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NASA Engineering and Safety Center
Materials Super Problem Resolution Team
Activity Report

Fatigue Crack Growth Rate of Inconel 718 Sheet at Cryogenic Temperatures

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December 2005

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Abstract

Inconel 718 sheet material was tested to determine fatigue crack growth rate (FCGR) at cryogenic conditions representative of a liquid hydrogen (LH_2) environment at -423°F. Tests utilized M(T) and ESE(T) specimen geometries and environments were either cold gaseous helium or submersion in LH_2. The test results support a significant improvement in the fatigue crack growth threshold at -423°F compared to -320°F or 70°F.

NESC Executive Summary

This report summarizes material characterization tests performed under the auspices of the Materials Super Problem Resolution Team (SPRT) to provide confirmation and closure for LH_2 FCGR properties utilized in the NASA Engineering and Safety Center (NESC) Independent Technical Assessment (ITA) of the Orbiter Flowliner system [ref. 5]. For comparison and completeness, prior tests run for the Space Shuttle Integration Office in gasified LHe are also included.

Introduction

A typical articulated joint in a cryogenic fuel or oxidizer supply line requires either an external gimbal support or an internal central support mechanism, and a formed, pressure carrying bellows to allow for motion. To keep the flow field in the line from interacting with the bellows, a liner is placed over the bellows to make the internal dimensions of the feedline smooth by hiding the bellows from the flow field. See Figures 1a and 1b. The lines within the Orbiter that carry LH_2 and liquid oxygen (LO_2) from the External Tank to the Space Shuttle Main Engines are fabricated of thin sheet Inconel 718 material and contain similar "flow-liners" at the articulated joints. In this case, slots were placed into the flow-liners to allow pressure communication between the main flow channel and the space between the liner and bellows. An example of flow-liners and their slots are shown in Figure 2. In the spring of 2002, a small number of cracks were identified growing from the slots on the flow-liners in the hydrogen supply lines on many of the Orbiters. An example of a transverse crack is shown in Figure 3. The FCGR data at LH_2 temperature is important to the damage tolerance assessment of the flow-liner structure, particularly when the test data supports a slower crack growth rate than is represented by existing data at -320°F or 70°F. To begin, FCGR data was generated at -423°F using a gasified LHe environment. This effort was funded directly by the Space Shuttle Integration Office to support ongoing flow-liner assessments at that time. During the NESC ITA of the Orbiter flow-liner system, the suitability of the gasified LHe test environment was questioned. Due to the potential for deleterious effects of hydrogen on Inconel 718 under some conditions (typically high pressure gaseous hydrogen at room temperature) and the potential influence of the liquid environment on FCGR, the Materials SPRT chose to support confirmation tests directly in LH_2. All of the tests at -423°F reported herein are complementary to the results published [ref. 1] for Inconel 718 base metal and welds at room and cryogenic temperatures down to -320^{o}F.

Materials

The materials used for the tests were processed to match the condition of the Orbiter flow-liner hardware as closely as possible. Thin sheet (0.050 inches) was ordered from SAE AMS 5596 [ref. 2], which supplies material in the solution heat-treated condition at 1,775^{o}F. The documentation pertaining to the fabrication of the flow-liner hardware dictates an aging cycle that is non-standard for Inconel 718: 3 hours at 1,400^{o}F. To match the hardware, the materials for these tests were aged in a vacuum environment for 3 hours +/- 10 minutes at 1,400^{o}F +/- 25^{o}F. The influence of this non-standard aging practice is discussed below with comparisons to existing data with more traditional heat-treated conditions. Materials [ref. 1] were also heat-treated to these conditions. Limited tensile testing of this material in LH_2 produced an average yield strength of 185 ksi and an average ultimate strength of 265 ksi.

Experimental Procedures

Test Procedures

All test procedures were in accordance with ASTM E 647, *Standard Test Method for Measurement of Fatigue Crack Growth Rates* [ref. 3]. All tests used digitally-controlled servo-hydraulic machines which were controlled directly by an ADwin Gold system from Fracture Technology Associates. Test techniques included constant load amplitude, constant load ratio with a controlled K-gradient and the K_{max} load shedding technique with an increasing load ratio. Crack lengths were measured continuously using compliance techniques with a front-face clip gage. Following test completion, the pre-crack and final crack lengths were measured optically. Small corrections were made to the compliance crack length data as needed based on the optical measurements.

Test Samples

Two test sample designs were used in this test series: the Eccentrically-loaded Single Edge crack Tension sample (ESE(T)) with a width of 1.5 inches and the Middle Crack Tension sample (M(T)) with a width of 2.0 inches. Figure 4 shows an example of both sample designs following testing. All test samples were pre-cracked in air at acceptable stress intensities to avoid load history interaction with the crack growth rates during the test. For all tests, the fracture samples were oriented in the T-L direction relative to the rolling direction of the material.

Environments

Test techniques were generally verified in room temperature air and liquid nitrogen (LN_2) environments prior to attempting the -423^{o}F environment with LHe or LH_2. The LHe tests were run using a continuous supply of LHe into a well insulated test chamber supported between the uprights of the test machine allowing the sample to move independently from the chamber. A system of small tubes with orifices distributed the LHe evenly within the box. The LHe is in a gaseous state by the time it is expelled from the tubes. See Figure 5. Therefore, a more accurate description of the test chamber environment is cold gaseous helium. To supply LHe continuously for the time required for these tests, a 5,000 gallon tanker truck was used. The ullage pressure in the tanker was maintained using a high purity gaseous helium supply trailer. The flow rate of LHe into the test rig was controlled with regulators, but the ullage pressure of the tanker had a strong influence on the actual flow rates realized. Therefore, the test rig required continuous monitoring. The test environment in the LHe rig was maintained at -423^{o}F +5^{o}F/-10^{o}F throughout the test operation. Thermocouples attached to both sides of the test sample and floating free in the chamber were continuously monitored.

The LH_2 environment was obtained in the NASA MSFC Hydrogen Test Facility (HTF). Specially designed for testing directly in various hydrogen environments, the HTF provides a unique ability to overcome the hazards of hydrogen testing and permits direct submersion of the test sample in LH_2 throughout the test. Figures 6a and 6b show the LH_2 cryogenic test rig. Proper test temperature is assured by maintaining complete submersion in LH_2 by means of an automated system for filling the cryostat. The sample temperature is known to be -423^{o}F after a moderate soak period.

Test Results and Discussion

A summary table of the tests reported is included in Table 1.

