion Block. The trunnion block shall have sufficient stiffness to resist the bending moment resulting from the ladle hook loads.

I-6.8 Attaching Block to Ladle. The trunnion block shall be adequately and rigidly attached to the ladle sidewalls to transmit the vertical lifting loads. When laminated plate construction is used for the pad design, rivets or pins are recommended (in addition to peripheral welds) to avoid plate separation (Fig. I-10d).

I-6.9 Installation of Pins. Unless the trunnion pins are cast or forged as an integral part of the trunnion block, they shall be press or shrink fitted into the block and shall be installed after the ladle has been stress relieved. The trunnion pin shall be installed and welded to the shell plate from inside the ladle after stress relieving has been performed, as shown in Fig. I-5a. There shall be no welding on the outside of the trunnion block to the trunnion pin.

I-6.10 Bending Stresses in Trunnion Blocks. The maximum bending stresses in trunnion blocks shall be calculated, such as for Point A in Fig. I-10b, Point B in Fig. I-10c, and Point C in Fig. I-10d, and shall be less than the allowable stresses defined earlier in Section I-5.

Referring to Fig. I-5a, the bending stress shall be computed by Eq I-17a:

$$f_b = \frac{W_2 e_2 g'}{2g S_1} \quad (\text{Eq I-17a})$$

Where:

$$S_1 = \frac{w t_T^2}{6} \quad (\text{Eq I-17b})$$

Where:

- g = Vertical distance between top band and bottom band centerlines, in. (Figs. I-5a and I-10)
- g' = The greater of g_T or g_B , where:
- g_T = The distance from the centerline of the trunnion pin to the centerline of the top band, in. (Fig. I-10d)
- g_B = The distance from the centerline of the trunnion pin to the centerline of the bottom band, in. (Fig. I-10d)
- S_1 = Section modulus of the combined shell and trunnion block at the point of interest such as Point C in Fig. I-10d, in.³ (Eq. I-17b)
- w = Net width of trunnion block at the point of interest, in. (Fig. I-10)

I-6.11 Ribbed Trunnion Block Design. Trunnion blocks in the form of slabs as described in the previous sections are usually provided and preferred in a ladle construction for all sizes of ladles. However, for small ladles such as 100 tons or less in capacity, a ribbed type of trunnion block may be permitted, in which the trunnion pins are bearing directly on the shell which is stiffened by ribs around the pins as shown in Fig. I-10b. Both bending stresses and bearing stresses of the ribbed blocks shall be calculated for comparisons with their respective allowable stresses as given in Sections I-5.4.2.2 and I-5.5.3.

The bending stress shall be calculated as described in Section I-6.10.

Referring to Fig. I-5b, the average bearing stress between the trunnion pin and the ribbed block shall be calculated by Eq I-17c:

$$f_B = \frac{W_2}{2(k t + 2 t_r m)} + \frac{W_2 e_2}{2 S_2} \quad (\text{Eq I-17c})$$

Where:

- k = Inner distance of two inner vertical ribs, in.
- S_2 = Section modulus of the combined shell and ribs (shown as shaded area of Fig. I-5b), in.³
- t_r = Thickness of ribs, in.
- t = Thickness of sidewall plate, in.
- m = Distance from inside shell surface to outside of vertical ribs, in. (Fig. I-5b)

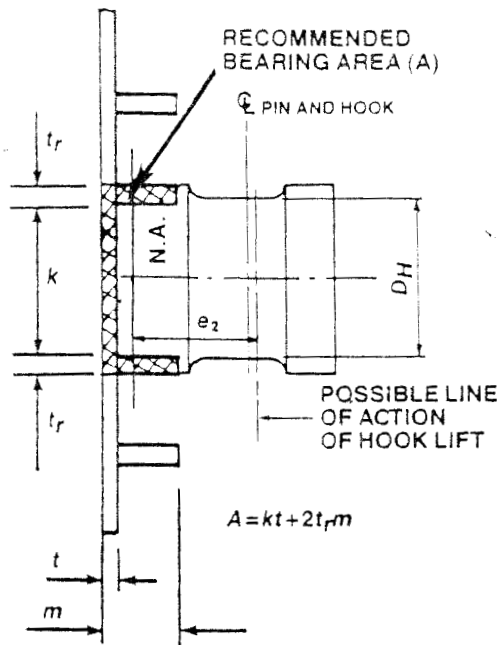


Fig. I-5b — Notations Applicable to the Ribbed Trunnion Block (horizontal cross-section)

I-7 DESIGN OF BOTTOM PLATES OF FLAT BOTTOM LADLES

I-7.1 General. The notation used in this section is shown in Fig. I-6. Thicknesses determined in this section are for operating conditions and materials as specified in Section I-3.2. Slightly dished ladle bottoms shall be considered as flat if the dishing radius, R_B (Fig. I-7), is more than 10 times the minimum bottom radius of the shell, $R_{S(min)}$, at the intersection with the bottom plate. For knuckle radius see Sections I-4.2 and I-4.3

I-7.2 Thickness of Circular Flat Bottoms. Circular flat bottoms with no reinforcing plate shall have a thickness not less than:

$$T_B = \frac{D}{139} \sqrt{\frac{qH}{\sigma_a}} \quad (\text{Eq I-18a})$$

Where:

- D = Bottom plate diameter in circular ladle, in.
- H = Vertical height of the ladle, in.
- T_B = Thickness of bottom plate, in.

I-7.3 Reinforcing Plate. The procedure in this section describes the riveting of a reinforcing plate to a circular

Fig. I-7 — Notations Applicable to Dished Bottom Ladles

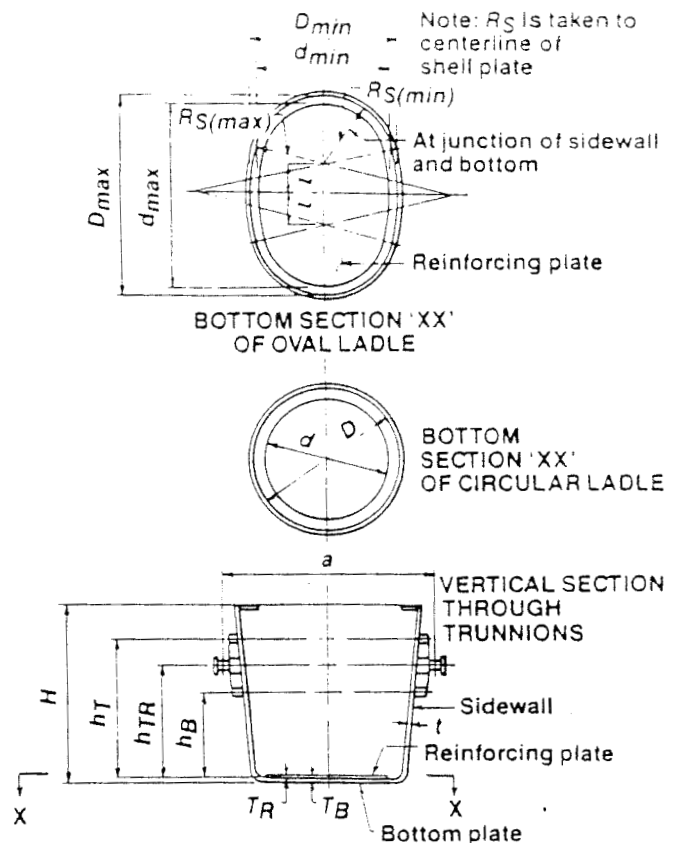
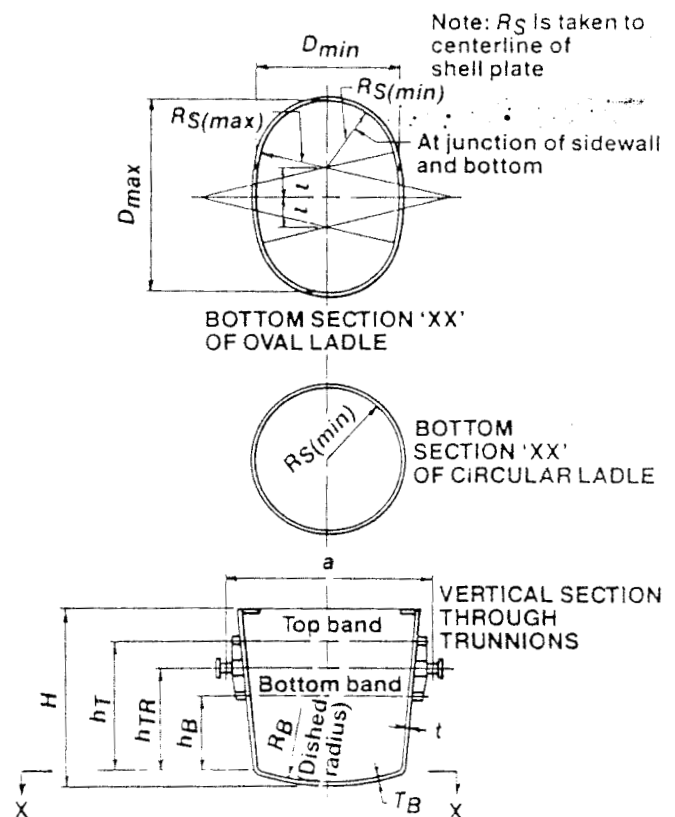


Fig. I-6 — Notations Applicable to Flat Bottomed Ladles



ladle bottom. For other ladle bottom configurations, the designer shall apply a similar method to insure adequacy of the riveted connection between the bottom and reinforcing plates.

I-7.3.1 Design of Reinforcing Plate. Reinforcing plates, if used, shall be placed on the inside of the ladle bottom and shall be riveted to the bottom plate in a row or rows around the circumference, as well as throughout the entire reinforcing plate area in order that the two plates act as a unit in accordance with the ASME Code, Section I (1971 edition only). The diameter, d , of the reinforcing plate shall not be less than 0.88 times the diameter, D , of the bottom plate.

I-7.3.2 Rivets. Horizontal shear in rivets between the reinforcing plate and bottom plate shall be calculated by Eq I-18b and shall not exceed the allowable shear stress specified in Section I-5.6.

$$\tau_2 = \frac{\tau_1 \pi (R_M^2 - R_{M-1}^2)}{A_r N_m} \quad (\text{Eq I-18b})$$

Where:

τ_2 = Horizontal shear stress in rivet, ksi

τ_1 = Average horizontal shear stress in plate, ksi

$$\tau_1 = \frac{0.00105 q H R_M T_B T_R}{(T_R + T_B)^3} \quad (\text{Eq I-18c})$$

A_r = Area of driven rivet, sq in.

$$A_r = \frac{\pi d_r^2}{4}$$

d_r = Diameter of hole for driven rivet, in.

N_m = Number of rivets in top row of annulus area

R_M = Radius to top row of rivets of annulus area, in.

R_{M-1} = Radius to bottom row of rivets of annulus area, in.

T_R = Thickness of bottom reinforcing plate, in.

The area supported by one rivet is

$$\frac{\pi (R_M^2 - R_{M-1}^2)}{N_m} \text{ sq in.}$$

The distance between any two rivets (in the same row or different rows) should not be less than 4.5 times the rivet hole diameter.

The ladle designer has the obligation to add more rivets at the center of the ladle bottom plates as necessary to maintain the integrity of the bottom plates and to retard thermal distortion and buckling.

I-7.3.3 Postweld Heat Treatment. It is recommended, whenever possible, that all postweld heat treatment for the ladle be completed before riveting the bottom reinforcing plate.

I-7.4 Thickness of Bottom Plate and Reinforcing Plate.

When a reinforcing plate is used, the combined thicknesses of the reinforcing plate, T_R , and bottom plate, T_B , shall not be less than:

$$T_R + T_B = \frac{D}{114} \sqrt{\frac{q h}{\sigma_a}} \quad (\text{Eq I-19})$$

The thickness of the bottom plate (as distinguished from the reinforcing plate) shall be at least $\frac{1}{16}$ in. more than one-half of the combined thicknesses of the two plates.

I-7.5 Equivalent Diameter for Oval Ladles. For oval ladles having a maximum bottom plate diameter not more than 1.4 times the minimum bottom plate diameter (Fig. I-6), Eqs I-18a and I-19 for bottom plate thicknesses may be used by replacing the circular bottom plate diameter, D , by an equivalent diameter for the oval ladle, D_E , determined by

$$D_E = \frac{D_{\max} + D_{\min}}{2} \quad (\text{Eq I-20})$$

I-7.6 Stiffener Ribs for Bottom Plates. Flat bottom ladles may be designed with stiffener ribs as shown in Fig. I-8.

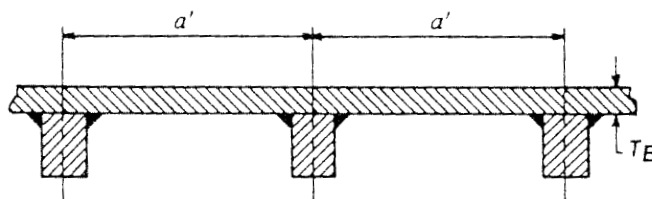


Fig. I-8 — Cross-Section Through Flat Bottomed Ladle with Stiffener Ribs

The portion of the ladle bottom plate which spans the stiffener rib and has a width extending to one-half the distance to adjacent ribs is considered as acting with the rib, forming a T beam. Ribs shall have identical sections and be spaced uniformly. The design shall be based on the tee section with the greatest span. Distance from center to center of ribs shall be not greater than one-fifth the maximum span, nor greater than is given by Eq I-21:

$$a' \leq \frac{L^2 T_B^2}{4 S} \quad (\text{Eq I-21})$$

Where:

a' = Center to center distance of stiffener ribs, in.

- L = Maximum span of stiffener ribs in bottom plate, in.
 S = The greater section modulus of the T beam section of stiffener rib in the bottom plate, in.³

The thickness of the bottom plate shall not be less than the thickness of the sidewall.

The T beam section shall be designed as a simple beam, uniformly loaded by the weight of maximum depth of molten metal, the bottom liner and the weight of the T beam section. The end reaction of the tee section shall be transferred by a double-groove full penetration weld acting in shear between the rib end and the ladle sidewall.

I-8 DESIGN OF BOTTOM PLATES OF DISHED BOTTOM LADLES.

I-8.1 General. The notations used in this section are shown in Fig. I-7. Thicknesses determined in this section are for operating conditions and materials as specified in Section I-3.2. A ladle bottom may be considered as dished providing the dishing radius, R_B , is less than 10 times the minimum radius of the shell, $R_{S(min)}$, at the intersection with the bottom plate. The dishing must conform to the shape of the spherical segment in circular ladles and in the end sections of oval ladles. Only the center section of an oval ladle may be dished to a cylindrical shape. For knuckle radius see Sections I-4.2 and I-4.3. The transition requirements for the connection between the sidewall plate and the bottom plate is described in Fig. I-1a.

I-8.2 Thickness of Dish Circular Ladle Bottoms.

The bottom plate thickness for dished circular bottoms shall be determined as the larger of the two values given by Eqs I-22a and I-22b.

$$T_B = R_B \left[\frac{q H R_{S(min)} \cos \phi}{4664 \sigma_a R_B \left(1 + \sqrt{\frac{R_{S(min)}}{R_B}} \right)} \right]^{1/2} \quad (\text{Eq I-22a})$$

$$T_B = \frac{q H R_B}{3638 \sigma_a} \quad (\text{Eq I-22b})$$

Where:

$$\phi = \sin^{-1} \left(\frac{R_{S(min)}}{R_B} \right)$$

R_B = Dish radius in dished bottom, in.

$R_{S(min)}$ = Minimum radius to middle plane of sidewall at bottom section, in.

I-8.3 Thickness of Dish Oval Ladle Bottoms. Dish oval ladle bottoms (Fig I-7) having a maximum diameter not more than 1.4 times the minimum diameter, shall have a bottom plate thickness determined as the larger of the two values given by Eqs I-23a and I-23b.

$$T_B = R_B \left[\frac{D_{max} q H R_{S(min)} \cos \phi}{4664 D_{min} \sigma_a R_B \left(1 + \sqrt{\frac{R_{S(min)}}{R_B}} \right)} \right]^{1/2} \quad (\text{Eq I-23a})$$

$$T_B = \frac{q H R_B}{1819 \sigma_a} \quad (\text{Eq I-23b})$$

I-8.4 Reinforcing Plates. Reinforcing plates, if used, are not to be considered as adding effectively to the strength of dished bottoms.

I-8.5 Stiffener Ribs for Dish Circular Bottom Plates.

As shown in Fig. I-9, the dished circular bottom ladle may be designed with stiffener ribs²⁴. The portion of the bottom plate which spans the stiffener rib and has a width extending to one-half the distance to adjacent ribs is considered as acting with the rib, forming a T beam. The ribs shall be uniformly spaced. The design shall be based on the midspan cross-section of the tee section with the greatest span. The distance from the center to center of ribs shall be no greater than one-fifth the maximum span.

The maximum membrane stress and bending stress in the dished circular bottom plate, in the direction spanning the ribs, shall satisfy the requirements of Eqs I-24a, I-24b and I-24c:

$$\frac{f_a}{\sigma_a} = \frac{q H R_B}{1819 (T_B + T'_B) \sigma_a} \leq 1.0 \quad (\text{Eq I-24a})$$

$$\frac{f_b}{\sigma_b} = \frac{q H a^2}{3638 T_B^2 \sigma_b} \leq 1.0 \quad (\text{Eq I-24b})$$

$$\frac{f_a}{\sigma_a} + \frac{f_b}{\sigma_b} \leq 1.0 \quad (\text{Eq I-24c})$$

Where:

T'_B = Effective plate thickness of the dished circular bottom plate in the direction of the ribs, in.

$$= T_B + \frac{T_I D_I}{a'}$$

T_I = Thickness of rib, in.

D_I = Depth of rib at midspan cross-section (minimum depth for dished circular bottom plate with ribs), in.

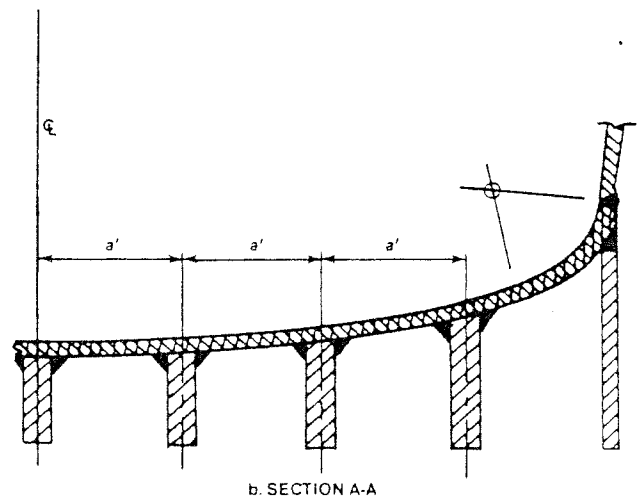
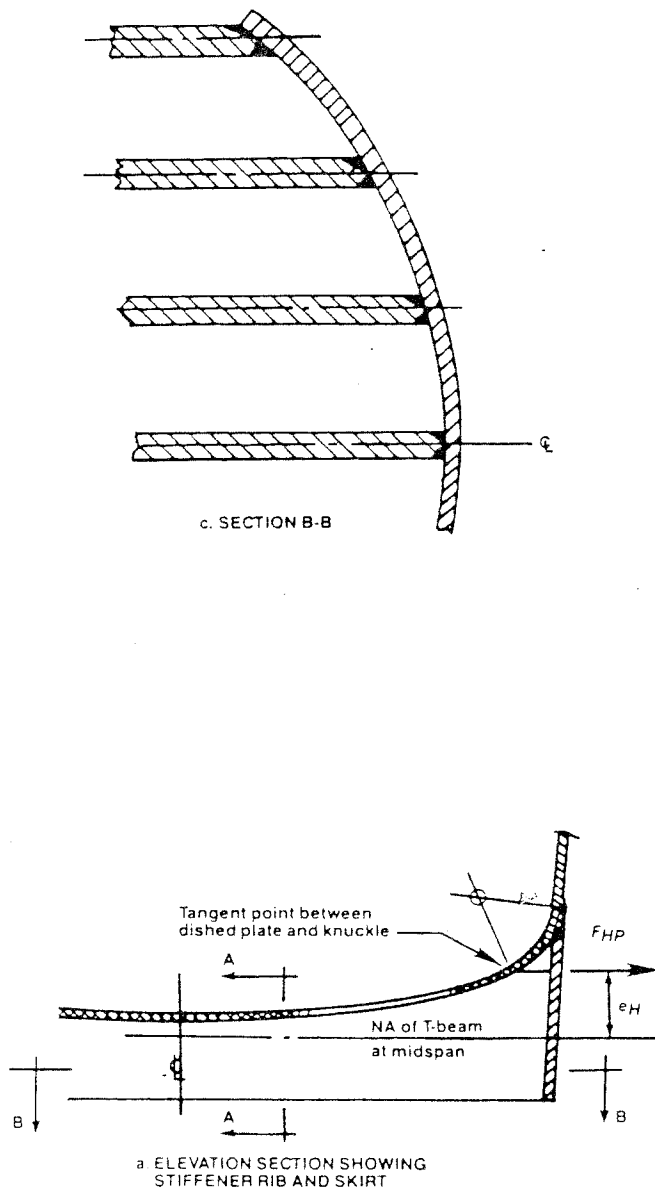


Fig. 1-9 — Stiffener Ribs for Dished Bottom Ladle

The axial and bending stresses at the midspan cross-section of the longest span T beam shall satisfy the requirements of Eqs I-25a, I-25b and I-25c:

$$\frac{f_a}{\sigma_a} = \frac{q H R_B}{3638 T'_B \sigma_a} \leq 1.0 \quad (\text{Eq I-25a})$$

$$\frac{f_b}{\sigma_b} = \frac{q H a'}{14552 S'_b} (L^2 - 4 R_B e_H) \leq 1.0 \quad (\text{Eq I-25b})$$

$$\frac{f_a}{\sigma_a} + \frac{f_b}{\sigma_b} \leq 1.0 \quad (\text{Eq I-25c})$$

Where:

- e_H = Vertical offset between the dished plate/knuckle tangent point and the neutral axis of the T beam at the midspan cross-section (see Fig. I-9b), in.
- F_{HP} = Horizontal component of the spherical membrane force in the dished plate; located at tangent of dished plate and knuckle (see Fig. I-9b)
- S' = The section modulus (maximum and minimum) of the midspan cross-section of the T beam, in.³

I-8.6 Stiffener Ribs for Dished Oval Bottom Plates. In the case of the dished oval ladle, having a maximum diameter not more than 1.4 times minimum diameter, the membrane stress and bending stress in the dished oval bottom plate in the direction spanning the ribs shall satisfy the requirements of Eqs I-26a, I-26b and I-26c:

$$\frac{f_a}{\sigma_a} = \frac{q H R_B}{909 (T_B + T'_B) \sigma_a} \leq 1.0 \quad (\text{Eq I-26a})$$

$$\frac{f_b}{\sigma_b} = \frac{q H a'^2}{3638 T_B^2 \sigma_b} \leq 1.0 \quad (\text{Eq I-26b})$$

$$\frac{f_a}{\sigma_a} + \frac{f_b}{\sigma_b} \leq 1.0 \quad (\text{Eq I-26c})$$

The maximum axial and bending stress at the midspan cross section of the longest span T beam shall satisfy the requirements of Eqs I-25a, I-25b and I-25c.

I-9 DESIGN OF STIFFENER BANDS.

I-9.1 General. The tendency of the ladle to collapse when suspended by the ladle hooks shall be resisted by two stiffener bands, one above and one below the trunnion block, designated by the subscripts *T* and *B*, for top and bottom, respectively. The lip reinforcement of the ladle is not to be considered in calculating the stresses in the ladle bands. The band stresses are to be calculated by the following procedure and must not exceed the allowable stresses as determined in Section I-5.4. The size of the bottom band is to be equal to or greater than that required by stress calculations at the cross axis and is to be made an integral part of the trunnion block. Cross axes are defined as those axes which are at right angles to the trunnion pin axis (Fig. I-10a). In addition to designing for strength, the equivalent combined top and bottom stiffener band section must meet a stiffness criterion given in Section I-11 so as to avoid excessive inward deflection of the trunnions. Minimum depth stiffener bands are recommended to minimize thermal gradient stresses. However, the minimum depth stiffener bands shall still satisfy the allowable stresses of Section I-5.4 and the stiffness criterion of Section I-11.

Uniform depth stiffener bands with gradual transitions in depth and width at the trunnion blocks (or other regions of the stiffener bands) are recommended. The dimensional changes in the stiffener band cross-section should occur over a minimum distance of three times the maximum depth of the stiffener band (Fig. I-11).

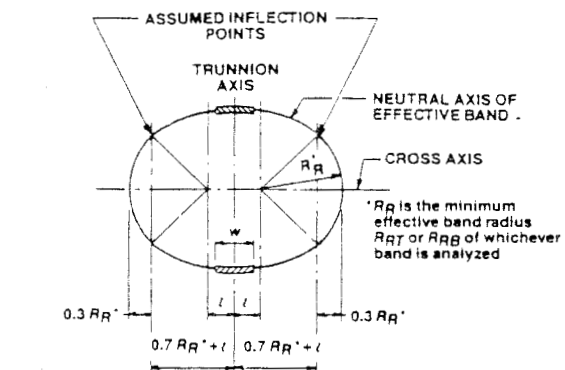
I-9.2 Effective Band. Each effective band shall consist of the stiffener band together with a portion of the adjacent ladle sidewall of effective width equal to b_e (Section I-9.3), provided that the band is welded or riveted to the ladle sides. Welding is recommended and shall be continuous. If the bands are not riveted or welded to the sides, no part of the sidewall shall be included in calculating the properties of the effective band.

I-9.3 Calculations of Effective Band Width. If the sidewall thickness is the same both above and below a band, the total width of the ladle shell to be used in calculating the section properties of the effective band shall be taken as:

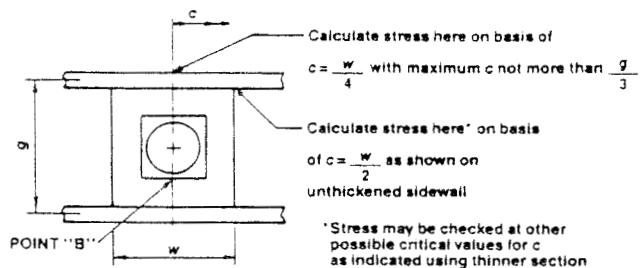
$$b_e = b_r + 1.4 \sqrt{R_S} t \quad (\text{Eq I-27})$$

Where:

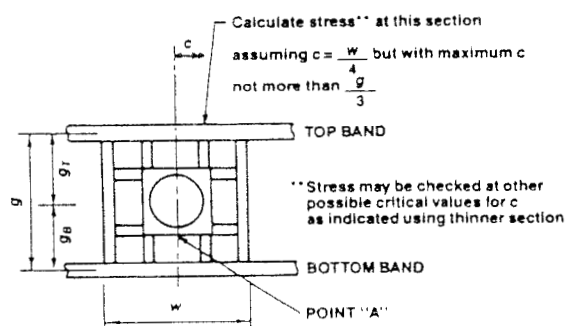
- b_e = Sidewall effective width acting with band, in.
- b_r = Width of band, in.
- R_S = Minimum radius to middle plane of sidewall at a band, in.
- t = Thickness of sidewall (ladle shell only), in.



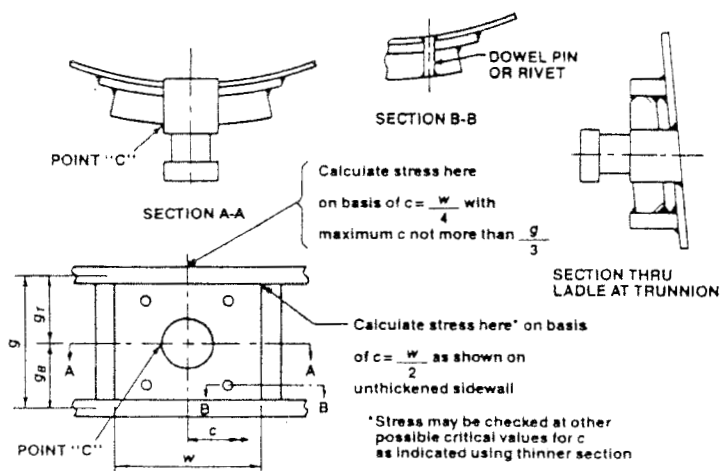
a. ASSUMPTIONS FOR CALCULATING BAND MOMENTS



c. TRUNNION BLOCK—PAD SUPPORT TYPE



b. TRUNNION BLOCK—OPEN BOX TYPE



d. TRUNNION BLOCK—LAMINATED PLATE TYPE

Fig. I-10 — Information for Calculating Stiffener Band Moments

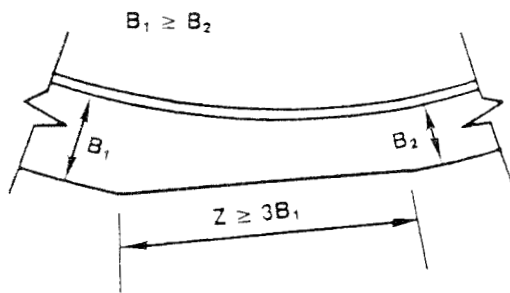


Fig. I-11 — Recommended Transition in Stiffener Bands

If the sidewall thickness changes at a band the total width of the effective band shall be taken as:

$$b_e = b_r + b_1 + b_2 \quad (\text{Eq I-28})$$

$$b_1 = 0.4\sqrt{R_S} (t_1 + 2t_2) \quad (\text{Eq I-29})$$

$$b_2 = 0.7\sqrt{R_S} t_2 \quad (\text{Eq I-30})$$

Where:

- b_1 = Effective width of the thicker portion of sidewall acting with stiffener band, in.
- b_2 = Effective width of the thinner portion of sidewall acting with stiffener band, in.
- t_1 = Larger effective thickness of sidewall, in.
- t_2 = Smaller effective thickness of sidewall, in.

Effective sidewall thickness, t_1 and t_2 , is defined as the sum of the sidewall thickness plus the thickness of any plates or blocks that are fastened to both the sidewall and band so that the sidewall and band act as an integral structure.

I-9.4 Properties of Bands. After determining the effective band width by Eqs I-27 through I-30 inclusive, the area, moment of inertia, section modulus and effective radius of each band are to be calculated. Effective radius should be interpreted as the radius of the neutral axis of the effective band at the centerline of the stiffener. The application of these properties is illustrated in Appendix A.

I-9.5 Calculations of Compressive Forces in Bands.

The effective bands develop compressive forces with the resultant force parallel to the trunnion pin axis. These compressive forces can be computed from Eqs I-31, I-32a, and I-32b.

$$C = \frac{I_{B2} h_B R_{RT}^3}{I_{T2} h_T R_{RB}^3} \quad (\text{Eq I-31})$$

$$F_T = \frac{W_2 (a - G R_{SM})}{8 (C h_B + h_T)} \quad (\text{Eq I-32a})$$

$$F_B = C F_T \quad (\text{Eq I-32b})$$

Where:

- a = Distance between lifting hook centerlines, in.
- C = A constant
- F_T = Force in top band, kips
- F_B = Force in bottom band, kips
- G = Load centroid distance ratio as given in Fig. I-12⁵
- h_B = Vertical distance between bottom band stiffener centerline and juncture of ladle bottom and sidewall, in.
- h_T = Vertical distance between top band centerline and juncture of ladle bottom and sidewall, in.
- I_{B2} = Moment of inertia of effective bottom band at cross axis, in.⁴
- I_{T2} = Moment of inertia of effective top band at cross axis, in.⁴
- R_{RB} = Minimum effective radius of bottom band, in.
- R_{RT} = Minimum effective radius of top band, in.
- R_{SM} = One-half of the minimum mid-height distance between middle planes of opposite sidewalls, in.

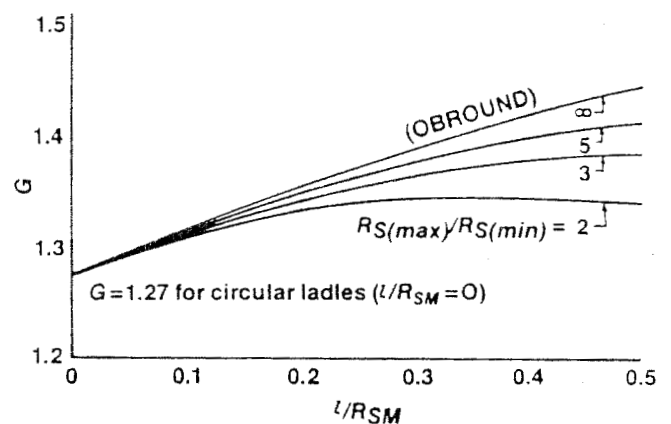


Fig. I-12 — Load Centroid Distance Ratio, Eq I-32a

I-9.6 Portion of Trunnion Block Included in Effective Band Section. The portion of the trunnion block included in the effective band section at the trunnion axis need not be reduced because of the incursion of the trunnion pin provided that:

- (1) The trunnion pin has a shrink fit in the trunnion block and is continuously welded to the inner side of the ladle
- (2) No more than 40% of the effective band section shall be provided by the trunnion pin material.

I-9.7 Band Bending Moment. The band bending moments are calculated by assuming that the inflection point of zero moment in each effective band is located at a distance $0.3 R_{RT}$ or $0.3 R_{RB}$ measured inward from the band neutral axis parallel with the cross axis of the ladle (Fig. I-10a). Use plus and minus signs exactly as given in Eqs I-33 through I-38b inclusive, which are based on the force diagram shown in Fig. I-13.

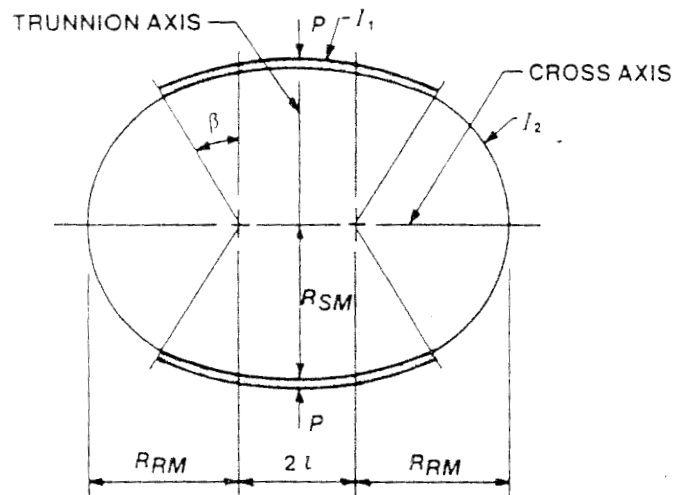


Fig. I-13 — Effective Combined Trunnion Ring
(Used in Calculation of Deflection Index,
Eq I-41, and Table I-4)

The plus sign for the band bending moments indicates compression on the outside of the band and tension on the inside of the band. The minus sign for the band bending moments indicates tension on the outside and compression on the inside of the band. Minus signs for stresses indicate compression and plus signs for stresses indicate tension in accordance with the usual practice.

I-9.8 Calculation of Band Bending Moments. Band bending moments are to be calculated as follows:

I-9.8.1 Top Band Near Trunnion Axis. The weakest section of the top band above the trunnion is at the trunnion axis in the case of open box framing (Fig. I-10a) or at the edge of the trunnion block (Fig. I-10c & I-10d) where the trunnion block is carried to the upper band and welded hereto. The ribs of the open box welded trunnion block shall be welded to develop their full strength. If there are other sudden changes in section, these also must be evaluated. The bending moment may be calculated as follows:

$$M_{T1} = F_T (0.7 R_{RT} + l - c) \quad (\text{Eq I-33})$$

Where:

- M_{T1} = Moment in top band at trunnion axis, kip-in.
- l = One-half the distance between radius points of end segments in oval ladle, in. ($l = 0$ for a circular ladle)
- c = Horizontal distance from vertical centerline through trunnion pin to the section of interest, in. (see Fig. I-10)

I-9.8.2 Top Band at Cross Axis. The bending moment in the top band at the cross axis 90 degrees from the trunnion axis is:

$$M_{T2} = -F_T (0.3 R_{RT}) \quad (\text{Eq I-34})$$

I-9.8.3 Bottom Band at Cross Axis. The bending moment in the bottom band at the cross axis 90 degrees from the trunnion axis is:

$$M_{B2} = -F_B (0.3 R_{RB}) \quad (\text{Eq I-35})$$

I-9.9 Combined Stresses in Bands. Combined stresses are not to exceed the allowable stresses as determined by Section I-5.4.3, and are to be calculated at each of the locations listed as follows:

I-9.9.1 Top Band Near Trunnion Axis:

$$\text{outside } f_O = - \frac{M_{T1}}{S_{TO}} \quad (\text{Eq I-36a})$$

$$\text{inside } f_I = + \frac{M_{T1}}{S_{TI}} \quad (\text{Eq I-36b})$$

Where:

- f_I = Stress in the inside surface of band, ksi
- f_O = Stress in the outside of band, ksi
- S_{TI} = Section modulus for the inside surface of the top band, in.³
- S_{TO} = Section modulus for the outside of the top band, in.³

I-9.9.2 Top Band at Cross Axis

$$\text{outside } f_O = - \frac{F_T}{A_T} - \frac{M_{T2}}{S_{TO}} \quad (\text{Eq I-37a})$$

$$\text{inside } f_I = - \frac{F_T}{A_T} + \frac{M_{T2}}{S_{TI}} \quad (\text{Eq I-37b})$$

Where: A_T = Effective area of top band, sq in.

NOTE: S_{TO} and S_{TI} may be different at locations 1 and 2 if band varies in cross section.

I-9.9.3 Bottom Band at Cross Axis:

$$\text{outside } f_O = -\frac{F_B}{A_B} - \frac{M_{B2}}{S_{BO}} \quad (\text{Eq I-38a})$$

$$\text{inside } f_I = -\frac{F_B}{A_B} + \frac{M_{B2}}{S_{BI}} \quad (\text{Eq I-38b})$$

Where:

- A_B = Effective area of bottom band, sq in.
- M_{B2} = Moment in bottom band at cross axis, kip-in.
- S_{BI} = Section modulus for the inside surface of the bottom band, in.³
- S_{BO} = Section modulus for the outside surface of the bottom band, in.³

I-10 DESIGN OF SIDEWALL PLATES.

I-10.1 Sidewall Plate Thickness. The sidewall plate thickness below the trunnions shall not be less than that given in Table I-7 and Section I-10.3. For intermediate capacities, sidewall thicknesses may be interpolated to nearest $\frac{1}{16}$ in. In the case of flanged bottom plates (Section I-4.2) the sidewall thickness may be less than the bottom plate thickness but must not be less than 0.75 times the required bottom plate thickness.

The thickness requirements for used ladles are discussed in Section I-5.4.7.

I-10.2 Sidewall Plate Joint. If the sidewall plate, below the trunnions, is made of different plate thicknesses (Fig. I-1b), the transition between these abutting plates shall be in accordance with the taper requirements in the ASME Code Section VIII, Divisions 1 and 2. The sidewall plate joint (full penetration butt weld connection) shall be located at a distance not less than:

$$e_T = 0.75\sqrt{R_S t} \quad (\text{Eq I-39})$$

from the edge of the stiffener band.

I-10.3 Supplementary Thickness. Supplementary to Table I-7 the sidewall thickness, $t_{\min}$, below the trunnion shall in no case be less than the greater of Eq I-40a or Eq I-40b:

$$t_{\min} = \frac{C_R q H D}{1819 \sigma_a} \quad (\text{Eq I-40a})$$

$$t_{\min} = \frac{2 C_R W_2}{\pi D \sigma_a} \quad (\text{Eq I-40b})$$

Where:

C_R = Constant to modify minimum plate thickness reflecting the type of joint connecting the bottom plate to the sidewall plate

C_R = 1.0 for full penetration butt weld joint

C_R = 1.18 for lap riveted connection (minimum net area is 85% of full plate cross-section)

The average normal stress through the thickness in the sidewall shall be calculated by the following formula:

$$\sigma_w = \frac{W_2}{\pi D t} \quad (\text{Eq I-40c})$$

Where:

σ_w = Average normal stress in sidewall, ksi

I-10.4 Upper Sidewall Plate Thickness. The side wall plate thickness above the top stiffener band shall not be less than 0.66 times the lower sidewall plate thickness.

I-11 INWARD DEFLECTION STIFFNESS AT TRUNNIONS.

The inward deflection of a ladle should be considered in the design of stiffener bands in order to provide adequate rigidity by minimizing the inward deflection at the trunnions. This condition should be evaluated in addition to the maximum stress conditions discussed in Section I-9.

The deflection index should not exceed 0.0026 for circular ladles, or 0.0020 for oval or obround ladles, based on shell radius as a reference dimension.

$$\lambda = \frac{C_D P R_{RM}^2}{E I_2} \quad (\text{Eq I-41})$$

Where:

λ = Deflection index for combined top and bottom stiffener bands

C_D = Deflection coefficient (Table I-8)

E = Modulus of elasticity (room temperature), ksi

I_1 = Moment of inertia of the effective band at trunnion axis (for deflection index calculation), in.⁴ (Fig. I-13, Eq I-42)

I_2 = Moment of inertia of the effective band at cross axis (for deflection index calculation), in.⁴ (Fig. I-13, Eq I-43)

P = Effective radial force applied at trunnion pin, kips (Eq I-44)

R_{RM} = Average minimum effective radius of top and bottom band, in. (Eq I-45)

Table I-8 — Deflection Coefficients, C_D

ANGLE BETA, DEGREES *

L/R_{RM}	I_2/I_1	0.0	5.0	10.0	15.0	20.0	25.0	30.0	35.0	40.0
0.0 **	0.30	0.0744	0.0632	0.0542	0.0473	0.0421	0.0384	0.0359	0.0344	0.0336
0.0	0.40	0.0744	0.0648	0.0573	0.0516	0.0474	0.0445	0.0426	0.0416	0.0411
0.0	0.50	0.0744	0.0665	0.0603	0.0557	0.0524	0.0502	0.0489	0.0482	0.0479
0.0	0.60	0.0744	0.0681	0.0633	0.0597	0.0572	0.0556	0.0547	0.0542	0.0541
0.0	0.70	0.0744	0.0697	0.0661	0.0636	0.0618	0.0607	0.0601	0.0598	0.0597
0.0	0.80	0.0744	0.0713	0.0690	0.0673	0.0662	0.0655	0.0652	0.0650	0.0650
0.0	0.90	0.0744	0.0728	0.0717	0.0709	0.0704	0.0701	0.0699	0.0699	0.0698
0.0	1.00	0.0744	0.0744	0.0744	0.0744	0.0744	0.0744	0.0744	0.0744	0.0744
0.10	0.30	0.0813	0.0706	0.0621	0.0556	0.0508	0.0475	0.0453	0.0441	0.0435
0.10	0.40	0.0836	0.0746	0.0676	0.0623	0.0585	0.0560	0.0545	0.0537	0.0534
0.10	0.50	0.0858	0.0785	0.0728	0.0687	0.0658	0.0640	0.0629	0.0624	0.0622
0.10	0.60	0.0880	0.0823	0.0779	0.0748	0.0727	0.0714	0.0707	0.0704	0.0703
0.10	0.70	0.0902	0.0860	0.0828	0.0806	0.0791	0.0783	0.0778	0.0777	0.0777
0.10	0.80	0.0924	0.0896	0.0876	0.0862	0.0853	0.0848	0.0845	0.0844	0.0844
0.10	0.90	0.0945	0.0931	0.0922	0.0915	0.0911	0.0908	0.0908	0.0907	0.0907
0.10	1.00	0.0966	0.0966	0.0966	0.0966	0.0966	0.0966	0.0966	0.0966	0.0966
0.20	0.30	0.0902	0.0800	0.0720	0.0659	0.0616	0.0586	0.0568	0.0558	0.0553
0.20	0.40	0.0952	0.0868	0.0803	0.0755	0.0722	0.0700	0.0688	0.0682	0.0680
0.20	0.50	0.1001	0.0933	0.0882	0.0845	0.0820	0.0805	0.0797	0.0794	0.0793
0.20	0.60	0.1048	0.0996	0.0957	0.0930	0.0913	0.0902	0.0897	0.0896	0.0896
0.20	0.70	0.1095	0.1057	0.1030	0.1011	0.0999	0.0992	0.0990	0.0989	0.0989
0.20	0.80	0.1141	0.1116	0.1099	0.1087	0.1080	0.1076	0.1075	0.1075	0.1075
0.20	0.90	0.1185	0.1173	0.1165	0.1160	0.1156	0.1155	0.1154	0.1154	0.1154
0.20	1.00	0.1229	0.1229	0.1229	0.1229	0.1229	0.1229	0.1229	0.1229	0.1229
0.30	0.30	0.1011	0.0914	0.0840	0.0784	0.0744	0.0719	0.0703	0.0696	0.0693
0.30	0.40	0.1093	0.1015	0.0956	0.0913	0.0884	0.0866	0.0857	0.0853	0.0852
0.30	0.50	0.1173	0.1111	0.1066	0.1034	0.1013	0.1001	0.0995	0.0993	0.0993
0.30	0.60	0.1250	0.1203	0.1170	0.1146	0.1132	0.1124	0.1121	0.1121	0.1120
0.30	0.70	0.1325	0.1292	0.1268	0.1252	0.1243	0.1239	0.1237	0.1237	0.1236
0.30	0.80	0.1397	0.1376	0.1361	0.1352	0.1347	0.1344	0.1344	0.1343	0.1343
0.30	0.90	0.1467	0.1457	0.1450	0.1446	0.1444	0.1443	0.1442	0.1442	0.1442
0.30	1.00	0.1534	0.1534	0.1534	0.1534	0.1534	0.1534	0.1534	0.1534	0.1534
0.40	0.30	0.1142	0.1052	0.0982	0.0931	0.0896	0.0874	0.0862	0.0856	0.0855
0.40	0.40	0.1263	0.1191	0.1137	0.1099	0.1075	0.1060	0.1053	0.1051	0.1051
0.40	0.50	0.1378	0.1322	0.1282	0.1254	0.1237	0.1228	0.1225	0.1224	0.1224
0.40	0.60	0.1488	0.1447	0.1418	0.1399	0.1387	0.1382	0.1380	0.1380	0.1380
0.40	0.70	0.1594	0.1565	0.1545	0.1533	0.1526	0.1523	0.1522	0.1522	0.1521
0.40	0.80	0.1696	0.1678	0.1666	0.1658	0.1655	0.1653	0.1653	0.1653	0.1652
0.40	0.90	0.1793	0.1784	0.1779	0.1776	0.1774	0.1774	0.1774	0.1774	0.1773
0.40	1.00	0.1886	0.1886	0.1886	0.1886	0.1886	0.1886	0.1886	0.1886	0.1886

* Refer to Fig I-13

** Circular when $L/R_{RM} = 0$

$$I_1 = I_{T1} \left(\frac{h_T}{h_{TR}} \right)^2 + I_{B1} \left(\frac{h_B}{h_{TR}} \right)^2 \quad (\text{Eq I-42})$$

$$I_2 = I_{T2} \left(\frac{h_T}{h_{TR}} \right)^2 + I_{B2} \left(\frac{h_B}{h_{TR}} \right)^2 \quad (\text{Eq I-43})$$

Where:

h_{TR} = Vertical distance between trunnion axis and juncture of ladle bottom and sidewall, in. (Figs. I-6, I-7)

I_{B1} = Moment of inertia of effective bottom band at trunnion axis, in.⁴

I_{T1} = Moment of inertia of effective top band at trunnion axis, in.⁴

$$P = 2 (F_T + F_B) \quad (\text{Eq I-44})$$

$$R_{RM} = \frac{R_{RT} + R_{RB}}{2} \quad (\text{Eq I-45})$$

The deflection coefficient, C_D , shown in Table I-8 can, as an alternative, be calculated from the equation shown in Appendix B.

I-12 DESIGN OF TILT MECHANISM.

I-12.1 General. The tilt mechanism is designed for use on charging and bottom pouring steelmaking ladles²⁴. It is used for tilting the ladle during deslagging operations and for dumping slag after caster or ingot teeming and shall be designed to include emergency pouring of an aborted heat. The configuration shown in this section is one of several available. The loads and stresses must be calculated based on the particular configuration.

I-12.2 Primary Functional Requirements. The tilt mechanism shall be designed to rotate the ladle to an inverted position and return the ladle to a vertical upright position. Rotating motion of the ladle is to be effected solely by use of the crane auxiliary hook.

The tilt mechanism shall be designed with a latching mechanism to allow safe attachment to the ladle while the tilt mechanism is not in use.

Design must permit the crane operator to be able to engage the tilt mechanism without assistance.

I-12.3 Loading Conditions. The tilt mechanism shall be designed for ladle loadings, as follows:

- (1) Deslagging. Use a design service molten metal weight with tilt angle limited to minimum required for deslagging.
- (2) Dumping slag and debris. Use a skull weight equal to 10% of the design service molten metal

weight during ladle tilting. It is assumed that the skull is attached to the ladle bottom lining. This accounts for the extreme condition of an aborted heat which results in an amount of frozen metal in the bottom.

(3) Loads imposed during positioning at maintenance and ladle heating stations. Use empty ladle weight (includes structural and lining weight) during ladle tilting for positioning the ladle.

(4) Loads imposed during disposition of aborted heats. Use a design service molten metal weight with a complete tilt.

I-12.4 Tilt Mechanism Description. The ladle tilt mechanism can vary in design from manufacturer to manufacturer. The primary structural components are described in Fig. I-14.

The primary structural components are defined as:

- (a) Bottom Pivot Plates. The horizontal tilt link is attached to the pivot plates by a pivot pin. The pivot plates connect the tilt mechanism to the ladle bottom. The pin can be shrunk fit as an option and the installation can be made with or without a wear sleeve.
- (b) Horizontal Tilt Link. This pin-connected member has a pivot on each end and connects the bottom pivot plates and the vertical tilt link.
- (c) Vertical Tilt Link. This pin-connected member connects the horizontal tilt link to the pick-up pin located on the upper end of the vertical tilt link.
- (d) Latch Plates. Latch plates support the tilt mechanism when it is not in use. They may also serve as a seat for the tilt linkage during the early stages of the ladle tilting.

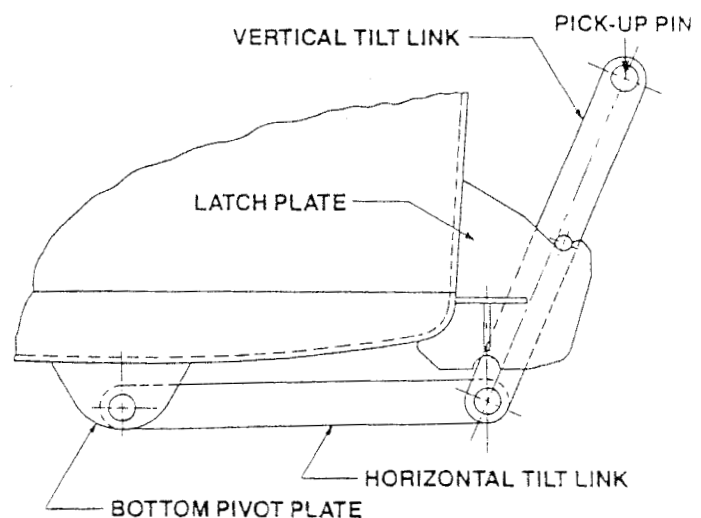


Fig. I-14 — Tilt Mechanism Components

I-12.5 Design Conditions. For the design conditions, the maximum forces imposed on the tilt mechanism shall be determined by evaluating tilt mechanism forces during various stages of ladle tilting. The load conditions used to design the tilt mechanism include the structural weight of the ladle, the maximum (full thickness) weight of the refractory lining, the design service molten metal weight and a skull weight equal to 10% of the design service molten metal weight. The tilting forces for the slag skimming condition are shown in Fig. I-15.

The force in the tilt mechanism developed by the lifting hook is calculated as:

$$F_S = \frac{W_D w_b + W_d w_a}{w_c} \quad (\text{Eq I-46})$$

Where:

- F_S = Maximum hook load on tilt mechanism during deslagging, kips
- W_D = Molten metal design weight, kips
- W_d = The structural weight of the ladle steelwork and full lining, kips
- w_a = Moment arm for W_d load, in.
- w_b = Moment arm for W_D load, in.
- w_c = Moment arm for F_S load, in.

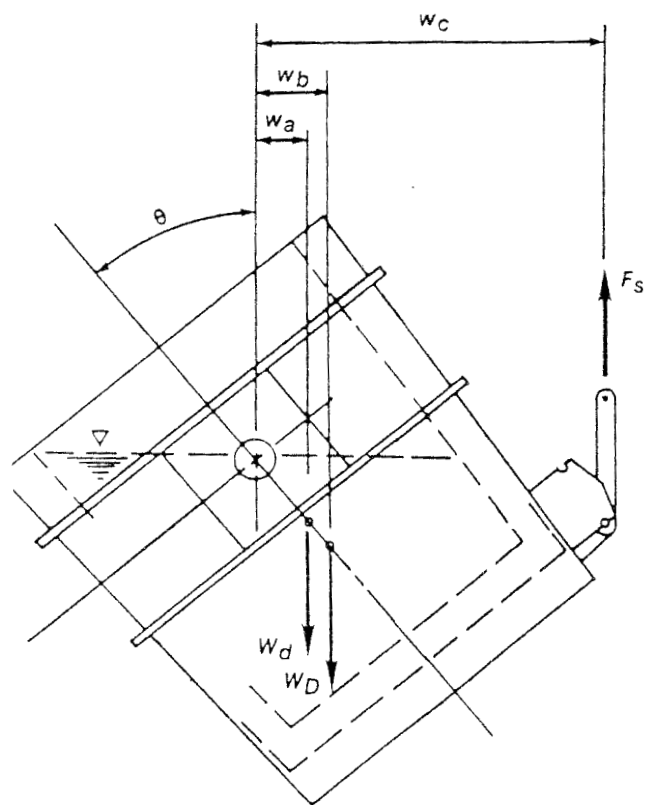


Fig. I-15 — Ladle Tilting Forces For Deslagging

As shown in Fig. I-16, the ladle tilting stages and forces can be categorized into three stages. The following functions are intended as a guide in designing the tilt mechanism and may not be typical for all tilt mechanisms.

