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A Study on Fabrication Criteria for Ductile Cast Iron Spent-Fuel Shipping Containers

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DISCLAIMER

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ABSTRACT

This report presents a study on criteria for fabricating ductile cast iron shipping containers used for transporting radioactive materials. Emphasis is on providing a specification that will not only describe the mechanical properties of the ductile iron but will, in addition, ensure that these properties will be reliably reproduced in production castings.

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EXECUTIVE SUMMARY

Ductile cast iron used for spent-fuel shipping containers is not, as yet, described by an authoritative specification. Nevertheless, a code or standard guiding fabrication should be identified in the Safety Analysis Report. In the absence of an authoritative standard it is recommended that the procedure adopted by the American Society of Mechanical Engineers (ASME) for new materials be used to characterize the ductile cast iron. The key recommendation in this report is that the material be described in American Society for Testing and Materials (ASTM) form. Emphasis is on providing guidelines for developing a specification that will completely characterize the ductile cast iron with regard to material properties. Furthermore, the submittal of an ASTM-type specification as part of the Safety Analysis Report will obligate the applicant to provide material meeting stated minimum requirements and to reject material not meeting these requirements. The guidelines here for preparing the specification are in ASTM format. They address considerations that are particularly relevant to the fabrication of ductile cast iron for spent-fuel shipping containers.

1.0 INTRODUCTION

To protect the public health and safety, shipments of radioactive materials are required to be in accordance with the provisions of 49 CFR 170-189[1] and 10 CFR 71.[2] The fabrication criteria presented in this report were developed for application to ductile cast iron shipping containers.

All activities that are related to the design and fabrication of shipping containers should be conducted under a quality-assurance program approved by the U.S. Nuclear Regulatory Commission (NRC). Measures must be implemented to ensure that the applicable regulatory requirements and the approved design provided in the Safety Analysis Reports (SAR) are correctly translated into specifications, drawings, procedures, and instructions for fabrication. The measures should also ensure that special fabrication processes, including casting, heat treating, and acceptance testing, are controlled and performed by qualified personnel using qualified procedures.

All codes and standards used in the fabrication of a shipping container should be designated in the SAR as part of the approved design. In the absence of codes or standards for a special process, information describing the process, controls, and quality-assurance measures should be included in the SAR.

Although the shipping-container industry uses many codes and standards for fabrication, no universal code or set of criteria has been adopted by industry for fabricating shipping containers. Fabrication criteria for shipping containers made of materials other than ductile cast iron have been given in NUREG/CR-3854[3]. This report identifies criteria to be used in the fabrication and acceptance testing of ductile cast iron shipping containers and does not duplicate the information given in NUREG/CR-3854.

2.0 BACKGROUND

The configuration of the shipping cask is set by a number of design requirements governing heat transfer, shielding and sealing to ensure minimum radiological hazards, and structural integrity of the cask components in their response to various types of loading. The performance of shipping containers should be assessed by either analytical evaluations or physical tests as specified in 10 CFR 71[2]. Acceptance criteria for meeting 10 CFR 71 are identified in Regulatory Guides 7.6[4] and 7.8[5].

While the requirements of 10 CFR 71 and the guidance outline in Regulatory Guides 7.6 and 7.8 apply to all shipping casks, Regulatory Guide 7.6, which deals with design criteria for the structural analysis of shipping casks, is oriented toward safety-related components made of steel. The introduction of ductile cast iron as a candidate material for spent-fuel shipping casks prompted concern about using Regulatory Guide 7.6 for this material. In addition, since ductile cast iron has considerably less toughness than austenitic stainless steel, which had heretofore been used for the primary containment of shipping casks, the ability of ductile cast iron to resist brittle fracture under dynamic loads was also questioned. To address these concerns, research programs were undertaken to evaluate the suitability of ductile cast iron for shipping casks and to provide a basis for developing regulatory guides to facilitate licensing such casks. These research efforts culminated in suggestions[6] for (1) design criteria that assume ductile behavior, and (2) for a drop test to qualify the ductile cast iron's resistance to brittle fracture under dynamic loads.

A significant finding of this research was the discovery that the mechanical-property values of thick sections of ductile cast iron may differ substantially from values given in standard specifications. The former were generally lower; moreover, tests performed on samples of generic ductile cast iron in "thick" sections revealed a large degree of variability.

