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Fatigue Crack Growth Database for Damage Tolerance Analysis

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16. Abstract

The objective of this project was to begin the process of developing a fatigue crack growth database (FCGD) of metallic materials for use in damage tolerance analysis of aircraft structure. For this initial effort, crack growth rate data in the NASGRO® database, the United States Air Force Damage Tolerant Design Handbook, and other publicly available sources were examined and used to develop a database that characterizes crack growth behavior for specific applications (materials). The focus of this effort was on materials for general commercial aircraft applications, including large transport airplanes, small transport commuter airplanes, general aviation airplanes, and rotorcraft. The end products of this project are the FCGD software and this report. The specific goal of this effort was to present fatigue crack growth data in three usable formats: (1) NASGRO equation parameters, (2) Walker equation parameters, and (3) tabular data points. The development of this FCGD will begin the process of developing a consistent set of standard fatigue crack growth material properties. It is envisioned that the end product of the process will be a general repository for credible and well-documented fracture properties that may be used as a default standard in damage tolerance analyses.

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Fatigue, Fracture, Crack growth rate, Damage tolerance, Curve fits, Database

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LIST OF ACRONYMS

ACO	Aircraft Certification Offices
DER	Designated engineering representatives
DTA	Damage tolerance analysis
FAA	Federal Aviation Administration
FCGD	Fatigue crack growth database
GUI	Graphic User Interface
SwRI	Southwest Research Institute
USAF	United States Air Force

EXECUTIVE SUMMARY

The objective of this project was to begin the process of developing a fatigue crack growth database (FCGD) of metallic materials for use in damage tolerance analysis (DTA) of aircraft structure. For this initial effort, crack growth rate data in the NASGRO® database, the United States Air Force Damage Tolerant Design Handbook, and other publicly available sources were examined and used to develop a database that characterizes crack growth behavior for specific applications (materials). The focus of this effort was on materials for general commercial aircraft applications, including large transport airplanes, small transport commuter airplanes, general aviation airplanes, and rotorcraft. The end products of this project are the FCGD software and this report. The specific goal of this effort was to present fatigue crack growth data in three usable formats: (1) NASGRO Equation parameters, (2) Walker Equation parameters, and (3) tabular data points. The development of this fatigue crack growth database will begin the process of developing a consistent set of standard fatigue crack growth material properties. It is envisioned that the final end product will be a general repository for credible and well-documented fracture properties that may be used as a default standard in damage tolerance analyses.

This report and software were developed under funding provided by the Airworthiness Assurance Branch of the Federal Aviation Administration William J. Hughes Technical Center. The NASA Johnson Space Center was the prime contractor and Lockheed Martin Space Operations and Southwest Research Institute were subcontractors.

1. INTRODUCTION.

1.1 OBJECTIVES.

The objective of this project was to begin the process of developing a Fatigue Crack Growth Database (FCGD) of metallic materials used in damage tolerance analysis (DTA) of aircraft structure. For this initial effort, crack growth rate data in the NASGRO® database [1], the United States Air Force (USAF) Damage Tolerant Design Handbook [2], and other publicly available sources were examined and used to develop the database that characterizes crack growth behavior for specific applications (materials). The focus of this effort was on materials for general commercial aircraft applications, including large transport airplanes, small transport commuter airplanes, general aviation airplanes, and rotorcraft. As such, an early objective of the project was to determine from the end users a prioritized list of materials for inclusion into the database. In addition, any voids or deficiencies in existing data were to be identified that would preclude characterization for any of the applications. In addition to this report, the end product of this project is the FCGD software. The specific goal of the effort was to present fatigue crack growth data in three usable formats: (1) NASGRO equation parameters, (2) Walker equation parameters, and (3) tabular data points.

1.2 BACKGROUND.

Fracture mechanics properties are required to perform damage tolerance evaluations of primary aircraft structure. These fracture mechanics properties principally include fatigue crack growth data and fracture toughness. More basic material properties such as yield strength, Poisson's ratio, and elastic modulus are also used in DTA but are not considered fracture mechanics properties.

Damage tolerance analyses are required to support the establishment of in-service inspection programs per Title 14 Code of Federal Regulations 25.571 and 23.573 and Advisory Circular 91-56. Currently, data used to perform damage tolerance analyses can vary significantly from applicant to applicant. Large original equipment manufacturers typically employ their own proprietary data developed from a significant amount of coupon testing. On the other hand, data used by consulting engineering firms, small manufacturers, supplemental type certificate holders, etc., may be of unknown or questionable origin. This can create a significant problem for the Federal Aviation Administration (FAA) Aircraft Certification Offices (ACO), Aviation Safety Engineers, and FAA designated engineering representatives (DER) with respect to evaluating the adequacy of applicant's demonstrations of compliance to FAA regulatory certification requirements.

There has been a vast amount of fracture mechanics data generated and collected over the past 30 years. The problem facing structural engineers is selecting the appropriate properties from the vast database. Uncertainties and inconsistencies in DTA input data create a problem for the FAA ACO engineers and FAA DERs when evaluating DTAs for compliance with the regulations. This FCGD task will initialize the process of developing a consistent set of standard fracture mechanics properties. It is envisioned that the end product will be a general repository for credible and well-documented fracture properties that may be used as a default standard in damage tolerance analyses. The intended end users of the FCGD are the applicants and their engineering staffs. The beneficiaries are the FAA DERs and FAA ACO engineers whose task is simplified by having available a credible material data set that can be used and referenced with confidence in performing, reviewing, and approving DTA. The use of this data set relieves the certification engineers of the task of having to validate the basic material data for compliance with the regulations. The initial phase of the FCGD development was focused on the characterization of fatigue crack growth rate behavior for specific applications as identified by the end users. Fracture toughness material properties are not addressed in the current effort.

2. DATA SOURCES.

2.1 INDUSTRY SURVEYS.

To identify and prioritize the material applications to be included in the FCGD, the FAA and Southwest Research Institute (SwRI) each developed a crack growth rate data questionnaire. The FAA questionnaire was distributed to approximately 150 FAA damage tolerance DERs (including candidates and applicants), while the SwRI questionnaire was distributed to the 14 members of the NASGRO Industry Consortium. Respondents were asked to supply a list of the most common materials that they work with by providing the alloy, temper, form, orientation, environment, and thickness of each application. These responses were used to assist in prioritizing and selecting data for inclusion in the database. Appendix A provides a compilation of the industry surveys and the resulting priority lists along with copies of the questionnaires. Thirteen and six responses were received from the FAA and SwRI questionnaires respectively.

2.2 EXISTING DATA.

The principal source for fatigue crack growth data examined for inclusion in the FCGD was the NASGRO material database [1]. The NASGRO database has been continuously improved over the years, and the NASGRO 4.0 database now contains material properties for fatigue crack growth and fracture for 476 different metallic materials, including 3000 sets of fatigue crack growth data, 6000 fracture toughness data points, and statistically derived crack growth equations for all 476 materials. These data were obtained over the years from a variety of sources in the literature and in-house, and other data collected by NASA Johnson Space Center, including Hudson's Compendiums [3 and 4], the USAF Damage Tolerant Design Handbook [2], and a University of Dayton Research Institute survey report [5]. In addition to the NASGRO database, data from FAA-funded projects were also considered [6-8].

3. CRITERIA FOR INCLUSION IN DATABASE.

To include data in the FCGD for use in developing curve fits for the crack growth models, a set of characterization criteria were developed. These criteria evolved during the course of the project as a result of discussions between the FAA project technical monitor and NASA, Lockheed Martin Space Operations, and SwRI project team. They were developed to ensure that the data chosen, sufficiently described a wide range of the parameters needed to perform the requisite curve fits. The criteria for including data in the database are as follows:

- Minimum of three positive, wide-ranging load ratios (e.g., $R = 0.1$, 0.4, and 0.7).

- Sufficient data covering a minimum of two log cycles on the crack growth rate (*da/dN*) scale.

- Data consistency (matching) requirements:

  - Three consistent sets (i.e., from three or more different sources) when other available data sets are not consistent

  - Two consistent data sets if there are no other conflicting data sets

- Laboratory air or high-humidity test environments

It was recognized that identifying and assessing the suitability of a given set of data for inclusion in the database necessitated considerable engineering judgment and experience, and a subjective evaluation was sometimes required.

4. CURVE FITTING METHODOLOGY.

In the fitting process, crack growth data are fitted with each of the following three equations: NASGRO, Walker, and cubic spline. The algorithms use least-squares minimization of error in the log-log domain to determine the constants for each fitting method. Figure 1 provides a schematic of a fatigue crack growth curve illustrating the three regions of behavior that are referenced by the different methods.

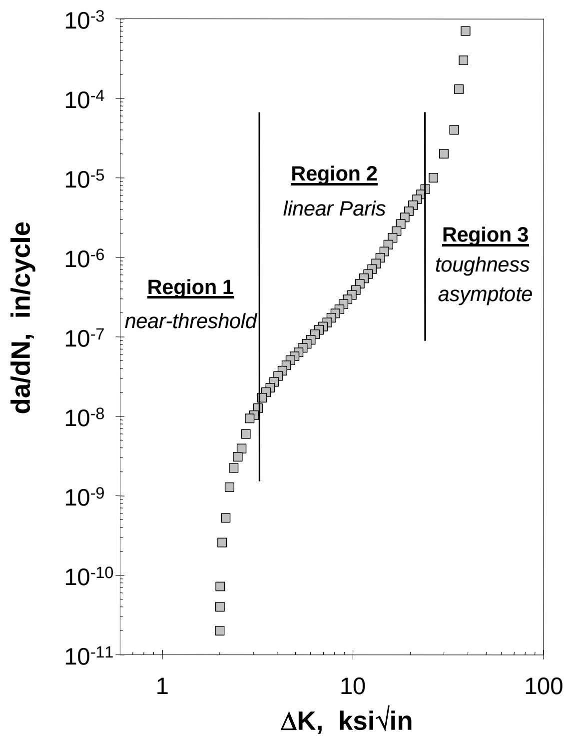


FIGURE 1. FATIGUE CRACK GROWTH RATE DATA ILLUSTRATING THE THREE REGIONS OF CRACK GROWTH BEHAVIOR

4.1 NASGRO EQUATION.

The NASGRO crack growth equation, described in detail in the NASGRO manual [1], is expressed as

$$\frac{da}{dN} = C\left(\frac{(1-f)}{(1-R)}\Delta K\right)^n \frac{\left(1-\frac{\Delta K_{th}}{\Delta K}\right)^p}{\left(1-\frac{K_{\max}}{K_c}\right)^q} \tag{1}$$

where *da/dN* is the crack growth rate, ΔK is the applied stress-intensity factor range, and *R* is the stress ratio; ΔK_{th} is the fatigue threshold, $K_{\max}$ is the stress-intensity factor corresponding to peak applied load, and K_c is the critical stress intensity; *p* and *q* control the shape of the asymptotes in the threshold and critical crack growth regions, respectively; *f* is Newman's crack opening function [9].

The constants *C* and *n*, the main fit parameters, are determined through minimization of the sum of square of the errors, where the error term corresponding to the *i*th data pair, $(\Delta K, da/dN)_i$, is

$$e_i = Log\left(\frac{da}{dN}\right)_i - Log(C) - n\,Log\left(\frac{(1-f)}{(1-R)}\Delta K\right)_i - Log\left(\frac{\left(1-\frac{\Delta K_{th}}{\Delta K}\right)^p}{\left(1-\frac{K_{\max}}{K_c}\right)^q}\right)_i \tag{2}$$

Curve fitting crack growth data is an iterative process, which consists of using established values of the various constants (other than *C* and *n*), specifying the data sets that typify the material, applying the least-squares algorithm to compute *C* and *n,* and plotting the data at various *R* values with the curve fit of each stress ratio. The process was continued by making slight modifications, if warranted, to the entered values until the best fit to the experimental data was obtained.

4.2 WALKER EQUATION.

The Walker crack growth equation [10] used a single linear segment to fit the data. The equation is given by

$$\frac{da}{dN} = C\left(\frac{\Delta K}{(1-R)^{1-m}}\right)^n \tag{3}$$

where the three constants, *C, n,* and *m* define the fit. The *i*th error term is given by

$$e_i = Log\left(\frac{da}{dN}\right)_i - Log(C) - n\,Log(\Delta K)_i + n(1-m)Log(1-R)_i \tag{4}$$

Application of the least-squares method [11] yields a nonlinear set of algebraic equations, which is solved using a three-stage numerical procedure. In the first stage, the Paris constants for the multiple-*R* data were obtained, ignoring the dependence on *R*. The second stage used a coarse trial-and-error process along trial intervals centered around the initially obtained values to obtain improved values of *C* and *n,* and a first estimate of *m.* In the third stage, the Newton-Raphson technique was used to solve the nonlinear set of error minimization equations and obtain final, accurate values of *C, n,* and *m.* Using the first two priming stages ensures that the Newton-Raphson technique is robust and converges to the correct results.

The Walker fit algorithms work best for crack growth data drawn from many different values of *R* and will not work at all unless at least two different *R* values are used. Since separate values of the exponent *m:* m^+ and m^- are obtained for positive and negative values of *R*, respectively, it is necessary that crack growth data be available for both positive and negative values of *R.* In the procedure used herein, the constants *C* and *n* (and m^+) are obtained exclusively from positive *R* data, and m^- is obtained from negative *R* data.

Fitting of the Walker equation was confined to the linear part of the data, region 2, as shown in figure 1. The lower and upper bounds for region 2 are set during the fitting process by examining the data for linearity. Eliminating data that depart from linearity (and belong in region 1 near-threshold, or region 3 near-criticality) ensures that the Walker fits are accurate representations of the linear portion of the crack growth. Generally, for any material, the same lower bound is applicable to all the *R* values for which data are available, while at the upper end, variable bounds are used since the point of departure from linearity tends to vary with *R*.

4.3 CUBIC SPLINE.

The cubic spline fit algorithm employed here divides the $Log(\Delta K)$ domain of the crack growth data into a uniformly spaced sequence of intervals and fits piecewise cubic polynomials that minimize the sum of the square of the errors

$$e_i = Log\left(\frac{da}{dN}\right)_i - \sum_{n=0}^{3} A_{I,n}\left(Log(\Delta K)_i\right)^n \tag{5}$$

for all the data. The $A_{I,n}$ in equation 5 are coefficients (to be determined) of the cubic polynomial for the *i*th interval, with the index *i* referring to the *i*th data pair. The piecewise polynomials were constructed according to the rules for splines: function and its first derivative continuities were imposed at the knots between intervals. However, in contrast to standard splines [12], no conditions were imposed on the second derivative, at either the knots or the end points. This hybrid procedure yields a curve that accommodates local movements of the data that can be matched well in their vicinity without extending their effects (as with standard splines) to distant parts of the curve.

Since the procedure achieves acceptably low values of the root mean square error by choice of an adequate number of uniformly spaced knots, any need to develop or use special curve-specific algorithms for knot placement is obviated. In the penultimate step of the procedure used, an over-determined system of equations with more equations than unknowns is obtained. This system is made square in the final step by minimization of the squares of components of the residual vector.

The spline fits use the same lower bounds that were used for the Walker equation fits. However, at the upper end, spline fitting is continued beyond the Walker bounds into the nonlinear region 3, producing a curve that fits the crack growth data near criticality.

5. SUMMARY OF FCGD DATA.

5.1 INCLUDED MATERIALS.

A list of the 13 materials included in this version of the database is given in table 1. The data for these materials met the criteria for inclusion, as discussed in section 3. Table 1 provides the name of the materials, conditions, and the orientations. In all cases, the environment was laboratory air or high-humidity air.

The last column of table 1 contains material identification codes that were chosen to be consistent with the ones used in the NASGRO and NASMAT databases [1]. The first letter of the material ID code identifies the material category or group (M = aluminum) and the second character (numeral) identifies the alloy group (2 = 2000 series, 7 = 7000 series, etc.). Subsequent letters and numbers identify the heat treatment, product form, crack orientation, environment, and temperature. A complete description of this nomenclature can be found in the NASGRO documentation [1].

TABLE 1. LIST OF MATERIALS IN THE DATABASE

Material	Condition	Orientation	Material ID Code
2014-T6	Sheet	T-L	M2AD12AB1
2024-T3	Clad and Bare Sheet	L-T	M2EA11AB1
2024-T3	Clad and Bare Sheet	T-L	M2EA02AB1
2024-T351	Plate	L-T	M2EB11AB1
2024-T3511	Extrusion	L-T	M2EC31AB1
2024-T62	Sheet and Plate	L-T	M2EG11AB1
2024-T81	Sheet	L-T	M2EI11AB01
7050-T7451	Plate	L-T	M7GJ11AB1
7075-T651	Plate	L-T	M7HB11AB1
7075-T7351	Plate	L-T	M7HH11AB1
7475-T7351	Plate	L-T	M7TF11AB1
7475-T761	Clad Sheet	L-T	M7TI01AB1
7475-T7651	Sheet and Plate	L-T	M7TJ11AB1

5.2 PRESENTATION.

For each material included in the database, appendix B provides material data summary tables and plots of each of the fitted crack growth equations (NASGRO, Walker, and cubic spline). The NASGRO and the Walker equation parameters are listed on their respective plots. The data for the spline curve fits are listed by stress ratio in separate tables for each material. Note that not every material included in the database contains curve fits for negative *R* value because the data either did not exist or were not sufficient to provide a reasonable fit.

Figures 2, 3, and 4 provide an illustration of the fits to 2000-series aluminum data for each of the three equations and positive *R* values. In each case, the plots show only the data points that were used to generate the curve fits. Figure 2 shows a plot of the full range of crack growth data since the NASGRO equation can accommodate all three regions: near-threshold (region 1), the linear or Paris regime (region 2), and the near-critical asymptotic behavior at higher ΔK (region 3). In comparison, since the fitting of the Walker equation was intended to span only the central linear region of the data, regions 1 and 3 data are excluded from the Walker plots, as shown in figure 3. Similarly, since the cubic spline fits did not consider the near-threshold region 1 data, figure 4 displays the spline fits for regions 2 and 3 data only. Table 2 lists the spline fit data points for three positive *R* values. Figures 2 through 4 and table 2 provide an illustration of the type of information for each material contained in appendix B. All the plots and tables provided in appendix B are accessible directly from the FCGD software.

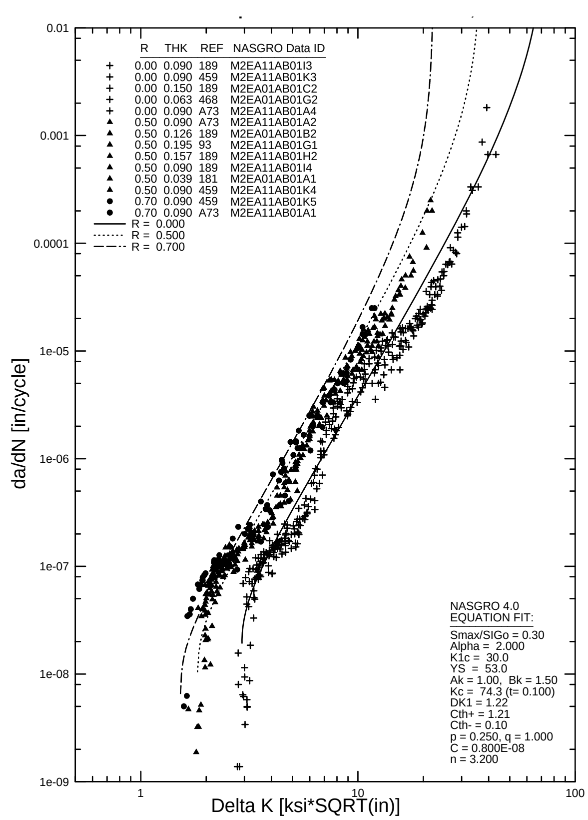


FIGURE 2. NASGRO EQUATION FIT FOR 2024-T3 CLAD AND BARE SHEET, L-T (M2EA11AB1)

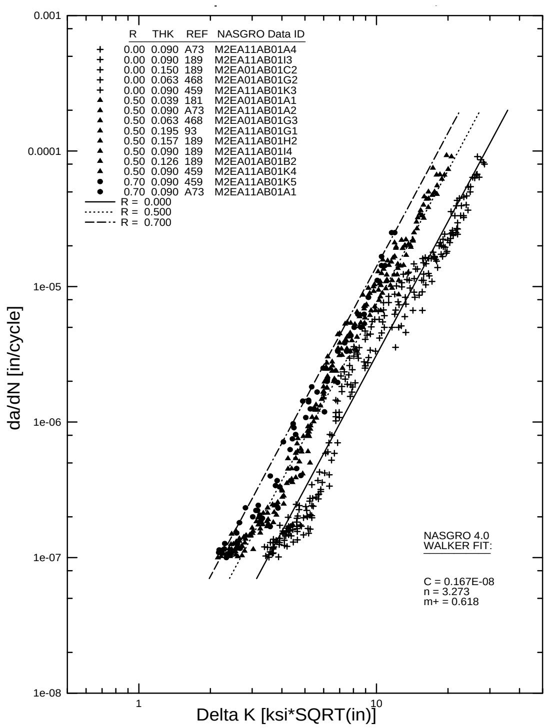


FIGURE 3. WALKER EQUATION FIT FOR 2024-T3 CLAD AND BARE SHEET, L-T (M2EA11AB1)

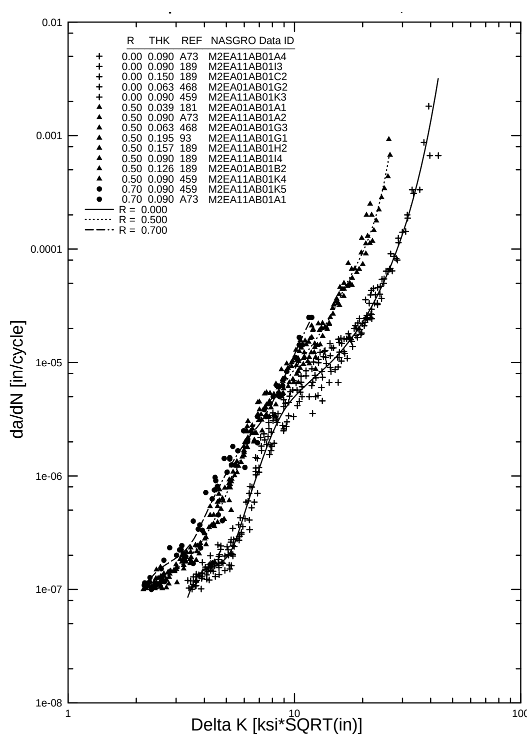


FIGURE 4. SPLINE CURVE FITS FOR 2024-T3 CLAD AND BARE SHEET, L-T (M2EA11AB1)

TABLE 2. SPLINE FIT DATA POINTS FOR 2024-T3 CLAD AND BARE SHEET, L-T (M2EA11AB1)

ID Code = M2EA11AB1 R = 0.0000	
da/dN	Δ*K*
8.5277e-08	3.3806
1.0000e-07	3.4799
1.8000e-07	4.8636
3.2000e-07	5.6622
6.0000e-07	6.2613
1.0000e-06	6.8082
1.8000e-06	7.5591
3.2000e-06	8.5678
6.0000e-06	10.9383
1.0000e-05	14.4607
1.8000e-05	18.4912
3.2000e-05	22.1001
6.0000e-05	25.6959
1.0000e-04	28.4466
1.8000e-04	31.4230
3.2000e-04	34.1080
6.0000e-04	36.8131
1.0000e-03	38.8665
1.8000e-03	41.0983
3.1829e-03	43.1519

(a)

ID Code = M2EA11AB1 R = 0.5000	
da/dN	Δ*K*
1.0285e-07	2.2182
1.8000e-07	3.3220
3.2000e-07	4.1352
6.0000e-07	4.8493
1.0000e-06	5.4034
1.8000e-06	6.0484
3.2000e-06	6.9138
6.0000e-06	8.6642
1.0000e-05	10.5084
1.8000e-05	12.9641
3.2000e-05	15.3066
6.0000e-05	17.8753
1.0000e-04	20.3083
1.8000e-04	22.6137
3.2000e-04	24.3847
6.0000e-04	25.9843
7.2687e-04	26.4241

(b)

ID Code = M2EA11AB1 R = 0.7000	
da/dN	Δ*K*
1.0217e-07	2.1677
1.8000e-07	2.8901
3.2000e-07	3.7327
6.0000e-07	4.3227
1.0000e-06	4.9276
1.8000e-06	5.8777
3.2000e-06	7.2772
6.0000e-06	8.5971
1.0000e-05	9.6496
1.8000e-05	11.0169
2.4964e-05	11.9399

(c)

6. FATIGUE CRACK GROWTH DATA SOFTWARE OPTIONS.

Figure 5 shows the opening window, of the FCGD software. This window provides either an access to the database of materials and the corresponding curve fits or the option to enter a set of data to compare with that in the FCGD. In addition, from this opening window, as well as any of the other windows, detailed source information regarding the materials contained in the database can be obtained by clicking on References in the menu bar. Specific details of the primary FCGD options are discussed in the sections that follow.

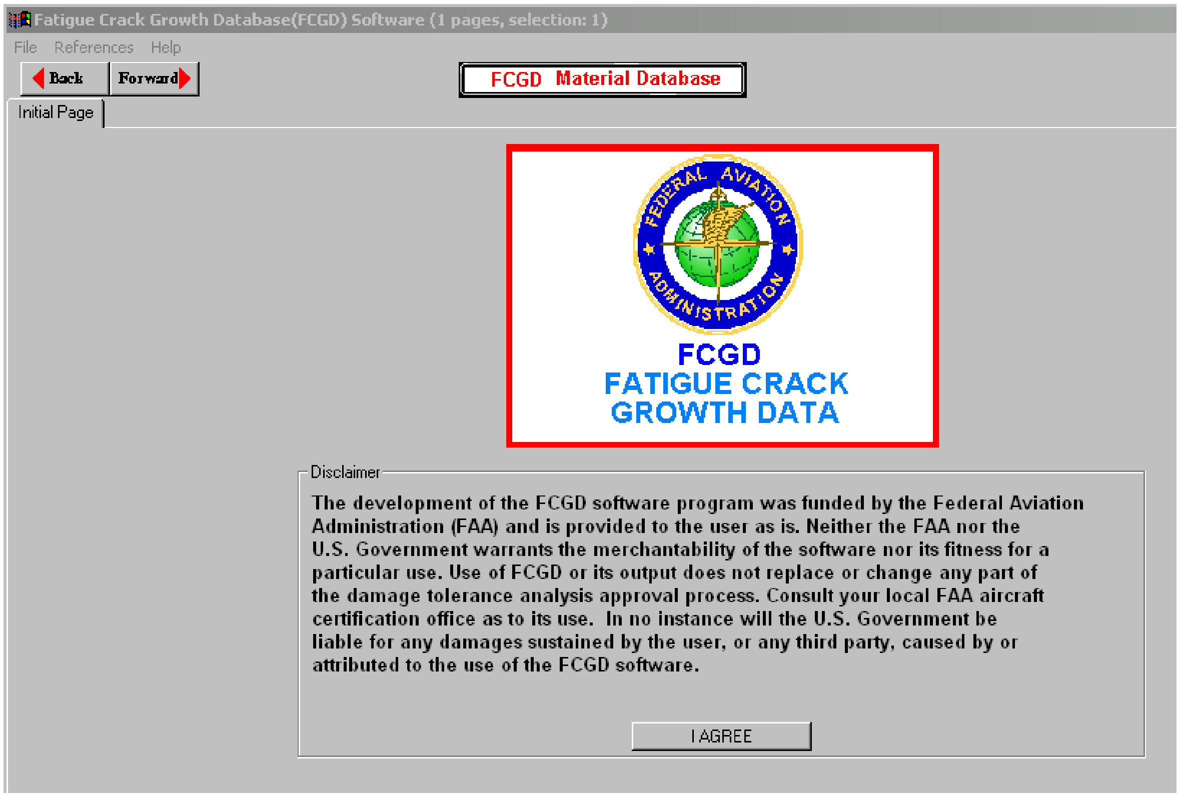


FIGURE 5. OPENING WINDOW OF THE FCGD SOFTWARE

6.1 VIEWING OF THE FCGD CURVE FITS.

To view the curve fits for a specific material in the material database, the user can select the Choose Material menu tab to display the window shown in figure 6. In figure 6, the 2024-T3 Clad and Bare Sheet (L-T) material has been selected, and note that the ID code for the material is automatically displayed in the material identification box for reference. Clicking on any of the buttons labeled NASGRO Equation, Walker Equation, or Spline displays each curve fit respectively. These curve fits are shown in appendix B for all the materials in the database. The data points of the spline fit can be saved to a text file by clicking on the Save Spline Tables button.

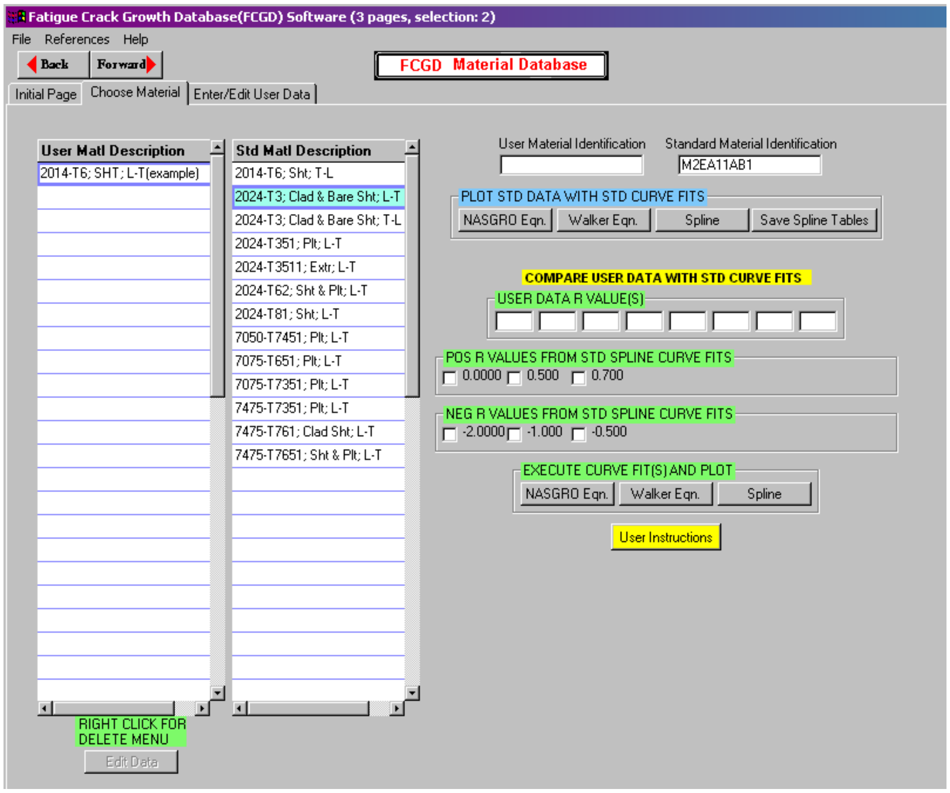


FIGURE 6. MATERIAL SELECTION WINDOW FOR PLOTTING STANDARD DATA AND CURVE FITS

6.2 COMPARE FCGD CURVES WITH USER DATA.

A key feature of the FCGD software is that user-entered fatigue crack growth data can be compared to data in the material database. The FCGD window shown in figure 7 facilitates this task and is selected by choosing the Enter/Edit User Data menu tab. This window allows the user to specify the characteristics of their material, create a material ID code for that data, and save it to a file. Data source types that can be accommodated include direct keyboard input and a text file. The capability to directly digitize fatigue crack growth (plots/curves) is also provided.