(1) *Stage 1 Tilting.* During stage 1 tilting, the vertical link is providing the primary lifting force to the ladle. In some cases the vertical link has a pin which is temporarily engaged in the latch plates. In other cases the horizontal link is cantilevered out beyond a bearing plate. In the latter case, the vertical link, horizontal link and pivot plates act to tilt the ladle. The range of the ladle tilt angle is from zero degrees to less than 90 degrees.

(2) *Stage 2 Tilting.* During stage 2 tilting, typically both the vertical and horizontal links are in pure tension and the load is transferred into the pivot plates. The range of the ladle tilt angle is from less than 90 degrees to about 180 degrees.

(3) *Stage 3 Tilting.* During stage 3 tilting, the ladle is in a full inverted position. The vertical link, horizontal link and pivot plates are in a complete tensile stress state and support the ladle design loads for slag dumping.

The tilting forces for the slag dumping operation can be calculated as:

$$F_D = \frac{W_S w_d + W_d w_a}{w_c} \quad (\text{Eq I-47})$$

Where:

- F_D = Maximum hook load on the tilt mechanism during slag dumping (no molten metal included), kips
- W_S = Skull load attached to ladle bottom equal to 10% of the molten metal design weight, kips
- w_d = Moment arm for W_S load, in.

I-12.6 Maximum Loads and Service Temperatures for the Tilt Mechanism Components. The design procedure is intended to provide the minimum necessary considerations in the design of tilt mechanism components. The maximum loadings imposed on the tilt mechanism components shall be determined using the design loads and design conditions as defined in Section I-12.3 and Section I-12.5. The maximum loadings shall be evaluated using the full range of ladle tilting for the various stages of the tilt angles. Any portion of the tilt mechanism which is connected directly to the ladle shell, such as the bottom pivot plates, shall be designed with an identical service temperature as the ladle shell. Design of the tilt mechanism components not connected directly to the ladle bottom or sidewall shall be designed at the maximum ladle shell service temperature.

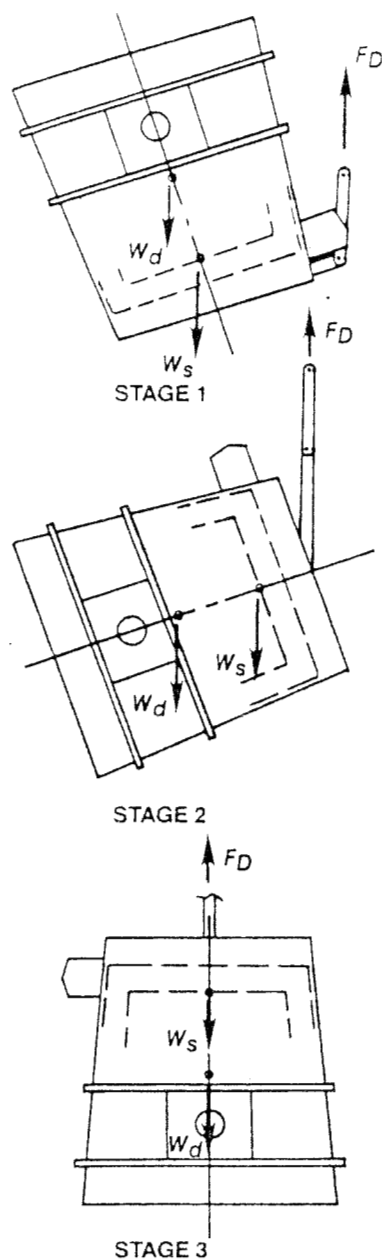


Fig. I-16 — Ladle Tilting Stages and Forces During Dumping

I-12.6.1 Design Stresses. Except for the pin-connected members, the average normal stress through the various sections of the tilt mechanism shall not exceed the allowable normal stress (σ_a) as determined by Eq I-2 or Eq I-3 and defined in Table I-3.

The bending stress in the various members of the tilt mechanism shall not exceed the allowable bending stress defined in Eq I-4.

The allowable limit of combined normal and bending stresses shall be governed by Eq I-8.

The allowable shear stress in the tilt mechanism components (excluding the pins and pin connections) shall be determined by Eq I-11. The effective area in resisting shear may be taken as the effective cross-sectional area in the plane of the shear force.

The allowable limit of combined normal, bending and shear stresses shall be governed by the following interaction equations:

$$\frac{f_a}{\sigma_a} \leq 1.0 \quad (\text{Eq I-48a})$$

$$\frac{f_b}{\sigma_b} \leq 1.0 \quad (\text{Eq I-48b})$$

$$\frac{f_s}{\sigma_s} \leq 1.0 \quad (\text{Eq I-48c})$$

$$\frac{f_a}{\sigma_a} + \frac{f_b}{\sigma_b} + \frac{f_s}{\sigma_s} \leq 1.0 \quad (\text{Eq I-48d})$$

Where:

f_s = Actual shear stress, ksi

In the case of emergency tilting, such as for an aborted heat, the allowable stresses shall be the yield strength of the material.

I-12.7 Design of Pin-Connected Members. A pin-connected member used in the tilt mechanism is classified as an eyebar or a pin-connected plate link. The design of the eyebar has been developed by accepted practices in regard to relative proportions and distribution of material in the eyebar head. Typically the pin-connected plate link is made by boring the holes for the pins near the ends of a plate link. Appropriate codes²¹ shall be used in the design of these members.

The allowable tension stress on the effective net area of a pin-connection member shall be determined by Eq I-49:

$$\sigma'_a = 0.75 \sigma_a \quad (\text{Eq I-49})$$

Where:

σ'_a = Allowable normal tension stress on the effective net area of the pin-connection member, ksi

I-12.7.1 Eybar Design. The eyebar shall be of uniform thickness without reinforcement at the pin holes. The eyebar shall have a 'circular' head in which the periphery of the head, beyond the pin hole, is concentric with the pin hole.

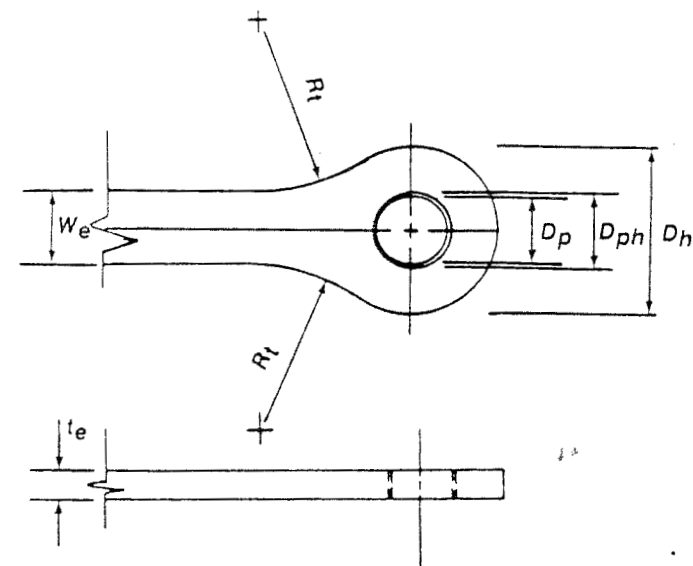
The transition radius between the circular head and the body of the eyebar shall be equal to, or greater than, the diameter of the head, as shown in Fig. I-17.

The width of the eyebar body shall not exceed 8 times the eyebar thickness and the thickness shall not be less than $\frac{1}{2}$ in.

The net area of the head through the pin hole, transverse to the axis of the eyebar, shall not be less than 1.33 nor more than 1.50 times the cross-sectional area of the body of the eyebar.

The diameter of the pin shall not be less than $\frac{7}{8}$ of the width of the body of the eyebar. The diameter of the pin hole shall not be more than $\frac{1}{32}$ in. greater than the diameter of the pin. For steels having a yield stress greater than 70 ksi, the diameter of the pin hole shall not exceed 5 times the plate thickness.

Thickness limitations on eyebars shall not be waived whenever external nuts are provided for tightening pin plates and filler plates into snug contact.



- R_t = Transition radius in eyebar, in.
 D_h = Outer diameter of eyebar, in.
 W_e = Width of bar portion of plate link or eyebar, in.
 t_e = Thickness of plate link or eyebar, in.
 D_p = Pin diameter, in.
 D_{ph} = Pin hole diameter in plate link or eyebar, in.

FOR ALL STEELS

$$\begin{aligned}
 R_t &\geq D_h \\
 t_e &\geq 0.5 \text{ in.} \\
 D_{ph} - D_p &\leq \frac{1}{32} \text{ in.} \\
 1.33 W_e t_e &\leq (D_h - D_{ph}) t_e \leq 1.50 W_e t_e
 \end{aligned}$$

FOR STEELS WITH σ_Y GREATER THAN 70 KSI

$$D_{ph} \leq 5 t_e$$

Fig. I-17 — Eyebare Geometry Requirements

I-12.7.2 Pin-Connected Plate Links. In pin-connected plates links, the tensile stress on the net area, transverse to the axis of the member, shall not exceed the allowable tensile stress defined by Eq I-49, and the bearing stress on the projected area of the pin shall not exceed the allowable average bearing stress determined by:

$$\sigma_{br} = 1.5 \sigma_a \quad (\text{Eq I-50})$$

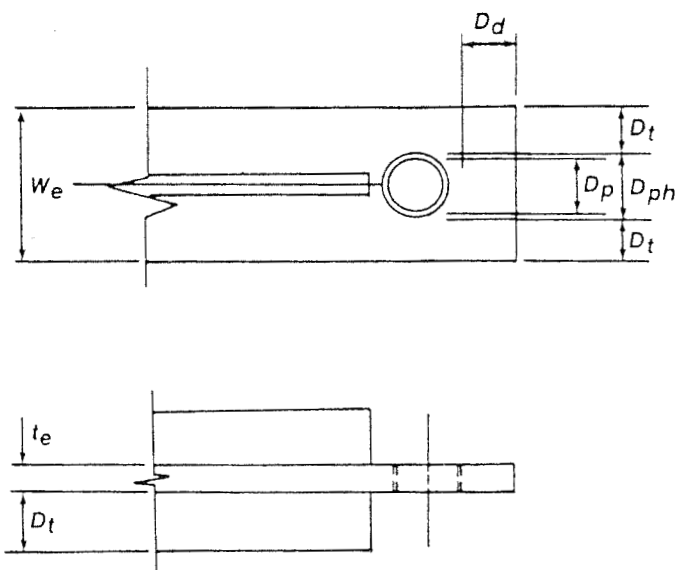
The minimum net area beyond the pin hole, parallel to the axis of the member (Fig. I-18 cross-section B-B), shall not be less than $\frac{2}{3}$ of the net area across the pin hole as described in Fig. I-18, cross-section A-A.

If stiffeners are used on a pin-connected plate link, their height shall not exceed 4 times the thickness at the pin hole. The diameter of the pin hole shall not be less than 1.25 times the smaller of the distances from the edge of the pin hole to the edge of the pin-connected plate link or separated element of a built up member at the pin hole.

In pin-connected plate links, the pin hole diameter shall not be more than $\frac{1}{32}$ in. greater than the pin diameter.

The corners beyond the pin hole may be cut at 45 degrees to the axis of the member, provided that the net area beyond the pin hole, on a plane perpendicular to the cut, is not less than that required beyond the pin hole parallel to the axis of the member.

Thickness limitations on the pin-connected plate link shall not be waived whenever external nuts are provided so as to tighten pin plates and filler plates into snug contact.



D_t - WIDTH OF PLATE EXTENSION ON PLATE LINK, IN.

$$\begin{aligned}
 D_t &\leq 4 t_e \\
 t_e &\geq 0.5 \text{ in.} \\
 D_{ph} &\geq 1.25 D_t \\
 D_d t_e &\geq \frac{2}{3} (W_e - D_{ph}) t_e \\
 D_{ph} &\leq D_p + \frac{1}{32} \text{ in.}
 \end{aligned}$$

Fig. I-18 — Pin-Connected Plate Link Geometry Requirements

I-12.8 Design of Latch Plates and Tilt Bearing Devices.

The latch plate is shown in Fig. I-14. If a latch plate or other tilt bearing device is to provide a compressive support for the linkage system, as shown in Fig. I-14, then it shall be designed by appropriate methods against all applicable modes of failure. Design stresses used shall be those defined in either Eq I-2 and Eq I-3 or Eq I-4.

If a reinforcing plate is used to attach the latch plate to the sidewall, then the thickness of the reinforcing plate shall equal the sidewall plate thickness. The reinforcing plate shall be connected to the sidewall plate by a continuous full thickness fillet weld. The reinforcing plate shall have a vent hole located away from the welds and latch plate attachment.

I-12.9 Design of Other Style Tilt Mechanisms. The use of tilt mechanisms made of chain links and cables is not encouraged. If chain links or cables are used, the manufacturer's breaking strength data at design service temperatures should be used to select the appropriate size of the member. The design load for the member shall be determined by applying appropriate factors of safety to the manufacturer's breaking strength data.

In the case where complicated forged or machined configurations of pin-connection members are used, detailed analytical procedures, such as finite element methods, shall be used to evaluate the design stresses. The design stresses shall satisfy the allowable stress limits for normal and bending stresses specified in Eqs I-2, I-3 and I-4, respectively.

I-12.10 Non-Structural Appurtenances. If the design includes non-structural appurtenances such as those used to permit unassisted coupling and uncoupling to the crane hook by the crane operator, the total design, including the appurtenances, shall not permit a decrease in the structural

strength of the tilt mechanism. The appurtenance may serve only to satisfy the functional requirements of the tilt mechanism.

Optional latch guard bars may be provided on the ladle to prevent or minimize accidental disengagement of the tilt mechanism while the ladle is set down on uneven surfaces. In some cases, bottom ribs and other primary structural members may serve as guard bars. If guard bars are included in the design, the guard bars shall be designed as load supporting members if the design assumes that operating loads are imposed on the guard bars during typical ladle operation.

If the design includes a guard plate attached to the outside of the ladle sidewall to protect the sidewall against impact damage imposed by the auxiliary hook, the design should specify that the guard plate be attached in such a manner as to minimize thermal expansion stresses developed in the ladle sidewall.

I-13 RIVETED SIDEWALL CIRCUMFERENTIAL CONNECTION JOINTS

I-13.1 General. The use of riveted sidewall connection design procedures may be required when it is necessary for the field assembly of a new ladle. In the case of an existing ladle that is revised to a caster and/or clean steel processing ladle, the existing riveted connection shall be upgraded according to the following design requirements²⁴.

A riveted sidewall circumferential connection joint is typically a sidewall plate connection below the bottom stiffener band and/or a sidewall plate to bottom plate connection.

In an existing ladle, if the rivet connection can not be revised to satisfy the following design requirements, the sidewall connection shall be revised to a welded connection.

I-13.2 Design of the Riveted Sidewall Connection. The riveted connection shall be a lap joint made of a single buttstrap. The buttstrap plate strength shall be at least equal to the sidewall plate strength.

The number of required rivets on each side of a single buttstrap type connection or a single riveted lap type connection shall be determined by Eq I-51:

$$N_r \geq 0.70 \frac{A_w \sigma_a}{A_r \tau_r} \quad (\text{Eq I-51})$$

Where:

A_w = Cross-section of the ladle sidewall measured adjacent to the bottom plate, sq in.

N_r = Number of required rivets on one side of the connection

τ_r = Allowable shear stress for rivet, ksi (Section I-5.6)

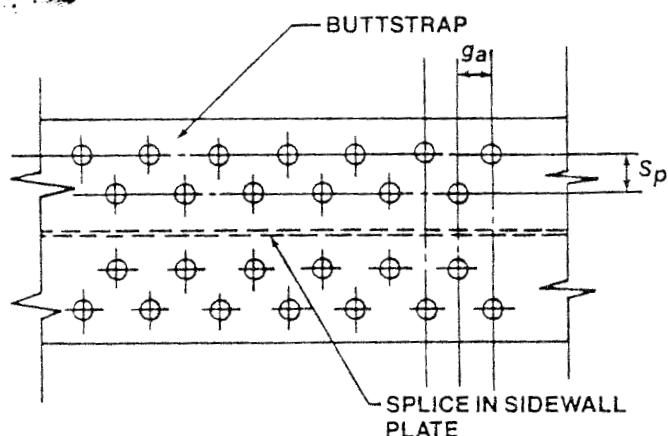


Fig. I-19 — Rivet Connection

I-13.3 Minimum Rivet Spacing and Edge Distance. For a typical staggered rivet pattern, as shown in Fig. I-19, the minimum spacing between the centers of rivet holes, measured in the circumferential direction, shall not be less than three times the rivet hole diameter ($3 d_r$). The minimum distance between adjacent circumferential rows of rivets shall be $1\frac{3}{4} d_r$.

The spacing between rivets may be less than the minimum values defined above provided the stress in the ligaments, between rivets in the circumferential direction and those in the diagonal direction, does not exceed the allowable normal stress defined by Eq I-52.

The minimum edge distance from the center of the rivet hole to the edge of the plate, except for rivet holes in the ends of the buttstraps, shall not be less than $1\frac{1}{4} d_r$ nor more than $1\frac{3}{4} d_r$.

In addition to rivet spacing and edge distance, the distance from the bottom edge of the bottom stiffener band to the first row of rivets shall not be less than the distance defined by Eq I-39.

I-13.4 Allowable Stresses in Rivets. The maximum allowable shear stress in a rivet is defined in Section I-5.6. The allowable shear stress is used in Eq I-51 to provide an initial estimate of the number of required rivets. The maximum allowable bearing stress in a rivet shall be twice that permitted for shear stress. In the case of a countersunk rivet, one-half the depth of the countersink shall be deducted in the calculation of the total bearing area of the rivet.

I-13.5 Allowable Stress in Sidewall Plate. The allowable sidewall plate stress defined in Eq I-52 is for the minimum net effective area of the sidewall plate in the vicinity of the riveted connection.

The calculation of stress in the sidewall plate, remote from the riveted connection, is not required for the riveted connection design since the sidewall plate thickness is defined in Section I-10.

The average normal tensile stress in the minimum net effective area of the sidewall plate and buttstrap at the rivet connection shall be defined by Eq I-52:

$$\sigma'_{ah} = \frac{W_2}{A_n} \leq 1.4 \sigma_a \quad (\text{Eq I-52})$$

Where:

A_n = Minimum net effective cross-sectional area in the sidewall plate and buttstrap plate shall be equal to the plate thickness times the minimum net width, in.² The minimum net width is calculated by subtracting the sum of the hole diameters in any given chain of holes from the total circumference, and ad-

ding for each diagonal gage space, the quan-

$$\text{tity: } \frac{S_p^2}{4 g_a}$$

g_a = Transverse spacing (gage) of two holes, in.
 σ'_{ah} = Average normal tensile stress in the minimum net effective area of the rivet connection plate, ksi
 S_p = Longitudinal spacing (pitch) of any two successive holes, in.

The allowable bearing stress imposed on the sidewall plate and the buttstrap plate by the rivets shall be defined by Eq I-53.

$$\sigma_{bh} = 1.6 \sigma_a \quad (\text{Eq I-53})$$

Where:

σ_{bh} = Allowable bearing stress imposed by the rivets on the sidewall plate, ksi

For countersunk rivets, one-half the countersink shall be deducted in calculating the total bearing area of the rivet.

In addition, the minimum net effective cross-sectional area (A_n) in the sidewall plate and buttstrap plate at the riveted connection shall be equal to or greater than 70% of the cross-sectional area of the sidewall plate measured at the bottom plate attachment.

I-13.6 Postweld Heat Treatment. It is recommended that whenever possible, that all heat treatment required for the ladle be completed before riveting the sidewall.

I-13.7 Preparation of Plate Edges. The edges of the sidewall plate, buttstraps, and bottom plate shall be chamfered to a depth of not less than one-fourth of the thickness of the material, but in no case more than $\frac{1}{8}$ in.

I-13.8 Buttstrap End Connection. The ends of a buttstrap shall be connected by a full penetration weld.

I-14 DESIGN OF SUPPORT LEGS FOR DISHED BOTTOM LADLES.

I-14.1 General. A dishd bottom ladle may be designed with support legs at the periphery of the dishd bottom²⁴. If support legs are chosen as a method of ladle support, then only three legs shall be used to provide stability to the ladle on an uneven resting surface.

I-14.2 Loading Conditions. Design of the legs shall be based on the following: during a ladle set down, assume that only two of the legs will be used to support the total design operating weight of the ladle. Also, the design shall include a simultaneous horizontal shear load equal to one half of the vertical leg load applied to each of the two load bearing legs. At rest, the ladle will be supported equally by the three legs.

I-14.3 Description of Support Legs. Each support leg shall be attached to the knuckle region of the dished bottom, as shown in Fig. I-20. The support leg shall be constructed of pipe or similar cylindrical stock. The support leg wall thickness shall not be less than the thickness of the sidewall plate below the trunnions. The bottom of the support leg shall be capped with a plate equal in thickness to the support leg wall thickness. A vent hole $\frac{3}{4}$ in. in diameter shall be drilled through the bottom cap plate. The top of the support leg shall be capped with a plate to prevent debris from collecting inside the support leg.

I-14.4 Design of the Support Leg. The cross-sectional size of the support leg shall have sufficient strength to satisfy Eqs I-54a, I-54b and I-54c:

$$\frac{F_V}{A_L \sigma_a} \leq 1.0 \quad (\text{Eq I-54a})$$

$$\frac{F_V L_A}{2 S_L \sigma_b} \leq 1.0 \quad (\text{Eq I-54b})$$

$$\frac{F_V}{A_L \sigma_a} + \frac{F_V L_A}{2 S_L \sigma_b} \leq 1.0 \quad (\text{Eq I-54c})$$

Where:

- A_L = Cross-sectional area of support leg, in.²
- S_L = Section modulus of support leg, in.³
- F_V = Vertical load on support leg equal to one-half the total design service load of the ladle, kips
- L_A = Maximum support leg length necessary to provide appropriate clearance under ladle, in.

The length of support leg (L_c) connected to the sidewall plate shall be determined by Eqs I-55a, I-55b, I-55c and I-55d:

$$L_c = L_c' + \sqrt{(L_c'')^2 + (L_c''')^2} \quad (\text{Eq I-55a})$$

Where:

$$L_c' = \frac{F_V}{2.35 T_L \sigma_s} \quad (\text{Eq I-55b})$$

$$L_c'' = \frac{F_V L_A}{4.70 r_m T_L \sigma_s} \quad (\text{Eq I-55c})$$

$$L_c''' = \frac{1}{1.24} \sqrt{\frac{F_V L_A}{T_L \sigma_s}} \quad (\text{Eq I-55d})$$

Where:

- L_c = Length of support leg actually connected to sidewall plate, in.

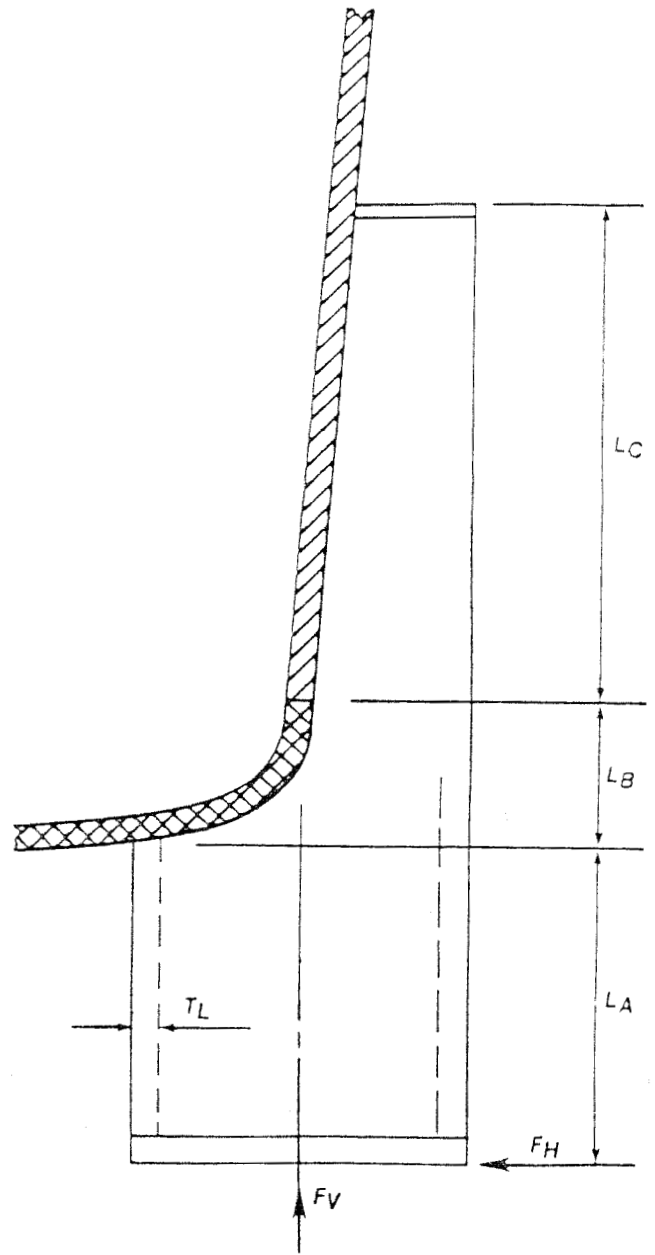


Fig. I-20 — Support Leg Geometry and Loads

- L_c' = Component leg length required for vertical force, F_V , in.
- L_c'' = Component leg length required for horizontal force in the plane of support leg and sidewall plate, in.
- L_c''' = Component leg length required for horizontal force normal to sidewall plate, in.
- T_L = Thickness of support leg wall, in.
- r_m = Mid-thickness radius of support leg, in.

The support leg attachment length is described in Fig. I-21. The length L_B (Fig. I-20) is a function of the shape of the dished head.

The support leg shall be attached to the bottom plate and sidewall plate with a continuous full penetration weld.

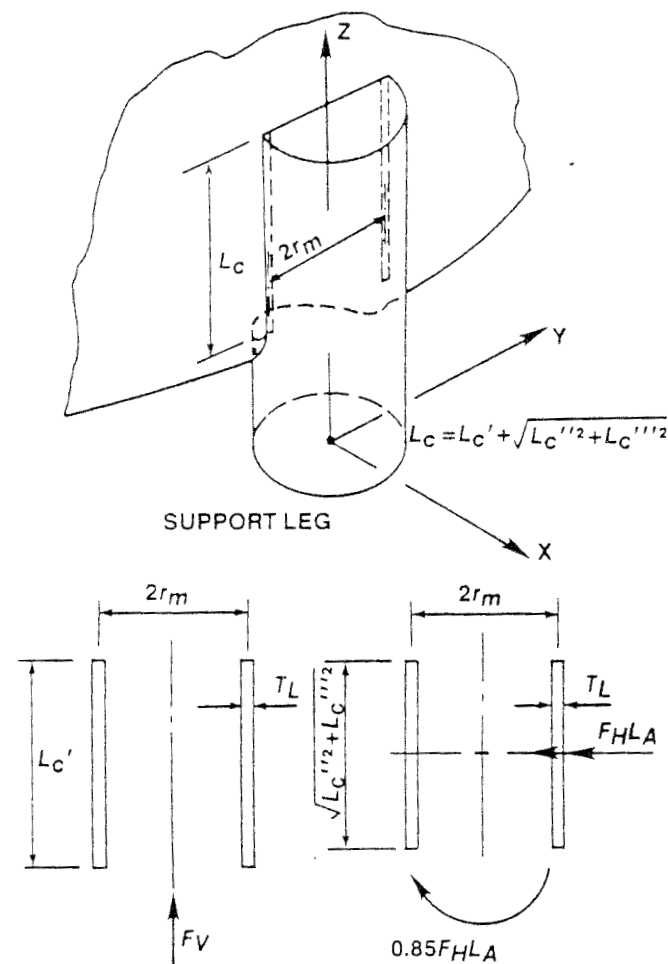


Fig. I-21 — Attachment Length (L_c) of Support Leg

15 ASSEMBLING AND WELDING LADLES IN THE SHOP AND FIELD

5.1 Fitting. Fitting of plates for butt welding shall be in accordance with the ASME Code, Section VII, Division 1. Wedging, clamping or heating is permitted to achieve proper alignment.

5.2 Cleaning. All joints must be free of scale, rust and other adherences. All paint or protective coatings must be completely removed before any welding begins.

I-15.3 Welding. Welders, operators and welding procedures shall be qualified in accordance with the ASME Code, Section VIII, Division 1. The requirements of Sections I-4.5 and I-4.6 shall be met.

I-15.4 Weld Defects. Visual weld quality shall be in accordance with the ASME Code, Section VIII, Division 1. Undercutting, lack of fusion, lack of penetration, overlap or bead cracking shall not be permitted. All repairs must be made prior to depositing subsequent beads or layers of welds. Defective areas must be removed by chipping, grinding or air-arc gouging. No flame gouging shall be permitted.

I-15.5 Inspection and Nondestructive Tests of Welds.

When visual inspection only is to be used, it shall be stated by the purchaser on the OIS. When nondestructive tests are required they shall be made and evaluated in accordance with the ASME Code, Section V, Nondestructive Examinations.

I-15.5.1 Recommended Nondestructive Tests. The following nondestructive tests are recommended as a minimum requirement:

- (1) Dimensional check of plate thicknesses
- (2) Visual inspection of weld preparation and workmanship
- (3) Verification that the welded surfaces are clean and free from moisture, hydrocarbonous residues and oxidation
- (4) Verification that the proper qualified welding procedure and filler metal have been employed
- (5) Visual inspection of the finished weld
- (6) Verification of repair of any defect in the weld before postweld heat treatment.

I-15.5.2 Optional Nondestructive Tests. The purchaser may request additional testing and inspection procedures such as:

- (1) Dye penetrant
- (2) Magnetic particle
- (3) Ultrasonic (in accordance with the ASME Code, Section V)
- (4) Radiographic (in accordance with the ASME Code, Section V)

PART II: LADLE DESIGN — REFRACTORY LINING

II-1 SCOPE.

Part II of this Technical Report addresses the use of high strength refractories in ladles to assist the user in obtaining optimal ladle life and in minimizing ladle repair.

II-2 LADLE LINING.

II-2.1 General. The specifications on ladle refractories include recommendations on the lining design and provide suggestions on the manner in which various operating conditions, such as preheating and other clean steel practices, are imposed on the ladle. The recommendations are not intended to restrict the use of the ladle, but rather to provide insight into improving ladle life and reducing adverse ladle environments.

II-2.2 Lining Insulating Capacity. The difference in insulating capacity between the bottom lining and the wall lining should be minimized in order to reduce the temperature difference between the bottom plate and the sidewall plate. The temperature difference becomes more pronounced during sustained ladle preheat and hot metal hold time.

II-2.3 Estimating Wall Working Lining Thermal Expansion Stress. During initial ladle preheat, resin-bonded dolomitic, high-alumina and direct-bonded mag-chrome refractory working linings develop considerable expansion forces if compressible expansion allowance material is not included in the ladle wall lining system. Circular ladle sidewall stress (circumferential stress) shall be determined by Eqs II-1a, II-1b and II-1c.

$$\delta = \alpha_{wl} \Delta\theta_{wl} R_{wl} - \alpha_s \Delta\theta_s R_{s(ave)} \quad (\text{Eq II-1a})$$

$$p = \frac{\delta}{\left[\frac{R_{wl}^2}{t_{wl} E_{wl}} + \frac{R_{s(ave)}^2}{t E_s} \right]} \quad (\text{Eq II-1b})$$

$$f_{ex} = p \frac{R_{s(ave)}}{t} \quad (\text{Eq II-1c})$$

Where:

- E_s = Modulus of elasticity of ladle sidewall plate, ksi
- E_{wl} = Average modulus of elasticity of wall working lining refractory, ksi
- f_{ex} = Circumferential stress in ladle sidewall plate resulting from thermal expansion of the wall working lining refractory, ksi
- p = Effective radial pressure applied to the ladle sidewall plate caused by the differential thermal

expansion between the working lining and the sidewall, ksi

- $R_{s(ave)}$ = Average radius of sidewall plate, in.
- R_{wl} = Mid-thickness radius of wall working lining, in.
- t = Thickness of ladle sidewall plate, in.
- t_{wl} = Thickness of wall working lining refractory, in.
- α_s = Linear coefficient of thermal expansion of the ladle sidewall plate, in./in. °F
- α_{wl} = Linear coefficient of thermal expansion of the wall working lining, in./in. °F
- $\Delta\theta_s$ = Increase in ladle sidewall plate temperature from ambient temperature, °F
- $\Delta\theta_{wl}$ = Increase in wall working lining mid-thickness temperature from ambient temperature, °F
- δ = Interference applied to the ladle sidewall resulting from differential expansion of wall working lining and ladle sidewall, in.

Obround or oval ladle sidewall stress shall be determined by Eqs II-1a, II-1b and II-1c and using the modification defined in Eq II-2a and Eq II-2b.

$R'_{s(ave)}$ and R'_{wl} are calculated from:

$$R'_{s(ave)} = \frac{R_{\max(ave)} + R_{\min(ave)}}{2} \quad (\text{Eq II-2a})$$

$$R'_{wl} = \frac{R_{w\max(ave)} + R_{w\min(ave)}}{2} \quad (\text{Eq II-2b})$$

Where:

- $R'_{s(ave)}$ = Effective average radius of sidewall plate of obround or oval ladle, in.
- R'_{wl} = Effective mid-thickness radius of wall working lining of obround or oval ladle, in.
- $R_{\max(ave)}$ = Maximum average radius of sidewall plate of oval or obround ladle, in.
- $R_{\min(ave)}$ = Minimum average radius of sidewall plate of oval or obround ladle, in.
- $R_{w\max(ave)}$ = Maximum average mid-thickness radius of working lining of oval or obround ladle, in.
- $R_{w\min(ave)}$ = Minimum average mid-thickness radius of working lining of oval or obround ladle, in.

II-2.4 Wall Working Lining Expansion Allowance. The purpose of wall lining expansion allowance is to reduce the thermal expansion forces of the working lining to reasonable values so the ladle shell is not exposed to undesirable levels of thermal expansion stresses¹⁰. The recommended provisions for expansion allowance material for wall working linings are in addition to the expansion allowance provided by the brick mortar joints.

The recommendations for expansion allowance apply only for expansion allowance use in the wall working lining and not in the bottom lining. Regardless of the type of working lining, plug type or other similar bottom lining designs do not require expansion allowance.

Fireclay brick, if used as a wall working lining, is a low strength refractory and therefore does not require expansion allowance consideration. Similarly, other low strength wall working lining materials, such as pitch-bonded refractories, do not require expansion allowance consideration.

The expansion allowance recommendations apply to the user that employs resin-bonded dolomitic, 70% alumina and direct-bonded mag-chrome working linings in combination with ladles exposed to standard or ramp preheat and hot metal hold times consistent with clean steel processes and continuous caster environments.

II-2.4.1 Wall Working Lining Radial Expansion Allowance. Table II-1 describes the range of recommended radial expansion allowance for the wall working lining. The three types of working lining refractories considered are resin-bonded dolomitic, 70% alumina and direct-bonded mag-chrome. In order to accommodate the recommended expansion allowance, the expansion allowance material is expected to be compressible and placed on the cold face side (Fig. II-1) of the working lining.

It is recommended the user thoroughly review Section IV-1 before using expansion allowance in the lining design.

Supplementary to Table II-1, the recommended amount of radial expansion allowance for the wall working lining

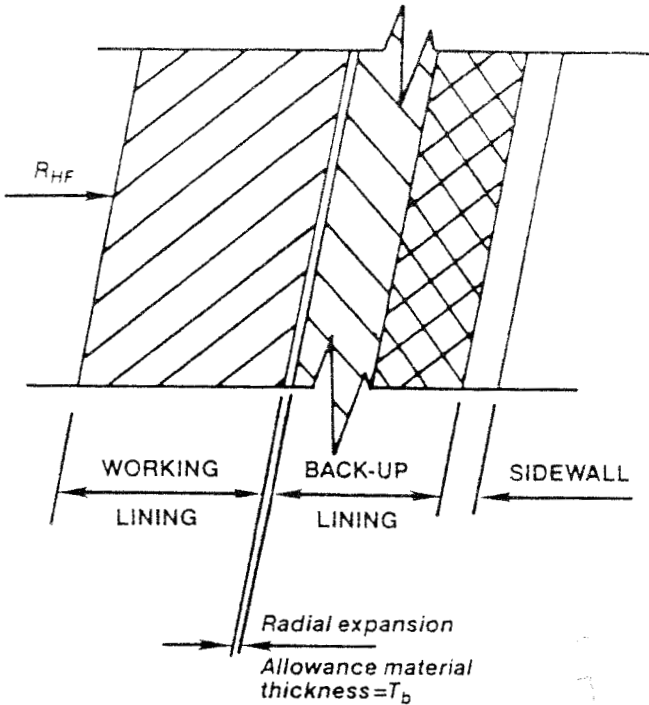


Fig. II-1 — Expansion Allowance Material for Radial Growth of Wall Working Lining

can be calculated using Eq II-3a and II-3b. In no case shall the calculated expansion allowance exceed the amount defined in Table II-1.

For 70% alumina or resin-bonded dolomitic brick working lining:

$$Z_R = 0.003 R_{HF} \tag{Eq II-3a}$$

For direct-bonded mag-chrome working lining:

$$Z_R = 0.006 R_{HF} \tag{Eq II-3b}$$

Where:

- R_{HF} = Hot face radius of wall working lining, in.
- Z_R = Amount of radial expansion allowance on the cold face side of the wall working lining, in.

Table II-1 — Recommended Amount of Radial Expansion Allowance, Z_R , for the Wall Working Lining

Type of Working Lining	Recommended Amount of Radial Expansion† Allowance, Z_R , in.			
	Size of Ladle, tons			
	50	100	200	> 300
70% Alumina	0	0	1/8	1/8
Resin-Bonded Dolomitic	0	1/8	1/8	1/4
Direct-Bonded Mag-Chrome	1/4	1/4	3/8	1/2

† Amount of compressibility of the expansion allowance material.
The compressibility of the mortar joints has been taken into consideration.

If slag zones (or other complete circumferential types of zoning) are used, the amount of radial expansion allowance is calculated using the applicable equation for the refractory used in the slag zone. For zones which occupy a partial circumferential distance, the radial expansion allowance is calculated using the summed portions of the refractory materials of the working lining.

If ramp preheat (100 to 200°F per hour) is used for a cold ladle with a 70% alumina working lining, expansion allowance is not required. In the case of standard preheating of a 70% alumina working lining, expansion allowance is required. However, for direct-bonded mag-chrome or resin-bonded dolomitic working linings, expansion allowance is recommended regardless of the preheating rate.

For wall working lining refractories, other than those described in Table II-1, investigations shall be undertaken by the ladle user to determine the appropriate need for expansion allowance.

Circular ladle sidewall stress (circumferential stress) with expansion allowance shall be determined by Eqs II-3c, II-1b and II-1c. Obround or oval ladle sidewall stress with expansion allowance shall be determined by Eqs II-3c, II-1b and II-1c and using the modification defined in Eqs II-2a and II-2b.

$$\delta = \alpha_{wl} \Delta\theta_{wl} R_{wl} - \alpha_s \Delta\theta_s R_{s(ave)} - Z_R \quad (\text{Eq II-3c})$$

II-2.4.2 Wall Working Lining Axial Expansion Allowance. Expansion allowance for axial growth of the wall working lining is recommended. The expansion allowance material shall be placed between the top of the wall lining and lip ring, as shown in Fig. II-2. The amount of axial thermal growth in the wall working lining is calculated as follows:

For 70% alumina brick or resin-bonded dolomitic working lining:

$$Z_A = 0.0033 L_{70,D} \quad (\text{Eq II-4a})$$

For direct-bonded mag-chrome working lining:

$$Z_A = 0.0069 L_{MC} \quad (\text{Eq II-4b})$$

Where:

$L_{70,D}$ = Axial length of 70% alumina or resin-bonded dolomitic wall working lining, in.

L_{MC} = Axial length of direct-bonded mag-chrome wall working lining, in.

Z_A = Amount of axial expansion allowance for wall lining, in.

If slag zones (or other complete circumferential types of zoning) are used, the axial expansion is calculated by summing the separate contributions of the various axial lengths of the 70% alumina brick and direct-bonded mag-chrome brick. For wall working lining zones which occupy a small part of a circumferential region, the axial expansion al-

lowance is calculated using the predominant refractory make-up of the wall working lining.

Compressible refractory materials are recommended for the axial expansion of the wall lining. These materials are used under the lip ring, as shown schematically in Fig. II-2. Typically, 2 to 3 in. (T_{EM}) of this type material is required to provide the appropriate amount of expansion allowance (Z_A). These materials are recommended providing the manufacturer can supply data on the percent of compressibility of the material when subjected to loads of 200 to 800 psi.

II-2.5 Compressible Expansion Allowance Materials.

Compressible refractory materials are recommended for the expansion allowance material. These materials include

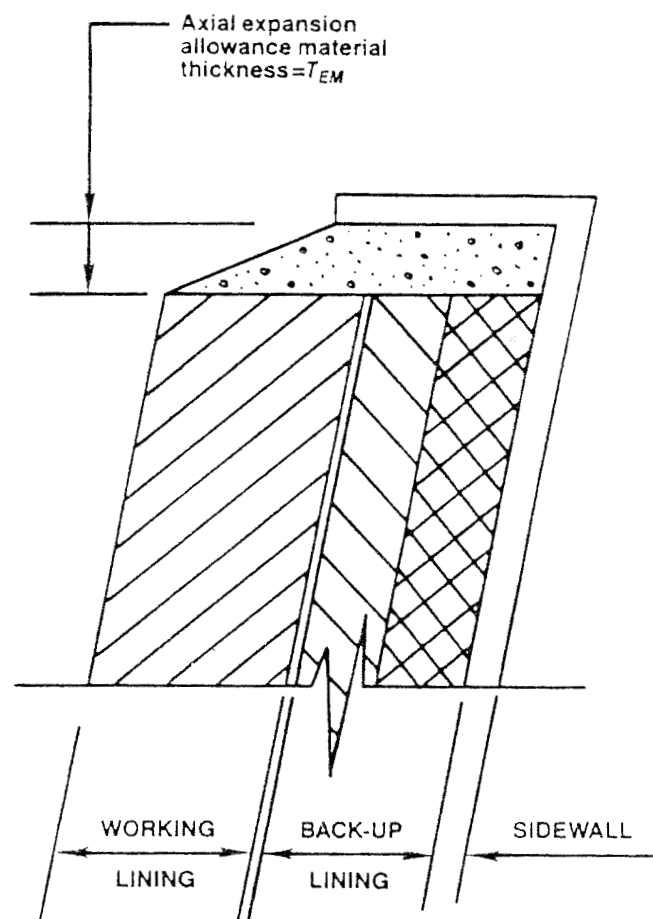


Fig. II-2 — Expansion Allowance for Axial Growth of Wall Working Lining

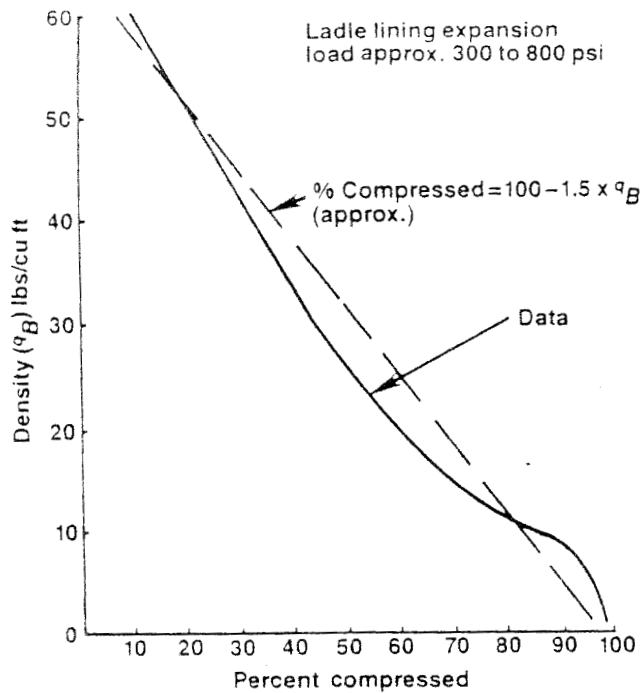


Fig. II-3 — Compressibility of Blanket Material

alumina or mineral fiber blanket and granular refractory backing materials. Based on experience and lining practices, the most appropriate working lining expansion allowance material shall be selected by the user.

For a typical range of working lining thermal expansion force, the percent of board and blanket compressibility is described in Fig. II-3. The percent of board and blanket type material compressibility is calculated as:

$$P_B = 100 - 1.5 q_B \quad (\text{Eq II-5})$$

Where:

P_B = Percent of compressibility of expansion allowance material

q_B = Density of expansion allowance material, lb/ft³

The expansion allowance material thickness is calculated as:

$$T_b = \frac{Z_R}{P_B} \times 100 \quad (\text{Eq II-6})$$

Where:

T_b = Thickness of expansion allowance material behind working lining, in.

The manufacturer's temperature rating should be considered in selecting the appropriate expansion allowance material.

The compressible expansion allowance material is placed on the cold face side of the working lining, thus allowing replacement of the expansion allowance material with each new working lining.

II-2.6 Lining Stabilization. When expansion allowance materials are employed in the ladle wall working lining, ladle tilting and resulting lining shift must be avoided. For an initial time period, vertical (upright position) ladle preheating is recommended in order to stabilize the lining. Table II-2 provides a range of recommended initial minimum preheat times for either a normal preheat or ramp preheat, using commercially available preheaters. The initial minimum preheat times assume a new working lining thickness of about 5 in. starting at ambient temperature, and do not include the effects of drying lances or other initial temperature effects.

If the preheating rates used are other than those shown in Table II-2, appropriate allowance should be made for the initial preheat time before ladle tilting.

Table II-2 — Recommended Initial Preheat Time Prior to Tilting Cold Ladle

Minimum Vertical Preheat Time before Ladle Tilting, hr

Thickness of Radial Expansion Allowance Material, in.	Standard Preheat†	Ramp Preheat (100 to 200°F/hr)
1/8	1/2	3
1/4	3/4	6
1/2	1	8

† Standard preheat increases the working lining hot face temperature to approximately 1500° to 2000°F within the first hour of preheat.

PART III: LADLE INSPECTION, REPAIR, ALTERATION AND MAINTENANCE

III-1 LADLE INSPECTION.

III-1.1 General. At a minimum, inspection of an active ladle is recommended once per year. Practices may dictate more frequent inspection. Inspection procedures similar to those described in Section I-15.5.1 and I-15.5.2 may be used.

III-1.2 Ladle Details for Inspection. Described in Fig. III-1 are details of the structural components recommended for inspection on active ladles. The components may not be representative of all ladles but are intended to provide guidance in identifying the more critical regions for inspection.

Detail I — The regions surrounding the circumferential welds of the stiffener bands. These regions include both the inside sidewall surface and the outside sidewall surface.

Detail II and III — Both the inside and outside surface of the full penetration butt welds in the ladle sidewall plate, especially the weld within a distance of $2\sqrt{R_s t}$ from each side of the stiffener bands.

Detail IV — The offset regions of the stiffener bands. Typically, the offsets occur at the edges of the trunnion block. Particular attention should be given to the radius region of the offset.

Detail V — The full penetration butt welds of the stiffener bands, especially in the region of the bands at the cross axis (section 90 degrees to trunnion axis of ladle) and in the region of the trunnions.

Detail VI — The full penetration butt weld (circumferential) connecting the bottom plate to the sidewall plate. The bottom plate can be dished or flat.

Detail VII — The trunnion pin, especially on the bottom side of the pin, in the region of the trunnion block and trunnion plates. Inspection in the trunnion region should include welds and pins connecting the trunnion block structure to the ladle sidewall and stiffener bands.

Detail VIII — (Not shown in Fig. III-1) The bottom ribs, in the region of welds connecting the stiffeners to the skirt, and the region of the welds connecting the ribs to the bottom plate. Also, the tilt mechanism should be routinely inspected for structural defects in the linkage, linkage pins and other parts of the mechanism.

For ladles in which corrosion, wear or other damage has resulted in a reduction in dimensions, the stresses are to be recalculated using actual measured dimensions. The criteria set forth in Sections I-5.4.7 and I-5.5.4 of this technical report are then to be utilized to determine the necessity for replacement or repair. Section I-5.4.7 covers stresses in used components other than trunnion pins and Section I-5.5.4 covers stresses in used trunnion pins.

If dimensional requirements of the ladle structural components are not satisfied, the ladle user shall have the structural integrity of the ladle evaluated by a ladle manufacturer or qualified agent.

In addition to inspection for dimensional changes, ladle components should be inspected for cracks and other types of structural deterioration. In the case of bent or severely distorted structural components, the component shall be replaced.

The recommended areas for inspection do not rule out the need for inspecting other structural details which may be unique to the users ladle design.

Ladle repair of the various structural components shall be made according to the details described in Section III-4.

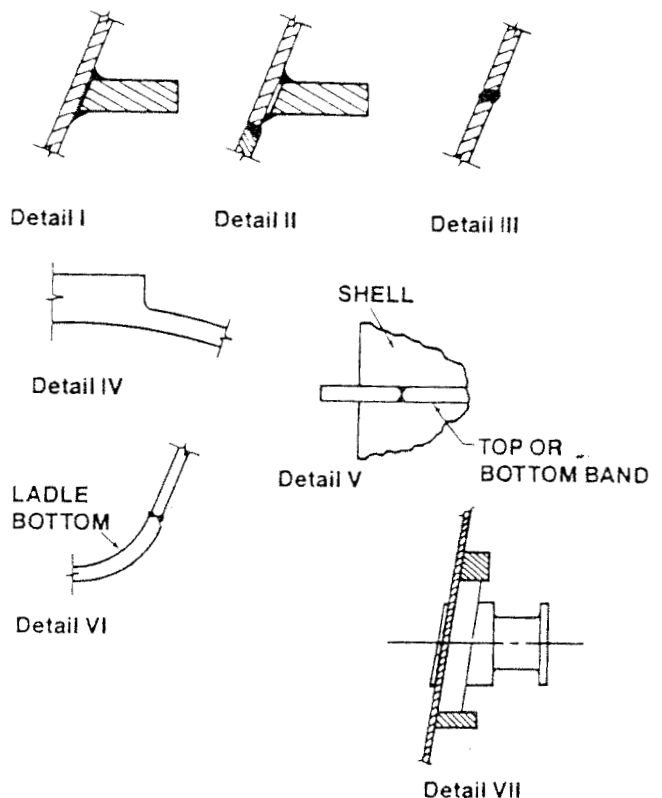


Fig. III-1 — Recommended Ladle Details for Inspection

III-2 LADLES WITH RIVETED LAP JOINTS.

The strength of riveted lap joints shall be evaluated in existing ladles that are used in continuous caster or clean steel environments in combination with high strength refractory working linings. The existing riveted lap joint

shall have strength greater than 70% of a riveted joint design, as defined in Section I-13. The strength of the existing riveted connection shall be based on actual measured dimensions and the allowable stresses of the ladle components. If the strength of the riveted connection does not satisfy the 70% strength criteria, due to loss of material from corrosion and wear, or due to insufficient strength in the connection design, then the existing riveted connection shall be replaced by either a revised riveted connection design or a full penetration weld connection satisfying the requirements in Part I of these specifications.

III-3 LADLE REPAIR AND ALTERATION PROCEDURES.

III-3.1 General. During ladle life, repair and alteration by the user may be required to maintain serviceable conditions and to maintain the structural integrity of the ladle. It is important to distinguish between a ladle repair and a ladle alteration.

A repair constitutes a rework of the ladle in order to maintain the structural integrity of the various ladle components. A repair is defined as a rework of the ladle without deviation from the original ladle design.

An alteration can be either a form of rework in which a structural component of the ladle is changed from the original specified geometry, or a change in the ladle operating conditions, such as changing from ingot teeming to continuous casting.

III-3.2 Procedure for Ladle Repair. A ladle repair may be made in the field by the ladle user or his agent. To make a satisfactory repair the following procedure is recommended:

- (1) The ladle user shall prepare a list of problem areas and operating restrictions.
- (2) The ladle manufacturer or qualified agent shall submit a rework plan to the ladle user for review and comment.
- (3) If the ladle manufacturer or qualified agent agrees the user has adopted an appropriate repair procedure, then the user can proceed with the proposed repair.
- (4) An inspection of the complete repair shall be made by the user or a qualified agent selected by the user. If the repair was made by a party selected by the user, the complete repair inspection results shall be made available to the repair party.

III-3.3 Procedure for Ladle Alteration. A ladle alteration may be made in the field by the ladle user or his agent. To make a ladle alteration the following procedure is recommended:

- (1) The ladle user shall prepare an outline of the proposed alteration.

- (2) The ladle manufacturer or qualified agent shall perform a structural analysis of the alteration consistent with the requirements of these specifications. Complete structural details and requirements shall be determined by the analysis and made available to the user.

- (3) Following the analysis, the ladle manufacturer or qualified agent shall prepare a proposal which includes details of the alteration and follow the procedures recommended for ladle repair.

In the case where the alteration is a change in the operating condition and not a structural alteration, the ladle user shall review the change in the operating conditions with a ladle manufacturer or qualified agent to determine the impact of the operating conditions on the structural integrity of the ladle. If necessary the recommended alteration procedure shall be followed.

III-4 REPAIR AND MAINTENANCE DETAILS OF STRUCTURAL COMPONENTS.

III-4.1 General. The ladle shall be maintained such that the structural components can function as intended in the original design. The refractory linings shall be maintained such that the design temperatures for the ladle are not exceeded during typical ladle operations.

Hardships and difficulties in making field repairs may require alternate methods, techniques and procedures from those normally used in ideal fabrication shop environments.

Routine ladle inspections should be made as recommended in Section III-1. Ladle repairs shall be made according to the procedure defined in Section III-3. Nondestructive testing and inspection of the repair is recommended. Ladle repairs shall be made according to the following details.

III-4.2 Sidewall or Bottom Patch. The sidewall or bottom patch shall be made to replace severely distorted or buckled sections of the sidewall or bottom plate, as well as any portion of the sidewall or bottom plate in which the thickness is less than 70% of the original design thickness.

In the case of a molten metal break-out, the opening shall be enlarged to a distance of three times the plate thickness beyond the edge of the break-out. The patch and matching cut-out portion of the sidewall or bottom plate shall have rounded corners with a radius equal to or greater than 3 times the plate thickness. The patch plate shall be welded with a butt joint attained by double welding or other means which will result in the same quality of deposited weld on the inside and outside weld surface.