Table 1. Summary of Test Samples and Conditions

Test ID	Sample Type	Environment	Load Ratio	Method
LHe-ESET-1	ESE(T)	Gasified LHe (-423^{o}F)	Increasing	K_{max} = 30
LHe-ESET-2	ESE(T)	Gasified LHe (-423^{o}F)	Increasing	K_{max} = 30
LHe-ESET-3	ESE(T)	Gasified LHe (-423^{o}F)	Increasing	K_{max} = 50
LHe-ESET-5	ESE(T)	Gasified LHe (-423^{o}F)	R = 0.1	Incr. K-grad.
LHe-ESET-6	ESE(T)	Gasified LHe (-423^{o}F)	R = 0.1	Incr. K-grad.
LN_2-ESET-1	ESE(T)	LN_2 (-320^{o}F)	Increasing	K_{max} = 30
RT-ESET-1	ESE(T)	Lab Air (70^{o}F)	Increasing	K_{max} = 30
RT-ESET-2	ESE(T)	Lab Air (70^{o}F)	Increasing	K_{max} = 30
LH_2-MT-1	M(T)	LH_2 (-423^{o}F)	R = 0.8	Const. load
LH_2-MT-2	M(T)	LH_2 (-423^{o}F)	R = 0.8	Const. load
LH_2-MT-3	M(T)	LH_2 (-423^{o}F)	R = 0.8	Const. load
LH_2-MT-4	M(T)	LH_2 (-423^{o}F)	R = 0.8	Const. load
LH_2-MT-5	M(T)	LH_2 (-423^{o}F)	R = 0.8	Const. load
LH_2-MT-6	M(T)	LH_2 (-423^{o}F)	R = 0.2	Const. load
LH_2-ESET-B	ESE(T)	LH_2 (-423^{o}F)	Increasing	K_{max} = 30
LH_2-ESET-C	ESE(T)	LH_2 (-423^{o}F)	Increasing	K_{max} = 30

Preliminary Tests

Prior to performing testing at -423^{o}F in LHe or LH_2, K_{max} tests were run using the ESE(T) sample in air at room temperature and in LN_2. A favorable comparison to the test data generated by Newman [ref. 1], and to available data in NASGRO®, confirmed the basic test techniques to be used for the colder tests. An example of this comparison is shown in Figure 7, where data by Garr [ref. 4] is plotted at three R-ratios against K_{max} data [ref. 1] from the current study. At high R-ratio (0.7 to 0.9), all data sources are in general agreement. The material heat treatment condition for the material [ref. 4] is as follows: solution heat treat at 1,900^{o}F followed by a two-step aging at 1,400^{o}F for 10 hours and 1,200^{o}F for 10 hours. This is a more common heat treat condition for Inconel 718 used at cryogenic temperatures. Inconel 718 is a complicated alloy relying on precipitation during aging for its properties. No effort was made during any of the flow-liner investigations to determine the effect of the non-standard aging practice on the development of the microstructure. Differences between the flow-liner aging and standard aging practice likely reveals itself in the microstructure, but it is not known how this may affect the mechanical behavior of the alloy. The agreement shown in Figure 7 for FCGR in LN_2 is the best available justification for the use of this data in other applications beyond the flow-liner assessment, which have a more traditional heat treatment.

Tests in Gasified LHe

Note in Figure 7 that the approximate high R-ratio threshold for these tests in LN_2 is about 3.5 ksi√in. The motivation for testing in an atmosphere representative of the LH_2 within the hydrogen feedline was to either support the use of the LN_2 data or improve on the data if possible, where improvement is considered a reduction in crack growth rate for a given ΔK. Figure 8 presents the results of five tests in the LHe rig, each using the ESE(T) sample. Three tests were run using the K_{max} methodology with K_{max} = 30 ksi√in for two tests and K_{max} = 50 ksi√in for the third test. Each test was run with a K-gradient of -20 in^{-1}. Two tests were run at constant load ratio, R = 0.1, with an increasing K-gradient. All tests were conducted at 20 Hz. The K_{max} tests are very consistent and are ordered appropriately with their final R-ratio values: at threshold, right to left in Figure 8, the R-ratio values are 0.72, 0.74 and 0.86. This data in LHe supports a considerable improvement in the crack growth rates over the available data in LN_2, particularly as the crack growth rates approach threshold. Steady state, region II, growth rates modestly improve as well.

Tests in LH_2

The confirmation tests performed in LH_2 were designed to take a different approach to confirm the results shown in LHe. Taking the extra effort to test directly in LH_2 provides an answer to many questions which naturally arise when representing the flow-liner environment solely by temperature alone in the LHe rig. The LH_2 tests are much closer to the actual use environment and allow any influence of the presence of hydrogen as well as the liquid itself to be included in the test. The only aspect of the flow-liner environment not included is the high frequency (>1000 Hz) of the cyclic loading in the hardware. All tests in LH_2 were conducted at 20 Hz. To provide an additional means of confirmation of the LHe results, the test sample design was changed to the M(T) sample and the loading conditions were set to keep the R-ratio constant with a constant load amplitude throughout the test. Thus, the crack growth alone creates the increasing K-gradient and it is not constant. Besides simplicity, an advantage this test procedure provides is an easy test history to model using crack growth analytical tools such as NASGRO® to verify the material constants derived from the data and used in the analysis. The results of six M(T) tests are shown in Figure 9a. The tests were designed to start at progressively lower initial ΔK values with the intent of eventually having the crack growing just above threshold. Test LH_2-MT-5 came closest, but was not considered a substantial confirmation of the LHe threshold value. The expense of LH_2 testing prevented another attempt at a lower initial ΔK value. Figure 9b shows the same constant-R M(T) data with the addition of the ESE(T) constant-R LHe data at R = 0.1. The data is consistent between the two test methods, noting that the R = 0.2 LH_2 data falls parallel and just above the LHe R = 0.1 data.

To improve the chances of getting data in the LH_2 environment that would confirm LHe threshold values, two tests were run using the same test technique employed in LHe: ESE(T) samples tested with the K_{max} methodology. Figure 10 shows the results of these two tests compared against the LHe K_{max} tests. In both cases, the LH_2 tests continued to shed until the ΔK reached approximately 10-11 ksi√in. At this point, the crack growth rates dropped substantially and did not follow the gentle curve to threshold shown by the LHe tests, which dropped to approximately 7-8 ksi√in. The cause of this change in behavior is not known. The early portions of the LH_2 tests are in good agreement with the LHe data and no test difficulties arose that would invalidate the tests. However, the early drop in crack growth rate compared to the LHe tests can not be construed as a higher threshold value.