Data that has been entered into the user-defined database can be compared to the curve fits in the database by returning to the material selection window (figure 6) and selecting the standard crack growth equation against which to compare the data.

In both this report and the FCGD software, all data are displayed using U.S. customary units (ksi√in and in/cycle). Note, however, that the window of figure 7 shows options to select different systems of units via the choose units pull-down menu to input data in SI units (MPa√m and m/cycle) as well as a number of other nonstandard unit combinations that are sometimes employed. These units of the data are then converted by the software to U.S. customary units for comparison with the FCGD standard curves.

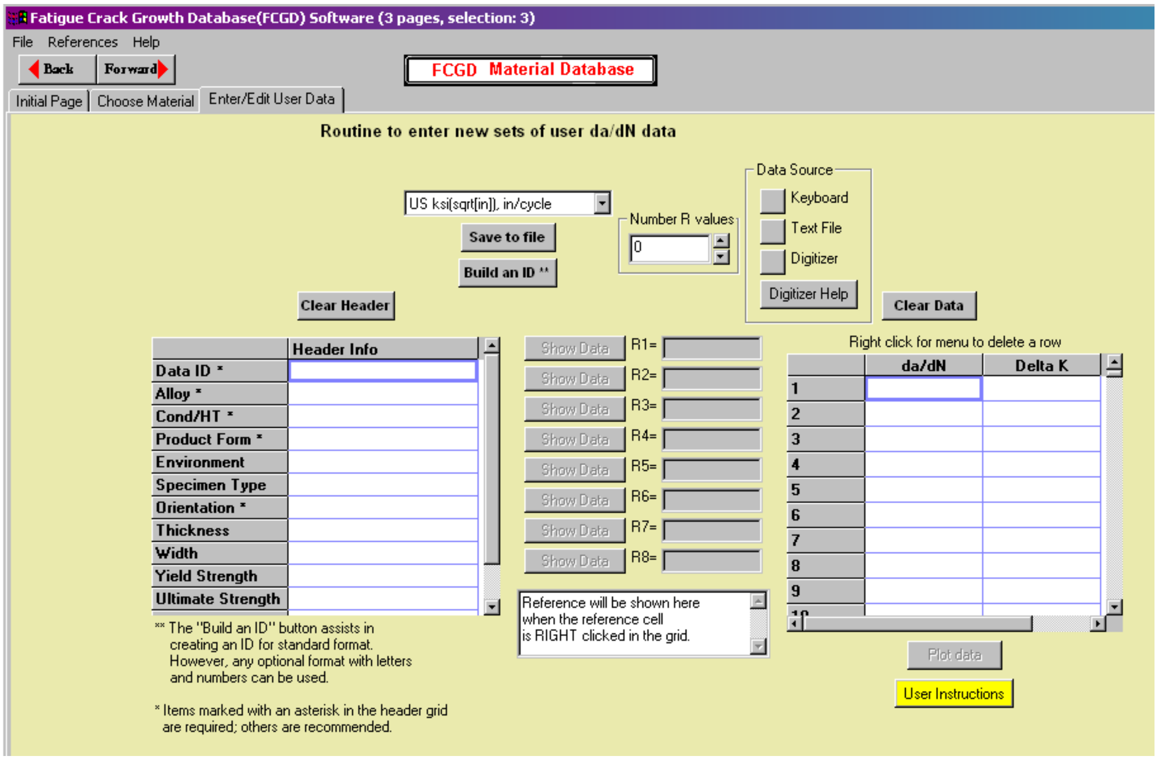


FIGURE 7. INPUT WINDOW FOR USER-DEFINED
FATIGUE CRACK GROWTH DATA

6.3 TUTORIAL.

The yellow User Instructions button displayed in figure 7 provides guidance to the user for input and plotting of data. Specific details of the operation of the FCGD software are described in appendix C, and a number of illustrative examples are provided in appendix D. Appendix C also summarizes system requirements for installation and operation of the software on a personal computer.

7. THE USE OF FCGD IN DTA.

The objective of this project was to develop a database of fatigue crack growth rate data of metallic materials used in DTAs of aircraft structure. The focus of this effort was on materials for general commercial aircraft applications, including large transport airplanes, small transport commuter airplanes, general aviation airplanes, and rotorcraft. Fatigue crack growth rate data (or model) is only one of the many key sets of input data that must be assembled to perform DTA.

The use of FCGD in a DTA will depend on the choice of fatigue crack growth analysis software and the level of expertise/experience of the analyst in performing fracture and fatigue crack growth analyses. In general, most commercially available fatigue crack growth analysis software contains a menu of different models (or laws) to choose from. In addition, most codes also accept as input fatigue crack growth rate data in tabular form (pairs of ΔK and da/dN data, at different stress ratios, R).

The FCGD curve fits to the NASGRO equation are intended for use with the latest version of the NASGRO software [1]. The NASGRO equation is unique among crack growth rate models in that it fits the asymptotes in both the threshold and critical crack growth regions, accounting for the influence of *R* on the fatigue threshold and considering the effects of crack closure. The parameters of the FCGD NASGRO equation fits can be entered into NASGRO via the NASGRO material property window.

The FCGD curve fits to the Walker equation result in the Walker constant values of *C, n,* and *m*; however, the separate values of the exponent *m* (m^+ and m^-) were obtained for positive and negative values, of *R* respectively. Care must be taken to ensure that the crack growth software being used accommodates this specific representation of the Walker model. This is particularly true for the negative *R* portion of the model since there are other Walker-type models that model negative *R* behavior differently, e.g., Walker-Chang.

The FCGD spline curve fits were developed with the intention of providing spline points (pairs of ΔK and *da/dN* data at different stress ratios, *R*) that could be input into crack growth software in tabular form to model crack growth rate data. These data are listed in appendix B, following the spline plots for each material.

As discussed in sections 4.2 and 4.3, neither the Walker nor the spline fits model the near-threshold region of the fatigue crack growth rate data. When using these models in DTA, the analyst must be cognizant of how the crack growth software extrapolates data to the crack growth rates beyond (above or below) the end of the data.

Ultimately, the analyst must make the choice of which fatigue crack growth rate model to use in DTA. In some cases, a given model may more accurately represent the behavior than another; however, it is not possible to state that a single model is always the best to use. Moreover, the analyst may be restricted in choice of models by the features available in the crack growth analysis software.

8. REFERENCES.

1. "NASGRO® Fracture Mechanics and Fatigue Crack Growth Analysis Software," Version 4.02, NASA-JSC and SwRI, September 2002.

2. "Damage Tolerant Design Handbook," WL-TR-94-4054, D.A. Skinn, J.P. Gallagher, A.P. Berens, P.D. Huber and J. Smith, eds., May 1994.

3. Hudson, M.C. and Seward, S.K., "Compendium of Sources of Fracture Toughness and Fatigue Crack Growth Data for Metallic Alloys," *International Journal of Fracture*, Vol. 14, 1978.

4. Hudson, M.C. and Seward, S.K., "Compendium of Sources of Fracture Toughness and Fatigue Crack Growth Data for Metallic Alloys," *International Journal of Fracture*, Vol. 20, 1982.

5. References in “Collection, Processing, and Reporting of Damage Tolerant Design Data for Non-Aerospace Structural Materials,” University of Dayton Research Institute Report UDR-TR-94-88, June 1994 – development performed under NASA JSC grant NAG9-600.

6. Cardinal, J.W., McMaster, F.J., and McKeighan, P.C., “Testing and Analysis for DTA of Fairchild SA226 Main Wing Spar Lower Cap at WS99,” Final Report, SwRI Project No. 06-8520, for Fairchild Aircraft, Inc., San Antonio, TX, January 1999.

7. Dwyer, W., “Development of a Supplemental Inspection Document for the Fairchild SA226 and SA227 Aircraft, Part 2,” Vols. 1 and 2, FAA Report DOT/FAA/AR-99/20, October 1999.

8. McKeighan, P.C., “Fatigue Testing in Support of Learjet Model 60 Service Life Analysis,” Final Report, SwRI Project No. 06-7571, for E-Systems, Inc., Greenville Division, Greenville, TX, April 1996.

9. Newman, Jr., J.C., “A Crack Opening Stress Equation for Fatigue Crack Growth,” *International Journal of Fracture,* Vol. 24, No. 3, March 1984, pp. R131-R135.

10. Walker, K., “The Effect of Stress Ratio During Crack Propagation and Fatigue for 2024-T3 and 7075-T6 Aluminum,” ASTM STP 462, *American Society for Testing and Materials*, 1970.

11. Carnahan, B., Luther, H.A., and Wilkes, J.O., *Applied Numerical Methods,* Wiley, 1969.

12. De Boor, C., *A Practical Guide to Splines,* Springer, 2001.

APPENDIX A—INDUSTRY SURVEY RESULTS AND PRIORITY LIST

TABLE A-1. STATUS OF MATERIALS EVALUATION AND FITTING

Material	Form	Orientation
2014-T6	Sheet and Plate	L-T
2014-T6	Sheet	T-L
2024-T3	Clad Sheet	L-T
2024-T3	Clad and Bare Sheet	T-L
2024-T351	Plate	L-T
2024-T3511	Extrusion	L-T
2024-T62	Sheet and Plate	L-T
2024-T81	Sheet	L-T
7050-T7451	Plate	L-T
7075-T651	Plate	L-T
7075-T7351	Plate	L-T
7475-T7351	Plate	L-T
7475-T761	Clad Sheet	L-T
7475-T7651	Sheet and Plate	L-T

(a) Materials curve fitted that met the criteria

Material	Form	Orientation
2024-T351	Sheet and Plate	T-L
2024-T4 and -T42	Sheet and Plate	
2024-T7351	Extrusion	
7050-T7451	Plate	T-L
7050-T76511	Extrusion	
7075-T6	Plate and Forged	
7075-T73	Plate and Forged	
7075-T76		

(b) Important materials identified (by 3 or more survey sheets) which lack sufficient data to meet criteria or to generally fit

Material
4340 (180-200UTS) steel
15-5Ph (H1025) steel
Ti-6-4 Annealed (?) titanium

(c) Other

Note: All materials listed in survey sheets having NASGRO fits were evaluated for meeting criteria.

TABLE A-2. SURVEY IDENTIFIED MATERIALS HAVING NASGRO 4.0 FITS

Material	Form	Orientation	Environment	Survey Votes
4340; 120-140 UTS	*Plate and Bar*			*1*
4340; 180-200 UTS	*Plate and Forged*		*LA and HHA*	*3*
300M; 270-300 UTS	*Plate and Forged*			*2*
AF1410; 220-240 UTS	*Plate and Forged*		*LA HHA/DW >1 Hz*	*1*
D6AC: 220-240 UTS	*Plate and Forged*		*Nom KIc (70)*	*2*
AISI 301/302	*½ Hard Sheet*			*1*
PH13-8Mo H1000	*Plate Forged Extrusion*			*1*
15-5PH H1025	*Forged*			*1*
17-4PH H1025	*Round Bar*	*C-L*		*2*
2014-T6	**Sheet**	**T-L**	**LA**	**1**
2024-T3	**Clad and Bare Sheet**	**L-T**	**LA**	**12**
2024-T3	**Clad and Bare Sheet**	**T-L**	**LA**	**1**
2024-T351	**Plate**	**L-T**	**LA**	**6**
2024-T351	*Plate and Sheet*	*T-L*	*LA and HHA*	*3*
2024-T3511	**Extrusion**	**L-T**	**LA and HHA**	**4**
2024-T62	**Sheet and Plate**	**L-T**	**LA HHA**	**1**
2024-T81	**Sheet**	**L-T**	**LA**	**1**
2219-T62	*Plate and Sheet*	*T-L*		*1*
6061-T6	*Plate*	*T-L*		*1*
7049-T73	*Forged*	*L-T*	*HHA*	*1*
7050-T73511	*Extrusion*	*L-T*	*DA/LA/HHA*	*2*
7050-T7451	**Plate**	**L-T**	**LA**	**2**
7050-T7451	*Plate and Sheet*	*T-L*	*LA*	*2*
7050-T7452	*Plate*	*L-T and T-L*	*LA*	*2*
7050-T7452	*Forged*	*L-T and T-L*	*LA*	*2*
7050-T76	*Clad Sheet*	*T-L*	*HHA*	*1*
7050-T76	*Sheet*	*T-L*	*HHA*	*1*
7050-T7651	*Plate and Sheet*	*L-T*	*LA*	*1*
7050-T76511	*Extrusion*	*L-T*	*LA*	*3 or 4*
7075-T651	**Plate**	**L-T**	**LA**	**2**

Notes:

1. Bold listed materials meet criteria for FCGD report and software.
2. The italic signifies a material that did not meet criteria for FCGD report and software.

TABLE A-2. SURVEY IDENTIFIED MATERIALS HAVING NASGRO 4.0 FITS (Continued)

Material	Form	Orientation	Environment	Survey Votes
7075-T6511	*Extrusion*	*L-T*	*LA and HHA*	*1*
7075-T73	*Plate and Sheet*	*T-L*	*LA*	*2*
7075-T73	*Forged*	*L-T*	*LA*	*3*
7075-T7351	**Plate**	**L-T**	**LA/HHA**	**2**
7075-T7351	*Plate and Sheet*	*T-L*	*LA*	*2*
7075-T73510	*Extrusion*	*L-T*	*LA*	*1*
7075-T73511	*Extrusion*	*L-T*	*LA/DA*	*2*
7075-T7352	*Plate*	*T-L*	*LA*	*1*
7075-T76	*Sheet*	*T-L*	*HHA*	*1*
7075-T76511	*Extrusion*	*L-T*	*DA*	*1*
7079-T6	*Plate and Forged*	*L-T and T-L*	*LA*	*2*
7150-T651	*Plate*	*L-T*	*LA*	*2*
7175-T74	*Forged*	*L-T and T-L*	*LA*	*1*
7178-T6 and T651	*Plate and Sheet*	*L-T*	*LA/HHA*	*2*
7475-T7351	**Plate**	**L-T**	**LA**	**3**
7475-T7351	*Plate*	*T-L*	*LA/HHA*	*1*
7475-T761	**Clad Sheet**	**L-T**	**LA and HHA**	**1**
7475-T7651	**Plate and Sheet**	**L-T**	**LA**	**1**
A357-T6 Cast Al;	*Cast*		*LA*	*2*
Ti-3Al-2.5V	*CW SR(750F) Extrusion*			*1*
Ti-6Al-4V	*MA(1350F/2h Forged)*			*1*
Ti-6Al-4V	*BA(1900F/.5h+ 1325F/2h) Plate and Sheet*		*LA DA3.5% Nacl*	*1*
Ti-6Al-4V	*RA(1700F/4h) Plate and Sheet*	*L-T and T-L*		*1*
Ti-6Al-4V	*RA (1700F/4h) Forged*			*1*
Ti-6Al-4V	*STA Plate and Sheet*			*1*
Ti-6Al-6V-2Sn	*MA Plate Forged Extrusion*		*LA DA HHA DW*	*1*

Notes:

1. Bold listed materials meet criteria for FCGD report and software.
2. The italic signifies a material that did not meet criteria for FCGD report and software.

TABLE A-3. FAA SURVEY IDENTIFIED MATERIALS NOT HAVING NASGRO 4.0 FITS

Aluminum Alloys	Form	Survey Votes
2010-T6 and T651	*Sheet and Plate*	*2*
2024-T3	*Bare Sheet*	*2*
2024-T3510	*Extrusion*	*2*
2024-T4	*Clad Sheet*	*1*
2024-T4 and T42	*Sheet and Plate*	*6*
2224-T3511	*Extrusion*	*1*
2329-T39	*Plate*	*1*
2525-T3 and T42	*Clad and Bare Sheet*	*1*
6013-T6	*Sheet*	*2*
6061-T3 and T4	*Sheet*	*2*
7010-T6	*Sheet*	*2*
7010-T6511	*Extrusion*	*1*
7050-T6	*Sheet (L-T)*	*2*
7075-T4	*Sheet*	*1*
7075-T6	*Plate (T-L and L-T)*	*7*
7075-T6	*Forged*	*3*
7075-T62	*Clad Sheet*	*1*
7075-T76	*Sheet (T-L)*	*1*
7149-T73	*Plate and Bar (S-T)*	*1*
7150-T7751	*Plate*	*1*
7150-T77511	*Extrusion*	*1*
7175-T74	*Plate*	*1*
7178-T651	*Extrusion*	*1*
AZ91C-T6		*1*
Steel Types		
4130	*Normalized*	*1*
4340 (150 ksi)		*1*
9310 (? HT)	*Bar*	*1*
HY100		*1*
15-5PH (? HT)	*Bar (L-T and T-L)*	*1*
PH13-8 (?HT)	*Bar (L-T and T-L)*	*1*
A301		*1*
301 – ¼	*Hard Sheet*	*1*

Note: Some materials may have data in NASMAT, but not sufficient for fitting.

TABLE A-4. MATERIALS IDENTIFIED IN SURVEY LACKING ADEQUATE DATA FOR INCLUSION IN THE DATABASE

Material
15-5 PH
INCO 718
Ti-6-4
4330V (Mod)
Ti-10V-2Fe-3Al

TABLE A-5. ADDITIONAL MATERIALS FROM RECENT FAA AND SwRI PROJECTS REVIEWED FOR INCLUSION IN THE DATABASE

Material	Form	Orientation
2024-T3	Sheet	L-T and T-L *
2014-T6511	Extrusion	L-T
7075-T7351	Plate	L-T
7475-T761	Sheet	L-T

*Used in data fits

Crack Growth Rate Standardization Questionnaire

An effort is being launched to develop a database for crack growth rate data for commonly used aerospace metals. This effort will include a review of all publicly available existing data for a particular application* and development (if certain criteria are met) of a recommended data set in several commonly used formats. Your input is requested to help focus this effort. Please list, in your order of priority, those applications that you recommend be addressed. You may direct any questions regarding this effort to John Bakuckas, FAA William J. Hughes Technical Center, 609-485-4784, john.bakuckas@faa.gov.

* Application = Alloy, Temper, Form, Orientation, Environment, Thickness, (e.g., 2024, T3, Sheet, L-T, Laboratory Air, 0.071 inch)

User Information:

Name:____Date:__________

Company:____

Address:____

Phone:________________FAX:_________________e-mail:_______________________

Priority	Alloy	Temper	Form	Orientation	Environment	Thickness (inch)
e.g.	2024	T3	Sheet	L-T	Laboratory Air	0.071
1.						
2.						
3.						
4.						
5.						
6.						
7.						
8.						
9.						
10.						
11.						
12.						
13.						
14.						
15.						
16.						
17.						
18.						
19.						
20.						

FIGURE A-2. FAA QUESTIONNAIRE

Crack Growth Rate Standardization Questionnaire

An effort is being launched to develop a database for crack growth rate data for commonly used aerospace metals. This effort will review publicly available existing data for a particular application (alloy, temper, form, orientation, environment, and thickness) and development of a recommended data set in several commonly used formats. Your input is requested to help focus this effort. Thanks for taking the time to complete this questionnaire.

User Information:

Name: ______________________ Date: ______________

Company: ______________________

Address: ______________________

Phone: ______________ e-mail: ______________________

---

(1) What type/models of aircraft/rotorcraft does your organization service?

____

____

____

(2) Briefly describe the features/scope of your damage tolerance analyses (DTAs) by checking as many of the boxes below that apply to your activities:

☐ linear elastic (LEFM)	Load Interaction Models:	Crack Growth Models:
☐ elastic plastic (EPFM)	☐ Wheeler	☐ NASGRO
☐ threshold behavior	☐ Willenborg (s)	☐ Walker
☐ residual strength	☐ Constant closure	☐ Forman
☐ coldworked holes	☐ Strip yield	☐ Tabular data
☐ ____________	☐ ____________	☐ ____________

(3) Use the table below to list the most common materials (applications) that you work with. Does your organization have data suitable for the database that is unavailable to others that you would be willing to include in the database? If so, please indicate in the last column of the table.

Priority	**Alloy**	**Temper**	**Form**	**Orien.**	**Environ.**	**Thickness (inch)**	**Data You Can Provide***
e.g.	2024	T3	Sheet	L-T	Laboratory Air	0.071	yes
1.							
2.							
3.							
4.							
5.							

FIGURE A-2. NASGRO INDUSTRY CONSORTIUM QUESTIONNAIRE

(4) What are the sources for the DTA material property data that you have used in the past or are currently using?

____

____

____

(5) For what materials do you ***not*** have adequate fatigue and fracture data available? If this material is listed in (3), simply indicate priority number.

____

____

____

(6) Where have you traditionally found the largest gaps in DTA material property data?

____

____

____

(7) In what instances do you find it necessary to make assumptions and/or use minimum values/curves for either fatigue or fracture properties? How do you establish what these minimums are?

____

____

____

(8) Would your organization like to be a beta test reviewer of the database once it has been developed? YES __________ NO__________

(9) Please provide any additional comments or feedback you feel would assist this effort.

____

____

____

____

____

____

Return questionnaire by e-mail or fax to:

Joseph W. Cardinal
Southwest Research Institute™
P. O. Drawer 28510
San Antonio, Texas 78228-0510
Fax: 210/522-3042
E-mail: jcardinal@swri.org

FIGURE A-2. NASGRO INDUSTRY CONSORTIUM QUESTIONNAIRE (Continued)

APPENDIX B—FATIGUE CRACK GROWTH DATA AND CURVE FITS

Included in the FCGD software menu is a Reference tab that opens up a complete list of references for the different materials selected. The following provides an explanation of the NASMAT Coding System used for Data Source References:

"A" Prefaced References

References in "Compendium of Sources of Fracture Toughness and Fatigue Crack Growth Data for Metallic Alloys", by Hudson, M.C. and Seward, S.K., IJF, Vol. 14, 1978.

"B" Prefaced References

References in "Compendium of Sources of Fracture Toughness and Fatigue Crack Growth Data for Metallic Alloys - Part II" by Hudson, M.C. and Seward, S.K., IJF, Vol. 20, 1982.

"C" Prefaced References

References in "Damage Tolerant Design Handbook", MCIC-HB-01, University of Dayton Research Institute, Prepared for Air Force Wright Aeronautical Laboratories, Dec. 1983.

"D" Prefaced References

References in "Damage Tolerant Design Handbook", WL-TR-94-4052, Materials Directorate, WPAFB, Ohio, May 1994.

"E" Prefaced References

References in FRAMES_2, European Space Agency data base software for metallic materials.

"F" Prefaced References

References in "Collection, Processing, and Reporting of Damage Tolerant Design Data for Non-Aerospace Structural Materials", University of Dayton Research Institute Report UDR-TR-94-88, June 1994 - development performed under NASA JSC Grant NAG 9-600.

Non-Prefaced References

References for other data obtained from NASA JSC in-house testing or from miscellaneous other sources.

TABLE B-1. MATERIAL DESCRIPTION AND SPECIMEN TESTING INFORMATION OF 2024-T6 SHEET, T-L

Material ID Code	M2AD12AB1
Alloy Type	2014 Al
Alloy Condition/HT	T6
Product Form	0.04″-0.063″ Sheet
Test Environments	Laboratory Air
Specimen Types	M(T)
Crack Orientation	T-L
Specimen Thickness (in.)	0.04-0.063
Specimen Width (in.)	6.0-6.3
Yield Strength (ksi)	60-67
Ultimate Strength (ksi)	70-74
Cyclic Frequency, Hz	2-30

Data References for Table B-1.

112 Data of 2014-T6, 7475-T61, 2024-T62, 7475-T761, 2124-T851, 7475-T7351 - Materials received from L. Schwarmann, MBB Transport, Germany.

C83 Smith, S.H., "Fracture Mechanics Application to Materials Evaluation and Selection for Aircraft Structure and Fracture Analysis," Report No. D6-17756, The Boeing Company, Commercial Airplane Division, Renton, Washington, July 19, 1966.

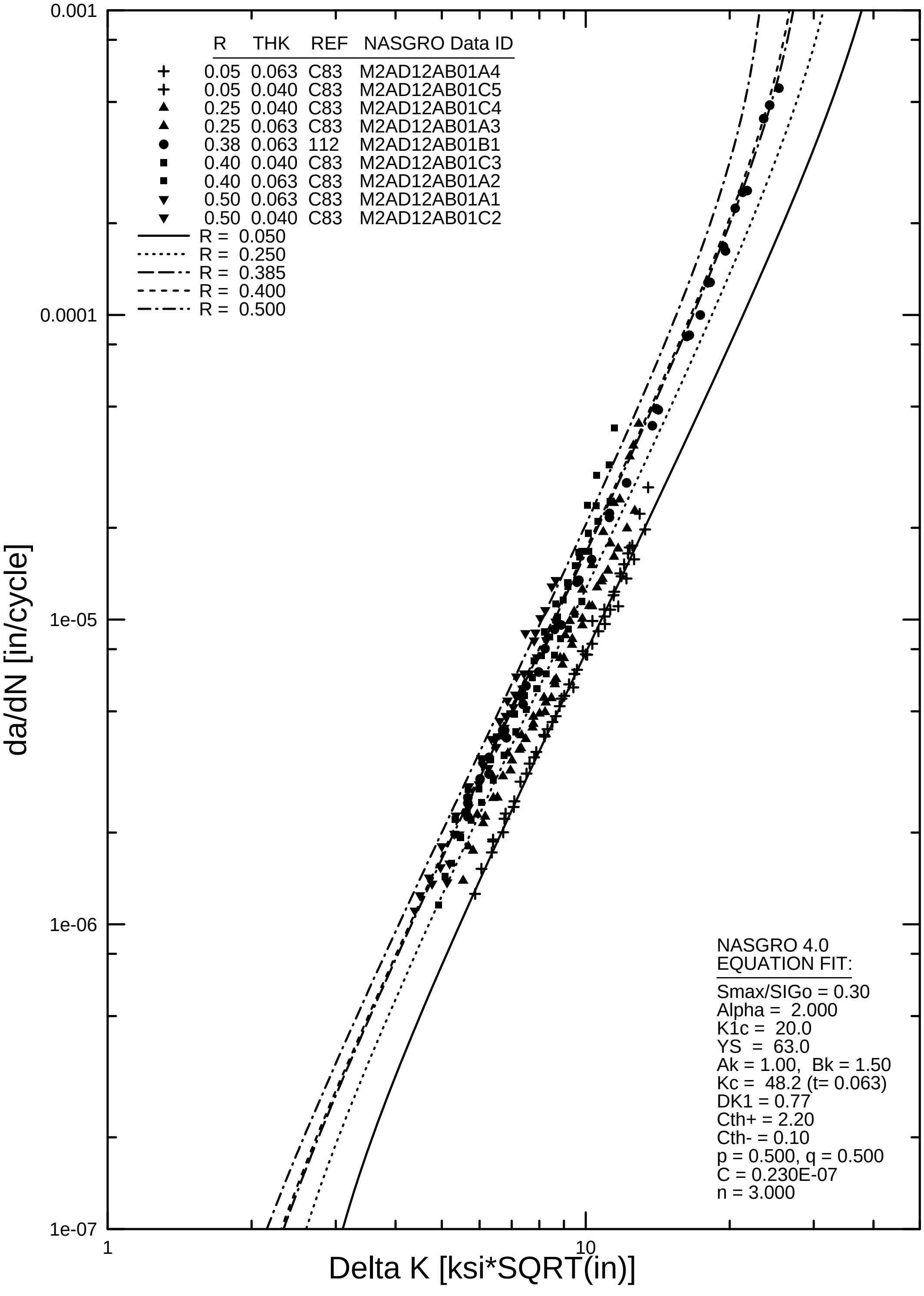


FIGURE B-1. NASGRO EQUATION FOR FIT 2014-T6 SHEET, T-L (M2AD12AB1)