Notwithstanding, an appropriate specification for the mechanical properties of ductile cast iron shipping containers is essential to establishing design allowable stress limits. In the absence of an appropriate American Society for Testing and Materials (ASTM) specification, Regulatory Guide 7.6, by implication, specifies the American Society of Mechanical Engineers (ASME) code rules for new materials as an alternative method for establishing mechanical properties data. In accordance with the requirements of Section III of the ASME Boiler and Pressure Vessel (BPV) Code, mechanical-property values given by an ASTM specification are acceptable to define allowable stresses when these allowable stresses are not furnished by the code. In the event that no applicable ASTM specification exists, acceptability for a period of three years is based upon (1) evidence that a specification for the material is before ASTM, (2) evidence that the material is commercially available, (3) evidence that there is a demand for the material, (4) a request for approval of the material in ASTM specification form, and (5) all the data specified in IV-1200 and IV-1300 of Article IV-1000, Section III, Div. 1, Appendices of the ASME BPV Code. The recommendations in Reference 6 for specifying the properties of ductile cast iron follow those outlined by the ASME BPV Code except that in the event that no ASTM specification is available, a specification should be submitted by the licensee to the NRC in ASTM form for approval. It was further suggested that steps be taken to develop an ASTM standard for ductile cast iron in the thickness range applicable to spent-fuel shipping casks. Until such steps are taken, developing fabrication criteria for ductile cast iron suitable for shipping casks should focus on guidelines for preparation of an acceptable standard for this material.

Fabrication guidelines for ductile cast iron spent-fuel shipping containers need to encompass more fundamental processes than those of the guidelines normally applied to the fabrication of steel shipping containers. In the case of steel, the material properties of the plate or forging are generally well characterized by small tests specimens. Even if there is some variation of material properties with geometry, they are usually thickness dependent, so it is not unusual to report the material properties of rolled and forged products as a function of thickness or at various locations throughout the section. In the case of ductile cast iron, or any casting for that matter, the material properties reflect not only the geometry of the casting but also all the processes involved in producing the casting from the melt. For a given chemical composition, the material properties of the casting may vary widely depending upon the size and shape of the casting and the cooling rate. For small ductile iron castings such as those produced for the automotive or fluid handling industry, the material properties are fairly well reflected by those obtained from separately cast test coupons. The material properties of the very large castings required for spent-fuel shipping containers may not necessarily be those obtained from relatively smaller, separately cast test specimens. Even the use of integrally cast test blocks is not an unequivocal guarantee that the blocks are fully representative of as-cast properties. Yet, the structural behavior of the shipping container is governed by the properties of the casting itself.

A further complication is that there do not yet exist specifications for ductile cast iron that apply to castings of the size associated with spent-fuel shipping containers. The basic specification for ductile cast iron in the United States is ASTM A-536,[7] which merely defines five grades of iron in terms of their ultimate tensile strength, yield strength, and percent elongation. The mechanical-property values are minima; no other requirements are specified other than those governing the configuration of the test specimens and the usual requirements for inspection, identification, certification, and preparation for delivery. The grades described range from fully ferritic, through various levels of pearlite content, to martensitic. Since only the primarily ferritic grade is suitable for spent-fuel shipping containers, ASTM A-536 is too ill-defined a specification to cover this use. Furthermore, the crucial property of fracture toughness is not addressed. ASTM specification A-395[8] does refer specifically to ferritic ductile iron but its application is restricted to pressure-retaining castings for use at elevated temperatures. This specification is based upon ASTM A-536 grade 60-40-18 but adds limits for total carbon, silicon, and phosphorous in the chemical composition. It, too, does not address fracture toughness requirements. Also inapplicable to spent-fuel shipping containers are ASTM specifications A-439 and A-571, which pertain to austenitic ductile iron castings. Federal Republic of Germany (FRG) specification DIN-1693 is similar to ASTM A-536 in that it covers a broad range of ductile iron grades. Here too, five grades of ductile iron are specified that roughly parallel those in ASTM A-536. However, DIN-1693 limits the applicability of this specification to castings with wall thicknesses no greater that 200 mm (8 in.). It addresses fracture toughness slightly by specifying minimum Charpy-type energy values for the ferritic grades that require impact resistance.

Since casting is the principal fabrication process for the primary containment of the ductile iron shipping cask and since there does not appear to be a specification in existence that addresses all the required mechanical properties, the guidelines in Chapter 3 should be followed in developing such a specification.