The patch plate material shall have a material specification number and grade equal to the original plate material.

Temporary or permanent patching through the use of overlapping patch plates attached with fillet welds is not recommended.

III-4.3 Closure of Vent Holes. The closure of existing vent holes is necessary where ladles will be exposed to vacuum in metallurgical stations.

Vent holes are typically 1/2 in. diameter on 9 in. centers. In order to provide adequate fill welds, the holes shall be enlarged to a minimum diameter equal to the plate thickness plus 1/4 in.

III-4.4 Repair of Welds. The repair of welds is necessary when the weld strength has deteriorated due to wear, corrosion or other causes resulting in loss of weld dimension or due to weld cracks and other signs of weld strength loss.

The existing weld should be removed, preferably by grinding, and replaced with a weld defined by the ladle design.

Preheat temperatures and post weld heat treatment shall be imposed based on the criticality of the weld, the thickness of material being welded, and other factors of the repair.

III-4.5 Crack Repair. Temporary crack repair shall be made by drilling holes at the ends of crack tips. The diameter of the drilled holes shall be equal to the thickness of the plate or the thickness of the material measured parallel to the crack tip.

The hole drilling technique is a temporary repair used only to curtail the crack growth. When the holes are drilled, immediate plans should be made to make permanent repair of the crack.

Permanent crack repair shall be made by either removing the cracked section and replacing with patch plates, or by complete gouging and grinding of the cracked section and replacement of the removed material with weld deposits.

III-5 ALTERATIONS TO LADLES.

III-5.1 General. Existing ladles may need to be altered to accommodate changed operating requirements. Alterations require the evaluation of the structural integrity of the ladle and shall be made according to the procedure defined in Section III-3. Nondestructive testing and inspection of the alteration is recommended. The following details are defined for each alteration.

III-5.2 Additional Freeboard. Additional freeboard requires the vertical extension of the sidewall, either above the upper stiffener band or below the bottom stiffener band. The freeboard plate shall have a material specification equal to the existing sidewall plate, and may be attached to the upper sidewall by a riveted or bolted lap connection joint or by a full penetration butt weld joint.

III-5.3 Slide Gates. The addition of slide gates to the ladle bottom typically involves modification of the ladle bottom. For the ribbed ladle bottom, ribs may be relocated requiring a complete evaluation of the strength of the modified ribs. For reinforcement of the opening in the ladle bottom, see Section I-4.4.

III-5.4 Sidewall and Bottom Plate Openings. The addition of openings in the sidewall or bottom plate may be required for the use of gas injection systems or other clean steel equipment. Square or rectangular openings with sharp corners are not recommended.

The major axis of elliptical or obround openings shall not exceed 1 1/2 times the minor axis of the opening.

For reinforcement provided around the opening, see Section I-4.4. Reinforcement is not required for openings which are equal to or smaller than a 2 in. pipe size.

The inside edge of the opening shall be ground smooth to remove all rough edges, burrs, sharp notches and irregular surfaces.

PART IV: USE OF LADLES

IV-1 RECOMMENDED OPERATING PRACTICES FOR MINIMIZATION OF SHELL FLEXING.

In ladle metallurgy systems, the ladle is exposed to long molten metal hold times and continuous high ladle temperatures. The ladle is actually a vessel of which the shell is a composite structure composed of refractory material and steel. Failure in any portion of the composite shell can result in a 'break-out' of the molten metal. The following recommendations are made to assist in the reduction of ladle flexing and, therefore, reduction of probability of premature failure of the composite shell structure.

(1) Minimization of the number of ladle lifts and set-downs for a ladle full of molten metal. In ladle metallurgy, a considerable number of ladle lift and setdown requirements are imposed on the ladle while full of molten metal, resulting in increased ladle flexing. It is recommended that the amount of flexing be reduced for a full ladle by minimizing the number of ladle lifts and setdowns.

(2) Use of a ladle stand. A ladle full of molten metal should be set down on a ladle stand (set on trunnion blocks) and not on the ladle bottom supports. Setting a ladle full of molten metal on a ladle stand will minimize ladle flexing and resulting mechanical deterioration of the wall refractory lining.

(3) Check stiffness of existing ladles. Upgrade, if necessary, the size of the upper and lower stiffener bands to satisfy the deflection index criteria in Section I-11 of this specification. This will reduce ladle flexing.

(4) Use an adequate lining insulation. Shell temperatures must be low enough to develop sufficient thermal expansion restraint on the hot face of the working lining. The thermal restraint on the working lining hot face provides a mechanical seal against molten metal breakout.

(5) Apply proper design practice to temporary lining. If the design of an existing ladle does not satisfy deflection index requirements it may be necessary to minimize the sidewall plate temperature by increasing the insulating capacity of the sidewall refractory lining design and eliminating the use of expansion allowance material. This results in a higher thermal restraint imposed on the refractory lining by the sidewall plate and additional mechanical seal to resist molten metal breakout.

This lining design practice should be considered temporary until the ladle stiffness is upgraded to the requirements in (Section I-10 and Section I-11) of this report, as it may result in undesirable deformation in the sidewall plate, resulting in lining installation difficulty as well as deterioration of the sidewall plate. If the temporary lining practice is used, it is important to use gradual heat-up rates as defined in Section II-2 of this specification.

(6) Maintain a hot ladle lining. Maintenance of working lining hot face temperature is recommended through the use of ladle heaters and ladle lids.

As defined in recommendations (4) and (5), the mechanical seal at the working lining hot face resists the molten metal from penetrating the wall lining. If the hot face is allowed to cool significantly prior to tapping into the ladle, the hot face joints will open allowing molten metal to penetrate the joints. By repeating this undesirable practice, the joints will rapidly deteriorate leading to loss of the mechanical seal and molten metal breakout.

IV-2 BRIMFUL LADLE.

In this specification, the loading of a ladle to 'brimful' (ladle filled to the top with molten metal) is considered to be an infrequent occurrence and to be used only in an emergency situation. It is recommended that steelmaking practices be developed to minimize or avoid the brimful condition. When the brimful condition does arise, the ladle should be emptied immediately using safe established procedures.

IV-3 LIP POURING CONSIDERATIONS.

Pouring the contents of a ladle over the lip of the ladle wall* is considered an emergency operation. When necessary to practice, the operator shall insure that the contents of the ladle, both steel and slag, are in the liquid phase. Frozen crusts and floating solid masses impede the free fluid flow over the lip and could cause dangerous splashes.**

If the User recognizes that lip pouring must be a normal part of the operation, modifications shall be required to the ladle design to protect the ladle structure and insure its stability.

* after the metal has been held for a considerable duration

** This is particularly true for teeming ladles due to the unconstrained nature of the pouring stream.

SYMBOLS — Part I

A_B	= Effective area of bottom band, in. ² (Eqs I-38a, I-38b)	D_B	= Bearing diameter of trunnion pin, in. (Fig. I-5a, Eq I-17)
A_L	= Cross-sectional area of support leg, in. ² (Eqs I-54a, I-54c)	D_E	= An equivalent diameter for oval ladle bottom plate, in. (Eq I-20)
A_n	= Minimum net effective cross-sectional area in sidewall plate and buttstrap plate shall be equal to the plate thickness times the minimum net width, in. ² (Eq I-52)	D_H	= Diameter of trunnion pin, in. (Figs. I-5a, I-5b)
A_r	= Area of driven rivet, in. ² (Eqs I-18b, I-51)	D_d	= Extension of link pin beyond pin hole, in. (Fig. I-18)
A_T	= Effective area of top band, sq in. (Eqs I-37a, I-37b)	D_h	= Outer diameter of eyebar, in. (Fig. I-17)
A_w	= Cross-section of ladle sidewall measured adjacent to the bottom plate, in. ² (Eq I-51)	D_l	= Depth of rib at midspan cross-section (minimum depth for dished circular bottom plate with ribs), in. (Eqs I-24a, I-25a)
a	= Distance between lifting hook centerlines, in. (Figs. I-6, I-7, Eq I-32a); also area, in. ² (Example A1 and A2)	$D_{\max}$	= Maximum diameter of bottom plate, oval ladle, in. (Figs. I-6, I-7, Eqs I-20, I-23a)
a'	= Center to center distance of stiffener ribs for bottom plates, in. (Figs. I-8, I-9a, Eqs I-21, I-24b, I-25b, I-26b)	$D_{\min}$	= Minimum diameter of bottom plate, oval ladle, in. (Figs. I-6, I-7, Eqs I-20, I-23a)
B_1	= Width of thicker portion of stiffener band, in. (Fig. I-11)	D_{ph}	= Pin hole diameter in plate link or eyebar, in. (Figs. I-17, I-18)
B_2	= Width of thinner portion of stiffener band, in. (Fig. I-11)	D_p	= Pin diameter, in. (Figs. I-17, I-18)
b_1	= Effective width of the thicker portion of sidewall acting with stiffener band, in. (Eqs I-28, I-29)	D_t	= Width of plate extension on plate link, in. (Fig. I-18)
b_2	= Effective width of the thinner portion of sidewall acting with stiffener band, in. (Eqs. I-28, I-30)	$D_{wr(\max)}$	= Inside diameter of worn lining at top of an oval or obround ladle as defined by the length between the mid-total thickness center lines of its new refractory measured at the long axis at the top of the ladle, in. (Eq I-1)
b_e	= Sidewall effective width acting with band, in. (Eqs I-27, I-28)	$D_{wr(\min)}$	= Inside diameter of the worn lining at the top of a ladle as defined by the diameter of the mid-total thickness center line of a new ladle lining of a circular ladle, or the length between the mid-total thickness center lines of the new ladle lining measured at the short axis at the top of an oval or obround ladle, in. (Eq I-1).
b_r	= Width of band, in. (Eqs I-27, I-28)	d	= Reinforcing plate diameter in circular ladle, in. (Fig. I-6)
C	= A constant (Eqs I-31, I-32a, I-32b)	$d_{\max}$	= Maximum diameter of reinforcing bottom plate for oval ladle, in. (Fig. I-6)
C_D	= Deflection coefficient (Table I-8, Eq I-41)	$d_{\min}$	= Minimum diameter of reinforcing bottom plate for oval ladle, in. (Fig. I-6)
C_R	= Constant to modify minimum plate thickness reflecting the type of joint connecting the bottom plate to the sidewall plate (Eqs I-40a, I-40b)	d_n	= Diameter of nozzle opening, in. (Figs. I-2a, I-2b)
c	= Horizontal distance from vertical centerline through trunnion pin to the section of interest, in. (Fig. I-10, Eq I-33)	d_r	= Diameter of hole for driven rivet, in. (Eq I-18b and Section I-13.3)
D	= Bottom plate diameter in circular ladle, in. (Fig. I-6, Eqs I-18a, I-19, I-40a, I-40b, I-40c)	E	= Modulus of elasticity, ksi (Eq I-41)
D_A	= Diameter of nozzle opening reinforcing plate, in. (Fig. I-2a)		

C_2	= Distance from the centerline of the ladle hook (positioned for lifting as far from the body of the ladle as permitted by the geometry of the trunnion pin) to the centerline of trunnion block on trunnion axis, in. (Figs. I-5a, I-5b, Eqs I-17, I-17a, I-17c)	f_B	= Average bearing stress between the trunnion pin and trunnion block, ksi (Eqs I-17, I-17c)
C	= Offset distance between centerline of sidewall plate and centerline of bottom plate, in. (Fig. I-1a)	f_b	= Actual bending stress, ksi (Eqs I-8, I-17a, I-24b, I-24c, I-25b, I-25c, I-26b, I-26c, I-48b, I-48d)
H	= Vertical offset between the dished plate/knuckle tangent point and the neutral axis of the T beam at the midspan cross-section, in. (Fig. I-9b, Eq I-25b)	f_I	= Stress in the inside surface of band, ksi (Eqs I-36b, I-37b, I-38b)
F	= Distance of sidewall plate full penetration weld from edge of stiffener band, in. (Eq I-39)	f_O	= Stress in the outside surface of band, ksi (Eqs I-36a, I-37a, I-38a)
B	= Force in bottom band, kips (Eqs I-32b, I-35, I-38a, I-38b, I-44)	f_s	= Actual shear stress, ksi (Eqs I-48c, I-48d)
D	= Maximum hook load on tilt mechanism during slag dumping, kips (Fig. I-16, Eq I-47)	G	= Load centroid distance ratio (Fig. I-12, Eq I-32a)
H	= Horizontal component of loading on support leg, kips (Figs. I-20, I-21)	g	= Vertical distance between top band and bottom band centerlines, in. (Figs. I-5a, I-10, Eq I-17a)
HP	= Horizontal component of the spherical membrane force in the dished plate; located at tangent of dished plate and knuckle (Fig. I-9b)	g'	= The greater of g_T or g_B (Eq I-17a)
S	= Maximum hook load on tilt mechanism during deslagging, kips (Fig. I-15, Eq I-46)	g_T	= The distance from the centerline of the trunnion pin to the centerline of the top band, in. (Figs. I-10b, I-10d)
T	= Force in top band, kips (Eqs I-32a, I-32b, I-33, I-34, I-37a, I-37b, I-44)	g_B	= The distance from the centerline of the trunnion pin to the centerline of the bottom band, in. (Figs. I-10b, I-10d)
V	= Vertical load on support leg equal to one-half the total design service load of ladle, kips (Figs. I-20, I-21, Eqs I-54a, I-54b, I-54c, I-55b, I-55c, I-55d)	g_a	= Transverse spacing (gage) of the same two holes, in. (Fig. I-19, Section I-13.5)
F_d	= Fabrication derating factor (Tables I-3, I-4, I-5, I-6, Eqs I-2, I-3, I-9a, I-9b, I-10, I-12, I-13)	H	= Vertical height of the ladle, in. (Figs. I-6, I-7, Eqs I-18a, I-18c, I-19, I-22a, I-22b, I-23a, I-23b, I-24a, I-24b, I-25a, I-25b, I-26a, I-26b, I-40a)
I	= Impact factor (Eqs I-2, I-3, I-12, I-13)	h	= Artificial ladle height, in. (Section I-5.1)
T_d	= Temperature derating factor (Tables I-1, I-2, and Eqs I-2, I-3, I-9a, I-9b, I-10, I-12, I-13)	h_B	= Vertical distance between bottom stiffener band centerline and juncture of ladle bottom and sidewall, in. (Figs. I-6, I-7, Eqs I-31, I-32a, I-42, I-43)
F_{d1}	= Components of fabrication derating factor as defined in Section I-5	h_T	= Vertical distance between top band centerline and juncture of ladle bottom and sidewall, in. (Figs. I-6, I-7, Eqs I-31, I-32a, I-42, I-43)
σ	= Actual normal stress, ksi (Eqs I-8, I-24a, I-24c, I-25a, I-25c, I-26a, I-26c, I-48a, I-48d)	h_{TR}	= Vertical distance between trunnion axis and juncture of ladle bottom and sidewall, in. (Figs. I-6, I-7, Eqs I-42, I-43)
		I_B	= Moment of inertia of effective bottom band, in. ⁴
		I_{B1}	= Moment of inertia of effective bottom band at trunnion axis, in. ⁴ (Eq I-42)
		I_{B2}	= Moment of inertia of effective bottom band at the cross axis, in. ⁴ (Eqs I-31, I-43)
		I_T	= Moment of inertia of effective top band, in. ⁴
		I_{T1}	= Moment of inertia of effective top band at trunnion axis, in. ⁴ (Eq I-42)

$I_{/2}$	= Moment of inertia of effective top band at the cross axis, in. ⁴ (Eqs I-31, I-43)	N_m	= Number of rivets in top row of annulus area (Eq I-18b)
I_1	= Moment of inertia of the effective band at trunnion axis (for deflection index calculation), in. ⁴ (Table I-4, Fig. I-13, Eq I-42)	N_t	= Number of required rivets on one side of the connection (Eq I-51)
I_2	= Moment of inertia of the effective band at cross axis (for deflection index calculation), in. ⁴ (Table I-4, Fig. I-13, Eqs I-41, I-43)	P	= Effective radial force applied at trunnion pin, kips (Fig. I-13, Eqs I-41, I-44)
J	= Distance from the trunnion axis along the longitudinal axis of the ladle (vertical when untilted) to the point of intersection with the vertical line through the center of gravity of the tilted ladle and its contents, ft (Fig. I-4)	q	= Density of molten metal, kips/ft ³ (Eqs I-1, I-18a, I-18c, I-19, I-22a, I-22b, I-23a, I-23b, I-24a, I-24b, I-25a, I-25b, I-26a, I-26b, I-40a)
j	= Minimum distance between the trunnion axis and center of gravity of the full untilted ladle such as to provide static and dynamic stability in all positions, ft (Fig. I-4, Eq I-1)	R_B	= Dish radius in dished bottom, in. (Fig. I-7, Eqs I-22a, I-22b, I-23a, I-23b, I-24a, I-25a, I-25b, I-26a)
k	= Inner distance of two inner vertical ribs, in. (Fig. I-5b, Eq I-17c)	R_M	= Radius to top row of rivets of annulus area (Eqs I-18b, I-18c)
L	= The maximum span of stiffener ribs in bottom plate, in. (Eqs I-21, I-25b)	R_{M-1}	= Radius to bottom row of rivets of annulus area (Eq I-18b)
L_A	= Maximum support leg length necessary to provide appropriate clearance under ladle, in. (Figs. I-20, I-21, Eqs I-54b, I-54c, I-55c, I-55d)	R_R	= Minimum effective band radius R_{RT} or R_{RB} of whichever band is analyzed (Fig. I-10a)
L_B	= Required support leg length to transition around the knuckle region of the bottom plate, in. (Fig. I-20)	R_{RB}	= Minimum effective radius of bottom band, in. (Fig. I-10a, Eqs I-31, I-35, I-45)
L_c	= Length of support leg actually connected to sidewall plate, in. (Figs. I-20, I-21, Eq I-55a)	R_{RM}	= Average minimum effective radius of top and bottom band, in. (Table I-4, Fig. I-13, Eqs I-41, I-45)
L_c'	= Component leg length required for vertical force F_v , in. (Fig. I-21, Eqs I-55a, I-55b)	R_{RT}	= Minimum effective radius of top band, in. (Fig. I-10a, Eqs I-31, I-33, I-34, I-45)
L_c''	= Component leg length required for horizontal force in the plane of support leg and sidewall plate, in. (Fig. I-21, Eqs I-55a, I-55c)	R_S	= Minimum radius to middle plane of sidewall at a band, in. (Eqs I-27, I-29, I-30, I-39)
L_c'''	= Component leg length required for horizontal force normal to sidewall plate, in. (Fig. I-21, Eqs I-55a, I-55d)	R_{SM}	= One-half of the minimum mid-height distance between middle planes of opposite sidewalls, in. (Figs. I-12, I-13, Eq I-32a)
l	= One half the distance between radius points of end segments in an oval ladle, in. (Table I-4, Figs. I-6, I-7, I-10a, I-12, Eq I-33)	$R_{S(max)}$	= Maximum radius to middle plane of sidewall at bottom section in. (Figs. I-6, I-7, I-12)
M_{B2}	= Moment in bottom band at cross axis, kip-in. (Eqs I-35, I-38a, I-38b)	$R_{S(min)}$	= Minimum radius to middle plane of sidewall at bottom section, in. (Figs. I-6, I-7, I-12, Eqs I-22a, I-23a)
M_{T1}	= Moment in top band at trunnion axis, kip-in. (Eqs I-33, I-36a, I-36b)	R_t	= Transition radius in eyebar, in. (Fig. I-17)
M_{T2}	= Moment in top band at cross axis, kip-in. (Eqs I-34, I-37a, I-37b)	r	= Fillet radius, in. (Fig. I-5a)
m	= Distance from inside shell surface to outside of vertical ribs, in. (Fig. I-5b, Eq I-17c)	r_m	= Mid-thickness radius of support leg wall, in. (Fig. I-21, Eq I-55c)
		S	= The greater section modulus of the T beam section of stiffener ribs in the bottom plate, in. ³ (Eq I-21)
		S'	= The section modulus (maximum and minimum) of the midspan cross-section of the T beam, in. ³ (Eq I-25b)
		S_1	= Section modulus of the combined shell and trunnion block at the point of interest such as Point C in Fig. I-10d, in. ³ (Fig. I-10d, Eqs I-17a, I-17b)

S_2	= Section modulus of the combined shell and ribs (shown as shaded area in Fig. I-5b) in. ³ (Fig. I-5b, Eq I-17c)	t_T	= Combined thickness of trunnion block and sidewall, in. (Fig. I-5a, Eqs I-17, I-17b)
S_{BI}	= Section modulus for the inside surface of the bottom band, in. ³ (Eq I-38b)	W	= Total weight of a brimful ladle including molten metal, worn lining (defined as the condition at which half the total new wall refractory thickness has eroded and the full bottom thickness is intact), ladle steelwork, and ladle lid if applicable, kips (Eq I-1)
S_{BO}	= Section modulus for the outside surface of the bottom band, in. ³ (Eq I-38a)	W_2	= Total weight of ladle (design weight of molten metal, slag, ladle steelwork, refractory lining and ladle lid), kips (Eqs I-17, I-17a, I-17c, I-32a, I-40b, I-40c, I-52)
S_L	= Section modulus of support leg, in. ³ (Eqs I-54b, I-54c)	W_D	= Molten metal design weight, kips (Fig. I-15, Eq I-46)
S_p	= Longitudinal spacing (pitch) of any two successive holes, in. (Fig. I-19, Section I-13.5)	W_d	= The structural weight of the ladle steelwork and full lining, kips (Figs. I-15, I-16, Eqs I-46, I-47)
S_{TI}	= Section modulus for the inside surface of the top band, in. ³ (Eqs I-36b, I-37b)	W_e	= Width of bar portion of plate link or eyebar, in. (Figs. I-17, I-18)
S_{TO}	= Section modulus for the outside surface of the top band, in. ³ (Eqs. I-36a, I-37a)	W_S	= Skull load attached to ladle bottom equal to 10% of the molten metal design weight, kips (Fig. I-16, Eq I-47)
$(SF)_u$	= Safety factor against ultimate strength (Eqs I-2, I-12)	w	= Net width of trunnion block at the point of interest, in. (Fig. I-10, Eq I-17b)
$(SF)_y$	= Safety factor against yielding (Eqs I-3, I-13)	w_a	= Moment arm for W_d load, in. (Fig. I-15, Eqs I-46, I-47)
T_A	= Thickness of nozzle opening reinforcing plate, in. (Fig. I-2a.)	w_b	= Moment arm for W_D load, in. (Fig. I-15, Eq I-46)
T_A'	= Thickness of nozzle opening reinforcing plate, in. (Fig. I-2b)	w_c	= Moment arm for F_S load, in. (Fig. I-15, Eqs I-46, I-47)
T_B	= Thickness of bottom plate, in. (Figs. I-1a, I-2a, I-2b, I-6, I-7, I-8, Eqs I-18a, I-18c, I-19, I-21, I-22a, I-22b, I-23a, I-23b, I-24a, I-24b, I-26a, I-26b)	w_d	= Moment arm for W_S load, in. (Eq I-47)
T_B'	= Effective plate thickness of the dished circular bottom plate in the direction of the ribs, in. (Eqs I-24a, I-25a, I-26a)	y	= Offset distance between sidewall plate and bottom plate, in. (Fig. I-1)
T_I	= Thickness of rib, in. (Eqs I-24a, I-25a)	Z	= Transition length between thicker and thinner portions of stiffener band, in. (Fig. I-11)
T_L	= Thickness of support leg wall, in. (Figs. I-20, I-21, Eqs I-55b, I-55c, I-55d)	z	= Transition length for offset y between sidewall plate and bottom plate, in. (Fig. I-1)
T_R	= Thickness of bottom reinforcing plate, in. (Fig. I-6, Eqs I-18c, I-19)	β	= Angle at which effective band moment of inertia changes from I_1 to I_2 , degrees (Fig. I-13)
t	= Thickness of sidewall plate, in. (Figs. I-1a, I-5b, I-6, I-7, Table I-3, Eqs I-17c, I-27, I-39, I-40c)	λ	= Deflection index for combined top and bottom stiffener bands (Eq I-41)
t_1	= Larger effective thickness of sidewall in. (Eq I-29)	σ_a	= Allowable normal stress, ksi (Table I-3, Eqs. I-4, I-5a, I-6, I-7, I-8, I-11, I-18a, I-19, I-22a, I-22b, I-23a, I-23b, I-24a, I-24c, I-25a, I-25c, I-26a, I-26c, I-40a, I-40b, I-48a, I-48d, I-49, I-50, I-51, I-52, I-53, I-54a, I-54c)
t_2	= Smaller effective thickness of sidewall, in. (Eqs I-29, I-30)		
t_e	= Thickness of plate link or eyebar, in. (Figs. I-17, I-18)		
t_{min}	= Minimum supplementary sidewall thickness, in. (Eqs I-40a, I-40b)		
t_r	= Effective thickness of ribbed block as calculated by Eq I-17c, in. (Fig. I-5b, Eq I-17c)		

σ'_{ai}	= Allowable normal tension stress on the effective net area of the pin-connection member, ksi, (Eq I-49)	σ_{du}	= Allowable total stress based on minimum ultimate strength, ksi (Eq I-9a)
σ'_{ah}	= Average normal tensile stress in the minimum net effective area of the rivet connection plate, ksi (Eq I-52)	σ_{dy}	= Allowable total stress based on minimum yield strength, ksi (Eq I-9b)
σ_{au}	= Allowable normal stress based on minimum ultimate strength, ksi (Eq I-2)	σ_{dl}	= Allowable total stress when the working lining expansion forces are included, ksi (Table I-5, Eq I-10)
σ_{ay}	= Allowable normal stress based on minimum yield strength, ksi (Eq I-3)	σ_p	= Allowable bending stress in trunnion pin with protective bushings, ksi (Eq I-14)
σ_b	= Allowable bending stress, ksi (Table I-6, Eqs I-4, I-5a, I-5b, I-8, I-14, I-15, I-16a, I-24b, I-24c, I-25b, I-25c, I-26b, I-26c, I-48b, I-48d, I-54b, I-54c)	σ_s	= Allowable shear stress, (excluding welds and rivets), ksi (Eqs I-11, I-15, I-16b, I-48c, I-48d, I-55b, I-55c, I-55d)
σ_{bc}	= Allowable bending stress in compression, ksi (Eq I-7)	σ_u	= Minimum ultimate strength at room temperature, ksi (Eqs I-2, I-9a, I-12)
σ_{bh}	= Allowable bearing stress imposed by the rivets on the sidewall plate, ksi (Eq I-53)	σ_w	= Average normal stress in sidewall, ksi (Eq I-40c)
σ_{br}	= Allowable average bearing stress, ksi (Eqs I-5b, I-16a, I-50)	σ_y	= Minimum yield strength at room temperature, ksi (Eqs I-3, I-9b, I-10, I-13, I-16b)
σ_{bt}	= Allowable bending stress in tension, ksi (Eq I-6)	ϕ	= $\sin^{-1} \left(\frac{R_{S(\min)}}{R_B} \right)$ (Eqs I-22a, I-23a)
σ_{bu}	= Allowable bending stress based on minimum ultimate strength, ksi (Eq I-12)	τ_1	= Maximum unit shear stress in plate, ksi (Eqs I-18b, I-18c)
σ_{by}	= Allowable bending stress based on minimum yield strength, ksi (Eq I-13)	τ_2	= Shear stress in rivet, ksi (Eq I-18b)
σ_d	= Allowable total stress, ksi (Table I-4)	τ_r	= Allowable shear stress for rivet, ksi, defined in Section I-5.6 (Eq I-51)

SYMBOLS — Part II

E_s	= Modulus of elasticity of ladle sidewall plate, ksi (Eq II-1b)		mal expansion between the working lining and the sidewall, ksi (Eqs II-1b, II-1c)
E_{wl}	= Average modulus of elasticity of wall working lining refractory, ksi (Eq II-1b)	q_B	= Density of expansion allowance material, lb/ft ³ (Fig. I-3, Eq II-5)
f_{ex}	= Circumferential stress in ladle sidewall plate resulting from thermal expansion of the wall working lining refractory, ksi (Eq II-1c)	R_{HF}	= Hot face radius of wall working lining, in. (Fig. II-1, Eqs II-3a, II-3b)
$L_{70.D}$	= Axial length of 70% alumina or resin-bonded dolomitic wall working lining, in. (Eq II-4a)	$R_{\max(ave)}$	= Maximum average radius of sidewall plate of oval or obround ladle, in. (Eq II-2a)
L_{MC}	= Axial length of direct-bonded mag-chrome wall working lining, in. (Eq II-4b)	$R_{\min(ave)}$	= Minimum average radius of sidewall plate of oval or obround ladle, in. (Eq II-2a)
P_B	= Percent of compressibility of expansion allowance material (Eqs II-5, II-6)	$R_{s(ave)}$	= Average radius of sidewall plate, in. (Eqs II-1a, II-1b, II-1c)
p	= Effective radial pressure applied to the ladle sidewall plate caused by the differential thermal expansion between the working lining and the sidewall, ksi (Eqs II-1b, II-1c)	$R'_{s(ave)}$	= Effective average radius of sidewall plate of obround or oval ladle, in. (Eq II-2a)
		R_{wl}	= Mid-thickness radius of wall working lining, in. (Eqs II-1a, II-1b)

R'_{wl}	= Effective mid-thickness radius of wall working lining, of obround or oval ladle, in. (Eq II-2b)	Z_A	= Amount of axial expansion allowance for wall lining, in. (Eqs II-4a, II-4b)
$R_{wmax(ave)}$	= Maximum average mid-thickness radius of working lining of oval or obround ladle, in. (Eq II-2b)	Z_R	= Amount of radial expansion allowance on the cold face side of the wall working lining, in. (Table II-1, Eqs II-3a, II-3b, II-6)
$R_{wmin(ave)}$	= Minimum average mid-thickness radius of working lining of oval or obround ladle, in. (Eq II-2b)	α_s	= Linear coefficient of thermal expansion of the ladle sidewall plate, in./in. °F (Eq II-1a)
T_b	= Thickness of expansion allowance material behind working lining, in. (Fig. II-1, Eq II-6)	a_{wl}	= Linear coefficient of thermal expansion of the wall working lining, in./in. °F (Eq II-1a)
T_{EM}	= Thickness of expansion allowance material beneath lip ring, in. (Fig. II-2)	$\Delta\theta_s$	= Increase in ladle sidewall plate temperature from ambient temperature, °F (Eq II-1a)
t	= Thickness of ladle sidewall plate, in. (Eqs II-1b, II-1c)	$\Delta\theta_{wl}$	= Increase in wall working lining mid-thickness temperature from ambient temperature, °F (Eq II-1a)
t_{wl}	= Thickness of wall working lining refractory, in. (Eq II-1b)	δ	= Interference applied to the ladle sidewall resulting from differential expansion of wall working lining and ladle sidewall, in. (Eqs. II-1a, II-1b)

COMMENTARY

The following commentary on AISE Technical Report No. 9, Specifications for Design and Use of Ladles, is referenced to the various sections of the report. The comments herein are not part of the specifications but are added as supplementary information to expand upon certain sections. Numerals in parentheses refer to the section number in the text. The formulae presented in Part II are the best available at the time of publication. Revisions will be issued as additional information becomes available.

General (I-1.1). Part I of these specifications is primarily concerned with ladle design and has been updated to reflect the impact of the new operating environments¹⁰ resulting from clean steel and continuous caster practices. Stiffer, stronger wall working lining refractories and longer processing and hot metal hold time in the ladle have brought about an increased concern over the structural integrity of the ladle. As a result of this concern and the central role the ladle plays in iron and steelmaking, Part I has been updated in the areas of design detail, connection requirements, allowable stresses and various other related structural items.

Specific Assumptions (I-1.3). Ladles designed to these specifications should be repaired, reinforced or retired whenever necessary for continued conformity to this report.

Materials (I-3). Materials specified for the construction of ladles have been updated for various temperature ranges, including operating temperatures exceeding 650°F.

Ladle Bottoms (I-4.2). Case history studies have indicated that the juncture between the ladle bottom and sidewall is exposed to high stress conditions inducing undesirable effects such as yielding and cracking. Stiffer working linings and sustained processing temperatures, typically used with clean steel and continuous caster practices, are some of the primary contributing factors to the high stress conditions. For these high stress conditions, Section I-4.3 is recommended for ladle bottom design.

Continuous Caster and Clean Steel Ladles (I-4.3).

In most dished bottom ladles the bottom plate is typically thicker than the sidewall plate. The use of a taper between connecting plates is required due to the higher expansion stresses resulting from the use of a stronger working lining. A three to one taper is consistent with the ASME Code, Section VIII, Divisions 1 and 2, and greatly reduces stress concentration effects at this connection.

Reinforcement for Nozzle Openings (I-4.4). Previous recommendations are contained in this section which include alternate designs for reinforced openings in the bottom plate. These designs are based partially on finite element thermal analysis on the nozzle opening areas.

Where nozzle openings are provided, the bottom plate immediately surrounding the opening should be reinforced by a doubler plate or equivalent metal replacement. An adapter plate can be considered for reinforcement provided it is attached properly, is of sufficient section to replace the metal removed, and the method of such calculations conforms with the procedures defined in Section I-4.4.

Since the bottom plate segments near the trunnion axis plane are stressed higher than those 90 degrees away from the trunnion axis, it is suggested that the location of nozzle openings be within 60 degrees from the ladle cross axis, and preferably be placed as near as possible to the 90 degree plane from the trunnion axis.

As a result of the higher expansion forces resulting from the use of stronger working linings, square or rectangular openings with sharp corners are not recommended. Circular, elliptical or obround openings are recommended since they typically have less stress concentration effects in the ladle shell plate.

Lap Riveted Connections (I-4.5.1). It is recognized that rivet connections are no longer as popular as welded connections. However, if riveted connections are selected by the user it is important that the connection strength equals the plate strength. This avoids the working lining expansion displacements from being concentrated at the more flexible (weaker) riveted connection. With a riveted connection strength equivalent to the plate strength, the working lining expansion displacements are equally distributed throughout the riveted connection and plate.

The distances between rivet holes and the edge distance are defined by structural codes (such as AISC Specification) which typically do not consider temperatures that are significantly above ambient. Therefore the reduced strength of the ladle structural steel at higher operating temperatures is factored into the rivet spacing and edge distance.

Stress Relieved Welds (I-4.6). The requirements for preheat and interpass temperatures, as well as stress relieving, have been specified to comply with the ASME Code, Section VIII, Division 1.

Vent Holes (I-4.10). Vent or weep holes are to be provided according to the user's request on the OIS. If the user needs to maintain a vacuum on the ladle during clean metal processing, then vent holes may not be required. However, without vent holes longer curing time is required for a newly relined ladle.

Design Assumptions and Allowable Stresses (I-5). The design weights included in the ladle design have been updated to include additional freeboard, ladle lid and other load environments which may impose additional weight on the ladle beyond the typical weight considerations of ladle shell, refractory and hot metal. The user of the ladle is required to define all load environments to the ladle

manufacturer such that the ladle will be designed for the complete operating conditions.

The allowable total stress which includes weight stresses, thermal stresses, other secondary stresses and discontinuity stresses is reduced if the thermal expansion stresses include the wall working lining expansion stresses (described by Eq I-10). However, the ladle user is responsible for the lining design, the preheating rate and other factors relating to ladle shell stresses that result from the expansion of the working lining. Therefore, Eq I-10 is provided for the convenience of the ladle user in designing the refractory lining.

Eq I-9a and Eq I-9b are used only if the thermal stresses in the ladle structure are not a result of the wall working lining thermal expansion, where the allowable total stress can exceed the yield stress of the ladle structural material. However, with the higher allowable total stress, shakedown will occur within the first few loadings and plastic distortion will not continue in subsequent loadings. If the working lining is allowed to develop significant thermal stress in the ladle sidewall plate, beyond the allowable specified stress of Eq I-10, then shakedown will not occur. That is, each new working lining will continue to yield the sidewall plate resulting in a continued plastic distortion of the ladle sidewall plate. The allowable total stress defined by Eq I-10 will not allow continued distortion with each new load condition and each new relining.

Ladle Volume and Metal Density (I-5.2). Typical densities of molten metal shown in Fig. I-3 have been expanded to cover a broader range of carbon content and temperatures. The design equations include an actual density term, ρ . The actual density should be specified on the OIS by the purchaser.

Location of the Trunnion Axis (I-5.3). The equation, based on various analytical derivations, for locating the centerline of the trunnions specifies the minimum vertical distance for the trunnion axis to be located above the center of gravity of the ladle, including the refractory lining and contents, to prevent instability when the ladle is slightly tipped. This is a minimal recommendation and wherever practicable it is desirable to use a greater distance than that specified. The factor of safety (or ratio of restoring moment divided by overturning moment) depends on the refractory lining thickness, and is approximately equal to the fourth power of the ratio of the minimum diameter of the unlined ladle at the top divided by the minimum diameter of the inner surface of the ladle lining at the top.

Allowable Stresses in Ladle Components (I-5.4). The necessity for establishing the allowable stress based on both the yield strength and ultimate tensile strength arises from the fact that the yield strength of some materials, particularly the high strength steels, is closer to the ultimate strength than for others. Except for trunnion pins, the safety factors

recommended in this report are based on the ultimate/yield strength ratio of 1.667. For materials with this ratio (such as A 36, A 387 Class 1 Gr 2 and 12, A 387 Class 2 Gr 11, 21 and 22) the allowable stresses against both yield and ultimate strengths are identical. For a material whose ultimate/yield ratio exceeds 1.667 (such as A 285 Gr C, A 515, and A 516), the allowable stress is governed by the yield strength, while for materials with an ultimate/yield ratio below 1.667 (such as A 242, A 441, and A 387 Class 2 Gr 12), the allowable stress is governed by the ultimate strength.

The introduction of derating factors for fabrication and temperature in the determination of allowable stresses is an attempt to quantify the effect of various fabrication methods and operating temperature ranges on the ladle design. In the case of fabrication methods, different design requirements can arise between hot forming and cold forming, between flame straightening and other straightening procedures (such as removing distortion by cutting and rewelding), between welded, riveted and bolted construction, between circular and noncircular ladles, or between different plate surfaces (such as thermally cut, machined, plasma cut and sheared surfaces). The values recommended in this report are based on experimental investigations and engineering judgment. In the case of temperature, reliable quantitative information is available on the effect of temperature on yield strength and ultimate strength. The temperature derating factor (unity at room temperature) is approximately the ratio of the yield or ultimate strength at a particular elevated temperature to that at room temperature. Thus a designer needs to know only the room temperature properties of the materials, and the temperature derating factor will establish the temperature effect on the ladle design characteristics.

Similarly, the introduction of an impact factor in the allowable stress formulas would eliminate the need for calculating the dynamic stresses in the design of ladle components. The recommended magnitude of 20% impact is consistent with other AISE technical reports on the lifting devices which are used for handling ladles.

The calculated total stresses are considered to include the general membrane, local membrane and bending, and secondary membrane plus bending stresses. The allowable total stress specified in Section I-5.4.4 is three times the general allowable stress which is either five-eighths of the yield strength or one-fourth of the ultimate strength, whichever is less, modified by the appropriate temperature, impact and fabrication derating factors.

Fatigue Stress (I-5.4.6). The design considerations of Part I and the ladle lining recommendations of Part II of these specifications have been incorporated as a result of the severe environments imposed on the ladle by the clean steel ladle metallurgy practice, continuous caster practice and the user's desire for increased lining life with maximized volume.

If the ladle design and ladle operating conditions result in a need for fatigue analysis, the criteria of ASME Section VIII, Division 2 shall apply. However, the new design details have been incorporated in an attempt to reduce fatigue usage and to eliminate the need for fatigue analysis when ladles are exposed to the severe operating environments.

Allowable Stresses in Trunnion Pins (I-5.5). The safety factors for trunnion pins are based on the ultimate/yield strength ratio of 2.

Allowable Shear Stresses in Rivets (I-5.6). This section specifies the allowable shear stress for various rivet materials. The allowable levels are selected based on successful rivet design practice.

Allowable Shear Stress in Pins Of Tilt Mechanism (I-5.7). The specified allowable level is that specified in AISC Specifications and comparable to the ASME Code.

Design of Trunnion Block and Pin (I-6). Trunnion pins should be checked and measured for wear at least every six months.

The calculation of the section modulus of a worn trunnion pin should be based on a circle whose diameter is equal to the actual minimum diameter of the worn trunnion. Trunnion diameters should be measured at 45 degree intervals around the circumference, for comparison with a predetermined minimum dimension.

Trunnion pins should be inspected for cracks and abnormal defects at least annually by magnetic particle, ultrasonic, radiographic or dye penetrant test methods. The trunnion sleeve and its interface with the trunnion pin should also be checked for wear.

In redesigning existing trunnions to take sleeves, the trunnion pin diameter may be reduced to accommodate the sleeve provided that the maximum bending stress does not exceed the allowable stress specified in Section I-5.5.

New formulae have been added for calculating bending stresses in trunnion blocks (I-6.10) and bearing stresses in ribbed trunnion blocks (I-6.11).

Thickness of Circular Flat Bottoms (I-7.2). In this section, Eq I-18a is given for the thickness of flat bottom plates and has been derived from the bending theory of circular plates, considering the restraint of the sidewalls as having fully fixed edges. Eq I-18a has factored into the constant, 139, 95% of the ladle height H as the magnitude of the ferro-static pressure applied to the bottom of the ladle.

Reinforcing Plate (I-7.3). Formulas have been included to facilitate design calculations for the riveted reinforcing plate in a circular ladle. Similar methods can be used for an oval or obround ladle.

Eq I-19 has been derived from the circular flat plate bending theory considering the edge restraint of approximately 75% of full fixity. Eqs I-18c and I-19 have factored 95% of the ladle height H as the magnitude of the ferro-static pressure applied to the bottom of the ladle. Eq I-18c has been revised to include the average shear stress through the plate thickness.

Equivalent Diameter for Oval Ladles (I-7.5). A study of the bending of elliptical plates, together with the recognition that the flat portions of the ladle sidewalls offer much less bending restraint than the circular sections, showed that an equivalent diameter, equal to the average of the maximum and minimum diameters, could be used in Eqs I-18a and I-19.

Design of Bottom Plates of Dished Bottom Ladles (I-8). The equations for calculating the thickness of dished bottom ladles given in Section I-8 were obtained by a theoretical analysis of the local bending stresses at the juncture between the ladle bottom and sidewall. Eq I-22a and I-23a insure that the bending stress at the juncture is less than $3\sigma_a$. Eqs I-22b and I-23b insure that the normal stress in the dish is less than σ_a .

Stiffener Ribs for Dished Bottom Ladles (I-8.5 and I-8.6). The design procedure for the dished bottom ladle with ribs is similar to the design procedure for the flat bottom ladle with ribs. In the case of the dished bottom with a very large head radius, the behavior of the dished bottom with ribs and the flat bottom with ribs is very similar.

The shear plates are a vital part of the dished bottom with ribs. Shear plates cause working lining vertical expansion loads to be evenly distributed into the sidewall plate.

Design of Stiffener Bands (I-9). The notation used in the design of stiffener bands is given in Figs. I-6, I-7, I-10, I-11, I-12 and I-13. The design procedure is illustrated in Appendix A for ladle types shown in Figs. A1 and A17.

In Section I-9.8 a computation is not required for the bottom band at the trunnion because the results of an AISE ladle study^{1,2} showed that these stresses were less than at other locations. In addition, the bottom band is sometimes strengthened at this position in order that the ladle can be set in a ladle stand seat.

In this report the ladle lip ring is not considered as a structural member which provides additional strength to the ladle because, in practice, the lip ring frequently contains discontinuities such as pouring spouts and can be exposed to metal and slag splash.

Parameter G , the load centroid distance ratio, is used in Eq I-32a to facilitate the design of oval ladles with flat walls (obround ladles). A curvilinear relationship for determining the value of G is given in Fig. I-12.

Case history studies have shown that stiffener bands with offsets in the region of the trunnion blocks cause undesirable

stress concentrations and are more susceptible to cracking than stiffener bands with gentle transitions. The recommended transition detail for stiffener bands is intended to eliminate the undesirable stress concentrations.

Design of Sidewall Plates (I-10). This section includes thickness requirements of materials used at various temperature levels (Table I-7). Also, the range of plate thicknesses is given to include ladle capacities up to 480 short tons.

Minimum sidewall thicknesses have been established for various ladle capacities and operating temperatures in addition to the requirement that sidewall thicknesses should not be less than 0.75 times the required bottom plate thickness. The latter requirement is established to provide adequate restraint or fixity to the edge of the bottom plate, whenever the minimum allowed thickness is used.

The supplementary sidewall plate thickness equations (Eqs I-40a and I-40b) are updated to reflect the influence of riveted connections on the minimum plate thickness. If riveted connections are used, the minimum plate thickness is increased through the parameter C_R to reflect the plate material lost in the rivet holes. With full penetration butt weld connections no plate material is lost.

The sidewall plate transition between plates of different thicknesses is made with a taper as specified by the ASME Code, Section VIII, Division 1 and 2 (Fig. I-1b). The full penetration butt welds are to be located at a distance not less than the distance defined by Eq I-39. This removes the full penetration weld away from the region of high bending stress imposed on the sidewall plate by the restraint of the stiffener band.

Forward Deflection Stiffness at Trunnions (I-11). The purpose of this section is to provide a method for determining whether a ladle is sufficiently rigid to avoid excessive forward deflection at the trunnions. Experience has shown (in some cases) that cracks developed or a reduced lining life was encountered when the ladles were too flexible. The forward deflection of the ladle should be considered in the design of the stiffener bands, in addition to the stress conditions discussed in Section I-9. In general, the design of stiffener bands which meet the allowable stress requirements will also result in a design having satisfactory rigidity at the trunnions. In some cases, however, a redesign may be required even though the calculated stresses are within the specified limits.

The recommended deflection index equation, Eq I-41, has been checked against actual ladle designs using a wide range of clean steel practices by a number of steelmaking shops. Revised empirical limits have been specified for the circular, oval and obround ladle. These limits are based on examples which have been proved satisfactory in actual service and by analytical studies.

The deflection limits have been upgraded reflecting the need for stiffer ladles due to the more severe operating environments imposed on the refractory working linings by clean steel and continuous caster practices.

The deflection index equation has been revised and is expressed in terms of the radius of the deflecting section rather than in terms of the height of the deflecting section above the bottom plate.

The deflection coefficient in Table I-8 is based on the bending deflection of a circular or obround stiffener band with equal and opposite concentrated loads. The deflection coefficient for an oval stiffener band was also calculated and found to closely approximate the values shown. Thus, Table I-8 is applicable to both obround and oval bands, as well as circular stiffener bands. The equations used for calculating values for C_D (given in Table I-8) are summarized in Appendix B and may be used to calculate specific values of C_D instead of interpolated values.

Design of Tilt Mechanism (I-12). This section has been included to provide guidance in the design of a tilt mechanism for a steel ladle.

The tilt mechanism design uses well established design rules for pin-connected members. Other forms of structural members are acceptable; however, detailed stress analysis is required to make certain that allowable stress limits are satisfied. Chains and cables are not encouraged since they can become twisted, deformed and worn without visible evidence of loss in structural integrity.

The load conditions imposed on the tilt mechanism are compatible with clean steel and ladle metallurgy practices.

The bottom pivot plates are a critical part of the tilt mechanism. When adding a tilt mechanism to a ladle, a considerably thicker bottom plate or additional doubler plate may be required to attach the pivot plates to the ladle bottom plate without stiffener ribs. The use of stiffener ribs in the ladle bottom plate provides a compatible means of attaching the tilt mechanism.

Riveted Sidewall Circumferential Connection Joints (I-13). Previous field studies²⁰ have been made of existing ladles regarding strength in the riveted sidewall circumferential joints. The strength of the riveted connection should be equal to or greater than the sidewall plate strength.

It is recognized that riveted connections are used very infrequently in current ladle design; however, it is necessary to establish a design procedure in order to evaluate the adequacy of existing riveted connections, especially for ladles designated for clean steel and continuous caster practices.

Design of Support Legs for Dished Bottom Ladles (I-14). As a result of the use of slide gates and other necessary equipment on the dished bottom ladle, the use of three support legs has become a popular method of providing ladle bottom support.

The recommended location for the three support legs is at the periphery of the dished bottom. The location of a support leg in the spherical portion of the bottom plate is not recommended due to the resulting high shell stresses and shell displacements.

Each of the legs is effectively designed with a total vertical load of one half the total design weight of the ladle and a simultaneously applied horizontal load of one half the vertical load. In addition, an impact factor of 1.2 is inherent in the allowable stress. These considerations are primarily for the initial setdown condition of the ladle.

Assembling and Welding Ladles in the Shop and Field (I-15). This section is based on the consensus of experience of ladle users and manufacturers represented on AISE Subcommittee No. 9. Essential features are covered pertaining to good practice in construction and inspection of ladles.

Scope (II-1). Part II of this technical report is primarily concerned with the user's influence on the structural integrity of the ladle. Studies^{10,26} have shown that the combination of strong working linings (70% alumina, resin-bonded dolomitic and direct-bonded mag-chrome) and sustained temperature environments have a significant influence on stress levels imposed on the ladle shell and stiffener bands. In most cases, older ladles have been exposed to mild environments consisting of fireclay (bloating fireclay) working linings and short mold teeming hot metal hold times. Thus with proper maintenance the structural integrity of these ladles has not diminished significantly, but it is recognized that the new more severe operating environments may be imposed on these older ladles.

One of the main purposes of Part II of this report is to inform the user of the more severe operating environments, new ladle lining practices and to recommend ladle use which will assist in maintaining the structural integrity of the ladle.

Ladle Lining (II-2). Field investigations of ladle lining practices have shown that the bottom lining is typically thicker than the wall lining. This lining practice, coupled with rapid preheating, creates significant bending stresses in the connection region of the sidewall plate and the bottom plate. The bottom plate remains colder (due to the greater insulation) than the sidewall plate thereby restricting the radial growth of the bottom region of the sidewall plate and resulting in high bending stresses. This coupled with the differential expansion between the hot high strength refractory working lining and the cold shell can result in high circumferential and axial sidewall plate stresses, especially during rapid preheat of a cold ladle.

The use of a resin-bonded dolomitic or a direct-bonded mag-chrome working lining without expansion allowance also results in high axial and circumferential sidewall plate stresses, even when gradual ramp preheating is employed.

Estimating Wall Working Lining Thermal Expansion Stress (II-2.3). The recommended expansion allowance reduces the thermal expansion stresses imposed by the stiff refractory working lining on the ladle sidewall plate. Through the use of appropriate expansion allowance, structural integrity of the shell and primary structural components are maintained. An additional benefit of the use of an expansion allowance may result in longer lining life; however, this benefit is not the intent of these recommendations.

Studies have shown that maximum sidewall plate thermal expansion stresses resulting from the thermal growth of the working lining are reached after a few hours of standard (rapid) preheat. Standard preheat is the condition when the working lining hot face is brought from ambient to temperatures approaching 2000°F within approximately the first half hour of preheating; a specified ramp preheat is not used. For ramp preheating, longer times would be required to reach the maximum sidewall plate stresses.

Example A1, of Appendix A (particularly Section A1.8), provides sample calculations in estimating the amount of expansion allowance required for a resin-bonded dolomitic, a 70% alumina or a direct-bonded mag-chrome working lining. For refractory linings which have stiffness and strength values similar to or greater than these refractories, appropriate investigations should be conducted by the user to determine the need for expansion allowance. The softer working linings of fireclay do not require expansion allowance.

Wall Working Lining Expansion Allowance (II-2.4). The expansion allowance material should be placed on the cold face side of the working lining so replacement can be made with each new working lining. If placed against the shell, the expansion allowance material can not be replaced with each new working lining since the back-up lining is typically replaced with each third or fourth working lining replacement. The expansion allowance material may remain permanently compressed after the initial loading. Therefore, if expansion allowance material is used against the shell, subsequent working lining and replacements after the initial complete relining would not have expansion allowance.

The heat transfer calculations should reflect the compressibility and resulting alteration of the insulating properties of the expansion allowance material. Since the material may be compressed to a small fraction of the initial installed thickness, the insulating properties may be lost due to the complete mechanical restructuring of the material. As shown in Example A1, Appendix A, several hundred psi

loading is applied to the expansion allowance material as a result of the working lining expansion force.

Expansion allowance between the top of the wall working lining and lip ring is also recommended. Analytical studies and field investigations have shown that excessive lip ring distortions are apparently a result of wall working lining expansion as well as lip ring abuse during lining clean out.

Compressible Expansion Allowance Materials (II-2.5).

The expansion allowance materials shown are blanket and board type insulating materials since compressibility tests have been conducted on these type materials.

The user should choose expansion allowance material which is compatible for the temperature environment and for which the compressibility is known.

Both light weight and dense materials may be used for expansion allowance. In either case the resulting change in the insulating capacity of the material should be known due to the loss in thickness resulting from the compressive expansion forces of the working lining. In addition, the temperature rating of the expansion allowance material should be determined as well as other environmental factors which relate to the deteriorating effects imposed on the material.

Lining Stabilization (II-2.6). When expansion allowance material is used behind the working lining, special attention is given to the handling of the cold ladle to avoid lining shift. Ideally, the cold ladle should be preheated in the vertical (upright) position for a sufficient time period to stabilize the lining in the expanded position. Once the ladle is hot and in use in typical clean steel process cycles, tilting can be done without causing lining shift. If ladles with lining expansion allowance materials are allowed to cool then the ladle reheat should be redone with the ladle in the vertical position.

It should be noted that ladle linings, with the appropriate expansion allowance, will exert expansion forces (during the hot condition) similar to the magnitudes developed by the softer bloating fireclay working linings. Since the bloating fireclay linings are assumed to remain stable during the hot condition, it is assumed the stiffer working linings with

appropriate expansion allowance will also remain stable during hot conditions.

Ladle Inspection (III-1). At a minimum, inspection of an active ladle is recommended once per year. The details described for inspection do not rule out other structural details unique to the user's ladle which have regions of high stress concentration. It should be noted that some existing ladles may have been exposed to mild environments, such as the use of bloating fireclay working linings in combination with short mold teeming hot metal hold times, while others may have been exposed to more severe environments in which high strength refractory working linings without the use of expansion allowance were coupled with intermediate hot metal hold times. This implies that some existing ladles may have significant more fatigue life than others.