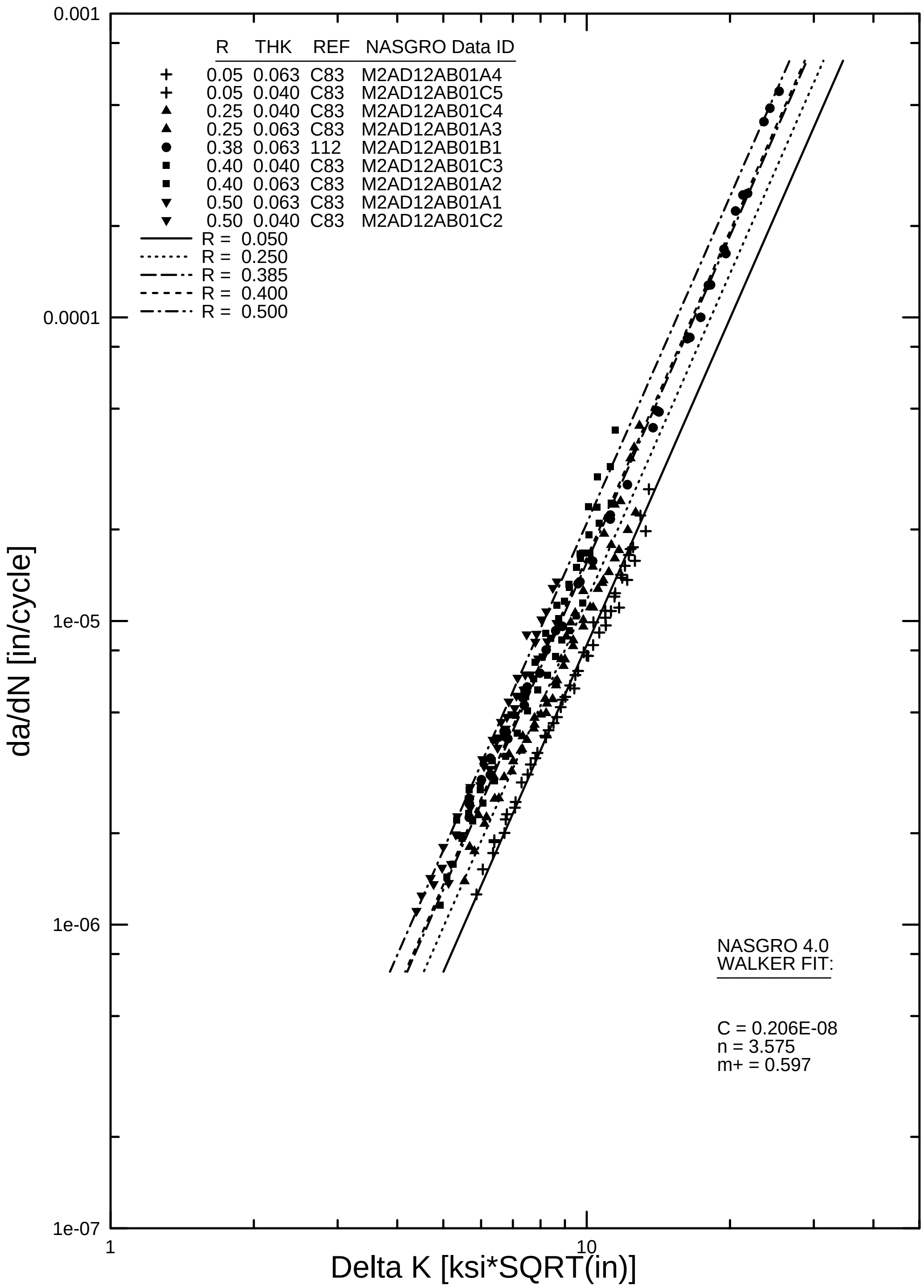


FIGURE B-2. WALKER EQUATION FIT FOR 2014-T6 SHEET, T-L (M2AD12AB1)

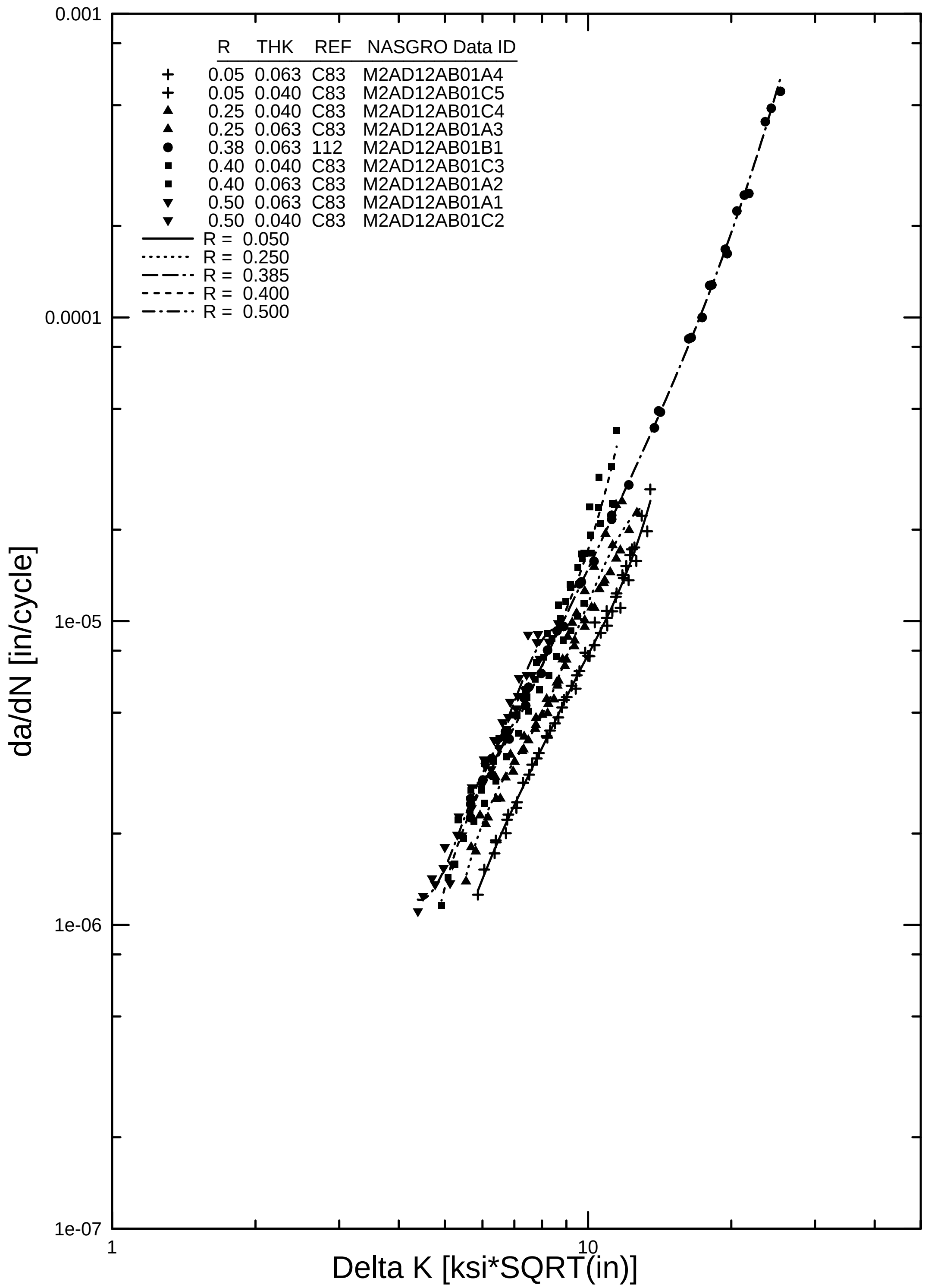


FIGURE B-3. SPLINE FIT FOR 2014-T6 SHEET, T-L (M2AD12AB1)

TABLE B-2. *da/dN*-Δ*K* SPLINE FIT DATA FOR 2014-T6 SHEET T-L (M2AD12AB1)

ID Code = M2AD12AB1 *R* = 0.0500	
da/dN	Δ*K*
1.0909e-06	5.6494
1.8000e-06	6.3876
3.2000e-06	7.5718
6.0000e-06	9.1953
1.0000e-05	10.8559
1.8000e-05	12.6778
2.4745e-05	13.5207

(a)

ID Code = M2AD12AB1 *R* = 0.2500	
da/dN	Δ*K*
1.4164e-06	5.5463
1.8000e-06	5.7737
3.2000e-06	6.7665
6.0000e-06	8.4463
1.0000e-05	9.7512
1.8000e-05	11.6662
2.9142e-05	12.9122

(b)

ID Code = M2AD12AB1 *R* = 0.3850	
da/dN	Δ*K*
2.4613e-06	5.6624
3.2000e-06	6.1848
6.0000e-06	7.5733
1.0000e-05	8.8701
1.8000e-05	10.5918
3.2000e-05	12.5655
6.0000e-05	15.0162
1.0000e-04	17.1638
1.8000e-04	19.7483
3.2000e-04	22.3548
6.0000e-04	25.2594
6.1196e-04	25.3513

(c)

ID Code = M2AD12AB1 *R* = 0.400	
da/dN	Δ*K*
1.2033e-06	4.9204
1.8000e-06	5.3015
3.2000e-06	6.2179
6.0000e-06	7.6336
1.0000e-05	8.7926
1.8000e-05	10.0942
3.2000e-05	11.1996
3.7598e-05	11.4815

(d)

ID Code = M2AD12AB1 *R* = 0.500	
da/dN	Δ*K*
1.1057e-06	4.2658
1.8000e-06	5.2013
3.2000e-06	6.0382
6.0000e-06	7.1813
1.0000e-05	8.2055
1.1770e-05	8.6696

(e)

TABLE B-3. MATERIAL DESCRIPTION AND SPECIMEN TESTING INFORMATION FOR 2024-T3 CLAD SHEET, L-T

Material ID Code	M2EA11AB1
Alloy Type	2024 Al
Alloy Condition/HT	T3
Product Form	0.04″-0.15″ Clad Sheet
Test Environments	Laboratory Air
Specimen Types	M(T)
Crack Orientation	L-T
Specimen Thickness (in.)	0.04-0.15
Specimen Width (in.)	4.0-15.7
Yield Strength (ksi)	41-51
Ultimate Strength (ksi)	62-64
Cyclic Frequency, Hz	5-15

Data References for Table B-3.

181 Frediani, University of PISA experimantal results forwarded to JSC by ESA.

189 Wanhill, R.J.H., "Low Stress Intensity Fatigue Crack Growth in 2024-T3 and T351," *Engineering Fracture Mechanics*, Vol. 30, 1988.

469 McKeighan, P., Data for FAA Project provided to JSC, May 2003.

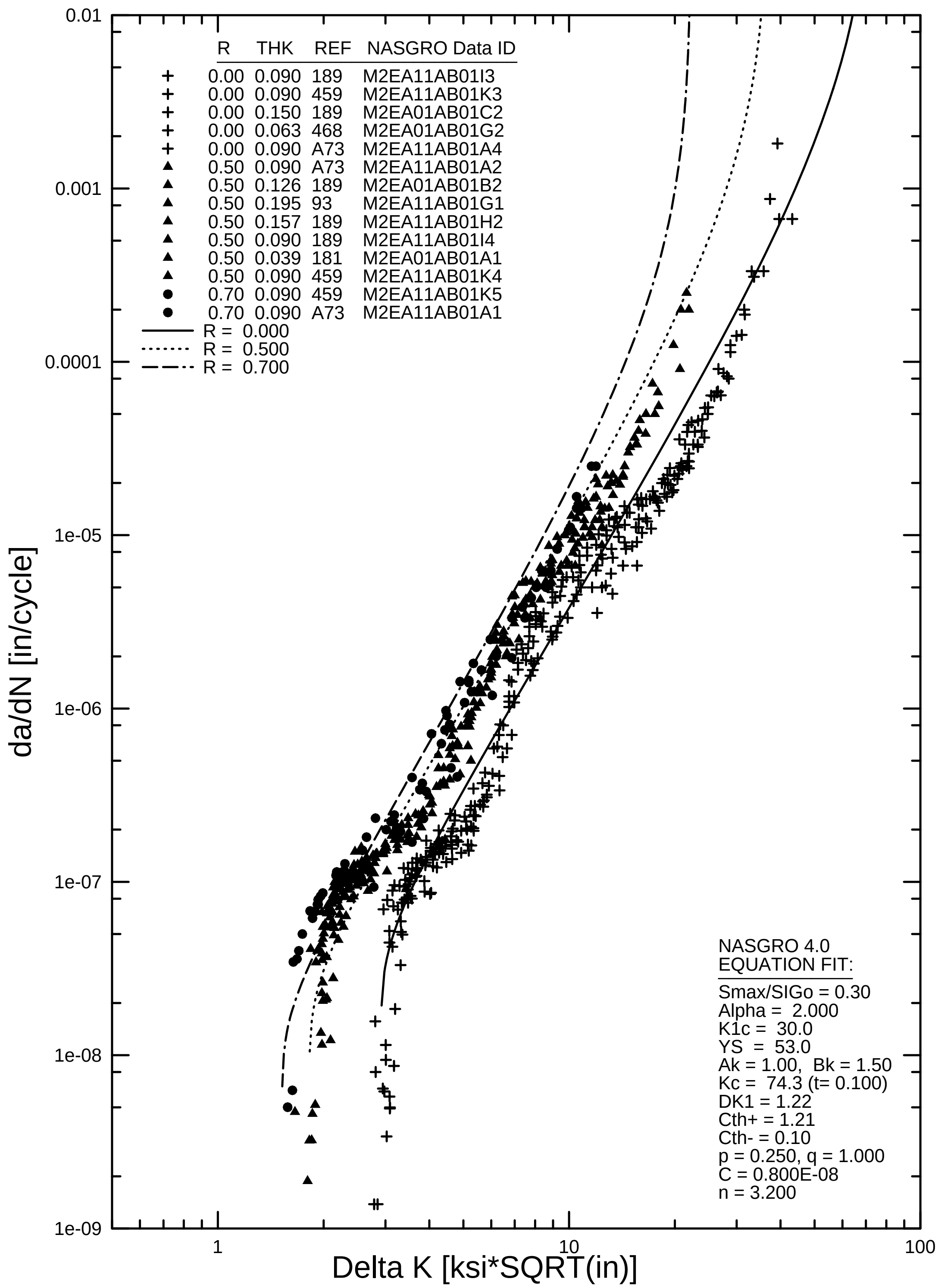


FIGURE B-4a. NASGRO EQUATION FIT FOR 2024-T3 CLAD AND BARE SHEET, L-T (M2EA11AB1) WITH POSITIVE *R* VALUES

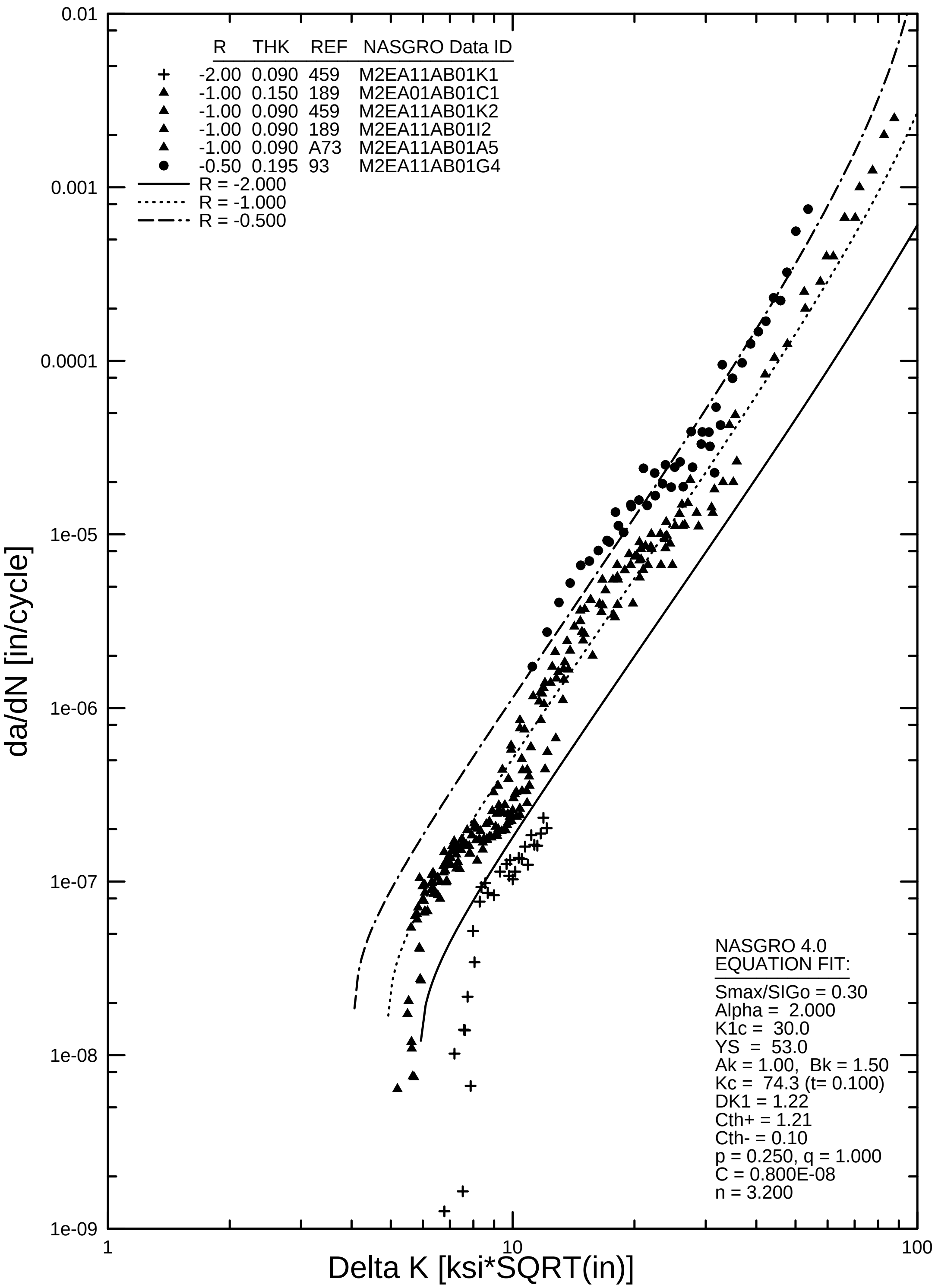


FIGURE B-4b. NASGRO EQUATION FIT FOR 2024-T3 CLAD AND BARE SHEET, L-T (M2EA11AB1) WITH NEGATIVE *R* VALUES

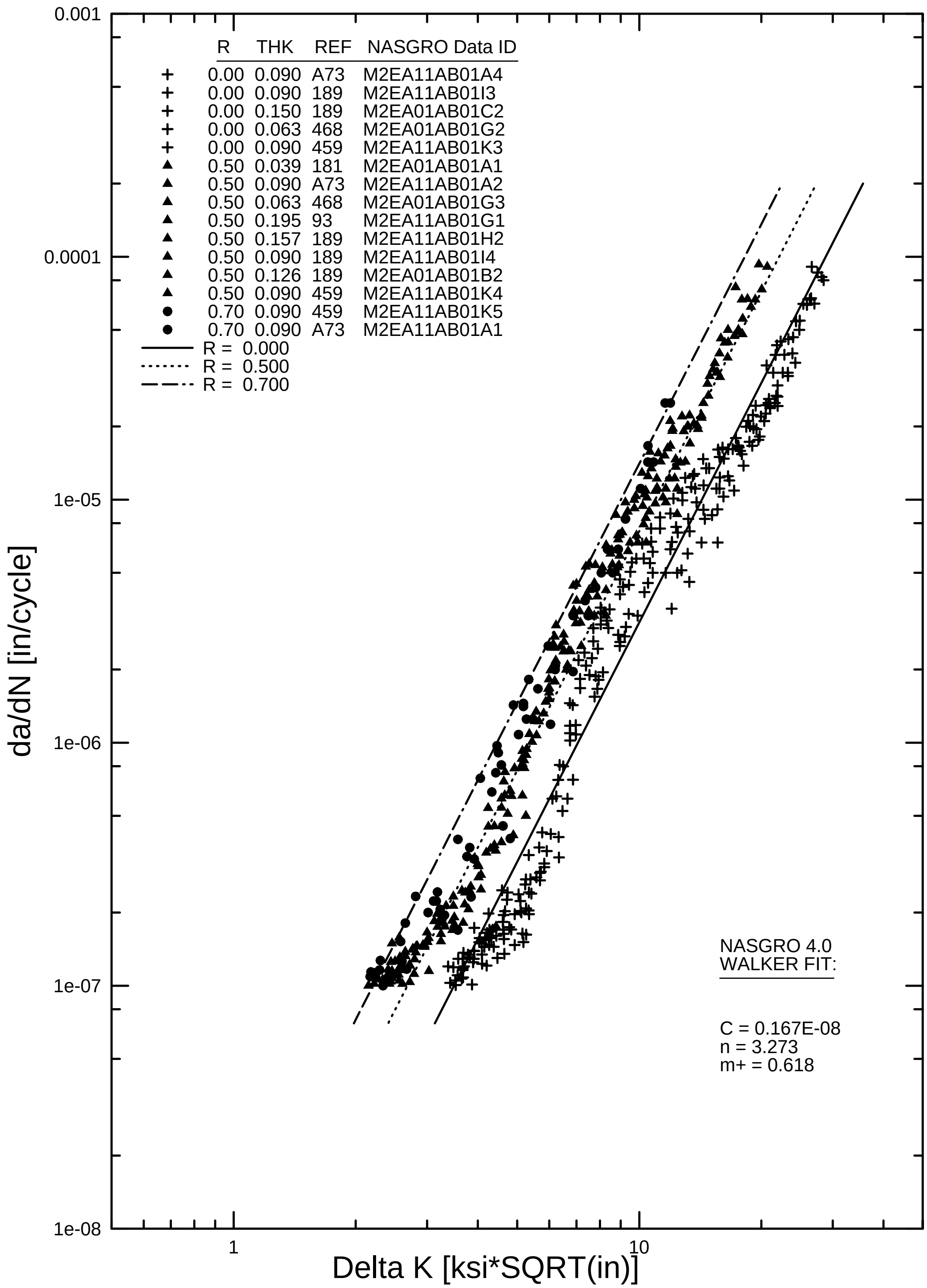


FIGURE B-5a. WALKER EQUATION FIT FOR 2024-T3 CLAD AND BARE SHEET, L-T (M2EA11AB1) WITH POSITIVE *R* VALUES

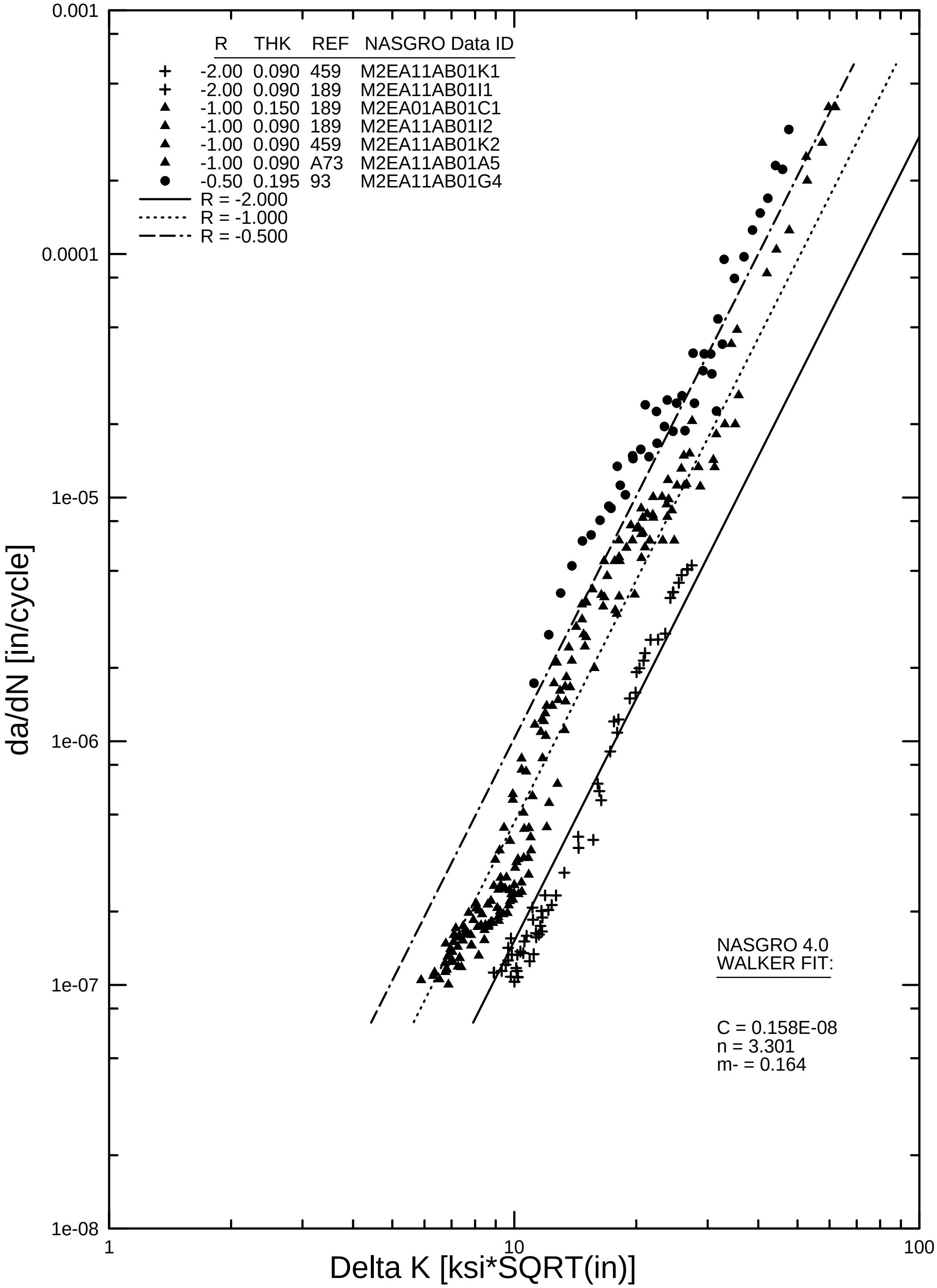


FIGURE B-5b. WALKER EQUATION FIT FOR 2024-T3 CLAD AND BARE SHEET, L-T (M2EA11AB1) WITH NEGATIVE *R* VALUES

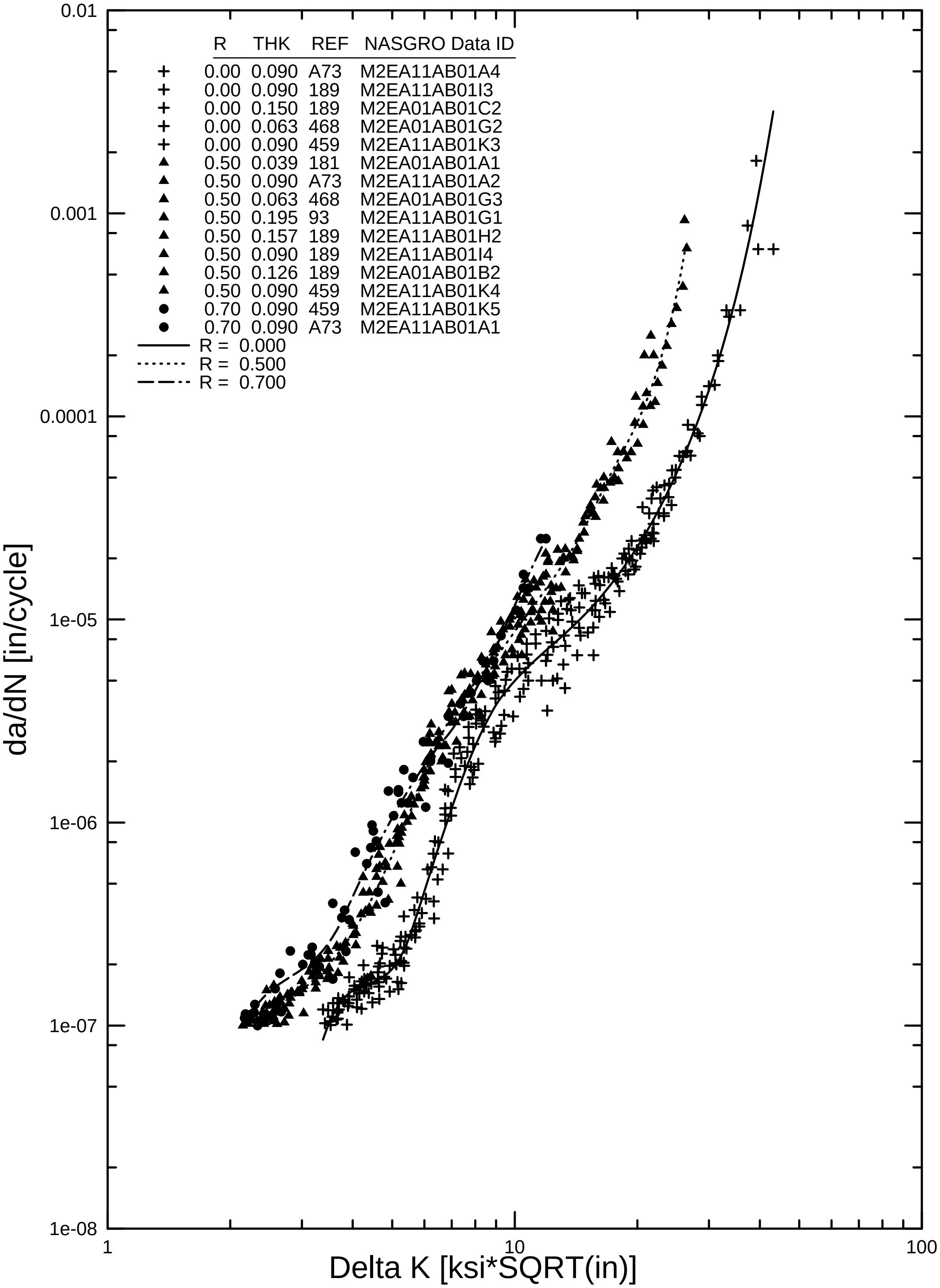


FIGURE B-6a. SPLINE FIT FOR 2024-T3 CLAD AND BARE SHEET, L-T (M2EA11AB1) WITH POSITIVE *R* VALUES

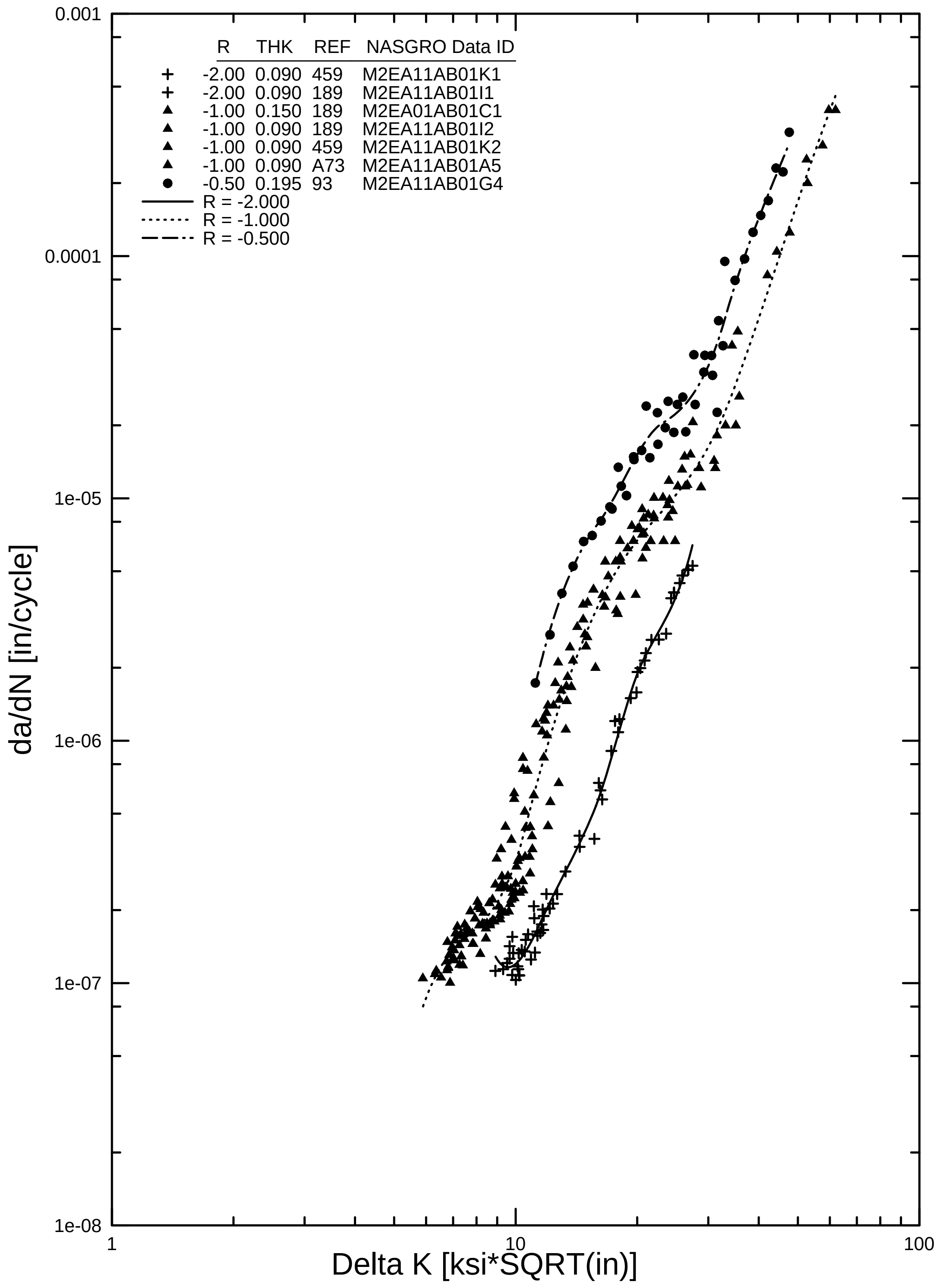


FIGURE B-6b. SPLINE FIT FOR 2024-T3 CLAD AND BARE SHEET, L-T (M2EA11AB1) WITH NEGATIVE *R* VALUES

TABLE B-4a. *da/dN*-Δ*K* SPLINE FIT DATA FOR 2024-T3 CLAD AND BARE SHEET, L-T WITH POSITIVE *R* VALUES

ID Code = M2EA11AB1 *R* = 0.0000	
da/dN	Δ*K*
8.5277e-08	3.3806
1.0000e-07	3.4799
1.8000e-07	4.8636
3.2000e-07	5.6622
6.0000e-07	6.2613
1.0000e-06	6.8082
1.8000e-06	7.5591
3.2000e-06	8.5678
6.0000e-06	10.9383
1.0000e-05	14.4607
1.8000e-05	18.4912
3.2000e-05	22.1001
6.0000e-05	25.6959
1.0000e-04	28.4466
1.8000e-04	31.4230
3.2000e-04	34.1080
6.0000e-04	36.8131
1.0000e-03	38.8665
1.8000e-03	41.0983
3.1829e-03	43.1519

