SSC-300

SUMMARY OF NONDESTRUCTIVE INSPECTION STANDARDS FOR HEAVY SECTION CASTINGS, FORGINGS, AND WELDMENTS

SHIP STRUCTURE COMMITTEE

1981

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An Interagency Advisory Committee
Dedicated to Improving the Structure of Ships

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SR-1255
March 1981

As vessels have expanded in size and deadweight during the last fifteen years, there has been a similar increase in the size of forgings, castings and heavy weldments used in vessels. Some examples of such components are stem and stern frames, rudder horns, stern tubes, tail shafts, propellers, and some engine parts. The Ship Structure Committee became aware of the need to develop quantitative guidelines for the nondestructive inspection of these components.

A project was initiated to survey the literature and write an interpretative report of the state of the art in this field. While various methods and practices were reviewed and discussed, the user must still specify the acceptance limits to meet the intended service.

The results of the project are contained in this report.

Henry H. Bell
Rear Admiral, U.S. Coast Guard
Chairman, Ship Structure Committee

Technical Report Documentation Page

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16. Abstract

Code bodies, notably ASTM, have produced procedural guides, standard methods, and recommended practices which can be used to assure proper inspection for the various methods of nondestructive testing. These guides and practices in private industry have been reviewed for their applicability to quality control of heavy steel castings, forgings, and weldments. Acceptance criteria are not set forth, and recommendations are not suggested. They do, however, define levels of quality and describe the parameters generally agreed to be of significance which should be a part of the contractural agreement. The user must quantify these parameters according to service requirements and other considerations.

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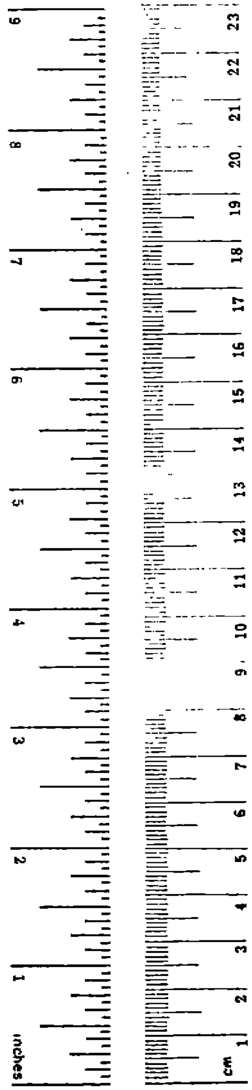
METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

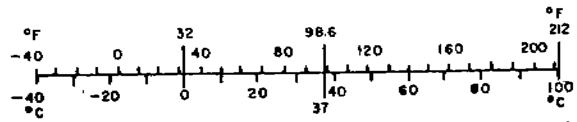
Symbol	When You Know	Multiply by	To Find	Symbol
	LENGTH			
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
	AREA			
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
	MASS (weight)			
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
	VOLUME			
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
	TEMPERATURE (exact)			
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in = 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.



Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
	LENGTH			
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
	AREA			
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
	MASS (weight)			
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
	VOLUME			
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
	TEMPERATURE (exact)			
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



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INTRODUCTION

The Rules For Building and Classifying Steel Vessels (American Bureau of Shipping) requires of the shipbuilder that hull steel castings and forgings be inspected and found free of injurious defects. This is to be done to the satisfaction of the attendant surveyor, and there may be differences in acceptance criteria between shipyards. In the interests of uniformity and also as a help in contractually specifying desired casting quality, the Ship Structures Committee has contracted with the Naval Surface Weapons Center to prepare a state-of-the-art report on procedures whereby casting and forging quality can be controlled.

In addition, incorporating these large castings and forgings into the hull structure involves welding thicknesses well in excess of ordinary hull welds. This report also considers procedures for inspecting and controlling the quality of these welds.

OBJECTIVE AND SCOPE

The objective of this task has been to determine the present state-of-the-art for controlling the quality of large steel castings, forgings and thick welds using nondestructive inspection techniques. This has been done by a review of specifications and standards set forth by code bodies and a survey of representative manufacturers.

BACKGROUND

According to the Rules For Building and Classifying Steel Vessels set forth by the American Bureau of Shipping, "All castings are to be inspected by the Surveyors after final heat treatment and thorough cleaning and they shall be found free from injurious defects." Minor defects may be repaired at the discretion of the foundry. Major defects may be repaired with the approval of the attendant surveyor.

Repair is done by chipping or grinding to sound metal and then rewelding by an approved procedure. In the case of major discontinuity removal, verification of complete removal is accomplished by subjecting the excavation to either radiographic or magnetic particle inspection.

The Rules For Building and Classifying Steel Vessels also require that hull steel forgings be inspected by the surveyor after final heat treatment and be found free from injurious

NONDESTRUCTIVE INSPECTION - GENERAL

In regard to material evaluation using nondestructive inspection techniques, there are five ordinary methods - Radiography, Ultrasonics, Magnetic Particle, Liquid Penetrant, and Visual Inspection.

Of these, only radiography or ultrasonic inspection can provide proof of internal integrity and they are considered the primary methods. However, visual inspection and the magnetic particle method are easy to apply and can be a valuable adjunct to the other primary methods. In particular, visual standards can be used to specify a required surface texture and magnetic particle inspection can be used to inspect for cracks near the surface. Also, when defects are found beneath the surface by either radiography or ultrasonics, and are to be removed by chipping or grinding, magnetic particle inspection can be used to verify complete removal of those defects.

Liquid penetrant is not much used on large steel pieces because magnetic particle inspection is usually superior for discontinuity detection and is much faster to do. However, it can be done and its use will be considered.

NONDESTRUCTIVE INSPECTION OF STEEL CASTINGS

Radiography. Controlling the quality of steel castings using radiographic inspection requires first of all a means for ensuring that the inspection is done properly. This can be accomplished by specifying good practice according to ASTM E-94, Recommended Practice for Radiographic Testing. This document is primarily educational and considers the "preferred" parameters of industrial radiography without discussing the principles of physics upon which these are based. Both x-ray and gamma-ray radiation sources are reviewed. Neither interpretation nor acceptance criteria are covered - these are left to contractual agreement. It should be noted, however, that unless otherwise specified a radiographic quality level of 2% (2-2T) is implied.

Satisfactory film quality can be controlled with ASTM E-142, Controlling Quality of Radiographic Testing. This method standardizes the techniques for controlling the reliability or quality of radiographic images. Unless otherwise specified, a minimum 2% (2-2T) quality level is required.

The image quality indicator (penetrameter) is defined and

Objects with varying thickness can be expected to result in radiographs exhibiting density variation. Permissible limits for one penetrameter are defined as -15 to +30%. Variations in excess of this require two penetrameters placed at film density extremes to qualify the area between.

The types of casting discontinuities that may be revealed by radiographic inspection are illustrated in graded series in reference radiographs published by ASTM as listed below:

ASTM E-186 Reference Radiographs for Steel Castings (2-4 1/2" section)

Category A - Gas Porosity - Severity levels		1 - 5
B - Sand and Slag Inclusions levels		1 - 5
C - Shrinkage		
	Type 1 - Severity levels	1 - 5
	2 - Severity levels	1 - 5
	3 - Severity levels	1 - 5
D - Linear discontinuity severity level		1 - 5
E - Inserts		
	Type 1 - Severity levels	1 - 5
	2 - Severity levels	1 - 5

Figures 1 - 8 are paper prints which illustrate the most severe level for each of these discontinuity types. These are presented for illustrative purposes only and may not be used as acceptance criteria.

The ASTM E-186 series is available for three conditions of radiographic exposure: Gamma Rays (Co^{60}, Ra), 1 - 2 MeV X-rays, and 10 - 24 MeV X-rays.

ASTM E-280 Reference Radiographs for Steel Castings (4 1/2 - 12" sections)

Category A - Gas Porosity - Severity levels		1 - 5
B - Sand and Slag Inclusions levels		1 - 5
C - Shrinkage		
	Type 1 - Severity levels	1 - 5
	2 - Severity levels	1 - 5
	3 - Severity levels	1 - 5
D - Hot tears & cracks severity level		1 - 5
E - Inserts		
	Type 1 - Severity levels	1 - 5
	2 - Severity levels	1 - 5

The E-280 series is available for two conditions of radiographic exposure: Gamma Rays (Co^{60}, Ra), and 10 - 24 MeV X-rays.