3.0 FABRICATION CRITERIA

Where applicable, the criteria for fabricating metal components for shipping containers used for transporting radioactive materials should be based on NUREG/CR-3854.[3] The following specific criteria apply only to components made of ductile cast iron.

The specification for ductile cast iron to be used in shipping containers should identify minimum mechanical-property values that can serve not only as bases for acceptance or rejection of the casting but also as bases for establishing design stress-intensity limits. These values are presumably based upon comprehensive tests performed by the applicant. Also included should be the specification of maximum allowable flaw size and minimum fracture toughness emerging from the prototype cask test program. Furthermore, the specifications should define testing and inspection procedures that will add confidence in the mechanical properties reported and should define procedures that will maintain the quality of the shipping containers throughout the production cycle. The following guidelines are designed to reflect the rules contained in Article IV-1000, Section III, Div. 1, Appendices of the ASME BPV Code. Particular attention should be given to the requirement that the specification be written in ASTM format.

This section deals with guidelines that should be followed by the applicant in preparing the material specification. Assistance in establishing these guidelines was provided by a panel representing both the shipping container industry and a segment of the foundry industry experienced in the production of large ductile iron castings.

3.1 Title

The title should be as concise as possible but complete enough to identify the material covered by the specification. Titles are used in lists, tables of contents, and indexes. It is most important that they be brief but inclusive. A suggested title is "Standard Specification for Ductile Iron Castings for Spent-Fuel Shipping Containers."

3.2 Scope

3.2.1 This specification covers castings made of ductile cast iron that are applicable to the fabrication of thick-wall nuclear spent-fuel shipping casks over eight inches thick.

The type of ductile cast iron designated for this application is limited to the predominantly ferritic grade (as defined in 3.11.1) in which the graphite is substantially spheroidal in shape and essentially free of other forms.

3.2.2 The values stated in inch-pound units are to be regarded as the standard.

3.3 Applicable Documents

3.3.1 ASTM Standard

E-59 "Standard Method of Sampling Steel and Iron for Determination of Chemical Composition."

E-30 "Standard Method for Chemical Analysis of Steel, Cast Iron, Open Hearth Iron and Wrought Iron."

E-8 "Standard Method of Tension Testing of Metallic Materials."

E-24.03* "Standard Method of Test for Instrumented Impact Testing of Precracked Charpy Specimens of Metallic Materials."

E-606 "Standard Recommended Practice for Constant Amplitude Low Cycle Fatigue Testing."

3.4 Ordering Information

Orders for material under this specification should include the following information.

3.4.1 Detailed chemical-composition requirements to which the material must conform. The following information should be clearly indicated:

3.4.1.1 Name of each constituent specified.

3.4.1.2 Whether the requirement is a maximum, minimum, or range.

3.4.1.3 Whether an allowance for measurement error is incorporated in these limits.

3.4.1.4 Applicable units.

3.4.1.5 Specification of appropriate analytical methodology.

3.4.2 Detailed requirements regarding mechanical physical properties to which the material should conform. The following information should be clearly indicated:

3.4.2.1 Minimum ultimate tensile strength.

3.4.2.2 Minimum yield strength.

3.4.2.3 Young's modulus.

3.4.2.4 Poisson's ratio.

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*Refers to ASTM Subcommittee E-24.03, "Alternative Fracture Test Methods."

3.4.2.5 S-N curve for fatigue.

3.4.2.6 Percent elongation and percent reduction in area.

3.4.2.7 Dynamic fracture toughness.

3.4.2.8 Creep threshold temperature.

3.4.2.9 Coefficient of thermal expansion.

3.4.2.10 Temperature range over which the mechanical properties apply.

3.5 Materials and Manufacture

3.5.1 The melting method and the nodularizing practice should be at the option of the foundry.

3.5.2 A ferritizing heat treatment may be applied, ensuring uniform mechanical properties throughout each section and producing an essentially ferritic structure that contains no massive carbides.

3.6 Chemical Composition

3.6.1 The composition of the ductile cast iron should be optional. However, analysis should show that the composition and limits established for elements conform to the acceptance standards specified by the applicant.

3.6.2 The carbon equivalent defined by C + 1/3 Si should not exceed 4.45%.

3.6.3 Chemical analysis should be performed in accordance with ASTM E-59 or E-30. The chemical composition may also be determined by spectrographic methods but, should a dispute arise concerning the chemical composition, ASTM E-59 or E-30 should be used to resolve it.