(a)

ID Code = M2EA11AB1 *R* = 0.5000	
da/dN	Δ*K*
1.0285e-07	2.2182
1.8000e-07	3.3220
3.2000e-07	4.1352
6.0000e-07	4.8493
1.0000e-06	5.4034
1.8000e-06	6.0484
3.2000e-06	6.9138
6.0000e-06	8.6642
1.0000e-05	10.5084
1.8000e-05	12.9641
3.2000e-05	15.3066
6.0000e-05	17.8753
1.0000e-04	20.3083
1.8000e-04	22.6137
3.2000e-04	24.3847
6.0000e-04	25.9843
7.2687e-04	26.4241

(b)

ID Code = M2EA11AB1 *R* = 0.7000	
da/dN	Δ*K*
1.0217e-07	2.1677
1.8000e-07	2.8901
3.2000e-07	3.7327
6.0000e-07	4.3227
1.0000e-06	4.9276
1.8000e-06	5.8777
3.2000e-06	7.2772
6.0000e-06	8.5971
1.0000e-05	9.6496
1.8000e-05	11.0169
2.4964e-05	11.9399

(c)

TABLE B-4b. *da/dN*-Δ*K* SPLINE FIT DATA FOR 2024-T3 CLAD AND BARE SHEET, L-T WITH NEGATIVE *R* VALUES

ID Code = M2EA11AB1 *R* = -2.0000	
da/dN	Δ*K*
1.2075e-07	8.9125
1.8000e-07	11.6085
3.2000e-07	13.6923
6.0000e-07	16.1057
1.0000e-06	17.9171
1.8000e-06	20.0262
3.2000e-06	22.6636
4.5772e-06	27.4157

(a)

ID Code = M2EA11AB1 *R* = -1.0000	
da/dN	Δ*K*
1.0888e-07	6.3533
1.8000e-07	8.2301
3.2000e-07	9.6250
6.0000e-07	11.1004
1.0000e-06	12.3732
1.8000e-06	14.0171
3.2000e-06	15.9597
6.0000e-06	18.9031
1.0000e-05	24.3345
1.8000e-05	30.9254
3.2000e-05	35.8164
6.0000e-05	41.0296
1.0000e-04	45.4478
1.8000e-04	50.9521
3.2000e-04	57.0239
6.0000e-04	64.8903
1.0000e-03	72.8839
1.8000e-03	85.8906
1.9123e-03	87.7001

(b)

ID Code = M2EA11AB1 *R* = -0.500	
da/dN	Δ*K*
2.0231e-06	11.1944
3.2000e-06	12.6387
6.0000e-06	14.8885
1.0000e-05	17.1952
1.8000e-05	21.3866
3.2000e-05	29.1606
6.0000e-05	33.8456
1.0000e-04	37.4357
1.8000e-04	41.8421
3.2000e-04	46.9176
5.6040e-04	53.7032

(c)

TABLE B-5. MATERIAL DESCRIPTION AND SPECIMEN TESTING INFORMATION FOR 2024-T3 CLAD AND BARE SHEET, T-L

Material ID Code	M2EA02AB1
Alloy Type	2024 Al
Alloy Condition/HT	T3
Product Form	0.04″-0.09″ Clad and Bare Sheet
Test Environments	Laboratory Air
Specimen Types	M(T)
Crack Orientation	T-L
Specimen Thickness (in.)	0.04-0.09
Specimen Width (in.)	4.0-15.7
Yield Strength (ksi)	Clad: 41-46 Bare: 47-53
Ultimate Strength (ksi)	Clad: 62-66 Bare: 66-68
Cyclic Frequency, Hz	5-15

Data References for Table B-5.

361 Larson, B.F., "C-17 Material Specimen Tests for Fracture Mechanics Data," Phase I, Lot 1 Aluminum Alloys.

362 Kahandal, R.S., "C-17 Material Specimen Tests for Fracture Mechanics Data," Phase I, Lot 2 Aluminum Alloys.

468 Widespread Fatigue Damage Evaluation Final Report, Submitted to FAA Technical Center, The Boeing Co. Phantom Works, February 2003.

C104 MacKay, T.L., "Fatigue Crack Propagation Rate at Low Delta K of Two Aluminum Sheet Alloys - 2024-T3 and 7075-T6," *Engineering Fracture Mechanics*, Volume II, 1979, pp.753-761.

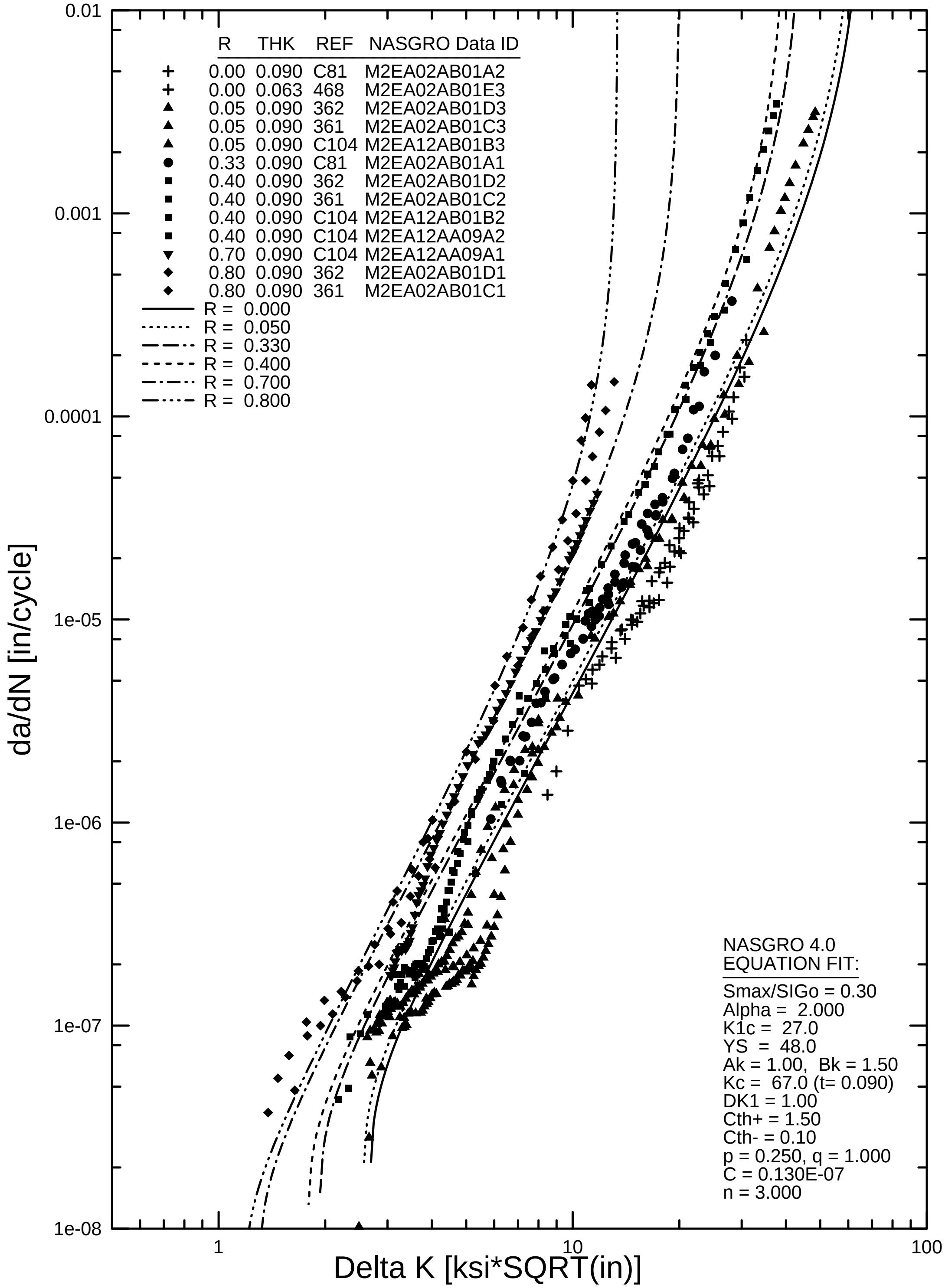


FIGURE B-7. NASGRO EQUATION FIT FOR 2024-T3 CLAD AND BARE SHEET, T-L (M2EA02AB1)

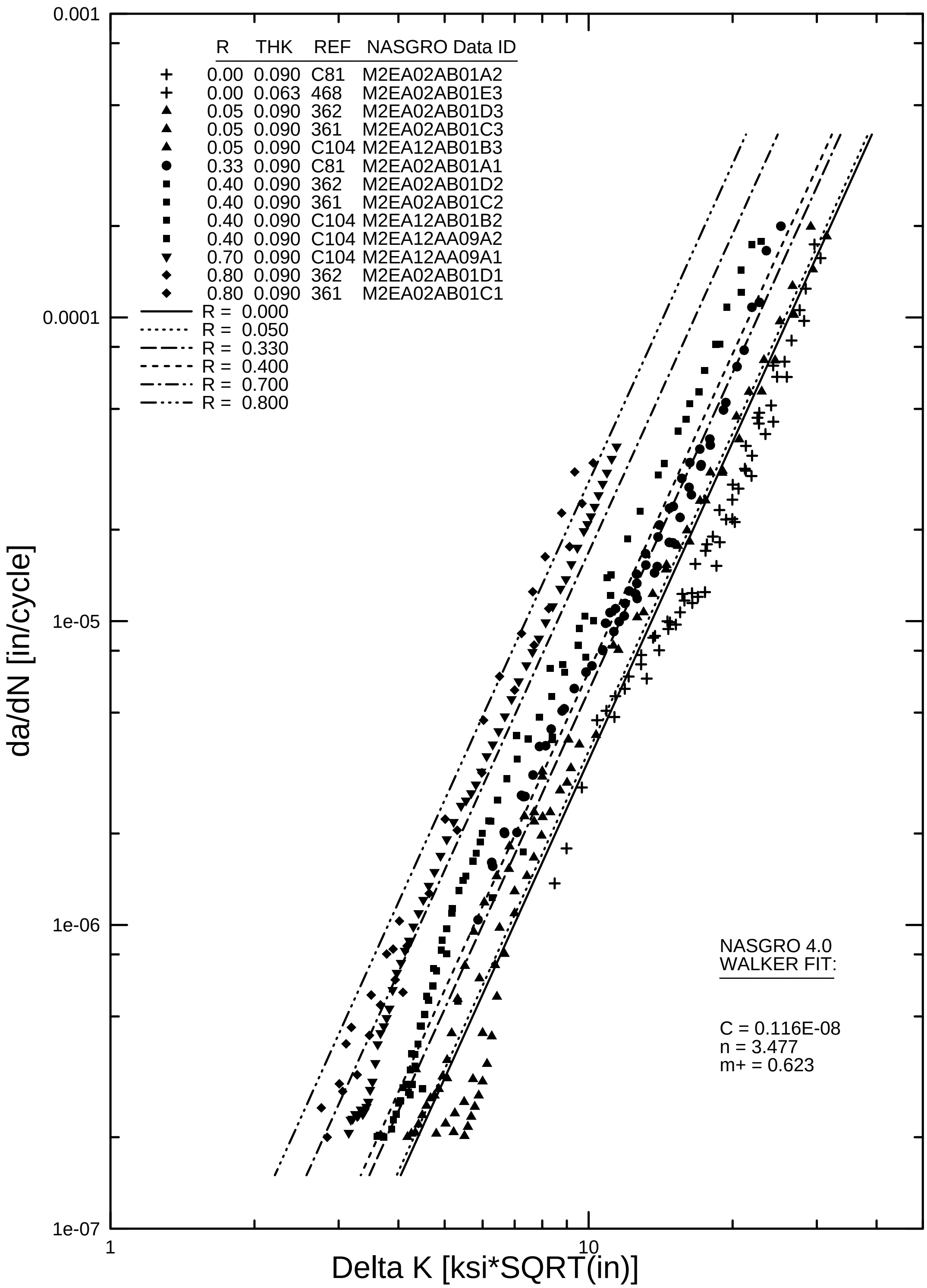


FIGURE B-8. WALKER EQUATION FIT FOR 2024-T3 CLAD AND BARE SHEET, T-L (M2EA02AB1)

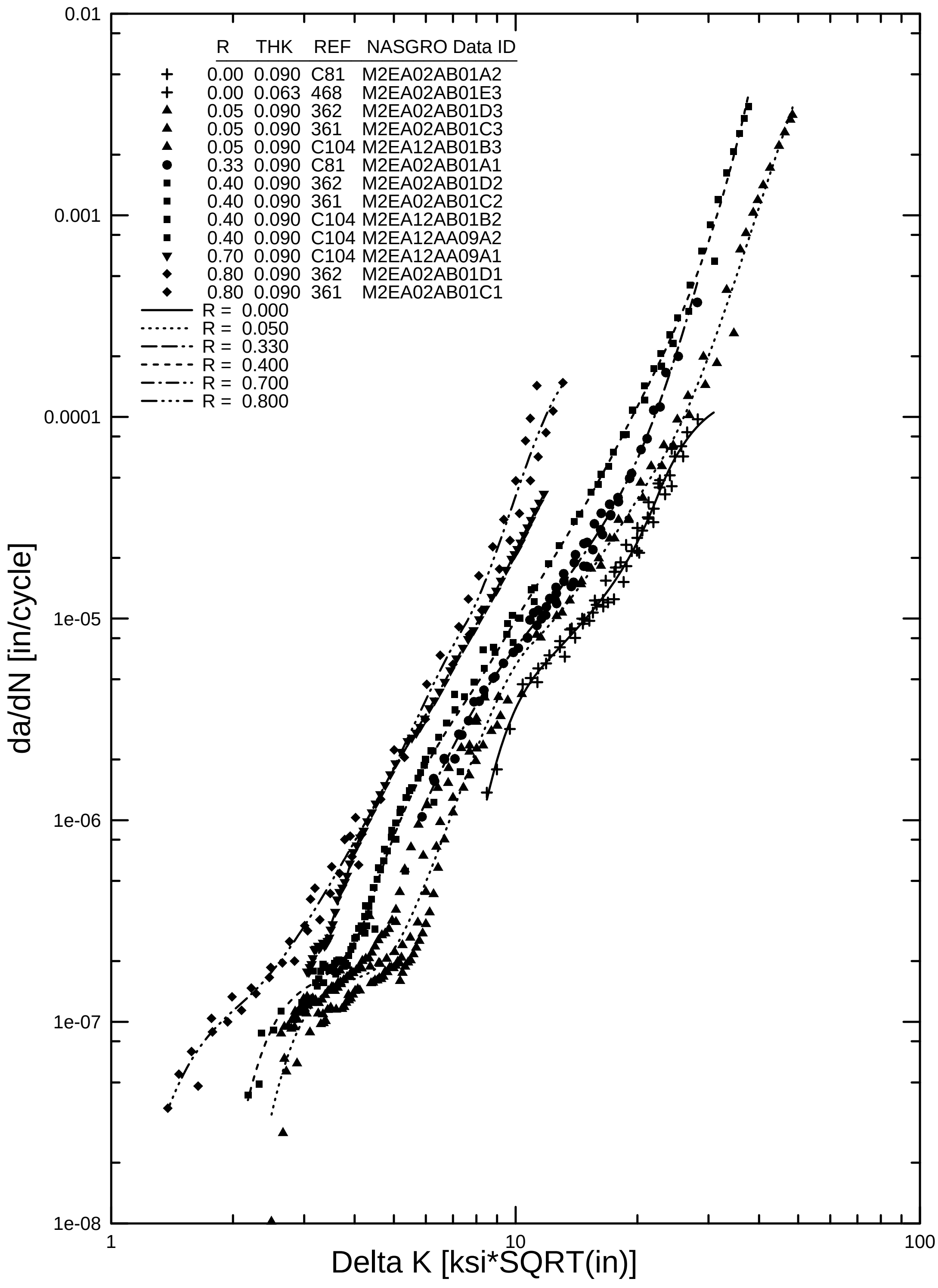


FIGURE B-9. SPLINE FIT FOR 2024-T3 CLAD AND BARE SHEET, T-L (M2EA02AB1)

TABLE B-6. *da/dN*-Δ*K* SPLINE FIT DATA FOR 2024-T3 CLAD AND BARE SHEET, T-L (M2EA02AB1)

ID Code = M2EA02AB1 *R* = 0.0000	
da/dN	Δ*K*
1.3265e-06	8.4918
1.8000e-06	8.8929
3.2000e-06	9.8437
6.0000e-06	11.7948
1.0000e-05	14.8983
1.8000e-05	18.4770
3.2000e-05	21.4044
6.0000e-05	24.5501
1.0000e-04	27.4624
1.6591e-04	30.9030

(a)

ID Code = M2EA02AB1 *R* = 0.050	
da/dN	Δ*K*
7.2719e-08	2.6303
1.0000e-07	2.8505
1.8000e-07	4.5371
3.2000e-07	5.4593
6.0000e-07	6.1800
1.0000e-06	6.8122
1.8000e-06	7.6375
3.2000e-06	8.6277
6.0000e-06	10.1978
1.0000e-05	12.6918
1.8000e-05	15.5656
3.2000e-05	18.5999
6.0000e-05	22.8197
1.0000e-04	26.3730
1.8000e-04	29.5891
3.2000e-04	32.6070
6.0000e-04	36.0431
1.0000e-03	39.1073
1.8000e-03	43.1970
3.2000e-03	48.3751
3.2125e-03	48.4172

(b)

ID Code = M2EA02AB1 *R* = 0.4000	
da/dN	Δ*K*
8.7184e-08	2.3496
1.0000e-07	2.4807
1.8000e-07	3.5217
3.2000e-07	4.2284
6.0000e-07	4.7368
1.0000e-06	5.1743
1.8000e-06	5.9073
3.2000e-06	7.0457
6.0000e-06	8.7120
1.0000e-05	10.0453
1.8000e-05	11.9807
3.2000e-05	14.3355
6.0000e-05	17.1197
1.0000e-04	19.3656
1.8000e-04	22.3736
3.2000e-04	25.6294
6.0000e-04	29.0384
1.0000e-03	31.5700
1.8000e-03	34.2346
3.2000e-03	36.6329
4.1606e-03	37.6704

(c)

ID Code = M2EA02AB1 *R* = 0.700	
da/dN	Δ*K*
1.9071e-07	3.0479
3.2000e-07	3.5258
6.0000e-07	3.8992
1.0000e-06	4.2919
1.8000e-06	5.0071
3.2000e-06	5.9231
6.0000e-06	7.0672
1.0000e-05	8.1534
1.8000e-05	9.5707
3.2000e-05	11.0110
4.1155e-05	11.7490

(d)

TABLE B-6. *da/dN*-Δ*K* SPLINE FIT DATA FOR 2024-T3 CLAD AND BARE SHEET, T-L (M2EA02AB1) (Continued)

ID Code = M2EA02AB1 *R* = 0.8000	
da/dN	Δ*K*
7.0726e-08	1.5812
1.0000e-07	1.8180
1.8000e-07	2.5351
3.2000e-07	3.0626
6.0000e-07	3.7047
1.0000e-06	4.2768
1.8000e-06	4.9757
3.2000e-06	5.7129
6.0000e-06	6.6530
1.0000e-05	7.6199
1.8000e-05	8.7015
3.2000e-05	9.6146
6.0000e-05	10.6938
1.0000e-04	11.8212
1.4088e-04	13.0918

(e)

TABLE B-7. MATERIAL DESCRIPTION AND SPECIMEN TESTING INFORMATION FOR 2024-T351 PLATE, L-T

Material ID Code	M2EB11AB1
Alloy Type	2024 Al
Alloy Condition/HT	T351
Product Form	0.25″-1.2″ Plate
Test Environments	Laboratory Air
Specimen Types	C(T), M(T)
Crack Orientation	L-T
Specimen Thickness (in.)	C(T): 0.25-0.5 M(T): 0.16-0.0
Specimen Width (in.)	C(T): 2.0 M(T): 4-12
Yield Strength (ksi)	48-57
Ultimate Strength (ksi)	66-71
Cyclic Frequency, Hz	3-30

Data References for Table B-7.

91 Schra, L., et al., "Engineering Property Comparisons for 2324-T39 and 2024-T351 Aluminum Alloy Plate," National Aerospace Laboratory, Amsterdam, The Netherlands, NLR TR 84021 U, 1984.

93 Levy, M., "Assessment of Damage Tolerance Requirements and Analyses - Tasks II and IV Report," AFWAL-TR-86-3003, Vol. 4,1986.

361 Larson, B.F., "C-17 Material Specimen Tests for Fracture Mechanics Data," Phase I, Lot 1 Aluminum Alloys."

B218 Liu, A.F., et al., "Effect of Multi-axial Loading on Crack Growth," Vol. I & II, AFFDL-TR-78-175, 1978.

C8 Fatigue Crack Growth Rate Data Sheets on Al Alloys 2024, 7010, 7050, 7075, 7475 and Steel Alloys 17-4 PH, 17-7PH, 4340, A286, H-11, HY-180 and 12-9-2, Sent by Paul Abelkis, Douglas Aircraft Co., Long Beach, CA, 1982.

C122 Cervay, R.R., "An Empirical Model for Load Ratio and Test Temperature Effects on the Fatigue Crack Growth Rate of Aluminum Alloy 2024-T351," UDRI, Dayton, OH, Report AFWAL-TR-82-4025, March 1982.