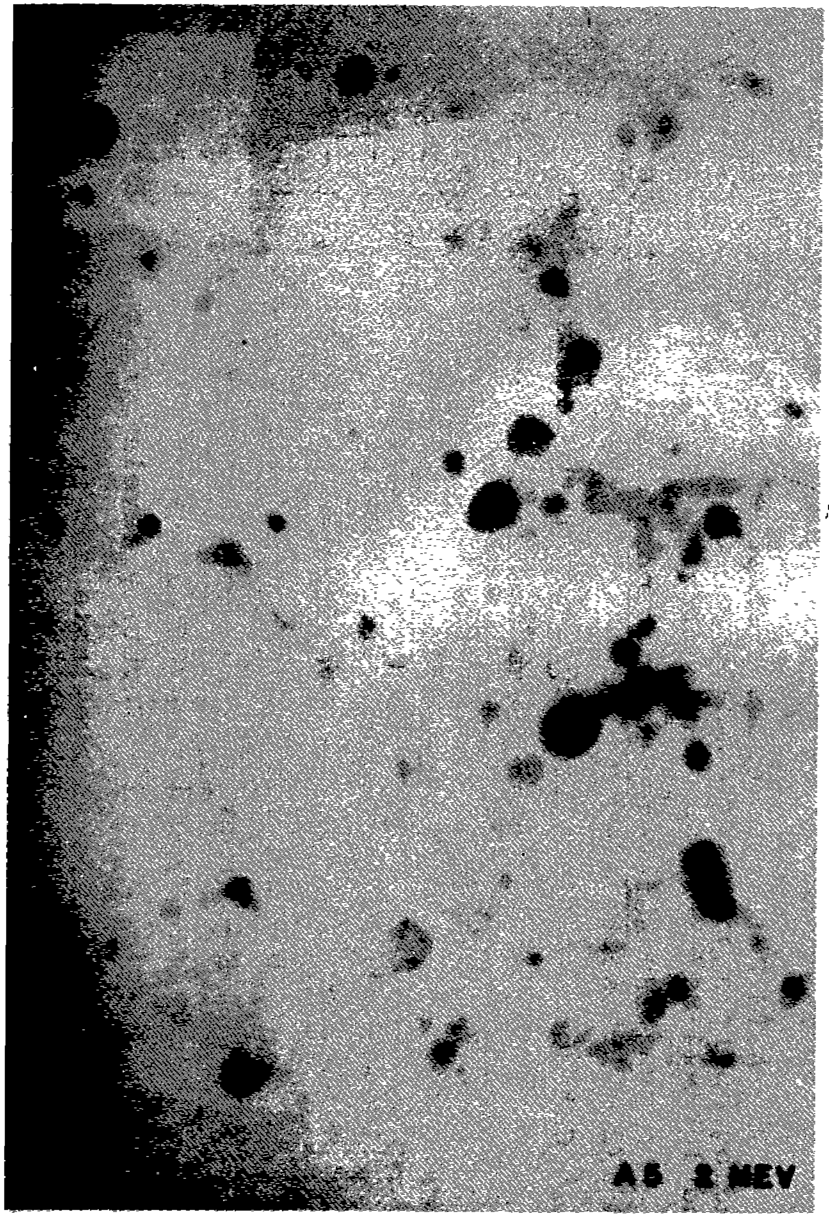

FIG. 1 - Illustration of Gas Porosity, Category A, Severity level 5 - from ASTM E-186, Reference Radiographs for Steel Castings

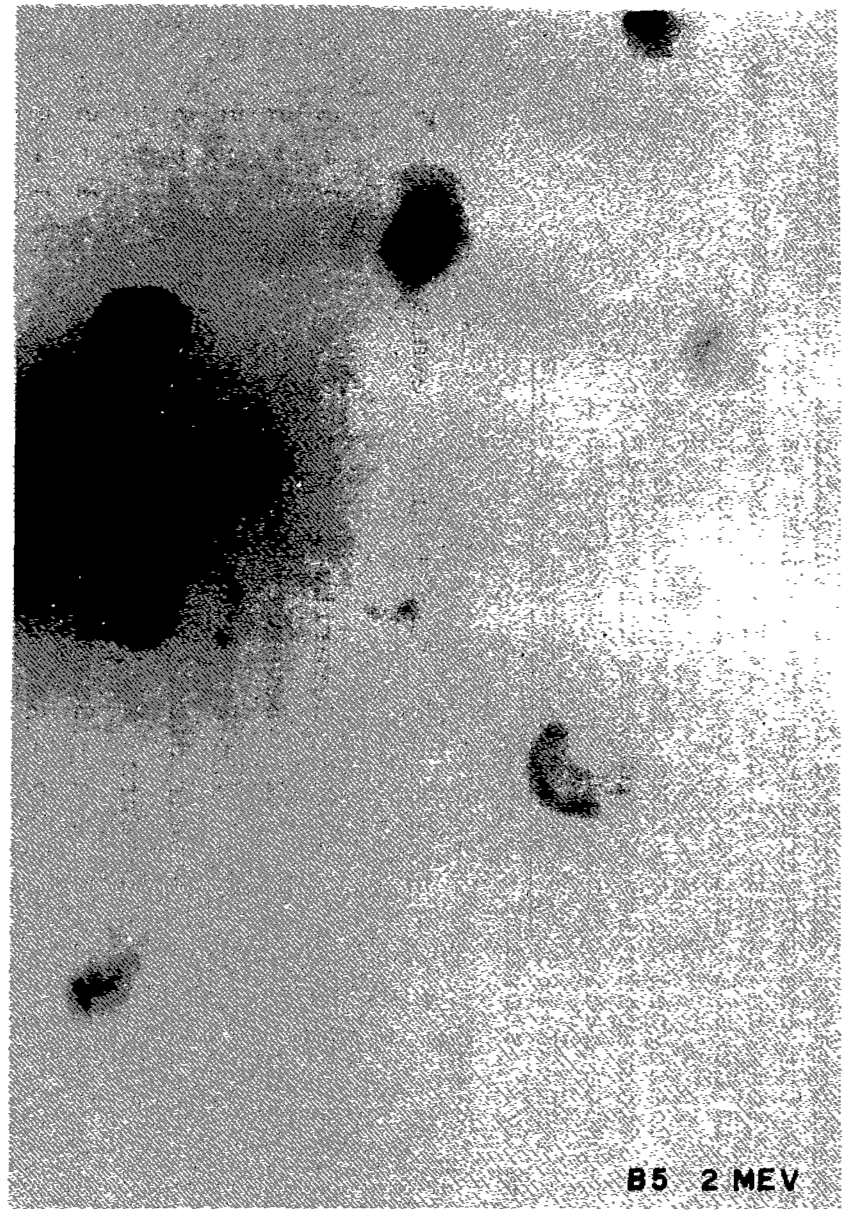

FIG. 2 - Illustration of Sand and Slag Inclusions, Category B, Severity level 5 - from ASTM E-186, Reference Radiographs for Steel Castings.