Conclusions

Though none of the tests run in LH_2 recorded data within the ASTM-defined threshold regime, the agreement of the results between LHe and LH_2 on all accounts is good. The tests in LH_2 did confirm that no unforeseen effects of the LH_2 environment influenced the results generated in LHe. The primary product of this test series is the change in FCGR threshold for Inconel 718 with decreasing temperature. Figure 11 shows a summary of test results taken from this study and [ref. 1]. Results are grouped by temperature and are shown at 70°F, -320°F and -423°F. The increase in threshold is clearly evident and is supported by all test data. The high R-ratio threshold at -423°F, 7 ksi√in is approximately twice that at -320°F, 3.5 ksi√in. The FCGR values for Inconel 718 in LH_2 used in the flow-liner assessment [ref. 5] are fully supported by tests in LHe and LH_2. For reference only, a revised curve-fit for an average representation of the data in NASGRO® (version 4.x) is provided in Figure 12.

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2. "Nickel Alloy, Corrosion and Heat Resistant, Sheet, Strip, Foil and Plate; 52.5NI-19Cr-3.0Mo-5.1Cb-0.90Ti-0.50Al-18Fe; Consumable Electrode or Vacuum Induction Melted, 1775F (968C) Solution Heat Treated", Society of Automotive Engineers Aerospace Material Specification, SAE AMS 5596, SAE International, 400 Commonwealth Drive, Warrendale, PA 15096-0001.

3. "Standard Test Method for Measurement of Fatigue Crack Growth Rates", *Annual Book of ASTM Standards*, Vol. 3.01, E 647, American Society for Testing and Materials, West Conshohocken, PA, 2001.

4. NASGRO® Fracture Mechanics and Fatigue Crack Growth Rate Software. Developed and distributed under the terms of a Space Act Agreement between NASA Johnson Space Center and Southwest Research Institute (www.nasgro.swri.org). Material data referenced under code Q3LC10LA4: Garr, K. R., Fatigue Crack Growth Rate and J-Integral Fracture Toughness of Inconel 718", Rockwell International – Rocketdyne Division. Data received from Ken Garr on June 24, 1988.

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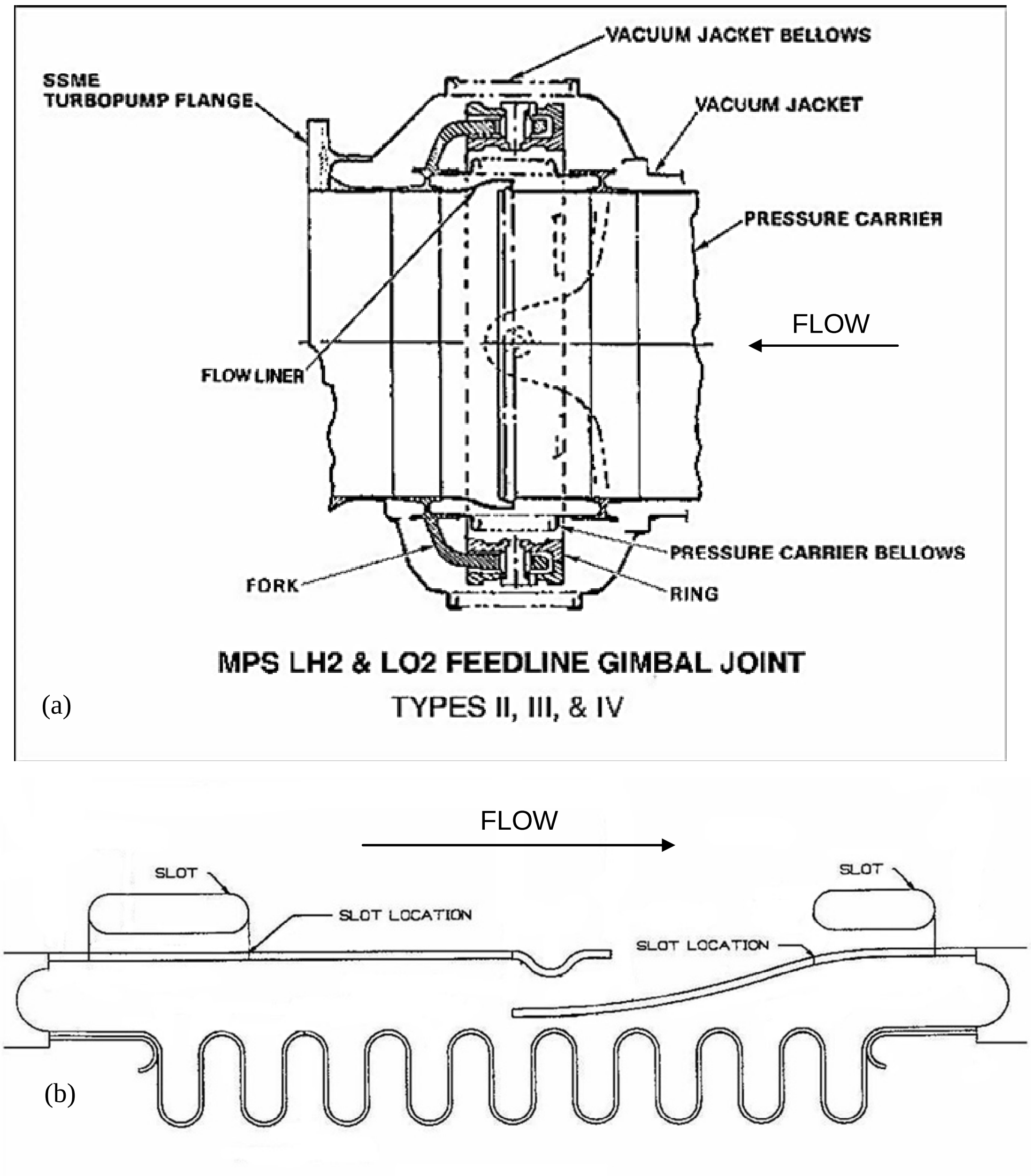

Figure 1a, b. Typical configuration of flow-liner components. Pressure Carrier Bellows provides containment and flexibility in the feed-line while flow-liner hides the bellows from the flow field.

Figure 2. Inconel 718 flow-liners shown during inspection. Cracks in the flow-liners in the liquid hydrogen supply lines were only found at the gimbal joint location directly adjacent to the Main Engine Low Pressure Fuel Pump Flange, shown.

Figure 3. An example of a crack identified in the flow-liner. In this case, a transverse crack likely influenced by the proximity of a repair weld.