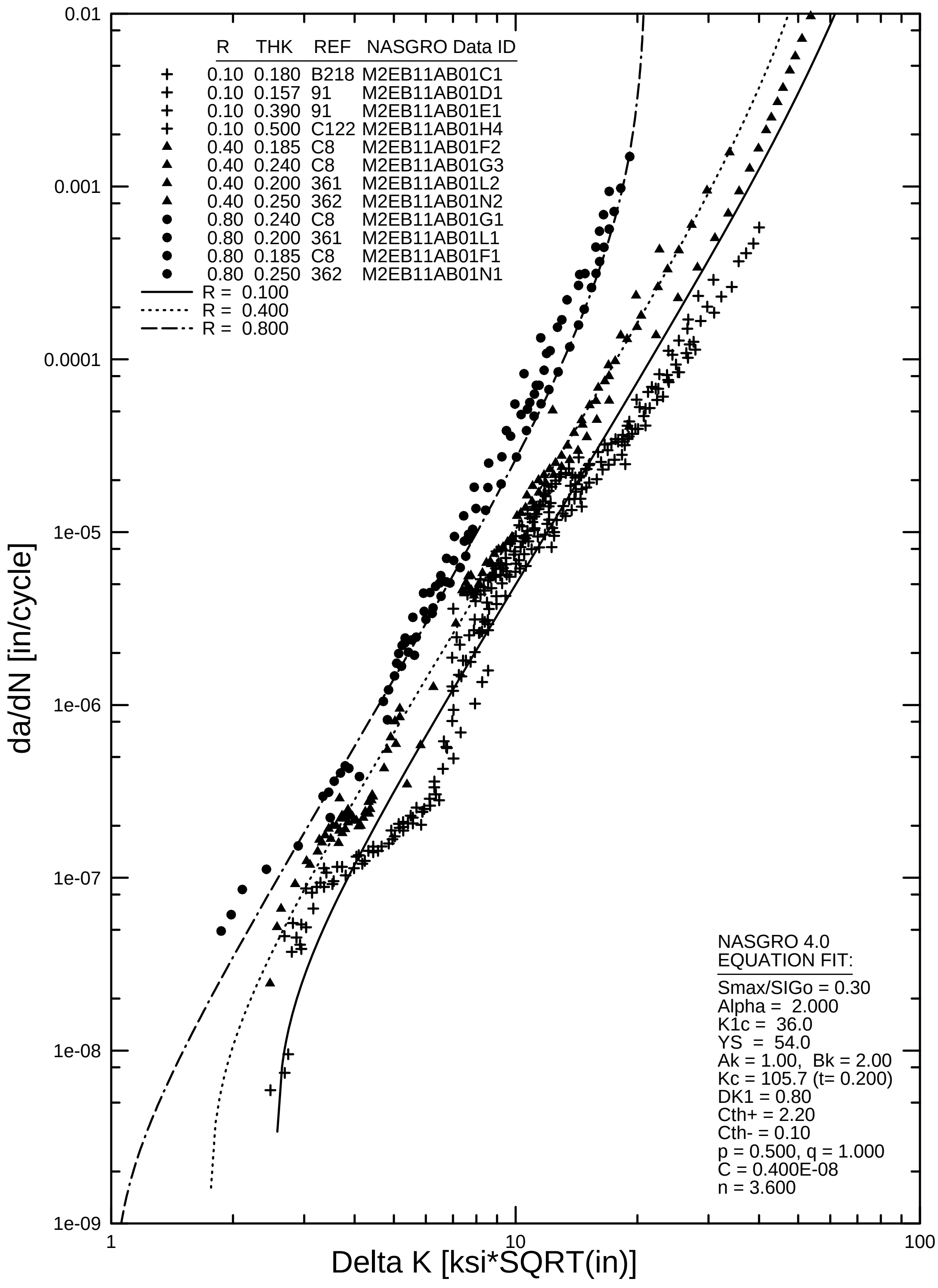


FIGURE B-10a. NASGRO EQUATION FIT FOR 2024-T351 PLATE, L-T (M2EB11AB1) WITH POSITIVE *R* VALUES

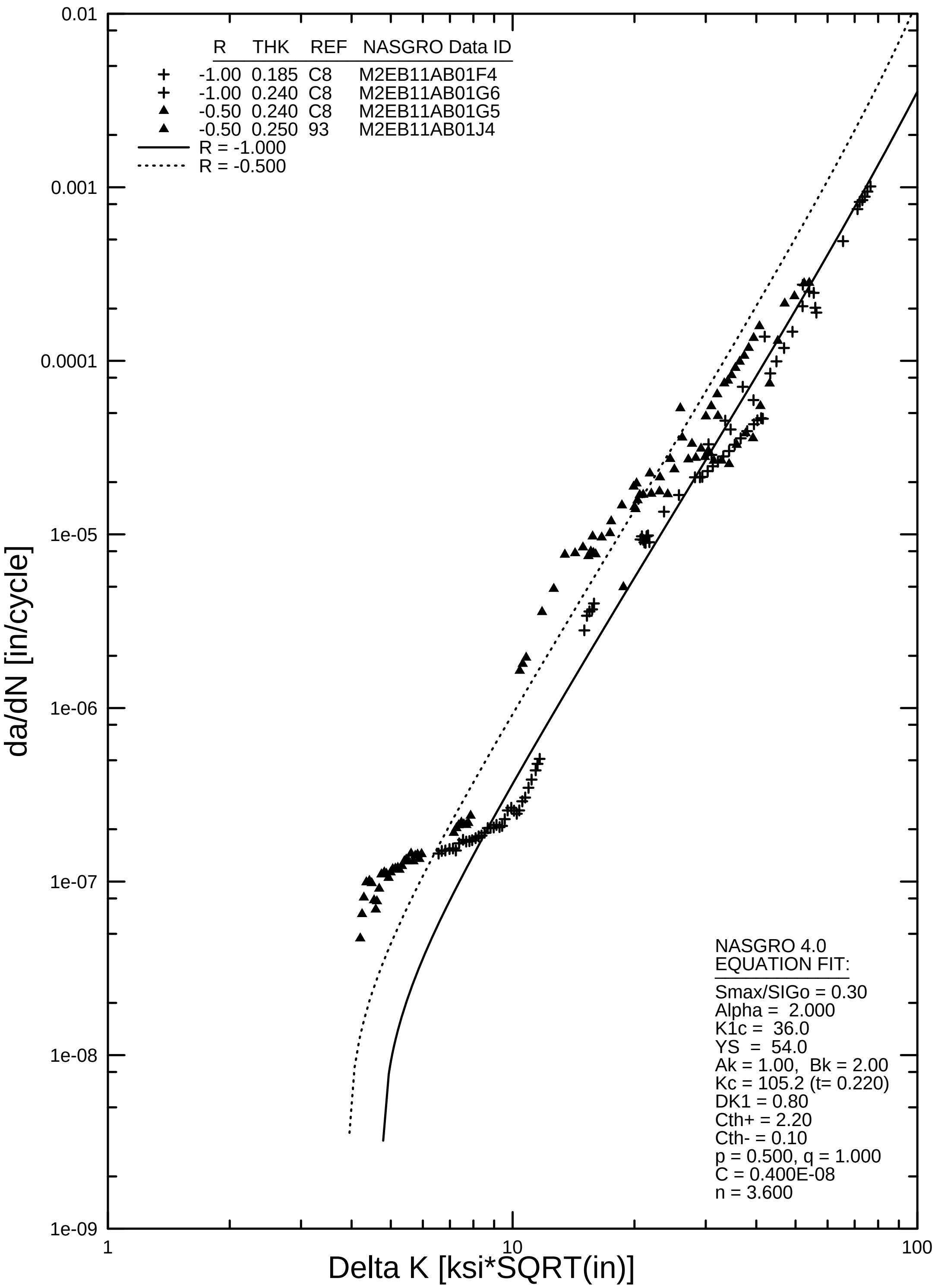


FIGURE B-10b. NASGRO EQUATION FIT FOR 2024-T351 CLAD AND BARE SHEET, L-T (M2EB11AB1) WITH NEGATIVE *R* VALUES

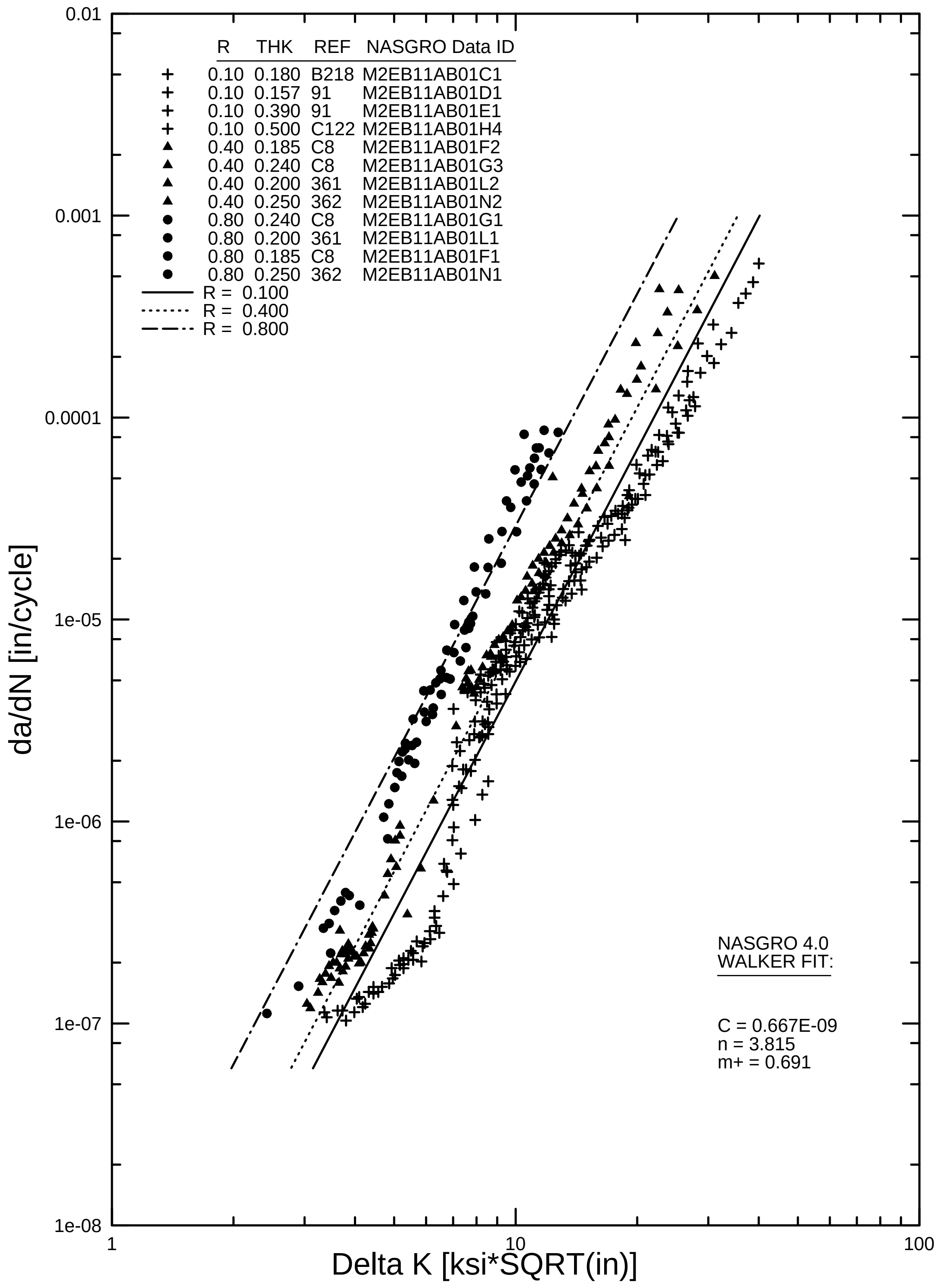


FIGURE B-11a. WALKER EQUATION FIT FOR 2024-T351 PLATE, L-T (M2EB11AB1) WITH POSITIVE *R* VALUES

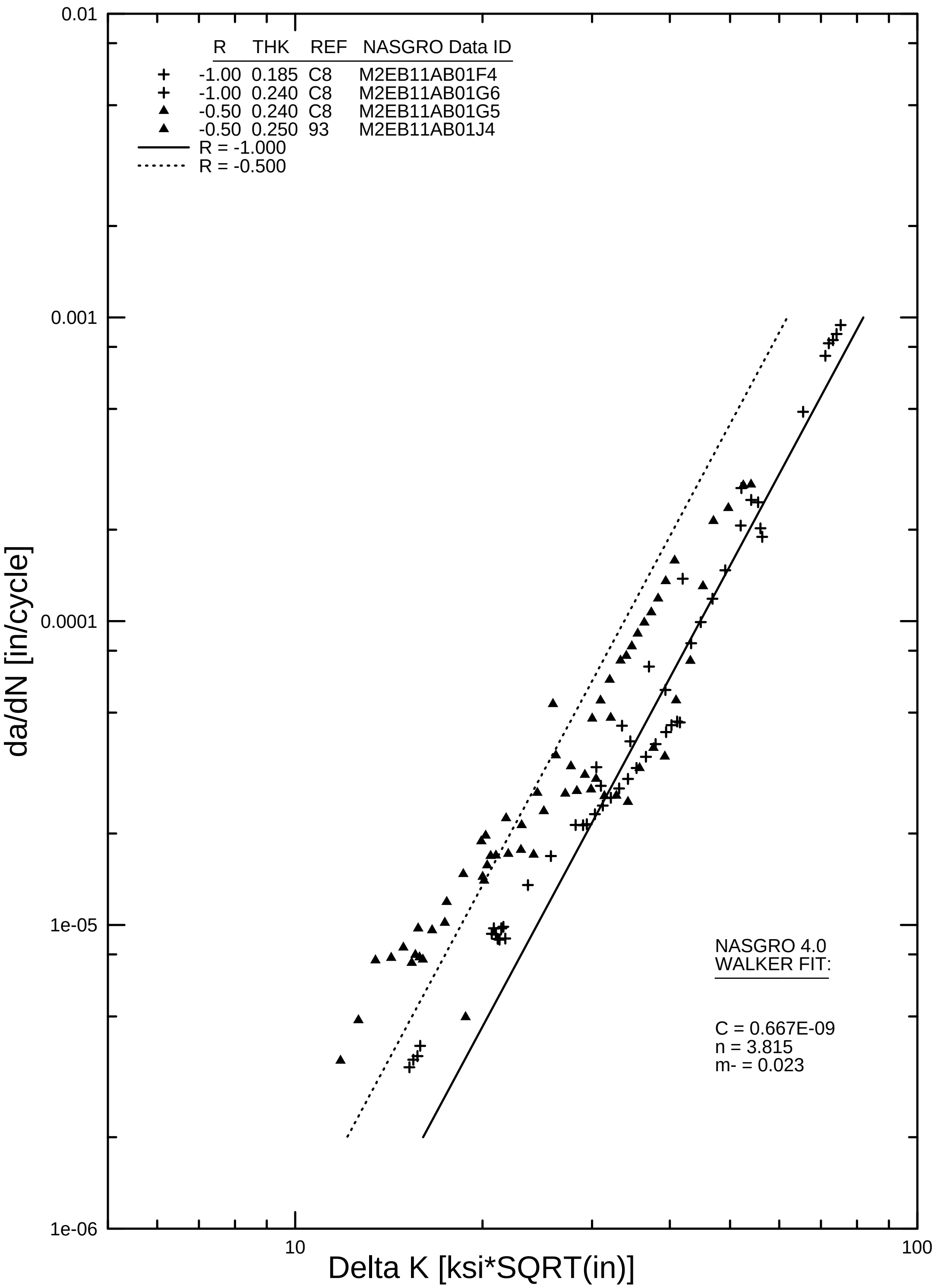


FIGURE B-11b. WALKER EQUATION FIT FOR 2024-T351 PLATE, L-T (M2EB11AB1) WITH NEGATIVE *R* VALUES

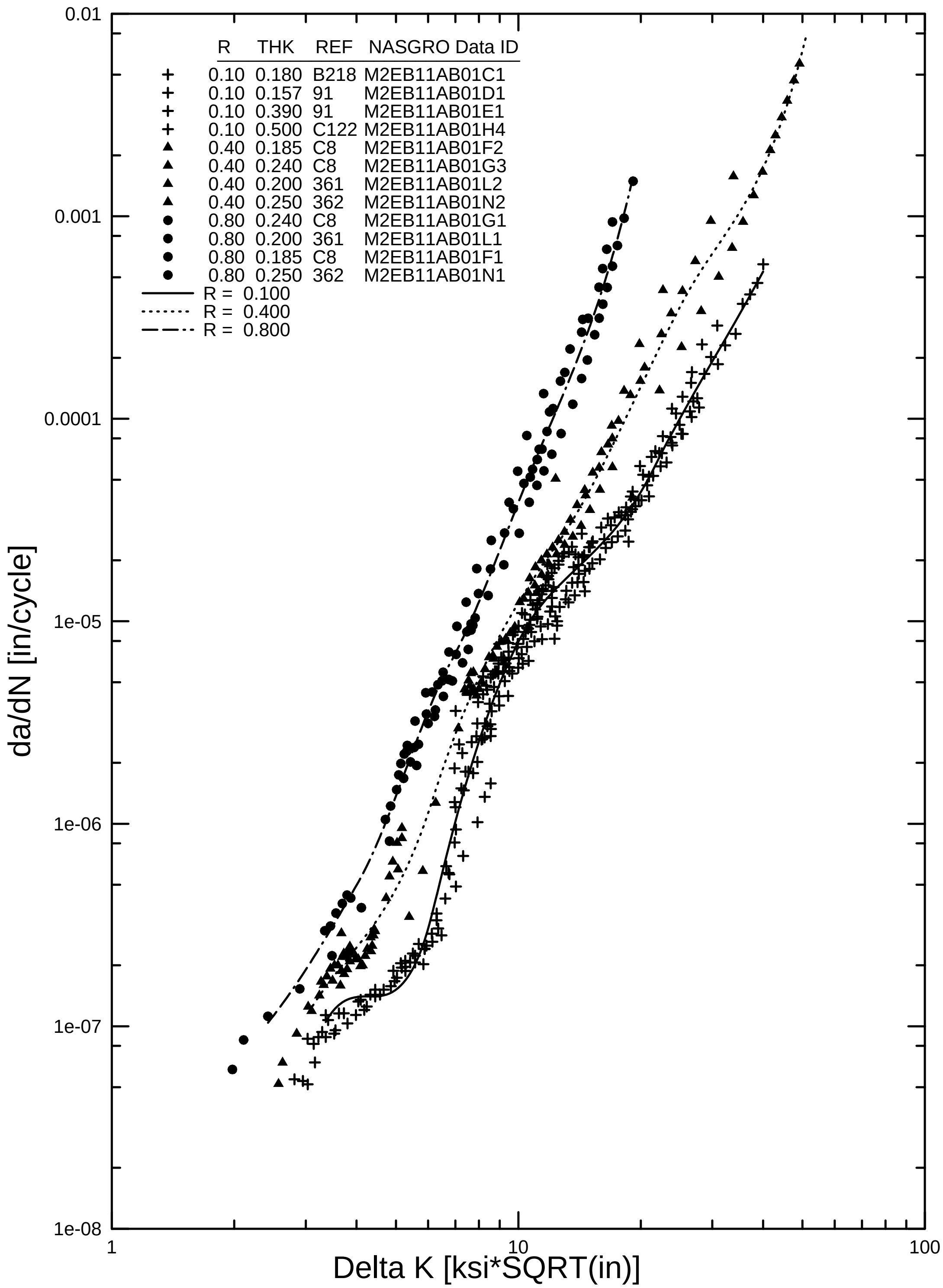


FIGURE B-12a. SPLINE FIT FOR 2024-T351 PLATE, L-T (M2EB11AB1) WITH POSITIVE *R* VALUES

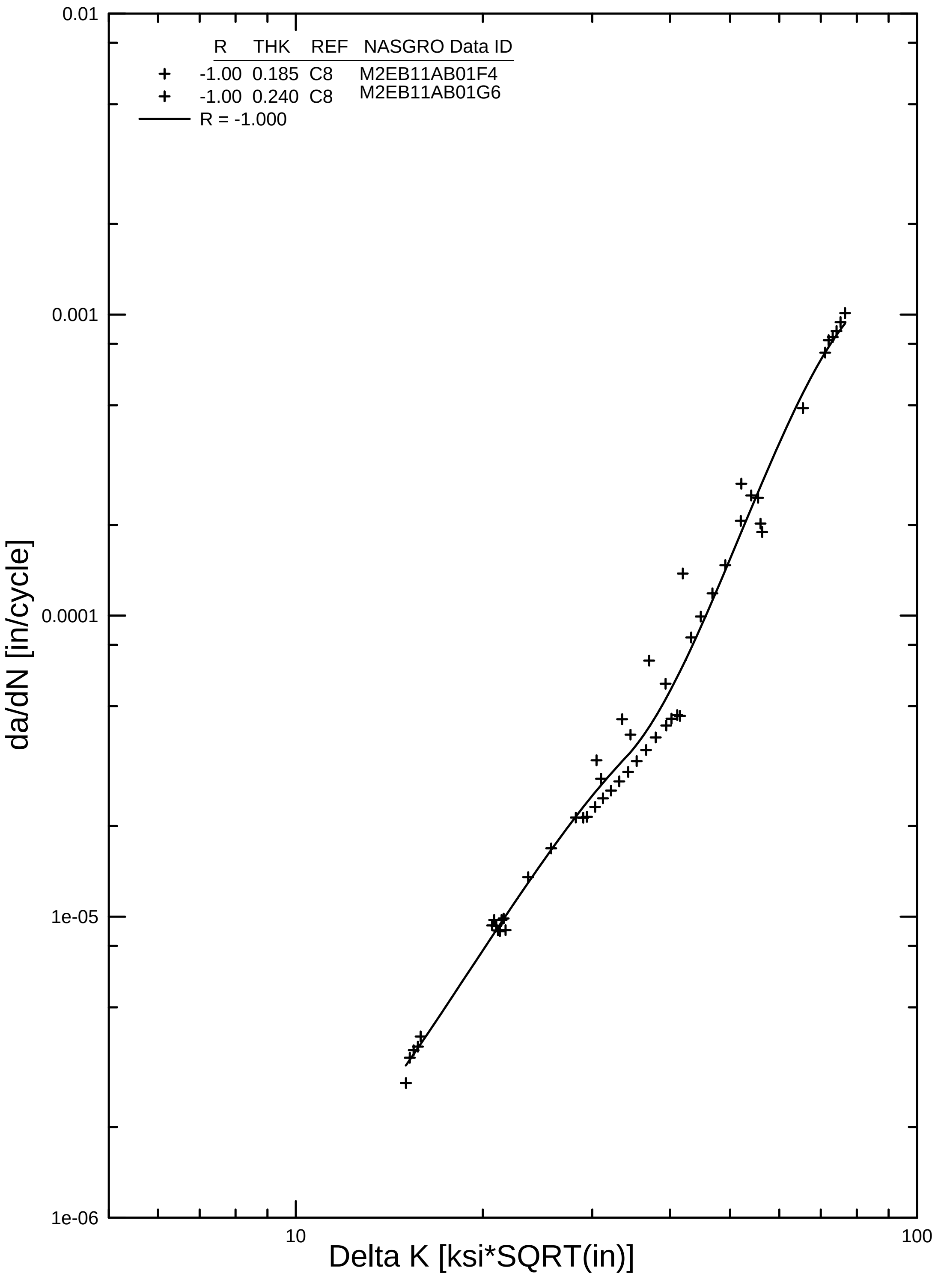


FIGURE B-12b. SPLINE FIT FOR 2024-T351 PLATE, L-T (M2EB11AB1) WITH NEGATIVE *R* VALUE

TABLE B-8a. *da/dN*-Δ*K* SPLINE FIT FOR 2024-T351 PLATE, L-T WITH POSITIVE *R* VALUES (M2EB11AB1)

ID Code = M2EB11AB1 *R* = 0.1000	
da/dN	Δ*K*
6.3673e-08	3.0339
1.0000e-07	3.3757
1.8000e-07	5.1702
3.2000e-07	5.9223
6.0000e-07	6.5530
1.0000e-06	7.0657
1.8000e-06	7.6931
3.2000e-06	8.3879
6.0000e-06	9.3368
1.0000e-05	10.5182
1.8000e-05	13.8864
3.2000e-05	18.0508
6.0000e-05	21.9594
1.0000e-04	24.9567
1.8000e-04	28.9025
3.2000e-04	34.6169
3.9892e-04	39.9945

(a)

ID Code = M2EB11AB1 *R* = 0.4000	
da/dN	Δ*K*
9.2159e-08	2.8510
1.0000e-07	2.9115
1.8000e-07	3.5314
3.2000e-07	4.4315
6.0000e-07	5.2924
1.0000e-06	5.8499
1.8000e-06	6.4669
3.2000e-06	7.2092
6.0000e-06	8.2548
1.0000e-05	9.3848
1.8000e-05	11.2285
3.2000e-05	13.7530
6.0000e-05	16.2123
1.0000e-04	18.2590
1.8000e-04	20.9230
3.2000e-04	24.2488
6.0000e-04	29.6101
1.0000e-03	34.5724
1.8000e-03	40.0619
3.2000e-03	44.9797
6.0000e-03	49.8926
1.0000e-02	53.6063
1.0138e-02	53.7032

(b)

TABLE B-8b. *da/dN*-Δ*K* SPLINE FIT FOR 2024-T351 PLATE, L-T WITH NEGATIVE *R* VALUES (M2EB11AB1)

ID Code = M2EB11AB1 R = 0.800	
da/dN	Δ*K*
7.6776e-08	2.1086
1.0000e-07	2.3709
1.8000e-07	2.9481
3.2000e-07	3.5670
6.0000e-07	4.2057
1.0000e-06	4.6605
1.8000e-06	5.2121
3.2000e-06	5.8584
6.0000e-06	6.8357
1.0000e-05	7.6194
1.8000e-05	8.5390
3.2000e-05	9.5439
6.0000e-05	10.9219
1.0000e-04	12.2700
1.8000e-04	13.7774
3.2000e-04	15.2465
6.0000e-04	16.8709
1.0000e-03	18.2183
1.4100e-03	19.1426

(a)

ID Code = M2EB11AB1 R = -1.0000	
da/dN	Δ*K*
3.2007e-06	15.0314
6.0000e-06	18.4501
1.0000e-05	21.7282
1.8000e-05	26.4713
3.2000e-05	33.1420
6.0000e-05	40.6908
1.0000e-04	45.7057
1.8000e-04	51.5887
3.2000e-04	58.0457
6.0000e-04	66.9812
9.3364e-04	76.5597

(b)

ID Code = M2EB11AB1 R = -0.500	
da/dN	Δ*K*
A spline fit for R = -0.500 data was not done since there is considerable scatter in them; consequently, a table was not developed for R = -0.500.	

(c)

TABLE B-9. MATERIAL DESCRIPTION AND SPECIMEN TESTING INFORMATION FOR 2024-T3511 EXTRUSION, L-T

Material ID Code	M2EC31AB1
Alloy Type	2024 Al
Alloy Condition/HT	T3511
Product Form	Extrusion
Test Environments	Laboratory Air, High-Humidity Air
Specimen Types	C(T), M(T)
Crack Orientation	L-T
Specimen Thickness (in.)	C(T): 0.25-0.37 M(T): 0.19-0.37
Specimen Width (in.)	C(T): 2.0-4.0 M(T): 2.25-5.0
Yield Strength (ksi)	48-58
Ultimate Strength (ksi)	62-79
Cyclic Frequency, Hz	9-20

Data References for Table B-9.

93 Levy, M., “Assessment of Damage Tolerance Requirements and Analyses -Tasks II and IV Report,” AFWAL-TR-86-3003, Vol.4, Raw Test Data, 1986.

C65 Horsely, J.J., et al., “Durability and Damage Tolerance Assessment (DADTA) of B-52 G/H Structure, Task II, Damage Tolerance Assessment Final Report,” Boeing Company, Wichita, KS, Contract No. F34601-79-C-1515, Document No. D3-11560-3, June 1980.

D4 Fitzgerald, J., Southwest Research Institute, San Antonio, Texas, submitted data.

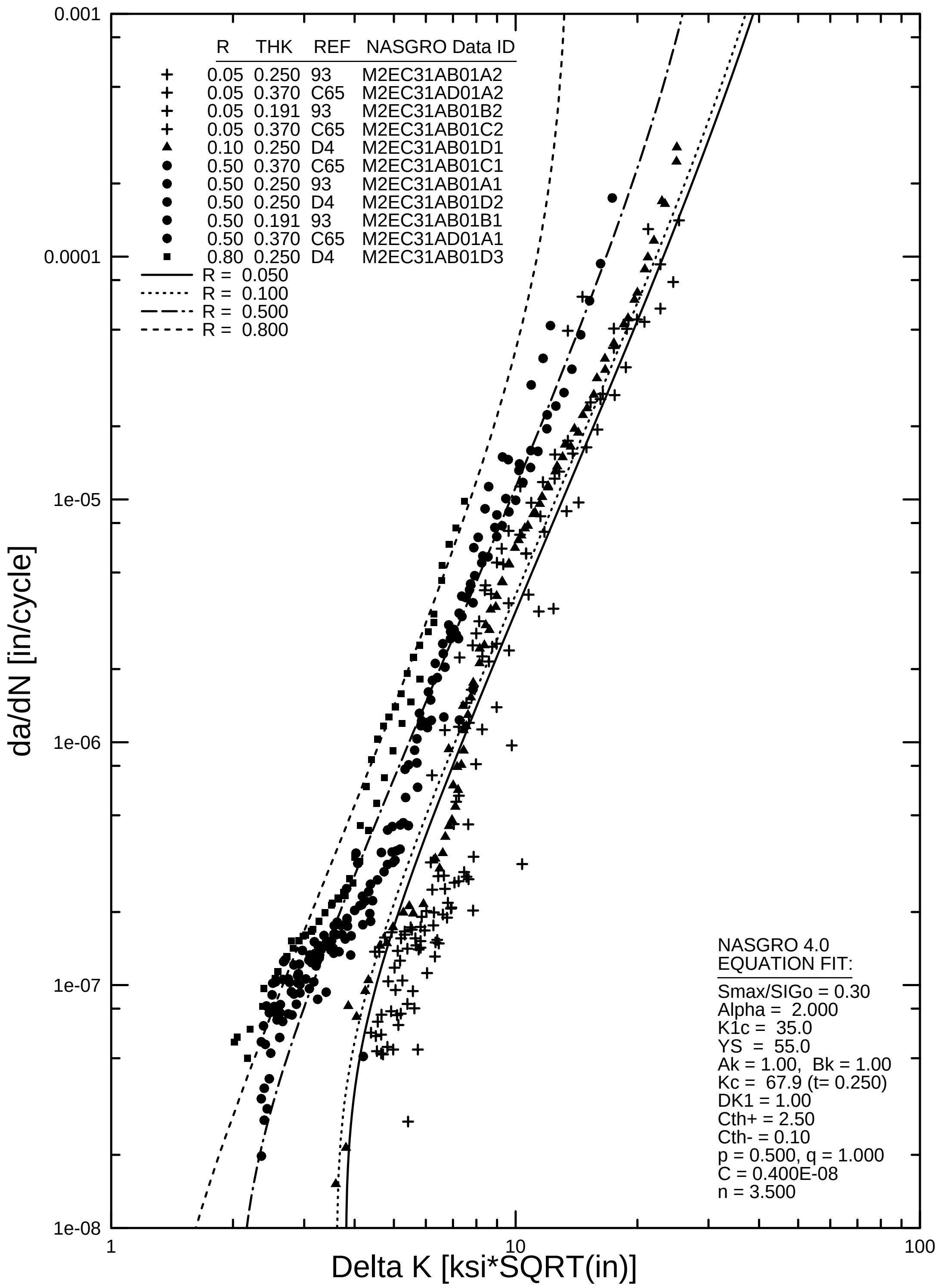


FIGURE B-13. NASGRO EQUATION FIT FOR 2024-T3511 EXTRUSION, L-T (M2EC31AB1)

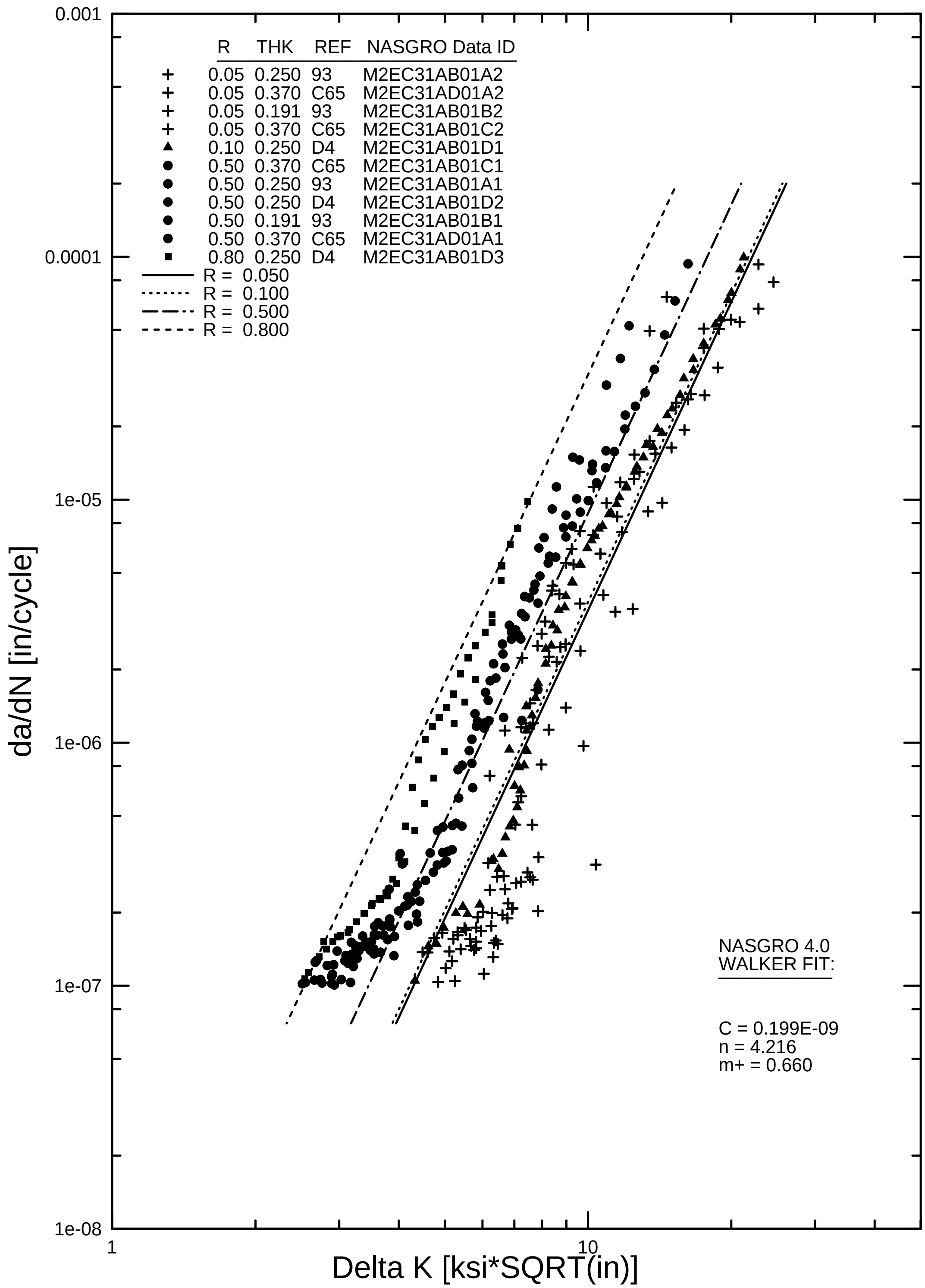


FIGURE B-14. WALKER EQUATION FIT FOR 2024-T3511 EXTRUSION, L-T (M2EC31AB1)