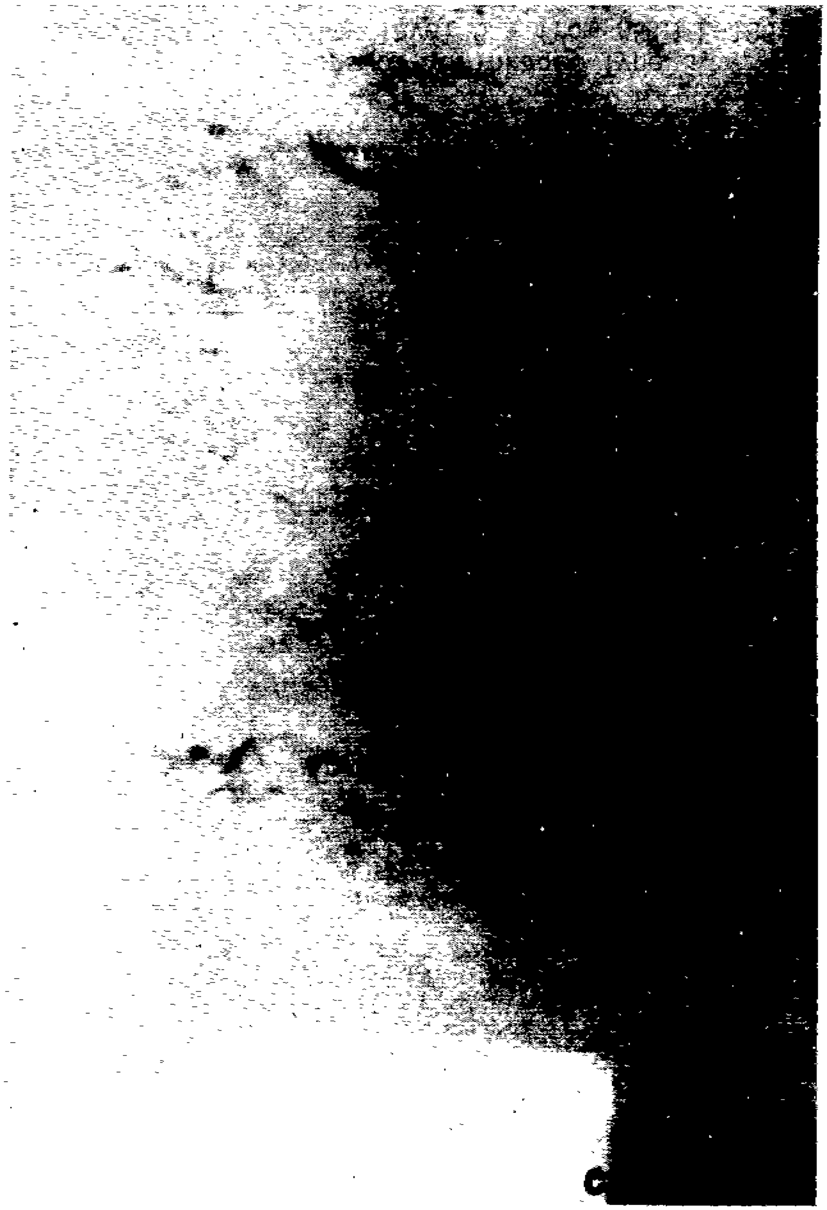

FIG. 3 - Illustration of Shrinkage, Type 1, Category C, Severity level 5 - from ASTM E-186, Reference Radiographs for Steel Castings.

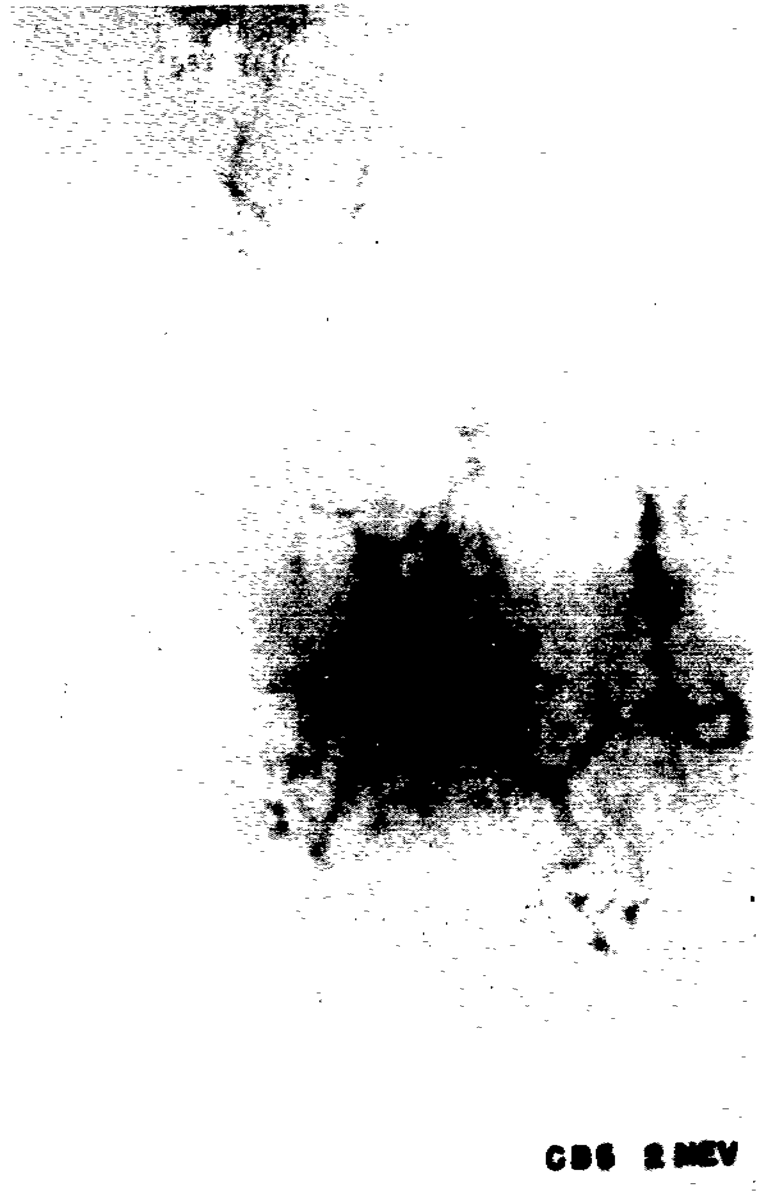

FIG. 4 - Illustration of Shrinkage, Type 2, Category C, Severity level 5 - from ASTM E-186, Reference Radiographs for Steel Castings.

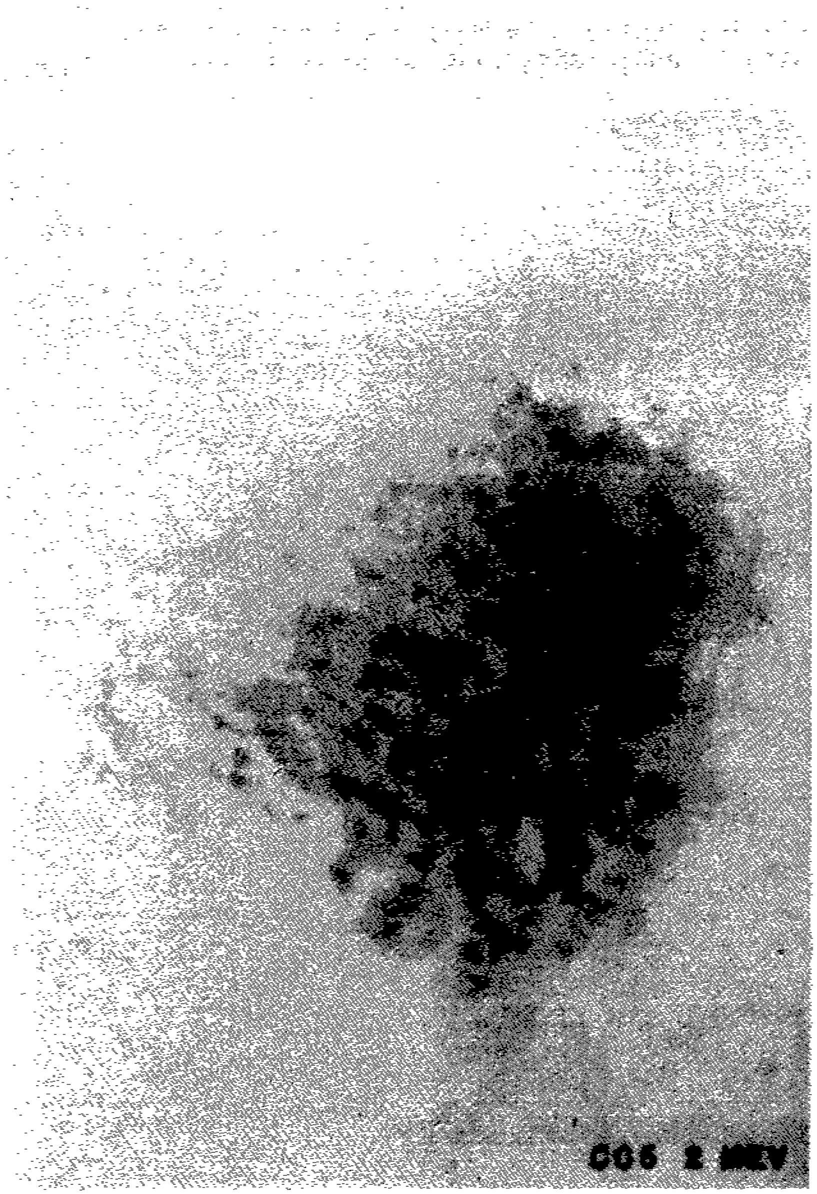

FIG. 5 - Illustrations of Shrinkage, Type 3, Category C, Severity level 5 - from ASTM E-186, Reference Radiographs for Steel Castings.