3.7 Tensile Tests

3.7.1 The ultimate tensile strength, yield strength, and percent elongation of a ductile cast iron test block as shown in Fig. 1 should meet minimum acceptance standards specified by the purchaser. Testing for these mechanical properties should be performed in accordance with ASTM E-8.

3.7.2 The standard machined 1/2-in. (13-mm) round tension test specimen with a 2-in. (50.8-mm) gage length as shown in Fig. 2 should be used.

3.7.3 The yield strength should be determined in accordance with ASTM E-8 using the 0.2% offset method.

3.8 Test Blocks

3.8.1 The separately cast test blocks from which the tension and fracture toughness test specimens are machined should be cast to the size and shape

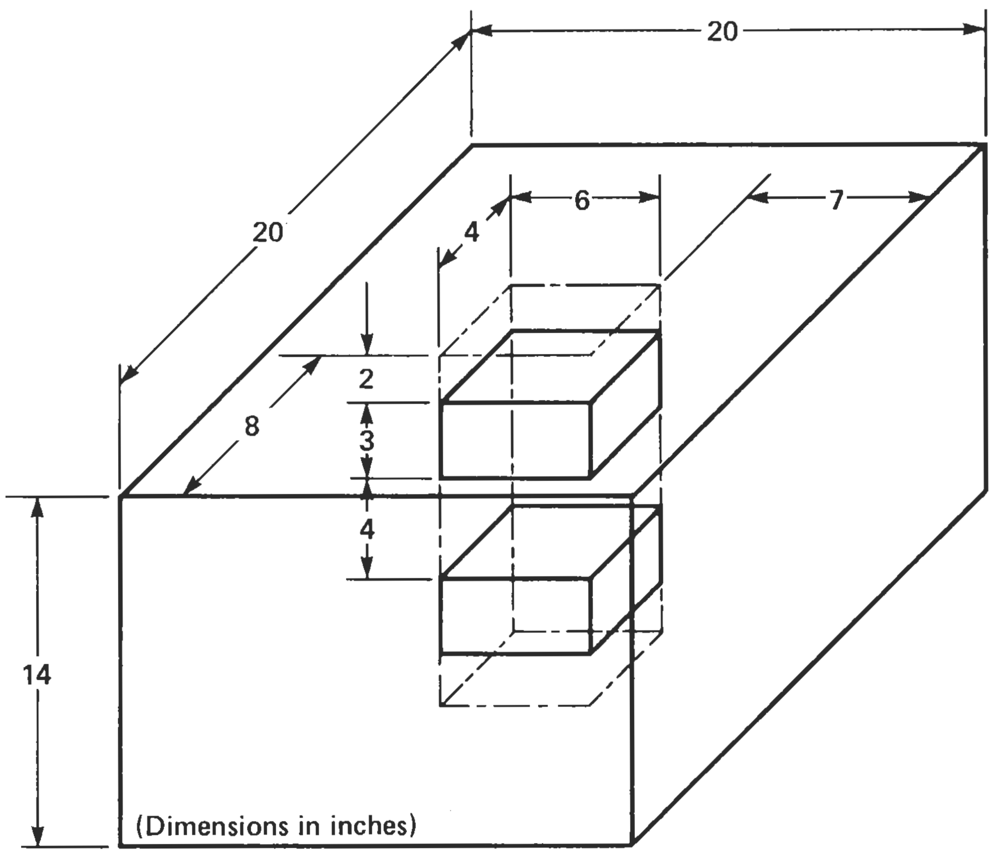
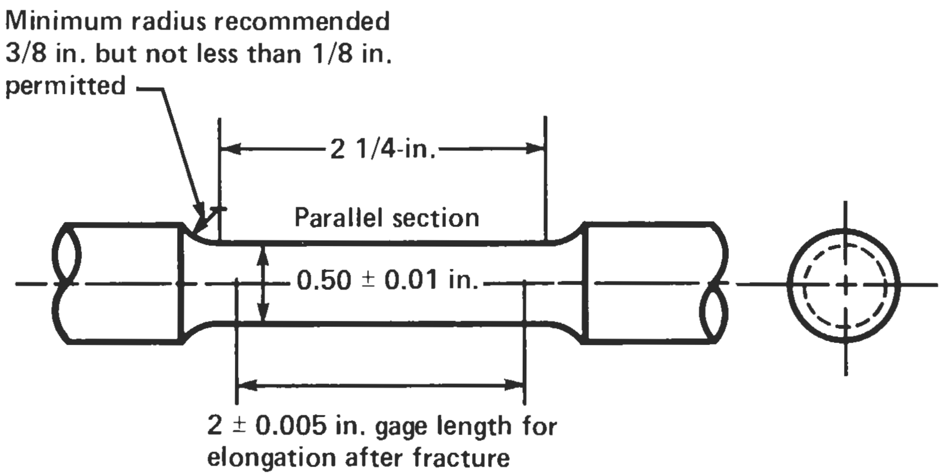


Figure I. Test block for ductile cast iron shipping cask.