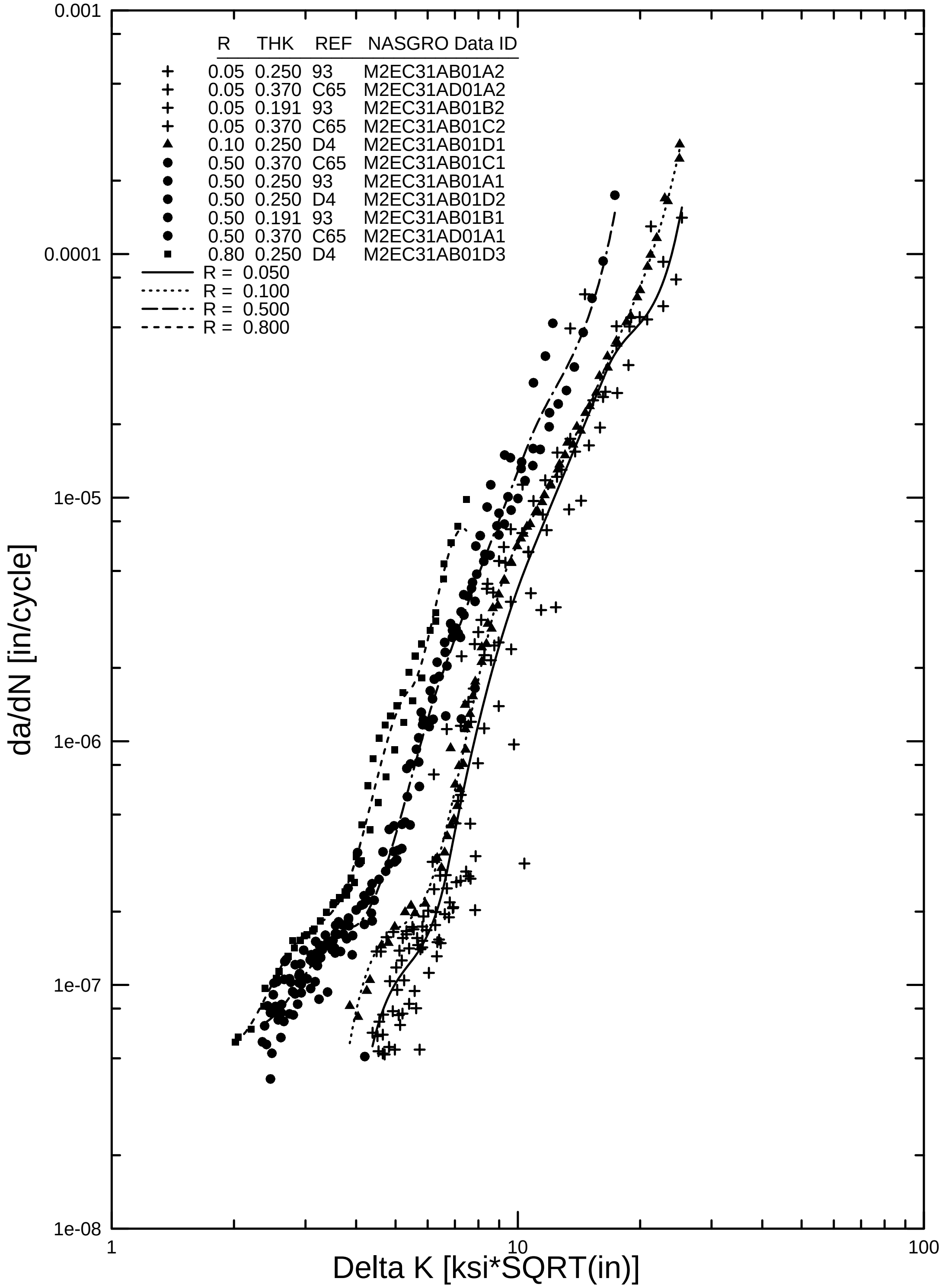


FIGURE B-15. SPLINE FIT FOR 2024-T3511 EXTRUSION, L-T (M2EC31AB1)

TABLE B-10. *da/dN*-Δ*K* SPLINE FIT FOR 2024-T3511 EXTRUSION, L-T (M2EC31AB1)

ID Code = M2EC31AB1 *R* = 0.050	
da/dN	Δ*K*
6.3335e-08	4.3853
1.0000e-07	4.7880
1.8000e-07	6.1551
3.2000e-07	6.7743
6.0000e-07	7.3027
1.0000e-06	7.8133
1.8000e-06	8.5306
3.2000e-06	9.4419
6.0000e-06	10.8713
1.0000e-05	12.2808
1.8000e-05	14.1614
3.2000e-05	16.6422
6.0000e-05	21.1610
9.3906e-05	25.3513

(a)

ID Code = M2EC31AB1 *R* = 0.100	
da/dN	Δ*K*
5.7363e-08	3.8548
6.0000e-08	3.8733
1.0000e-07	4.1521
1.8000e-07	5.2943
3.2000e-07	6.3406
6.0000e-07	6.9574
1.0000e-06	7.4276
1.8000e-06	7.9973
3.2000e-06	8.6517
6.0000e-06	9.7726
1.0000e-05	11.5597
1.8000e-05	13.8763
3.2000e-05	16.1539
6.0000e-05	19.0579
1.0000e-04	21.3785
1.8000e-04	23.6624
2.7258e-04	25.0611

(b)

ID Code = M2EC31AB1 *R* = 0.500	
da/dN	Δ*K*
8.4541e-08	2.3823
1.0000e-07	2.8834
1.8000e-07	3.8821
3.2000e-07	4.7230
6.0000e-07	5.3165
1.0000e-06	5.8043
1.8000e-06	6.4553
3.2000e-06	7.2914
6.0000e-06	8.4439
1.0000e-05	9.4712
1.8000e-05	10.6305
3.2000e-05	13.6914
6.0000e-05	15.2424
1.0000e-04	15.9647
1.8000e-04	16.6074
3.2000e-04	17.1308
4.1185e-04	17.3380

(c)

ID Code = M2EC31AB1 *R* = 0.800	
da/dN	Δ*K*
5.8218e-08	2.0137
6.0000e-08	2.0732
1.0000e-07	2.4725
1.8000e-07	3.2892
3.2000e-07	3.9600
6.0000e-07	4.4063
1.0000e-06	4.8039
1.8000e-06	5.5313
3.2000e-06	6.1777
6.0000e-06	6.8245
9.7299e-06	7.4645

(d)

TABLE B-11. MATERIAL DESCRIPTION AND SPECIMEN TESTING INFORMATION FOR 2024-T62 SHEET AND PLATE, L-T

Material ID Code	M2EG11AB1
Alloy Type	2024 Al
Alloy Condition/HT	T62
Product Form	0.08″-0.13″ Sheet, 1.5″ Plate
Test Environments	Laboratory Air, High-Humidity Air, A/C Sump Water
Specimen Types	C(T), M(T)
Crack Orientation	L-T
Specimen Thickness (in.)	C(T): 0.05-1.50 M(T): 0.08-0.12
Specimen Width (in.)	C(T): 10 M(T): 6.0-6.3
Yield Strength (ksi)	53-60
Ultimate Strength (ksi)	64-75
Cyclic Frequency, Hz	0.1-30

Data References for Table B-11.

25 LaSalle, R.M., Rockwell Space Div. Lab. Report LTR 1242-4126, 1976.

112 Data of 2014-T6, 7475-T61, 2024-T62, 7475-T761, 2124-T851, 7475-T7351-Materials received from L. Schwarmann.

C108 Wolnaski, Z.R., "2024-T81 and -T62 0.125-Inch Sheet Metal Allowables," General Dynamics, Fort Worth Div., Report No.16 PR853, October 1978.

E 2 MBB Transport, Germany developed data, copied from ESA Software FRAMES-2.

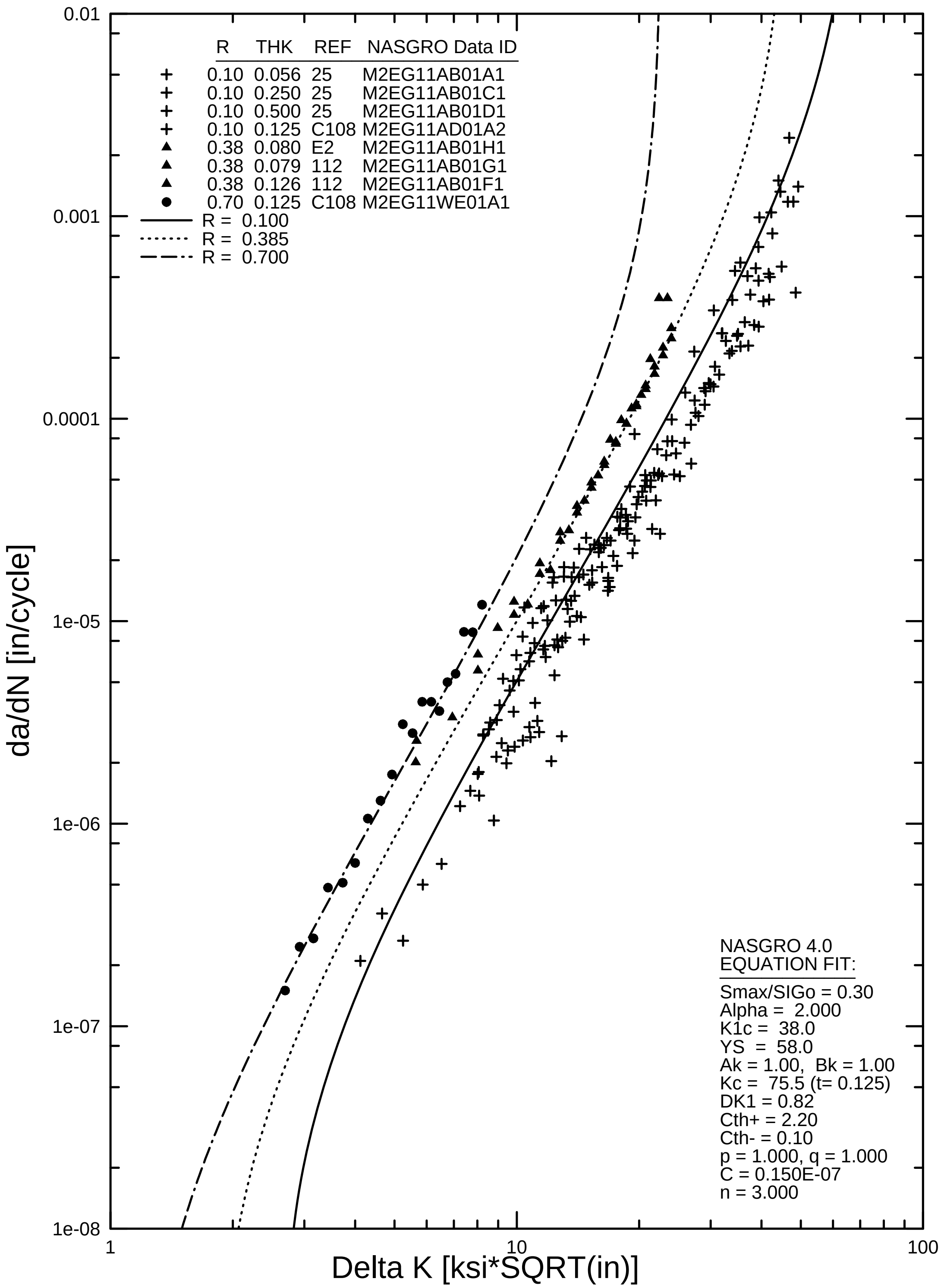


FIGURE B-16. NASGRO EQUATION FIT FOR 2024-T62 SHEET AND PLATE, L-T (M2EG11AB1)

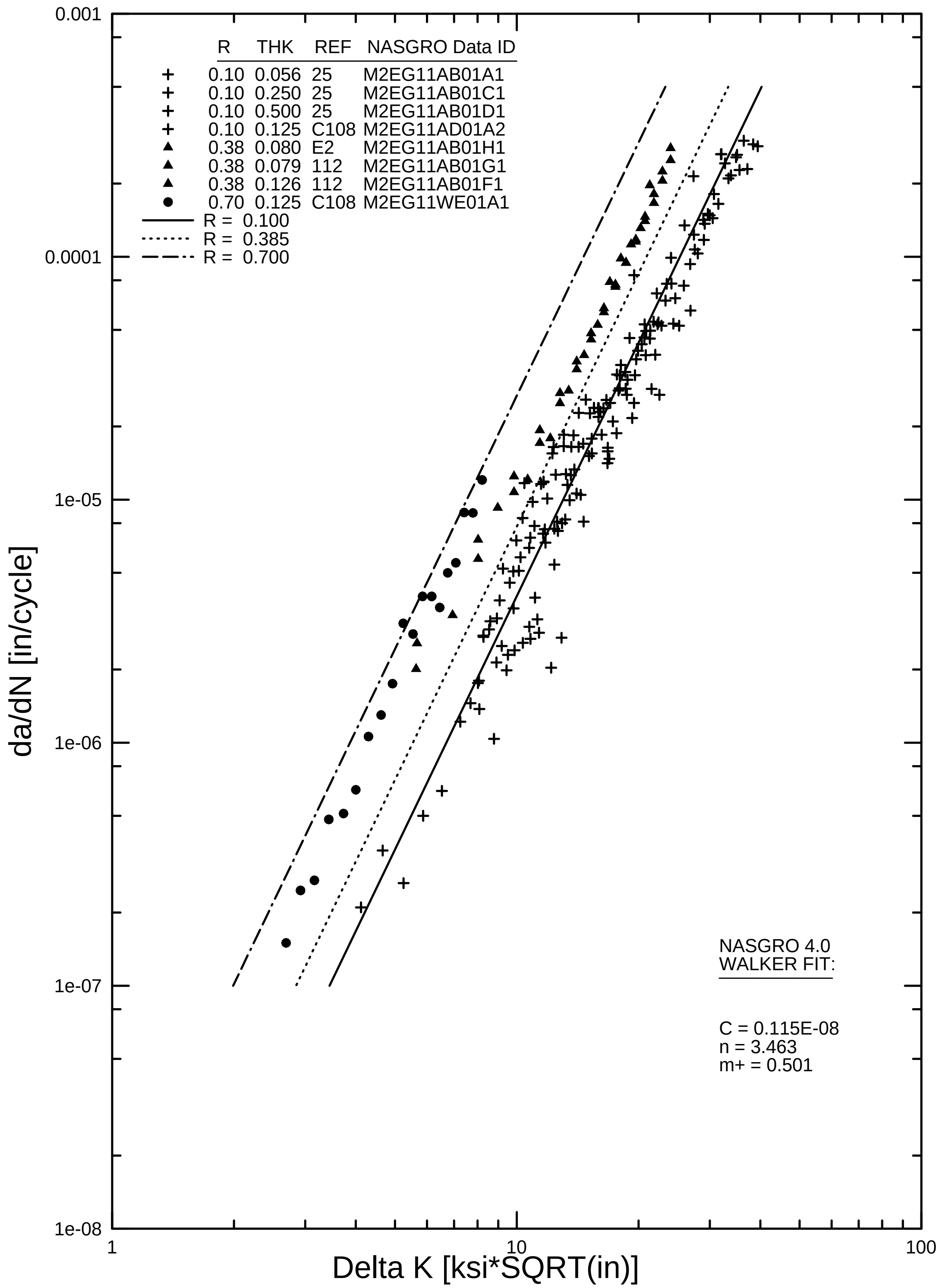


FIGURE B-17. WALKER EQUATION FIT FOR 2024-T62 SHEET AND PLATE, L-T (M2EG11AB1)

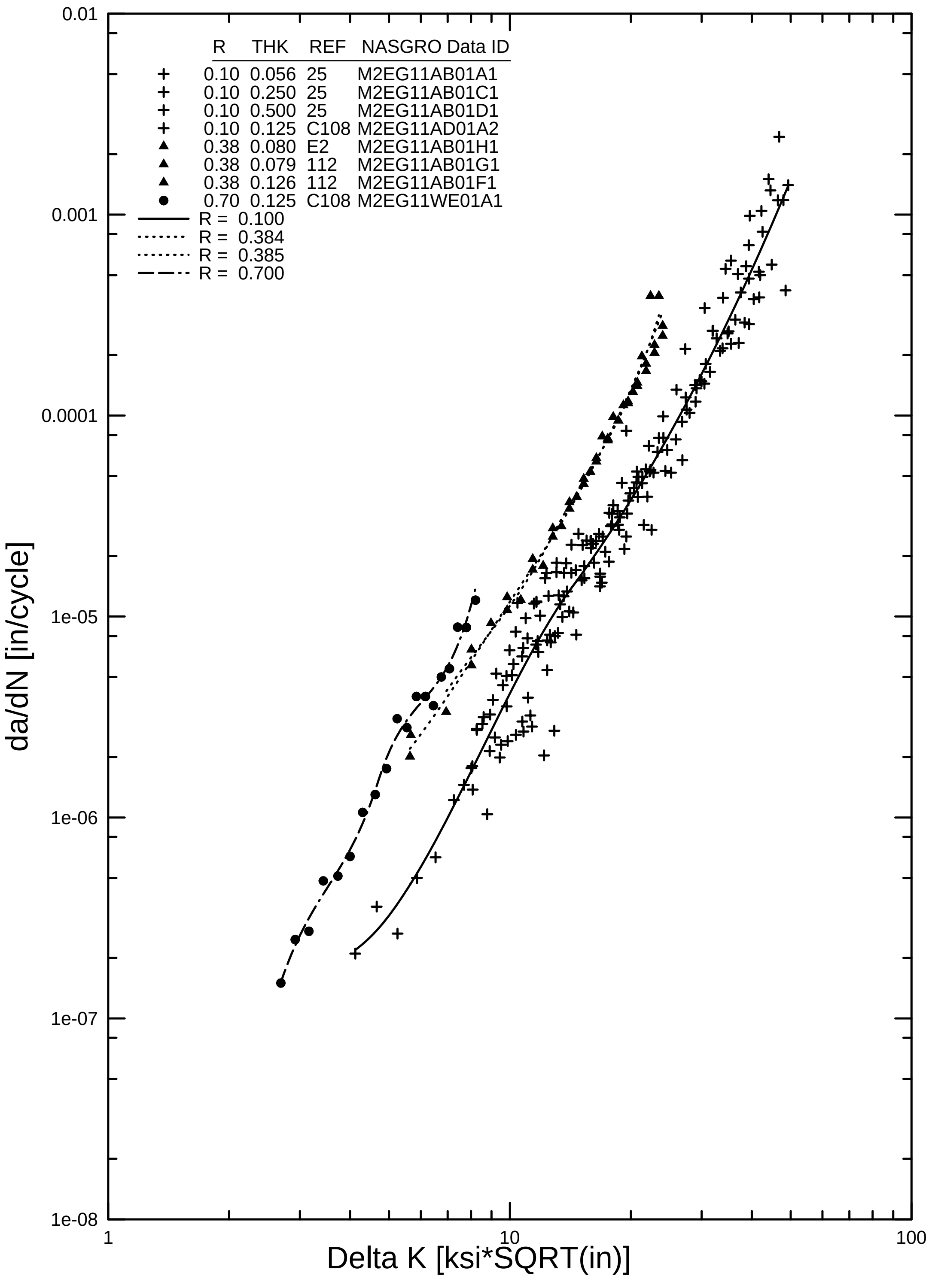


FIGURE B-18. SPLINE FIT FOR 2024-T62 SHEET AND PLATE, L-T (M2EG11AB1)

TABLE B-12. *da/dN*-Δ*K* SPLINE FIT FOR 2024-T62 SHEET AND PLATE, L-T (M2EG11AB1)

ID Code = M2EG11AB1 *R* = 0.1000	
da/dN	Δ*K*
2.1948e-07	4.1210
3.2000e-07	4.9695
6.0000e-07	6.0992
1.0000e-06	7.0058
1.8000e-06	8.1254
3.2000e-06	9.3701
6.0000e-06	11.0177
1.0000e-05	12.7550
1.8000e-05	15.6337
3.2000e-05	18.9492
6.0000e-05	22.9383
1.0000e-04	26.4748
1.8000e-04	30.8858
3.2000e-04	35.5726
6.0000e-04	41.1287
1.0000e-03	45.9928
1.3924e-03	49.3174

(a)

ID Code = M2EG11AB1 *R* = 0.384	
da/dN	Δ*K*
4.2249e-06	6.9343
6.0000e-06	7.8788
1.0000e-05	9.5663
1.8000e-05	11.6353
3.2000e-05	13.6142
6.0000e-05	16.3879
1.0000e-04	18.8175
1.8000e-04	21.3611
3.1543e-04	23.4963

(b)

ID Code = M2EG11AB1 *R* = 0.385	
da/dN	Δ*K*
2.1979e-06	5.6364
3.2000e-06	6.4701
6.0000e-06	8.0071
1.0000e-05	9.4599
1.8000e-05	11.4805
3.2000e-05	13.7988
6.0000e-05	16.4519
1.0000e-04	18.6709
1.8000e-04	21.2781
3.2000e-04	23.8784
3.2781e-04	23.9883

(c)

ID Code = M2EG11AB1 *R* = 0.700	
da/dN	Δ*K*
1.5180e-07	2.6915
1.8000e-07	2.7754
3.2000e-07	3.1725
6.0000e-07	3.8440
1.0000e-06	4.3601
1.8000e-06	4.8417
3.2000e-06	5.6437
6.0000e-06	7.1096
1.0000e-05	7.8526
1.3756e-05	8.2035

(d)

TABLE B-13. MATERIAL DESCRIPTION AND SPECIMEN TESTING INFORMATION FOR 2024-T81 SHEET, L-T

Material ID Code	M2EI11AB1
Alloy Type	2024 Al
Alloy Condition/HT	T81
Product Form	0.063″-0.12″ Sheet
Test Environments	Laboratory Air, Dry Air
Specimen Types	C(T), M(T)
Crack Orientation	L-T
Specimen Thickness (in.)	0.063-0.125
Specimen Width (in.)	C(T): 5.0 M(T): 6-24
Yield Strength (ksi)	57-65
Ultimate Strength (ksi)	70-71
Cyclic Frequency, Hz	1-25

Data References Table B-13.

8 LaSalle, R.M., Rockwell Space Div. Lab. Report LTR 1242-4110, 1975.

A71 Hudson, C.M., NASA TN D-2743, 1965.

C82 "Rockwell International, B-1 Program, da/dN Data, Center-Cracked Tension Specimens," Lockheed California Company, Burbank, CA, Report LR25152, Received July 1973, Memo from E.W. Cawthorne, July 10, 1973.

C108 Wolnaski, Z.R., "2024-T81 and -T62 0.125-Inch Sheet Metal Allowables," General Dynamics, Fort Worth Division, Report No. 16 PR853, October 1978.

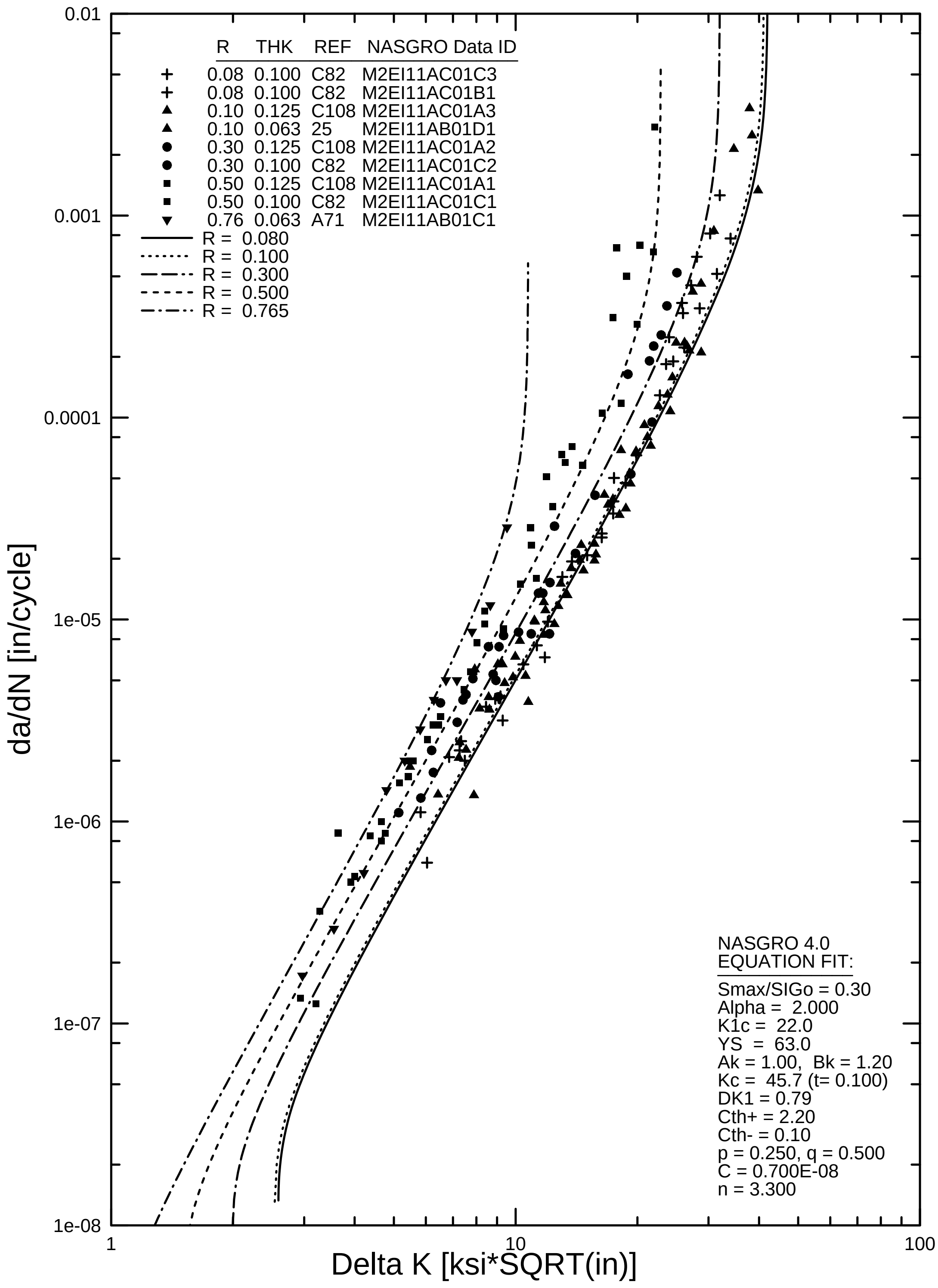


FIGURE B-19. NASGRO EQUATION FIT FOR 2024-T81 SHEET, L-T (M2EI11AB1)

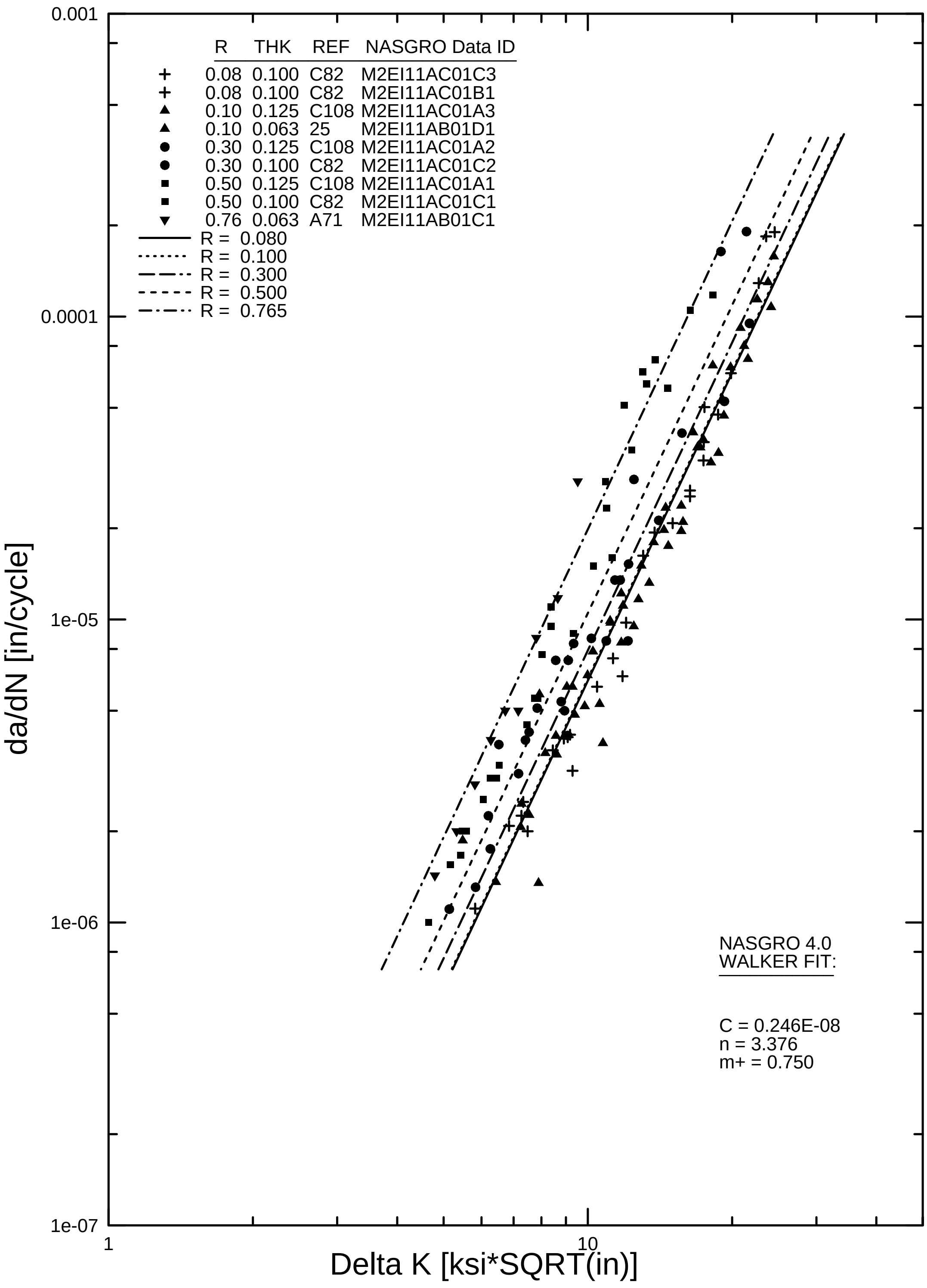


FIGURE B-20. WALKER EQUATION FIT FOR 2024-T81 SHEET, L-T (M2EI11AB1)

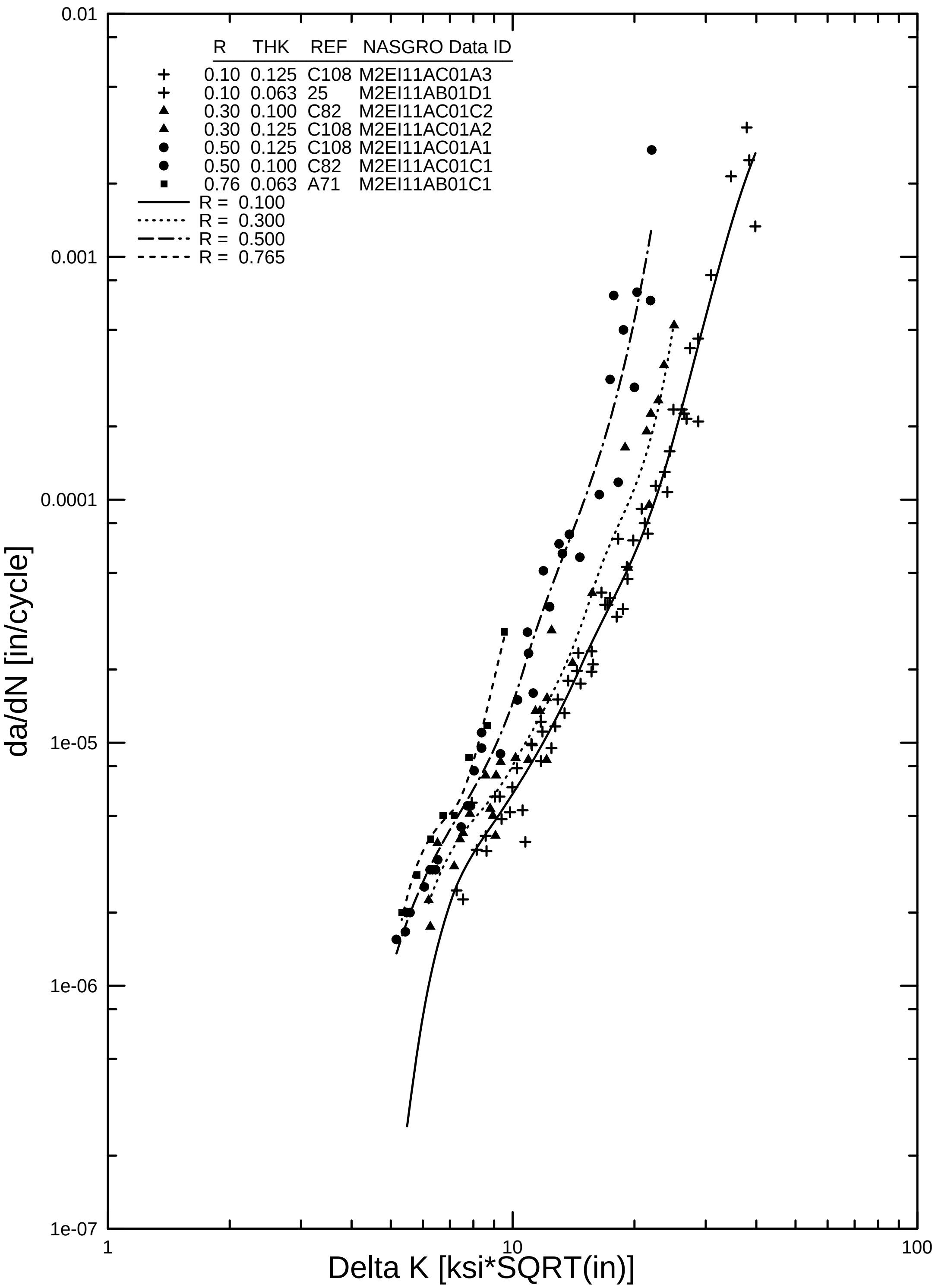


FIGURE B-21. SPLINE FIT FOR 2024-T81 SHEET, L-T (M2EI11AB1)

TABLE B-14. *da/dN*-Δ*K* SPLINE FIT FOR 2024-T81, L-T (M2EI11AC1)

ID Code = M2EI11AC1 *R* = 0.0800	
da/dN	Δ*K*
A spline fit for *R* = 0.08 data was not done since these data were overlapped by *R* = 0.1 data, and the fits ran into each other; consequently, a table was not developed for *R* = 0.08.	