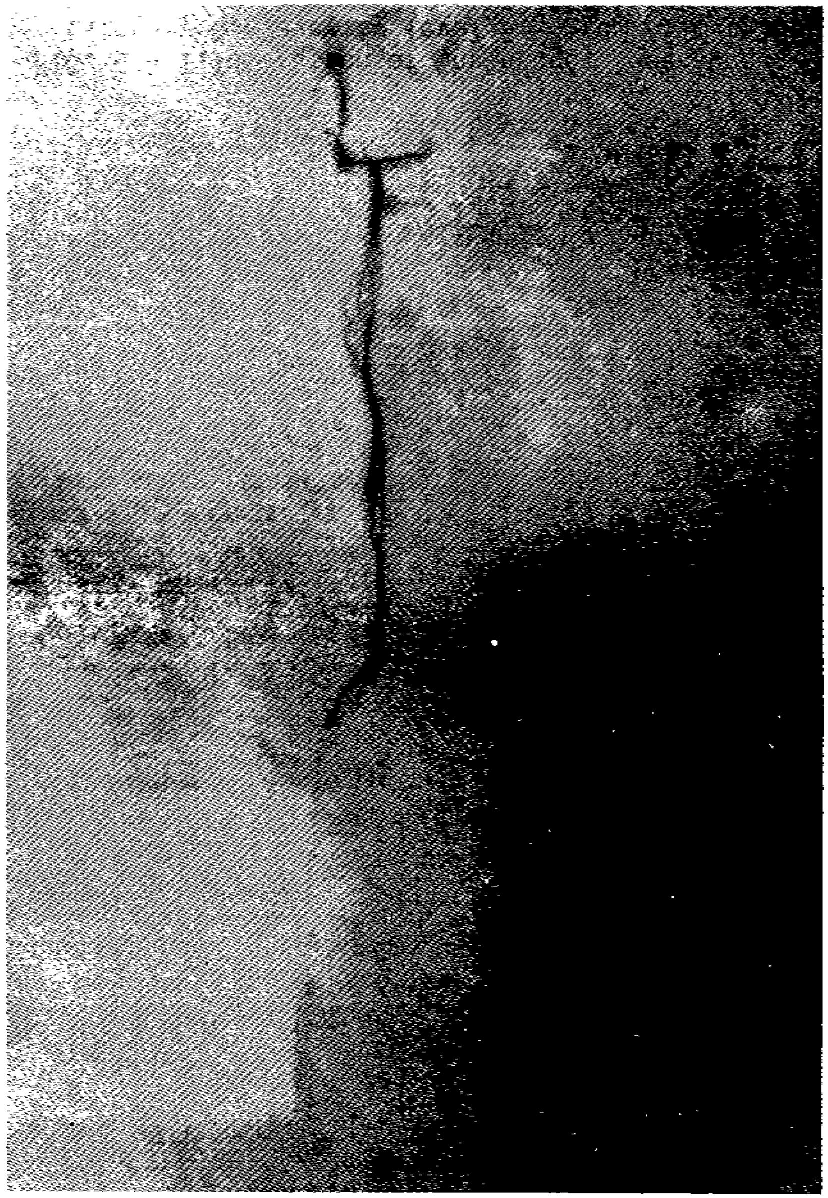

FIG. 6 - Illustration of Linear discontinuity, Category D, Severity level 5 - from ASTM E-186, Reference Radiographs for Steel Castings.

FIG. 7 - Illustration of Inserts, Type 1, Category E, Severity level 5 - from ASTM E-186, Reference Radiographs for Steel Castings.

FIG. 8 - Illustration of Inserts, Type 2, Category E, Severity level 5 - from ASTM E-185, Reference Radiographs for Steel Castings.

If reference radiographs are to be used as a means for controlling casting quality, it must be realized that they are not in themselves a standard. Their use must be supplemented by contractual specifications setting forth the maximum acceptable level of severity for each type of discontinuity illustrated. In addition, this should be done for each section of the casting requiring radiographic inspection and for which different service requirements are recognized.

The severity levels for the types of discontinuities illustrated are not equivalent. Acceptance criteria based upon ASTM Reference Radiographs should reflect separate consideration for each type. For example, referencing E-186, maximum acceptable discontinuities regarding a specific part of the casting are as follows:

Category A - Gas Porosity - Severity level		4
B - Sand and Slag Inclusions level		3
C - Shrinkage		
	Type 1 - Severity level	1
	2 - Severity level	2
	3 - Severity level	2
D - Linear discontinuity		none
E - Inserts		
	Type 1 - Severity level	4
	2 - Severity level	4

It should also be noted that the size of the reference radiograph is inherently a part of the acceptance criteria. As for example: Using a radiograph 5" x 7", then no 5" x 7" area of the casting radiographs can exhibit discontinuities in excess of that illustrated in the specified maximum level severity for that discontinuity type.

Ultrasonic Inspection. Ultrasonic inspection is being used to control the quality of steel castings in both the United States and overseas. Long recognized as a valuable supplementary tool to radiographic inspection, many foundries and their customers now use ultrasonic inspection as the sole nondestructive testing method for determining subsurface casting integrity.

When the ultrasonic method is to be used as a primary method for inspecting steel castings, procedure can be controlled by specifying ASTM A-609, Longitudinal Beam Ultrasonic Inspection of Carbon and Low Alloy Steel Castings.

This specification may be used contractually to establish a required quality level. It must be stated if the quality level is to be for the entire casting or only for certain sections.

Examination is by the ultrasonic pulse-echo method using the longitudinal beam (straight) technique. Requirements are set forth regarding the ultrasonic instrument. It must be capable of generating frequencies between 1 and 5 MHz and have vertical linearity within ± 5% for 75% of the screen height. A signal attenuator accurate to within 10% is also required. Primary inspection is to be done using either one inch square or one inch diameter transducers.

Reference blocks containing flat bottomed holes are used to establish the instrument sensitivity. The diameter of the hole is held constant at 1/4 inch but the blocks comprising the set vary in length from 1 - 10 inches with provision for testing thicknesses greater than 10 inches.

The personnel performing the ultrasonic examination must be qualified, and general guidance in this regard is provided. Qualification to ASNT TC-1A is suggested but not required; but, a record must be kept of personnel qualification.

Any heat treatment for mechanical properties must be done before ultrasonic examination. There is a requirement for the cleaning of the casting surface.

The inspection of the casting is to be done at a rate not to exceed six inches per second and the transducer passes must overlap.

In some cases, it may be advantageous or necessary to use an angle beam technique. Proper procedure can be specified using ASTM E-587-76, Standard Recommended Practice for Ultrasonic Angle Beam Examination By The Contact Method. This recommended practice considers the ultrasonic examination of materials at angular incidence. Four types of waves are considered: Longitudinal, Shear, Rayleigh, and Lamb. The physics and methods of generating each type of wave are set forth. In addition, attention is given to possible test complications which might arise due to the coexistance of two different types of waves under certain conditions.

A calibration procedure is suggested utilizing the reflection from a side-drilled hole. The diameter of the hole is not specified and so must be described contractually. In regard to acceptance criteria, it is suggested that advance agreement be made regarding interpretation and a rejection level.

In addition to these documents produced through code bodies, some foundries have created ultrasonic inspection procedures designed to replace radiographic inspection of a stated severity level - usually with economic advantage. These procedures are invariably proprietary and, therefore, not generally available except on a case-by-case basis.

Castings are often complex in configuration and complete inspection done using ultrasonics may require innovative techniques. Valuable guidance in this regard has been provided in the following publications by technical societies: Ultrasonic Testing of Steel Castings, Steel Founders Society of America, Rocky River, Ohio, June, 1976; Atlas of Some Steel Casting Flaws as shown by Non-Destructive Testing, Steel Castings Research and Trade Association, Sheffield, England, 1968.

Magnetic Particle Inspection. Steel castings may be inspected with the magnetic particle method. Proper procedure can be assured for wet method using ASTM E-138, Wet Magnetic Particle Inspection. This standard method, applicable to all ferromagnetic materials, presents techniques for the wet method of magnetic particle inspection. It does not present or suggest standards for the evaluation of indications obtained. It is recognized though that evaluation is necessary and the recommendation is made that contractual agreement include the acceptance criteria. In addition, it further recommends that the contract specify the area to be inspected, the type of magnetizing current (AC or DC), the direction of the magnetic field, how many "shots" are to be used, the method of Magnetization (longitudinal, circular, over-all or local), the magnetization current or ampere turns to be used on each "shot" and the sequence of operation (continuous or residual). It is stated that "All of these techniques cause variations in results and must be standardized if reproducible results are to be obtained upon which acceptance standards are to be based." The balance of this standard method sets forth the principles of good practice.

If the dry method is to be used, the procedure can be controlled using ASTM E-109, Dry Powder Magnetic Particle Inspection. This method considers all of the magnetizing procedures used in the wet method and also includes, in addition, magnetization using electrical prods. As with the wet method, acceptance criteria is neither set forth nor suggested. Further, as with the wet method, this standard requires a specific agreement between the contractural parties which accurately defines indications considered acceptable and those considered unacceptable - this in regard to type, location and direction.

The document reviews the equipment, materials and procedure related to good practice. Specific guidance is presented for magnetizing technique, direction of magnetization and the sequence of operations. The requirements for adequate electrical current are set forth in a table which considers both prod spacing and section thickness.

Appendix 1 of ASTM E-109 presents Additional Procedures, which includes direct and indirect methods for accomplishing overall magnetization, techniques relating to longitudinal magnetization, the use of alternating current, the utilization of residual magnetization and procedures for demagnetization.