Metric equivalents

in.	mm	in.	mm
0.005	0.13	0.50	12.7
0.10	2.5	2	50.8
1/8	3.2		
3/8	9.5	2 1/4	57.2

Note - The gage length and fillets shall be as shows, but the ends may be of any shape to fit the holders of the testing machine in such a way that the load shall be axial. The reduced section shall have a gradual taper from the ends toward the center, with the ends 0.003 to 0.005 in. (0.08 to 0.13 mm) larger in diameter than the center.

Figure 2. Standard round tension-test specimen with 2-in. gage length (Ref. 7).

shown in Fig. 1. The sectioning procedure for removing test specimens from the test block is also shown in Fig. 1. These test blocks should be separately cast immediately after the castings. They should represent the melt used for, and be identified with, the production castings.

3.8.2 Test blocks should be cast in open molds made of sand, similar to the mold used for the production casting and having a minimum sand thickness of seven inches. The blocks should be left in the mold until they cool to a black color (approximately 800^{o}F or less).

3.8.3 The test blocks should be subjected to the same treatment applied to the production casting prior to their use for the preparation of test specimens.

3.9 Fracture Toughness Tests

3.9.1 The fracture toughness of the ductile cast iron represented by the large test block material should meet minimum acceptance standards specified by the purchaser.

3.9.2 Testing for fracture toughness should be performed in accordance with ASTM Subcommittee E-24.03 proposal "Standard Method of Test for Instrumented Impact Testing of Precracked Charpy Specimens of Metallic Materials."

3.9.3 A precracked Charpy-impact-test specimen as shown in Fig. 3, should be used to establish fracture toughness properties.

3.10 Fatigue Tests

3.10.1 Fatigue properties of ductile cast iron spent-fuel shipping containers should be provided in a format similar to and derived in the same manner as those that appear in Appendix I of Section III of the ASME BPV Code.

3.10.2 Testing for fatigue properties should be preformed in accordance with ASTM E-606.

3.11 Microstructure

3.11.1 Tests for nodularity should be performed using optical metallographic techniques. Acceptance criteria should be 75% (Min.) Type I and Type II nodules, as shown in Fig. 4, with a maximum of 20% pearlite and 3% free carbides.

3.11.2 The numbers of each graphite type should be determined by counting the nodules in the field and reported in percentages that total 100. Magnification should be 50x.