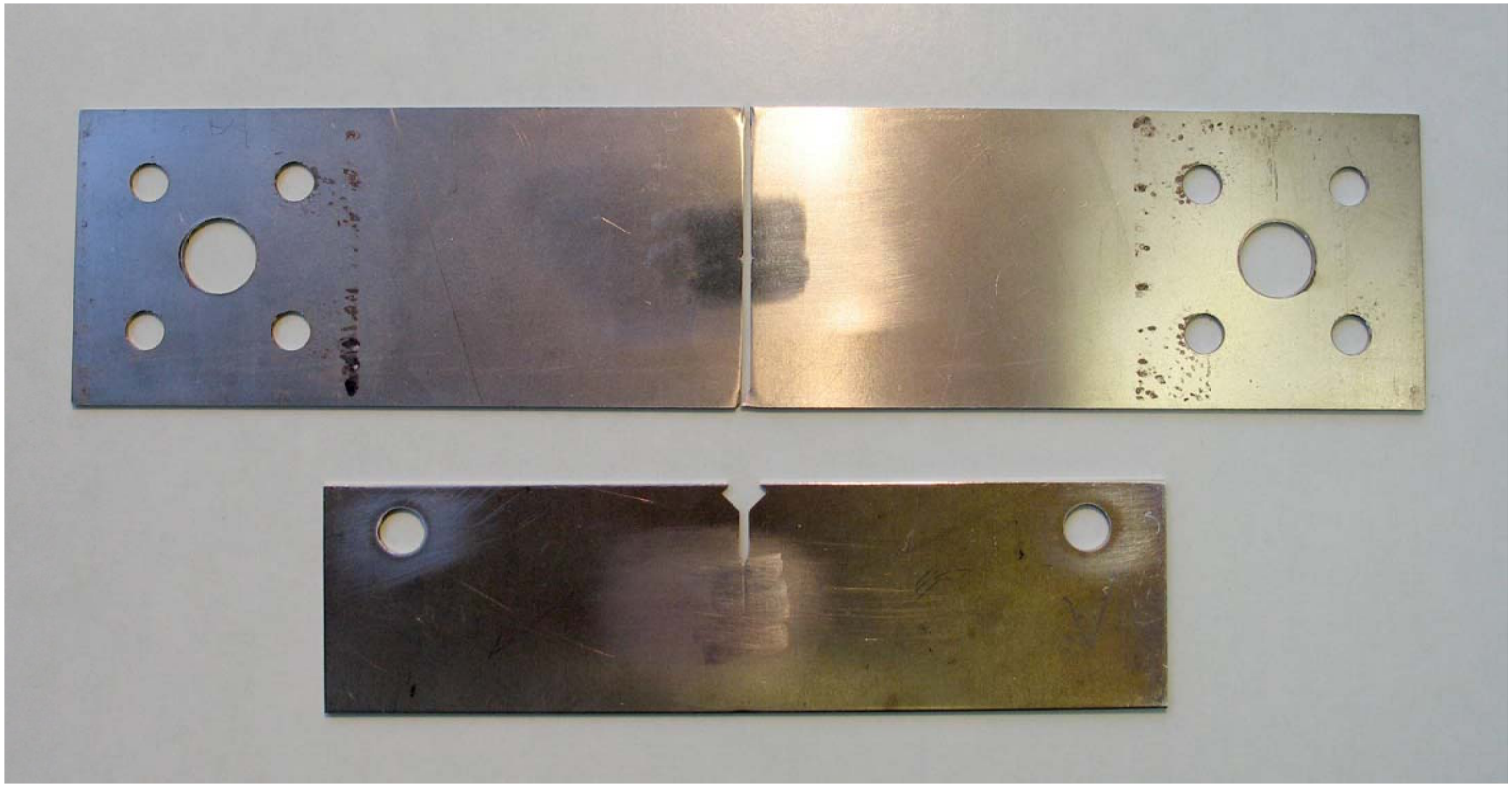

Figure 4. Test samples in use in the current study. Middle Crack Tension, M(T) (top) and the Eccentrically Loaded Single-Edge Crack Tension, ESE(T).

Figure 5. Temporary cryostat fabricated to perform gasified liquid helium tests. Note the interlaced copper spray-bar arrangement which provided even cooling of the chamber and a more gentle introduction of the cold helium gas. Liquid helium is pumped into the box, but it gasifies before exiting the spray-bar system.

Figure 6a,b. Liquid hydrogen test rig shown in open (a) and closed (b) configurations. The servo-hydraulic machine has its actuator at the top cross-member. The load reaction structure is attached to the top cross-member as well. The cryostat is brought up from below to submerge the sample and load reaction in LH_2 throughout the test.

(a)

(b)