Existing Ladles with Riveted Lap Joints (III-2). It is recognized that riveted connections are no longer used in the majority of new ladle designs. However, investigative field studies¹⁰ have shown that existing ladles with riveted connections are still used in a large number of iron and steel-making shops. Detailed calculations on these riveted connections show the riveted connection strength in relation to the plate strength. If the ladles are lined with high strength refractory (resin-bonded dolomitic, 70% alumina or direct-bonded mag-chrome), if the riveted connection is weaker or more flexible than the plate, it will experience the predominant portion of the wall working lining expansion displacement. Ideally the plate and riveted connection should share equally the total expansion displacement of the wall working lining. If high strength working linings are to be used in ladles with riveted connections that are not equivalent to the sidewall plate or bottom plate strength, then the appropriate measures described in these specifications should be taken.

Maintenance of Structural Components (III-3). The primary concern is the maintenance of the various structural components. The primary items which should be addressed are the loss of component strength, loss of component material and cracks and distortions of components.

CODES, SPECIFICATIONS AND STANDARDS CITED

This section provides a summary of the principal codes, specifications and standards cited in this report and the addresses of the issuing organizations or societies.

These following editions of codes, specifications and standards are cited in this edition of this AISE Technical Report No. 9. The latest editions should be used in contracts for ladle design and construction unless otherwise agreed to by the purchaser and manufacturer.

The American Society of Mechanical Engineers, United Engineering Center, 345 East 47th Street, New York, NY 10017

ASME Boiler and Pressure Vessel Code, 1987 edition: Sections I, IV, VIII (Divisions 1 and 2) and IX (Note: Section I cited is the 1971 edition)

American Society for Testing and Materials, 1916 Race Street, Philadelphia, PA 19103

Annual Book of ASTM Standards, latest edition

American Welding Society, 2501 Northwest Seventh Street, Miami, FL 33125

Filler Metal Specifications, 1986

Structural Welding Code D1.1, 1986

Association of Iron and Steel Engineers, Suite 2350, Three Gateway Center, Pittsburgh, PA 15222

AISE Standard No. 7, Specifications for Design of Ladle Hooks, 1976

REFERENCES

This section of the report summarizes published papers on which portions of this specification are based. Designers are encouraged to refer to these papers for more detailed and advanced treatment of the subject matter.

1. Knudsen, K.E., "Structural Analysis of Hot-Metal Ladles," Dissertation submitted to Lehigh University, October 1948.
2. Knudsen, K.E., Munse, W.H. and Johnston, B.G., "Stresses in Hot Metal Ladles," *Iron and Steel Engineer Year Book* 1949.
3. Makeev, I.M., "An Investigation into the Strength of Steel-Casting Ladles and a Method for Its Calculation," *Stal*, No. 9, September 1960.
4. Corradi, L., "Welded Steel Ladles," *Stal*, No. 2, 1962.
5. Bolbrinker, A., and Peuker, G., "Temperature and Expansion Measurements on an 80-Ton Hot Metal Ladle," *Stahl und Eisen*, June 1972 (English translation BISI 11109, January 1974).
6. Krivitsky, M.E., and Dubrovin, G.A., "Steel Ladle of Light Construction," *Journal of the Iron and Steel Institute*, October 1948.
7. Hoffman, J.P., "Temperature Distribution in Teeming Ladle," Homer Research Laboratories Report, Bethlehem Steel Corp., July 1975.
8. Anonymous, "Lightweight Ladles — Structural Analysis of Ladles," *Journal of the Iron and Steel Institute*, January 1962.
9. Dobroskok, I.I., Brovman, M.Y., Kuryanov, L.P., and Surin, E.V., "Steel-Casting Ladles of Lightweight Design," *Stal*, No. 9, September 1960.
10. Schacht, C.A., "AISE Ladle Study SC-9-1, AISE Interim Reports No. 1 through No. 4 and Final Report," September 1984.
11. Esztergar, E.P., "Development of Design Rules for Dished Pressure Vessel Heads," *Welding Research Council Bulletin* No. 215, May 1976, Welding Research Council, 345 E. 47th St., New York, NY.
12. Gerdeen, J.C., "The Effect of Geometrical Variations on the Limit Pressure for 2:1 Ellipsoidal Head Vessels under Internal Pressure," *Welding Research Council Bulletin* No. 215, May 1976.
13. Cloud, R.L., "Interpretive Report on Pressure Vessel Heads," *Welding Research Council Bulletin* No. 119, January 1967.
14. Kirshenbaum, A.D., and Cahill, J.A., "The Density of Liquid from the Melting Point to 2500° K," *Transactions of the Metallurgical Society of AIME*, Vol. 204, August 1962.
15. Elliot, J.F., Gleiser, M., and Ramakrishna, V., *Thermochemistry for Steelmaking*, Vol. II, Addison-Wesley, 1963, pp 501 and 626.
16. Degenkolbe, J. and Musgen, G., "Relationship Between the Ratio of Yield Strength to Tensile Strength and Brittle Fracture Behavior of Structural Steels," Report No. 1788 of the Material Committee of Vereins Deutscher Eisenhüttenleute, *Stahl und Eisen*, No. 93 (25), pp 1218-1221, 1973.
17. "Structural Properties of High Strength Steels at Elevated Temperatures," AISI Committee on Building Research and Technology, January 1965.
18. Rothman, R.L. and Monroe, R.E., "Effect of Temperature and Strain Upon Ship Steels," Final Technical Report SSC-235, 1973 Ship Structure Committee, U.S. Coast Guard Headquarters, Washington, DC, 20590.
19. Goldberg, F., "Influence of Thermal Cutting and its Quality on the Fatigue Strength of Steel," *Welding Research Council Supplement*, September 1973.
20. Kihara, H., Suhara, J., Kurokawa, T., Kataoka, S., Nakajima, M., and Yajima, H., "Effect of Fabricating Process on Notch Toughness of Shipbuilding Steel Plates (Report 1)," *Transactions of JWRI*, Vol 3, No. 2, 1974.
21. AISC Steel Construction Manual, Ninth Ed., 7/89, pp 5-91.
22. "Mechanical and Physical Properties of Ferrous Forgings," prepared by Illinois Institute of Technology for AISI, 1965.
23. Schacht, C.A., "The Effects of Mortar Joints on the Thermomechanical Behavior of Refractory Brick Lining Systems in Cylindrical Vessels," AISE Spring Conference, Birmingham, Alabama, March 1985.
24. Schacht, C.A., "AISE Ladle Study SC-9-02, AISE Report," March 1986.
25. Schacht, C.A., "Evaluation of AISE TR9 Flexibility Criteria, AISE Final Report," AISE SC-9-2 Study, January 1987.
26. Schacht, C.A., "Investigative Study on the Thermomechanical Behavior of Resin-Bonded Dolomitic Brick Working Lining," AISE Mini-Study, March 1987.
27. Beedle, Lynn S., et. al, *Structural Steel Design*, The Ronald Press Co., New York, 1964, pp 550-554.

APPENDIX A — DESIGN EXAMPLES

The two examples in this Appendix illustrate the use of this Technical Report in the design of ladles. Only the general features of the ladles are considered. Numbered equations from the text are noted.

A1 Example 1 — 280-Ton Circular Ladle.

The general dimensions are determined by the 280-ton capacity ladle shown in Fig. A1. The molten metal density, q , is assumed to be 0.42 kips/cu ft for this example only. The operating temperatures of the bottom, sidewalls and trunnion block do not exceed 650°F, while the operating temperature of the trunnion pin does not exceed 500°F. Note: This example is to be referred to for calculation purposes only. It does not necessarily represent a practical design.

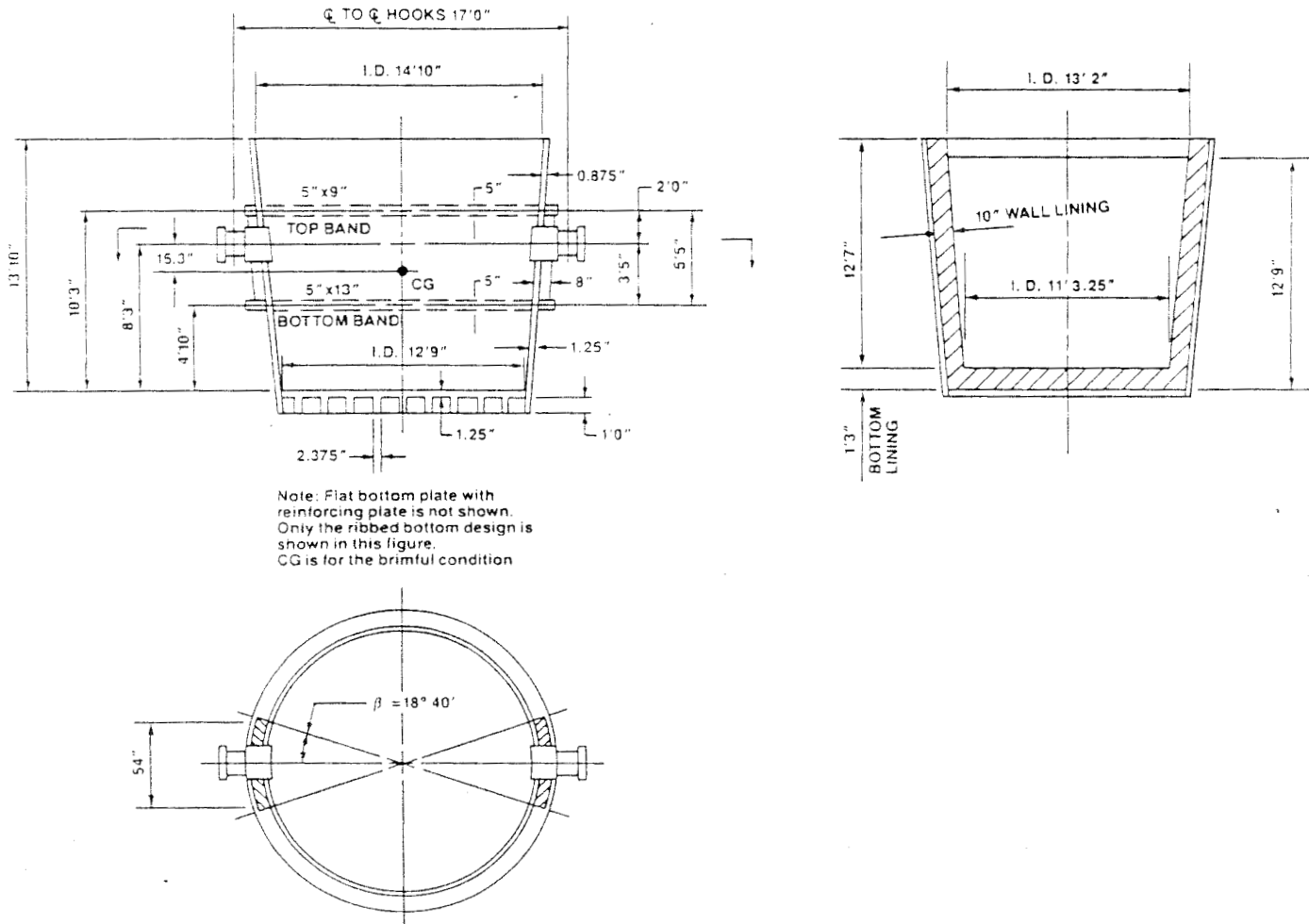


Fig. A1 — Dimensions Used in Example 1 Calculation for a 280-Ton Circular Ladle

A1.1 Ladle Weight. The OIS specified a rated operating capacity of 280 tons and a freeboard height of 13 in. These specifications result in a vertical ladle height, H , of 166 in. (13 ft 10 in.) as described in Fig. A1. The design procedure of Section I-5.1 is used only if the freeboard exceeds 10% of H . For the 280-ton ladle, the freeboard percentage of ladle height is:

$$\frac{13}{166} \times 100 = 7.83\%$$

Therefore the design procedure of Section I-5.1 is not required.

The design capacity molten metal weight is calculated as 280 tons. The normal design load, W_2 , for the ladles is estimated as:

$$\begin{aligned}\text{Design molten metal weight} &= 560 \text{ kips} \\ \text{Ladle steelwork weight} &= 125 \text{ kips} \\ \text{Ladle lid weight} &= 25 \text{ kips} \\ \text{Ladle lining weight} &= \underline{90} \text{ kips} \\ W_2 &= 800 \text{ kips}\end{aligned}$$

Note that if the ladle steelwork weight is unknown at the beginning of the design state, an approximate normal design load can be estimated as follows:

$$\frac{\text{Design molten metal weight}}{0.75} = \frac{560}{0.75} = 746.7 \text{ kips}$$

Adding the lid weight, the first trial for W_2 would be $746.7 + 25 = 771.7$ kips.

After evaluating ladle dimensions, the actual weight shall be established and the design process may be repeated.

A1.2 Bottom Plate

A1.2.1 Flat Bottom. The required thickness for a flat bottom circular ladle is:

$$T_B = \frac{D}{139} \sqrt{\frac{qH}{\sigma_a}} \quad (\text{Eq I-18a})$$

Use ASTM A285, Grade C material (Section I-3.2). The minimum room temperature tensile properties are given in the ASTM A285 specification as $\sigma_y = 30$ ksi (yield strength) and $\sigma_u = 55$ ksi (ultimate strength). The allowable normal stress (Section I-5.4.1) is:

$$\begin{aligned}\sigma_a &= \min \{ \sigma_{ay} ; \sigma_{au} \} \\ &= \min \left\{ \frac{F_f F_t \sigma_y}{F_t (SF)_y} ; \frac{F_f F_t \sigma_u}{F_t (SF)_u} \right\} \quad (\text{Eqs I-2 and I-3})\end{aligned}$$

$$F_f = f_1 f_2 f_3 f_4 f_5 = 1.0(1.0)(1.0)(1.0)(1.0) = 1.0$$

Tables I-5, I-6, I-7 (Tables I-1, I-2, I-3)

$$F_t = 0.729 \text{ (Table I-1, temperature} = 650^\circ\text{F)}$$

$$F_t = 1.2, (SF)_y = 2.28, (SF)_u = 3.80$$

$$\sigma_a = \min \left\{ \frac{1.0(0.729)(30)}{1.2(2.28)} ; \frac{1.0(0.729)(55)}{1.2(3.8)} \right\}$$

$$= \min \{ 7.99 ; 8.79 \}$$

$$= 7.99 \text{ ksi}$$

$$D = 153 \text{ in.}, q = 0.42 \text{ kips/cu ft}, H = 166 \text{ in.}$$

$$T_B = \frac{153}{139} \sqrt{\frac{0.42(166)}{7.99}} = 3.25 \quad (\text{Eq I-18a})$$

This is greater than 2 in. and thus too thick for the material specified (Section I-3.2). Use a flanged bottom with reinforcing plate:

$$T_R + T_B = \frac{D}{114} \sqrt{\frac{qH}{\sigma_a}} = \frac{153}{114} \sqrt{\frac{0.42(166)}{7.99}} = 3.96 \quad (\text{Eq I-19})$$

3

A1.2.2 Bottom Plate Rivet Design Calculation. Use a 135-in. diameter reinforcing plate with 1¼-in. ASTM A31, Grade A rivets and 1⅝-in. holes arranged in a circular pattern. The allowable rivet shear stress (Section I-5.6) is 12.3 ksi. Driven rivet area is:

2

The shear stress in the plate is:

1

The rivet shear stress is:

(Eq 1-18b)

Locate outermost row of rivets at a distance of three rivet diameters = $3(1.3125) = 3.94$ in. inward from outer edge of plate. Maintain a rivet spacing greater than or equal to $4.5(1.3125) = 5.91$ in. between rivet centers in the circumferential direction of the rivet row. The 5.91-in. spacing shall also be maintained in the radial direction between rivet rows if the rivet rows are not staggered. The rivet radius pattern is shown in Fig. A2 using a staggered pattern for the two outside rivet rows.

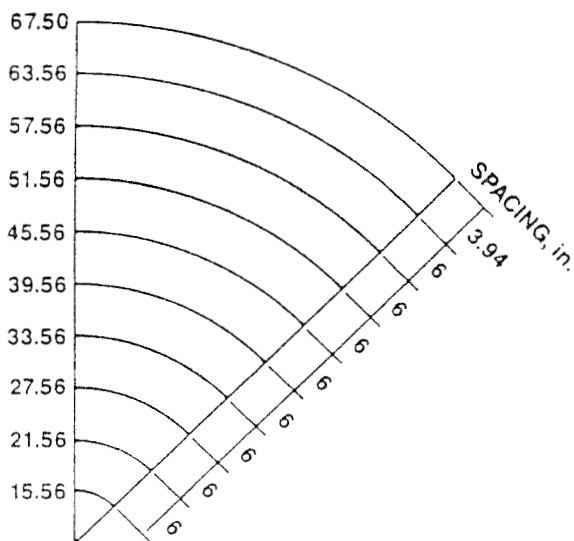
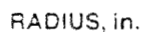


Fig. A2 — Ladle Bottom Rivet Spacing

Substituting the known parameters into the plate shear stress equation:

$$\tau_1 = \frac{0.00105(0.42)(166) R_M(2.125)(1.875)}{(2.125 + 1.875)^3} = 0.004558 R_M$$

Substituting the value for τ_1 into the rivet shear stress equation:

If rivet stress in the outside rows is too great using a $4.5 d_r$ annulus, rotate the rivets of the inner row to a staggered pattern which allows the radius of the inner row to be larger while maintaining the pitch at $4.5 d_r$. The number of rivets must be the same in each staggered row. The following calculation shows the derivation of the maximum inner row radius (R_{M-1}) for two staggered rows R_M and R_{M-1} .

From Fig. A2:

$$\text{Radius outside row} = R_M = 67.5 - 3(1.3125) = 63.56 \text{ in.}$$

$$\text{Circumference} = c = 2 \pi R_M$$

$$\text{Rivet spacing} = s = \frac{c}{N_m}$$

$$\text{Angle between rivets in same row} = \theta = \frac{s}{R_M}$$

$$\text{Angle between rivets in different rows} = \alpha = \frac{\theta}{2}$$

$$x = R_M \sin \alpha$$

$$y = R_M \cos \alpha$$

$$\text{Pitch} = p = 4.5 d_r$$

$$z = \sqrt{p^2 - x^2}$$

$$R_{M-1} = y - z$$

Substitute back:

$$\begin{aligned} R_{M-1} &= R_M \cos \alpha - \sqrt{p^2 - x^2} \\ &= R_M \cos \alpha - \sqrt{(4.5 d_r)^2 - R_M^2 \sin^2 \alpha} \end{aligned}$$

Also:

$$\alpha = \frac{\theta}{2} = \frac{c}{N_m 2 R_M} = \frac{2 \pi R_M}{N_m 2 R_M} = \frac{\pi}{N_m} \text{ radians} = \frac{180 \text{ degrees}}{N_m}$$

$$N_m = \frac{2 \pi R_{M-1}}{4.5 d_r}$$

$$\begin{aligned} R_{M-1} &= R_M \cos \left(\frac{180}{N_m} \right) - \sqrt{(4.5 d_r)^2 - R_M^2 \sin^2 \left(\frac{180}{N_m} \right)} \\ &= R_M \cos \left[\frac{180(4.5 d_r)}{2 \pi R_{M-1}} \right] - \sqrt{(4.5 d_r)^2 - R_M^2 \sin^2 \left[\frac{180(4.5 d_r)}{2 \pi R_{M-1}} \right]} \end{aligned}$$

Rearranging; to satisfy the minimum rivet spacing requirement of $4.5 d_r$ the rivet row spacing for the staggered rivet rows R_M and R_{M-1} is:

$$R_M^2 \cos^2 \left(\frac{128.92 d_r}{R_{M-1}} \right) - 2 R_{M-1} R_M \cos \left(\frac{128.92 d_r}{R_{M-1}} \right) + R_{M-1}^2 = (4.5 d_r)^2 - R_M^2 \sin^2 \left(\frac{128.92 d_r}{R_{M-1}} \right)$$

Solving for the inside rivet row radius R_{M-1} :

$$R_{M-1}^2 - 2 R_{M-1} R_M \cos \left(\frac{128.92 d_r}{R_{M-1}} \right) - (4.5 d_r)^2 + R_M^2 = 0$$

The above equation for R_{M-1} assumes that the circumferential rivet spacing is $4.5 d_r$. However, when the actual number of rivets is chosen, the actual circumferential spacing will most likely be greater than $4.5 d_r$. Using the actual number of rivets, N_m , the above equation for R_{M-1} with staggered rivet rows, becomes:

$$R_{M-1}^2 - 2 R_{M-1} R_M \cos \left(\frac{180}{N_m} \right) - (4.5 d_r)^2 + R_M^2 = 0$$

It should be noted that the above equation for R_{M-1} is valid if the two rivet rows in question have the same number of rivets. If the number of rivets differ in the two rows of interest, then the pattern assumed in Fig. A2 for the two outer rows would not apply and the above equation for R_{M-1} could not be used. For consecutive rivet rows, each with a different number of rivets, the radial spacing between rows is $4.5 d_r$.

For Row No. 1 and Row No. 2:

In the following example, the outer two rows are to have the same number of rivets and are to be staggered.

$$N_m = \frac{2 \pi R_M}{4.5 d_r} = 67 \text{ rivets, maximum number to satisfy the minimum spacing requirement. Try 40 rivets.}$$

$$\tau_2 = 0.010583 \frac{R_M}{N_m} (R_M^2 - R_{M-1}^2) = 12.22 \text{ ksi} < 12.3 \text{ ksi; OK}$$

Typically, less rivets are required to satisfy the rivet shear stress requirement than are required based on satisfying spacing rules. This implies that the following equation for the row radius can be calculated to satisfy the rivet shear stress requirement. However, the previous equation on row spacing to satisfy the rivet spacing requirement of $4.5 d_r$ should also be checked.

$$R_{M-1}^2 = R_M^2 - \frac{\tau_2 2 \pi R_M}{4.5 d_r (0.010583) R_M} = R_M^2 - (131.93) \frac{\tau_2}{d_r}$$

For the case in which the rivet spacing within the rivet row is greater than $4.5 d_r$, the next interior rivet row radius can be obtained by rearranging the previous equation to satisfy both the rivet shear stress, τ_2 , and solving for the unknown radius:

$$R_{M-1}^2 = R_M^2 - \frac{N_m \tau_2}{0.010583 R_M} = R_M^2 - \frac{94.49 N_m \tau_2}{R_M}$$

The minimum radial spacing between rows 1 and 2 is 3.37 in. to satisfy the diagonal minimum spacing of $4.5 d_r$ (5.91 in.) between rivets. A radial spacing of 6 in. is selected between rows 1 and 2.

or Row No. 3 through Row No. 9:

Rivet design requirements for row 3 through row 9 each have a different number of rivets. Therefore the rivet spacing in the circumferential and radial direction is based on the $4.5 d_r$ criteria. That is, the staggered row criteria cannot be used here. As shown in the following radial spacing of the rivet rows, the radial and circumferential spacing exceeds $4.5 d_r$ and can be arbitrary as long as the shear stress limit is satisfied for the number of rivets used. In rows 3 through 9, the radial row spacing is set at 6.0 in.

The results are shown in the summary table which indicates rivet shear stresses, τ_2 , are within the allowable value of 12.3 ksi.

Additional rivets should be added near the center of the ladle bottom to retard thermal distortion and buckling.

SUMMARY OF RIVET SPACING

Row	R_M , in.	R_{M-1} , in.	N_m	τ_2 , ksi
1	63.56	57.56	40	12.22
2	57.56	51.56	40	9.97
3	51.56	45.56	26	12.23
4	45.56	39.56	21	11.73
5	39.56	33.56	15	12.25
6	33.56	27.56	11	11.84
7	27.56	21.56	7	12.28
8	21.56	15.56	5	10.16
9	15.56	0.00	3	8.28

A1.2.3 Flat Bottom with Stiffener Ribs. As an alternative, consider a flat bottom with stiffener ribs and material specification ASTM A516 Gr55. The bottom plate must be at least as thick as the sidewall (Section I-7.6), so use 1.25 in. plate with $2\frac{3}{8} \times 12$ in ribs, spaced at $a' = 15.3$ in. (Fig. A3).

The properties of the T beam are:

$$\text{Area} = 15.3(1.25) + 12(2.375) = 47.63 \text{ sq in.}$$

$$e = \frac{15.3(1.25)(6 + 0.625)}{47.63} = 2.66 \text{ in.}$$

$$I = \frac{2.375(12)^3}{12} + \frac{15.3(1.25)^3}{12} + 19.125(3.965)^2 + 28.5(2.66)^2 = 847 \text{ in.}^4$$

$$S_1 = \frac{847}{4.59} = 184.5 \text{ in.}^3$$

$$S_2 = \frac{847}{8.66} = 97.8 \text{ in.}^3$$

$$S = \max \{S_1 ; S_2\} = 184.5 \text{ in.}^3$$

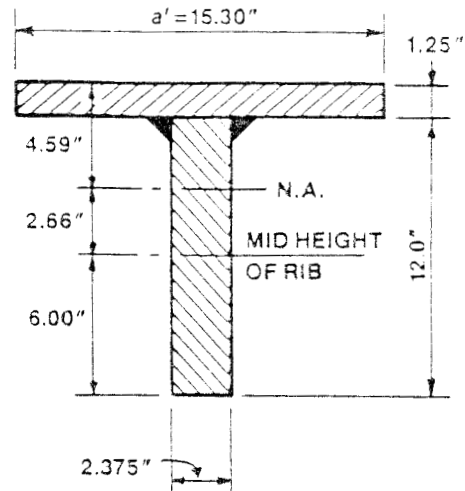


Fig. A3 — Effective T Beam

Checking the requirements of Section I-7.6.

$$\frac{L}{5} = \frac{153}{5} = 30.60 \text{ in.}$$

$$\frac{L^2 T_B^2}{4 S} = \frac{(153)^2 (1.25)^2}{4(184.5)} = 49.56 \text{ in.} \quad (\text{Eq I-21})$$

The rib spacing of 15.3 in. is less than both 30.60 in. and 49.56 in., as required.

Assume the load on the tee section is:

$$P_t = a' \frac{\text{Weight of Molten Metal}}{\text{Area of Bottom}} = 15.3 \frac{560(4)}{\pi(153)^2} = 0.4660 \text{ kips/in.}$$

$$M_{\max} = \frac{P_t L^2}{8} = \frac{0.4660(153)^2}{8} = 1364 \text{ kip-in.}$$

and the tensile and compressive bending stresses are:

$$\sigma_{\text{ten}} = \frac{1364}{97.8} = 13.95 \text{ ksi}$$

$$\sigma_{\text{ten}} < \sigma_{bt} = 2\sigma_a = 2(7.99) = 15.98 \text{ ksi; OK} \quad (\text{Eq I-6})$$

$$\sigma_{\text{comp}} = \frac{1364}{184.5} = 7.39 \text{ ksi}$$

$$\sigma_{\text{comp}} < \sigma_{bc} = 1.25 \sigma_a = 1.25(7.99) = 9.99 \text{ ksi; OK} \quad (\text{Eq I-7})$$

The maximum shear stress is $\tau_{\max} = \frac{VQ}{Ib}$

$$V = 0.4660 \left(\frac{153}{2} \right) = 35.65 \text{ kips}$$

$$Q = 8.66(2.375) \left(\frac{8.66}{2} \right) = 89.06 \text{ in.}^3$$

$$I = 847 \text{ in.}^4$$

$$b = 2.375 \text{ in.}$$

$$\tau_{\max} = \frac{VQ}{Ib} = \frac{35.65(89.06)}{847(2.375)}$$

$$= 1.58 \text{ ksi} < 0.6\sigma_a = 0.6(7.99) = 4.79 \text{ ksi; OK} \quad (\text{Eq I-11})$$

For the connection between the rib and sidewall, use a double groove full penetration weld as required by Section I-7.6.

The equivalent thickness of the ribbed bottom equals:

$$1.25 + \frac{2.375(12)}{15.3} = 3.11 \text{ in.}$$

This is less than the 4 in. thickness needed for an unribbed flat bottom.

A1.3 Sidewall. The minimum sidewall plate thickness below the top band (Section I-10) is 1 1/4 in. for ASTM A285 Grade C material for temperatures up to 650°F (Table I-7).

The supplementary thickness requirement below the top band is met, since:

$$t_{\min} = \frac{C_R q H D}{1819 \sigma_a} = \frac{1(0.42)(166)(153)}{1819(7.99)} = 0.7340 \text{ in.}$$

(Eq I-40a)

$$t_{\min} = \frac{2 C_R W_2}{\pi D \sigma_a} = \frac{2(1)(800)}{\pi(153)(7.99)} = 0.417 \text{ in.}$$

(Eq I-40b)

$$1.25 \text{ in.} > 0.7340 \text{ in.; OK}$$

The minimum required thickness above the top band (Section I-10.4) = $0.66(1.25) = 0.825 \text{ in.}$ Use 7/8 in.

The average normal stress in the sidewall is:

$$\sigma_w = \frac{W_2}{\pi D t} = \frac{800}{\pi(153)(1.25)} = 1.33 \text{ ksi} < \sigma_a = 7.99 \text{ ksi, OK} \quad (\text{Eq I-40c})$$

An increase of more than 30% in the sidewall stress due to thinning of the sidewall from wear, corrosion or other means, should be cause for replacement or repair (Section I-5.4.7). The minimum permissible worn thickness is $\frac{1.25}{1.30} = 0.96 \text{ in.}$

below the top band and $\frac{0.825}{1.30} = 0.64 \text{ in.}$ above the top band.

A1.4 Trunnion Pin and Block (Fig. A4).

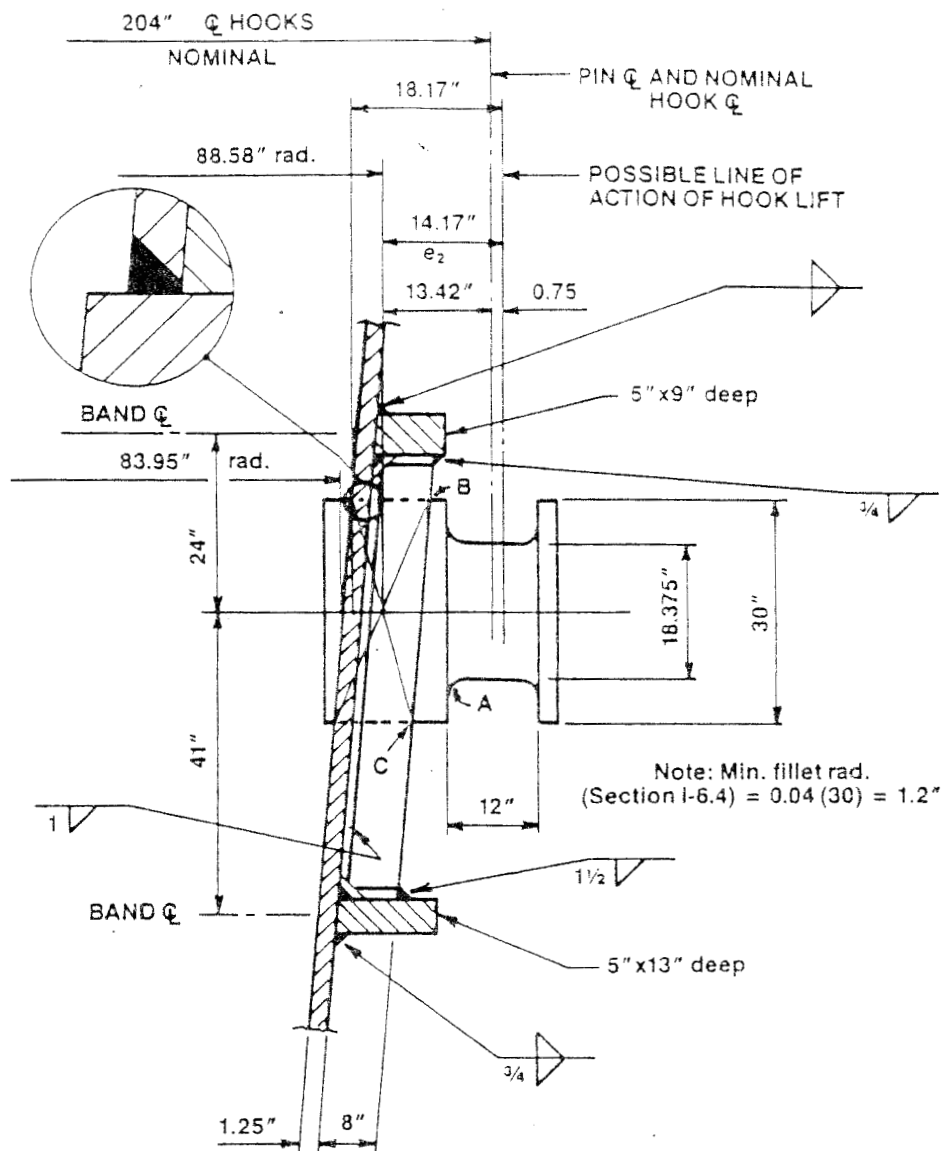


Fig. A4 — Trunnion Details

A1.4.1 Trunnion Pin. Try an 18 3/8-in. diameter pin of ASTM A668, Class C material without protective bushings.

$$\text{Area} = \frac{\pi(18.375)^2}{4} = 265.2 \text{ sq in.}$$

$$S = \frac{\text{Area (Radius)}}{4} = 265.2 \frac{(9.188)}{4} = 609.2 \text{ in.}^3$$

The room temperature tensile properties given in the ASTM specification for A668, Class C material are:

$$\sigma_y = 33 \text{ ksi; } \sigma_u = 66 \text{ ksi.}$$

For a maximum operating temperature at the pin of 500°F, the temperature derating factor is:

$$F_t = 0.808 \text{ (Table I-2, temperature = 500°F. Also see Table I-6 for calculated allowable } \sigma_b \text{ values).}$$

The allowable pin bending stress (Section I-5.5.1) is:

$$\begin{aligned}\sigma_b &= \min \left\{ \frac{F_f F_t \sigma_y}{F_t (SF)_y} ; \frac{F_f F_t \sigma_u}{F_t (SF)_u} \right\} \\ &= \min \left\{ \frac{1(0.808)(33)}{1.2(4.56)} ; \frac{1(0.808)(66)}{1.2(9.12)} \right\} \\ &= \min (4.873 ; 4.873) \\ &= 4.873 \text{ ksi}\end{aligned}$$

(Eq I-12 and I-13)

The allowable shear stress (Section I-5.5.2) is:

$$0.533 \sigma_b = 0.533(4.873) = 2.60 \text{ ksi} \quad (\text{Eq I-15})$$

The bending stress at the base of the pin (Fig. A4, Point A) is:

$$\sigma_{\text{bend}} = \frac{800(6.75)}{2(609.1)} = 4.433 \text{ ksi} < 4.873 \text{ ksi}; \text{ OK}$$

The average shear stress in the pin is:

$$\tau_{\text{avg}} = \frac{800}{2(263)} = 1.51 \text{ ksi} < 2.60 \text{ ksi}; \text{ OK}$$

The pin must be replaced when the calculated stresses are greater than the allowable stresses by 45% (Section I-5.5.4). Because bending stresses are proportional to the cube of the diameter, the minimum permissible worn pin diameter is, therefore:

$$\begin{aligned}D_{H(\min)} &= 18.375 \left[\frac{4.433}{1.45(4.873)} \right]^{1/3} \\ &= 15.73 \text{ in.}\end{aligned}$$

A1.4.2 Bearing Stress on Pin. Since the pin length is 12 in., the hook width is 10.5 in. according to AISE Technical Report No. 7. The minimum inside radius of the shell at the trunnion pin centerline elevation (Fig. A4) is

$$76.5 + \left(\frac{99}{166} \right) (89 - 76.5) = 83.95 \text{ in.}$$

and the radius to the trunnion block mid-thickness is

$$83.95 + \frac{9.25}{2} = 88.58 \text{ in.}$$

The horizontal distance from the pin mid-length to the trunnion block mid-thickness is therefore

$$102 - 88.58 = 13.42 \text{ in.}$$

The moment arm from the hook centerline to the centerline of the trunnion block is:

$$e_2 = 13.42 + 0.75 = 14.17 \text{ in.}$$

The bearing stress at Point B (Fig. A4) is:

$$f_B = \frac{800}{2(30)(9.25)} \left[1 + \frac{6(14.17)}{9.25} \right] = 14.7 \text{ ksi} \quad (\text{Eq I-17})$$

The allowable bearing stress is the lesser of Eq I-5b and I-16:

$$\sigma_{br} = 1.36(1.38 \sigma_a) = 1.36(1.38)(8) = 15.01 \text{ ksi} \quad (\text{Eq I-5b})$$

$$\sigma_{br} = 3.33\sigma_{b, \text{pin}} = 3.33(4.873) = 16.23 \text{ ksi} \quad (\text{Eq I-16a})$$

$$\text{Use } \sigma_{br} = 15.01 \text{ ksi}$$

$$f_B = 14.7 < 15.01 \text{ ksi; OK}$$

A1.4.3 Trunnion Block Bending Stresses. The trunnion block is connected to the shell by longitudinal fillet welds which transmit the vertical load to the shell (Fig. A4). The moment arm on the trunnion block is $e_2 = 14.17$ in.

Using an 8×54 in. block and neglecting conservatively the curvature of the block, and assuming that the trunnion block acts as an integral part with the shell plate, the section modulus at the centerline of the trunnion is:

$$S = \frac{(54 - 30)(9.25)^2}{6} = 342.3 \text{ in.}^3 \quad (\text{Eq I-17b})$$

Use ASTM A27, Grade 60-30 material for the block. The allowable normal stress (Section I-5.4.1) is:

$$\begin{aligned} \sigma_a &= \min \left\{ \sigma_{ay} \quad ; \quad \sigma_{au} \right\} \\ &= \min \left\{ \frac{F_f F_t \sigma_y}{F_i (SF)_y} \quad ; \quad \frac{F_f F_t \sigma_u}{F_i (SF)_u} \right\} \end{aligned} \quad (\text{Eqs I-2 and I-3})$$

$$\sigma_y = 30 \text{ ksi; } \sigma_u = 60 \text{ ksi}$$

$$F_f = f_1 f_2 f_3 f_4 f_5 = 1.0(1.0)(1.0)(1.0)(1.0) = 1.0$$

$$F_t = 0.730 \text{ (Table I-1, temperature = 650°F)}$$

$$F_i = 1.2, (SF)_y = 2.28, (SF)_u = 3.80$$

$$\begin{aligned} \sigma_a &= \min \left\{ \frac{1.0(0.730)(30)}{1.2(2.28)} \quad ; \quad \frac{1.0(0.730)(60)}{1.2(3.8)} \right\} \\ &= \min \{ 8.00 \quad ; \quad 9.61 \} \\ &= 8.00 \text{ ksi} \end{aligned}$$

Allowable bending stress in block (Section I-5.4.2.2) is:

$$\sigma_b = 1.38\sigma_a = 1.38(8) = 11.0 \text{ ksi} \quad (\text{Eq I-5a})$$

The maximum trunnion block bending stress is located at the centerline of the trunnion and is:

$$f_b = \frac{800(14.17)(41)}{2(65)(342.3)} = 10.44 \text{ ksi} < 11.0 \text{ ksi; OK} \quad (\text{Eq I-17a})$$

A1.4.4 Weld Stresses. The throat area of the vertical welds connecting the trunnion block to the sidewall is

$$2(0.707)(1.0)(60) = 84.84 \text{ sq in.}$$

and the average shear stress in the welds is

$$\frac{800}{2(84.84)} = 4.71 \text{ ksi}$$

The weld must meet the fatigue stress provisions of the AWS Structural Welding Code (Section I-5.4.6). Designing for an infinite number of cycles, the AWS allowable stress is 8.0 ksi (AWS Code, 1980 Ed., Category F, Fig. 9.4B), and the weld stress of 4.71 ksi is OK.

The radial force on each of the welds at the top and bottom of the trunnion block (welds connecting block to the band) is:

$$\frac{W_2 e_2}{2g} = \frac{800(14.17)}{2(65)} = 87.20 \text{ kips}$$

The shear stress in the weld is:

$$\text{At top: } \frac{87.20}{0.75(0.707)(54)} = 3.04 \text{ ksi}$$

$$\text{At bottom: } \frac{87.20}{1.5(0.707)(54)} = 1.52 \text{ ksi}$$

These stresses will be combined with the circumferential shear stresses following the band design calculations.

A1.4.5 Location of Trunnion Axis. The minimum distance of the trunnion axis above the center of gravity of a brimful ladle, including refractory lining and contents (Section I-5.3) is:

$$j = 3.236 \times 10^{-6} \left[\frac{0.42}{918} \right] (168)(168)^3 \quad (\text{Eq I-1})$$

$$= 1.18 \text{ ft} = 14.16 \text{ in.} < 15.3 \text{ in. (actual } j \text{ distance); OK}$$

Where the brimful weight, W , of the ladle is estimated as:

Brimful molten metal weight	= 708 kips	(worn lining)
Ladle steelwork weight	= 125 kips	
Ladle lid weight	= 25 kips	
Ladle lining weight	= 60 kips	(worn lining)
W	= 918 kips	

1.5 Stiffener Bands. The effective band properties are determined first followed by band forces, band weld stresses and deflection index.

A1.5.1 Effective Band Properties.

Top band:

$$R_S = 76.5 + \frac{10.25}{13.833} (89 - 76.5) + \frac{1.25}{2} = 86.4 \text{ in.}$$

The location of the sidewall plate joint above the top band is:

$$e_T = 0.75 \sqrt{86.4(1.25)} = 7.79 \text{ in.} \quad (\text{Eq I-39})$$

Panel size: 5 in. wide $\times$ 9 in. deep all around.

Properties at trunnion axis (Fig. A5):

$$b_1 = 0.4 \sqrt{86.4(9.25 + 2.50)} = 12.7 \text{ in.} \quad (\text{Eq I-29})$$

$$b_2 = 0.7 \sqrt{86.4(1.25)} = 7.3 \text{ in.} \quad (\text{Eq I-30})$$

$$h_c = 5 + 12.7 + 7.3 = 25 \text{ in.} \quad (\text{Eq I-28})$$

$$A_{\text{net}} = 12.7(9.25) + 5(10.25) + 7.3(1.25) = 177.8 \text{ sq in.}$$

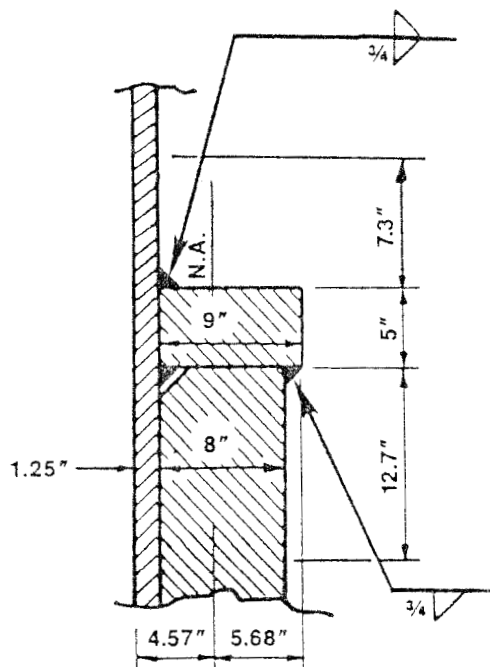


Fig. A5 — Top Band at Trunnion Axis

Locate neutral axis:

$$\begin{aligned}
 e &= \frac{12.7(9.25)^2 + 5(10.25)^2 + 7.3(1.25)^2}{2(177.3)} \\
 &= 4.57 \text{ in.} \\
 I &= \frac{12.7(9.25)^3}{12} + \frac{5(10.25)^3}{12} + \frac{7.3(1.25)^3}{12} \\
 &\quad + 12.7(9.25)(0.06)^2 + 5(10.25)(0.56)^2 \\
 &\quad + 7.3(1.25)(3.94)^2 \\
 &= 1446 \text{ in.}^4
 \end{aligned}$$

Section modulus:

$$\begin{aligned}
 \text{outside } S_O &= \frac{1446}{5.68} = 254.6 \text{ in.}^3 \\
 \text{inside } S_I &= \frac{1446}{4.57} = 316.4 \text{ in.}^3
 \end{aligned}$$

Properties at cross axis (Fig. A6):

$$b_e = 5 + 1.4 \sqrt{86.4(1.25)} = 19.55 \text{ in.} \quad (\text{Eq I-27})$$

$$\text{Area} = 14.6(1.25) + 5(10.25) = 69.5 \text{ sq in.}$$

Locate neutral axis:

$$\begin{aligned}
 e &= \frac{14.6(1.25)^2 + 5(10.25)^2}{2(69.5)} \\
 &= 3.94 \text{ in.} \\
 I &= \frac{14.6(1.25)^3}{12} + \frac{5(10.25)^3}{12} \\
 &\quad + 14.6(1.25)(3.32)^2 + 5(10.25)(1.18)^2 \\
 &= 724 \text{ in.}^4
 \end{aligned}$$

Section modulus:

$$\begin{aligned}
 \text{outside } S_O &= \frac{724}{6.31} = 114.7 \text{ in.}^3 \\
 \text{inside } S_I &= \frac{724}{3.94} = 183.8 \text{ in.}^3
 \end{aligned}$$

Bottom band:

$$R_S = 76.5 + \frac{4.833}{13.333} (89 - 76.5) + \frac{1.25}{2} = 81.5 \text{ in.}$$

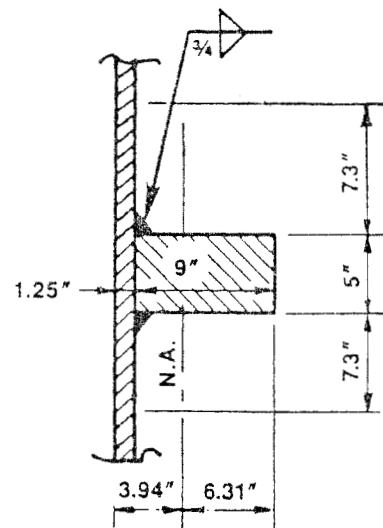


Fig. A6 — Top Band at Cross Axis

Trial size: 5 in. wide $\times$ 13 in. deep all around.

Properties at trunnion axis (Fig. A7):

$$b_1 = 0.4 \sqrt{81.5(9.25 + 2.5)} = 12.4 \text{ in.} \quad (\text{Eq I-29})$$

$$b_2 = 0.7 \sqrt{81.5(1.25)} = 7.1 \text{ in.} \quad (\text{Eq I-30})$$

$$b_c = 5 + 12.4 + 7.1 = 24.5 \text{ in.} \quad (\text{Eq I-28})$$

$$\text{Area} = 5(14.25) + (12.4)(9.25) + 7.1(1.25) = 194.8 \text{ sq in.}$$

Locate neutral axis:

$$e = \frac{7.1(1.25)^2 + 5(14.25)^2 + 12.4(9.25)^2}{2(194.8)}$$

$$= 5.36 \text{ in.}$$

$$I = \frac{7.1(1.25)^3}{12} + \frac{5(14.25)^3}{12} + \frac{12.4(9.25)^3}{12} + 7.1(1.25)(4.74)^2 + 5(14.25)(1.77)^2 + 12.4(9.25)(0.74)^2 = 2510 \text{ in.}^4$$

Section modulus:

$$\text{outside } S_O = \frac{2510}{8.89} = 282.3 \text{ in.}^3$$

$$\text{inside } S_I = \frac{2510}{5.36} = 468.3 \text{ in.}^3$$

Properties at cross axis (Fig. A8):

$$b_c = 5 + 1.4 \sqrt{81.5(1.25)} = 19.1 \text{ in.} \quad (\text{Eq I-27})$$

$$\text{Area} = 19.1(1.25) + 5(13) = 88.9 \text{ sq in.}$$

Locate neutral axis:

$$e = \frac{14.1(1.25)^2 + 5(14.25)^2}{2(88.9)}$$

$$= 5.83 \text{ in.}$$

$$I = \frac{5(13)^3}{12} + \frac{19.1(1.25)^3}{12} + 5(13)(1.92)^2 + 19.1(1.25)(5.21)^2 = 1806 \text{ in.}^4$$

Section modulus:

$$\text{outside } S_O = \frac{1806}{8.42} = 214.5 \text{ in.}^3$$

$$\text{inside } S_I = \frac{1806}{5.83} = 309.8 \text{ in.}^3$$

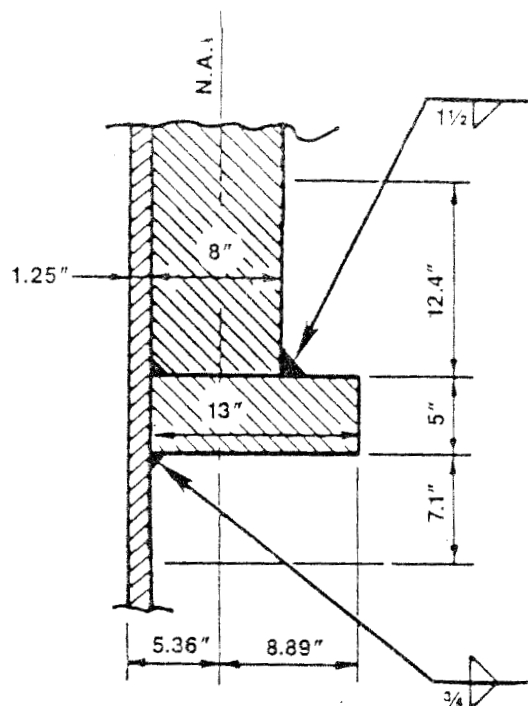


Fig. A7 — Bottom Band at Trunnion Axis

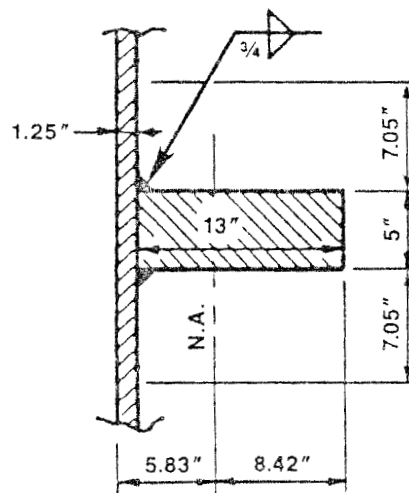


Fig. A8 — Bottom Band at Cross Axis

SUMMARY OF EFFECTIVE BAND PROPERTIES				
Property	Top Band		Bottom Band	
	At Trunnion	At Cross Axis	At Trunnion	At Cross Axis
Area, in. ²	177.8	69.5	194.8	88.9
<i>I</i> , in. ⁴	1446	724	2510	1806
<i>S</i> _O , in. ³	254.6	114.7	282.3	214.5
<i>S</i> _T , in. ³	316.4	183.8	468.3	309.8

A1.5.2 Band Forces.

$$R_{RT} = 86.4 + 3.94 - 0.625 = 89.72 \text{ in.}$$

$$R_{RB} = 81.5 + 5.83 - 0.625 = 86.71 \text{ in.}$$

$$C = \frac{1806(58)(89.72)^3}{724(123)(86.71)^3} = 1.303 \quad (\text{Eq I-31})$$

$$R_{SM} = \frac{76.5 + 89}{2} + 0.625 = 83.38 \text{ in.}$$

$$G = 1.27 \text{ (Fig. I-12, } \frac{l}{R_{SM}} = 0)$$

$$F_T = \frac{800 [204 - 1.27(83.38)]}{8 [1.303(58) + 123]} = 49.42 \text{ kips} \quad (\text{Eq I-32a})$$

$$F_B = 1.303(49.42) = 64.39 \text{ kips} \quad (\text{Eq I-32b})$$

$$\begin{aligned} M_{T1} \text{ (at trunnion axis)} &= 49.42 [0.7(89.72) - 13.5] \\ &= 2437 \text{ kip-in.} \end{aligned} \quad (\text{Eq I-33})$$

$$\begin{aligned} M_{T1} \text{ (adjacent to trunnion block)} &= 49.42 [0.7(89.72) - 27] \\ &= 1769 \text{ kip-in.} \end{aligned} \quad (\text{Eq I-33})$$

$$\begin{aligned} M_{T2} \text{ (at cross axis)} &= -49.42(0.3)(89.72) \\ &= -1330 \text{ kip-in.} \end{aligned} \quad (\text{Eq I-34})$$

$$\begin{aligned} M_{B2} \text{ (at cross axis)} &= -64.39(0.3)(86.71) \\ &= -1675 \text{ kip-in.} \end{aligned} \quad (\text{Eq I-35})$$

A1.5.3 Band Stresses.

Top band at trunnion axis:

$$f_o = -\frac{2437}{254.6} = -9.57 \text{ ksi} \quad (\text{Eq I-36a})$$

$$f_l = +\frac{2437}{316.4} = +7.70 \text{ ksi} \quad (\text{Eq I-36b})$$

Top band adjacent to trunnion block:

$$f_o = -\frac{1769}{114.7} = -15.42 \text{ ksi} \quad (\text{Eq I-36a})$$

$$f_l = +\frac{1769}{183.8} = +9.62 \text{ ksi} \quad (\text{Eq I-36b})$$

Top band at cross axis:

$$f_o = -\frac{49.42}{69.5} + \frac{1330}{114.7} = +10.88 \text{ ksi} \quad (\text{Eq I-37a})$$

$$f_l = -\frac{49.42}{69.5} - \frac{1330}{183.8} = -7.95 \text{ ksi} \quad (\text{Eq I-37b})$$

Bottom band at cross axis:

$$f_o = -\frac{64.39}{88.9} + \frac{1675}{214.4} = +7.09 \text{ ksi} \quad (\text{Eq I-38a})$$

$$f_l = -\frac{64.39}{88.9} - \frac{1675}{309.8} = -6.13 \text{ ksi} \quad (\text{Eq I-38b})$$

Use ASTM A516, Grade 55 material for the bands. This material has the same tensile and yield strength as A285, Grade C material used for the sidewalls and $\sigma_a = 7.99$ ksi at 650°F. The allowable combined stress is the same at all band locations and is $2(7.99) = 15.98$ ksi (Section I-9.9). The band stresses determined above are satisfactory at all locations.

A1.5.4 Band Weld Stresses. The fillet welds connecting the band to the trunnion block and the band to the shell transmit shear force given by:

$$f'_s = \frac{Vay}{I}$$

where:

a = Area beyond vertical shear plane (and fillet welds) of interest in trunnion block region, sq in.

f'_s = Shear force over the vertical shear plane of interest, kips/in.