3.11.3 The microstructure specified above should be representative of the separately cast test block as shown in Fig. 1.

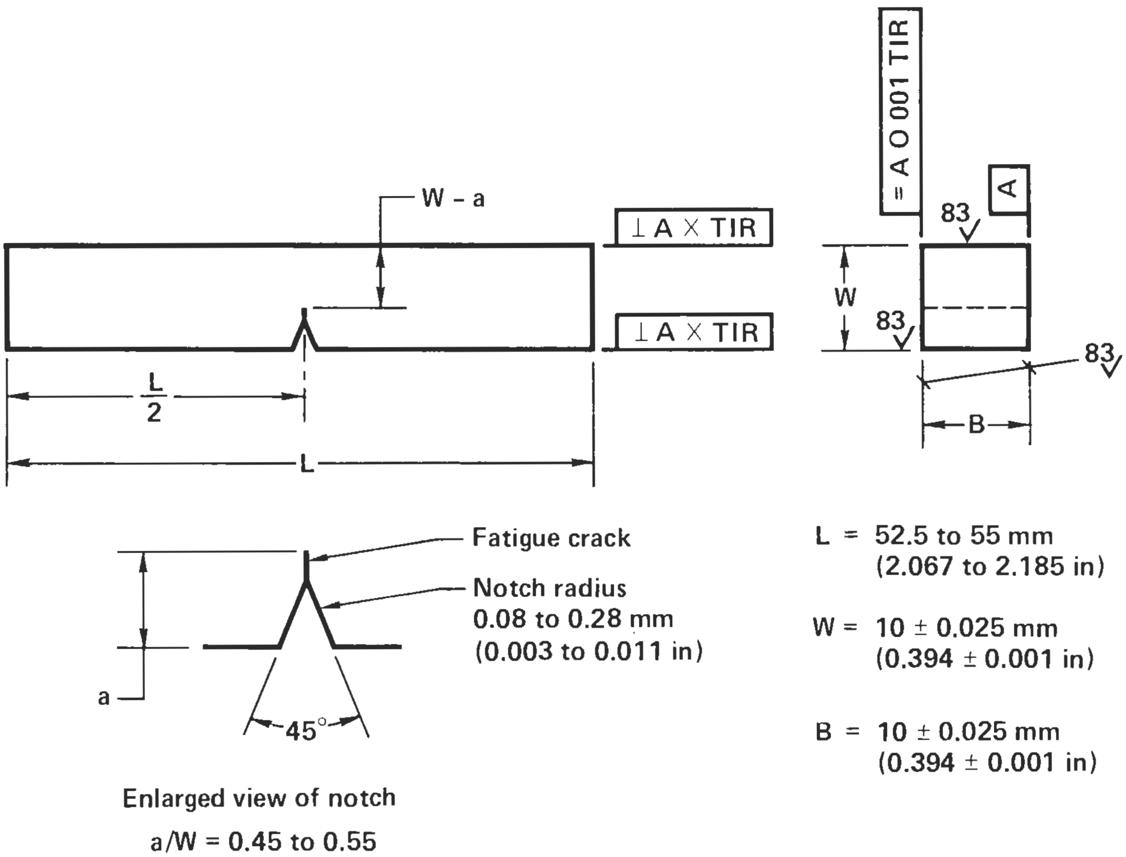
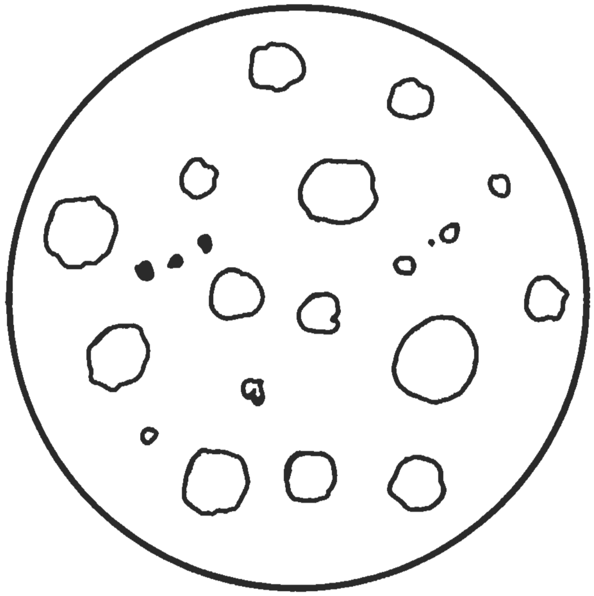
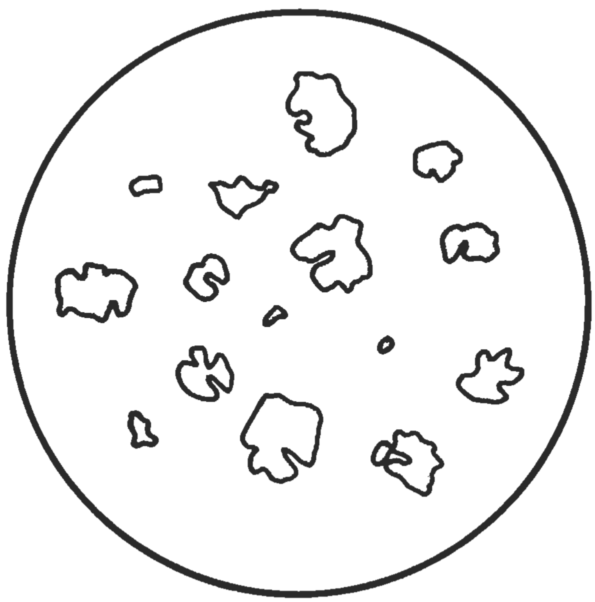


Figure 3. Precracked Charpy fracture toughness test specimen.