NOTE: ASTM E-109 and E-138 have been deleted and replaced by ASTM E-709.

Appendix 2 of ASTM E-109 includes Typical Indications. This is a set of reference photographs illustrating indications on castings, welds, rolled or forged material and non relevant indications.

Difficulties are frequently encountered in attempts to contractually specify acceptable or unacceptable conditions as revealed by magnetic particle inspection. This has prompted ASTM to assemble a set of reference photographs to provide assistance in this regard. These are published as: ASTM E-251-63, Reference Photographs For Magnetic Particle Indications on Ferrous Castings. These reference photographs are applicable to ferromagnetic castings inspected by the dry powder magnetic particle method. By comparing the discontinuities revealed in magnetic particle inspection with these reference photographs, specifications and/or acceptance criteria may be established. It is necessary to contractually state the limiting degree of severity and the locations to be inspected.

Five types of casting discontinuities are considered. These are: Linear discontinuities - five levels of severity, three examples each; Shrinkage - five levels of severity, one example each; Inclusions - five levels of severity, one example each; Internal chills and chaplets - five levels of severity, one example each; Porosity - two examples.

In addition, reference photographs are included for welds which may be incorporated into the casting: One example each of weld porosity, incomplete penetration, undercutting, inclusions in the weld, and crater cracking.

Five examples are presented of false indications and five examples are included of magnetic anomalies.

It is called to the users attention that there is no correlation or equivalency between the levels of severity of the various discontinuities.

Liquid Penetrant Inspection Method. If liquid penetrant inspection is to be used to inspect steel castings, proper procedure may be ensured through ASTM E-165, Liquid Penetrant Inspection Method. This is a standard recommended practice applicable to nonporous metallic materials suited to the detection of discontinuities which are open to the surface, such as cracks, seams, laps, coldshuts, laminations and lack of fusion.

Standards for evaluating indications are neither indicated nor suggested. Therefore, contractual agreement must include specifications defining the type, size, location, and direction of indications considered acceptable and unacceptable. Further, a "strong recommendation" is made that the specific techniques be a part of the agreement.

Fluorescent and visible liquid methods are considered. For each of these, three subgroups are recognized: water-washable, post-emulsifiable, and solvent-removable. Procedures relating to good practice are set forth for each.

A cautionary note is included regarding the sulfur and chlorine content of the penetrant inspection materials. In some cases, the parts tested may be adversely affected. Limitations on these substances may be an essential part of the contractual agreement.

The description of indications as revealed by penetrant inspection can be difficult. Some assistance is available through reference photographs in ASTM E-433, Liquid Penetrant Inspection. This standard is a set of reference photographs of surface discontinuities revealed by liquid penetrant inspection. Although no attempt has been made to establish limits of acceptability, it is stated that these photographs may be used as a reference in specifications or acceptance standards. Such use must be supplemented by limitations on actual discontinuity length and the number of indications acceptable per unit area.

The reference photographs recognize a distinction between indications for which neither of the measurable dimensions is three times greater than the other and indications for which this is true. For each category four subgroups are presented: Single, Multiple Unaligned, Multiple Aligned and the Intersection of surfaces such as corners or fillets.

Visual Inspection. The Manufacturers Standardization Society of the Valve and Fittings Industry have developed visual standards for evaluating steel castings: S-P-55, 1971 edition (reaffirmed 1975), Quality Standard For Steel Castings For Valves, Flanges and Fittings and Other Piping Components (Visual Method). Figure 9 which illustrates the surface conditions wrinkles, laps, and coldshuts[1], is an example of the visual standards set forth in this document.

These standards illustrate steel casting surface conditions that may be evaluated visually. Twelve categories are presented in five gradations of severity with suggested degrees of acceptability:

TYPE 1: HOT TEARS AND CRACKS, Linear surface discontinuities or fractures caused by either internal or external stresses or a combination of both acting on the casting. They may occur during or subsequent to solidification. In general, visible surface cracks and/or hot tears are not acceptable.

TYPE 2: SHRINKAGE, A void left in cast metals as a result of solidification shrinkage and the progressive freezing of metal which is exposed upon cutting off risers and gates.

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1. Reproduced by permission of the Manufacturers Standardization Society of the Valve and Fittings Industry, 1815 North Fort Myer Drive, Arlington, VA 22209.

ACCEPTABLE

a

b

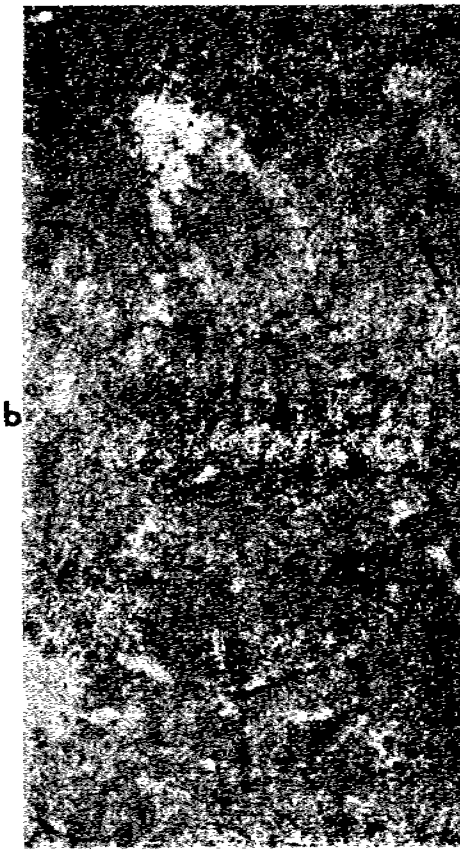

FIG. 9 - WRINKLES, LAPS, FOLDS, AND COLDSHUTS from Quality Standard for Steel Castings S-P-55 (Visual Method).

NON ACCEPTABLE

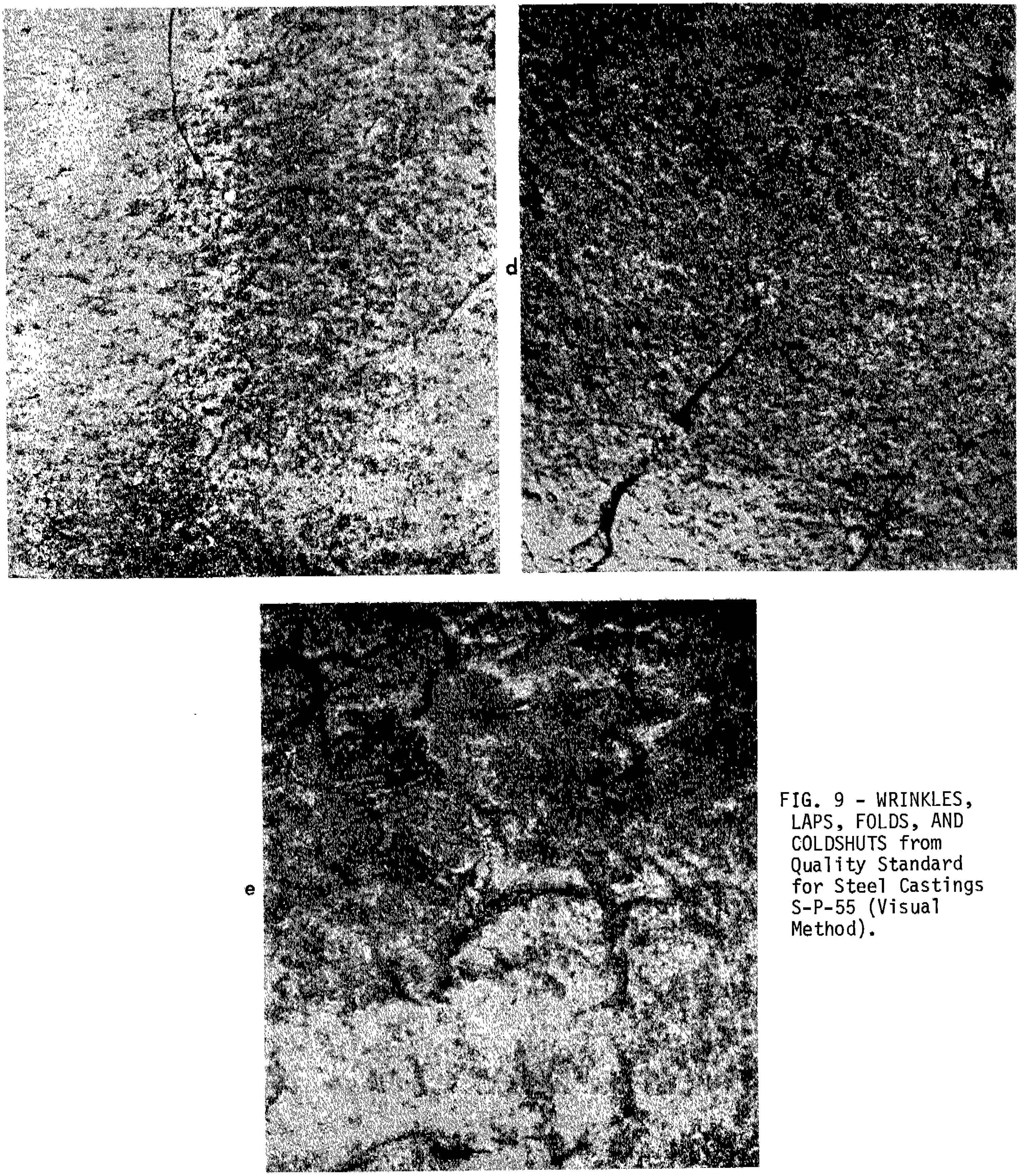

FIG. 9 - WRINKLES, LAPS, FOLDS, AND COLDSHUTS from Quality Standard for Steel Castings S-P-55 (Visual Method).