(a)

ID Code = M2EI11AC1 *R* = 0.100	
da/dN	Δ*K*
1.5121e-06	5.4828
1.8000e-06	6.3183
3.2000e-06	8.1673
6.0000e-06	10.0740
1.0000e-05	11.7932
1.8000e-05	14.1838
3.2000e-05	16.9242
6.0000e-05	19.7824
1.0000e-04	22.1049
1.8000e-04	24.8411
3.2000e-04	27.6247
6.0000e-04	30.8212
1.0000e-03	33.5613
1.8000e-03	36.8973
2.9210e-03	39.8107

(b)

ID Code = M2EI11AC1 *R* = 0.300	
da/dN	Δ*K*
2.1182e-06	6.1944
3.2000e-06	6.7855
6.0000e-06	8.9449
1.0000e-05	10.8038
1.8000e-05	12.9153
3.2000e-05	14.9254
6.0000e-05	17.2020
1.0000e-04	19.5218
1.8000e-04	21.8930
3.2000e-04	23.7335
5.2549e-04	25.0611

(c)

ID Code = M2EI11AC1 *R* = 0.500	
da/dN	Δ*K*
1.3578e-06	5.1642
1.8000e-06	5.4607
3.2000e-06	6.3196
6.0000e-06	7.8112
1.0000e-05	9.1432
1.8000e-05	10.4372
3.2000e-05	11.6590
6.0000e-05	13.4082
1.0000e-04	15.0431
1.8000e-04	16.9024
3.2000e-04	18.5695
6.0000e-04	20.2093
1.0000e-03	21.4259
1.3373e-03	22.0800

(d)

TABLE B-14. *da/dN*-Δ*K* SPLINE FIT FOR 2024-T81, L-T (M2EI11AC1)
(Continued)

ID Code = M2EI11AC1 R = 0.765	
da/dN	Δ*K*
1.4563e-06	4.7973
1.8000e-06	5.2542
3.2000e-06	5.9156
6.0000e-06	7.4386
1.0000e-05	8.2427
1.8000e-05	9.0014
2.7254e-05	9.5280

(e)

TABLE B-15. MATERIAL DESCRIPTION AND SPECIMEN TESTING INFORMATION FOR 7050-T7451 PLATE, L-T

Material ID Code	M7GJ11AB1
Alloy Type	7050 Al
Alloy Condition/HT	T7451
Product Form	1″-6″ Plate
Test Environments	Laboratory Air, Dry Air
Specimen Types	C(T), M(T)
Crack Orientation	L-T
Specimen Thickness (in.)	C(T): 0.5-1.0 M(T): 0.18-0.39
Specimen Width (in.)	C(T): 3-6 M(T): 3.9-6.3
Yield Strength (ksi)	62-68
Ultimate Strength (ksi)	72-80
Cyclic Frequency, Hz	6-50

Data References for Table B-15.

1 Forman, R.G., Unpublished NASA Johnson Space Center test data.

108 "Test Data (crack propagation) of 7050 Material," ref. 4231, LBF, Darmstadt, received from L. Schwarmann, MBB Transport, Germany.

C2 "Fracture Toughness Data Collection, Rockwell International Corporation, from B-1 Program," Rockwell International Corporation, Los Angeles, CA, April 1973.

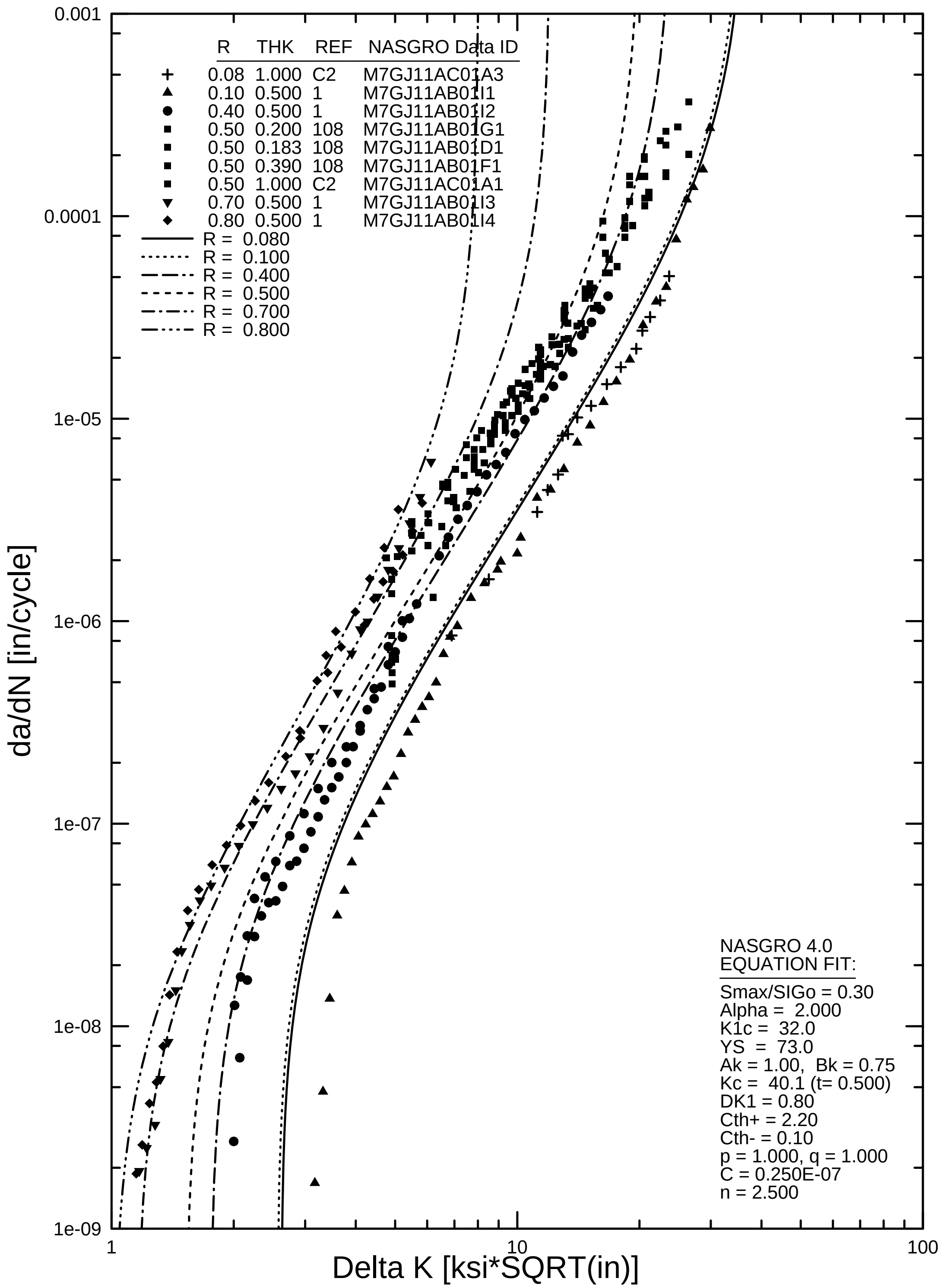


FIGURE B-22. NASGRO EQUATION FIT FOR 7050-T7451, L-T (M7GJ11AC1)

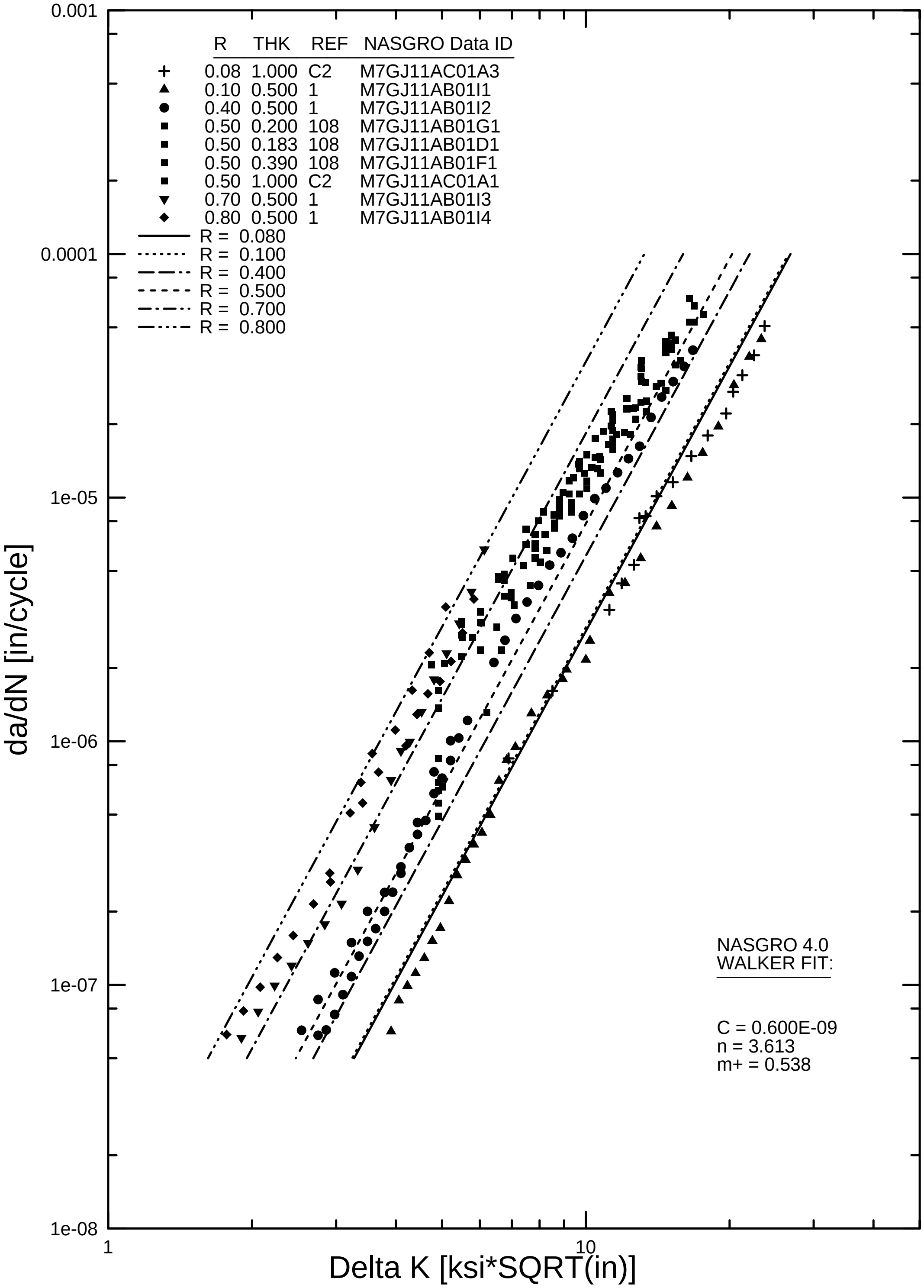


FIGURE B-23. WALKER EQUATION FIT FOR 7050-T7451 PLATE, L-T (M7GJ11AB1)

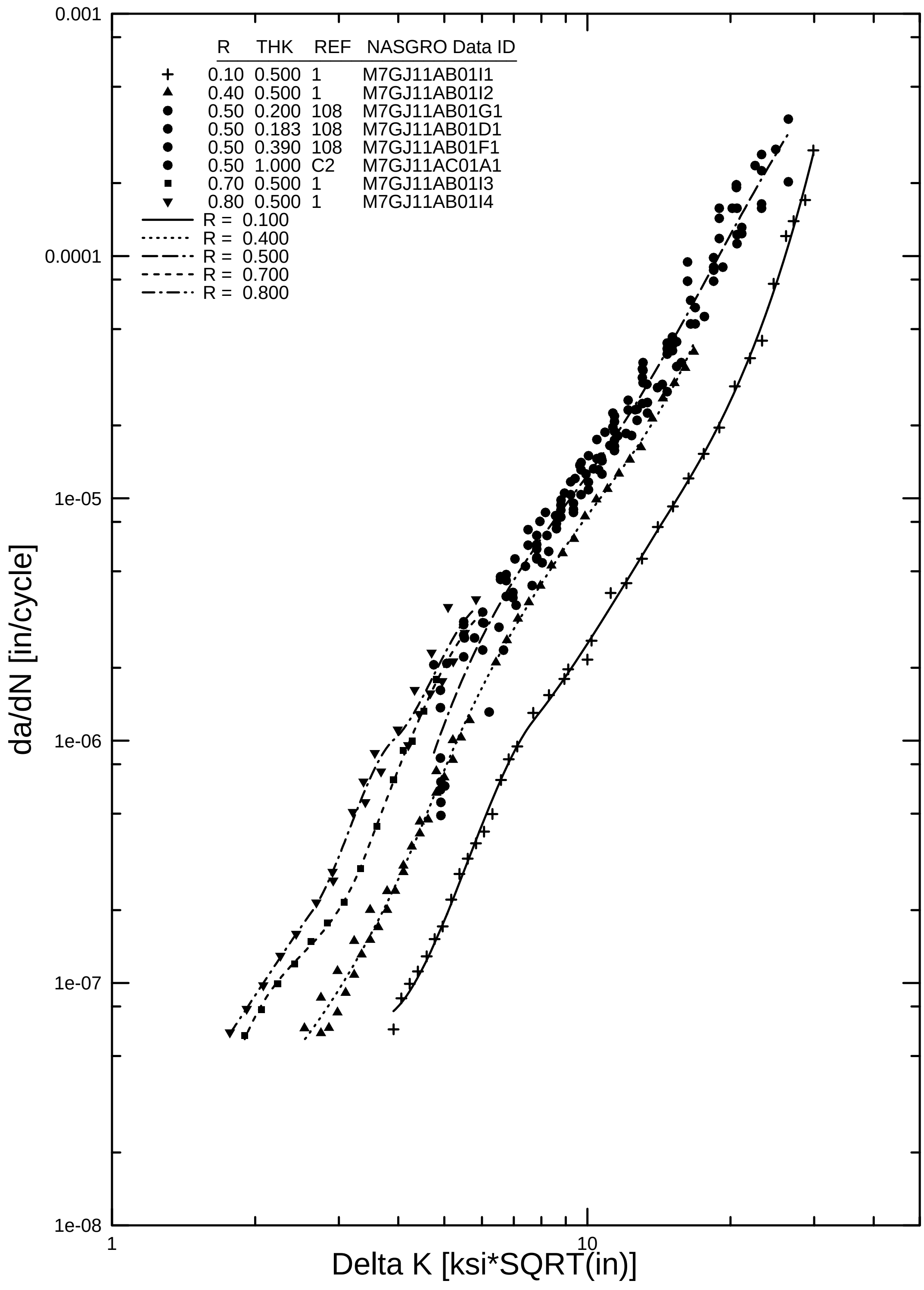


FIGURE B-24. SPLINE FIT FOR 7050-T7451 PLATE, L-T (M7GJ11AB1)

TABLE B-16. *da/dN*-Δ*K* SPLINE FIT FOR 7050-T7451, L-T (M7GJ11AC1)

ID Code = M7GJ11AC1 *R* = 0.0800	
da/dN	Δ*K*
8.1560e-07	6.8865
1.0000e-06	7.1373
1.8000e-06	8.5740
3.2000e-06	11.2303
6.0000e-06	12.6427
1.0000e-05	13.7598
1.8000e-05	18.5817
3.2000e-05	21.4952
6.0000e-05	23.1962

(a)

ID Code = M7GJ11AC1 *R* = 0.100	
da/dN	Δ*K*
5.8598e-08	3.9084
6.0000e-08	3.9241
1.0000e-07	4.2994
1.8000e-07	4.8354
3.2000e-07	5.5089
6.0000e-07	6.4799
1.0000e-06	7.5038
1.8000e-06	8.9768
3.2000e-06	10.6903
6.0000e-06	13.0444
1.0000e-05	15.4584
1.8000e-05	18.3955
3.2000e-05	21.1440
6.0000e-05	23.9296
1.0000e-04	26.0453
1.8000e-04	28.3481
2.6886e-04	29.8538

(b)

ID Code = M7GJ11AC1 *R* = 0.400	
da/dN	Δ*K*
5.8374e-08	2.5410
6.0000e-08	2.5675
1.0000e-07	3.0591
1.8000e-07	3.6212
3.2000e-07	4.1691
6.0000e-07	4.7674
1.0000e-06	5.3145
1.8000e-06	6.1336
3.2000e-06	7.2176
6.0000e-06	8.8385
1.0000e-05	10.6337
1.8000e-05	13.1499
3.2000e-05	15.5498
4.3702e-05	16.7494

(c)

ID Code = M7GJ11AC1 *R* = 0.500	
da/dN	Δ*K*
8.9219e-07	4.7534
1.0000e-06	4.8525
1.8000e-06	5.4633
3.2000e-06	6.2946
6.0000e-06	7.6432
1.0000e-05	9.2110
1.8000e-05	11.4217
3.2000e-05	13.7010
6.0000e-05	16.4040
1.0000e-04	18.8969
1.8000e-04	22.2837
3.2000e-04	26.4682
3.2064e-04	26.4850

(d)

TABLE B-16. *da/dN*-Δ*K* SPLINE FIT FOR 7050-T7451, L-T (M7GJ11AC1)
(Continued)

ID Code = M7GJ11AC1 *R* = 0.700	
da/dN	Δ*K*
5.8414e-08	1.9011
6.0000e-08	1.9119
1.0000e-07	2.2139
1.8000e-07	2.8924
3.2000e-07	3.3723
6.0000e-07	3.8130
1.0000e-06	4.2446
1.8000e-06	4.8279
3.2000e-06	5.4787
5.4116e-06	6.1235

(e)

ID Code = M7GJ11AC1 *R* = 0.800	
da/dN	Δ*K*
6.3591e-08	1.7701
1.0000e-07	2.0983
1.8000e-07	2.5583
3.2000e-07	2.9669
6.0000e-07	3.3785
1.0000e-06	3.8713
1.8000e-06	4.7429
3.2000e-06	5.5754
3.9566e-06	5.8345

(f)

TABLE B-17. MATERIAL DESCRIPTION AND SPECIMEN TESTING INFORMATION FOR 7075-T651 PLATE, L-T

Material ID Code	M7HB11AB1
Alloy Type	7075 Al
Alloy Condition/HT	T651
Product Form	1″-5″ Plate
Test Environments	Laboratory Air
Specimen Types	C(T), M(T), SE(B)
Crack Orientation	L-T
Specimen Thickness (in.)	C(T): 0.2 M(T): 0.15-0.5 SE(B): 0.2
Specimen Width (in.)	C(T): 3.0 M(T): 4.0 SE(B): 1.5
Yield Strength (ksi)	74-80
Ultimate Strength (ksi)	75-87
Cyclic Frequency, Hz	0.1-30

Data References for Table B-17.

29 Kathiresan, K., et al., AFWAL-TR-84-3080, 1984.

367 Henkener, J.A., “The Fatigue Crack Growth Behavior of an Experimental Ternary Al-2.6Li-0.09Zr Alloy,” M.S. Thesis, School of Aeronautics and Astronautics, Purdue University, December 1989.

368 Walker, K.F., “The Effect on Fatigue Crack Growth Under Spectrum Loading of an Imposed “g” Limit,” M.S. Thesis, School of Aeronautics and Astronautics, Purdue University, December 1987.

C92 FCGR Data Sheets on Aluminum Alloys 7075-T651, -T6510, -T7351, T73510, Plates, Bars, and Extrusions, received from R.J. Bucci, Alcoa Laboratories, August 1982.

C111 Garland, K., et al., “Evaluation of Stress Level Effects Under Plane Stress and Plane Strain Conditions,” McDonnell Aircraft Company, St. Louis, MO, Report No. TR 301-346, TM 256-5597, July 1979.

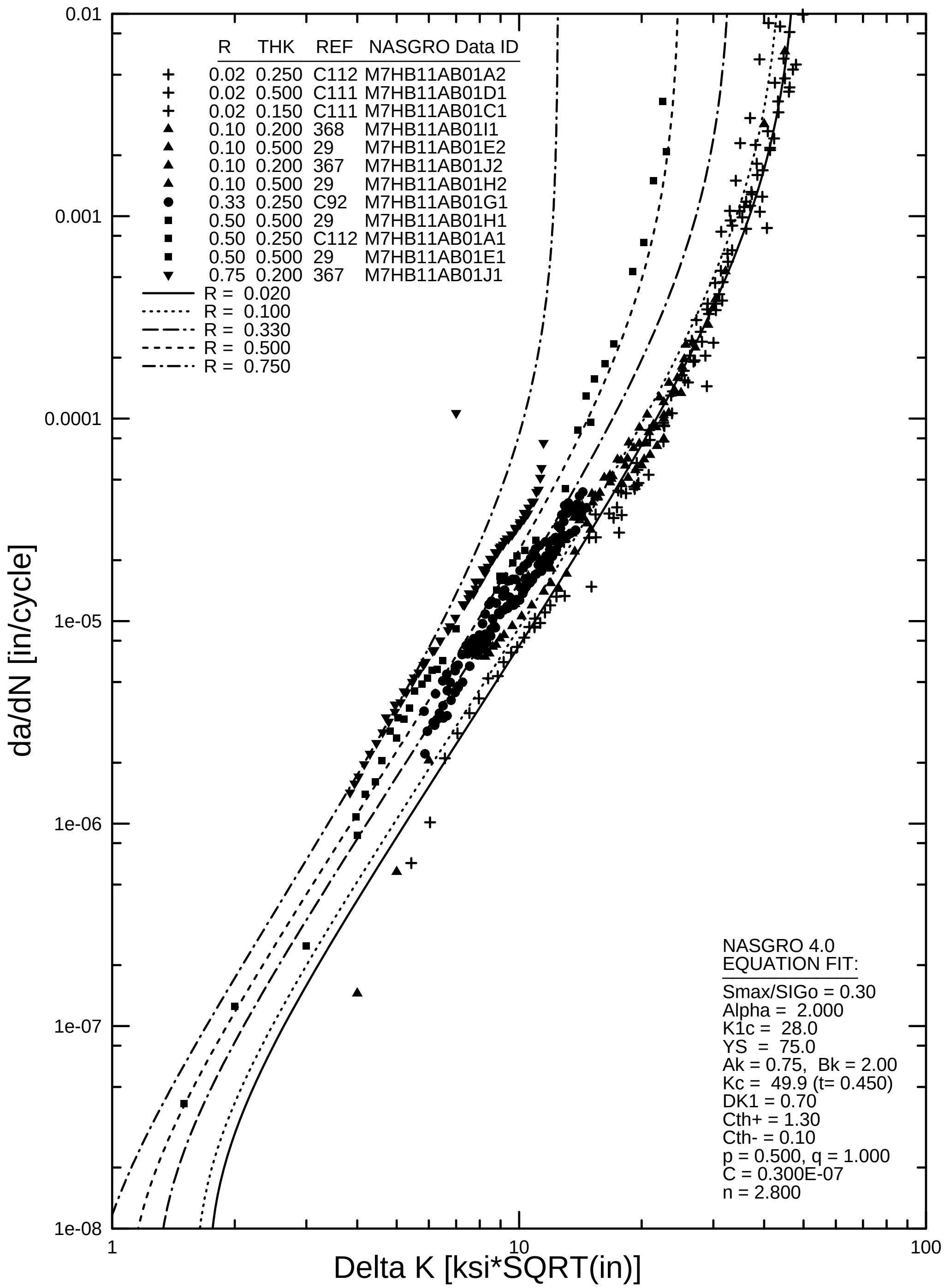


FIGURE B-25. NASGRO EQUATION FIT FOR 7075-T651 PLATE, L-T (M7HB11AB1)

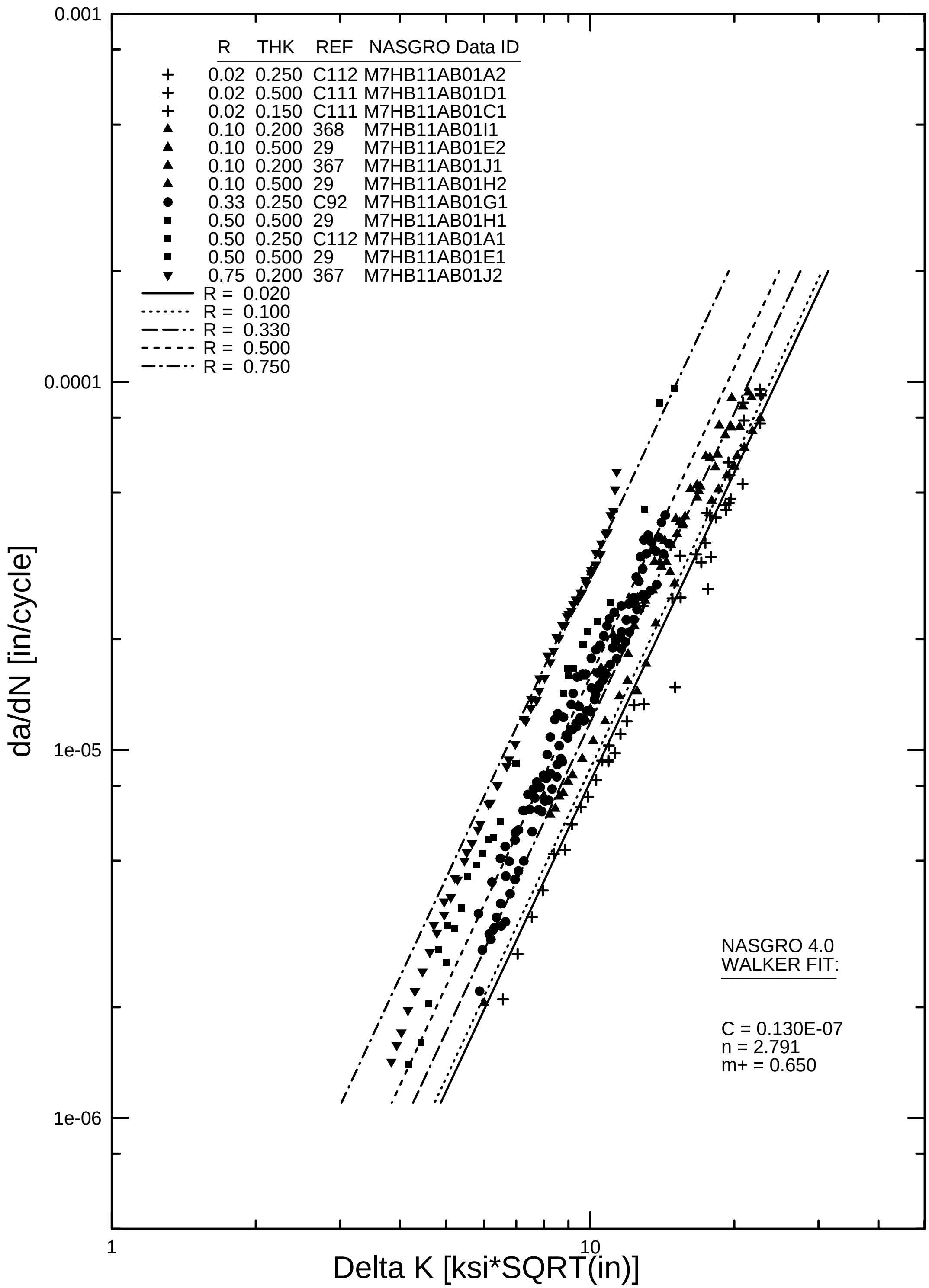


FIGURE B-26. WALKER EQUATION FIT FOR 7075-T651 PLATE, L-T (M7HB11AB1)