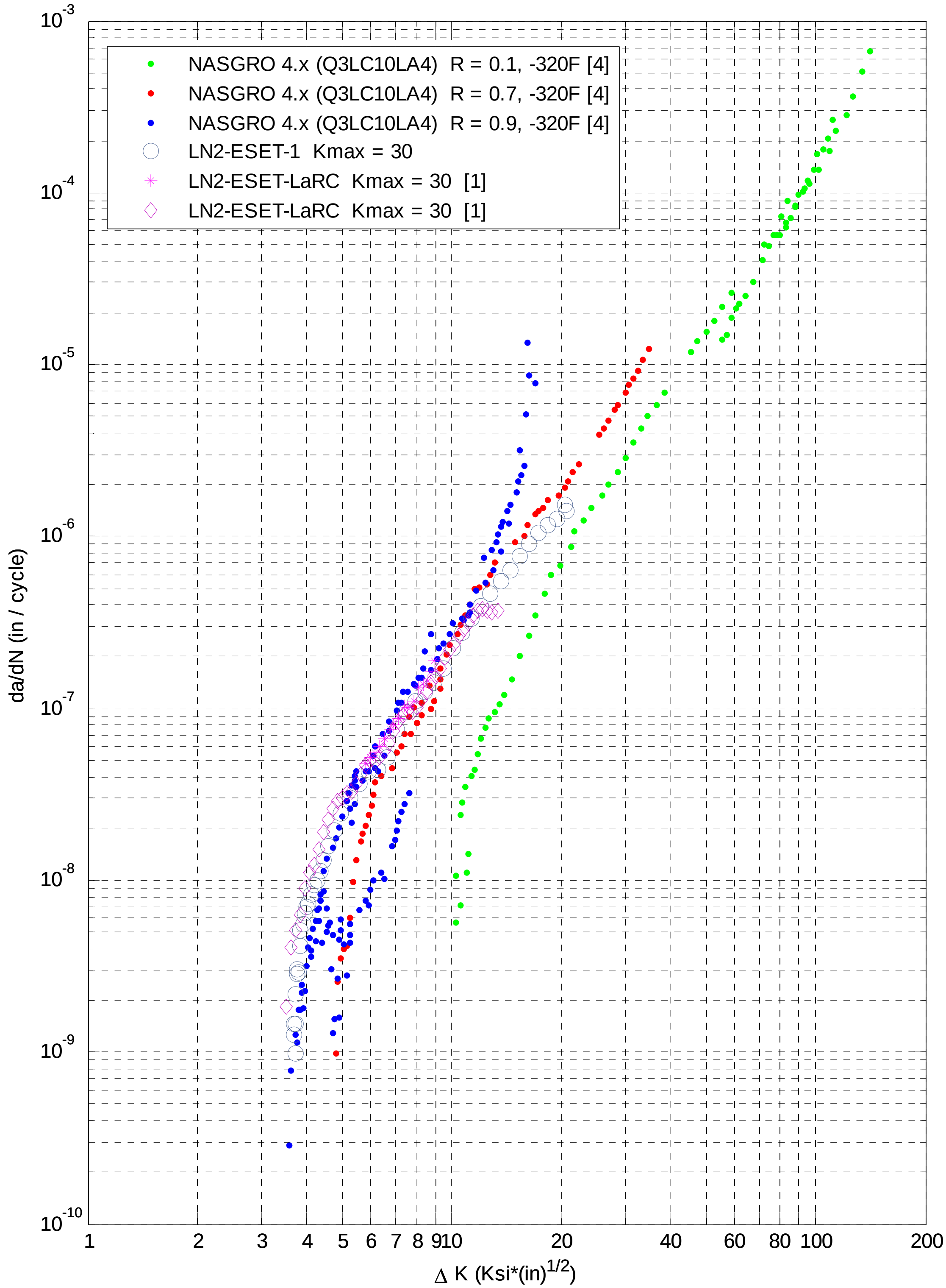

Figure 7. Comparison of liquid nitrogen (-320F) test results for Inconel 718 from the NASGRO database and the present study

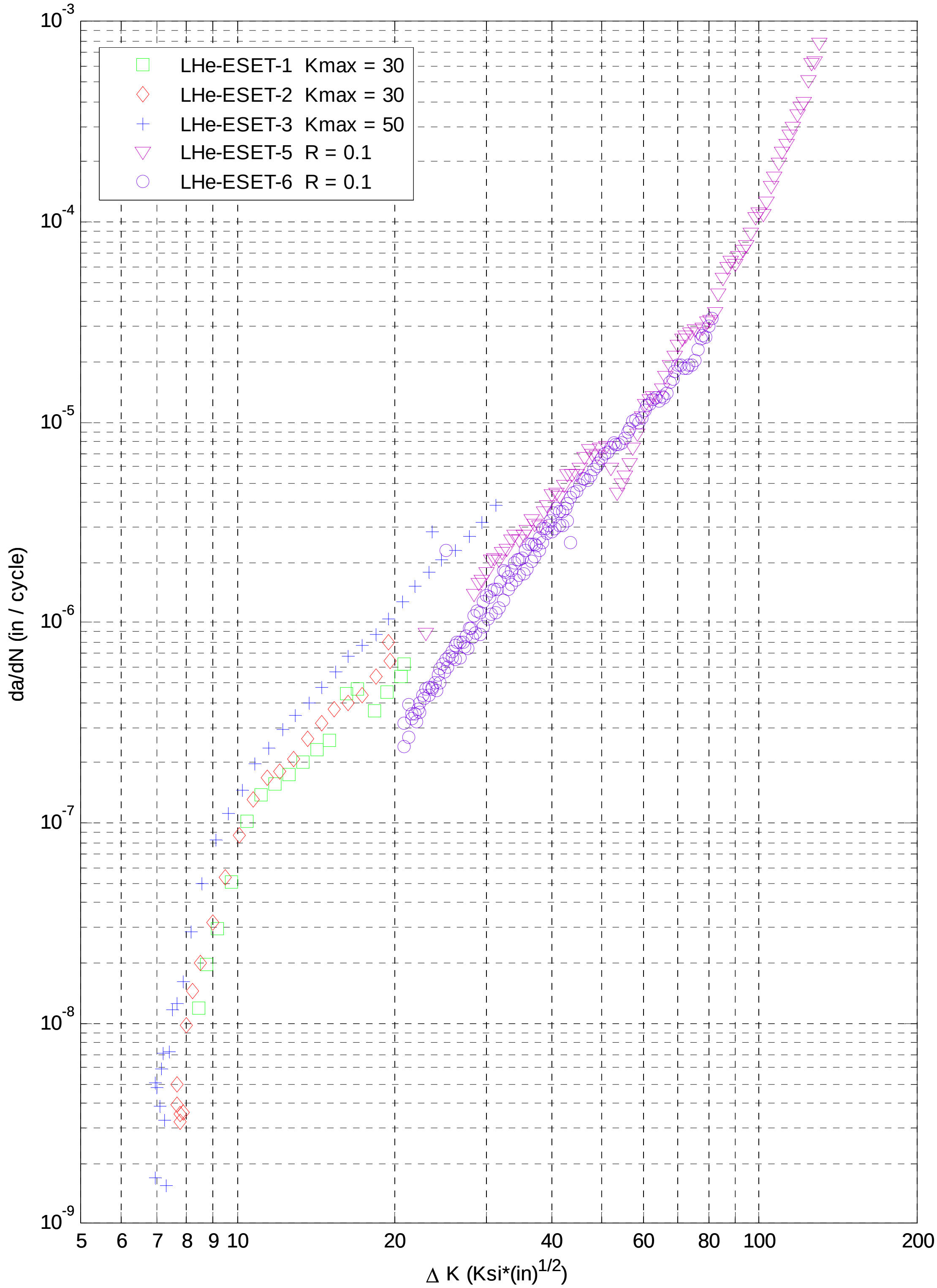

Figure 8. Test results for Inconel 718 in gasified liquid helium at -423F.