I = Moment of inertia of trunnion block/band cross-sectional region (see Summary of Effective Band Properties, Section A1.5.1), in.⁴

V = Radial force on band in region of trunnion block, kips

y = Distance from neutral axis (neutral axis determined in evaluation of band properties) of trunnion block/band cross-sectional region to centroid of area, a , in.

Evaluation of shear stress in the two circumferential $\frac{3}{4}$ -in. fillet welds (Fig. A5) connecting the top band to the sidewall plate.

$$V = F_T = 49.42 \text{ kips}$$

From the top band trunnion axis property calculations (Section A1.5.1, Fig. A5):

$$e = 4.57 \text{ in. (location of neutral axis)}$$

$$I = 1446 \text{ in.}^4$$

The area beyond the vertical shear plane of interest (area beyond the two $\frac{3}{4}$ -in. fillet welds, see Fig. A5) is the $1\frac{1}{4}$ -in. sidewall plate:

$$a = (12.7 + 5 + 7.3)(1.25) = 31.25 \text{ in.}^2$$

The centroid location of area, a , from the neutral axis is:

$$y = e - \frac{t}{2} = 4.57 - \frac{1.25}{2} = 3.94 \text{ in.}$$

Then:

$$f'_s = \frac{49.42(31.25)(3.94)}{1446} = 4.21 \text{ kips/in.}$$

The shear stress in the two $\frac{3}{4}$ -in. fillet welds (through the throat of the welds) is:

$$\tau = \frac{f'_s}{b} = \frac{4.21}{2(0.75)(0.707)} = 3.97 \text{ ksi}$$

This is less than the allowable limit (Section I-5.4.6) of $1.2 \times 7.99 = 9.59 \text{ ksi}$, and also less than the AWS endurance limit of 8.0 ksi.

Evaluation of shear stress in the single circumferential $\frac{3}{4}$ -in. fillet weld connecting the trunnion block to the outer edge of the top band.

From the top band trunnion axis property calculations (Section A1.5.1, Fig. A5):

$$e = 5.68 \text{ in.}$$

$$I = 1446 \text{ in.}^4$$

The area beyond the vertical shear plane of interest is the one inch projection of the top band beyond the trunnion block. Therefore:

$$a = 5(1) = 5 \text{ in.}^2$$

$$y = 5.68 - 0.5 = 5.18 \text{ in.}$$

Then

$$f'_s = \frac{49.42(5)(5.18)}{1446} = 0.885 \text{ kips/in.}$$

The shear stress in the single $\frac{3}{4}$ -in. fillet weld is:

$$\tau = \frac{0.885}{0.75(0.707)} = 1.67 \text{ ksi}$$

This weld must also carry the radial force considered previously (Section A1.4.4).

The equivalent shear stress is:

$$\tau_{eq} = \sqrt{1.67^2 + 3.04^2} = 3.47 \text{ ksi} < 8.0 \text{ ksi}; \quad \text{OK}$$

For the bottom band-to-sidewall welds (two circumferential 3/4-in. fillet welds, Fig. A7):

$$a = 1.25(24.5) = 30.63 \text{ sq in.}$$

$$I = 2510 \text{ in.}^4$$

$$v = F_B = 64.39 \text{ kips}$$

$$y = 5.36 - 0.625 = 4.74 \text{ in.}$$

$$f'_s = \frac{64.39(30.63)(4.74)}{2510} = 3.72 \text{ kips/in.}$$

$$\tau = \frac{3.72}{2(0.75)(0.707)} = 3.51 \text{ ksi} < 8.0 \text{ ksi}; \quad \text{OK}$$

For the bottom band to block weld (single circumferential 1 1/2-in. fillet weld, Fig. A7):

$$a = 5(5) = 25 \text{ sq in.}$$

$$y = 8.89 - 2.5 = 6.39 \text{ in.}$$

$$f'_s = \frac{64.39(25)(6.39)}{2510} = 4.10 \text{ kips/in.}$$

$$\tau = \frac{4.10}{1.5(0.707)} = 3.87 \text{ ksi}$$

$$\tau_{eq} = \sqrt{3.87^2 + 1.52^2} = 4.16 \text{ ksi} < 8.0 \text{ ksi}; \quad \text{OK}$$

Since the shear force is zero at the cross axis, the weld stresses at the cross axis will be negligible.

A1.5.5 Deflection Index.

The deflection index (Section I-11) is:

$$\lambda = \frac{C_D P R_{RM}^2}{E I_2} \quad (\text{Eq I-41})$$

Determine C_D by interpolation from Table I-8, using β , $\frac{I}{R_{RM}}$ and $\frac{I_2}{I_1}$

From Fig. A1, the inside radius at the average band height is:

$$= 76.5 + \frac{(58 + 123)(89 - 76.5)}{2(166)} = 83.31 \text{ in.}$$

$$\beta = \frac{180(27)}{\pi(83.31)} = 18.57 \text{ degrees}$$

$$\frac{I}{R_{RM}} = 0 \text{ (circular ladle)}$$

$$I_2 = 724 \left(\frac{123}{99} \right)^2 + 1806 \left(\frac{58}{99} \right)^2 = 1737 \text{ in.}^4 \quad (\text{Eq 1-43})$$

$$I_1 = 1446 \left(\frac{123}{99} \right)^2 + 2510 \left(\frac{58}{99} \right)^2 = 3094 \text{ in.}^4 \quad (\text{Eq 1-42})$$

$$\frac{I_2}{I_1} = \frac{1737}{3094} = 0.56$$

$$C_D = 0.0560$$

$$P = 2(F_T + F_B) = 2(49.42 + 64.39) = 227.62 \text{ kips} \quad (\text{Eq 1-44})$$

$$R_{RM} = \frac{R_{RT} + R_{RB}}{2} = \frac{89.96 + 86.71}{2} = 88.34 \text{ in.} \quad (\text{Eq 1-45})$$

$$E = 29,500 \text{ ksi}$$

$$\lambda = \frac{0.0560(227.62)(88.34)^2}{29500(1737)}$$

$$= 0.00194 < 0.0026: \text{ OK}$$

A1.6 Riveted Sidewall Connection.

The 280-ton circular ladle may be fabricated with a welded or riveted circumferential sidewall connection. The user of this ladle has requested the ladle manufacturer to calculate the requirements of a riveted connection in order to make a decision on the feasibility of a riveted field connection.

A1.6.1 Design of the Riveted Sidewall Connection. The required number of rivets on each side of the single buttstrap connection is:

$$N_r \geq 0.70 \frac{A_w \sigma_a}{A_r \tau_r} \quad (\text{Eq 1-51})$$

From the previous design conditions:

$$\sigma_a = 7.99 \text{ ksi} \quad (\text{Eq 1-2 and 1-3})$$

For the rivets, ASTM A31, Grade B, is selected:

$$\tau_r = 15.5 \text{ ksi}$$

The cross-sectional area of the sidewall plate remote from the riveted connection (at the ladle bottom) is:

$$A_w = \pi(153)(1.25) = 600.83 \text{ in.}^2$$

Using 1 1/4 in. diameter rivets, the cross-sectional area of the rivet is:

$$A_r = \pi \left(\frac{1.25}{2} \right)^2 = 1.23 \text{ in.}^2$$

The required number of rivets is:

$$N_r \geq \frac{(0.70)(600.83)(7.99)}{1.23(15.5)} = 176.26; \text{ use 178 rivets.}$$

A1.6.2 Rivet Spacing and Edge Distances. The minimum spacing between rivets for the buttstrap and sidewall plate is:

$$3 d_r = 3(1.25) = 3.75 \text{ in.}$$

The minimum spacing (Section I-13.3) between the circumferential rows of rivets is:

$$1\frac{3}{4} d_r = 1.75(1.25) = 2.1875 \text{ in.}$$

The minimum edge distance from the center of the rivets to the plate edge is:

$$1\frac{1}{4} d_r = 1.25(1.25) = 1.5625 \text{ in.}$$

The maximum edge distance from the center of the rivets to the plate edge is:

$$1\frac{3}{4} d_r = 1.75(1.25) = 2.1875 \text{ in.}$$

The circumferential sidewall splice between the riveted connection is located two ft below the bottom stiffener band. The maximum number of rivets per circumferential row is (using average inside shell radius at the connection splice):

$$= \frac{2 \pi (79.06)}{3.75} \approx 132$$

Since the total number of rivets required on each side of the connection is 178, at least two rows of rivets, at 89 rivets per row, are required. Since 89 rivets are used per row, the minimum spacing between rivets is satisfied. That is, the spacing between rivets is:

$$= \frac{2 \pi (79.06)}{89} = 5.58 \text{ in.}$$

A1.6.3 Maximum Bearing Stress in Rivets.

The maximum allowable bearing stress in the rivets is twice the allowable shear stress. Therefore, the allowable bearing stress is:

$$= 2(15.5) = 31.0 \text{ ksi}$$

The inside portion of the rivet is countersunk to reduce the interference with the refractory lining, as shown in Fig. A9. The depth of the countersink is $\frac{1}{2}$ in. The total effective length of the rivet is therefore 1.0 in. (sidewall plate thickness, less one half the countersink depth). The estimated load on the riveted connection, W_2' , is 800 kips less the ladle steelwork weight above the riveted connection 30 kips. Then:

$$W_2' = 800 - 30 = 770 \text{ kips}$$

The total bearing area is:

$$= 1.0(1.25)(178) = 222.5 \text{ in.}^2$$

The bearing stress on the rivets is:

$$= \frac{770}{222.5} = 3.46 \text{ ksi} < 31.0 \text{ ksi; OK}$$

A1.6.4 Stresses in Sidewall Plate. The maximum normal tensile stress in the sidewall plate as defined by Eq I-52 is:

$$1.4 \sigma_a = 1.4(7.99) = 11.19 \text{ ksi}$$

The maximum normal stress is:

$$\sigma'_{\text{min}} = \frac{W_2}{A_n} \leq 1.4 \sigma_a \quad (\text{Eq I-52})$$

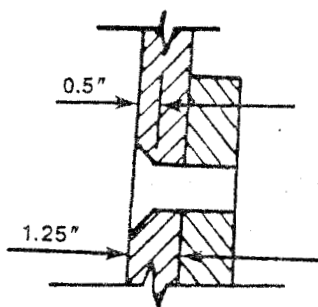


Fig. A9 — Rivet Countersink

The weight W_2 is defined as 800 kips. The minimum effective net area is calculated as:

Trial Section 1:

$$(5.58 - d_r)(N_r)(t) = (5.58 - 1.25)(89)(1.25) \\ = 481.71 \text{ in.}^2$$

Trial Section 2:

$$= \left[5.58 - 2 d_r + 2 \left(\frac{s^2}{4g} \right) \right] (N_r)(t) \\ = \left[5.58 - 2(1.25) + 2 \left(\frac{2.1875^2}{4(1.875)} \right) \right] (89)(1.25) \\ = [5.58 - 2.50 + 1.276](89)(1.25) \\ = [4.356](89)(1.25) \\ = 484.61 \text{ in.}^2$$

Therefore:

$$\sigma'_{ah} = \frac{800}{484.61} = 1.65 \text{ ksi} \leq 1.4 (7.99) = 11.19 \text{ ksi: OK} \quad (\text{Eq I-52})$$

The previously calculated bearing stress in the rivets was 3.46 ksi. The bearing stress limit for the sidewall plate is defined as:

$$\sigma_{bh} = 1.6(7.99) = 12.78 \text{ ksi} \quad (\text{Eq I-53})$$

Therefore:

$$3.46 \leq 12.78 \text{ ksi: OK}$$

The minimum distance from the first row of rivets to the bottom side of the bottom stiffener band is defined by Eq I-39 and calculated as:

$$e_T = 0.75 \sqrt{(79.06)(1.25)} = 7.46 \text{ in.} \quad (\text{Eq I-39})$$

Therefore, with two circumferential rows of rivets at a spacing of 2.1875 in. (say 2¼ in.) and an edge distance of 1.5625 in. (1⅞ in.), the minimum distance from the splice to the bottom side of the bottom stiffener band is:

$$= 7.46 + 2.25 + 1.5625 = 11.2725 \text{ in.}$$

A check of the minimum effective area of the sidewall plate at the riveted connection shows that it is greater than 70% of the cross-sectional area of the bottom sidewall plate:

$$= \frac{484.61}{2 \pi \left(\frac{153}{2} \right) 1.25} = 0.81$$

A1.7 Design of Tilt Mechanism.

A tilt mechanism is designed which is similar to the mechanism defined in Section I-12. The pin-connected members are designed as pin-connected plate links. The tilt mechanism is to be fabricated from ASTM A516 Grade 70 material. The allowable normal design stress for the design temperature of 600°F (see Table I-3) is:

$$\sigma_a = 10.26 \text{ ksi}$$

A1.7.1 Tilt Loads Imposed on Tilt Mechanism. For a design service molten metal weight, M_D , of 280 tons, the moment arm during deslagging is:

$$w_b = 3 \text{ in.}$$

The moment arm of the ladle structure, ladle lid and lining weight is:

$$w_a = 5 \text{ in.}$$

Therefore (with $w_c = 128 \text{ in.}$) the auxiliary hook load is:

$$F_S = \frac{56(3) + 240(5)}{128} = 22.50 \text{ kips} \quad (\text{Eq I-46})$$

A check on the tilt loads at the same tilt angle (approximately 11 degrees) with only a skull load (10% of 280 tons) attached to the ladle bottom:

$$w_d = 17 \text{ in.}$$

The auxiliary hook load is:

$$F_D = \frac{56(17) + 240(5)}{128} = 16.81 \text{ kips} \quad (\text{Eq I-47})$$

Therefore the deslagging loads govern at the tilt angle for deslagging.

For a tilt angle of 45 degrees, the moment arms are:

$$w_a = 10 \text{ in.}$$

$$w_c = 150 \text{ in.}$$

$$w_d = 60 \text{ in.}$$

The auxiliary hook load is:

$$F_D = \frac{56(60) + 240(10)}{150} = 38.40 \text{ kips} \quad (\text{Eq I-47})$$

For a tilt angle of 90 degrees, the moment arms are:

$$w_a = 14 \text{ in.}$$

$$w_c = 100 \text{ in.}$$

$$w_d = 85 \text{ in.}$$

The auxiliary hook load is:

$$F_D = \frac{56(85) + 240(14)}{100} = 81.20 \text{ kips} \quad (\text{Eq I-47})$$

For the complete inverted ladle position (tilt angle of approximately 180 degrees), the auxiliary hook load is equal to the structural plus lining weight of the ladle and the 56 kip skull:

$$F_D = 56 + 240 = 296 \text{ kips}$$

For an emergency aborted heat, at a tilt angle of 19 degrees, the molten metal moment arm is:

$$w_b = 6 \text{ in.}$$

The moment arm for the ladle structural and lining weight is:

$$w_a = 5 \text{ in.}$$

Therefore (with $w_c = 139$ in.) the auxiliary hook load is:

$$F_S = \frac{560(6) + 240(5)}{139} = 32.81 \text{ kips} \quad (\text{Eq I-46})$$

For an emergency aborted heat, at a tilt angle of about 35 degrees, the molten metal moment arm is:

$$w_b = 7 \text{ in.}$$

The moment arm for the ladle structural and lining weight is:

$$w_a = 9 \text{ in.}$$

Therefore (with $w_c = 149$ in.) the auxiliary hook load is (molten metal weight at 200 tons):

$$F_S = \frac{400(7) + 240(9)}{149} = 33.29 \text{ kips} \quad (\text{Eq I-46})$$

For an emergency aborted heat, at a tilt angle of about 49 degrees, the molten metal moment arm is:

$$w_b = 2 \text{ in.}$$

The moment arm for the ladle structural and lining weight is:

$$w_a = 11 \text{ in.}$$

Therefore (with $w_c = 149$ in.) the auxiliary hook load is (molten metal weight at 150 tons):

$$F_S = \frac{300(2) + 240(11)}{149} = 21.74 \text{ kips} \quad (\text{Eq I-46})$$

Therefore the peak auxiliary hook load during emergency aborted heat is at the early stages of tilting.

A1.7.2 Design of Tilt Mechanism Components. The vertical tilt link is subjected to a maximum auxiliary hook load of 296 kips. The allowable tensile stress is (using ASTM A516 Grade 70 at 600°F with a $F_f = 1.0$):

$$\sigma'_a = 0.75(10.26) = 7.70 \text{ ksi} \quad (\text{Eq I-49})$$

The minimum area at section A-A (Fig. A12) is:

$$A = \frac{296}{7.70} = 38.44 \text{ sq in.}$$

Using two 3¼-in. thick, t_e , plates (two parallel plates), the width, $W_e - D_{ph}$, (Fig. A10) of the two plates making up the vertical link is:

$$W_e - D_{ph} = \frac{38.44}{2(3.25)} = 5.91 \text{ in.}$$

The diameter of the pin, D_p , is evaluated by considering double shear. The selected pin material is ASTM A668 Grade B. The allowable pin shear is calculated using Eq I-16b of Section I-5.7. The yield strength of A668 Grade B is 30.0 ksi.

Therefore:

$$\sigma_s = 0.40(30.0) = 12.0 \text{ ksi} \quad (\text{Eq I-16b})$$

The required pin area is:

$$A = \frac{296}{2(12.0)} = 12.33 \text{ sq in.}$$

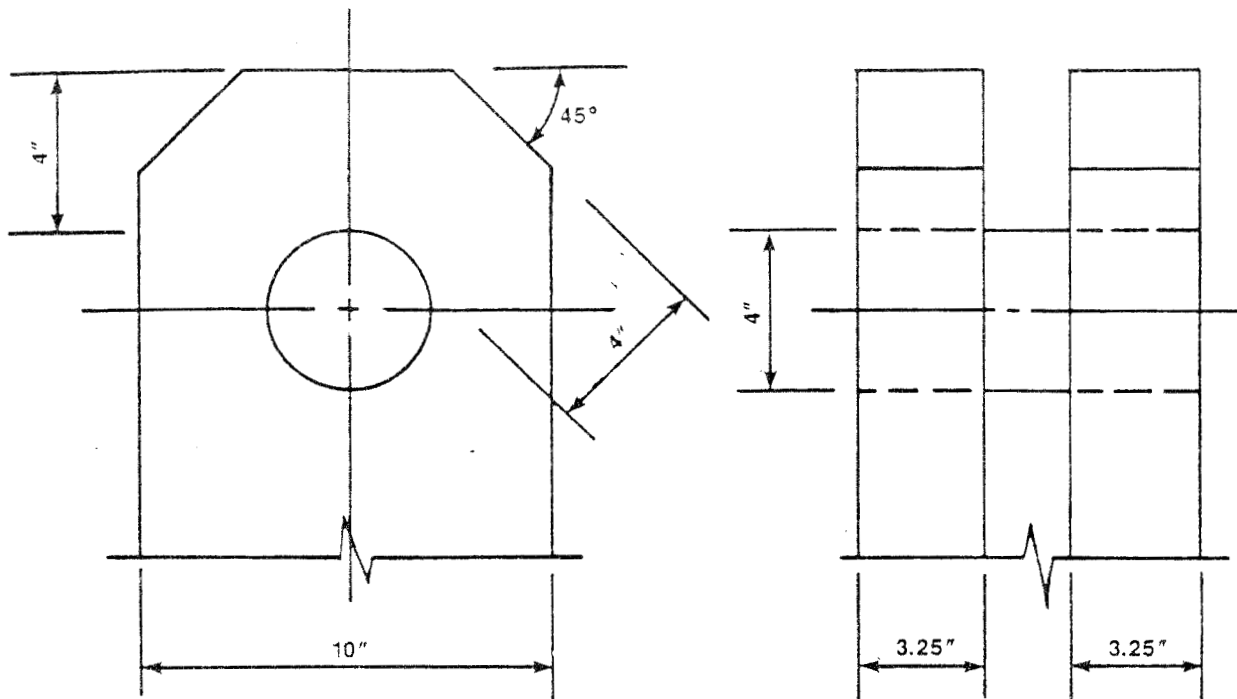


Fig. A10 — Hook Pin End of Vertical Pin-Connected Plate Link

The required pin diameter is:

$$\frac{\pi D_p^2}{4} = 12.33; D_p = 3.96 \text{ in.}; \text{ Use } D_p = 4 \text{ in.}$$

Note: The designer has the option to increase this diameter by a nominal wear and tear allowance.

The total depth, W_e , (Fig. I-18) of the vertical tilt link is:

$$W_e = 5.91 + 4.00 + 0.03125 = 9.94 \text{ in.}$$

Use a trial cross-section of 10 in. $\times$ 3¼ in. for each of the two plate members of the vertical tilt link and a pin diameter of 4 in. for the auxiliary crane hook. Checking on the requirements of the design parameters of the tilt link (see Fig. I-18):

$$D_{ph} = 4 + 0.03125 = 4.0312 \text{ in.}$$

$$D_t + \frac{10 - 4.0312}{2} = 2.984 \text{ in.}$$

$$4 t_e = 4(3.25) = 13 \text{ in.}$$

$$D_t < 4 t_e; \text{ OK}$$

$$1.25 D_t = 1.25(2.984) = 3.73 \text{ in.}$$

$$D_{ph} > 1.25 D_t; \text{ OK}$$

$$t_e > 0.5 \text{ in.}; \text{ OK}$$

$$D_d t_e \geq (2\frac{1}{2})(W_e - D_{ph}) t_e$$

$$D_d = (2\frac{1}{2})(10 - 4.03125) = 3.98 \text{ in.}; \text{ use } 4 \text{ in.}$$

Since all parameters are satisfied, the vertical pin-connected plate links are two 10 in. $\times$ 3¼-in. plates (see Fig. A10). The auxiliary crane hook pin is 4 in. in diameter.

Since the horizontal pin-connected plate link is exposed to the same maximum load environment as the vertical pin-connected plate link, it can be designed in a similar manner. However, three plates will be used for the horizontal link in order to provide appropriate redundancy in the structural strength. Each of the three plate thicknesses, t_e , is:

$$t_e = \frac{2(3.25)}{3} = 2.167; \text{ use } 2 \frac{3}{16} \text{ in. plates}$$

Use three 10 in. $\times$ 2 $\frac{3}{16}$ in. plates. Checking on the requirements of the design parameters:

$$D_t = 2.984 \text{ in.}$$

$$4 t_e = 4(2.1875) = 8.75 \text{ in.}$$

$$D_t < 4 t_e; \text{ OK}$$

$$D_{ph} = 4.03125 \text{ in.}$$

$$1.25 D_t = 1.25(2.984) = 3.73 \text{ in.}$$

$$D_{ph} > 1.25 D_t; \text{ OK}$$

$$t_e > 0.5 \text{ in.}; \text{ OK}$$

$$D_d = (33) (10 - 4.03125) = 3.98 \text{ in.}; \text{ use } 4 \text{ in.}$$

The pin hole diameter, D_{ph} , is made $\frac{1}{32}$ in. larger than the pin to allow rotation between the vertical and horizontal links and to satisfy the design parameter requirements of Fig. I-18.

The pivot pin connecting the vertical link to the horizontal link has a minimum area (four shear areas, see Fig. A11):

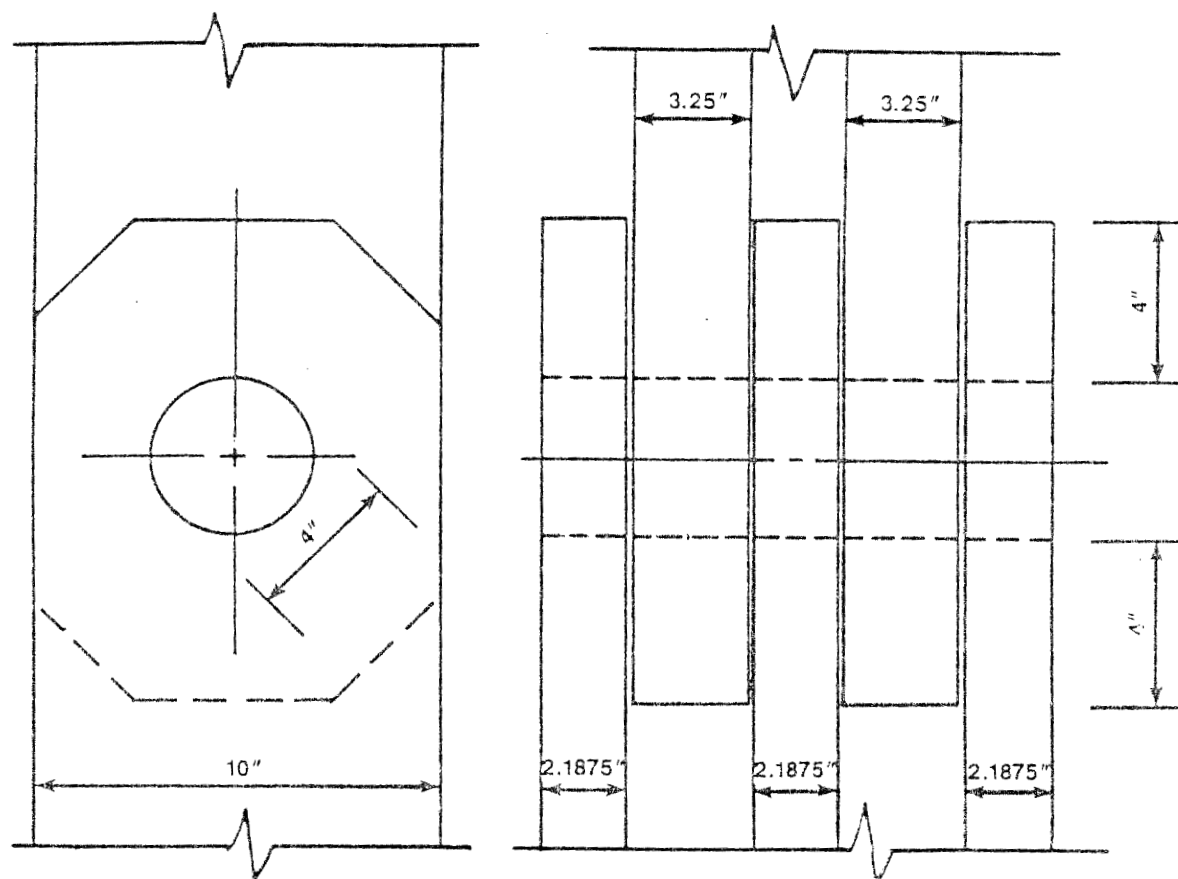


Fig. A11 — Pivot Pin Details

$$A = \frac{296}{4(12.0)} = 6.167 \text{ sq in.}$$

The required pin diameter is:

$$\frac{\pi D_p^2}{4} = 6.167$$

$$D_p = 2.80 \text{ in.}$$

Use $D_p = 2\frac{7}{8} \text{ in.}$; $D_{ph} = 2.875 + 0.03125 = 2.906 \text{ in.}$

Checking on the requirements of the design parameters:

$$D_t = \frac{10 - 2.906}{2} = 3.547 \text{ in.}$$

$$4 t_e = 4(2.1875) = 8.75 \text{ in. (using minimum thickness of horizontal links)}$$

$$D_t < 4 t_e; \text{ OK}$$

$$D_{ph} = 2.906 \text{ in.}$$

$$1.25 D_t = 1.25(3.547) = 4.43 \text{ in.}$$

$$D_{ph} < 1.25 D_t; \text{ unsatisfactory}$$

Use larger pin diameter. Try $D_{ph} = 3\frac{1}{2} \text{ in.}$

Rechecking the design parameters:

$$D_t = \frac{10 - 3.531}{2} = 3.23 \text{ in.}$$

$$4 t_e = 4(2.1875) = 8.75 \text{ in.}$$

$$D_t < 4 t_e; \text{ OK}$$

$$D_{ph} = 3.531 \text{ in.}$$

$$1.25 D_t = 1.25(3.23) = 4.04 \text{ in.}$$

$$D_{ph} < 1.25 D_t; \text{ Unsatisfactory}$$

Use pivot pin diameter same as auxiliary crane hook pin diameter.

Checking on bearing stress in the link plates; the allowable bearing stress is defined by Eq I-50:

$$\sigma_{br} = 1.5(10.26) = 15.39 \text{ ksi} \quad (\text{Eq I-50})$$

The allowable bearing stress in the pin material is greater than the allowable bearing stress in the plate links.

For the two 10 in. $\times$ 3 $\frac{1}{4}$ in. plates at the auxiliary crane hook pin the bearing stress, f_{br} , developed by the pin is:

$$f_{br} = \frac{296}{2(3.25)(4.0)} = 11.38 \text{ ksi} < 15.39 \text{ ksi}; \text{ OK}$$

For the three 10 in. $\times$ 2 $\frac{3}{4}$ in. plates at the pivot pin the bearing stress, f_{br} , developed by the pin is:

$$f_{br} = \frac{296}{3(2.1875)(4.0)} = 11.28 \text{ ksi} < 15.39 \text{ ksi}; \text{ OK}$$

The bottom pivot plates are incorporated into the flat bottom plate stiffener ribs. As shown in Fig. A12, the bottom ribs are positioned such that the four center ribs will support the tilt mechanism. The rib depth must be increased to 18 in. to support the weight of the ladle in the inverted position.

The section moduli are defined using the four center ribs:

$$e = \frac{4(18)(2.375)(10.25) + 61.2(1.25)(0.625)}{247.5}$$

$$= 7.28 \text{ in.}$$

$$I = \frac{4(2.375)(18)^3}{12} + \frac{61.2(1.25)^3}{12} + 4(18)(2.375)(2.97)^2 + 61.2(1.25)(6.655)^2$$

$$I = 9523 \text{ in.}^4$$

$$S_1 = \frac{9523}{11.97} = 795.6 \text{ in.}^3$$

$$S_2 = \frac{9523}{7.28} = 1308 \text{ in.}^3$$

The tensile and compressive stresses in the inverted ladle position are:

$$\sigma_{\text{comp}} = \frac{11,100}{1308} = 8.48 \text{ ksi}$$

$$\sigma_{\text{comp}} < \sigma_{bc} = 1.25 \sigma_a = 1.25(7.99) = 9.99 \text{ ksi; OK} \quad (\text{Eq I-7})$$

$$\sigma_{\text{ten}} = \frac{11,100}{795.6} = 13.95 \text{ ksi}$$

$$\sigma_{\text{ten}} < \sigma_{bt} = 2 \sigma_a = 2(7.99) = 15.98 \text{ ksi; OK} \quad (\text{Eq I-6})$$

The maximum shear stress at ends of the four center ribs is:

$$\tau_{\text{max}} = \frac{V Q}{I b}$$

$$V = \frac{296}{2} = 148 \text{ kips}$$

$$Q = 4(2.375) \left(\frac{18.0^2}{8} \right) = 384.75 \text{ in.}^3$$

$$I = 9523 \text{ in.}^4$$

$$b = (4)(2.375) = 9.5 \text{ in.}$$

$$\tau_{\text{max}} = \frac{148(384.75)}{9523(9.5)}$$

$$= 0.63 \text{ ksi} < 0.6 \sigma_a = 0.6(7.99) = 4.79 \text{ ksi; OK} \quad (\text{Eq I-11})$$

or the connection between the rib and sidewall, use a double groove full penetration weld as required by Section I-7.6.

As shown in Fig. A12, the shear plates are connected to the four ribs which support the ladle in the inverted position. The thickness of the shear plates are equal to the rib thickness and are attached to the ribs by full penetration welds.

The maximum latch plate loading occurs during emergency abort. The maximum load imposed on both latch plates is $2.81 \cos 19^\circ = 31 \text{ kips}$. As shown in Fig. A13, the latch plate is nearly square in configuration. The minimum ratio of width to thickness (using ASTM A285 Grade C at 650°F , $\sigma_a = 7.99 \text{ ksi}$) for stability²⁷ against buckling is:

$$\frac{b}{t} = \frac{180}{\sqrt{\sigma_y}} = \frac{180}{\sqrt{30}} = 32.9$$

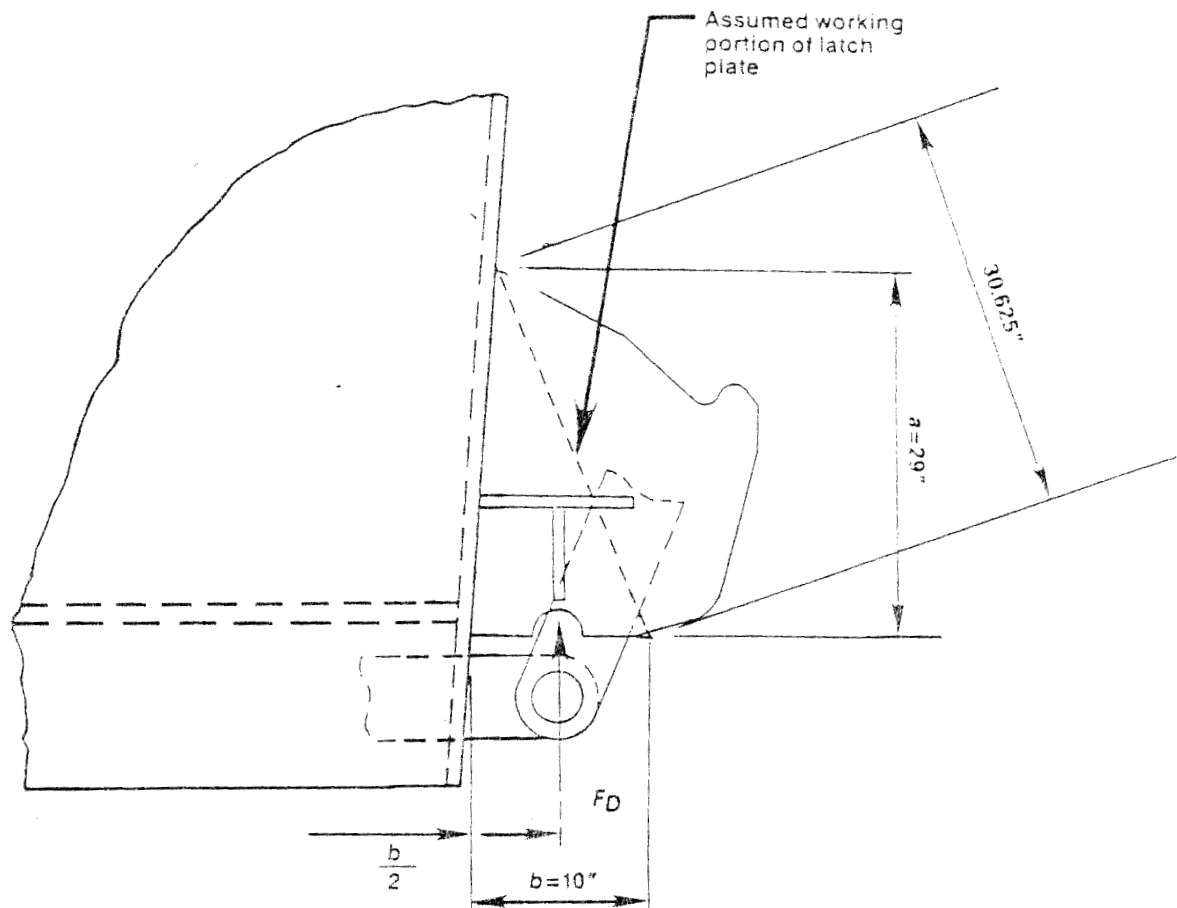


Fig. A13 — Latch Plate

For a width, b , of 10 in., the minimum required thickness for buckling consideration is:

$$t = \frac{b}{32.9} = \frac{10}{32.9} = 0.304 \text{ in.}$$

The design thickness²⁷ for eccentric loading (using two parallel latch plates and two triangular working portions as described in Fig. A13) is:

$$\begin{aligned} t &= \frac{F_D}{\sigma_{bc} b \cos^2 \alpha} \left(1 + \frac{6e}{b} \right) \\ &= \frac{31}{2(1.25)(7.99)(10) \left(\frac{10}{29} \right)^2} \left(1 + \frac{6(0)}{10} \right) \\ t &= 1.31 \text{ in.} \end{aligned}$$

Therefore the required thickness for eccentric loading governs. For latch plates use two 1 $\frac{3}{8}$ -in. thick plates.

The stresses imposed on the sidewall by each plate are:

$$M = \frac{31(5)}{2} = 77.5 \text{ kip-in.}$$

The section modulus is:

$$S = \frac{b d^2}{6} = \frac{(1.375)(29)^2}{6} = 192.7 \text{ in.}^3$$

The maximum bending stress is:

$$\sigma_{\text{ten}} = \sigma_{\text{comp}} = \frac{77.5}{192.7} = 0.40 \text{ ksi}$$

$$\sigma_{\text{comp}} < \sigma_{bc} = 1.25(7.99) = 9.99 \text{ ksi; OK} \quad (\text{Eq I-7})$$

The maximum shear stress is:

$$\tau_{\text{max}} = \frac{V Q}{I b}$$

$$V = \frac{31}{2} = 15.5 \text{ kips}$$

$$b = 1.375 \text{ in.}$$

$$Q = 1.375 \left(\frac{29^2}{8} \right) = 144.55 \text{ in.}^3$$

$$I = \frac{b d^3}{12} = \frac{(1.375)(29)^3}{12} = 2794.6 \text{ in.}^4$$

$$\tau_{\text{max}} = \frac{15.5(144.55)}{2794.6(1.375)} = 0.58 \text{ ksi}$$

$$\tau_{\text{max}} < 0.6(7.99) = 4.79 \text{ ksi; OK} \quad (\text{Eq I-11})$$

Therefore the latch plate does not impose significant stresses on the ladle sidewall during tilting. As shown in Fig. A13, racing plates are used on each latch plate to provide additional stiffness to the latch plates.

These computations, based on the ladle weight (A1.1), are considered as preliminary. After evaluating ladle dimensions, the actual weights shall be established. The resulting stresses, using the actual weights, shall not exceed the allowable stresses. If the allowable stresses are exceeded, change in component sizes shall be required, new weights established and stresses computed such that those stresses are equal to or less than the allowable ones.

1.8 Estimating Wall Working Lining Expansion Allowance. The sidewall plate stresses caused by the expansion of the wall working lining are evaluated^{10, 26}. The ladle wall temperatures during preheating are defined in Fig. A14. The evaluations are made for a 70% alumina brick working lining, a direct-bond mag-chrome working lining and a resin-bond dolomite working lining. These evaluations are a part of the lining design and the primary responsibility of the ladle user.

A1.8.1 Estimated Thermal Expansion Forces. The thermal expansion allowance and thermal expansion forces are estimated for 70% alumina brick, direct-bond mag-chrome and resin-bond dolomite linings. Each lining is assumed to be 6 in. thick.

For the 70% alumina and the direct-bond mag-chrome linings, the expansion allowance and expansion forces are calculated for the standard preheat condition. In the case of the resin-bond dolomite brick lining, the expansion allowance is determined for the steady state temperature condition at the end of a ramped preheat.

The following equations are used for evaluating the expansion forces:

$$\delta = \alpha_{wl} \Delta \theta_{wl} R_{wl} - \alpha_s \Delta \theta_s R_{s(\text{ave})} \quad (\text{Eq II-1a})$$

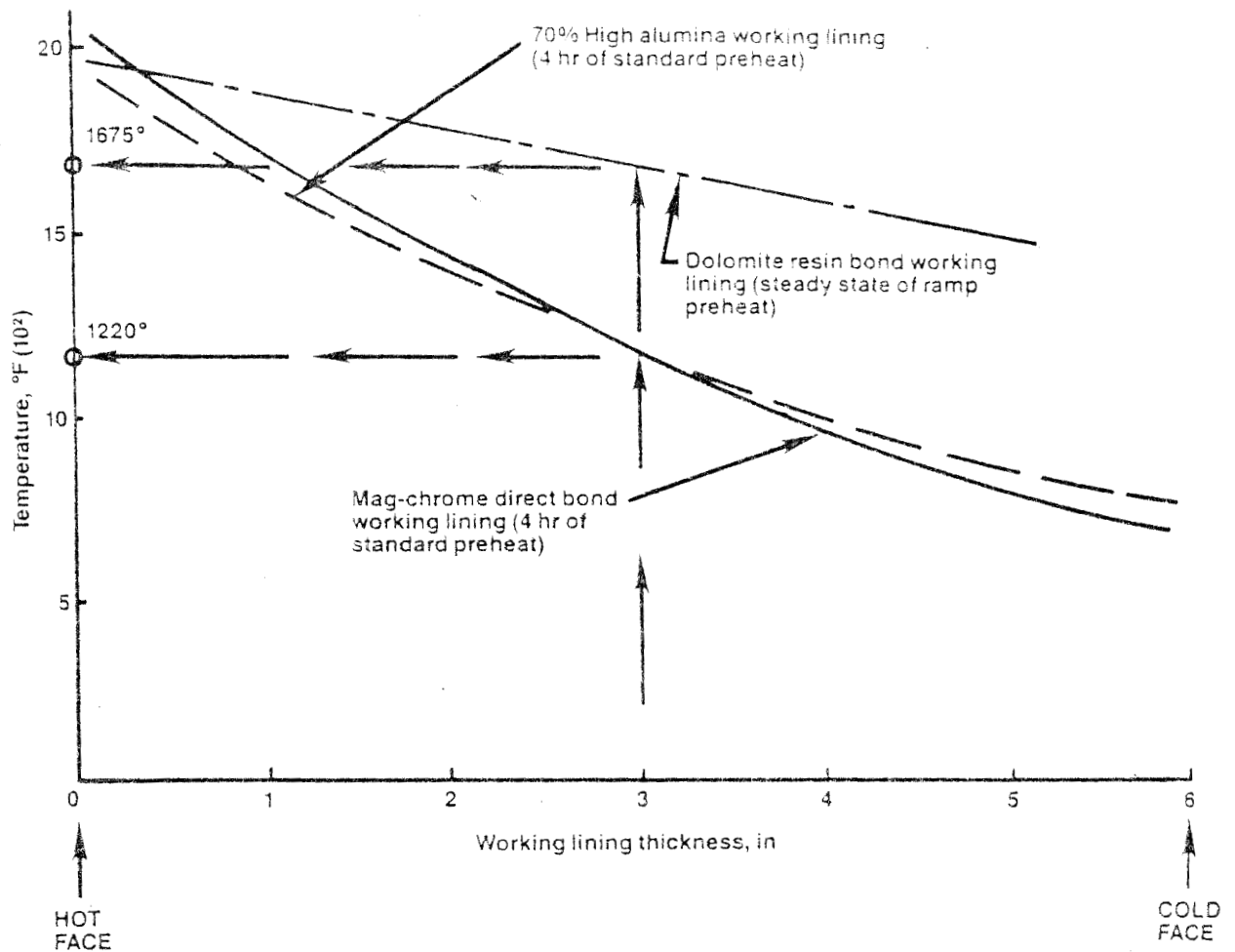


Fig. A14 — Assumed Working Lining Temperature Distribution During Preheat

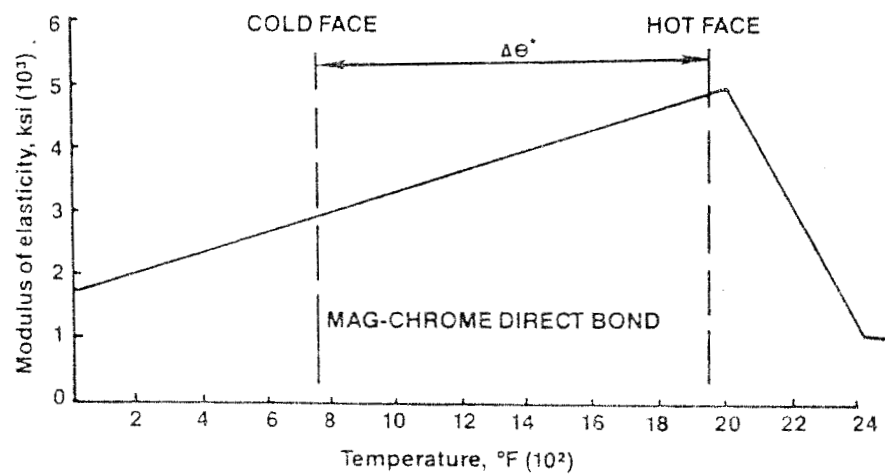
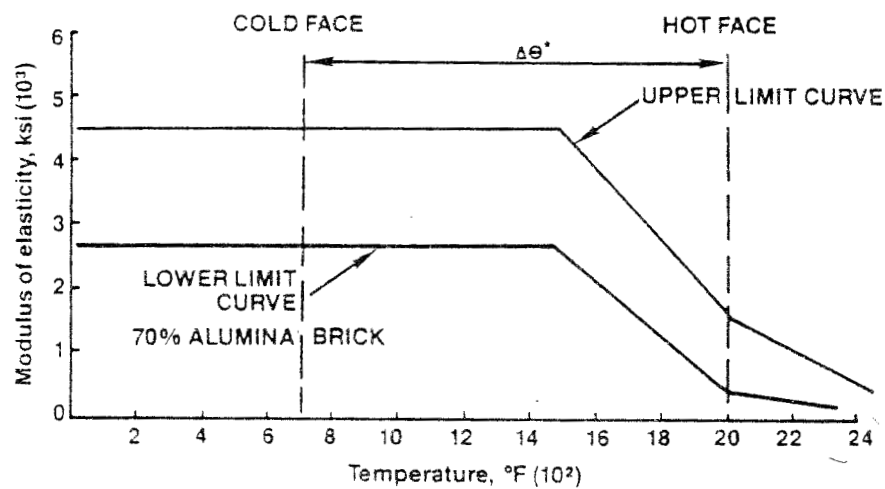
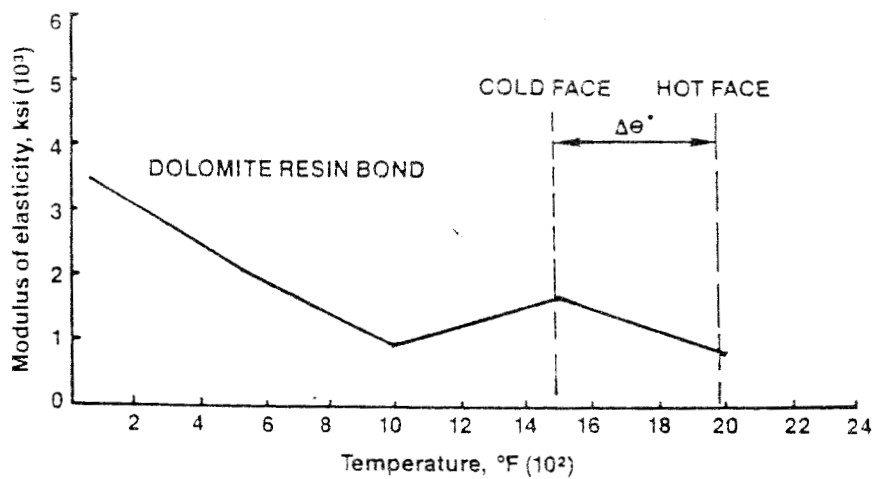
$$p = \frac{\delta}{\left[\frac{R_{wl}^2}{t_{wl} E_{wl}} + \frac{R_s(ave)^2}{t E_s} \right]} \quad (\text{Eq II-1b})$$

$$f_{ex} = \frac{p R_s(ave)}{t} \quad (\text{Eq II-1c})$$

The temperature distributions during transient preheat in the three working lining materials to be evaluated are shown in Fig. A14^{10, 26}.

The temperature-dependent elastic modulus of each working lining refractory to be evaluated is described in Fig. A15^{10, 26}. The elastic modulus is derived from the stress/strain tests conducted on each refractory^{10, 26} and is defined as the effective modulus of elasticity since mortar joint²³ compressibility is included.

The thermal expansion coefficient for each material was obtained from manufacturer's data. Average ladle wall dimensions are shown in Fig. A16.



*See Fig. A14 for lining temperatures

Fig. A15 — Temperature Dependent Elastic Modulus of Working Lining Refractories

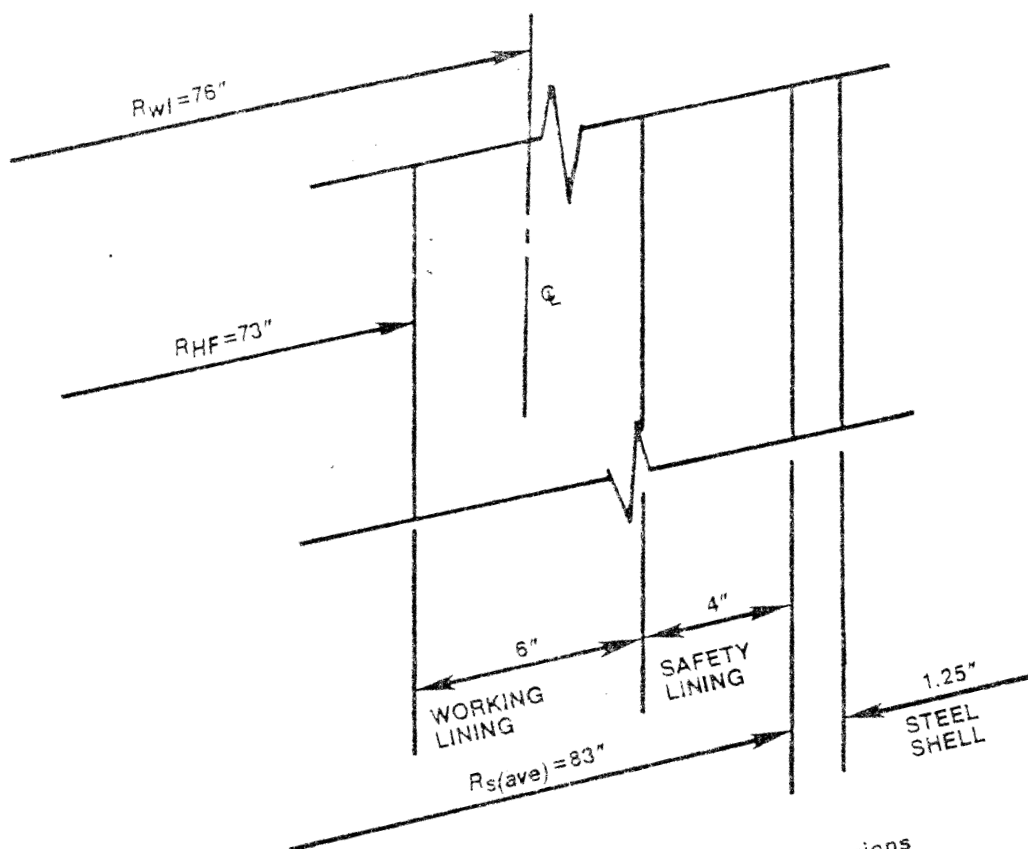


Fig. A16 — Typical Ladle Wall Dimensions

A1.3.2 Estimated Thermal Expansion Force for the 70% Alumina Wall Working Lining for Transient Preheat

Conditions:

$$\alpha_{wl} = 3.3 \times 10^{-6} \text{ in./in.}^\circ\text{F}$$

$$\Delta\theta_{wl} = 1220^\circ - 70^\circ = 1150^\circ\text{F (See Fig. A14)}$$

$$R_{wl} = 76 \text{ in. (See Fig. A16)}$$

$$\alpha_s = 6.5 \times 10^{-6} \text{ in./in.}^\circ\text{F}$$

In this example problem, the ladle sidewall temperature is assumed to be 500°F .

$$\Delta\theta_s = 500^\circ - 70^\circ = 430^\circ\text{F}$$

$$R_{s(ave)} = 83 \text{ in. (See Fig. A16)}$$

$$\delta = 3.3 \times 10^{-6} (1150)(76) - 6.5 \times 10^{-6} (430)(83)$$

$$= 0.288 - 0.232 = 0.056 \text{ in.}$$

The average elastic modulus of the working lining (See Fig. A15) is estimated as $4.2 \times 10^3 \text{ ksi}$.

$$p = \frac{0.056}{\frac{76^2}{6(4.20 \times 10^3)} + \frac{83^2}{1.25(30 \times 10^3)}}$$

$$= \frac{0.056}{2.29 \times 10^{-1} + 1.84 \times 10^{-1}}$$

$$p = \frac{0.056}{4.13 \times 10^{-1}} = 0.136 \text{ ksi}$$

(Eq II-1a)

(Eq II-1b)

The radial pressure of 0.136 ksi is imposed on the insulating brick. The insulating brick is exposed to potential crushing loads and should have the strength to resist these loads.

The resulting circumferential tensile stress in the ladle sidewall plate is:

$$f_{cx} = \frac{0.136(83)}{1.25} = 9.03 \text{ ksi} \quad (\text{Eq II-1c})$$

The thermal expansion of the 70% alumina working lining at steady state preheat condition develops sidewall stress of 9.03 ksi. The ferrostatic pressure also introduces a hoop stress of 2.34 ksi (see Section A1.8.3). The combined stress is 11.37 ksi. The allowable total stress is:

$$\sigma_{dl} = 1.0 F_f F_t \sigma_y = 1.0(1.0)(0.729)(30.0) = 21.87 \text{ ksi} \quad (\text{Eq I-10})$$

Since 11.37 ksi < 21.87 ksi, the lining design is satisfactory.

Section II-2.4.1 should be reviewed regarding the evaluation of the wall working lining expansion allowance.

A1.8.2.1 Estimated Thermal Expansion Force for Steady State Preheat Conditions: The maximum temperature at which the 70% alumina brick maintains significant strength (See Fig. A15) is approximately 1800°F. The maximum radial thermal expansion of the working lining (ΔR_{wl}) is:

$$\begin{aligned} \Delta R_{wl} &= R_{HF} \alpha_{wl} (\Delta T_{wl}) \\ &= 73(3.3 \times 10^{-6})(1800 - 70) = 0.417 \text{ in.} \end{aligned}$$

Where:

R_{HF} = Radius of working lining hot face, in.

ΔT_{wl} = Increase in hot face temperature from ambient up to 1800°F

The maximum radial expansion of the sidewall plate, ΔR_s is:

$$\begin{aligned} \Delta R_s &= R_{s(ave)} \alpha_s (\Delta T_s) \\ &= 83(6.5 \times 10^{-6})(650 - 70) = 0.313 \text{ in.} \end{aligned}$$

Where:

$R_{s(ave)}$ = Average radius of sidewall shell, in.

ΔT_s = Increase in sidewall shell temperature from ambient to maximum steady state condition, °F

The resulting interference between the wall working lining and sidewall plate is:

$$\Delta R_{wl} - \Delta R_s = 0.417 - 0.313 = 0.104 \text{ in.}$$

Therefore the lining expands 0.104 in. greater than the shell expansion. For steady state preheat conditions the radial pressure:

$$p = \frac{0.104}{4.13 \times 10^{-1}} = 0.252 \text{ ksi} \quad (\text{Eq II-1b})$$

and the resulting shell stress is:

$$f_{cx} = \frac{0.252(83)}{1.25} = 16.7 \text{ ksi}$$

This stress plus the ferrostatic hoop stress of 2.34 ksi (see Section A1.8.3) would be 19.04 ksi. This is within the allowable total stress of 21.87 ksi (see Section A1.8.2).

