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FRACTURE TOUGHNESS MASTER CURVE DEVELOPMENT: APPLICATION OF MASTER CURVE FRACTURE TOUGHNESS METHODOLOGY FOR FERRITIC STEELS

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Foreword

In the early 1970s the ASME Boiler and Pressure Vessel Code Committee recognized the need for a fracture mechanics based analysis procedure for the determination of safe operating limits for pressure and temperature for normal heat up and cool down operations. They developed the fracture mechanics analysis procedure found in Appendix G of Section III of the ASME Code. The fracture toughness information used in the fracture analysis in Appendix G was obtained from the K_{IR} curve presented in that Appendix. The K_{IR} curve is a representation of fracture toughness versus temperature curve with the temperature axis normalized by the RT_{NDT} temperature of individual heats of pressure vessel material. The RT_{NDT} is determined from the results of drop weight tests and Charpy impact tests. In this way the variations of the temperature region of the brittle to ductile transition between heats and types of pressure vessel materials could be accounted for. Appendices G and H to 10 CFR 50 of the United States Code of Federal Regulations adopted the ASME procedure and added a procedure for adjusting the RT_{NDT} reference temperature for irradiation.

These processes were developed in the 1970s while fracture mechanics procedures were in the early stages of development for materials which exhibited a brittle to ductile transition. The only ASTM Standard Test Method in existence at the time was ASTM E-399. This procedure was developed with high strength aircraft materials that do not exhibit a brittle to ductile transition. ASTM E-399 is based on linear elastic fracture mechanics concepts and is not well suited for obtaining fracture toughness information on pressure vessel materials, which experience a brittle to ductile transition.

An ASTM Task Group worked for over 15 years to develop a standard test method for fracture toughness testing in the brittle to ductile transition region. One of the hardest issues to resolve was the large variability in the measured fracture toughness values in this region. This variability necessitated that the test method be based on a statistical interpretation of the test data. In 1997 the ASTM adopted a new standard test method, E-1921 Standard Method for Determination of Reference Temperature, T_o, for Ferritic Steels in the Transition Range. This new test method presents a procedure for the evaluation of the fracture toughness of the ferritic pressure vessel steels. The technical basis of the procedure is discussed briefly in Bulletins 457, 458 and 459. A more detailed discussion of the technical basis is included in Reference 1.

In 1996, the PVRC established a Task Group on the application of the Master Curve. An objective of the Task Group was to develop an alternative to the ASME Section III RT_{NDT} procedure based on T_o, with the objective of developing an ASME Code Case.

This WRC Bulletin is one of a set of three Bulletins on Fracture Toughness Master Curve Development. The three Bulletins should be used as a set.

- WRC Bulletin 457: Fracture Toughness of Ferritic Steels and ASTM Reference Temperature (T_o)
- WRC Bulletin 458: Application of Master Curve Fracture Toughness for Ferritic Steels (Ref. 2)
- WRC Bulletin 459: Master curve Strategies for RPV Assessment (Ref. 3)

These Bulletins document the Task Group activities to accomplish this objective.

Bulletin 457, "Fracture Toughness of Ferritic Steels and ASTM Reference Temperature (T_o)," describes the results of the three-phase project that was initiated by the Committee on Failure Modes of Components of the Pressure Vessel Research Council (PVRC). The objectives of these work phases are (1) to verify the Master Curve approach for pressure vessel steels, (2) to develop a database which can be used in the future development of ASME Boiler and Pressure Vessel Code procedures which make use of T_o or the Master Curve approach and (3) to use the data to develop and verify an ASME Code Case. These objectives have been accomplished.

It was desired to obtain a large database of fracture toughness data on ferritic pressure vessel steels which could be used to further verify the reference temperature, T_o, and Master Curve procedures and also be used in the development of an alternative fracture toughness method for incorporation into the ASME Boiler and Pressure Vessel Code.

To accomplish this objective, a total of twenty-five fracture toughness data sets in the brittle to ductile transition range was collected. The reference temperature, T_o, and Master Curve were determined for each heat of material investigated. This report presents the finding from these data set analyses, especially those sets that have a large number of data points. The data are presented with a median curve, 5% and 95% tolerance bounds on the Master Curve. It is concluded that the Master Curve method applies to all the data sets of ferritic steels for pressure vessel materials in this study.

A proposed ASME Code Case is presented which uses the current K_{Ic} curve, but is shifted using an equivalent reference temperature, which is based on the fracture toughness reference temperature, T_o, rather than the RT_{NDT} value based on Charpy impact and drop weight test results. Two separate Code Cases based on the proposed draft have been approved by the ASME B&PV Committee as Code Cases N-629 and N-631 for Section XI and Section III applications, respectively.