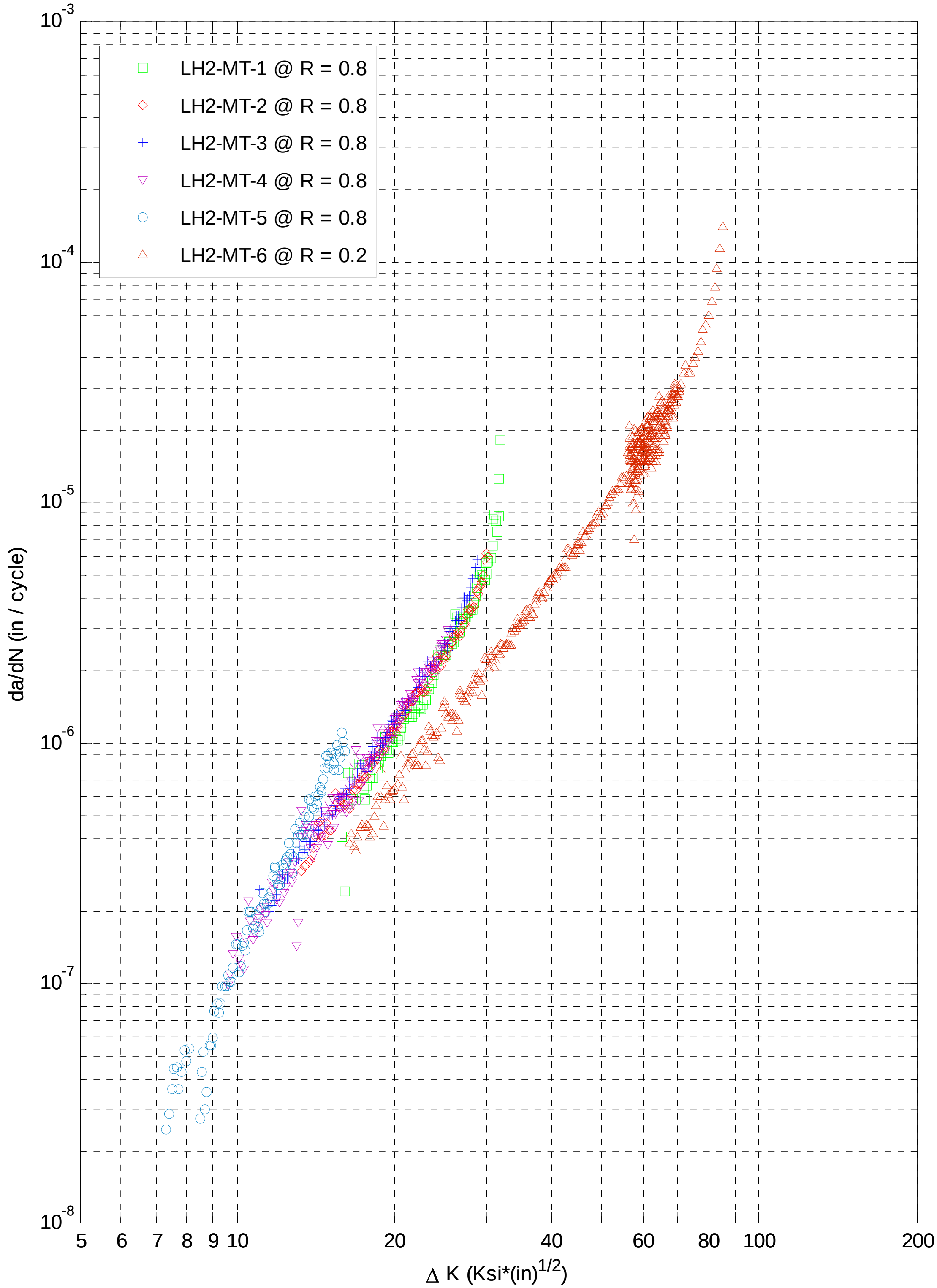

Figure 9a. Test results for Inconel 718 in liquid hydrogen (-423F) using M(T) samples and a constant load ratio and amplitude.

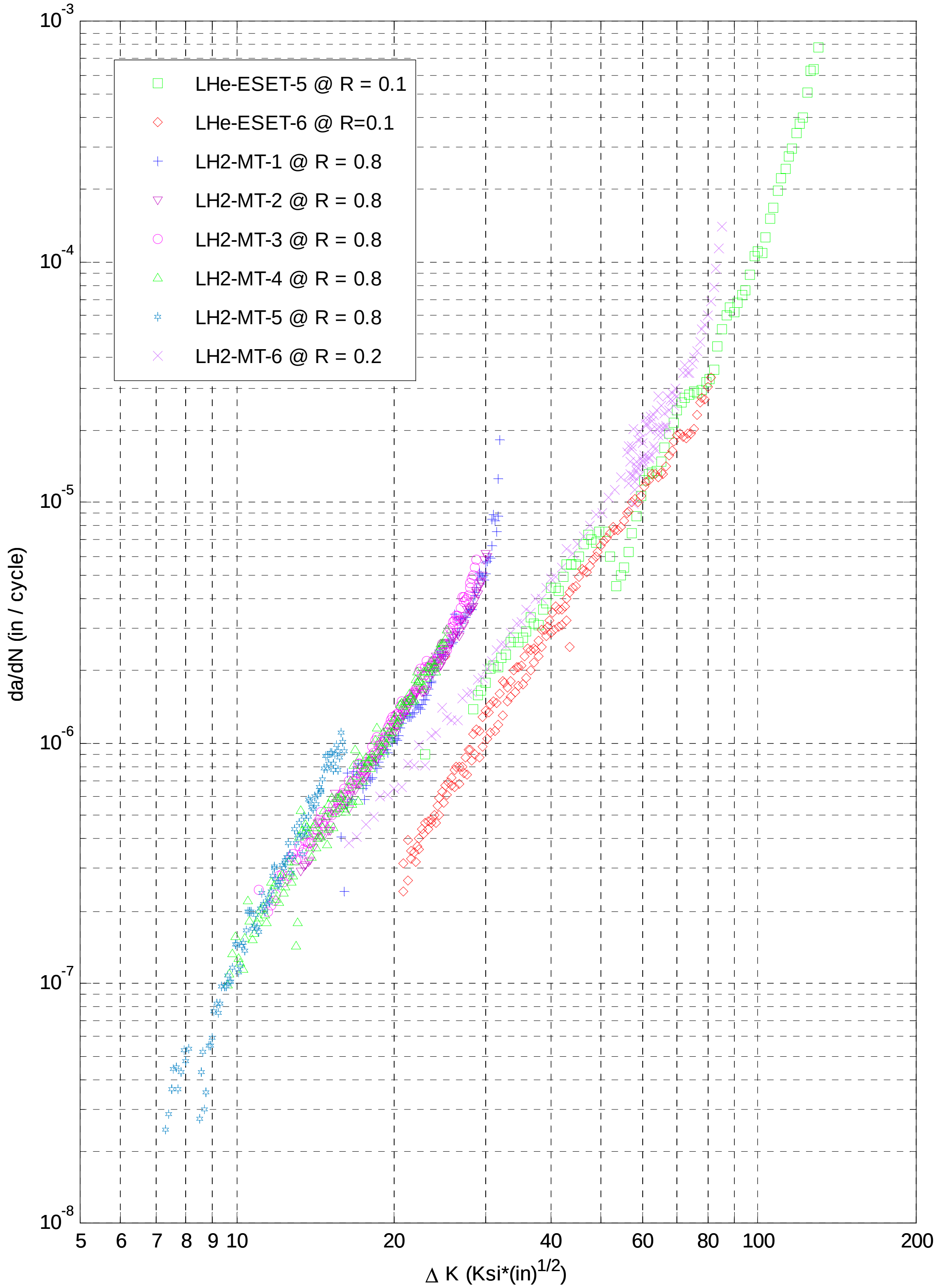

Figure 9b. Constant load ratio tests in LHe (-423F) for Inconel 718 show consistency with results in LH_2