The above calculations are for ramp (slow heat-up) preheating. This implies that if ramp preheating is used the shell stresses do not exceed the allowable total stress and expansion allowance would not be required for ramp preheating a 70% alumina working lining.

The amount of expansion allowance required if standard (rapid heat up) preheat is used is estimated as:

$$\begin{aligned} Z_R &= 0.003 R_{HF} \\ &= 0.003(73) = 0.22 \text{ in.} \end{aligned} \quad (\text{Eq II-3})$$

Since Table II-1 governs the amount of expansion allowance, an expansion allowance no greater than $\frac{1}{8}$ in. should be used for this ladle.

The compressibility of the expansion allowance material (using 30 lb/ft³ blanket material) is determined as:

$$\begin{aligned} P_B &= 100 - 1.5q_B \\ P_B &= 100 - 1.5(30) \\ P_B &= 55\% \end{aligned} \quad (\text{Eq II-5})$$

The desired thickness of the blanket material is:

$$T_b = \frac{0.125}{55} \times 100 = 0.23 \text{ in.; use } \frac{1}{4} \text{ in. 30 lb/ft}^3 \text{ blanket material} \quad (\text{Eq II-6})$$

As previously noted, if a ramped preheat of about 100 to 200°F per hour is used instead of the standard preheat, then no expansion allowance is required.

The amount of expansion allowance between the lip ring and well lining is calculated as:

$$\begin{aligned} Z_A &= 0.0033 L_{70,D} \\ &= 0.0033(166) \\ &= 0.55 \text{ in.} \end{aligned} \quad (\text{Eq II-4a})$$

Assuming that an expansion allowance material has a compressibility of about 66%, the thickness of the expansion allowance material, T_{EM} , between the lip ring and the top of the wall lining (using the procedure of Eq II-6) is:

$$T_{EM} = \frac{0.55}{66} \times 100 = 0.83 \text{ in.; use approximately a 1-in. layer of material.}$$

A1.8.3 Sidewall Plate Thermal Expansion Force During Standard Preheat With Expansion Allowance Material for the 70% Alumina Working Lining. The following example is provided to demonstrate the use of expansion allowance material when rapid heat up is employed.

It is assumed the user has determined the working lining and shell temperatures during rapid preheat and conducted the calculations as previously described in this Section 1.8. The results:

$$f_{ex} = 28 \text{ ksi} > \sigma_{cl} = 21.87 \text{ ksi; unsatisfactory}$$

In order for $f_{ex} = 28 \text{ ksi}$, the temperature of the working lining at the mid-thickness would have to be 1690°F.

$$\theta_{wl} = 1690^\circ - 70^\circ = 1620^\circ$$

$$Z_R = 0.125$$

$$\delta = 3.3 \times 10^{-6} (1620)(76) - (6.5 \times 10^{-6}) (430)(83) = 0.125 \quad (\text{Eq II-3c})$$

$$\delta = 0.406 - 0.232 - 0.125 = 0.049$$

$$p = \frac{0.049}{4.13 \times 10^{-1}} = 0.119 \text{ ksi}$$

$$f_{ex} = \frac{0.119 (83)}{1.25} = 7.90 \text{ ksi}$$

The sidewall plate circumferential stress, during hot metal transport, near the bottom of the wall resulting from ferrostatic pressure is calculated from the pressure vessel stress equation:

$$f_{cir} = \frac{P_r R}{t}$$

Where:

P_r = Ferrostatic pressure applied to bottom region of sidewall, ksi

$$= 0.95 q H = \frac{0.95(0.42)(166)}{1728} = 0.0383 \text{ ksi}$$

R = Radius at bottom of sidewall plate, in.

t = Thickness of sidewall plate, in.

Substituting the appropriate values:

$$f_{cir} = \frac{0.0383(76.5)}{1.25} = 2.34 \text{ ksi}$$

The sidewall plate axial stress is calculated using a similar form of the previous equation. During hot metal transport, the sidewall plate axial stress near the bottom of the wall resulting from the ferrostatic load is:

$$f_{ax} = \frac{P_r R}{2t} = \frac{0.0383(76.5)}{2(1.25)} = 1.17 \text{ ksi}$$

The allowable stress (plate at 650°F) for the total maximum sidewall plate stress (Section I-5.4.4, Eq I-10) is:

$$\sigma_{dl} = 1.0(1.0)(0.729)(30) = 21.87 \text{ ksi} \quad (\text{Eq I-10})$$

The maximum total stress is calculated as:

$$f_{total\ cir} = 7.90 + 2.34 = 10.24 < 21.87 \text{ ksi; OK}$$

Based on strain gage tests, the lining expansion stress in the axial direction can be assumed to be equal to the hoop lining expansion stress.

$$f_{total\ ax} = 7.90 + 1.17 = 9.07 < 21.87 \text{ ksi; OK}$$

Note that the rapid heat up required the use of expansion allowance material. However this practice may result in an undesirable loose lining at the steady state heated conditions (end of preheat and during molten metal hold) of the lining.

A1.8.4 Estimated Thermal Expansion Force for a Direct-Bond Mag-Chrome Wall Working Lining for Transient Preheat Conditions:

$$\alpha_{wl} = 5.5 \times 10^{-6} \text{ in./in. } ^\circ\text{F}$$

$$\Delta\theta_{wl} = 1220^\circ - 70^\circ = 1150^\circ\text{F (See Fig. A14)}$$

$$R_{wl} = 76 \text{ in. (See Fig. A16)}$$

$$\alpha_s = 6.5 \times 10^{-6} \text{ in./in. } ^\circ\text{F}$$

$$\Delta\theta_s = 500^\circ - 70^\circ = 430^\circ\text{F}$$

$$R_{s(ave)} = 83 \text{ in. (See Fig. A16)}$$

$$\delta = (5.5 \times 10^{-6})(1150)(76) - (6.5 \times 10^{-6})(430)(83) \quad (\text{Eq II-1a})$$

$$= 0.481 - 0.232 = 0.249 \text{ in.}$$

$$E_{wl} = 3.75 \times 10^3 \text{ ksi (See Fig. A15)}$$

$$p = \frac{0.249}{\left[\frac{76^2}{(6)(3.75 \times 10^3)} + \frac{83^2}{(1.25)(30 \times 10^3)} \right]} \quad (\text{Eq II-1})$$

$$= \frac{0.249}{2.57 \times 10^{-1} + 1.84 \times 10^{-1}} = \frac{0.249}{4.41 \times 10^{-1}} = 0.565 \text{ ksi}$$

$$f_{ex} = \frac{0.565(83)}{1.25} = 37.52 \text{ ksi} > \sigma_{dl} = 21.87 \text{ ksi; unsatisfactory} \quad (\text{Eq II-1})$$

The thermal expansion of the direct-bond mag-chrome working lining develops a sidewall stress that is beyond the allowable stress of the sidewall plate. Therefore expansion allowance material is required.

The maximum temperature at which the direct-bond mag-chrome exhibits significant strength is 2200°F. The maximum radial thermal expansion of the working lining (ΔR_{wl}) is:

$$\begin{aligned} \Delta R_{wl} &= R_{HF} \alpha_{wl} (\Delta T_{wl}) \\ &= 73 (5.5 \times 10^{-6}) (2200 - 70) = 0.855 \text{ in.} \end{aligned}$$

The maximum radial expansion of the sidewall plate ΔR_s , using the maximum steady state sidewall plate temperature, is:

$$\begin{aligned} \Delta R_s &= R_{s(ave)} \alpha_s (\Delta T_s) \\ &= 83 (6.5 \times 10^{-6}) (650 - 70) = 0.313 \text{ in.} \end{aligned}$$

The resulting interference between the wall working lining and sidewall plate for steady state temperature condition is:

$$\Delta R_{wl} - \Delta R_s = 0.855 - 0.313 = 0.542 \text{ in.} \quad (\text{Eq II-1b})$$

$$p = \frac{0.542}{4.41 \times 10^{-1}} = 1.229 \text{ ksi}$$

$$f_{ex} = \frac{1.229(83)}{1.25} = 81.61 \text{ ksi} > \sigma_{dl} = 21.87 \text{ ksi; unsatisfactory} \quad (\text{Eq II-1c})$$

The thermal expansion of the direct-bond mag-chrome working lining at steady state heated conditions develops a sidewall stress that is beyond the allowable stress of the sidewall plate. Therefore expansion allowance is required.

The amount of expansion allowance is estimated as:

$$\begin{aligned} Z_R &= 0.006 R_{HF} \\ &= 0.006(73) = 0.44 \end{aligned} \quad (\text{Eq II-3b})$$

By interpolating Table II-1, an expansion allowance no greater than 0.47 in. should be used in the wall lining; however, the interference of the wall lining with the sidewall plate without expansion allowance is only 0.249 in.; therefore:

$$Z_R = 0.249$$

The compressibility of the expansion allowance material (using 25 lb/ft³ blanket material) is determined as:

$$P_g = 100 - 1.5(25) = 62.5\% \quad (\text{Eq II-5})$$

The desired thickness of blanket material is:

$$T_b = \frac{0.249}{62.5} \times 100 = 0.398 \text{ in.}$$

Use $\frac{3}{8}$ in. of 25 lb/ft³ blanket material.

It should be noted that even with ramp (slow heat up) preheating expansion allowance is recommended for the direct-bond mag-chrome working lining.

The amount of axial expansion allowance between the lip ring and wall lining is calculated as:

$$\begin{aligned} Z_A &= 0.0069 L_{MC} \\ &= 0.0069(166) \\ &= 1.15 \text{ in.} \end{aligned} \quad (\text{Eq II-4b})$$

Assuming the expansion allowance material has a compressibility of about 66%, the thickness of the expansion allowance material, T_{EM} , between the lip ring and the top of the wall lining (using the procedure of Eq II-6) is:

$$T_{EM} = \frac{1.15}{66} \times 100 = 1.74 \text{ in.; use } 1\frac{3}{4} \text{ in. of compressible refractory material}$$

A1.8.5 Sidewall Plate Thermal Expansion Force With Expansion Allowance Material for a Direct-Bond Mag-Chrome Working Lining. The sidewall stress resulting from the expansion of the direct-bond mag-chrome working lining with $\frac{3}{8}$ in. expansion allowance material is:

$$Z_R = \frac{0.375(62.5)}{100} = 0.234 \text{ in.}$$

$$\delta = (5.5 \times 10^{-6})(1150)(76) - (6.5 \times 10^{-6})(430)(83) = 0.234 \quad (\text{Eq II-3c})$$

$$\delta = 0.481 - 0.232 - 0.234 = 0.015 \text{ in.}$$

$$p = \frac{0.015}{4.41 \times 10^{-1}} = 0.034 \text{ ksi} \quad (\text{Eq II-1b})$$

$$f_{ex} = \frac{0.034(83)}{1.25} = 2.26 \text{ ksi} \quad (\text{Eq II-1c})$$

The expansion stress in the ladle sidewall satisfies the allowable stress defined in Eq I-10. Since the maximum stress condition is being determined, the sidewall stress resulting from ferrostatic pressure must also be included.

The sidewall circumferential and axial plate stresses, during hot metal transport, were previously calculated in Section A1.8.3.

The sidewall stresses (See A1.8.3) resulting from the ferrostatic pressure are:

$$f_{cir} = 2.34 \text{ ksi}$$

$$f_{ax} = 1.17 \text{ ksi}$$

The allowable stress for the total maximum sidewall plate stress (Section I-5.4.4, Eq I-10) is:

$$\sigma_{all} = 21.87 \text{ ksi} \quad (\text{Eq I-10})$$

The maximum total stress is calculated as;

$$f_{total \text{ cir}} = 2.26 + 2.34 = 4.60 \text{ ksi} < 21.87 \text{ ksi; OK}$$

$$f_{total \text{ ax}} = 2.26 + 1.17 = 3.43 \text{ ksi} < 21.87 \text{ ksi; OK}$$

In this example problem the expansion stresses are quite low. This brings into question the adequacy of the mechanical seal between bricks. A reduced expansion allowance should be considered which would result in an acceptable total stress and adequate mechanical seal. As a general rule, the expansion stresses should be considerably higher than the stresses resulting from ferrostatic pressure, while maintaining an upper limit not exceeding the maximum allowable sidewall plate stress.

A1.8.6 Estimated Thermal Expansion Force for the Resin-Bond Dolomite Wall Working Lining.

Based on preheating conditions the midthickness lining temperature was found to be 1675°F and the sidewall plate temperature to be 550°F (See Fig. A14).

$$\alpha_{wl} = 6.4 \times 10^{-6} \text{ in./in. } ^\circ\text{F}$$

$$\Delta\theta_{wl} = 1675^\circ - 70^\circ = 1605^\circ\text{F (See Fig. A14)}$$

$$R_{wl} = 76 \text{ in. (See Fig. A16)}$$

$$\alpha_s = 6.5 \times 10^{-6} \text{ in./in. } ^\circ\text{F}$$

$$\Delta\theta_s = 550^\circ - 70^\circ = 480^\circ\text{F}$$

$$R_{s(\text{ave})} = 83 \text{ in. (See Fig. A16)}$$

$$\delta = (6.4 \times 10^{-6})(1605)(76) - (6.5 \times 10^{-6})(480)(83) = 0.522 \text{ in. (Eq II-1a)}$$

$$E_{wl} = 1.5 \times 10^3 \text{ ksi (See Fig. A15)}$$

$$p = \frac{0.522}{\left[\frac{76^2}{(6)(1.5 \times 10^3)} + \frac{83^2}{(1.25)(30 \times 10^3)} \right]} \quad \text{(Eq II-1b)}$$

$$= \frac{0.522}{6.42 \times 10^{-1} + 1.84 \times 10^{-1}}$$

$$p = \frac{0.522}{8.26 \times 10^{-1}} = 0.632 \text{ ksi}$$

The resulting circumferential tensile stress in the sidewall plate is:

$$f_{ex} = \frac{0.632(83)}{1.25} = 41.96 \text{ ksi (Eq II-1c)}$$

The amount of radial expansion allowance is estimated as:

$$Z_R = 0.003 R_{HF} = 0.003(73) = 0.22 \text{ in. (Eq II-3a)}$$

By interpolating Table II-1, an expansion allowance no greater than 0.225 in. should be used for this ladle.

Using a compressible material that compresses to about 50% of the original installed thickness, the required thickness of the expansion allowance material is:

$$T_b = \frac{0.225}{50} \times 100 = 0.45 \text{ in. (Eq II-6)}$$

Therefore, 1/2 in. of the expansion allowance material is required behind the working lining. Typically, granular material is placed behind the working lining which acts as an effective expansion allowance material.

The amount of expansion allowance material between the lip ring and wall lining is calculated as:

$$\begin{aligned} Z_A &= 0.0033 L_{70D} \\ &= 0.0033(166) \\ &= 0.55 \text{ in.} \end{aligned} \quad (\text{Eq II-4a})$$

Using an expansion allowance material that compresses to about 50% of the original installed thickness, the thickness of the expansion allowance material, T_{EM} , under the lip ring (using the procedure of Eq II-6) is:

$$T_{EM} = \frac{0.55}{50} \times 100 = 1.10 \text{ in.}$$

A1.8.7 Sidewall Plate Thermal Expansion Force with Expansion Allowance Material in a Resin Bond Dolomite Working Lining. The sidewall stress resulting from the expansion of the resin bond dolomite working lining with 1/2-in. expansion allowance material is:

$$\begin{aligned} Z_R &= 0.225 \\ \delta &= (6.4 \times 10^{-6})(1605)(76) - (6.5 \times 10^{-6})(480)(83) - 0.225 \end{aligned} \quad (\text{Eq II-3c})$$

$$\delta = 0.781 - 0.259 - 0.225 = 0.297 \text{ in.}$$

$$p = \frac{0.297}{8.26 \times 10^{-1}} = 0.360 \text{ ksi}$$

$$f_{ex} = \frac{0.360(83)}{1.25} = 23.90 \text{ ksi} > \sigma_{dl} = 21.87 \text{ ksi; unsatisfactory} \quad (\text{Eq II-1c})$$

Even with expansion allowance the stresses in the side wall plate are beyond the allowable stress. A next logical step would be to evaluate the actual expansion allowance provided by an alternate material.

A2 Example 2 — 380-Ton Dished Ladle.

The general dimensions are determined by the 380-ton capacity ladle shown in Fig. A17. An obround shape with straight sides is used. The molten metal density, q , is 0.44 kips/cu ft. The operating temperatures of the bottom, sidewalls and trunnion block do not exceed 650°F, while the operating temperature of the trunnion pin does not exceed 500°F. Note: This example is to be referred to for calculation purposes only. It does not necessarily represent a practical design.

A2.1 Ladle Weight. The OIS specified a rated operating capacity of 380 tons and a freeboard height of 22 in. These specifications result in a vertical ladle height, H , of 198 in. (16 ft 6 in.) as described in Fig. A17. Since the freeboard of 22 in. represents 11% of the ladle height, the design procedure of Section I-5.1 is required.

The design capacity molten metal weight is calculated as 380 tons. The normal design load, W_2 , for the ladles is estimated as:

$$\begin{aligned} \text{Design molten metal weight} &= 760 \text{ kips} \\ \text{Ladle steelwork weight} &= 161 \text{ kips} \\ \text{Ladle lid weight} &= 25 \text{ kips} \\ \text{Ladle lining weight} &= 122 \text{ kips} \\ W_2 &= 1068 \text{ kips} \end{aligned}$$

Fig. A17 describes the ladle dimensions using the design procedure of Section I-5.1. According to Step 2b of Section I-5.1, an artificial height, h , is developed with a freeboard height of 5% of the total ladle height, H .

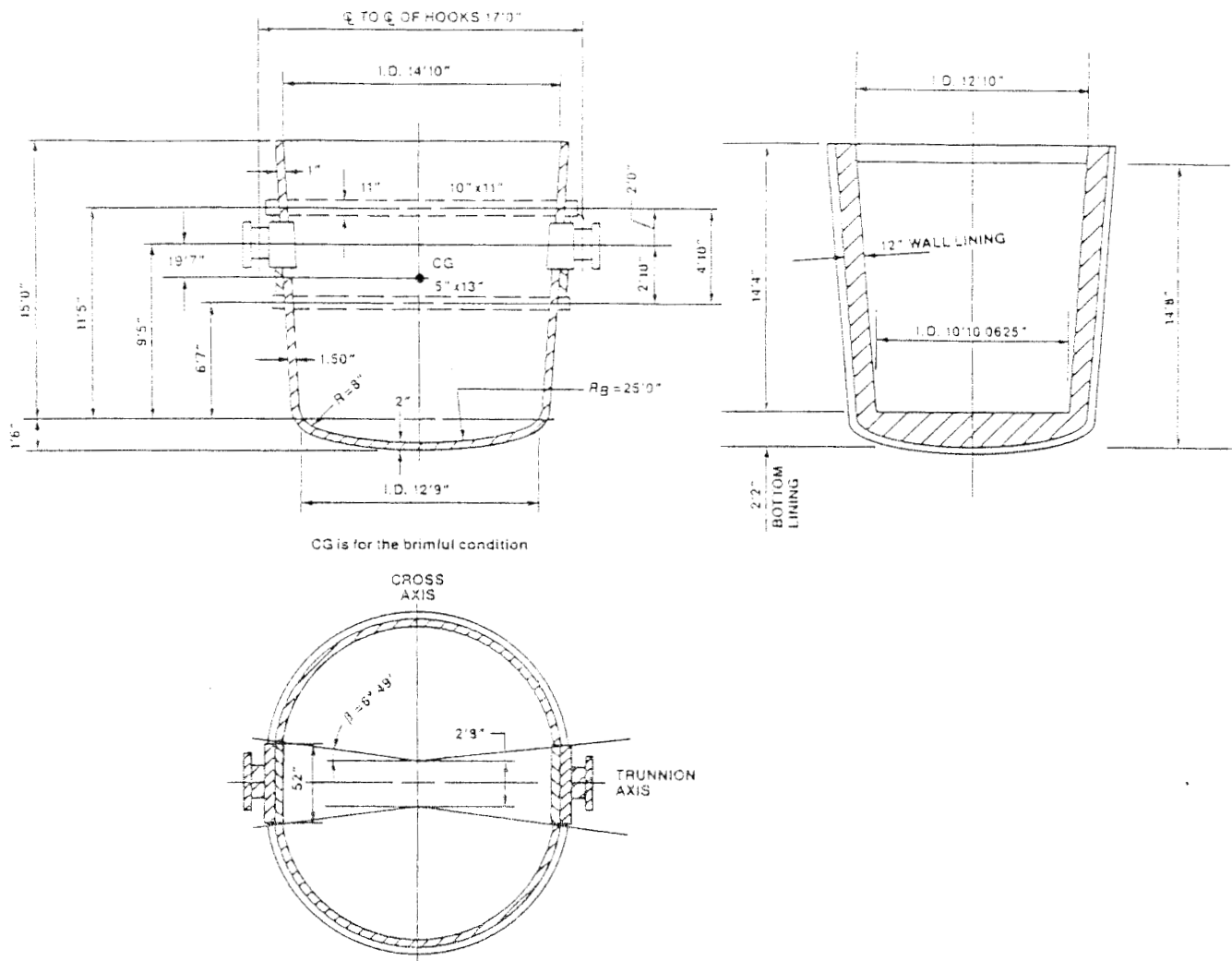


Fig. A17 — Dimensions Used in Example 2 Calculation for a 380-Ton Obround Ladle

The 5% freeboard = $0.05H = 0.05(198) = 9.9$ in. Use 10 in.

The height measured from the ladle bottom plate to the meniscus of the molten metal is 14 ft 8 in. (176 in.)

The artificial ladle height, h , = $176 + 10 = 186$ in.

The following design procedure is conducted with the artificial height incorporated where appropriate into the design procedure.

Since the allowable stress limits for the brimful design load is 130% of the allowable stress limits for the normal design load, the design of the ladle based on normal design requirements will satisfy the brimful design load requirements (Section A2.8).

A2.2 Bottom Plate. The required thickness for a dished bottom, obround ladle (Section I-8.3) is:

$$T_B = R_B \left[\frac{D_{\max} q H R_{S \min} \cos \phi}{4664 D_{(\min)} \sigma_a R_B \left(1 + \sqrt{\frac{R_{S(\min)}}{R_B}} \right)} \right]^{2/3} \quad (\text{Eq I-23a})$$

Use ASTM A285, Grade C material (Section I-3.2). The minimum room temperature tensile properties are given in the ASTM A285 specification as $\sigma_y = 30$ ksi (yield strength) and $\sigma_u = 55$ ksi (ultimate strength). The allowable normal stress (Section I-5.4.1) is:

$$\begin{aligned}\sigma_a &= \min \{ \sigma_{ay} ; \sigma_{au} \} \\ &= \min \left\{ \frac{F_f F_t \sigma_y}{F_l (SF)_y} ; \frac{F_f F_t \sigma_u}{F_l (SF)_u} \right\} \quad (\text{Eqs I-2 and I-3})\end{aligned}$$

$$F_f = f_1 f_2 f_3 f_4 f_5 = 1.0(1.0)(1.0)(1.0)(0.95) = 0.95$$

$$(f_5 = 0.95 \text{ for noncircular ladle})$$

$$F_t = 0.729 \text{ (Table I-1, temperature} = 650^\circ\text{F)}$$

$$F_l = 1.2, (SF)_y = 2.28, (SF)_u = 3.80$$

$$\sigma_a = \min \left\{ \frac{0.95(0.729)(30)}{1.2(2.28)} ; \frac{0.95(0.729)(55)}{1.2(3.8)} \right\}$$

$$= \min (7.59 ; 8.35)$$

$$= 7.59 \text{ ksi}$$

$$\text{Let } R_B = 300 \text{ in. (dish radius)}$$

$$D_{\max} = 185 \text{ in., } D_{\min} = 153 \text{ in.}$$

$$R_{S(\min)} = 76.5 + 0.75 = 77.25 \text{ in.}$$

$$\phi = \sin^{-1} \frac{77.25}{300} = 14.92 \text{ degrees, } \cos \phi = 0.966$$

$$H = h = 186 \text{ in., } q = 0.44 \text{ kips/cu ft}$$

$$T_B = 300 \left[\frac{185(0.44)(186)(77.25)(0.966)}{4664(153)(7.59)(300) \left(1 + \sqrt{\frac{77.25}{300}} \right)} \right]^{2/3}$$

$$= 1.79 \text{ in.}$$

Supplementary check (Section I-8.3):

$$T_B = \frac{0.44(186)(300)}{1819(7.59)} = 1.78 \text{ in.} \quad (\text{Eq I-23b})$$

$$\text{Use } T_B = 2.0 \text{ in.}$$

The minimum permissible worn thickness is:

$$\begin{aligned}T_{\min. \text{ worn}} &= \max \left\{ \frac{1.78}{1.30} ; \frac{1.78}{(1.30)^{2/3}} \right\} \\ &= \max (1.37 ; 1.50) = 1.50 \text{ in.}\end{aligned}$$

A2.3 Sidewall. The minimum sidewall plate thickness below the top band (Section I-10) is $1\frac{1}{8}$ in. for ASTM A285 Gr. C material for temperatures up to 650°F (Table I-7).

$$0.75 T_B = 0.75(1.78) = 1.34 \text{ in.} < 1\frac{1}{8} \text{ in.}$$

Use $1\frac{1}{2}$ in. for thickness requirement below the top band. Note that $1\frac{1}{8}$ in. plate is acceptable.

The supplementary thickness requirement below the top band is met, since:

$$t_{\min} = \frac{C_R q H D}{1819 \sigma_a} = \frac{1(0.44)(186)(185)}{1819(7.59)} = 1.10 \text{ in.} \quad (\text{Eq I-40a})$$

$$t_{\min} = \frac{2 C_R W_2}{\pi D \sigma_a} = \frac{2(1)(1068)}{\pi(185)(7.59)} = 0.48 \text{ in.} \quad (\text{Eq I-40b})$$

$$1.34 \text{ in.} > 1.10 \text{ in.; OK}$$

The minimum required thickness above the top band (Section I-10.4) = $0.66(1.34) = 0.88$ in. Use 1 in.

A2.4 Trunnion Pin and Block (Fig. A18).

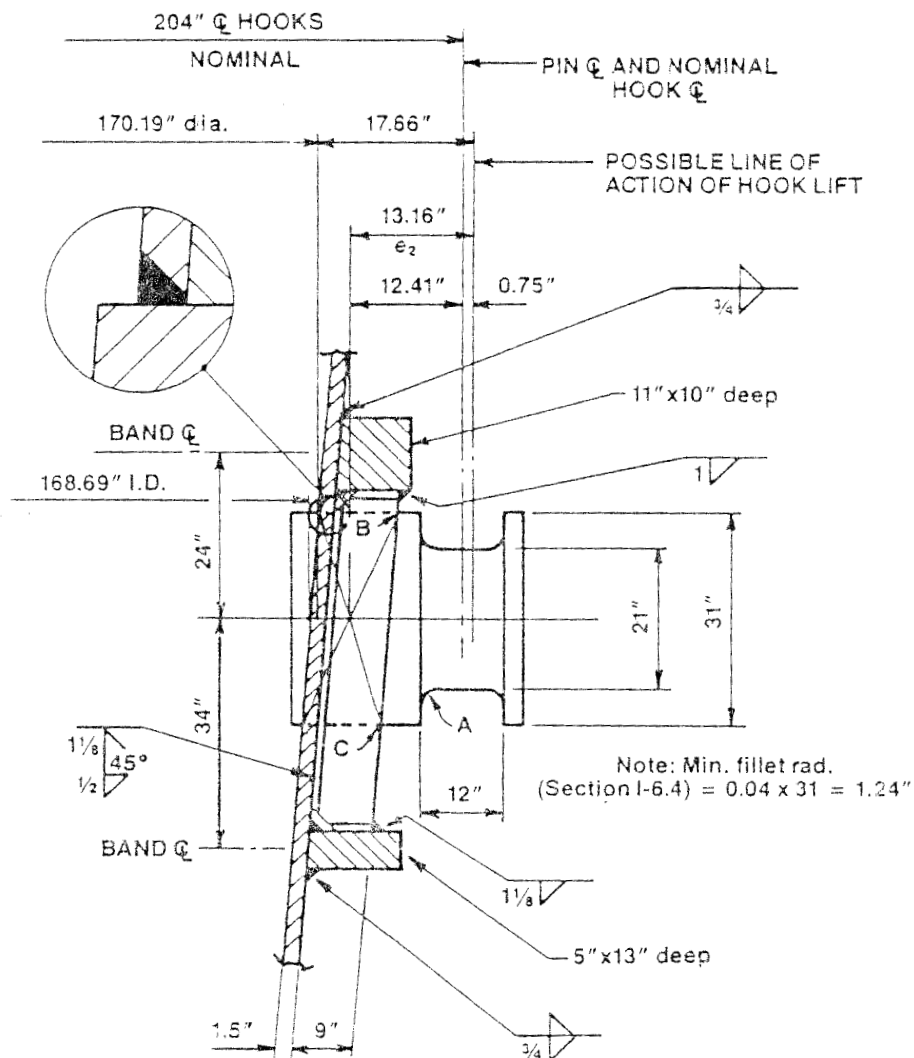


Fig. A18 — Trunnion Details

3

An increase of more than 30% in the sidewall stress due to thinning of the sidewall from wear, corrosion or other sources, should be cause for replacement or repair (Section I-5.4.7). The minimum permissible worn thickness is $1.341.30 = 1.03$ in. below the top band and $0.881.30 = 0.68$ in. above the top band.

A2.4.1 Trunnion Pin. Try a 21-in. diameter pin of ASTM A668, Class C material without protective bushings.

$$\text{Area} = \frac{\pi(21)^2}{4} = 346.4 \text{ sq in.}$$

$$S = \frac{\text{Area (Radius)}}{4} = 346.4 \frac{(10.50)}{4} = 909.3 \text{ in.}^3$$

The room temperature tensile properties given in the ASTM specification for A668, Class C material are:

$$\sigma_y = 33 \text{ ksi; } \sigma_u = 66 \text{ ksi.}$$

For a maximum operating temperature at the pin of 500°F, the temperature derating factor is:

$$F_t = 0.808 \text{ (Table I-2, temperature = 500°F. Also see Table I-6 for calculated allowable } \sigma_b \text{ values).}$$

$$F_f = 1.0$$

The allowable pin bending stress (Section I-5.5.1) is:

$$\begin{aligned} \sigma_b &= \min \left\{ \frac{F_f F_t \sigma_y}{F_t (SF)_y} ; \frac{F_f F_t \sigma_u}{F_t (SF)_u} \right\} && \text{(Eq I-12 and I-13)} \\ &= \min \left\{ \frac{1(0.808)(33)}{1.2(4.56)} ; \frac{1(0.808)(66)}{1.2(9.12)} \right\} \\ &= \{4.873 ; 4.873\} \\ &= 4.873 \text{ ksi} \end{aligned}$$

The allowable shear stress (Section I-5.5.2) is:

$$0.533 \sigma_b = 0.533(4.873) = 2.60 \text{ ksi} \quad \text{(Eq I-15)}$$

The bending stress at the base of the pin (Fig. A18, Point A) is:

$$\sigma_{\text{bend}} = \frac{1068(6.75)}{2(909.3)} = 3.964 \text{ ksi} < 4.873 \text{ ksi; OK}$$

The average shear stress in the pin is:

$$\tau_{\text{avg}} = \frac{1068}{2(346.4)} = 1.542 \text{ ksi} < 2.60 \text{ ksi; OK}$$

The minimum permissible worn pin diameter is:

$$\begin{aligned} D_{H(\text{min})} &= 21 \left[\frac{3.964}{1.45(4.873)} \right]^{1/3} \\ &= 17.32 \text{ in.} \end{aligned}$$

A2.4.2 Bearing Stress on Pin. Since the pin length is 12 in., the hook width is 10.5 in. according to AISE Technical report No. 7. The minimum internal distance between the sidewalls at the trunnion pin centerline elevation is

$$153 + \left(\frac{113}{180} \right) (178 - 153) = 168.69 \text{ in.}$$

and the horizontal distance from trunnion block mid-thickness to the trunnion pin mid-length is

$$\frac{(204 - 163.69 - 10.5)}{2} = 12.41 \text{ in. (Fig. A18).}$$

The moment arm from the hook centerline to the centerline of the trunnion block is:

$$e_2 = 12.41 + 0.75 = 13.16 \text{ in.}$$

The bearing stress at Point B (Fig. A18) is:

$$f_B = \frac{1068}{2(31)(10.5)} \left[1 + \frac{6(13.16)}{10.5} \right] = 13.98 \text{ ksi} \quad (\text{Eq I-17})$$

The allowable bearing stress is the lesser of Eq I-5b and I-16:

$$\sigma_{br} = 1.36(1.38 \sigma_b) = 1.36(1.38)(7.59) = 14.26 \text{ ksi} \quad (\text{Eq I-5b})$$

$$\sigma_{br} = 3.33 \sigma_{b, \text{pin}} = 3.33(4.873) = 16.23 \text{ ksi} \quad (\text{Eq I-16a})$$

$$\text{Use } \sigma_{br} = 14.26 \text{ ksi}$$

$$f_B = 13.98 < 14.26 \text{ ksi; OK}$$

A2.4.3 Trunnion Block Bending Stresses. The trunnion block is connected to the shell by longitudinal fillet welds which transmit the vertical load to the shell (Fig. A18). The moment arm on the trunnion block is $e_2 = 13.16$ in.

Using a 9×52 in. block and assuming that the trunnion block acts as an integral part with the shell plate, the section modulus at the centerline of the trunnion is:

$$S_1 = \frac{(52 - 31)(10.5)^2}{6} = 385.9 \text{ in.}^3 \quad (\text{Eq I-17b})$$

Use ASTM A27, Grade 60-30 material for the block. The allowable normal stress (Section I-5.4.1) is:

$$\begin{aligned} \sigma_a &= \min \{ \sigma_{ay} ; \sigma_{au} \} \\ &= \min \left\{ \frac{F_f F_t \sigma_y}{F_l (SF)_y} ; \frac{F_f F_t \sigma_u}{F_l (SF)_u} \right\} \end{aligned} \quad (\text{Eqs I-2 and I-3})$$

$$\sigma_y = 30 \text{ ksi, } \sigma_u = 60 \text{ ksi}$$

$$F_f = 1.0(1.0)(1.0)(1.0)(0.95) = 0.95$$

$$(f_s = 0.95 \text{ for noncircular ladle})$$

$$F_t = 0.730 \text{ (Table I-1, assume maximum temperature } = 650^\circ\text{F)}$$

$$F_l = 1.2, (SF)_y = 2.28, (SF)_u = 3.80$$

$$\sigma_a = \min \left\{ \frac{0.95(0.730)(30)}{1.2(2.28)} ; \frac{0.95(0.730)(60)}{1.2(3.80)} \right\}$$

$$= \min \{ 7.60 ; 9.13 \}$$

$$= 7.60 \text{ ksi}$$

Allowable bending stress in block (Section I-5.4.2.2) is:

$$\sigma_b = 1.38 \sigma_a = 1.38(7.60) = 10.5 \text{ ksi} \quad (\text{Eq I-5a})$$

The maximum trunnion block bending stress is located at the centerline of the trunnion (Fig. A18) and is:

$$f_b = \frac{1068(13.16)(34)}{2(58)(385.9)} = 10.7 \text{ ksi} > 10.5 \text{ ksi; unsatisfactory} \tag{Eq I-17a}$$

The designer should optimize the pin diameter and size the trunnion block in order to satisfy bearing and bending stress requirements.

A2.4.4 Weld Stresses. Use a combination bevel and fillet weld to connect the trunnion block to the sidewall so that the minimum throat is 1.125 in. (Fig. A19).

For the two vertical welds on each side of the trunnion block:

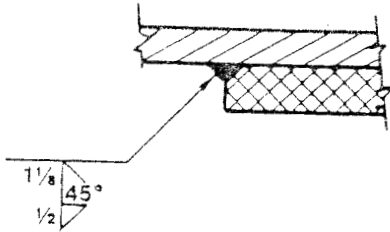


Fig. A19 — Sidewall to Trunnion Block Welded Connection

$$Area = 2(1.125)(50) = 112.5 \text{ sq in.}$$

$$\text{Average shear stress} = \frac{1068}{2(112.5)} = 4.75 \text{ ksi}$$

This is less than the limit in Section I-5.4.6 of $1.2\sigma_a = 9.12 \text{ ksi}$ and also less than the AWS endurance limit of 8.0 ksi.

Use a 1-in. continuous fillet weld to connect the trunnion block to the top band, and use a 1 1/8-in. continuous fillet weld to connect the trunnion block to the bottom band.

The radial force on each of the welds at the top and bottom of the trunnion block (welds connecting block to the band) is:

$$\frac{W_2 e_2}{2 g} = \frac{1068(13.16)}{2(58)} = 121.16 \text{ kips}$$

The shear stress in the weld is:

$$\text{At top: } \frac{121.16}{1(0.707)(52)} = 3.30 \text{ ksi}$$

$$\text{At bottom: } \frac{121.16}{1.125(0.707)(52)} = 2.93 \text{ ksi}$$

These stresses will be combined with the circumferential shear stresses following the band design calculations.

A2.4.5 Location of Trunnion Axis. The minimum distance of the trunnion axis above the center of gravity of a brimful ladle, including refractory lining and contents (Section I-5.3) is:

$$j = 3.236 \times 10^{-6} \left[\frac{Q}{W} \right] \left[D_{wr(\min)} \right] \left[D_{wr(\max)} \right]^3 \tag{Eq I-1}$$

$$D_{wr(\min)} = 166 \text{ in.}$$

$$D_{wr(\max)} = 166 + 32 = 198 \text{ in.}$$

$$j = 3.236 \times 10^{-6} \left[\frac{0.44}{1301} \right] (166)(198)^3$$

$$= 1.41 \text{ ft} = 16.9 \text{ in.} < 19.7 \text{ in. (actual } j \text{ distance); OK}$$

Here the brimful weight, W , of the ladle is estimated as (use actual ladle height H and not artificial ladle height h for weight calculations):

Brimful molten metal weight	=	1033 kips
Ladle steelwork weight	=	161 kips
Ladle lid weight	=	25 kips
Ladle lining weight	=	82 kips
W	=	1301 kips

$$I = \frac{16(1.5)^3}{12} + \frac{11(11.5)^3}{12} + 16(1.5)(4.2)^2 + 11(11.5)(0.8)^2 = 1903 \text{ in.}^4$$

Section modulus:

$$\text{outside } S_O = \frac{1903}{6.55} = 290.5 \text{ in.}^3$$

$$\text{inside } S_I = \frac{1903}{4.95} = 384.4 \text{ in.}^3$$

Bottom band:

$$R_S = 76.5 + \frac{6.583}{15.0} (89 - 76.5) + \frac{1.5}{2} = 82.7 \text{ in.}$$

Trial size: 5 in. wide $\times$ 13 in. deep all around.

Properties at trunnion axis (Fig. A22):

$$b_1 = 0.4 \sqrt{82.7(10.5 + 3)} = 13.4 \text{ in.} \quad (\text{Eq I-29})$$

$$b_2 = 0.7 \sqrt{82.7(1.5)} = 7.80 \text{ in.} \quad (\text{Eq I-30})$$

$$b_e = 5 + 13.4 + 7.8 = 26.2 \text{ in.} \quad (\text{Eq I-28})$$

$$\text{Area} = 13.4(10.5) + 5(14.5) + 7.80(1.5) = 224.9 \text{ in.}^2$$

Locate neutral axis:

$$e = \frac{13.4(10.5)^2 + 5(14.5)^2 + 7.8(1.5)^2}{2(224.9)} = 5.66 \text{ in.}$$

$$I = \frac{13.4(10.5)^3}{12} + \frac{5(14.5)^3}{12} + \frac{7.8(1.5)^3}{12} + 13.4(10.5)(0.41)^2 + 5(14.5)(1.59)^2 + 7.8(1.5)(4.91)^2 = 3054 \text{ in.}^4$$

Section modulus:

$$\text{outside } S_O = \frac{3054}{8.84} = 345.5 \text{ in.}^3$$

$$\text{inside } S_I = \frac{3054}{5.66} = 539.6 \text{ in.}^3$$

Properties at cross axis (Fig. A23):

$$b_e = 5 + 1.4 \sqrt{82.7(1.5)} = 20.6 \text{ in.} \quad (\text{Eq I-27})$$

$$\text{Area} = 15.6(1.5) + 5(14.5) = 95.9 \text{ in.}^2$$

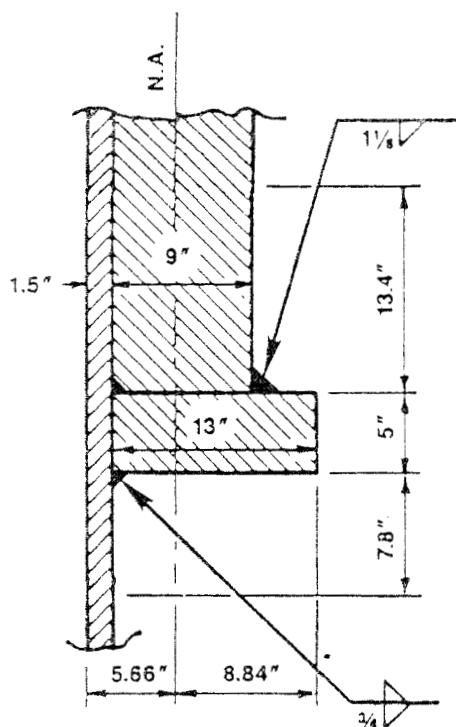


Fig. A22 — Bottom Band at Trunnion Axis

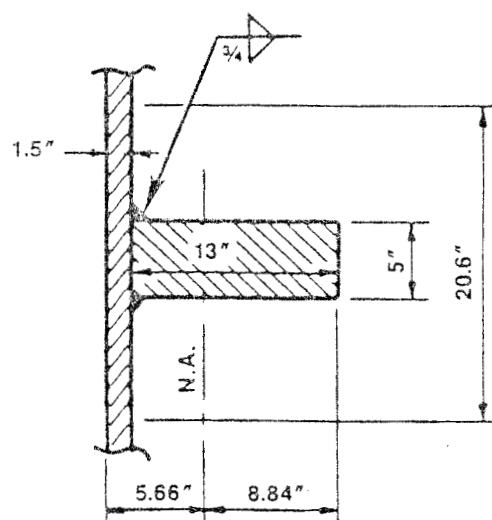


Fig. A23 — Bottom Band at Cross Axis

Locate neutral axis:

$$e = \frac{15.6(1.5)^2 + 5(14.5)^2}{2(95.9)}$$

$$= 5.66 \text{ in.}$$

$$I = \frac{15.6(1.5)^3}{12} + \frac{5(14.5)^3}{12}$$

$$+ 15.6(1.5)(4.91)^2 + 5(14.5)(1.59)^2$$

$$= 2022 \text{ in.}^4$$

Section modulus:

$$\text{outside } S_O = \frac{2022}{8.84} = 228.7 \text{ in.}^3$$

$$\text{inside } S_I = \frac{2022}{5.66} = 357.2 \text{ in.}^3$$

SUMMARY OF EFFECTIVE BAND PROPERTIES				
Property	Top Band		Bottom Band	
	At Trunnion	At Cross Axis	At Trunnion	At Cross Axis
Area, in. ²	282.4	150.5	224.9	95.9
I, in. ⁴	2992	1903	3054	2022
S _O , in. ³	481.0	290.5	345.5	228.7
S _I , in. ³	567.7	384.4	539.6	357.2

A2.5.2 Band Forces.

$$R_{RT} = 86.8 + 4.95 - 0.75 = 91.00 \text{ in.}$$

$$R_{RB} = 82.7 + 5.66 - 0.75 = 87.61 \text{ in.}$$

$$C = \frac{2022(79)(91.0)^3}{1903(137)(87.61)^3} = 0.687 \quad (\text{Eq I-31})$$

$$R_{SM} = \frac{89 + 76.5}{2} + 0.75 = 83.50 \text{ in.}$$

$$\frac{R_{S\max}}{R_{S\min}} = \infty \text{ (obround ladle)}$$

$$\frac{I}{R_{SM}} = \frac{16}{83.5} = 0.19$$

$$G = 1.35 \text{ (Fig. I-12)}$$

$$F_T = \frac{1068 [204 - 1.35(83.5)]}{8 [0.69(79) + 137]} = 63.63 \text{ kips} \quad (\text{Eq I-32a})$$

$$F_B = 0.687(63.63) = 43.71 \text{ kips} \quad (\text{Eq I-32b})$$

$$\begin{aligned} M_{T1} \text{ (at trunnion axis)} &= 63.63 \left[0.7(91.0) + 16 - \frac{52}{4} \right] \\ &= 4244 \text{ kip-in.} \end{aligned} \quad (\text{Eq I-33})$$

$$\begin{aligned} M_{T1} \text{ (adjacent trunnion block)} &= 63.63 \left[0.7(91.0) + 16 - \frac{52}{2} \right] \\ &= 3417 \text{ kip-in.} \end{aligned} \quad (\text{Eq I-33})$$

$$\begin{aligned} M_{T2} \text{ (at cross axis)} &= -63.63(0.3)(91.0) \\ &= -1737 \text{ kip-in.} \end{aligned} \quad (\text{Eq I-34})$$

$$\begin{aligned} M_{B2} \text{ (at cross axis)} &= -43.71(0.3)(87.61) \\ &= -1149 \text{ kip-in.} \end{aligned} \quad (\text{Eq I-35})$$

A2.5.3 Band Stresses.

Top band at trunnion axis:

$$f_O = - \frac{4244}{481} = -8.82 \text{ ksi} \quad (\text{Eq I-36a})$$

$$f_I = + \frac{4244}{567.7} = +7.47 \text{ ksi} \quad (\text{Eq I-36b})$$

Top band adjacent to trunnion block:

$$f_O = - \frac{3417}{290.5} = -11.76 \text{ ksi} \quad (\text{Eq I-36a})$$

$$f_I = + \frac{3417}{384.4} = +8.89 \text{ ksi} \quad (\text{Eq I-36b})$$

Top band at cross axis:

$$f_O = - \frac{63.63}{150.5} + \frac{1737}{290.5} = +5.56 \text{ ksi} \quad (\text{Eq I-37a})$$

$$f_I = - \frac{63.63}{150.5} - \frac{1737}{384.4} = -4.94 \text{ ksi} \quad (\text{Eq I-37b})$$

Bottom band at cross axis:

$$f_O = - \frac{43.71}{95.9} + \frac{1149}{228.7} = +4.56 \text{ ksi} \quad (\text{Eq I-38a})$$

$$f_I = - \frac{43.71}{95.9} - \frac{1149}{357.2} = -3.67 \text{ ksi} \quad (\text{Eq I-38b})$$

Use ASTM A516, Grade 55 material for the bands. This material has the same tensile and yield strength as A285, Grade material used for the sidewalls and $\sigma_a = 7.59$ ksi at 650°F. The allowable combined stress is the same at all band location and is $2(7.59) = 15.18$ ksi (Section I-9.9). The band stresses determined above are satisfactory at all locations.

A2.5.4 Band Weld Stresses. The circumferential shear force in the welds connecting the band to the shell is given by

$$f'_s = \frac{Vay}{I}$$

Where:

- a = Area beyond vertical shear plane (and fillet welds) of interest in trunnion block region, in.²
- f'_s = Shear force over the vertical shear plane of interest, kips/in.
- I = Moment of inertia of trunnion block/band cross-sectional region (see Summary of Effective Band Properties, Section A2.5.1), in.⁴
- V = Radial force on band in region of trunnion block, kips
- y = Distance from neutral axis (neutral axis determined in evaluation of band properties) of trunnion block/band cross-sectional region to centroid of area, a , in.

Evaluation of shear stress in the two circumferential 3/4-in. fillet welds (Fig. A20) connecting the top band to the sidewall plate.

$$V = F_T = 63.63 \text{ kips}$$

From the top band trunnion axis property calculations (Section A2.5.1, Fig. A20):

$$e = 5.28 \text{ in. (location of neutral axis)}$$

$$I = 2992 \text{ in.}^4$$

The area beyond the vertical shear plane of interest (area beyond the two 3/4 in. fillet welds, Fig. A20) is the 1 1/2-in. sidewall plate:

$$a = (13.7 + 11 + 8)(1.5) = 49.05 \text{ in.}^2$$

The centroid location of area, a from the neutral axis is:

$$y = e - \frac{t}{2} = 5.28 - \frac{1.5}{2} = 4.53 \text{ in.}$$

Then:

$$f'_s = \frac{63.63(49.05)(4.53)}{2992} = 4.73 \text{ kips/in.}$$

The shear stress in the two 3/4-in. fillet welds (through the throat of the welds) is:

$$\tau = \frac{f'_s}{b} = \frac{4.73}{2(0.75)(0.707)} = 4.46 \text{ ksi}$$

This is less than the allowable limit (Section I-5.4.6) of $1.2 \times 7.59 = 9.11$ ksi, and also less than the AWS endurance limit of 8.0 ksi.

Evaluation of shear stress in the single circumferential 1-in. fillet weld connecting the trunnion block to the outer edge of the top band (Fig. A20).

From the top band trunnion axis property calculations (Section A2.5.1, Fig. A20):

$$e = 6.22 \text{ in.}$$

$$I = 2992 \text{ in.}^4$$

The area beyond the vertical shear plane of interest is the 1 in. projection of the top band beyond the trunnion block. Therefore:

$$a = 11(1) = 11 \text{ in.}^2$$

$$y = 6.22 - 0.5 = 5.72 \text{ in.}$$

Then:

$$f'_s = \frac{63.63(11)(5.72)}{2992} = 1.34 \text{ kips/in.}$$

The shear stress in the single 1-in. fillet weld is:

$$\tau = \frac{1.34}{1.0(0.707)} = 1.89 \text{ ksi}$$

This weld must also carry the radial force considered previously (Section A2.4.4)

The equivalent shear stress is:

$$\tau_{eq} = \sqrt{1.89^2 + 3.30^2} = 3.80 \text{ ksi} < 8.0 \text{ ksi; OK}$$

For the bottom band to sidewall welds (two circumferential 3/4-in. fillet welds (Fig. A22):

$$a = 1.5(26.2) = 39.30 \text{ sq in.}$$

$$I = 3054 \text{ in.}^4$$

$$V = F_B = 43.71 \text{ kips}$$

$$y = 5.66 - 0.75 = 4.91 \text{ in.}$$

$$f'_s = \frac{43.71(39.30)(4.91)}{3054} = 2.76 \text{ kips/in.}$$

$$\tau = \frac{2.76}{2(0.75)(0.707)} = 2.60 \text{ ksi} < 8.0 \text{ ksi; OK}$$

For the bottom band to trunnion block weld (single circumferential 1 1/8-in. fillet weld, Fig. A22)

$$a = 4(5) = 20 \text{ in.}^2$$

$$y = 8.84 - 2 = 6.84 \text{ in.}$$

$$f'_s = \frac{43.71(20)(6.84)}{3054} = 1.96 \text{ kips/in.}$$

$$\tau = \frac{1.96}{1.125(0.707)} = 2.46 \text{ ksi}$$

$$\tau_{eq} = \sqrt{2.46^2 + 2.93^2} = 3.83 \text{ ksi} < 8.0 \text{ ksi; OK}$$

Since the shear force is zero at the cross axis, the weld stresses at the cross axis will be negligible.

A2.5.5 Deflection Index.

The deflection index (Section I-11) is:

$$\lambda = \frac{C_D P R_{RM}^2}{E I_2} \quad (\text{Eq I-41})$$

Determine C_D by interpolation from Table I-8, using β , $\frac{I}{R_{RM}}$ and $\frac{I_2}{I_1}$

From Fig. A17, the inside radius at the average band height is:

$$= 76.5 + \left(\frac{79 + 137}{2} \right) \left(\frac{178}{2} - \frac{153}{2} \right) \frac{1}{180} = 84.00 \text{ in.}$$

$$\beta = \frac{180(26 - 16)}{\pi(84.00)} = 6.82 \text{ degrees}$$

$$l = 16 \text{ in.}$$

$$R_{RM} = \frac{R_{RT} + R_{RB}}{2} = \frac{91.0 + 87.61}{2} = 89.31 \text{ in.} \quad (\text{Eq I-45})$$

$$\frac{l}{R_{RM}} = \frac{16}{89.31} = 0.1792$$

$$I_2 = 1903 \left(\frac{137}{113} \right)^2 + 2022 \left(\frac{79}{113} \right)^2 = 3785 \text{ in.}^4 \quad (\text{Eq I-43})$$

$$I_1 = 2992 \left(\frac{137}{113} \right)^2 + 3054 \left(\frac{79}{113} \right)^2 = 5891 \text{ in.}^4 \quad (\text{Eq I-42})$$

$$\frac{I_2}{I_1} = \frac{3785}{5891} = 0.643$$

$$C_D = 0.0967$$

$$P = 2(F_T + F_B) = 2(63.63 + 43.71) = 214.68 \text{ kips} \quad (\text{Eq I-44})$$

$$E = 29,500 \text{ ksi}$$

$$\lambda = \frac{0.0967(214.68)(89.31)^2}{29500(3785)}$$

A2.6 Support Legs. The obround ladle is to be supported by three support legs. Each leg extends 22 in. down from the knuckle region of the dished bottom plate for the necessary clearance beneath the ladle.