WRC Bulletin 458 includes the report entitled "Application of Master Curve Fracture Toughness Methodology for Ferritic Steels" (Ref. 2). This report was prepared as an EPRI activity working with the PVRC Task Group, and provides background information and technical arguments in support of using the Master Curve fracture toughness approach to provide an alternative definition of the existing reference temperature (RT_{NDT}) and statistically defined fracture toughness curves for ferritic pressure vessel steels. The origin and bases of the ASME Boiler and Pressure Vessel Code, Sections III and XI, lower bound fracture toughness curves using the RT_{NDT} referencing approach are reviewed and contrasted with the new Master Curve method. The activities of a task group of the PVRC are described as they relate to final recommendations for incorporating the Master Curve Methodology into the ASME Code. EPRI published this report to formally document the 1970s bases for the current ASME Code reference temperature approach and lower bound fracture toughness curves and to present alternatives that use more relevant and advanced fracture mechanics approaches. The Bulletin includes the basis for application of the Master Curve methodology to irradiated pressure vessel steels, as well as the originally intended application to unirradiated ferritic pressure boundary steels.

WRC Bulletin 459, "Master Curve Strategies for RPV Assessment" (Ref. 3) is an example of an application of this methodology. This report describes the application of the Master Curve methodologies described in the first two reports to an actual vessel integrity evaluation. The objective of this report was to integrate the results obtained using the Master Curve procedure to the existing reactor pressure vessel integrity evaluation methodology. It is not intended that by including the description of this approach that the PVRC is recommending that this approach should be adopted.

REFERENCES

1) J. G. Merkle, K. Wallin and D. E. McCabe, "Technical Basis for an ASTM Standard on Determining the Reference Temperature, T_o, for Ferritic Steels in the Transition Range," NUREG/CR-5504, Oak Ridge National Laboratory, Oak Ridge, TN, November 1998.

2) "Application of Master Curve Fracture Toughness Methodology for Ferritic Steels," (PWRMRP-01) EPRI TR-108390-R1, Final Report, Electric Power Research Institute, Charlotte, North Carolina, May 1999.

3) EDRE-EMT-884, "Master Curve Strategies for RPV Assessment," Prepared for the Westinghouse Owners Group (WOG) by Westinghouse Electric Company, Energy Systems, Pittsburgh, PA.

Fracture Toughness Master Curve Development: Application of Master Curve Fracture Toughness Methodology for Ferritic Steels

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Abstract

This report provides background information and technical arguments in support of using the Master Curve fracture toughness approach to provide an alternative definition of the existing reference temperature (RT_{NDT}) and statistically defined fracture toughness curves for ferritic pressure vessel steels. The origin and bases of the ASME Boiler and Pressure Vessel Code, Sections III and XI, lower bound fracture toughness curves using the RT_{NDT} referencing approach are reviewed and contrasted with the new Master Curve method. The activities of a task group of the Pressure Vessel Research Council are described as they relate to final recommendations for incorporating the Master Curve methodology into the ASME Code. EPRI is publishing this report to formally document the 1970s bases for the current ASME Code reference temperature approach and lower bound fracture toughness curves, and to present alternatives that use more relevant and advanced fracture mechanics approaches. Revision 1 of this report includes the basis for application of the Master Curve methodology to irradiated pressure vessel steels, as well as the originally intended application to unirradiated ferritic pressure boundary steels.

1 Introduction

Recent nuclear industry attention has been focused on the direct use of measured fracture toughness properties in the assessment of reactor pressure vessel (RPV) integrity. Specifically, efforts have been initiated to develop procedures for determining a material transition temperature, designated as T_o, based on measured fracture toughness testing using the Master Curve approach. This is in contrast to the historically utilized approach to first determine an initial unirradiated reference temperature, RT_{NDT}, based on a combination of Charpy V-notch and drop weight nil-ductility transition (NDT) temperature test methods, and adjust for neutron radiation damage by adding the Charpy transition temperature shift measured at 30 ft-lb (41 J). The direct determination of material fracture toughness and a transition temperature associated with measured fracture toughness represents a more precise measure of material resistance to crack initiation than earlier methods and should provide a more realistic assessment of RPV integrity.

Significant efforts are presently underway in the research, codes and standards, and regulatory arenas to:

- Collect all relevant and available fracture toughness data and generate additional data for RPV materials
- Develop consensus procedures for the determination of T_o
- Demonstrate the validity of using T_o as a fracture toughness transition reference temperature
- Incorporate the new approach into the appropriate codes, standards, and regulations

These activities involve the participation of all aspects of the nuclear industry including individual utilities, nuclear steam supply system (NSSS) vendors, vendor Owners Groups, EPRI, research laboratories, the U.S. Nuclear Regulatory Commission (NRC), and other domestic and international experts.

This section briefly introduces the need for an alternative approach for determining RT_{NDT}, specifically using T_o via the Master Curve methodology. In addition, coordination of industry activities to demonstrate the validity of the Master Curve approach and the role of this report in supporting its application to pressure vessel integrity assessments are

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