TYPE 3: SAND INCLUSIONS, Sand which becomes entrapped in the molten metal and shows on casting surfaces.

TYPE 4: GAS POROSITY, Voids in cast metal caused by entrapment of gas during solidification.

TYPE 5: VEINING, Features on the surface of castings appearing as a ridge and associated with movement or cracking of sand.

TYPE 6: RAT TAILS, Features on the surface of castings appearing as a depression resulting from faulting or buckling of the mold surfaces.

TYPE 7: WRINKLES, LAPS, FOLDS AND COLDSHUTS, Surface irregularities caused by incomplete fusing or by folding of molten metal surfaces.

TYPE 8: CUTTING MARKS, Irregularities in casting surfaces resulting from burning or mechanical means used in the cleaning of castings.

TYPE 9: SCABS, Slightly raised surface blemishes which are usually sand crusted over by a thin porous layer of metal.

TYPE 10: CHAPLETS, Evidence of chaplets on surface of casting disclosing incomplete fusion, which likewise can apply to internal chills.

TYPE 11: WELD REPAIR AREAS, Evidence of improper surface preparation after welding.

TYPE 12: SURFACE ROUGHNESS, Surface texture due to design, pattern, gating and sand conditions.

NONDESTRUCTIVE INSPECTION OF STEEL FORGINGS

Radiographic Inspection. The forging process squeezes shut volume-type discontinuities within cast material and flattens out foreign material such as slag. Laminations related to these conditions have narrow dimensions which are unfavorable to detection by radiography. Similarly, cracks must be unfavorably oriented for detection. Consequently, radiography should not be used as a primary tool for forging evaluation.

Ultrasonic Inspection. Ultrasonic inspection is an excellent tool for examining heavy forgings. However, its use as a primary inspection method does require assurance of proper procedure. This can be accomplished by specifying ASTM A-388, Ultrasonic Examination Of Heavy Steel Forgings. This recommended practice covers both straight beam and angle beam techniques for the examination of heavy steel forgings.

This is to be done with the pulse-echo reflection type instrument. A nominal frequency of 2 1/4 MHz is recommended wherever practical. However, for course grained materials, 1 MHz is permitted and a frequency as low as 0.4 MHz is acceptable for difficult to penetrate materials such as austenitic steel. The active area of the transducer is restricted to a maximum of 1 square inch for straight beam work and either 1" x 1" or 1" x 1/2" for angle-beam scanning.

Approved couplants include: water, glycerin, motor oil, or pine oil, but it is cautioned that coupling characteristics can be expected to differ and consistency must be maintained between the calibration procedure and the actual work. This is emphasized in a graph in that appendix in which the signal amplitude from reference reflectors is plotted against surface curvature. The curve for oil and glycerin differ significantly.

Requirements are set forth for instrument linearity regarding signal amplitude. This is to be done using approved reference blocks containing flat-bottomed holes. The same blocks are to be used to establish the instrument sensitivity for scanning the work material.

The surface to be inspected must be free of extraneous material such as loose scale or dirt and the surface roughness is not to exceed 250 μ inch unless so stated in the contract. If the forging is to be heat treated, then examination is to be done after that is completed.

In performing the ultrasonic examination, a 15% overlap of passes is required at a scanning rate not to exceed 6 in./sec; and, if possible, at two perpendicular directions. Guidance is presented for the scanning technique to be used on forgings of specific geometry-cylinders, hollows, etc.

As an alternate to calibration using reference blocks, a technique is presented whereby for straight beam examination, the reflection from the back surface can be set at 75% of full-screen height and sensitivity can then be increased by using the decibel attenuator. If the forging thickness changes, recalibration is required.

During examination of the forging, in addition to monitoring signals from within the forging volume, the operator is required to also monitor the reflection from the back surface. This is done because a signal reduction may be indicative of flaws and also could alert the operator to conditions of poor coupling or nonparallel surfaces.

For angle-beam scanning, a 45° angle-beam search unit is recommended and calibration is to be done on a rectangular or 60° "V-notch" cut 3% of the nominal thickness or 1/4" whichever is smaller. Rings and hollow forgings are to have a notch on both surfaces and a reference level curve is to be constructed to compensate for attenuation and beam scatter: Sensitivity is set by adjusting the signal from the reference notch on the back side to 75% of full-screen height.

It is stated in this recommended practice that forgings are too diverse to establish a universal quality level, and that acceptance criteria should be based upon a realistic appraisal of service requirements.

Guidance is provided, however, in two separate ways: First, certain type indications are to be recorded. These include (1) signals 10% the amplitude of the back reflection signal or those equal to or in excess of 100% of the reference amplitude obtained using the calibration block, (2) indications continuous on a plane, (3) indications which travel with motion of the search unit, (4) clusters of indications, (5) reduction in back reflection signal amplitude exceeding 20% of the original amplitude, (6) for angle beam examination - any signal 50% or larger than the reference line. Second, it is suggested that acceptance be established based upon one or more of the following criteria: (1) a limit on signal amplitude expressed as a percentage of the back reflection, (2) a limit on signal amplitude expressed in relation to the signal amplitude obtained in calibration using a reference block, (3) a limit on the reduction in signal amplitude of the back surface reflection - expressed as a percentage, (4) a combination of signal amplitude and reduction in back surface signal amplitude, and (5) for angle beam examination - a limit on signal amplitude expressed as a percentage of the reference line.

Magnetic Particle Inspection. Steel forgings may also be inspected for disconitnuities open to the surface using either the wet or dry method of magnetic particle testing. Procedure can be controlled by specifying ASTM A-275, Magnetic Particle Examination Of Steel Forgings. This standard method considers both wet and dry magnetic particle testing of steel forgings. It provides procedural guidance constituting good practice for the continuous, surge, and residual methods of magnetization and the two general types of magnetization, longitudinal and circular. It requires that two approximately mutually perpendicular examinations be conducted separately on each area.

This standard does not present any acceptance standards and does not define any quality levels. However, it states that standards for acceptance shall be specified in the contract or order.

Although acceptance criteria is not set forth, this standard does define and describe the types of indications which may be obtained. These are grouped into three broad categories: (1) surface defects such as forging laps and folds, laminar defects, flakes, and cracks due to heat treating, shrinkage, grinding, and etching or plating; (2) subsurface cracks such as stringers of nonmetallic inclusions, large nonmetallics, cracks in the underbead of welds and forging bursts; and (3) nonrelevant indications such as magnetic writing, changes in section, weld edges and flow lines.

Nonrelevant indications must be resolved by other methods of nondestructive testing and demonstrated nonrelevant or eliminated by surface consitioning. Since subsurface indications cannot be found using alternating current, and if this type of discontinuity is of importance, the use of methods employing direct current must be specified. Criteria for evaluating discontinuities should be based on size, number, location and for linear indications the length and direction.

Use of this standard is to be supplemeted by the previously mentioned E-183-63 and E-109-63 which consider the wet and dry methods of magnetic particle inspection.

Liquid Penetrant Inspection. While magnetic particle inspection is a superior and faster way to inspect steel forgings, liquid penetrant testing can be done and involves the same standards and procedures previously set forth for castings.

Visual Inspection. If surface texture is important, the American National Standard ASNI B46.1 Surface Texture can be used for this purpose.

NONDESTRUCTIVE INSPECTION OF THICK WELDS

Radiography. The quality of radiography for steel welds is controlled using the same specifications E-94 and E-142, previously discussed under the radiographic inspection of steel castings. Discontinuities revealed by radiography can be evaluated using ASTM E-390, Reference Radiographs For Steel Fusion Welds. Volume II is applicable to welds between 1 1/2" and 3". Volume III is for welds 3" - 8" thickness. Table 1 lists the types and number of grades of severity in each volume.