A2.6.1 Calculating Required Leg Size. The design service load (Section I-14) for each leg is:

$$F_V = \frac{1068}{2} = 534 \text{ kips}$$

The maximum required leg length below the dished bottom plate is:

$$L_A = 22 \text{ in.}$$

It is assumed that the legs are made of ASTM A106 Grade A material ($\sigma = 30 \text{ ksi}$, $F_t = 0.729$ for 650°F , $F_t = 1.2$ and $F_f = 1.0$). Therefore:

$$\sigma_a = 7.67 \text{ ksi} \quad (\text{Eqs I-2 and I-3})$$

$$\sigma_b = 1.25(7.67) = 9.59 \text{ ksi} \quad (\text{Eq I-7})$$

$$\sigma_s = 0.6 \sigma_a = 4.60 \text{ ksi} \quad (\text{Eq I-11})$$

The leg thickness must be equal to or greater than the sidewall (1½ in.) thickness. Selecting a trial size of 26 in. OD and a wall thickness T_L of 2½ in., the cross sectional properties are:

$$A_L = 184.6 \text{ in.}^2$$

$$S_L = 991.2 \text{ in.}^3$$

Substituting the appropriate parameters into Eqs I-54a, I-54b and I-54c:

$$\frac{534}{184.6(7.67)} = 0.38 < 1.0; \text{ OK} \quad (\text{Eq I-54a})$$

$$\frac{534(22)}{2(991.2)(9.59)} = 0.62 < 1.0; \text{ OK} \quad (\text{Eq I-54b})$$

$$\frac{534}{184.6(7.67)} + \frac{534(22)}{2(991.2)(9.59)} = .995 < 1.0; \text{ OK} \quad (\text{Eq I-54c})$$

The length L_c of the portion of the leg which is connected to the sidewall is calculated by Eqs I-55a, I-55b, I-55c and I-55d:

$$L'_c = \frac{534}{2.35(2.5)(4.60)} = 19.76 \text{ in.} \quad (\text{Eq I-55b})$$

$$L''_c = \frac{534(22)}{4.70(11.75)(2.5)(4.60)} = 18.50 \text{ in.} \quad (\text{Eq I-55c})$$

$$L'''_c = \frac{1}{1.24} \sqrt{\frac{534(22)}{(2.5)(4.60)}} = 25.78 \text{ in.} \quad (\text{Eq I-55d})$$

$$L_c = 18.50 + \sqrt{18.50^2 + 25.78^2} = 51.49 \text{ in.} \quad (\text{Eq I-55a})$$

The bottom and top of the leg is capped with a 2½-in. thick plate. A ¾-in. hole is drilled in the bottom plate. Each leg is connected to the bottom plate and sidewall with a full penetration weld.

A2.7 Dished Obround Bottom With Stiffener Ribs. The obround ladle is evaluated for an alternative bottom support using ribs. The ribs are parallel to the cross axis of the obround ladle. The basic dimensions of the center T beam are described in Fig. A24.

The properties of the T beam are:

$$L = 185 \text{ in.}$$

$$\text{Area} = 15(2.375) + 15.3(1.5) = 35.625 + 22.95 = 58.575 \text{ in.}^2$$

$$e = \frac{(15.3)(1.5)(8.25)}{58.575} = 3.23 \text{ in.}$$

Where e = Eccentricity from neutral axis of T beam to mid-height of web.

$$\begin{aligned} I &= \frac{2.375(15)^3}{12} + \frac{15.3(1.5)^3}{12} + 15.3(1.5)(5.02)^2 + (15)(2.375)(3.23)^2 \\ &= 668.0 + 4.3 + 578.3 + 371.7 = 1622.3 \text{ in.}^4 \end{aligned}$$

$$S_1 = \frac{1622.3}{5.77} = 281.2 \text{ in.}^3$$

$$S_2 = \frac{1622.3}{10.73} = 151.2 \text{ in.}^3$$

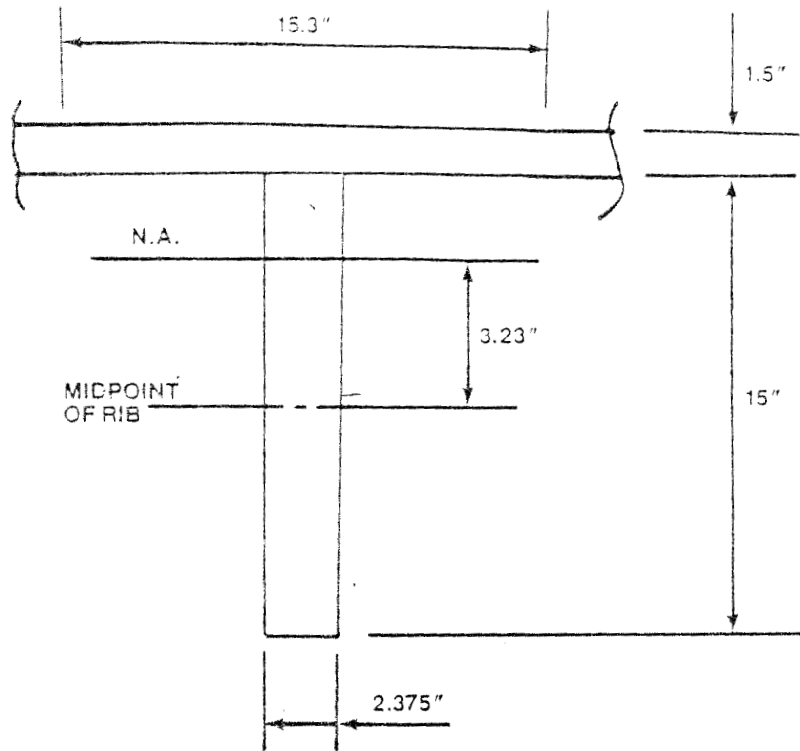


Fig. A24 — T Beam Cross-Section

Maximum rib spacing check:

$$\frac{L}{5} = \frac{185}{5} = 37 \text{ in.} > 15.3 \text{ in.; OK}$$

Checking on plate stress requirements:

$$T'_B = 1.5 + \frac{(2.375)(15)}{15.3} = 3.83 \text{ in.}$$

Substituting into Eqs I-26a, I-26b and I-26c, (Note: use artificial height, h):

$$\frac{f_a}{\sigma_a} = \frac{(0.44)(186)(300)}{(909)(1.5 + 3.83)(7.59)} = 0.67 < 1.0; \text{ OK} \quad (\text{Eq I-26a})$$

$$\frac{f_b}{\sigma_b} = \frac{(0.44)(186)(15.3)^2}{(3638)(1.5)^2(1.25)(7.59)} = 0.25 < 1.0; \text{ OK} \quad (\text{Eq I-26b})$$

$$\frac{f_a}{\sigma_a} + \frac{f_b}{\sigma_b} = 0.67 + 0.25 = 0.92 < 1.0; \text{ OK} \quad (\text{Eq I-26c})$$

Checking the T beam stresses. The axial stress requirement is:

$$\frac{f_a}{\sigma_a} = \frac{(0.44)(186)(300)}{(3638)(3.83)(7.59)} = 0.23 < 1.0; \text{ OK} \quad (\text{Eq I-25a})$$

The top fiber bending stress requirement is:

$$\frac{f_b}{\sigma_b} = \frac{(0.44)(186)(15.3)}{(14552)(281.2)(1.25)(7.59)} \left[185^2 - 4(300)(11.48) \right] = 0.66 < 1.0; \text{ OK} \quad (\text{Eq I-25b})$$

The total top fiber bending stress requirement is:

$$\frac{f_a}{\sigma_a} + \frac{f_b}{\sigma_b} = |0.23 + (-0.66)| = 0.43 < 1.0; \text{ OK} \quad (\text{Eq I-25c})$$

The bottom fiber bending stress requirement is:

$$\frac{f_b}{\sigma_b} = \frac{(0.44)(186)(15.3)}{(14552)(151.2)(2)(7.59)} \left[185^2 - 4(300)(11.48) \right] = 0.77 < 1.0; \text{ OK} \quad (\text{Eq I-25b})$$

The total bottom fiber bending stress requirement is:

$$\frac{f_a}{\sigma_a} + \frac{f_b}{\sigma_b} = 0.23 + 0.77 = 1.00 \leq 1.0; \text{ Satisfactory} \quad (\text{Eq I-25c})$$

A2.8 Comment on Brimful Condition. When the freeboard exceeds 10% of the ladle height, H , the design procedure defined in Section I-5.1 is required. In addition, the design of the ladle should be verified for the brimful condition with allowable stresses increased by 30%. The brimful weight is greater than the design weight by the following percentage:

$$\frac{1321 - 1068}{1068} \times 100 = 24\%$$

The ladle design procedures are linear functions of the ladle weight. The allowable increase in stresses for the brimful condition is 30%, therefore, the brimful design condition in Example 2 satisfies the requirements of Section I-5.1.

These computations, based on the ladle weight (A2.1), are considered preliminary. After evaluating the ladle dimensions, the actual weights are to be established. The resulting stresses, using the actual weight, are not to exceed the allowable stresses. If the allowable stresses are exceeded, change in component sizes will be required, new weights established and stresses computed such that those stresses are equal to or less than the allowable ones.

A2.9 Estimating Wall Working Lining Expansion Allowance. The calculations for determining expansion allowance for the obround and oval ladle are similar to those described for the circular ladle in Example 1, A1.8. The effective radius of the obround and oval ladle is determined by Eq II-2a and Eq II-2b:

$$R'_{s(ave)} = \frac{98.75 + 82.75}{2} = 90.75 \text{ in.} \quad (\text{Eq II-2a})$$

$$R'_{wl} = R'_{s(ave)} - 8 \text{ in.} = 82.75 \text{ in.} \quad (\text{Eq II-2b})$$

The remainder of the calculations for estimating the wall working lining expansion allowance for the obround and oval ladle are similar to those described previously for the circular ladle in Example 1, A1.8.

APPENDIX B — METHOD OF DETERMINING LADLE DEFLECTION COEFFICIENT

The deflection coefficient, C_D , is used in determining the inward deflection index, λ , of a ladle (Section I-11, Eq I-41). This coefficient was computer-calculated for a range of values of $\frac{l}{R_{RM}}$, $\frac{l_2}{l_1}$ and β , and the results are listed in Table I-8.

The values for C_D may be calculated independently from Eq B4 for oval ladles and from Eq B6 for obround ladles. For circular ladles, C_D can be calculated from either Eq B4 or B6 by letting $l = 0$, which leads to $\gamma = 0$. The radial deflection of shell, δ , the deflection index, λ , and the corresponding circumferential bending moment on shell, M_o , can be calculated from Eqs B1, B2 and B3, respectively.

$$\delta = \frac{C_D P R_{RM}^3}{E I_2} \quad (\text{Eq B1})$$

$$\lambda = \frac{\delta}{R_{RM}} \quad (\text{Eq B2})$$

$$M_o = \frac{P R_{RM}}{2} (K_1 \text{ or } K_2) \quad (\text{Eq B3})$$

Where:

- E = Modulus of elasticity (room temperature), ksi
- I_2 = Moment of inertia of the effective band at cross axis (for deflection index calculation), in.⁴ (Fig. I-13, Eq I-43)
- K_1 = A geometric factor for oval ladles (Eq B5)
- K_2 = A geometric factor for obround ladles (Eq B7)
- M_o = Circumferential bending moment on shell, kip-in. (Eq B3, Fig. B2)
- P = Effective force, kips (Eq I-44)
- R_{RM} = Average minimum effective radius of top and bottom band, in. (Eq I-45, Figs. I-13, B1, B2)
- δ = Radial deflection of shell, in. (Eq B1)
- λ = Deflection index (Eqs I-41, B2)

There are two cases for calculating C_D :

Case 1 — Oval ladles.

$$C_D = \frac{1}{2} \left\{ \rho^3 \alpha \left(\frac{\psi}{2} - \frac{\sin 2\psi}{4} \right) + \alpha \left(-\gamma^2 \psi + 2\gamma \cos \psi - \frac{\psi}{2} + \frac{\sin 2\psi}{4} \right) \right. \\ \left. + \frac{\pi}{2} (\gamma^2 + \frac{1}{2}) + (1 - \alpha) \left(-\gamma^2 \beta + 2\gamma \cos \beta - \frac{\beta}{2} + \frac{\sin 2\beta}{4} \right) \right. \\ \left. - K_1 \left[\rho^2 \alpha (1 - \cos \psi) + \alpha (-\gamma \psi + \cos \psi) + \gamma \frac{\psi}{2} + (1 - \alpha) (\cos \beta - \gamma \beta) \right] \right\} \quad (\text{Eq B4})$$

Where:

$$K_1 = \frac{\left[\rho^2 \alpha (1 - \cos \psi) + \gamma \alpha (\beta - \psi) - \alpha (\cos \beta - \cos \psi) + \gamma \left(\frac{\psi}{2} - \beta \right) + \cos \beta \right]}{\left[\rho \alpha \psi + \alpha (\beta - \psi) + \left(\frac{\psi}{2} - \beta \right) \right]} \quad (\text{Eq B5})$$

$$\alpha = \frac{l_2}{l_1}$$

β = Angle at which effective band moment of inertia changes from l_1 to l_2 , radians in formulas but degrees in Table I-8 (Figs. I-13, B1, B2)

$$\gamma = \frac{l}{R_{RM}}$$

$$\rho = \frac{R_E}{R_{RM}}$$

$$\psi = \sin^{-1} \left(\frac{\gamma}{\rho - 1} \right) \quad (\text{Fig. B1, B2})$$

and:

I_1 = Moment of inertia of the effective band at the trunnion axis, in.⁴ (Eq I-42)

R_E = Radius at minor axis, in. (Figs. B1, B2)

l = One half the distance between radius points of end segments in an oval ladle, in. (Figs I-13, B1, B2)

Fig. B1 —
Oval Ring
Geometry for
Deflection
Analysis

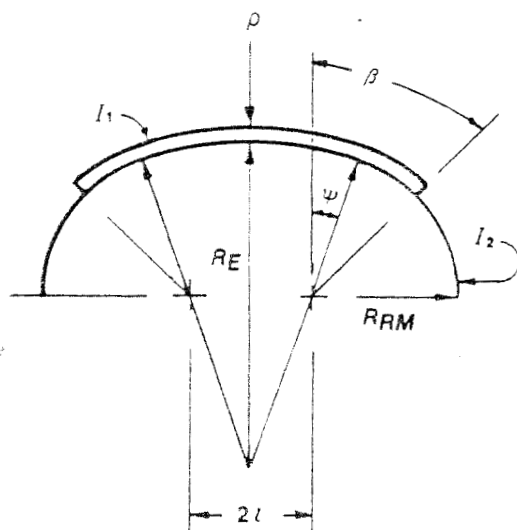
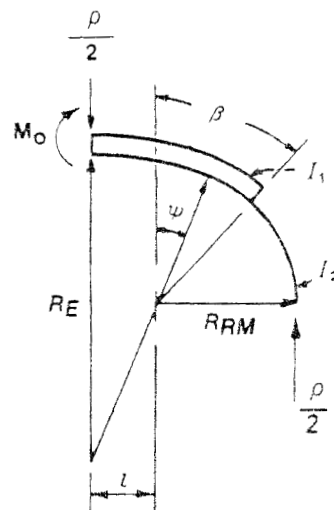


Fig. B2 —
Ring Forces



Case 2 — Obround ladles:

$$C_D = \frac{1}{2} \left\{ \frac{\alpha \gamma^3}{3} + 2 \alpha \gamma + \frac{\pi}{2} (\gamma^2 + 1/2) + (1 - \alpha) \left(-\gamma^2 \beta + 2 \gamma \cos \beta - \frac{\beta}{2} + \frac{\sin 2\beta}{4} \right) - K_2 \left[\frac{\alpha \gamma^2}{2} + \alpha + \frac{\gamma \pi}{2} + (1 - \alpha) (\cos \beta - \gamma \beta) \right] \right\} \quad (\text{Eq. B6})$$

Where:

$$K_2 = \frac{\left[\frac{\alpha \gamma^2}{2} + \gamma \alpha \beta - \alpha (\cos \beta - 1) + \gamma \left(\frac{\pi}{2} - \beta \right) + \cos \beta \right]}{\left(\alpha \gamma + \alpha \beta + \frac{\pi}{2} - \beta \right)} \quad (\text{Eq B7})$$

It should be noted that the values for the deflection coefficient, C_D , shown in Table I-8, represent conditions for an obround ladle where $\frac{R_E}{R_{RM}} = \infty$ (i.e., infinity). Additional calculations were made for oval ladles where $\frac{R_E}{R_{RM}} \neq \infty$. A comparison of results showed that the deflection coefficients were slightly higher for oval ladles than for obround ladles because of the larger arc length with an oval ladle. The differences were, however, negligible. For example, the maximum difference was approximately

1% for $\frac{R_E}{R_{RM}} = 2$, approximately 0.3% for $\frac{R_E}{R_{RM}} = 3$, and 0.1% for $\frac{R_E}{R_{RM}} = 5$.

Sidewalls:
 dia, in. _____ spacing, in. _____
 Tilt mechanism: _____

Yes No

Material

Bottom plate (Section I-3.3)
 Bottom plate stiffener ribs (Section I-3.3)
 Shell plate:
 Upper (Section I-3.3)
 Lower (Section I-3.2)
 Stiffener bands (Section I-3.3)
 Splash plate (Section I-3.3)
 Lip ring:
 Fabricated (Section I-3.4)
 Casting (Section I-3.4)
 Trunnion pin (Section I-3.5)
 Trunnion block (Section I-3.6)
 Additional testing procedures (Section I-3.10) _____

ASTM _____
 ASTM _____

 ASTM _____
 ASTM _____

 ASTM _____
 ASTM _____

Grade _____
 Grade _____

 Grade _____
 Grade _____

 Grade _____
 Grade _____

Refractory lining (Section II-2): (please attach lining drawing)

REFRACTORY	WALL LINING			BOTTOM LINING		
	Type	Thickness	Density	Type	Thickness	Density
Working Lining						
Safety Lining						
Insulating Lining						

Total refractory weight in ladle, lbs _____

Welds
 Thermal stress relieving (Section I-4.6):
 Field welds are to be stress relieved in accordance with the
 ASME Code, Section VIII, Division 1

Yes No

OWNER'S INFORMATION SHEET (OIS)

Information sheet to be completed and submitted to the fabrication contractor

Design Parameters

Intended primary use of ladle _____

Ladle rated capacity, short tons _____ Metal to be transported _____

Metal density (Section I-5.2), kips/ft³ _____ Metal temperature range, °F _____

Metal composition _____ Type of construction (riveted or welded) _____

Maximum height _____ ft, _____ in.

Freeboard to be 5% of height (Section I-5.1)

If freeboard is not 5% of height _____ ft, _____ in.

Geometric configuration:

Shell (round, oval or obround) _____ Bottom (flat or dished) _____

Maximum service temperature, °F:

Sidewall _____ Bottom (flat or dished) _____

Trunnion block _____ Trunnion pin _____

Hook on trunnion:

Thickness, in. _____ Diameter at trunnion seat, in. _____

Centerline to centerline of ladle hooks _____ ft, _____ in.

Skulls:

Weight, kips _____ Location _____

Maximum level of molten metal in the spout during pouring (Section I-5.2), in. _____

Ladle lid to be used

Weight of ladle lid—with refractory, lbs _____

Center of gravity of lid—with refractory
(please attach drawing):

a. vertical _____ ft, _____ in.

b. horizontal _____ ft, _____ in.

Continuous Caster Ladles (Section I-4.3):

Specify if knuckle radius/plate thickness ratio of 4 is required: _____

Specify if heat protection shield is required: _____

Trunnion wear sleeve to be provided (Section I-4.7): _____

Specify if vent holes are required (Section I-4.10): _____

Ladle bottom: _____

dia, in. _____ spacing, in. _____

Marking and Reports		
UCS-115	General	200
Pressure Relief Devices		
UCS-125	General	200
Nonmandatory Appendix CS		
UCS-150	General	200
UCS-151	Creep-Rupture Properties of Carbon Steels.....	200
UCS-160	Vessels Operating at Temperatures Colder Than the MDMT Stamped on the Nameplate.....	200
Figures		
UCS-66	Impact Test Exemption Curves [See UCS-66(a)]	139
UCS-66.1	Reduction in Minimum Design Metal Temperature Without Impact Testing	193
UCS-66.2	Diagram of UCS-66 Rules for Determining Lowest Minimum Design Metal Temperature (MDMT) Without Impact Testing.....	194
UCS-66.3	Some Typical Vessel Details Showing the Governing Thicknesses as Defined in UCS-66	196
Tables		
UCS-56	Postweld Heat Treatment Requirements for Carbon and Low Alloy Steels.....	180
UCS-56.1	Alternative Postweld Heat Treatment Requirements for Carbon and Low Alloy Steels.....	187
UCS-57	Thickness Above Which Full Radiographic Examination of Butt Welded Joints Is Mandatory	187
UCS-66	Tabular Values for Fig. UCS-66.....	192

ASME - SECTION VIII - DIVISION 1

PART UCS

A02

General

UCS-1	Scope.....	177
-------	------------	-----

Materials

UCS-5	General.....	177
UCS-6	Steel Plates.....	177
UCS-7	Steel Forgings.....	177
UCS-8	Steel Castings.....	177
UCS-9	Steel Pipe and Tubes.....	177
UCS-10	Bolt Materials.....	178
UCS-11	Nuts and Washers.....	178
UCS-12	Bars and Shapes.....	178

Design

UCS-16	General.....	178
UCS-19	Welded Joints.....	178
UCS-23	Maximum Allowable Stress Values.....	178
UCS-27	Shells Made From Pipe.....	179
UCS-28	Thickness of Shells Under External Pressure.....	179
UCS-29	Stiffening Rings for Shells Under External Pressure.....	179
UCS-30	Attachment of Stiffening Rings to Shell.....	179
UCS-33	Formed Heads, Pressure on Convex Side.....	179
UCS-56	Requirements for Postweld Heat Treatment.....	179
UCS-57	Radiographic Examination.....	187

Low Temperature Operation

UCS-65	Scope.....	187
UCS-66	Materials.....	187
UCS-67	Impact Tests of Welding Procedures.....	195
UCS-68	Design.....	198

Fabrication

UCS-75	General.....	198.1
UCS-79	Forming Shell Sections and Heads.....	198.1
UCS-85	Heat Treatment of Test Specimens.....	199

Inspection and Tests

UCS-90	General.....	200
--------	--------------	-----

stress values for pipe or tubes of welded manufacture are given in Table 1A of Section II, Part D.

UCS-10 BOLT MATERIALS

(a) Approved specifications for bolt materials of carbon steel and low alloy steel are given in Table UCS-23. A tabulation of allowable stress values at different temperatures (see UG-12) are given in Table 3 of Section II, Part D.

(b) Nonferrous and high alloy steel bolts, studs, and nuts may be used provided they are suitable for the application. They shall conform to the requirements of Part UNF or UHA, as applicable.

UCS-11 NUTS AND WASHERS

(a) Except as otherwise provided in (b)(4) below, materials for nuts shall conform to SA-194, SA-563, or to the requirements for nuts in the specification for the bolting material with which they are to be used. Nuts of special design, such as wing nuts, may be made of any suitable wrought material listed in Table UCS-23 or Table UHA-23 and shall be either: hot or cold forged; or machined from hot-forged, hot-rolled, or cold-drawn bars. Washers may be made from any suitable material listed in Table UCS-23 and Table UHA-23.

(b) Materials for nuts and washers shall be selected as follows.

(1) Carbon steel nuts and carbon steel washers may be used with carbon steel bolts or studs.

(2) Carbon or alloy steel nuts and carbon or alloy steel washers of approximately the same hardness as the nuts may be used with alloy steel bolts or studs for metal temperatures not exceeding 900°F (482°C).

(3) Alloy steel nuts shall be used with alloy steel studs or bolts for metal temperatures exceeding 900°F (482°C). Washers, if used, shall be of alloy steel equivalent to the nut material.

(4) Nonferrous nuts and washers may be used with ferrous bolts and studs provided they are suitable for the application. Consideration shall be given to the differences in thermal expansion and possible corrosion resulting from the combination of dissimilar metals. Nonferrous nuts and washers shall conform to the requirements of UNF-13.

(c) Nuts shall be semifinished, chamfered, and trimmed. Nuts shall be threaded to Class 2B or finer tolerances according to ASME B1.1. For use with flanges conforming to the standards listed in UG-44,

nuts shall conform at least to the dimensions given in ASME/ANSI B18.2.2 for Heavy Series Nuts. For use with connections designed in accordance with the rules in Appendix 2, nuts may be of the ANSI Heavy Series, or they may be of other dimensions as permitted in (d) below.

(d) Nuts of special design or of dimensions other than ANSI Heavy Series may be used provided their strength is equal to that of the bolting, giving due consideration to bolt hole clearance, bearing area, thread form and class of fit, thread shear, and radial thrust from threads [see U-2(g)].

UCS-12 BARS AND SHAPES

(a) Approved specifications for bar and shape materials of carbon steel are given in Table UCS-23. A tabulation of allowable stress values at different temperatures are given in Table 1A of Section II, Part D.

(b) Bolt materials as described in UCS-10 may be used as bar materials.

(c) Parts made from bars, on which welding is done, shall be of material for which a P-Number for procedure qualification is given in Section IX, QW-422 (see UW-5).

DESIGN

UCS-16 GENERAL

The rules in the following paragraphs apply specifically to the design of pressure vessels and vessel parts that are constructed of carbon and low alloy steel and shall be used in conjunction with the general requirements for *Design* in Subsection A and with the specific requirements for *Design* in Subsection B that pertain to the method of fabrication used.

UCS-19 WELDED JOINTS

When radiographic examination is required for butt welded joints by UCS-57, joints of Categories A and B (see UW-3) shall be of Type No. (1) or No. (2) of Table UW-12.

UCS-23 MAXIMUM ALLOWABLE STRESS VALUES

Tables 3 (for bolting) and 1A (other materials) in Section II, Part D give the maximum allowable stress values at the temperature indicated for materials con-

PART UCS

REQUIREMENTS FOR PRESSURE VESSELS CONSTRUCTED OF CARBON AND LOW ALLOY STEELS¹

GENERAL

UCS-1 SCOPE

The rules in Part UCS are applicable to pressure vessels and vessel parts that are constructed of carbon and low alloy steels and shall be used in conjunction with the general requirements in Subsection A, and with the specific requirements in Subsection B that pertain to the method of fabrication used.

MATERIALS

UCS-5 GENERAL

(a) All carbon and low alloy steel material subject to stress due to pressure shall conform to one of the Specifications given in Section II and shall be limited to those listed in Table UCS-23 except as otherwise provided in UG-10 and UG-11.

(b) Carbon or low alloy steel having a carbon content of more than 0.35% by heat analysis shall not be used in welded construction or be shaped by oxygen cutting (except as provided elsewhere in this Division).

(c) Small parts used under the provisions of UG-11(a)(2) in welded construction shall be of good weldable quality.

UCS-6 STEEL PLATES

(a) Approved specifications for carbon and low alloy steel plates are given in Table UCS-23. A tabulation of allowable stress values at different temperatures are given in Table 1A of Section II, Part D (see UG-5).

(b) Steel plates conforming to SA-36, SA/CSA-G40.21 38W, and SA-283 Grades A, B, C, and D may

be used for pressure parts in pressure vessels provided all of the following requirements are met.

(1) The vessels are not used to contain lethal substances, either liquid or gaseous.

(2) The material is not used in the construction of unfired steam boilers [see U-1(g)].

(3) With the exception of flanges, flat bolted covers, and stiffening rings, the thickness of plates on which strength welding is applied does not exceed $\frac{5}{8}$ in. (16 mm).

UCS-7 STEEL FORGINGS

Approved specifications for forgings of carbon and low alloy steel are given in Table UCS-23. A tabulation of allowable stress values at different temperatures are given in Table 1A of Section II, Part D (see UG-6).

UCS-8 STEEL CASTINGS

Approved specifications for castings of carbon and low alloy steel are given in Table UCS-23. A tabulation of allowable stress values at different temperatures are given in Table 1A of Section II, Part D. These stress values are to be multiplied by the casting quality factors of UG-24. Castings that are to be welded shall be of weldable grade.

UCS-9 STEEL PIPE AND TUBES

Approved specifications for pipe and tubes of carbon and low alloy steel are given in Table UCS-23. A tabulation of allowable stress values of the materials from which the pipe or tubes are manufactured are given in Table 1A of Section II, Part D. Net allowable

¹ Low alloy steels — those alloy steels listed in Table UCS-23.

01

TABLE UCS-56
POSTWELD HEAT TREATMENT REQUIREMENTS FOR CARBON AND LOW ALLOY STEELS

Material	Normal Holding Temperature, °F (°C), Minimum	Minimum Holding Time at Normal Temperature for Nominal Thickness [See UW-40(f)]		
		Up to 2 in. (51 mm)	Over 2 in. to 5 in. (51 mm to 127 mm)	Over 5 in. (127 mm)
P-No. 1 Gr. Nos. 1, 2, 3	1100 (593)	1 hr/in. (25 mm), 15 min minimum	2 hr plus 15 min for each additional inch (25 mm) over 2 in. (51 mm)	2 hr plus 15 min for each additional inch (25 mm) over 2 in. (51 mm)
Gr. No. 4	NA	None	None	None

NOTES:

- (1) When it is impractical to postweld heat treat at the temperature specified in this Table, it is permissible to carry out the postweld heat treatment at lower temperatures for longer periods of time in accordance with Table UCS-56.1.
- (2) Postweld heat treatment is mandatory under the following conditions:
 - (a) for welded joints over $1\frac{1}{2}$ in. (38 mm) nominal thickness;
 - (b) for welded joints over $1\frac{1}{4}$ in. (32 mm) nominal thickness through $1\frac{1}{2}$ in. (38 mm) nominal thickness unless preheat is applied at a minimum temperature of 200°F (93°C) during welding;
 - (c) for welded joints of all thicknesses if required by UW-2, except postweld heat treatment is not mandatory under the conditions specified below:
 - (1) for groove welds not over $\frac{1}{2}$ in. (13 mm) size and fillet welds with a throat not over $\frac{1}{2}$ in. (13 mm) that attach nozzle connections that have a finished inside diameter not greater than 2 in. (51 mm), provided the connections do not form ligaments that require an increase in shell or head thickness, and preheat to a minimum temperature of 200°F (93°C) is applied;
 - (2) for groove welds not over $\frac{1}{2}$ in. (13 mm) in size or fillet welds with a throat thickness of $\frac{1}{2}$ in. (13 mm) or less that attach tubes to a tubesheet when the tube diameter does not exceed 2 in. (51 mm). A preheat of 200°F (93°C) minimum must be applied when the carbon content of the tubesheet exceeds 0.22%.
 - (3) for groove welds not over $\frac{1}{2}$ in. (13 mm) in size or fillet welds with a throat thickness of $\frac{1}{2}$ in. (13 mm) or less used for attaching nonpressure parts to pressure parts provided preheat to a minimum temperature of 200°F (93°C) is applied when the thickness of the pressure part exceeds $1\frac{1}{4}$ in. (32 mm);
 - (4) for studs welded to pressure parts provided preheat to a minimum temperature of 200°F (93°C) is applied when the thickness of the pressure part exceeds $1\frac{1}{4}$ in. (32 mm);
 - (5) for corrosion resistant weld metal overlay cladding or for welds attaching corrosion resistant applied lining (see UCL-34) provided preheat to a minimum temperature of 200°F (93°C) is maintained during application of the first layer when the thickness of the pressure part exceeds $1\frac{1}{4}$ in. (32 mm).

NA = not applicable

at temperature as specified in Table UCS-56 need not be continuous. It may be an accumulation of time of multiple postweld heat treatment cycles.

(c) When pressure parts of two different P-Number groups are joined by welding, the postweld heat treatment shall be that specified in either of Tables UCS-56 or UHA-32, with applicable notes, for the material requiring the higher postweld temperature. When non-pressure parts are welded to pressure parts, the postweld heat treatment temperature of the pressure part shall control.

(d) The operation of postweld heat treatment shall be carried out by one of the procedures given in UW-40 in accordance with the following requirements.

(1) The temperature of the furnace shall not exceed 800°F (427°C) at the time the vessel or part is placed in it.

(2) Above 800°F (427°C), the rate³ of heating shall be not more than 400°F/hr (222°C/hr) divided by the maximum metal thickness of the shell or head plate in inches, but in no case more than 400°F/hr (222°C/hr). During the heating period there shall not be a greater variation in temperature throughout the portion of the vessel being heated than 250°F (139°C) within any 15 ft (4.6 m) interval of length.

(3) The vessel or vessel part shall be held at or above the temperature specified in Table UCS-56 or Table UCS-56.1 for the period of time specified in the Tables. During the holding period, there shall not be

³The rates of heating and cooling need not be less than 100°F/hr. However, in all cases consideration of closed chambers and complex structures may indicate reduced rates of heating and cooling to avoid structural damage due to excessive thermal gradients.

01

forming to the specifications listed therein.² Values may be interpolated for intermediate temperatures. (See UG-23.) For vessels designed to operate at a temperature below -20°F (-29°C), the allowable stress values to be used in design shall not exceed those given in Table 3 or 1A in Section II, Part D for 100°F (38°C).

UCS-27 SHELLS MADE FROM PIPE

(a) Shells of pressure vessels may be made from seamless pipe or tubing listed in Table 1A of Section II, Part D provided the material of the pipe is manufactured by the open-hearth, basic oxygen, or electric-furnace process.

(b) Shells of pressure vessels may be made from electric resistance welded pipe or tubing listed in Table 1A of Section II, Part D in nominal diameters up to 30 in. (762 mm) provided the material is manufactured by the open-hearth, basic oxygen, or electric-furnace process [see UG-16(d)].

UCS-28 THICKNESS OF SHELLS UNDER EXTERNAL PRESSURE

(a) Cylindrical and spherical shells under external pressure shall be designed by the rules in UG-28, using the applicable figures in Subpart 3 of Section II, Part D and the temperature limits of UG-20(c).

(b) Examples illustrating the use of the charts in the figures for the design of vessels under external pressure are given in Appendix L.

(c) Corrugated shells subject to external pressure may be used in pressure vessels in accordance with PFT-19 of Section I.

UCS-29 STIFFENING RINGS FOR SHELLS UNDER EXTERNAL PRESSURE

Rules covering the design of stiffening rings are given in UG-29. An example illustrating the use of these rules is given in Appendix L.

UCS-30 ATTACHMENT OF STIFFENING RINGS TO SHELL

Rules covering the attachment of stiffening rings are given in UG-30.

UCS-33 FORMED HEADS, PRESSURE ON CONVEX SIDE

Ellipsoidal, torispherical, hemispherical, and conical heads having pressure on the convex side (minus heads) shall be designed by the rules of UG-33, using Fig. CS-1 or Fig. CS-2 of Subpart 3 of Section II, Part D. Examples illustrating the application of this paragraph are given in Appendix L.

UCS-56 REQUIREMENTS FOR POSTWELD HEAT TREATMENT

(a) Before applying the detailed requirements and exemptions in these paragraphs, satisfactory weld procedure qualifications of the procedures to be used shall be performed in accordance with all the essential variables of Section IX including conditions of postweld heat treatment or lack of postweld heat treatment and including other restrictions listed below.

Except as otherwise specifically provided in the notes to Table UCS-56 and Table UCS-56.1, all welds in pressure vessels or pressure vessel parts shall be given a postweld heat treatment at a temperature not less than specified in those Tables when the nominal thickness, as defined in UW-40(f), including corrosion allowance, exceeds the limits in those Tables. The exemptions provided in Table UCS-56 or Table UCS-56.1 are not permitted when postweld heat treatment is a service requirement as set forth in UCS-68, when welding ferritic materials greater than $\frac{1}{8}$ in. (3.2 mm) thick with the electron beam welding process, or when welding P-No. 3, P-No. 4, P-Nos. 5A, 5B, and 5C, and P-No. 10 materials of any thickness using the inertia and continuous drive friction welding processes. Electroslag welds in ferritic materials over $1\frac{1}{2}$ in. (38 mm) thickness at the joint shall be given a grain refining (austenitizing) heat treatment. Electrogas welds in ferritic materials with any single pass greater than $1\frac{1}{2}$ in. (38 mm) shall be given a grain refining (austenitizing) heat treatment. For P-No. 1 materials only, the heating and cooling rate restrictions of (d)(2) and (d)(5) below do not apply when the heat treatment following welding is in the austenitizing range.

The materials in Table UCS-56 are listed in accordance with Section IX P-Number material groupings of QW-422 and also listed in Table UCS-23.

(b) Except where prohibited in Table UCS-56, holding temperatures and/or holding times in excess of the minimum values given in Table UCS-56 may be used. Intermediate postweld heat treatments need not conform to the requirements of Table UCS-56. The holding time

²See Appendix 1 of Section II, Part D for the basis on which the allowable stress values have been established.

TABLE UCS-56
POSTWELD HEAT TREATMENT REQUIREMENTS FOR CARBON AND LOW ALLOY STEELS (CONT'D)

Material	Normal Holding Temperature, °F (°C), Minimum	Minimum Holding Time at Normal Temperature for Nominal Thickness [See UW-40(f)]		
		Up to 2 in. (51 mm)	Over 2 in. to 5 in. (51 mm to 127 mm)	Over 5 in. (127 mm)
P-No. 4 Gr. Nos. 1, 2	1100 (593)	1 hr/in. (25 mm), 15 min minimum	1 hr/in. (25 mm)	5 hr plus 15 min for each additional inch (25 mm) over 5 in. (127 mm)

NOTES:

- (1) Except for exemptions in Note (2), postweld heat treatment is mandatory under the following conditions:
- (a) on material of SA-202 Grades A and B over $\frac{5}{8}$ in. (16 mm) nominal thickness. For these materials postweld heat treatment is mandatory up to and including $\frac{7}{8}$ in. (16 mm) nominal thickness unless a welding procedure qualification described in UCS-56(a) has been made in equal or greater thickness than the production weld.
 - (b) on material of all thicknesses if required by UW-2
 - (c) on all other P-No. 4 Gr. Nos. 1 and 2 materials.
- (2) Postweld heat treatment is not mandatory under the conditions specified below:
- (a) for circumferential butt welds in pipe or tube of P-No. 4 materials where the pipe or tubes comply with all of the following conditions:
 - (1) a maximum nominal outside diameter of 4 in. (DN 100);
 - (2) a maximum nominal thickness of $\frac{5}{8}$ in. (16 mm);
 - (3) a maximum specified carbon content of not more than 0.15% (SA material specification carbon content, except when further limited by the purchaser to a value within the specification limits);
 - (4) a minimum preheat of 250°F (121°C).
 - (b) for P-No. 4 pipe or tube materials meeting the requirements of (2)(a)(1), (2)(a)(2), and (2)(a)(3) above, having nonpressure attachments fillet welded to them provided:
 - (1) the fillet welds have a maximum throat thickness of $\frac{1}{2}$ in. (13 mm);
 - (2) a minimum preheat temperature of 250°F (121°C) is applied.
 - (c) for P-No. 4 pipe or tube materials meeting the requirements of (2)(a)(1), (2)(a)(2), and (2)(a)(3) above, having studs welded to them, a minimum preheat temperature of 250°F (121°C) is applied.

(2) The total repair depth shall not exceed $1\frac{1}{2}$ in. (38 mm) for P-No. 1 Group Nos. 1, 2, and 3 materials and $\frac{5}{8}$ in. (16 mm) for P-No. 3 Group Nos. 1, 2, and 3 materials. The total depth of a weld repair shall be taken as the sum of the depths for repairs made from both sides of a weld at a given location.

(3) After removal of the defect, the groove shall be examined, using either the magnetic particle or the liquid penetrant examination methods, in accordance with Appendix 6 for MT and Appendix 8 for PT.

(4) In addition to the requirements of Section IX for qualification of Welding Procedure Specifications for groove welds, the following requirements shall apply.

(a) The weld metal shall be deposited by the manual shielded metal arc process using low hydrogen electrodes. The electrodes shall be properly conditioned in accordance with Section II, Part C, SFA-5.5, Appendix A5.6. The maximum bead width shall be four times the electrode core diameter.

(b) For P-No. 1 Group Nos. 1, 2, and 3 materials, the repair area shall be preheated and maintained at a minimum temperature of 200°F (93°C) during welding.

(c) For P-No. 3 Group Nos. 1, 2, and 3 materials, the repair weld method shall be limited to the half bead weld repair and weld temper bead reinforcement technique. The repair area shall be preheated and maintained at a minimum temperature of 350°F (177°C) during welding. The maximum interpass temperature shall be 450°F (232°C). The initial layer of weld metal shall be deposited over the entire area using $\frac{1}{8}$ in. (3.2 mm) maximum diameter electrodes. Approximately one-half the thickness of this layer shall be removed by grinding before depositing subsequent layers. The subsequent weld layers shall be deposited using $\frac{3}{32}$ in. (4 mm) maximum diameter electrodes in such a manner as to assure tempering of the prior weld beads and their heat affected zones. A final temper bead weld shall be applied to a level above the surface being repaired without contacting the base material but close enough to the edge of the underlying weld bead to

TABLE UCS-56
POSTWELD HEAT TREATMENT REQUIREMENTS FOR CARBON AND LOW ALLOY STEELS (CONT'D)

Material	Normal Holding Temperature, °F (°C), Minimum	Minimum Holding Time at Normal Temperature for Nominal Thickness [See UW-40(f)]		
		Up to 2 in. (51 mm)	Over 2 in. to 5 in. (51 mm to 127 mm)	Over 5 in. (127 mm)
P-No. 3 Gr. Nos. 1, 2, 3	1100 (593)	1 hr/in. (25 mm), 15 min minimum	2 hr plus 15 min for each additional inch (25 mm) over 2 in. (51 mm)	2 hr plus 15 min for each additional inch (25 mm) over 2 in. (51 mm)

NOTES:

- (1) When it is impractical to postweld heat treat at the temperatures specified in this Table, it is permissible to carry out the postweld heat treatment at lower temperatures for longer periods of time in accordance with Table UCS-56.1.
- (2) Postweld heat treatment is mandatory on P-No. 3 Gr. No. 3 material in all thicknesses.
- (3) Except for the exemptions in Note (4), postweld heat treatment is mandatory under the following conditions:
 - (a) on P-No. 3 Gr. No. 1 and P-No. 3 Gr. No. 2 over $\frac{5}{8}$ in. (16 mm) nominal thickness. For these materials, postweld heat treatment is mandatory on material up to and including $\frac{3}{4}$ in. (19 mm) nominal thickness unless a welding procedure qualification described in UCS-56(a) has been made in equal or greater thickness than the production weld.
 - (b) on material in all thicknesses if required by UW-2.
- (4) For welding connections and attachments to pressure parts, postweld heat treatment is not mandatory under the conditions specified below:
 - (a) for attaching to pressure parts that have a specified maximum carbon content of not more than 0.25% (SA material specification carbon content, except when further limited by the purchaser to a value within the specification limits) or nonpressure parts with groove welds not over $\frac{1}{2}$ in. (13 mm) in size or fillet welds that have a throat thickness of $\frac{1}{2}$ in. (13 mm) or less, provided preheat to a minimum temperature of 200°F (93°C) is applied;
 - (b) for circumferential butt welds in pipe or tube where the pipe or tube have both a nominal wall thickness of $\frac{1}{2}$ in. (13 mm) or less and a specified maximum carbon content of not more than 0.25% (SA material specification carbon content, except when further limited by the purchaser to a value within the specification limits);
 - (c) for studs welded to pressure parts that have a specified maximum carbon content of not more than 0.25% (SA material specification carbon content, except when further limited by the purchaser to a value within the specification limits) provided preheat to a minimum temperature of 200°F (93°C) is applied;
 - (d) for corrosion resistant weld metal overlay cladding or for welds attaching corrosion resistant applied lining (see UCL-34) when welded to pressure parts which have a specified maximum carbon content of not more than 0.25% (SA material specification carbon content, except when further limited by the purchaser to a value within the specification limits) provided preheat to a minimum temperature of 200°F (93°C) is maintained during application of the first layer.

a greater difference than 150°F (83°C) between the highest and lowest temperature throughout the portion of the vessel being heated, except where the range is further limited in Table UCS-56.

(4) During the heating and holding periods, the furnace atmosphere shall be so controlled as to avoid excessive oxidation of the surface of the vessel. The furnace shall be of such design as to prevent direct impingement of the flame on the vessel.

(5) Above 800°F (427°C), cooling shall be done in a closed furnace or cooling chamber at a rate³ not greater than 500°F/hr divided by the maximum metal thickness of the shell or head plate in inches, but in no case more than 500°F/hr (278°C). From 800°F (427°C) the vessel may be cooled in still air.

(e) Except as permitted in (f) below, vessels or parts of vessels that have been postweld heat treated in accordance with the requirements of this paragraph shall again be postweld heat treated after welded repairs have been made.

(f) Weld repairs to P-No. 1 Group Nos. 1, 2, and 3 materials and to P-No. 3 Group Nos. 1, 2, and 3 materials and to the weld metals used to join these materials may be made after the final PWHT but prior to the final hydrostatic test, without additional PWHT, provided that PWHT is not required as a service requirement in accordance with UW-2(a), except for the exemptions in Table UCS-56, or as a service requirement in accordance with UCS-68. The welded repairs shall meet the requirements of (1) through (6) below. These requirements do not apply when the welded repairs are minor restorations of the material surface, such as those required after removal of construction fixtures, and provided that the surface is not exposed to the vessel contents.

(1) The Manufacturer shall give prior notification of the repair to the user or to his designated agent and shall not proceed until acceptance has been obtained. Such repairs shall be recorded on the Data Report.

TABLE UCS-56
POSTWELD HEAT TREATMENT REQUIREMENTS FOR CARBON AND LOW ALLOY STEELS (CONT'D)

Material	Normal Holding Temperature, °F (°C), Minimum	Minimum Holding Time at Normal Temperature for Nominal Thickness [See UW-40(f)]
P-No. 9A Gr. No. 1	1100 (593)	1 hr minimum, plus 15 min/in. (25 mm) for thickness over 1 in. (25 mm)

NOTES:

- (1) When it is impractical to postweld heat treat at the temperature specified in this Table, it is permissible to carry out the postweld heat treatment at lower temperatures [1000°F (538°C) minimum] for longer periods of time in accordance with Table UCS-56.1.
- (2) Except for exemptions in Note (3), postweld heat treatment is mandatory under the following conditions:
 - (a) on material over $\frac{5}{8}$ in. (16 mm) nominal thickness. For material up to and including $\frac{5}{8}$ in. (16 mm) nominal thickness, postweld heat treatment is mandatory unless a welding procedure qualification described in UCS-56(a) has been made in equal or greater thickness than the production weld.
 - (b) on material of all thicknesses if required by UW-2.
- (3) Postweld heat treatment is not mandatory under conditions specified below:
 - (a) for circumferential butt welds in pipe or tubes where the pipe or tubes comply with all the following conditions:
 - (1) a maximum nominal outside diameter of 4 in. (DN 100);
 - (2) a maximum thickness of $\frac{1}{2}$ in. (13 mm);
 - (3) a maximum specified carbon content of not more than 0.15% (SA material specification carbon content, except when further limited by the purchaser to a value within the specification limits);
 - (4) a minimum preheat of 250°F (121°C).
 - (b) for pipe or tube materials meeting the requirements of (3)(a)(1), (3)(a)(2), and (3)(a)(3) above, having attachments fillet welded to them, provided:
 - (1) the fillet welds have a throat thickness of $\frac{1}{2}$ in. (13 mm) or less;
 - (2) the material is preheated to 250°F (121°C) minimum. A lower preheating temperature may be used provided specifically controlled procedures necessary to produce sound welded joints are used. Such procedures shall include but shall not be limited to the following:
 - (a) The throat thickness of fillet welds shall be $\frac{1}{2}$ in. (13 mm) or less.
 - (b) The maximum continuous length of fillet welds shall be not over 4 in. (102 mm).
 - (c) The thickness of the test plate used in making the welding procedure qualification of Section IX shall not be less than that of the material to be welded.
 - (c) for attaching nonpressure parts to pressure parts with groove welds not over $\frac{1}{2}$ in. (13 mm) in size or fillet welds that have a throat thickness of $\frac{1}{2}$ in. (13 mm) or less, provided preheat to a minimum temperature of 200°F (93°C) is applied;
 - (d) for studs welded to pressure parts provided preheat to a minimum temperature of 200°F (93°C) is applied;
 - (e) for corrosion resistant weld metal overlay cladding or for welds attaching corrosion resistant applied lining (see UCL-34) provided preheat to a minimum temperature of 200°F (93°C) is maintained during application of the first layer.
- (4) When the heating rate is less than 50°F (28°C)/hr between 800°F (427°C) and the holding temperature, the additional 15 min/in. (25 mm) holding time is not required. Additionally, where the manufacturer can provide evidence that the minimum temperature has been achieved throughout the thickness, the additional 15 min/in. (25 mm) holding time is not required.

TABLE UCS-56
POSTWELD HEAT TREATMENT REQUIREMENTS FOR CARBON AND LOW ALLOY STEELS (CONT'D)

Material	Normal Holding Temperature, °F (°C), Minimum	Minimum Holding Time at Normal Temperature for Nominal Thickness [See UW-40(f)]		
		Up to 2 in. (51 mm)	Over 2 in. to 5 in. (51 mm to 127 mm)	Over 5 in. (127 mm)
P-Nos. 5A, 5B Gr. No. 1, and 5C Gr. No. 1	1250 (677)	1 hr/in. (25 mm), 15 min minimum	1 hr/in. (25 mm)	5 hr plus 15 min for each additional inch (25 mm) over 5 in. (127 mm)
P-No. 5B Gr. No. 2	1300 (704)			

NOTES:

- (1) Except for exemptions in Note (2), postweld heat treatment is mandatory under all conditions.
- (2) Postweld heat treatment is not mandatory under the following conditions:
- (a) for circumferential butt welds in pipe or tube where the pipe or tubes comply with all of the following conditions:
 - (1) a maximum specified chromium content of 3.00%;
 - (2) a maximum nominal outside diameter of 4 in. (DN 100);
 - (3) a maximum nominal thickness of $\frac{5}{8}$ in. (16 mm);
 - (4) a maximum specified carbon content of not more than 0.15% (SA material specification carbon content, except when further limited by the purchaser to a value within the specification limits);
 - (5) a minimum preheat of 300°F (149°C) is applied.
 - (b) for pipe or tube materials meeting the requirements of (2)(a)(1), (2)(a)(2), (2)(a)(3), and (2)(a)(4) having nonpressure attachments fillet welded to them provided:
 - (1) the fillet welds have a maximum throat thickness of $\frac{1}{2}$ in. (13 mm);
 - (2) a minimum preheat temperature of 300°F (149°C) is applied.
 - (c) for pipe or tube materials meeting the requirements of (2)(a)(1), (2)(a)(2), (2)(a)(3), and (2)(a)(4) having studs welded to them provided a minimum preheat temperature of 300°F (149°C) is applied.
- (3) When it is impractical to postweld heat P-Nos. 5A, 5B Gr. No. 1, and 5C Gr. No. 1 materials at the temperature specified in this Table, it is permissible to perform the postweld heat treatment at 1200°F (649°C) minimum provided that, for material up to 2 in. (51 mm) nominal thickness, the holding time is increased to the greater of 4 hr minimum or 4 hr/in. (25 mm) of thickness; for thickness over 2 in. (51 mm), the specified holding times are multiplied by 4. The requirements of UCS-85 must be accommodated in this reduction in postweld heat treatment.

TABLE UCS-56
POSTWELD HEAT TREATMENT REQUIREMENTS FOR CARBON AND LOW ALLOY STEELS (CONT'D)

Material	Normal Holding Temperature, °F (°C), Minimum	Minimum Holding Time at Normal Temperature for Nominal Thickness [See UW-40(f)]
P-No. 10B Gr. No. 1	1100 (593)	1 hr minimum, plus 15 min/in. (25 mm) for thickness over 1 in. (25 mm)

NOTES:

- (1) Postweld heat treatment is mandatory for P-No. 10B materials for all thicknesses.
- (2) When the heating rate is less than 50°F (28°C)/hr between 800°F (427°C) and the holding temperature, the additional 15 min/in. (25 mm) holding time is not required. Additionally, where the manufacturer can provide evidence that the minimum temperature has been achieved throughout the thickness, the additional 15 min/in. (25 mm) holding time is not required.

Material	Normal Holding Temperature, °F (°C), Minimum	Minimum Holding Time at Normal Temperature for Nominal Thickness [See UW-40(f)]
P-No. 10C Gr. No. 1	1000 (538)	1 hr minimum, plus 15 min/in. (25 mm) for thickness over 1 in. (25 mm)

NOTES:

- (1) When it is impractical to postweld heat treat at the temperatures specified in this Table, it is permissible to carry out the postweld heat treatment at lower temperatures for longer periods of time in accordance with Table UCS-56.1.
- (2) Except for exemptions in Note (3), postweld heat treatment is mandatory under the following conditions:
 - (a) for material over 1½ in. (38 mm) nominal thickness. Postweld heat treatment is mandatory on materials over 1¼ in. (32 mm) nominal thickness through 1½ in. (38 mm) nominal thickness unless preheat is applied at a minimum temperature of 200°F (93°C) during welding.
 - (b) on material of all thicknesses if required by UW-2.
- (3) Postweld heat treatment is not mandatory under the conditions specified below:
 - (a) for groove welds not over ½ in. (13 mm) in size and fillet welds with throat not over ½ in. (13 mm) that attach nozzle connections that have a finished inside diameter not greater than 2 in. (51 mm) provided the connections do not form ligaments that require an increase in shell or head thickness and preheat to a minimum temperature of 200°F (93°C) is applied;
 - (b) for groove welds not over ½ in. (13 mm) in size or fillet welds having throat thickness of ½ in. (13 mm) or less used for attaching nonpressure parts to pressure parts and preheat to a minimum temperature of 200°F (93°C) is applied when the thickness of the pressure part exceeds 1¼ in. (32 mm);
 - (c) for studs welded to pressure parts provided preheat to a minimum temperature of 200°F (93°C) is applied when the thickness of the pressure part exceeds 1¼ in. (32 mm);
 - (d) for corrosion resistant weld metal overlay cladding or for welds attaching corrosion resistant applied lining (see UCL-34) provided preheat to a minimum temperature of 200°F (93°C) is maintained during application of the first layer when the thickness of the pressure part exceeds 1¼ in. (32 mm).
- (4) When the heating rate is less than 50°F (28°C)/hr between 800°F (427°C) and the holding temperature, the additional 15 min/in. (25 mm) holding time is not required. Additionally, where the manufacturer can provide evidence that the minimum temperature has been achieved throughout the thickness, the additional 15 min/in. (25 mm) holding time is not required.

Material	Normal Holding Temperature, °F (°C), Minimum	Minimum Holding Time at Normal Temperature for Nominal Thickness [See UW-40(f)]
P-No. 10F Gr. No. 1	1000 (538)	1 hr minimum, plus 15 min/in. (25 mm) for thickness over 1 in. (25 mm)

NOTES:

- (1) Postweld heat treatment is mandatory for P-No. 10F materials for all thicknesses.
- (2) When the heating rate is less than 50°F (28°C)/hr between 800°F (427°C) and the holding temperature, the additional 15 min/in. (25 mm) holding time is not required. Additionally, where the manufacturer can provide evidence that the minimum temperature has been achieved throughout the thickness, the additional 15 min/in. (25 mm) holding time is not required.