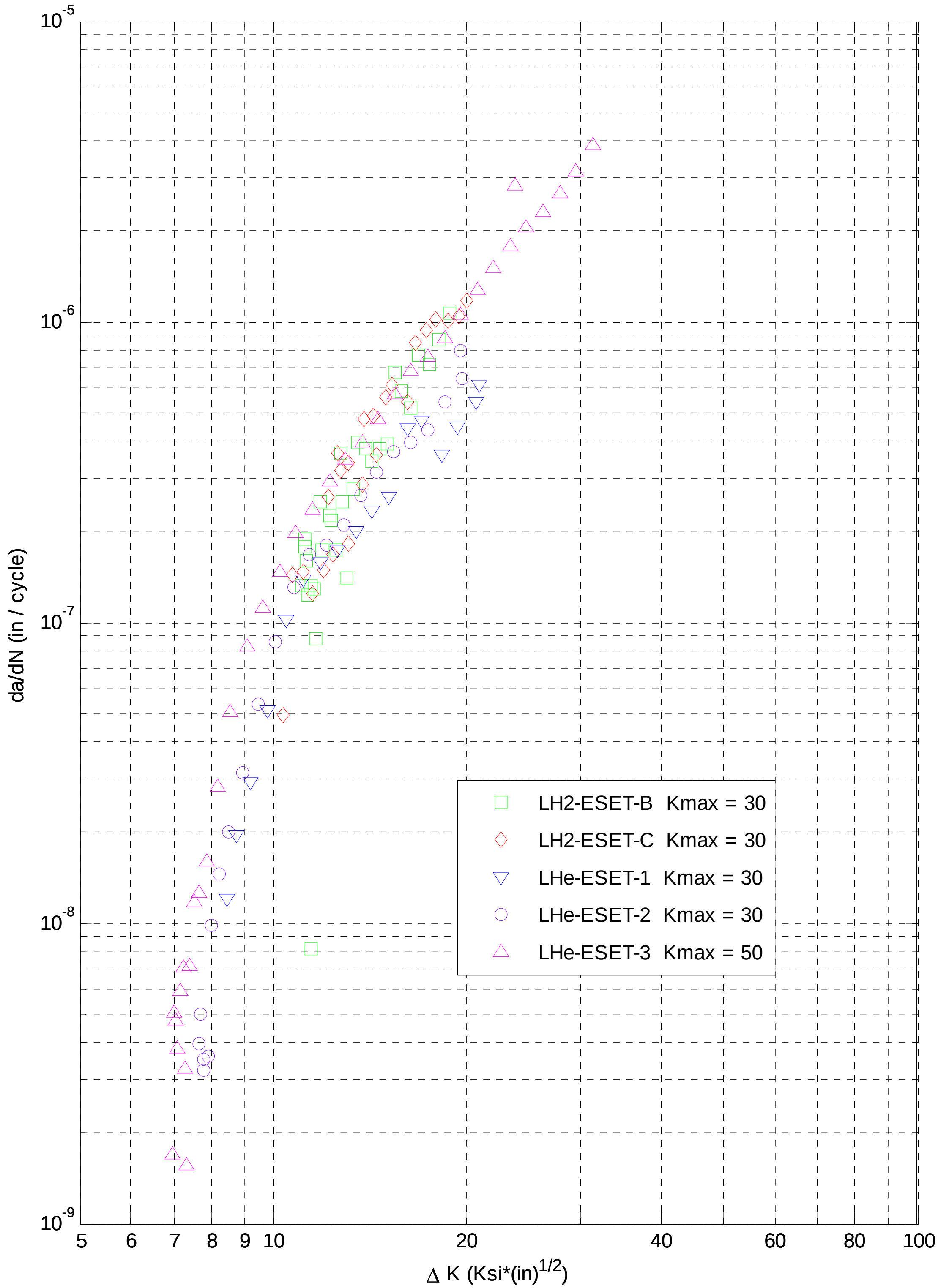

Figure 10. Comparison of ESE(T) Kmax tests for Inconel 718 at -423F in LHe and LH_2