Type I



Type II

Figure 4. Suggested classification of graphite form in ductile cast iron (Ref. 8). Graphite types are identical with Plate I of ASTM Recommended Practice A-247 and are so identified.

3.12 Sampling

3.12.1 The two 4 in. x 6 in. x 3 in. specimens from the test block should be cut to yield 12 tensile test specimens from one and 12 precracked Charpy impact specimens from the other.

3.12.2 As an alternative, tensile-test and precracked Charpy-impact specimens may be prepared from material taken directly from the casting.

3.12.3 Minimum values for ultimate tensile strength and dynamic fracture toughness should be established at an exceedance level of 95% assuming a log normal distribution of the test data.

3.13 Workmanship and Finish

3.13.1 The casting should be smooth, free of injurious defects, and should conform to the dimensions of the drawing supplied by the purchaser. The surface of the casting should be examined visually and be free from adhering sand, scale, and hot tears.

3.13.2 Other defects such as surface and subsurface cracks should meet acceptance standards specified by the purchaser. The limitations on surface and subsurface defects will be based upon the flaw sizes introduced in the casting meeting the drop test acceptance criteria.

3.14 Repair

3.14.1 Castings for spent-fuel shipping containers should not be repaired by plugging, welding, brazing, or impregnation. Shallow defects may be removed by grinding in a manner that leaves the area smooth and faired in with the surface.

3.14.2 Grinding out defects from structures that serve as shielding should not result in transmitted radiation levels higher than allowable.

3.15 Identification Marking

Each casting should be identified by a part number and a unique serial number in raised numerals. Location of markings should be as indicated on the applicable drawing.

3.16 Handling, Storage, and Preparation for Delivery

Unless otherwise specified, cleaning, drying, preservation, and packaging of castings should be in accordance with the manufacturer's commercial practice. However, these should be performed in a manner precluding damage or deterioration of the castings. When necessary, special handling, lifting, or storage facilities should be used to adequately preserve the castings. Packing and marking should be acceptable to the carrier for the mode of transportation employed.

4.0 VALUE IMPACT ASSESSMENT

This section considers the safety and industrial impact of the fabrication guidelines. The discussion covers only those recommendations not referenced to such widely accepted standards as those of ASTM and the ASME BPV Code. Here the evaluation cites a particular recommendation as it appears in the fabrication guidelines and follows it with a value impact assessment. References to "safety" do not refer to radiological hazards or risk but rather to the recommendation's impact on the structural integrity of the shipping cask.

4.1 Chemical Composition

4.1.1 The composition of the ductile cast iron should be at the manufacturer's option. However, analyses are required to show that the composition and limits established for elements conform to the acceptance standards specified by the purchaser.

4.1.2 Impact on Safety

The specific chemical composition is not specified in the guidelines because no optimal chemical composition has been established for ductile cast iron suitable for spent-fuel shipping casks. Furthermore, it is recognized that many factors associated with foundry practice contribute to the selection of an appropriate composition. It is likely that variation in composition from one manufacturer to the next may still result in castings having acceptable mechanical and physical properties. Nevertheless, once a prototype cask has passed prescribed acceptance tests, safety considerations dictate that subsequent production castings conform as closely to the prototype as possible. Since the effect of variations in chemical composition cannot easily be ascertained, it is imperative that these variations be held to a minimum to ensure a level of quality at least equal to that of the prototype. Consequently, the chemical composition of the prototype should become the standard formulation for the cask design that is ultimately granted a license. Adherence to a specific chemical composition should be enforced, at least until an authoritative standard for ductile cast iron suitable for spent-fuel shipping casks is published. The composition and limits for the various elements as licensing conditions should be specified in the standard as well as in the purchase order. The procedure for ensuring adherence to this guideline should appear in the applicant's quality assurance program plan.

4.1.3. Impact on Industry

The recommendations allow the industry a maximum degree of flexibility in formulating a chemical composition for ductile cast iron suitable for spent-fuel shipping casks. Uniform composition requirements within specific limits are not unusual or unreasonable for well equipped foundries with experience in producing large castings.

4.2 Tensile Tests

4.2.1 The ultimate tensile strength, yield strength, and percent elongation of a ductile cast iron test block, as shown in Fig. 1, should meet acceptance standards specified by the purchaser.