TABLE UCS-56
POSTWELD HEAT TREATMENT REQUIREMENTS FOR CARBON AND LOW ALLOY STEELS (CONT'D)

Material	Normal Holding Temperature, °F (°C), Minimum	Minimum Holding Time at Normal Temperature for Nominal Thickness [See UW-40(f)]
P-No. 9B Gr. No. 1	1100 (593)	1 hr minimum, plus 15 min/in. (25 mm) for thickness over 1 in. (25 mm)

NOTES:

- (1) When it is impractical to postweld heat treat at the temperatures specified in this Table, it is permissible to carry out the postweld heat treatment at lower temperatures [1000°F (538°C) minimum] for longer periods of time in accordance with Table UCS-56.1.
- (2) The holding temperature for postweld heat treatment shall not exceed 1175°F (635°C).
- (3) Except for exemptions in Note (4), postweld heat treatment is mandatory under the following conditions:
 - (a) on material over $\frac{5}{8}$ in. (16 mm) nominal thickness. For material up to and including $\frac{5}{8}$ in. (16 mm) nominal thickness, postweld heat treatment is mandatory unless a welding procedure qualification described in UCS-56(a) has been made in equal or greater thickness than the production weld.
 - (b) on material of all thicknesses if required by UW-2.
- (4) Postweld heat treatment is not mandatory under the conditions specified below:
 - (a) for attaching nonpressure parts to pressure parts with groove welds not over $\frac{1}{2}$ in. (13 mm) in size or fillet welds that have a throat thickness of $\frac{1}{2}$ in. (13 mm) or less, provided preheat to a minimum temperature of 200°F (93°C) is applied;
 - (b) for studs welded to pressure parts provided preheat to a minimum temperature of 200°F (93°C) is applied;
 - (c) for corrosion resistant weld metal overlay cladding or for welds attaching corrosion resistant applied lining (see UCL-34) provided preheat to a minimum temperature of 200°F (93°C) is maintained during application of the first layer.
- (5) When the heating rate is less than 50°F (28°C)/hr between 800°F (427°C) and the holding temperature, the additional 15 min/in. (25 mm) holding time is not required. Additionally, where the manufacturer can provide evidence that the minimum temperature has been achieved throughout the thickness, the additional 15 min/in. (25 mm) holding time is not required.

Material	Normal Holding Temperature, °F (°C), Minimum	Minimum Holding Time at Normal Temperature for Nominal Thickness [See UW-40(f)]
P-No. 10A Gr. No. 1	1100 (593)	1 hr minimum, plus 15 min/in. (25 mm) for thickness over 1 in. (25 mm)

NOTES:

- (1) (a) When it is impractical to postweld heat treat at the temperature specified in this Table, it is permissible to carry out the postweld heat treatment at lower temperatures for longer periods of time in accordance with Table UCS-56.1.
- (b) Consideration should be given for possible embrittlement of materials containing up to 0.15% vanadium when postweld heat treating at the minimum temperature and at lower temperature for longer holding times.
- (2) Except for exemptions in Note (3), postweld heat treatment is mandatory under the following conditions:
 - (a) on all thicknesses of SA-487 Class 1Q material;
 - (b) on all other P-No. 10A materials over $\frac{5}{8}$ in. (16 mm) nominal thickness. For these materials up to and including $\frac{5}{8}$ in. (16 mm) nominal thickness, postweld heat treatment is mandatory unless a welding procedure qualification described in UCS-56(a) has been made in equal or greater thickness than the production weld.
 - (c) on material of all thicknesses if required by UW-2.
- (3) Postweld heat treatment is not mandatory under the conditions specified below:
 - (a) for attaching to pressure parts that have a specified maximum carbon content of not more than 0.25% (SA material specification carbon content, except when further limited by the purchaser to a value within the specification limits) or nonpressure parts with groove weld not over $\frac{1}{2}$ in. (13 mm) in size or fillet welds having a throat thickness of $\frac{1}{2}$ in. (13 mm) or less, provided preheat to a minimum temperature of 200°F (93°C) is applied;
 - (b) for circumferential butt welds in pipes or tube where the pipe or tube has both a nominal wall thickness of $\frac{1}{2}$ in. (13 mm) or less and a specified maximum carbon content of not more than 0.25% (SA material specification carbon content, except when further limited by purchaser to a value within the specification limits) provided preheat to a minimum temperature of 200°F (93°C) is applied;
 - (c) for studs welded to pressure parts that have a specified maximum carbon content of not more than 0.25% (SA material specification carbon content, except when further limited by purchaser to a value within the specification limits) provided preheat to a minimum temperature of 200°F (93°C) is applied;
 - (d) for corrosion resistant weld metal overlay cladding or for welds attaching corrosion resistant applied lining (see UCL-34) when welded to pressure parts that have a specified maximum carbon content of not more than 0.25% (SA material specification carbon content, except when further limited by the purchaser to a value within the specification limits) provided preheat to a minimum temperature of 200°F (93°C) is maintained during application of the first layer.
- (4) When the heating rate is less than 50°F (28°C)/hr between 800°F (427°C) and the holding temperature, the additional 15 min/in. (25 mm) holding time is not required. Additionally, where the manufacturer can provide evidence that the minimum temperature has been achieved throughout the thickness, the additional 15 min/in. (25 mm) holding time is not required.

defined in (1), (2), or (3) below, and the minimum design metal temperature.

The following thickness limitations apply when using Fig. UCS-66.

(1) Excluding castings, the governing thickness t_g of a welded part is as follows:

(a) for butt joints except those in flat heads and tubesheets, the nominal thickness of the thickest welded joint [see Fig. UCS-66.3 sketch (a)];

(b) for corner, fillet, or lap welded joints, including attachments as defined above, the thinner of the two parts joined;

(c) for flat heads or tubesheets, the larger of (b) above or the flat component thickness divided by 4;

(d) for welded assemblies comprised of more than two components (e.g., nozzle-to-shell joint with reinforcing pad), the governing thickness and permissible minimum design metal temperature of each of the individual welded joints of the assembly shall be determined, and the warmest of the minimum design metal temperatures shall be used as the permissible minimum design metal temperature of the welded assembly. [See Fig. UCS-66.3 sketch (b), L-9.3.1, and L-9.5.2.]

If the governing thickness at any welded joint exceeds 4 in. and the minimum design metal temperature is colder than 120°F (49°C), impact tested material shall be used.

(2) The governing thickness of a casting shall be its largest nominal thickness.

(3) The governing thickness of flat nonwelded parts, such as bolted flanges, tubesheets, and flat heads, is the flat component thickness divided by 4.

(4) The governing thickness of a nonwelded dished head [see Fig. 1-6 sketch (c)] is the greater of the flat flange thickness divided by 4 or the minimum thickness of the dished portion.

(5) If the governing thickness of the nonwelded part exceeds 6 in. (152 mm) and the minimum design metal temperature is colder than 120°F (49°C), impact tested material shall be used.

Examples of the governing thickness for some typical vessel details are shown in Fig. UCS-66.3.

NOTE: The use of provisions in UCS-66 which waive the requirements for impact testing does not provide assurance that all test results for these materials would satisfy the impact energy requirements of UG-84 if tested.

(b) When the coincident ratio defined in Fig. UCS-66.1 is less than one, Fig. UCS-66.1 provides a basis for the use of components made of Part UCS materials

to have a colder MDMT than that derived from (a) above without impact testing.

(1)(a) For such components, and for a MDMT of -55°F (-48°C) and warmer, the MDMT without impact testing determined in (a) above for the given material and thickness may be reduced as determined from Fig. UCS-66.2. If the resulting temperature is colder than the required MDMT, impact testing of the material is not required. A02

(b) Figure UCS-66.1 may also be used for components not stressed in general primary membrane tensile stress, such as flat heads, covers, tubesheets, and flanges (including bolts and nuts). The MDMT of these components without impact testing as determined in UCS-66(a) or (c) may be reduced as determined from Fig. UCS-66.2. The ratio used in Step 3 of Fig. UCS-66.2 shall be the ratio of maximum design pressure at the MDMT to the maximum allowable pressure (MAP) of the component at the MDMT. If the resulting temperature is colder than the required MDMT, impact testing of the material is not required, provided the MDMT is not colder than -55°F (-48°C). A02

(c) In lieu of using (b)(1)(b) above, the MDMT determined in UCS-66(a) or (c) may be reduced for a flange attached by welding, by the same reduction as determined in (b)(1)(a) above for the neck or shell which the flange is attached.

NOTE: The bolt-up condition need not be considered when determining the temperature reduction for flanges.

(2) For minimum design temperatures colder than -55°F (-48°C), impact testing is required for all materials, except as allowed in (b)(3) below and in UCS-68(c).

(3) When the minimum design metal temperature is colder than -55°F (-48°C) and no colder than -155°F (-104°C), and the coincident ratio defined in Fig. UCS-66.1 is less than or equal to 0.35, impact testing is not required.

(c) No impact testing is required for the following flanges when used at minimum design metal temperatures no colder than -20°F (-29°C):

(1) ASME B16.5 flanges of ferritic steel;

(2) ASME B16.47 flanges of ferritic steel;

(3) split loose flanges of SA-216 GR WCB when the outside diameter and bolting dimensions are either ASME B16.5 Class 150 or Class 300, and the flange thicknesses are not greater than that of either ASME B16.5 Class 150 or Class 300, respectively.

(4) *Carbon and Low Alloy Steel Long Weld Neck Flanges.* Long weld neck flanges are defined as forged nozzles that meet the dimensional requirements of a flanged fitting given in ASME B16.5 but having a straight hub/neck. The neck inside diameter shall not A02

TABLE UCS-56.1
ALTERNATIVE POSTWELD HEAT TREATMENT
REQUIREMENTS FOR CARBON
AND LOW ALLOY STEELS

Applicable Only When Permitted in Table UCS-56

Decrease in Temperature Below Minimum Specified Temperature, °F (°C)	Minimum Holding Time [Note (1)] at Decreased Temperature, hr	Notes
50 (28)	2	...
100 (56)	4	...
150 (83)	10	(2)
200 (111)	20	(2)

NOTES:

- (1) Minimum holding time for 1 in. (25 mm) thickness or less. Add 15 minutes per inch (25 mm) of thickness for thicknesses greater than 1 in. (25 mm).
(2) These lower postweld heat treatment temperatures permitted only for P-No. 1 Gr. Nos. 1 and 2 materials.

assure tempering of the base material heat affected zone. After completing all welding, the repair area shall be maintained at a temperature of 400°F–500°F (204°C–260°C) for a minimum period of 4 hr. The final temper bead reinforcement layer shall be removed substantially flush with the surface of the base material.

(5) After the finished repair weld has reached ambient temperature, it shall be inspected using the same nondestructive examination that was used in (f)(3) above, except that for P-No. 3, Group No. 3 materials, the examination shall be made after the material has been at ambient temperature for a minimum period of 48 hr to determine the presence of possible delayed cracking of the weld. If the examination is by the magnetic particle method, only the alternating current yoke type is acceptable. In addition, welded repairs greater than $\frac{3}{8}$ in. (10 mm) deep in materials and in welds that are required to be radiographed by the rules of this Division, shall be radiographically examined to the requirements of UW-51.

(6) The vessel shall be hydrostatically tested after making the welded repair.

UCS-57 RADIOGRAPHIC EXAMINATION

In addition to the requirements of UW-11, complete radiographic examination is required for each butt welded joint at which the thinner of the plate or vessel wall thicknesses at the welded joint exceeds the

TABLE UCS-57
THICKNESS ABOVE WHICH FULL RADIOGRAPHIC
EXAMINATION OF BUTT WELDED JOINTS IS
MANDATORY

P-No. & Gr. No. Classification of Material	Nominal Thickness Above Which Butt Welded Joints Shall Be Fully Radiographed, in. (mm)
1 Gr. 1, 2, 3	1 $\frac{1}{4}$ (32)
3 Gr. 1, 2, 3	$\frac{3}{4}$ (19)
4 Gr. 1, 2	$\frac{5}{8}$ (16)
5A, 5B Gr. 1	0 (0)
9A Gr. 1	$\frac{5}{8}$ (16)
9B Gr. 1	$\frac{5}{8}$ (16)
10A Gr. 1	$\frac{3}{4}$ (19)
10B Gr. 2	$\frac{5}{8}$ (16)
10C Gr. 1	$\frac{5}{8}$ (16)
10F Gr. 6	$\frac{3}{4}$ (19)

thickness limit above which full radiography is required in Table UCS-57.

LOW TEMPERATURE OPERATION

UCS-65 SCOPE

The following paragraphs contain requirements for vessels and vessel parts constructed of carbon and low alloy steels with respect to minimum design metal temperatures.

UCS-66 MATERIALS

(a) Figure UCS-66 shall be used to establish impact testing exemptions for steels listed in Part UCS. Unless otherwise exempted by the rules of this Division, impact testing is required for a combination of minimum design metal temperature (see UG-20) and thickness (as defined below) which is below the curve assigned to the subject material. If a minimum design metal temperature and thickness combination is on or above the curve, impact testing is not required by the rules of this Division, except as required by (j) below and UCS-67(a)(2) for weld metal.

Components, such as shells, heads, nozzles, manways, reinforcing pads, flanges, tubesheets, flat cover plates, backing strips which remain in place, and attachments which are essential to the structural integrity of the vessel when welded to pressure retaining components, shall be treated as separate components. Each component shall be evaluated for impact test requirements based on its individual material classification, thickness as

A02 FIG. UCS-66 (CONT'D)

A03 GENERAL NOTES ON ASSIGNMENT OF MATERIALS TO CURVES:

(a) Curve A applies to:

- (1) all carbon and all low alloy steel plates, structural shapes, and bars not listed in Curves B, C, and D below;
- (2) SA-216 Grades WCB and WCC if normalized and tempered or water-quenched and tempered; SA-217 Grade WC6 if normalized and tempered or water-quenched and tempered.

(b) Curve B applies to:

- (1) SA-216 Grade WCA if normalized and tempered or water-quenched and tempered
SA-216 Grades WCB and WCC for thicknesses not exceeding 2 in. (51 mm), if produced to fine grain practice and water-quenched and tempered
SA-217 Grade WC9 if normalized and tempered
SA-285 Grades A and B
SA-414 Grade A
SA-515 Grade 60
SA-516 Grades 65 and 70 if not normalized
SA-612 if not normalized
SA-662 Grade B if not normalized
SA/EN 10028-2 P295GH as-rolled;
- (2) except for cast steels, all materials of Curve A if produced to fine grain practice and normalized which are not listed in Curves C and D below;
- (3) all pipe, fittings, forgings and tubing not listed for Curves C and D below;
- (4) parts permitted under UG-11 shall be included in Curve B even when fabricated from plate that otherwise would be assigned to a different curve.

(c) Curve C

- (1) SA-182 Grades 21 and 22 if normalized and tempered
SA-302 Grades C and D
SA-336 F21 and F22 if normalized and tempered
SA-387 Grades 21 and 22 if normalized and tempered
SA-516 Grades 55 and 60 if not normalized
SA-533 Grades B and C
SA-662 Grade A;
- (2) all material of Curve B if produced to fine grain practice and normalized and not listed for Curve D below.

(d) Curve D

- SA-203
SA-508 Grade 1
SA-516 if normalized
SA-524 Classes 1 and 2
SA-537 Classes 1, 2, and 3
SA-612 if normalized
SA-662 if normalized
SA-738 Grade A
SA-738 Grade A with Cb and V deliberately added in accordance with the provisions of the material specification, not colder than -20°F (-29°C)
SA-738 Grade B not colder than -20°F (-29°C)
SA/AS 1548 Grades 7-430, 7-460, and 7-490 if normalized
SA/EN 10028-2 P295GH if normalized [see Note (g)(3)]
SA/EN 10028-3 P275NH

General Notes and Notes continue on next page

be less than the nominal size of the flange and the outside diameter of the neck and any nozzle reinforcement shall not exceed the diameter of the hub as specified in ASME B16.5.

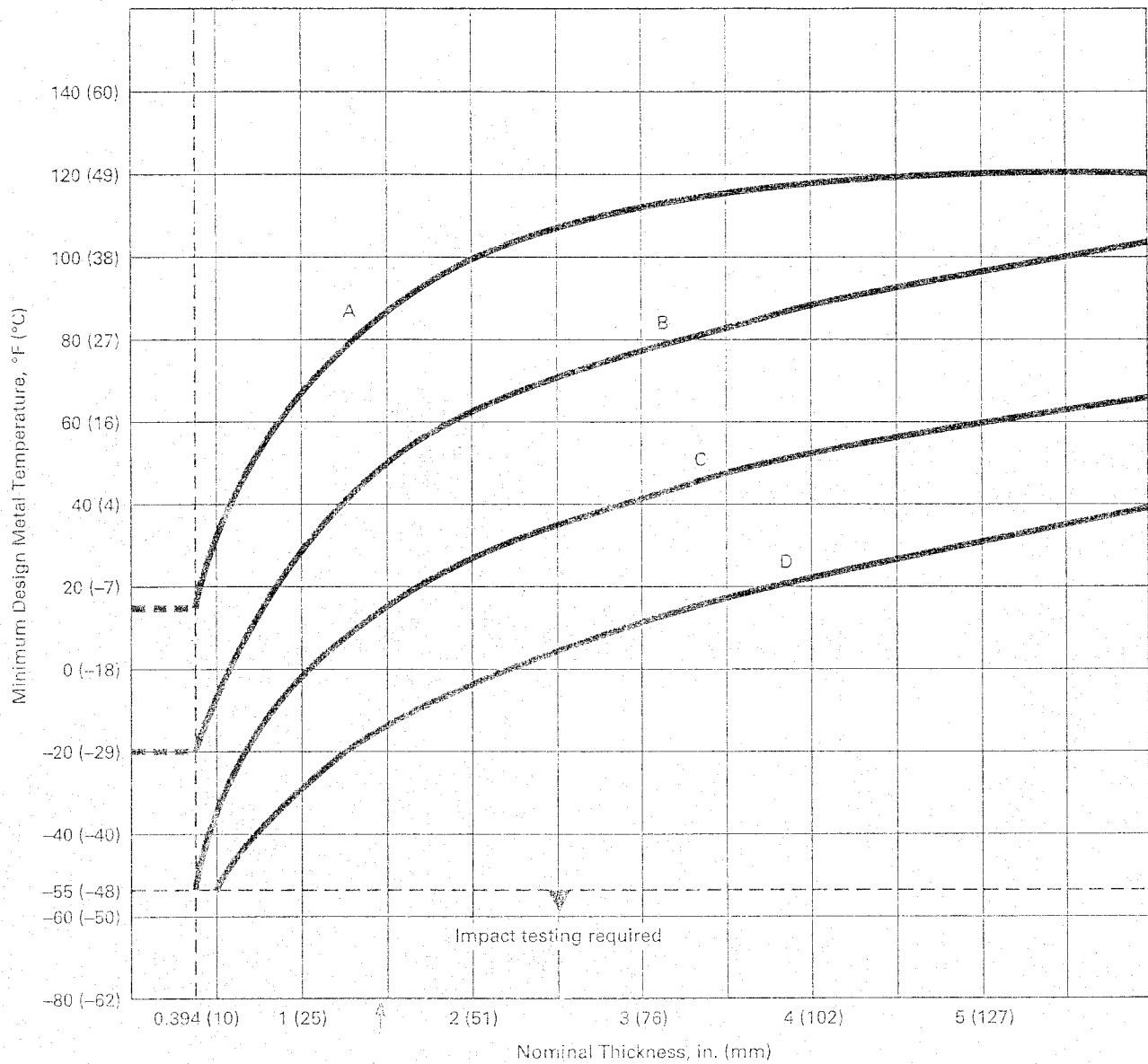
(d) No impact testing is required for UCS materials 0.10 in. (2.5 mm) in thickness and thinner, but such exempted UCS materials shall not be used at design metal temperatures colder than -55°F (-48°C). For vessels or components made from NPS 4 (DN 100) or smaller tubes or pipe of P-No. 1 materials, the following exemptions from impact testing are also permitted as a function of the material specified minimum yield strength (SMYS) for metal temperatures of -155°F (-104°C) and warmer:

SMYS, ksi (MPa)	Thickness, in. (mm)
20 to 35 (138 to 241)	0.237 (6.0)
36 to 45 (248 to 310)	0.125 (3.2)
46 (317) and higher	0.10 (2.5)

(e) The material manufacturer's identification marking required by the material specification shall not be stamped on plate material less than 1/4 in. (6 mm) in thickness unless the following requirements are met.

(1) The materials shall be limited to P-No. 1 Gr. Nos. 1 and 2.

(2) The minimum nominal plate thickness shall be 0.1875 in. (4.8 mm), or the minimum nominal pipe wall thickness shall be 0.154 in. (3.9 mm).



[Limited to 4 in. (102 mm) for Welded Construction]

General Notes and Notes follow on next two pages

FIG. UCS-66 IMPACT TEST EXEMPTION CURVES [SEE NOTES (1) AND (2)] [SEE UCS-66(a)]

(3) The minimum design metal temperature shall be no colder than -20°F (-29°C).

(f) Unless specifically exempted in Fig. UCS-66, materials having a specified minimum yield strength greater than 65 ksi (448 MPa) must be impact tested.

(g) Materials produced and impact tested in accordance with the requirements of the specifications listed in Fig. UG-84.1, General Note (c), are exempt from impact testing by the rules of this Division at minimum design metal temperatures not more than 5°F (3°C) colder than the test temperature required by the specification.

(h) No impact testing is required for metal backing strips which remain in place made of materials assigned to Curve A of Fig. UCS-66 in thicknesses not exceeding $\frac{1}{4}$ in. when the minimum design metal temperature is -20°F (-29°C) or warmer.

(i) For components made of Part UCS materials that are impact tested, Fig. UCS-66.1 provides a basis for the use of these components at MDMT colder than the impact test temperature, provided the coincident ratio defined in Fig. UCS-66.1 is less than one, and the MDMT is not colder than -155°F (-104°C).

(1) For such components, the MDMT shall not be colder than the impact test temperature less the allowable temperature reduction as determined from Fig. UCS-66.2.

(2) Figure UCS-66.1 may also be used for components not stressed in general primary membrane tensile stress, such as flat heads, covers, tubesheets, and flanges (including bolts and nuts). The MDMT shall not be colder than the impact test temperature less the allowable temperature reduction as determined from Fig. UCS-66.2. The ratio used in Step 3 of Fig. UCS-66.2 shall be the ratio of maximum design pressure at the MDMT to the maximum allowable pressure (MAP) of the component at the MDMT.

(3) In lieu of using (i)(2) above, the MDMT for a flange attached by welding shall not be colder than the impact test temperature less the allowable temperature reduction as determined in (i)(1) above for the neck or shell to which the flange is attached.

(j) When the base metal is exempt from impact testing by (g) above or by Fig. UCS-66 Curves C or D, -20°F is the coldest MDMT to be assigned for

A02 FIG. UCS-66 (CONT'D)

GENERAL NOTES ON ASSIGNMENT OF MATERIALS TO CURVES (CONT'D):

(e) For bolting and nuts, the following impact test exemption temperature shall apply:

Bolting			
Spec. No.	Grade	Diameter, in. (mm)	Impact Test Exemption Temperature, °F (°C)
SA-193	B5	Up to 4 (107 mm), incl.	-20 (-29)
	B7	Up to 2½ in. (64 mm), incl.	-55 (-48)
		Over 2½ (64 mm) to 7 (178 mm), incl.	-40 (-40)
		Up to 2½ (64 mm), incl.	-55 (-48)
	B7M	Up to 7 (178 mm), incl.	-20 (-29)
SA-307	B16	Up to 7 (178 mm), incl.	-20 (-29)
SA-320	B	All	-20 (-29)
	L7, L7A,	Up to 2½ (64 mm), incl.	See General Note (c) of Fig. UG-84.1
	L7M,	Up to 2½ (64 mm), incl.	See General Note (c) of Fig. UG-84.1
SA-325	L43	Up to 1 (25 mm), incl.	See General Note (c) of Fig. UG-84.1
	1	½ (13 mm) to 1½ (38 mm)	-20 (-29)
	BC	Up to 4 (102 mm), incl.	0 (-18)
SA-354	BD	Up to 4 (102 mm), incl.	+20 (-7)
SA-437	B4B, B4C	All diameters	See General Note (c) of Fig. UG-84.1
SA-449	...	Up to 3 (76 mm), incl.	-20 (-29)
SA-540	B21 Cl. All	All	Impact test required
SA-540	B22 Cl. 3	Up to 4 (102 mm), incl.	Impact test required
SA-540	B23 Cl. 1, 2	All	Impact test required
SA-540	B23 Cl. 3, 4	Up to 6 (152 mm), incl.	See General Note (c) of Fig. UG-84.1
SA-540	B23 Cl. 3, 4	Over 6 (152 mm) to 9½ (241 mm), incl.	Impact test required
SA-540	B23 Cl. 5	Up to 8 (203 mm), incl.	See General Note (c) of Fig. UG-84.1
SA-540	B24 Cl. 5	Over 8 (203 mm) to 9½ (241 mm), incl.	Impact test required
SA-540	B24 Cl. 1	Up to 6 (152 mm), incl.	See General Note (c) of Fig. UG-84.1
SA-540	B24 Cl. 1	Over 6 (152 mm) to 8 (203 mm), incl.	Impact test required
SA-540	B24 Cl. 2	Up to 7 (178 mm), incl.	See General Note (c) of Fig. UG-84.1
SA-540	B24 Cl. 2	Over 7 (178 mm) to 9½ (241 mm), incl.	Impact test required
SA-540	B24 Cl. 3, 4	Up to 8 (203 mm), incl.	See General Note (c) of Fig. UG-84.1
SA-540	B24 Cl. 3, 4	Over 8 (203 mm) to 9½ (241 mm), incl.	Impact test required
SA-540	B24 Cl. 5	Up to 9½ (241 mm), incl.	See General Note (c) of Fig. UG-84.1
SA-540	B24V Cl. 3	All	See General Note (c) of Fig. UG-84.1

Nuts		
Spec. No.	Grade	Impact Test Exemption Temperature, °F (°C)
SA-194	2, 2H, 2HM, 3, 4, 7, 7M, and 16	-55 (-48)
SA-540	B21/B22/B23/B24/B24V	-55 (-48)

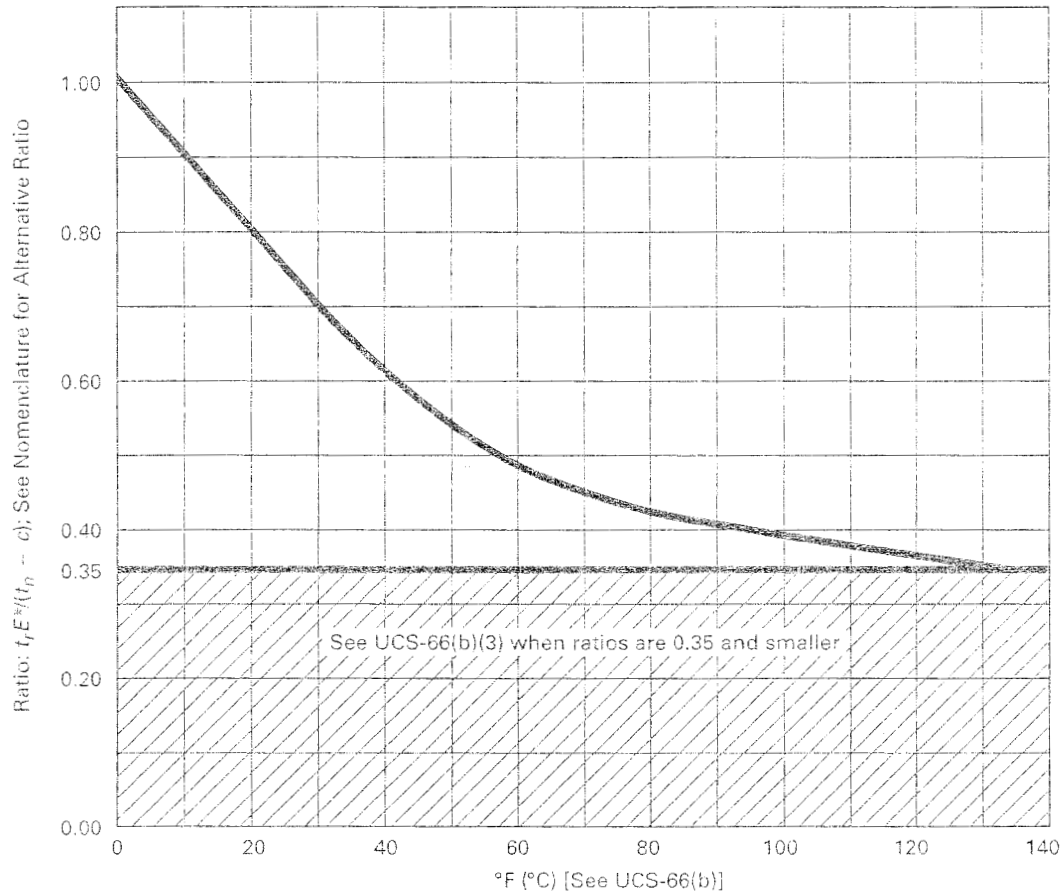
(f) When no class or grade is shown, all classes or grades are included.

(g) The following shall apply to all material assignment notes.

- (1) Cooling rates faster than those obtained by cooling in air, followed by tempering, as permitted by the material specification, are considered to be equivalent to normalizing or normalizing and tempering heat treatments.
- (2) Fine grain practice is defined as the procedure necessary to obtain a fine austenitic grain size as described in SA-20.
- (3) Normalized rolling condition is not considered as being equivalent to normalizing.

NOTES:

- (1) Tabular values for this Figure are provided in Table UCS-66.
- (2) Castings not listed in General Notes (a) and (b) above shall be impact tested.



Nomenclature (Note reference to General Notes of Fig. UCS-66-2.)

- t_r = required thickness of the component under consideration in the corroded condition for all applicable loadings [General Note (2)], based on the applicable joint efficiency E [General Note (3)], in. (mm)
- t_n = nominal thickness of the component under consideration before corrosion allowance is deducted, in. (mm)
- c = corrosion allowance, in. (mm)
- E^* = as defined in General Note (3).

Alternative Ratio = $S^* E^*$ divided by the product of the maximum allowable stress value from Table UCS-23 times E , where S^* is the applied general primary membrane tensile stress and E and E^* are as defined in General Note (3).

FIG. UCS-66.1 REDUCTION IN MINIMUM DESIGN METAL TEMPERATURE WITHOUT IMPACT TESTING

TABLE UCS-66
TABULAR VALUES FOR FIG. UCS-66

Thick., in.	Curve A, °F	Curve B, °F	Curve C, °F	Curve D, °F	Thick., in.	Curve A, °F	Curve B, °F	Curve C, °F	Curve D, °F
0.25	18	-20	-55	-55	3.1875	112	80	44	13
0.3125	18	-20	-55	-55	3.25	112	80	44	14
0.375	18	-20	-55	-55	3.3125	113	81	45	15
0.4375	25	-13	-40	-55	3.375	113	82	46	15
0.5	32	-7	-32	-55	3.4375	114	83	46	16
					3.5	114	83	47	17
0.5625	37	-1	-26	-51	3.5625	114	84	48	17
0.625	43	5	-22	-48	3.625	115	85	49	18
0.6875	48	10	-18	-45	3.6875	115	85	49	19
0.75	53	15	-15	-42	3.75	116	86	50	20
0.8125	57	19	-12	-38	3.8125	116	87	51	21
0.875	61	23	-9	-36	3.875	116	88	51	21
0.9375	65	27	-6	-33	3.9375	117	88	52	22
1	68	31	-3	-30	4	117	89	52	23
1.0625	72	34	-1	-28	4.0625	117	90	53	23
1.125	75	37	2	-26	4.125	118	90	54	24
1.1875	77	40	4	-23	4.1875	118	91	54	25
1.25	80	43	6	-21	4.25	118	91	55	25
1.3125	82	45	8	-19	4.3125	118	92	55	26
1.375	84	47	10	-18	4.375	119	93	56	27
1.4375	86	49	12	-16	4.4375	119	93	56	27
1.5	88	51	14	-14	4.5	119	94	57	28
1.5625	90	53	16	-13	4.5625	119	94	57	29
1.625	92	55	17	-11	4.625	119	95	58	29
1.6875	93	57	19	-10	4.6875	119	95	58	30
1.75	94	58	20	-8	4.75	119	96	59	30
1.8125	96	59	22	-7	4.8125	119	96	59	31
1.875	97	61	23	-6	4.875	119	97	60	31
1.9375	98	62	24	-5	4.9375	119	97	60	32
2	99	63	26	-4	5	119	97	60	32
2.0625	100	64	27	-3	5.0625	119	98	61	33
2.125	101	65	28	-2	5.125	119	98	61	33
2.1875	102	66	29	-1	5.1875	119	98	62	34
2.25	102	67	30	0	5.25	119	99	62	34
2.3125	103	68	31	1	5.3125	119	99	62	35
2.375	104	69	32	2	5.375	119	100	63	35
2.4375	105	70	33	3	5.4375	119	100	63	36
2.5	105	71	34	4	5.5	119	100	63	36
2.5625	106	71	35	5	5.5625	119	101	64	36
2.625	107	73	36	6	5.625	119	101	64	37
2.6875	107	73	37	7	5.6875	119	102	64	37
2.75	108	74	38	8	5.75	120	102	65	38
2.8125	108	75	39	8	5.8125	120	103	65	38
2.875	109	76	40	9	5.875	120	103	66	38
2.9375	109	77	40	10	5.9375	120	104	66	39
3	110	77	41	11	6	120	104	66	39
3.0625	111	78	42	12					
3.125	111	79	43	12					

GENERAL NOTE: See Fig. UCS-66 for SI values.

FIG. UCS-66.2 (CONT'D)

GENERAL NOTES:

- (1) For pipe where a mill undertolerance is allowed by the material specification, the thickness after mill undertolerance has been deducted shall be taken as the noncorroded nominal thickness t_n for determination of the MDMT to be stamped on the nameplate. Likewise, for formed heads, the minimum specified thickness after forming shall be used as t_n .
- (2) Loadings, including those listed in UG-22, which result in general primary membrane tensile stress at the coincident MDMT.
- (3) E is the joint efficiency (Table UW-12) used in the calculation of t_r ; E^* has a value equal to E except that E^* shall not be less than 0.80. For castings, use quality factor or joint efficiency E whichever governs design.
- (4) The construction of Fig. UCS-66 is such that the MDMT so selected is considered to occur coincidentally with an applied general primary membrane tensile stress at the maximum allowable stress value in tension from Table 1A of Section II Part D. Tabular values for Fig. UCS-66 are shown in Table UCS-66.
- (5) See UCS-66(a)(1), (2), and (3) for definitions of governing thickness.
- (6) If the basis for calculated test pressure is greater than the design pressure [UG-99(c) test], a Ratio based on the t_r determined from the basis for calculated test pressure and associated appropriate value of $t_n - c$ shall be used to determine the recommended coldest metal temperature during hydrostatic test and the coldest metal temperature permitted during the pneumatic test. See UG-99(h) and UG-100(c).
Alternatively, a Ratio of S^*E^* divided by the product of the maximum allowable stress value in tension from Table 1A of Section II Part D times E may be used, where S^* is the applied general primary membrane tensile stress and E and E^* are as defined in General Note (3).
- (8) For UCS-66(b)(1)(b) and (1)(2), a ratio of the maximum design pressure at the MDMT to the maximum allowable pressure (MAP) at the MDMT shall be used. The MAP is defined as the highest permissible pressure as determined by the design formulas for a component using the nominal thickness less corrosion allowance and the maximum allowable stress value from the Table 1A of Section II, Part D at the MDMT. For ferritic steel flanges defined in UCS-66(c), the flange rating at the warmer of the MDMT or 100°F may be used as the MAP.
- (9) For reductions in MDMT up to and including 40°F, the reduction can be determined by: reduction in MDMT = $(1 - \text{Ratio}) 100^\circ\text{F}$.
- (10) A colder MDMT may be obtained by selective use of impact tested materials as appropriate to the need (see UG-84). See also UCS-68(c).

welded components that do not meet the requirements of UCS-67(a)(2).

UCS-67(a)(3) when joining base metals exempt from impact testing by UCS-66(g) when the minimum design metal temperature is colder than -55°F (-48°C).

UCS-67(b) Welds in UCS materials made without the use of filler metal shall be impact tested when the thickness at the weld exceeds $\frac{1}{2}$ in. (13 mm) for all minimum design metal temperatures or when the thickness at the weld exceeds $\frac{5}{16}$ in. (8 mm) and the minimum design metal temperature is colder than 50°F (10°C). This requirement does not apply to welds made as part of the material specification.

UCS-67(c) Weld heat affected zones produced with or without the addition of filler metal shall be impact tested whenever any of the following apply:

UCS-67(c)(1) when the base metal is required to be impact tested by the rules of this Division; or

UCS-67(c)(2) when the welds have any individual weld pass exceeding $\frac{1}{2}$ in. (13 mm) in thickness, and the minimum design metal temperature is colder than 70°F (21°C); or

UCS-67(c)(3) when joining base metals exempt from impact testing by UCS-66(g) when the minimum design metal temperature is colder than -55°F (-48°C).

UCS-67(d) Vessel (production) impact tests in accordance with UG-84(i) may be waived for any of the following:

UCS-67(d)(1) weld metals joining steels exempted from impact testing by UCS-66 for minimum design metal temperatures of -20°F (-29°C) and warmer; or

403 UCS-67 IMPACT TESTS OF WELDING PROCEDURES

Except as exempted in UG-20(f), the Welding Procedure Qualification shall include impact tests of welds and heat affected zones (HAZ) made in accordance with UG-84 when required by the following provisions. The MDMT used below shall be the MDMT stamped on the nameplate or the exemption temperature of the welded component before applying the temperature reduction permitted by UCS-66(b) or UCS-68(c).

UCS-67(a) Welds made with filler metal shall be impact tested in accordance with UG-84 when any of the following apply:

UCS-67(a)(1) when either base metal is required to be impact tested by the rules of this Division; or

UCS-67(a)(2) when joining base metals exempt from impact testing by UCS-66(g) or Fig. UCS-66 Curve C or D and the minimum design metal temperature is colder than -20°F (-29°C) but not colder than -55°F (-48°C), unless welding consumables which have been classified by impact tests at a temperature not warmer than the MDMT by the applicable SFA specification used; or

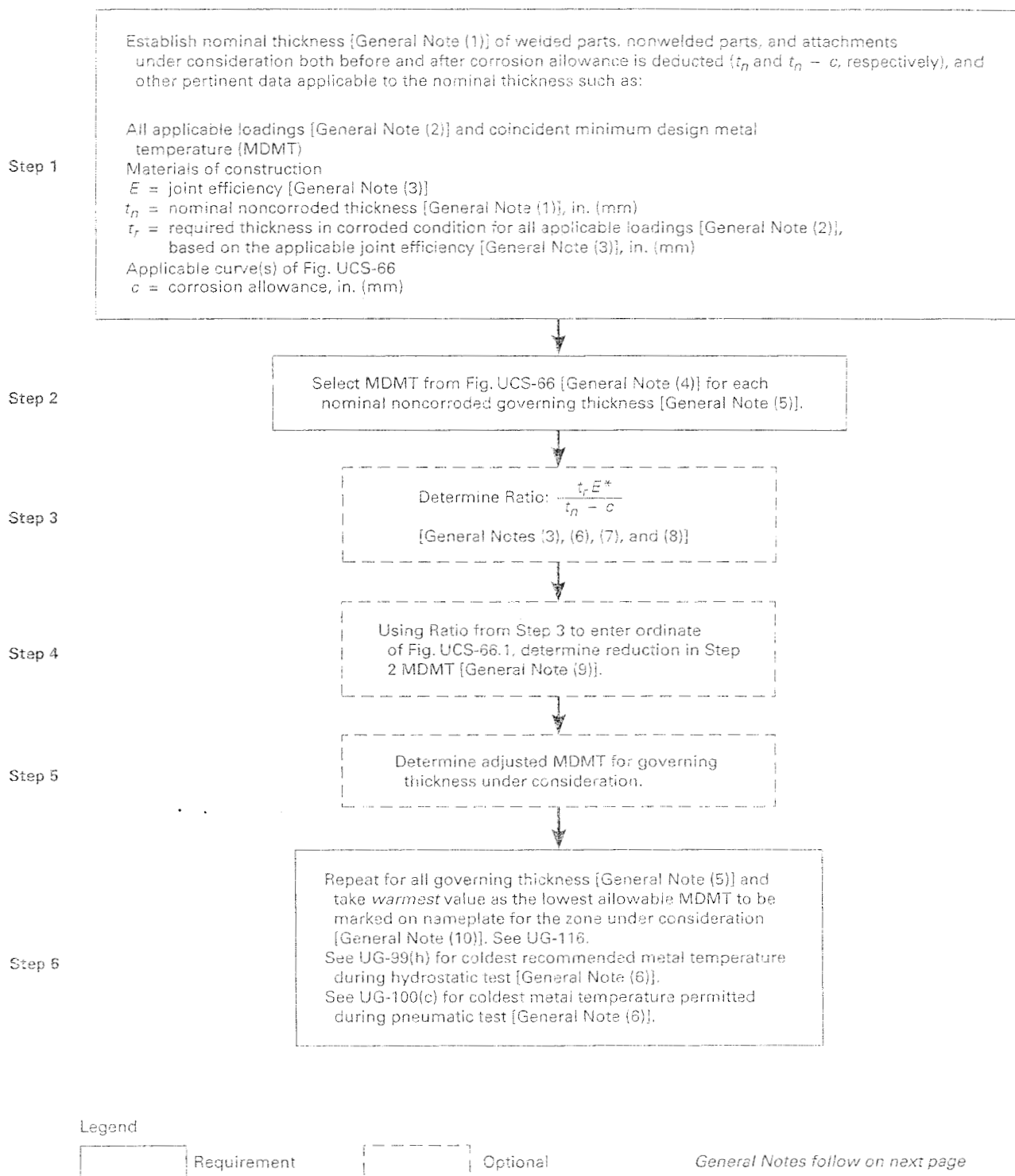


FIG. UCS-66.2 DIAGRAM OF UCS-66 RULES FOR DETERMINING LOWEST MINIMUM DESIGN METAL TEMPERATURE (MDMT) WITHOUT IMPACT TESTING

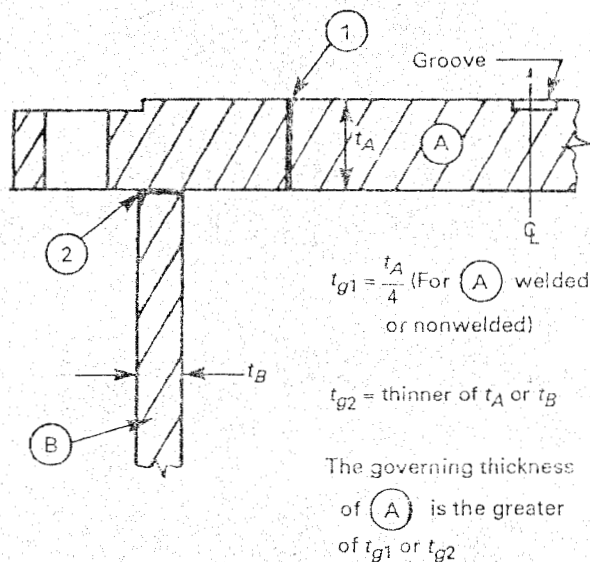
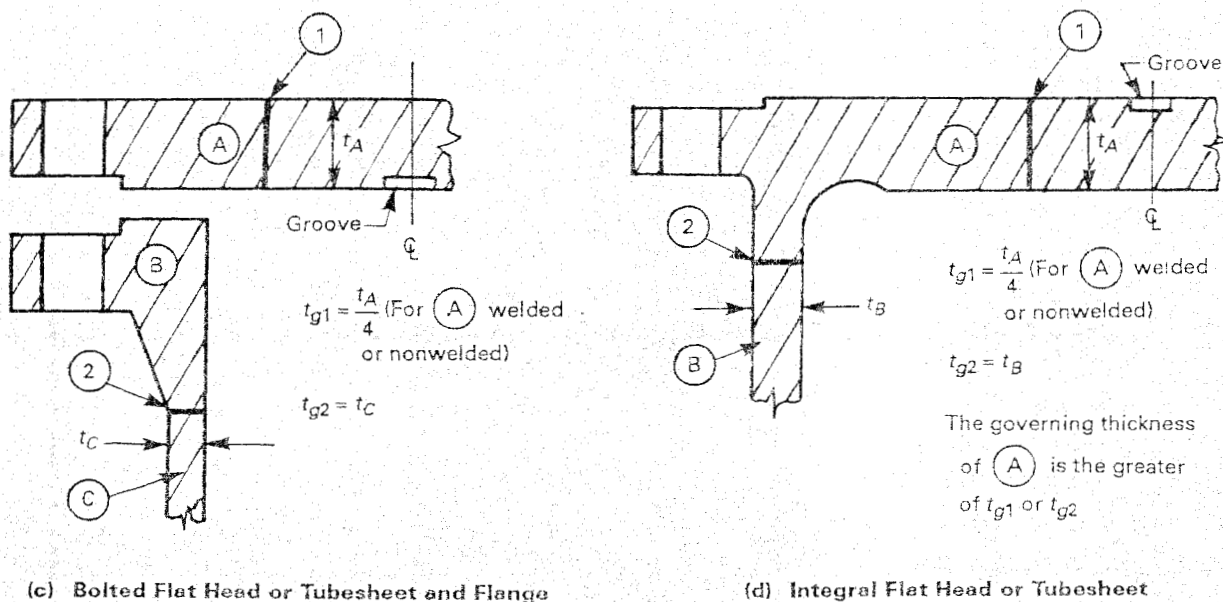
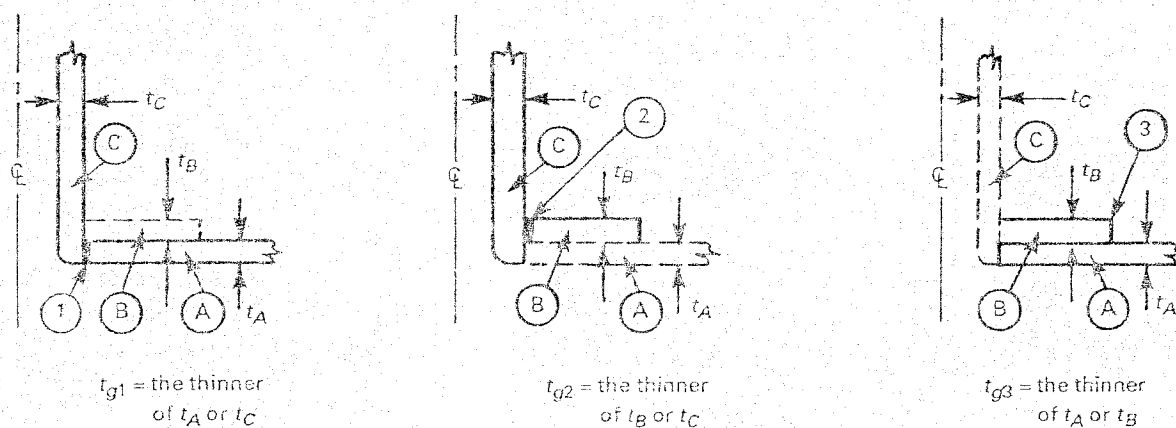
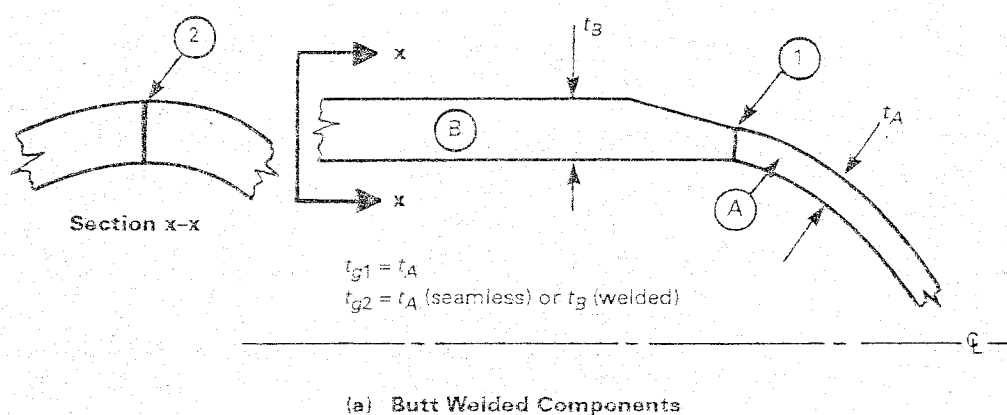


FIG. UCS-66.3 SOME TYPICAL VESSEL DETAILS SHOWING THE GOVERNING THICKNESSES AS DEFINED IN UCS-66 (CONT'D)



NOTE: Using t_{g1} , t_{g2} , and t_{g3} , determine the warmest MDMT and use that as the permissible MDMT for the welded assembly.

(b) Welded Connection with Reinforcement Plate Added

FIG. UCS-66.3 SOME TYPICAL VESSEL DETAILS SHOWING THE GOVERNING THICKNESSES AS DEFINED IN UCS-66

diographed. Category A and B joints attaching sections of unequal thickness shall have a transition with a slope not exceeding 3:1;

(2) fillet welds having leg dimensions not exceeding $\frac{3}{8}$ in. attaching lightly loaded attachments, provided the attachment material and the attachment weld meet requirements of UCS-66 and UCS-67. "Lightly loaded attachment," for this application, is defined as an attachment for which the stress in the attachment weld does not exceed 25% of the allowable stress. All such welds shall be examined by magnetic particle or liquid penetrant examination in accordance with Appendix 6 or Appendix 8.

UCS-68(c) If postweld heat treating is performed in it is not otherwise a requirement of this Division, a 30°F (17°C) reduction in impact testing exemption temperature may be given to the minimum permissible temperature from Fig. UCS-66 for P-No. 1 materials. The resulting exemption temperature may be colder than -55°F (-48°C).

UCS-68(d) The allowable stress values to be used in design at the minimum design metal temperature shall not exceed those given in Section II, Part D, Tables 3 for bolting and 1A for other materials for temperatures of 100°F (38°C).

FABRICATION

UCS-75 GENERAL

The rules in the following paragraphs apply specifically to the fabrication of pressure vessels and vessel parts that are constructed of carbon and low alloy steel and shall be used in conjunction with the general requirements for *Fabrication* in Subsection A, and with the specific requirements for *Fabrication* in Subsection B that pertain to the method of fabrication used.

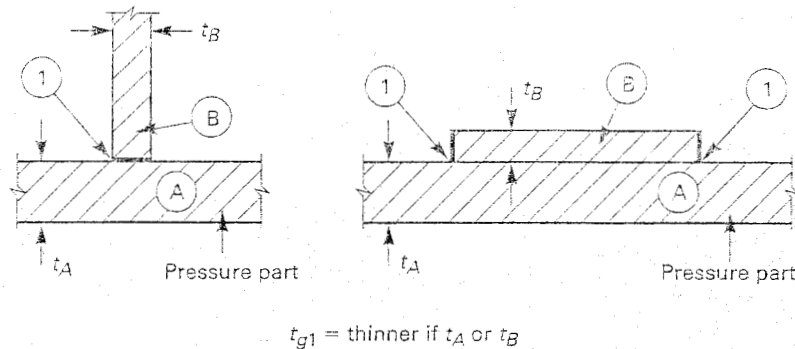
UCS-79 FORMING SHELL SECTIONS AND HEADS

(a) The following provisions shall apply in addition to the general rules for forming given in UG-79.

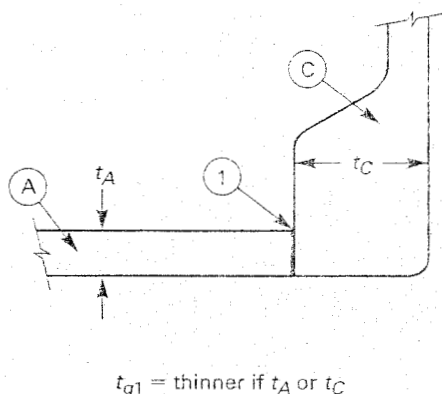
(b) Carbon and low alloy steel plates shall not be formed cold by blows.

(c) Carbon and low alloy steel plates may be formed by blows at a forging temperature provided the blows do not objectionably deform the plate and it is subsequently postweld heat treated.

(d) Vessel shell sections, heads, and other pressure boundary parts of carbon and low alloy steel plates



(f) Welded Attachments as Defined in UCS-66(a)



(g) Integrally Reinforced Welded Connection

NOTE: t_g = governing thickness of the welded joint as defined in UCS-66.

A02

FIG. UCS-66.3 SOME TYPICAL VESSEL DETAILS SHOWING THE GOVERNING THICKNESSES AS DEFINED IN UCS-66 (CONT'D)

UCS-67(d)(2) weld metals defined in (a)(2) above; or

UCS-67(d)(3) heat affected zones (HAZ) in steels exempted from impact testing by UCS-66, except when (c)(3) above applies.

A02 UCS-68 DESIGN⁴

UCS-68(a) Welded joints shall comply with UW-2(b) when the minimum design metal temperature is colder than -55°F (-48°C), unless the coincident ratio defined in Fig. UCS-66.1 is less than 0.35.

⁴No provisions of this paragraph waive other requirements of this Division, such as UW-2(a), UW-2(d), UW-10, and UCS-56.

UCS-68(b) Welded joints shall be postweld heat treated in accordance with the requirements of UW-40 when required by other rules of this Division. When the minimum design metal temperature is colder than -55°F (-48°C), and the coincident ratio defined in Fig. UCS-66.1 is 0.35 or greater, postweld heat treatment is required, except that this requirement does not apply to the following welded joints, in vessels or vessel parts fabricated of P-No. 1 materials that are impact tested at the MDMT or colder in accordance with UG-84. The minimum average energy requirement for base metals and weldments shall be 25 ft-lb (33 J) instead of the values shown in Fig. UG-84.1:

(1) Type 1 Category A and B joints, not including cone-to-cylinder junctions, which have been 100% ra-