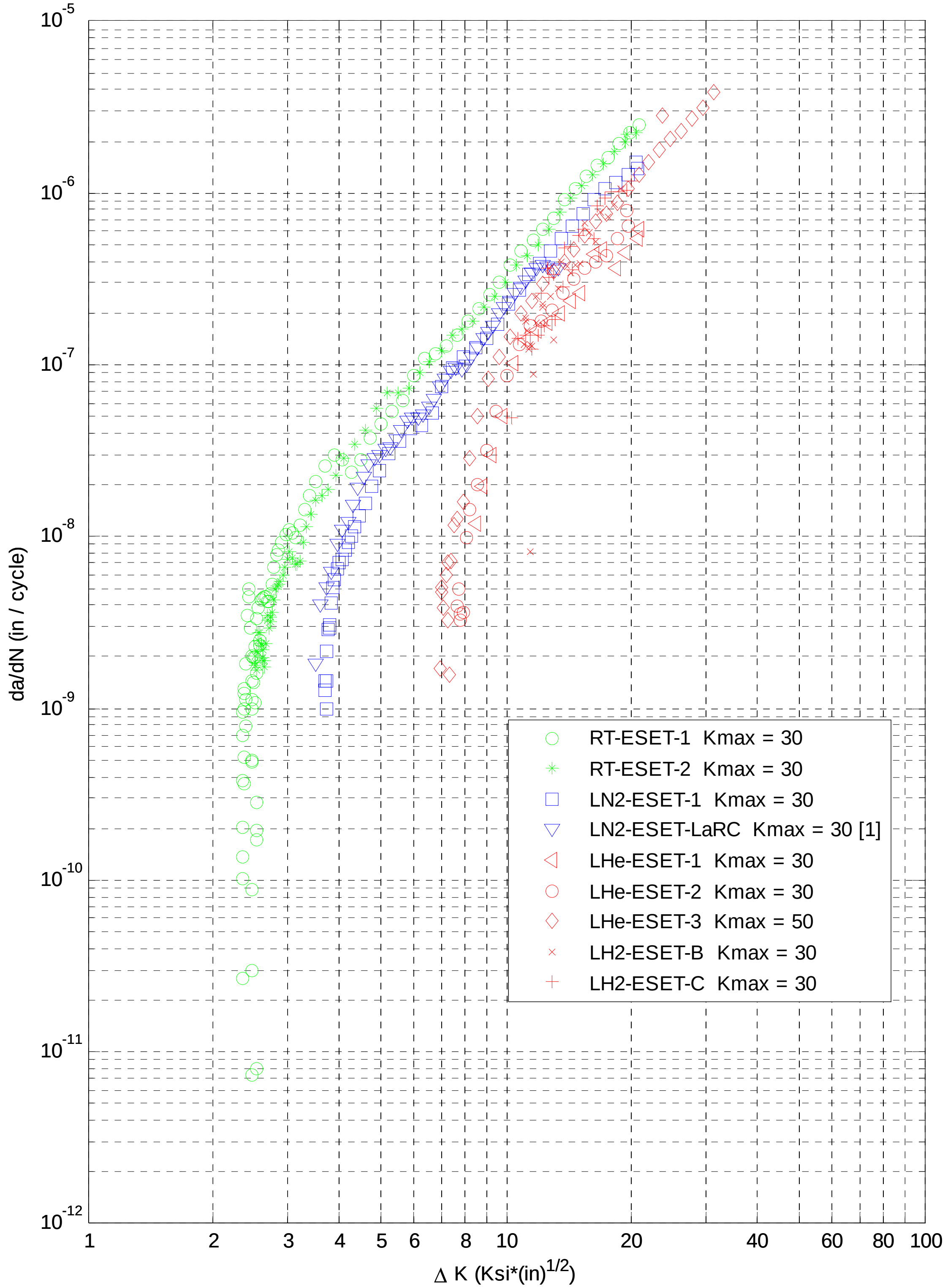

Figure 11. Test data supporting increasing high R-ratio threshold with decreasing temperature for Inconel 718 at 70F, -320F and -423F.

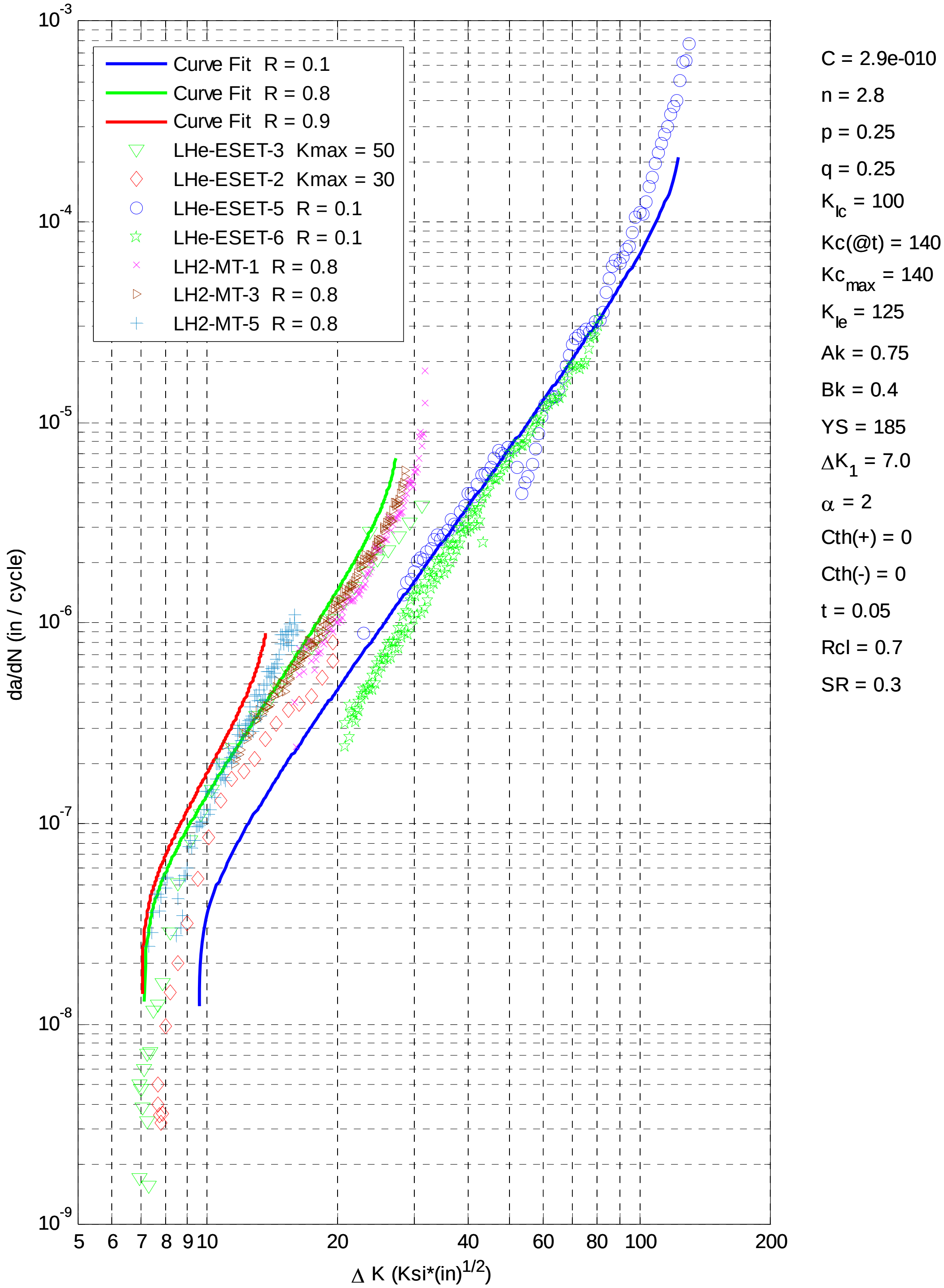

Figure 12. Potential NASGRO 4.x curve fit parameters shown for an average fit to Inconel 718 at -423F.

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14. ABSTRACT
Inconel 718 sheet material was tested to determine fatigue crack growth rate (FCGR) at cryogenic conditions representative of a liquid hydrogen (LH2) environment at -423 degree F. Tests utilized M(T) and ESE(T) specimen geometries and environments were either cold gaseous helium or submersion in LH2. The test results support a significant improvement in the fatigue crack growth threshold at -423 degree F compared to -320 degree F or 70 degree F.

15. SUBJECT TERMS
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