As with the casting reference radiographs, these are not standards in themselves; however, they can be used to create acceptance criteria by contractually specifying a maximum acceptable grade of severity for each type discontinuity. For example, referencing ASTM E-390, the maximum permissible severity level for each type discontinuity in a weld of 2 1/2" is as follows:

Fine Scattered Porosity	Grade 4
Coarse Scattered Porosity	Grade 3
Clustered Porosity	Grade 4
Linear Porosity	Grade 1
Elongated Porosity	None
Slag Inclusions	Grade 2
Tungsten Inclusions	N/A
Incomplete Penetration	Grade 1
Lack of Fusion	Grade 1
Burn Through	None
Icicles	None

Cracks	None
Undercut	None

Ultrasonic Inspection. The ultrasonic method can be used on thick welds with advantage. The ordinary angle beam method, slightly modified, is applicable and in addition that inspection can be complemented using the straight beam. The procedure, however, is more complex with thick welds and should be controlled in accordance with ASTM E-164, ULTRASONIC CONTACT EXAMINATION OF WELDMENTS. This standard recommended practice is applicable to welds up to eight inches thickness using either straight beam or angle beam techniques. Personnel performing the ultrasonic examination should be properly trained. SNT-TC-1A is referred to for qualification.

No acceptance criteria is presented and it is left to contractual agreement to establish calibration standards.

The ultrasonic instrument used for weld examination should have an "A-scan" presentation and a capability for generating the recommended inspection frequencies of 1.0 - 5.0 MHz. Quantitative evaluation of flaws requires the instrument to have either a linear amplifier, calibrated gain control or a distance compensating amplifier. There are requirements for horizontal linearity.

Search units as small as 1/4 inch diameter are recognized as suitable for some applications and sizes as large as 1 1/8 inch diameter are permitted. For shear wave inspection, rectangular probes having a length to width ratio greater than two are not recommended.

Shear wave angles are not specified, but a table is set forth whereby optimum angles are correlated with various base metal thicknesses. The nominal angle indication on the transducer wedge should be checked to avoid erroneous conclusions regarding discontinuity location. Two methods for accomplishing this, the polar coordinate and rectangular coordinate, are presented in an annex to ASTM E-164.

Calibration is considered in detail. A procedure is presented for determining the actual distance traveled. This is necessary in order to accurately locate discontinuities. An equal angle reflecting surface, incorporated into certain test blocks, is recommended, but this may also be done utilizing the reflection from a notch. Test blocks with side-drilled holes (illustrated in an annex) are useful for performing distance, amplitude, position and depth calibration. In addition, this type of test block can be used to determine the relation between depth or distance traveled and signal amplitude fluctuations. This is to be done either by constructing a curve on the oscilloscope screen or with instruments so equipped, using the distance - amplitude controls to obtain signals of equal screen height from all depths within the test range.

TABLE 1:

TYPES OF WELD DISCONTINUITIES AND LEVELS OF SEVERITY PRESENTED IN ASTM E-390

DISCONTINUITY TYPE	VOLUME II	VOLUME III
	1 1/2" - 3"	3" - 8"
Scattered porosity		Grade 1 - 5
Fine scattered porosity	Grade 1 - 5	
Coarse scattered porosity	Grade 1 - 5	
Clustered porosity	Grade 1 - 5	
Linear porosity (globular indications)	Grade 1 - 5	Grade 1 - 5
Elongated or worm hole porosity	Ungraded	
Slag inclusions	Grade 1 - 5	Grade 1 - 5
Tungsten inclusions	Ungraded	
Incomplete penetration	Grade 1 - 5	Grade 1 - 5
Lack of fusion	Grade 1 - 5	Grade 1 - 5
Burn through	Ungraded	
Icicles (teardrops)	Ungraded	
Longitudinal crack	Ungraded	Ungraded
Transverse crack	Ungraded	Ungraded
Crater crack	Ungraded	
Undercut	Ungraded	

It is recognized that there may be coupling differences between the test block surface and that of the work piece. A test block with surface roughness equivalent to that of the work would circumvent the difficulty but may not be feasible to prepare. Alternatively, a transfer technique may be used. This procedure utilizes a notch in the basic calibration block and a similar notch machined into the weld seam. The ratio of signal amplitude from these two notches permits adjustment of instrument sensitivity to achieve a valid calibration for use on the work piece. All of the calibration procedures and test blocks are described in detail in the test and annex.

When longitudinal waves (straight beam) are used in weld inspection, the calibration procedure is essentially identical to that for shear waves. It is pointed out, however, that if both methods are used and it is desired to have equivalent wave lengths within the test material, the longitudinal probe should be a frequency about double that of the angle probe.

This recommended practice is limited to specific weld geometries: Butt weld, "Tee" joints and corner joints. Both flat and curved surfaces are considered and specific inspection procedures are set forth for each.

Several techniques are suggested for discontinuity evaluation: signal amplitude can be used to measure defect severity, but it is emphasized that this should be based on experience with actual defects and not artificial reflectors; discontinuity dimensions can be determined locating the points where signal amplitude falls to one half; orientation can be deduced from relative signal amplitudes obtained by altering the direction of inspection; and reflector shape may be deduced from the relative sharpness of the signal.

The determination of discontinuity dimensions, orientation and shape may be useful but should not be a basis for acceptance criteria because of the great dependence on operator skill.

Magnetic Particle Inspection. The magnetic particle method may be used to inspect welds for discontinuities open to the surface before more sophisticated techniques are used. It can also be valuable for verifying complete defect removal prior to rewelding.

With the exception of the electrical current requirements, the technique for inspecting welds with magnetic particles is independent of the thickness. Good practice is set forth in the previously discussed document E-109.

Technical details involving the magnetic particle inspection of welds are presented in Welding Inspection of the American Welding Society and in SSC-253, A Guide for the Nondestructive Testing of Non-Butt Welds in Commercial Ships - Part One.

Visual Inspection. Aside from possible crack detection, the primary application of visual inspection is the determination of satisfactory weld contour requirements. Gauges may be useful and their use is described in SSC-253, previously listed.

EFFECT OF DISCONTINUITIES ON MECHANICAL PROPERTIES

Some guidance in regard to the effect of casting discontinuities on mechanical properties is available from the Steel Castings Handbook.[2] Figure 10 illustrates lengths of shrinkage cavity correlated with tensile and yield strengths. The results of another study of tensile strength for castings containing defects is presented in Table 2. Dynamic testing has also been correlated with casting discontinuities. This is illustrated in Figures 11, 12, and 13 which pertain to fatigue and Figures 14, and 15 which consider endurance limits. Table 3 compares casting and weld discontinuities in regard to the endurance ratios in bending and torsion. Here, the endurance ratio is defined as the endurance limit for cycles of reversed flexural stress divided by the tensile strength.

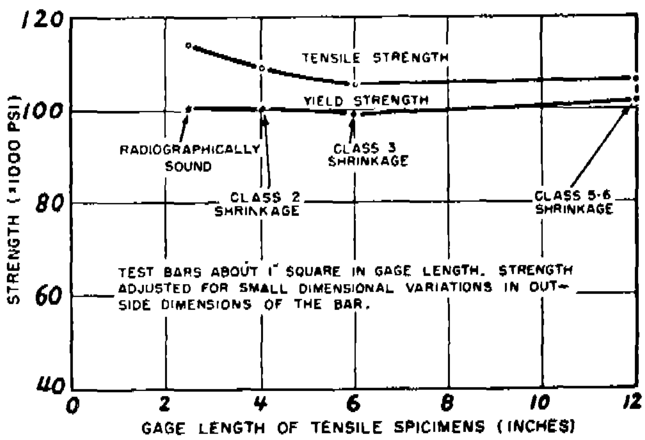

FIG. 10 - Average strength of cast tensile bars for various degrees of shrinkage severity.

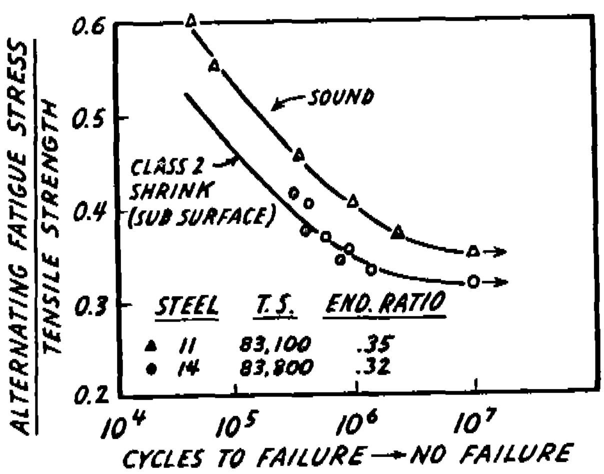

FIG. 11 - Effect of shrinkage on plate bending fatigue of cast sections of normalized and tempered 8630 Ni-Cr-Mo steel.