4.2.2 Impact on Safety

The reported values for the mechanical properties of ductile cast iron suitable for shipping casks display a wide variation just as do chemical composition values. Until an authoritative standard is published specifying minimum acceptable mechanical properties, these specifications are left to the manufacturer. This does not necessarily compromise safety because the cask design is constrained by stress-intensity limits determined by applying appropriate "safety factors" to the minimum value of ultimate tensile strength or yield strength. Thus, ductile cast irons of variable strengths can be used within a given range of stress-intensity limits. Suggestions for appropriate safety factors have been considered in connection with ductile cast iron design criteria.[6] Although specification of definite limits for the percent elongation has not been mandated in these fabrication guidelines, the potential licensee should be aware that a lower limit of 12% has been set by the guidelines in order to meet design criteria for ductile-behaving materials. Lower limits on percent elongation may be acceptable if the stress limits predicted by appropriate failure theories can be convincingly demonstrated to exceed applied stresses by adequate margins of safety.

Minimum mechanical-property values are not specified in this guideline, as it is anticipated that minimum values will be established by the manufacturer. Appropriate tests can be made on specimens from the test blocks associated with each pour and from the as-cast prototype casting. Adherence to the minimum mechanical-property requirements should be enforced, at least until an authoritative standard for ductile cast iron suitable for spent-fuel shipping casks is published. The minimum mechanical properties should be specified as licensing conditions and in the purchase order. The procedure for ensuring adherence to this guideline should appear in the applicant's quality assurance program plan.

4.2.3 Impact on Industry

This recommendation allows the industry considerable flexibility in establishing minimum mechanical properties for ductile cast iron suitable for spent-fuel shipping casks. The implementation of an adequate test program to establish these properties would not be unusual for a foundry qualified to produce large ductile iron castings or unreasonable in light of the limited experience in the use of this material for spent-fuel shipping casks.

4.3 Fracture Toughness Tests

4.3.1 The fracture toughness of the ductile cast iron represented by the large test block material should meet the minimum acceptance standards specified by the purchaser.

Testing for fracture toughness should be performed in accordance with ASTM Subcommittee E-24.03 proposal "Standard Method and Test for Instrumented Impact Testing of Precracked Charpy Specimens of Metallic Materials."

4.3.2 Impact on Safety

Reference 6 suggests that resistance to brittle fracture be evaluated by means of the response of a prototype cask to a 30-foot (9-meter) drop test on a hard unyielding surface. The specification for the drop test included a requirement that flaws be introduced at the most critically stressed portions of the cask. These stressed portions result from "striking the surface in such a position as to suffer maximum damage" (10 CFR 71.77). If the cask successfully passes the test, the toughness of the iron near the flaws is deemed sufficient for the highest dynamic loading conditions expected. It remains to ensure that the production casting does not display a lower toughness. If it does, a flaw size limit could be specified such that the minimum toughness expected will not, within specified margins of safety, result in unstable flaw propagation.

Because limits for the fracture toughness of ductile cast iron suitable for spent-fuel casks are not well established, these limits should be based upon the qualifying drop test. Although this guideline does not define any limits, production castings should be required to meet the limits established by this test. The test limits should be identified as licensing conditions and specified in the purchase order. The procedure for ensuring adherence to this guideline should appear in the applicant's quality assurance program plan.

The instrumented, precracked Charpy test, although not yet adopted as an ASTM standard, is considered to be a reliable indicator of comparative fracture toughness. Valid measures of fracture toughness obtained as indicated in ASTM E-399 are not essential. This is because the fracture-toughness measurements for test specimens taken from production runs of ductile iron will be compared to those for the qualified prototype-casting specimens. It should be noted that the major issues delaying adoption of the test as a standard by ASTM Subcommittee E-24.03 seem to involve the specification of valid calibration procedures. To avoid any questions about the validity of the testing procedure, it is strongly recommended that the potential licensee include information in his quality assurance document about calibration procedures used to establish fracture toughness values for the prototype casting and how these procedures will remain invariant during the testing of production-casting specimens.

4.3.3 Impact on Industry

This specification allows the industry considerable flexibility in establishing fracture toughness requirements for ductile cast iron suitable for spent-fuel shipping casks. The fracture toughness test recommended is relatively inexpensive and can be performed at a number of commercial test facilities.

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This report presents a study on criteria for fabricating ductile cast iron shipping containers used for transporting radioactive materials. Emphasis is on providing a specification that will not only describe the mechanical properties of the ductile iron but will, in addition, ensure that these properties will be reliably reproduced in production castings.

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