2. Figures 10 - 15 and Tables 2 and 3 are reproduced from the Steel Castings Handbook by permission of the Steel Founders Society.

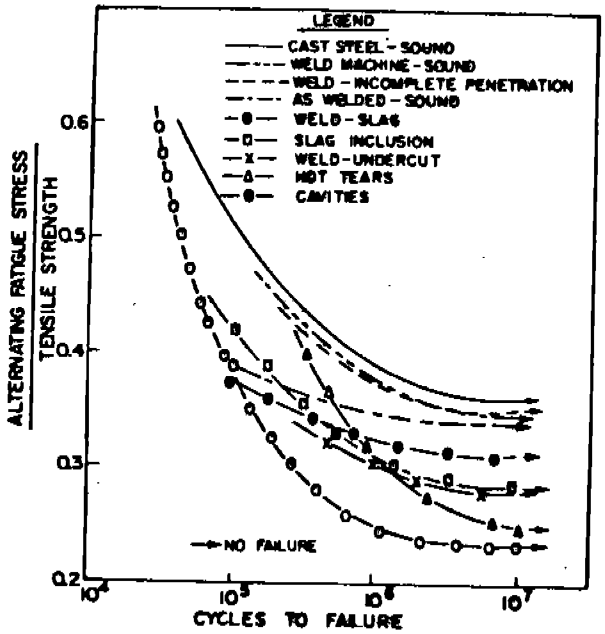

FIG. 12 - Bending fatigue for normalized and tempered 8630 cast steel containing surface discontinuities.

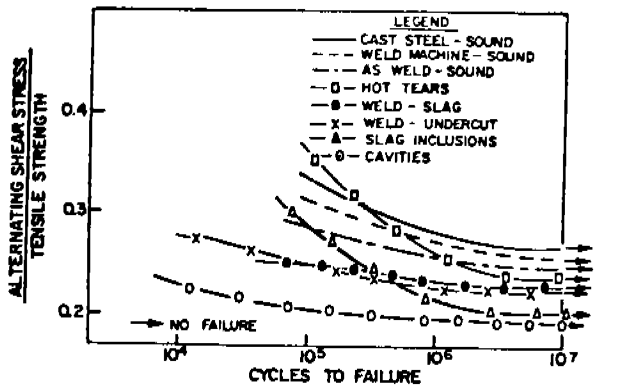

FIG 13 - Torsion fatigue for normalized and tempered 8630 cast steel containing surface discontinuities.

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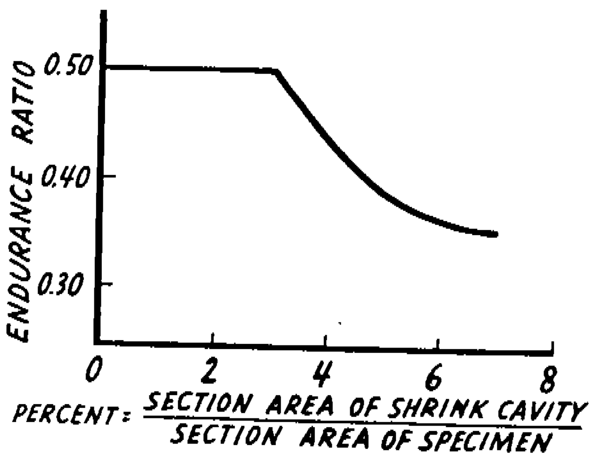

FIG 14 - Endurance limit in pulsating tension testing for cast steel sections containing shrinkage cavities.

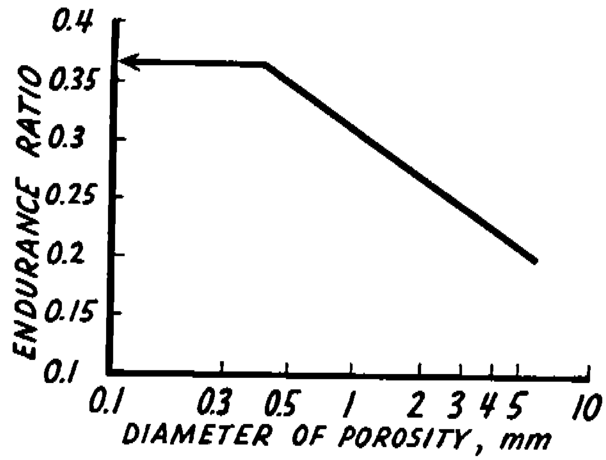

FIG 15 - Relation between diameter of surface gas cavities and the endurance ratio for 0.20 percent carbon cast steel.

TABLE 2

TENSILE PROPERTIES VS. SEVERITY OF RADIOGRAPHIC INDICATIONS

(For 3-inch Thick Steel Casting Plates)

0.26% Carbon Cast Steel 68,500 psi tensile strength.

(The slope b is the deterioration per grade of severity for th equation Y=a-b X, where Y is the property, X is the severity o the indication, and a is the average value for radiographicall sound castings.)

	Tensile Str.		Yield Str.	
	b 1000 psi/ Class	95% Tolerance Limit	b 1000 psi/ Class	95% Tolerance Limit
GAS POROSITY	-3.28	± 5.2	-0.43	*
INCLUSIONS	-0.03	*	-0.03	*
LINEAR SHRINKAGE	-8.11	± 6.2	-1.76	± 2.3
DENDRITIC SHRINKAGE	-8.11	± 9.2	-0.69	± 3.0
WORM HOLE SHRINKAGE	-7.60	± 5.4	-1.43	± 2.2
HOT TEARS	-8.06	± 6.8	-1.23	± 2.0
CHILL INSERTS	-2.58	± 5.2	-0.08	*
CHAPLET INSERTS	-4.93	± 5.4	-0.61	± 1.9

* No significant relationship indicated.

TABLE 3

COMPARISON OF ENDURANCE RATIOS IN BENDING AND TORSION

Type of Specimen	Endurance Ratio in Bending	Endurance Ratio in Torsion	(t,
QT			
Cast Steel-Sound*	0.310	0.298	0.
Weld-Machine-Sound	0.251	0.230	0.
Slag Inclusions	0.246	0.230	1.
As Welded-Sound	0.241	0.221	0.
Weld-Slag	0.234	0.184	0.
Weld-Undercut	0.233	0.195	0.
Cavities	0.117	0.100	0.
Hot Tears	0.274	0.146	0.
NT			
Cast Steel-Sound*	0.361	0.270	0.
Weld-Machine-Sound	0.352	0.261	0.
As Welded-Sound	0.345	0.250	0.
Weld-Slag	0.314	0.234	0.
Weld-Undercut	0.280	0.230	0.
Cavities	0.235	0.195	0.
Slag Inclusions	0.292	0.208	0.
Hot Tears	0.245	0.241	0.

** $(t/b) = \frac{\text{Endurance Ratio in Torsion}}{\text{Endurance Ratio in Bending}}$ † $(t/m) = \frac{\text{Endurance Rat}}{\text{Maxwell-VonMis}}$

* Endurance Ratio using R. R. Moore Specimen (QT unnotched .390, QT no
NT unnotched .395, NT notched .252).

SUMMARY AND CONCLUSIONS

Code bodies, notably ASTM, have produced procedural guides, standard methods and recommended practices which can be used to assure proper inspection procedure for the various methods of nondestructive testing. These are applicable to heavy steel castings, forgings, and weldments. In addition, ASTM offers reference radiographs and reference photographs, which may be used in contractual agreements. In the specific case of steel castings, ASTM defines several levels of quality for ultrasonic inspection. However, these documents do not set forth acceptance criteria or offer recommendations in that regard.

Discontinuities found by nondestructive testing must be evaluated and the ASTM documents discussed in this report do provide guidance in this regard. This is done by describing the parameters which are generally agreed to be of significance and which should be a part of the contractural agreement. It is left to the user to quantify these parameters according to service requirements or other considerations.

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SSC-287, *Examination of Service and Stress Data of Three Ships for Development of Hull Girder Load Criteria* by J. F. Dalzell, N. M. Maniar, and M. W. Hsu. 1979. AD-A072910.

SSC-288, *The Effects of Varying Ship Hull Proportions and Hull Materials on Hull Flexibility Bending and Vibratory Stresses* by P. Y. Chang. 1979. AD-A075477.

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SSC-293, *Underwater Nondestructive Testing of Ship Hull Welds* by R. Youshaw and C. Dyer. 1979. AD-A079445.

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