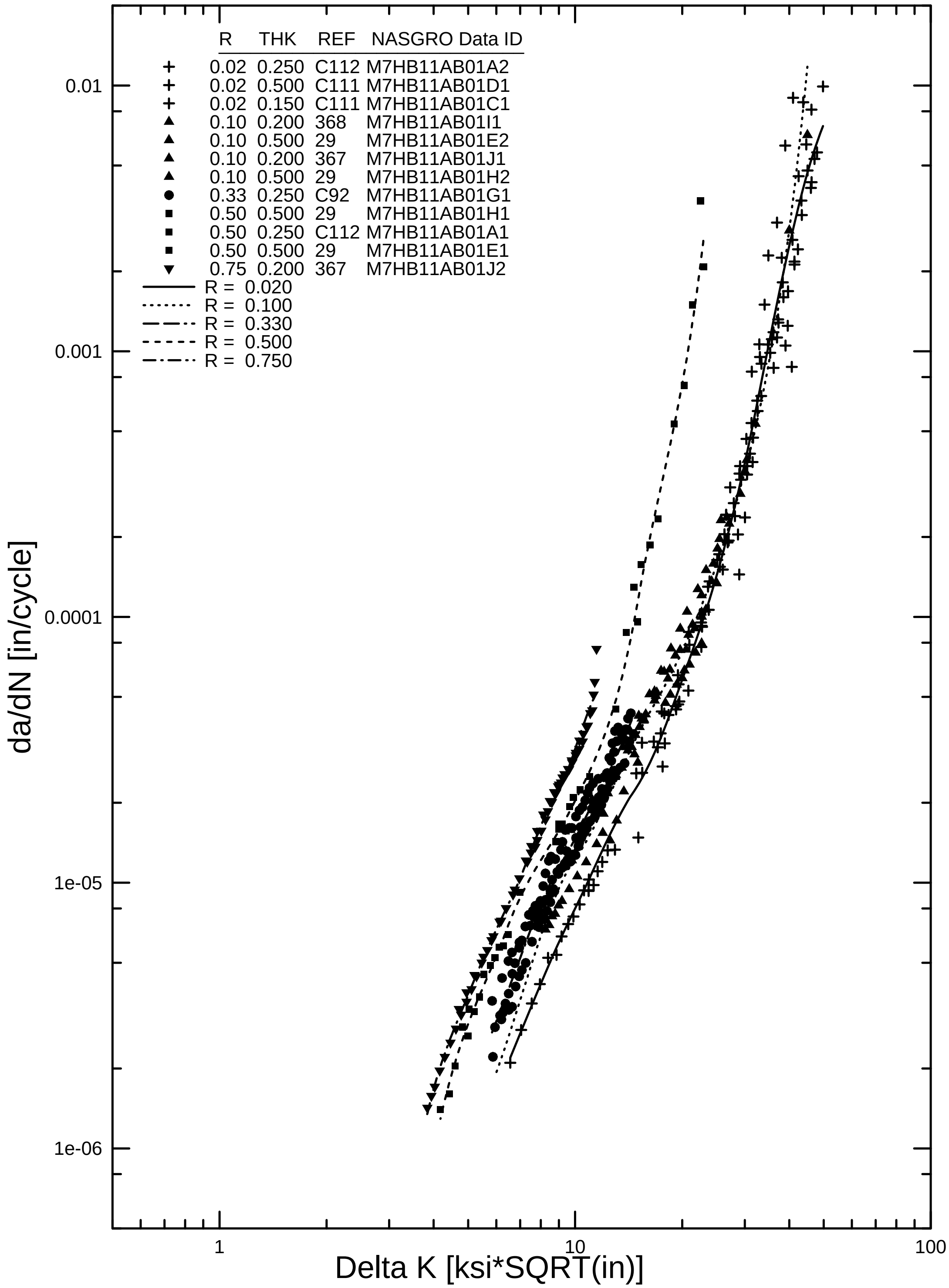


FIGURE B-27. SPLINE FIT FOR 7075-T651 PLATE, L-T (M7HB11AB1)

TABLE B-18. *da/dN*-Δ*K* SPLINE FIT FOR 7075-T651 PLATE, L-T (M7HB11AB1)

ID Code = M7HB11AB1 *R* = 0.0200	
da/dN	Δ*K*
1.5807e-06	6.5766
1.8000e-06	6.6888
3.2000e-06	7.3231
6.0000e-06	8.5829
1.0000e-05	10.8582
1.8000e-05	13.8534
3.2000e-05	16.7731
6.0000e-05	20.1339
1.0000e-04	23.0400
1.8000e-04	26.2657
3.2000e-04	29.1962
6.0000e-04	32.2217
1.0000e-03	34.7632
1.8000e-03	37.9747
3.2000e-03	41.7090
6.0000e-03	47.4713
7.0500e-03	49.7737

(a)

ID Code = M7HB11AB1 *R* = 0.100	
da/dN	Δ*K*
1.9393e-06	5.9979
3.2000e-06	6.5679
6.0000e-06	7.6743
1.0000e-05	9.2446
1.8000e-05	11.7065
3.2000e-05	14.3709
6.0000e-05	18.4718
1.0000e-04	22.0157
1.8000e-04	25.8284
3.2000e-04	29.3833
6.0000e-04	33.0371
1.0000e-03	35.6039
1.8000e-03	38.1755
3.2000e-03	40.3990
6.0000e-03	42.5860
1.0000e-02	44.2216
1.2814e-02	44.9780

(b)

ID Code = M7HB11AB1 *R* = 0.330	
da/dN	Δ*K*
2.7318e-06	5.8344
3.2000e-06	6.1088
6.0000e-06	7.2824
1.0000e-05	8.5283
1.8000e-05	10.7929
3.2000e-05	13.3698
4.3040e-05	14.6218

(c)

TABLE B-18. *da/dN*-Δ*K* SPLINE FIT FOR 7075-T651 PLATE, L-T (M7HB11AB1) (Continued)

ID Code = M7HB11AB1 R = 0.500	
da/dN	Δ*K*
1.2917e-06	4.1783
1.8000e-06	4.4434
3.2000e-06	5.1235
6.0000e-06	6.2293
1.0000e-05	7.3569
1.8000e-05	9.5381
3.2000e-05	11.7040
6.0000e-05	13.5667
1.0000e-04	14.7245
1.8000e-04	15.9835
3.2000e-04	17.5284
6.0000e-04	19.3648
1.0000e-03	20.7486
1.8000e-03	22.1482
2.7095e-03	23.0144

(d)

ID Code = M7HB11AB1 R = 0.750	
da/dN	Δ*K*
1.3468e-06	3.8371
1.8000e-06	4.0614
3.2000e-06	4.7505
6.0000e-06	5.7897
1.0000e-05	6.9182
1.8000e-05	8.2688
3.2000e-05	10.0100
5.1797e-05	11.4815

(e)

TABLE B-19. MATERIAL DESCRIPTION AND SPECIMEN TESTING INFORMATION FOR 7075-T7351 PLATE, L-T

Material ID Code	M7HH11AB1
Alloy Type	7075 Al
Alloy Condition/HT	T7351
Product Form	0.4″-5.0″ Plate
Test Environments	Laboratory Air, High-Humidity Air
Specimen Types	C(T), M(T)
Crack Orientation	L-T
Specimen Thickness (in.)	C(T): 0.25-0.5 M(T): 0.18-0.50
Specimen Width (in.)	C(T): 2-5 M(T): 4-7
Yield Strength (ksi)	60-64
Ultimate Strength (ksi)	72-74
Cyclic Frequency, Hz	0.1-40

Data References for Table B-19.

23 LaSalle, R.M., Rockwell Space Div. Lab. Report LTR 1242-4150, 1977.

B218 Liu, A.F., et al., "Effect of Multiaxial Loading on Crack Growth," Vol. I & II, AFFDL-TR-78-175, 1978.

C39 Garland, K., et al., "Evaluation of the Effect of Material Cyclic Softening and Hardening on Crack Initiation Life and Crack Growth, with and without Overloads, as a Function of Stress Ratio," McDonnell Aircraft Co., St. Louis, MO, April 1978.

C92 FCGR Data Sheets on Aluminum Alloy 7075-T651, T6510 T7351, T73510, Plates, Bars, and Extrusions; Received from R.J. Bucci, Alcoa Laboratories, August 1982.

C103 Ruff, P.E., et al., "Development of Mil-Hdbk-5 Design Allowable Properties and Fatigue Crack-Propagation Data for Several Aerospace Materials," Battelle Laboratories, Columbus, OH, AFML-TR-77-162, 1977.

C114 Chanani, G.R., et al., "Methodology for Evaluation of Fatigue Crack-Growth Resistance of Aluminum Alloys Under Spectrum Loading," Northrop Corp., Hawthorne, CA, Contract No. N00019-80-C-0427, 1982.

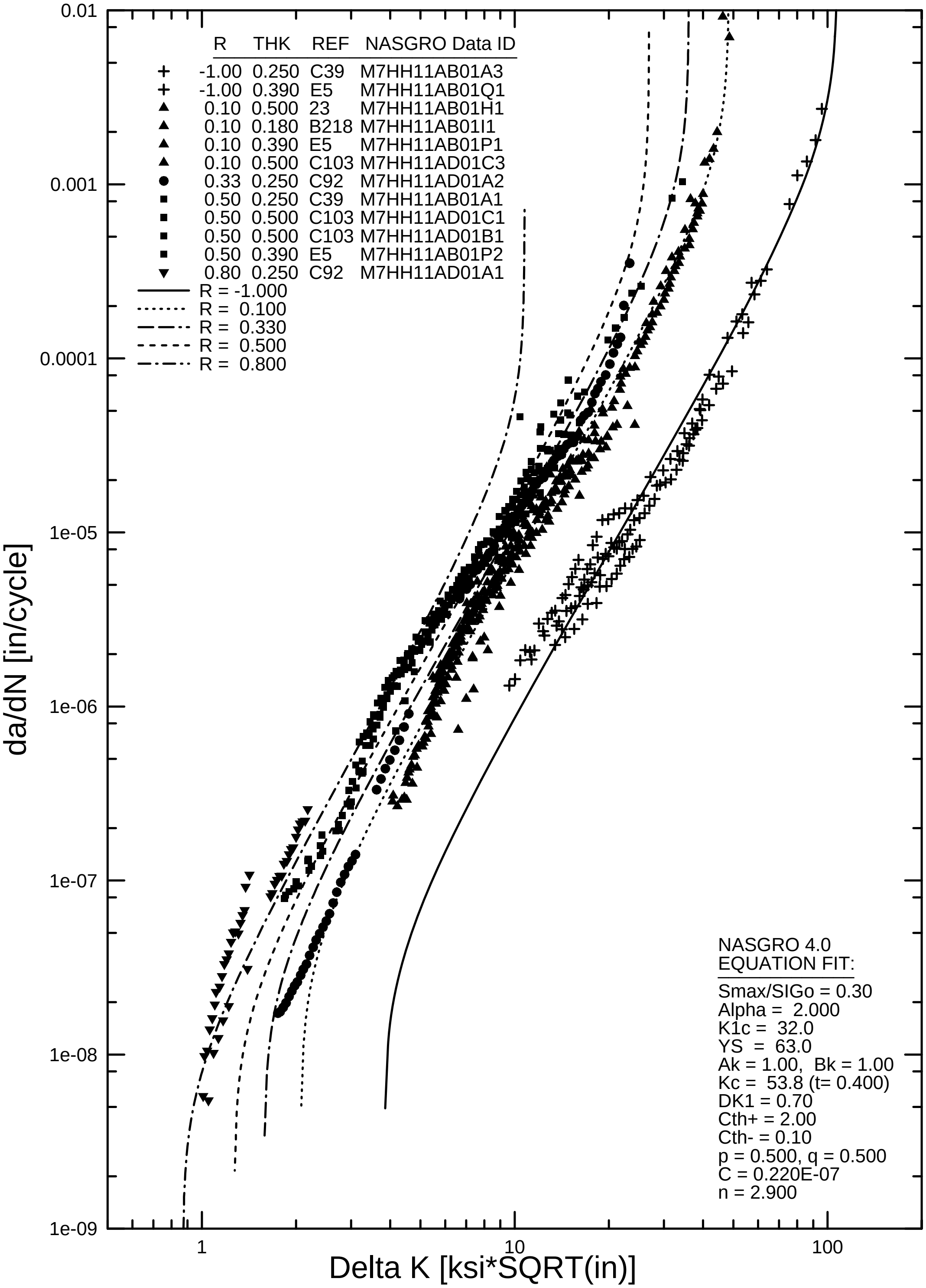


FIGURE B-28. NASGRO EQUATION FIT FOR 7075-T7351 PLATE, L-T (M7HH11AB1) WITH POSITIVE AND NEGATIVE *R* VALUES

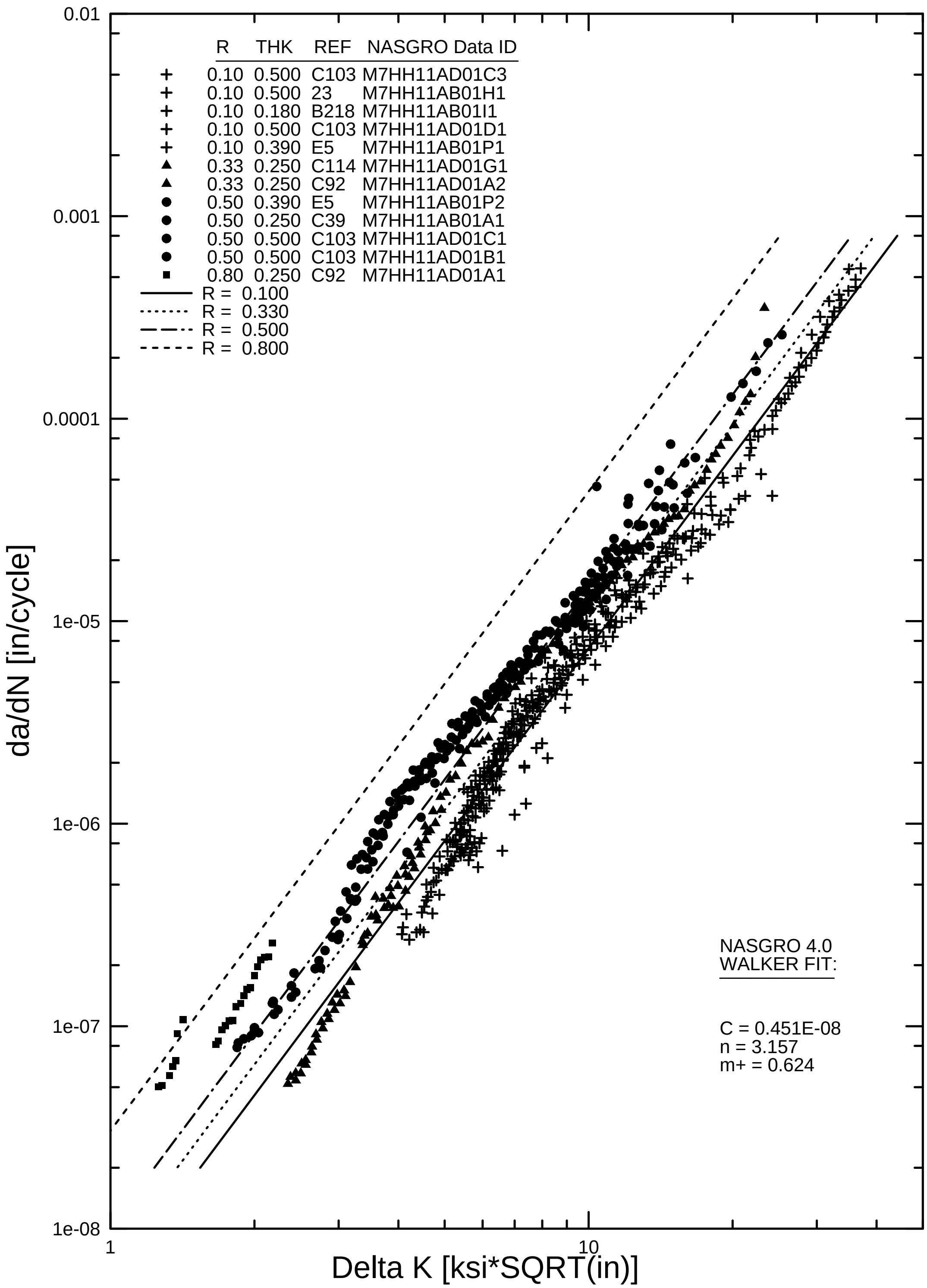


FIGURE B-29a. WALKER EQUATION FIT FOR 7075-T7351 PLATE, L-T (M7HH11AB1) WITH POSITIVE *R* VALUES

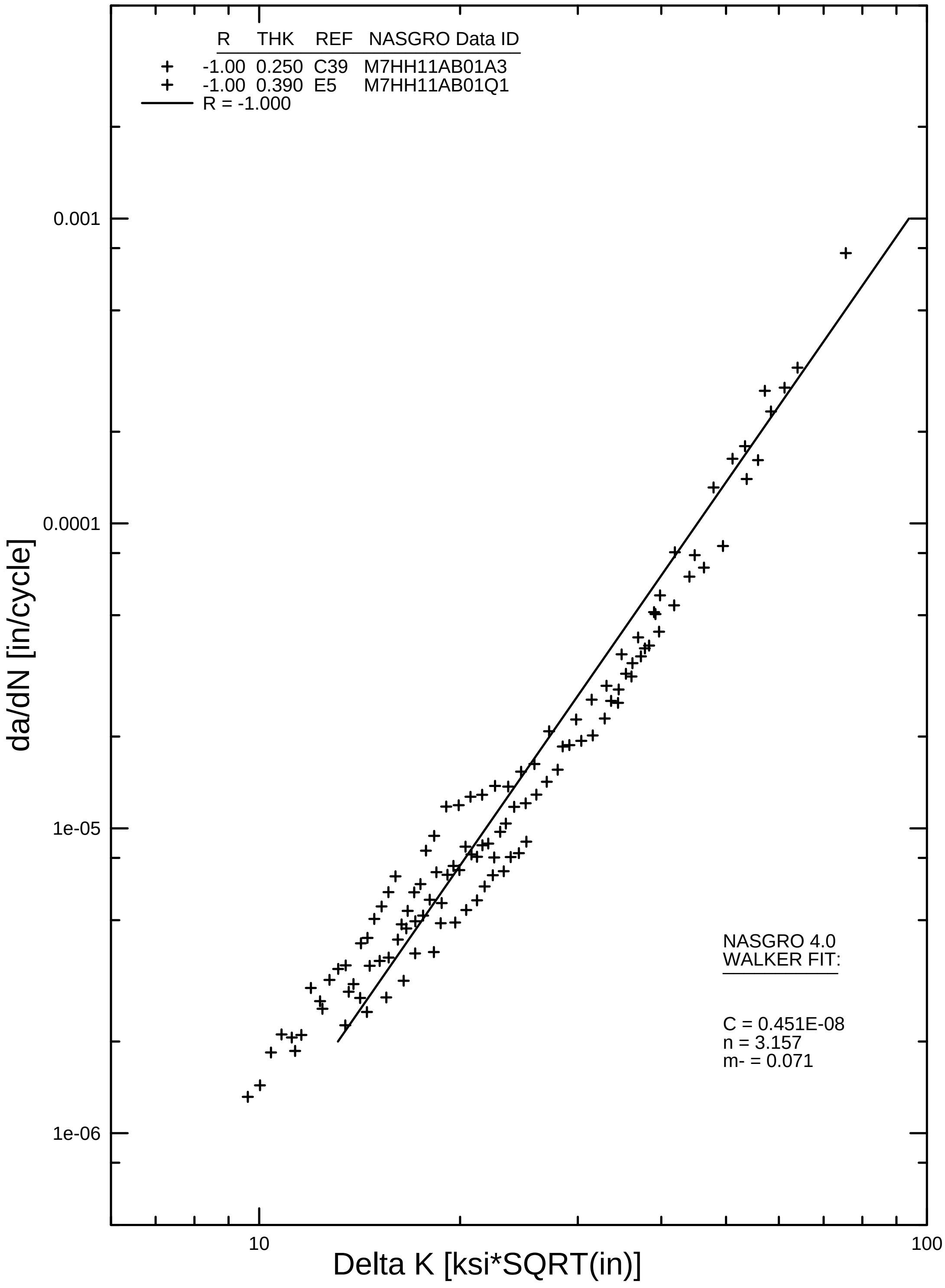


FIGURE B-29b. WALKER EQUATION FIT FOR 7075-T7351 PLATE, L-T (M7HH11AB1) WITH NEGATIVE *R* VALUE

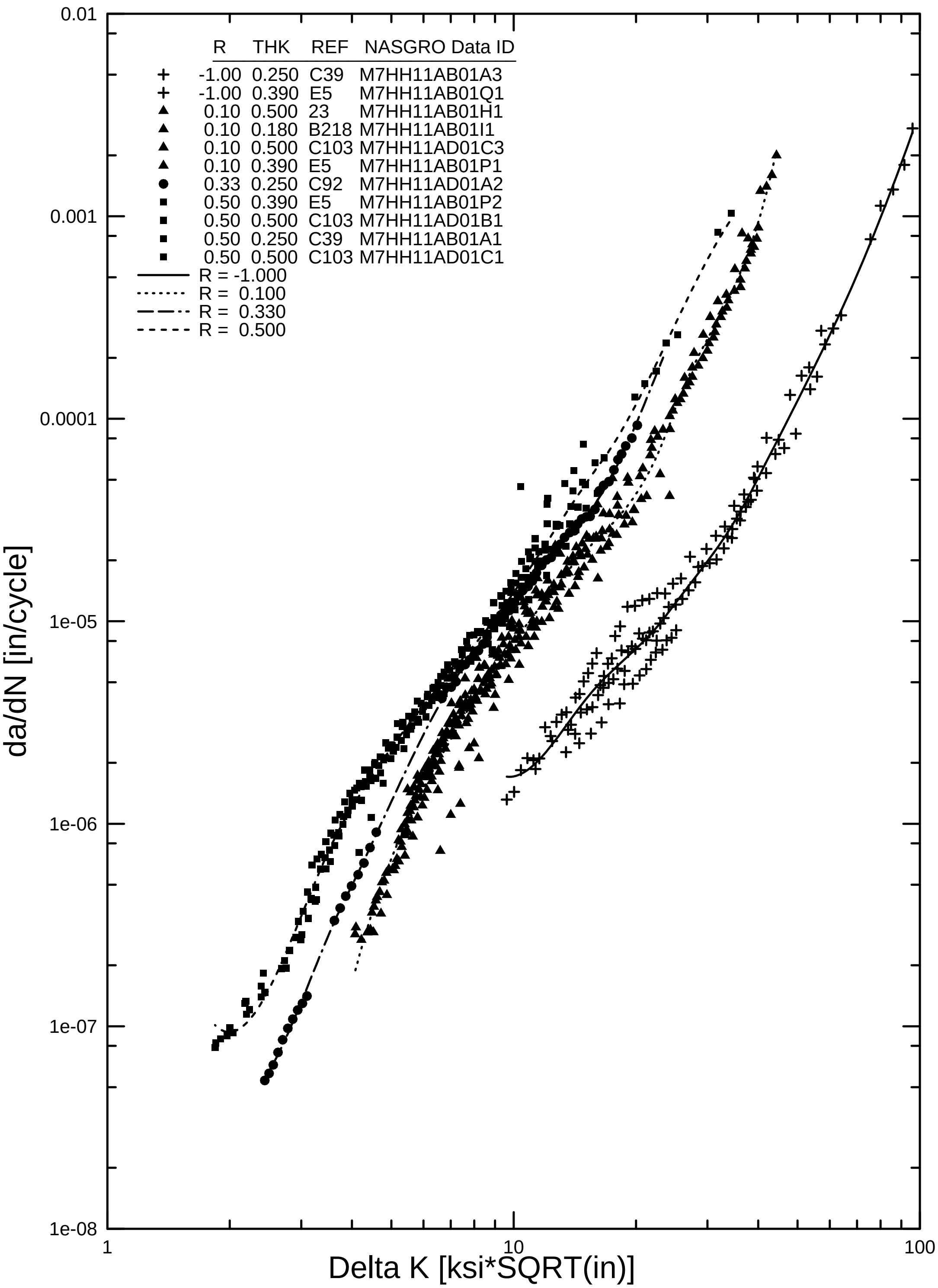


FIGURE B-30. SPLINE FIT FOR 7075-T7351 PLATE, L-T (M7HH11AB1) WITH POSITIVE AND NEGATIVE *R* VALUES

TABLE B-20. *da/dN*-Δ*K* SPLINE FIT FOR 7075-T7351 PLATE, L-T (M7HH11AB1)

ID Code = M7HH11AB1 *R* = -1.0000	
da/dN	Δ*K*
1.7090e-06	9.6161
1.8000e-06	10.6269
3.2000e-06	13.6988
6.0000e-06	17.9786
1.0000e-05	23.1466
1.8000e-05	28.9537
3.2000e-05	35.2654
6.0000e-05	41.6655
1.0000e-04	47.4594
1.8000e-04	54.9489
3.2000e-04	63.0452
6.0000e-04	72.3735
1.0000e-03	80.2754
1.8000e-03	89.7607
2.6027e-03	95.9401

(a)

ID Code = M7HH11AB1 *R* = 0.100	
da/dN	Δ*K*
2.3134e-07	4.0738
3.2000e-07	4.3388
6.0000e-07	4.9391
1.0000e-06	5.5348
1.8000e-06	6.3837
3.2000e-06	7.4536
6.0000e-06	9.0343
1.0000e-05	10.8263
1.8000e-05	13.8977
3.2000e-05	17.6080
6.0000e-05	21.4984
1.0000e-04	24.6793
1.8000e-04	28.4276
3.2000e-04	32.2244
6.0000e-04	36.5457
1.0000e-03	40.2063
1.8000e-03	44.5978
2.9807e-03	48.5289

(b)

ID Code = M7HH11AB1 *R* = 0.330	
da/dN	Δ*K*
6.4121e-08	2.5119
1.0000e-07	2.7960
1.8000e-07	3.1445
3.2000e-07	3.5413
6.0000e-07	4.2106
1.0000e-06	4.7130
1.8000e-06	5.3223
3.2000e-06	6.2131
6.0000e-06	7.6060
1.0000e-05	9.0726
1.8000e-05	11.6528
3.2000e-05	14.6955
6.0000e-05	18.2230
1.0000e-04	20.2243
1.8000e-04	22.0872
2.8314e-04	23.3346

(c)

ID Code = M7HH11AB1 *R* = 0.500	
da/dN	Δ*K*
1.0140e-07	1.8408
1.8000e-07	2.6025
3.2000e-07	2.9454
6.0000e-07	3.3527
1.0000e-06	3.7879
1.8000e-06	4.5449
3.2000e-06	5.5883
6.0000e-06	7.2156
1.0000e-05	8.8993
1.8000e-05	10.9133
3.2000e-05	13.1654
6.0000e-05	16.3186
1.0000e-04	19.1591
1.8000e-04	22.2397
3.2000e-04	25.5060
6.0000e-04	29.8414
9.6208e-04	34.3558

(d)

TABLE B-20. *da/dN*-Δ*K* SPLINE FIT FOR 7075-T7351 PLATE, L-T (M7HH11AB1) (Continued)

ID Code = M7HH11AB1 *R* = 0.800	
da/dN	Δ*K*
A spline fit for *R* = 0.800 data was not done because of considerable scatter in them; consequently, a table was not developed for *R* = 0.800.	

(e)

TABLE B-21. MATERIAL DESCRIPTION AND SPECIMEN TESTING INFORMATION FOR 7475-T7351 PLATE, L-T

Material ID Code	M7TF11AB1
Alloy Type	7475 Al
Alloy Condition/HT	T7351
Product Form	1.5″-3″ Plate
Test Environments	Laboratory Air
Specimen Types	C(T), M(T)
Crack Orientation	L-T
Specimen Thickness (in.)	C(T): 0.5-0.75 M(T): 0.2-0.3
Specimen Width (in.)	C(T): 0.5-5.0 M(T): 6.3-12.0
Yield Strength (ksi)	60-67
Ultimate Strength (ksi)	69-75
Cyclic Frequency, Hz	1-20

Data References for Table B-21.

140 Zhang, S., et al., "Crack Propagation Studies on Al 7475 on the Basis of Constant Amplitude and Selective Amplitude Loading Histories," Fatigue Fract Engr Matr Struct, Vol. 10, No. 4, 1987, pp. 315-332.

361 Larson, B.F., "C-17 Material Specimen Tests for Fracture Mechanics Data," Phase I, Lot 1 Aluminum Alloys.

B177 Cervay, R.R., AFML-TR-75-20, 1975.

C77 Cervay, R.R., "Engineering Design Data for Aluminum Alloy 7475 in the T761 and T61 Condition," Report AFML-TR-72-173, UDRI, Dayton OH, Contract F33615-71-C-1054, September 1972.

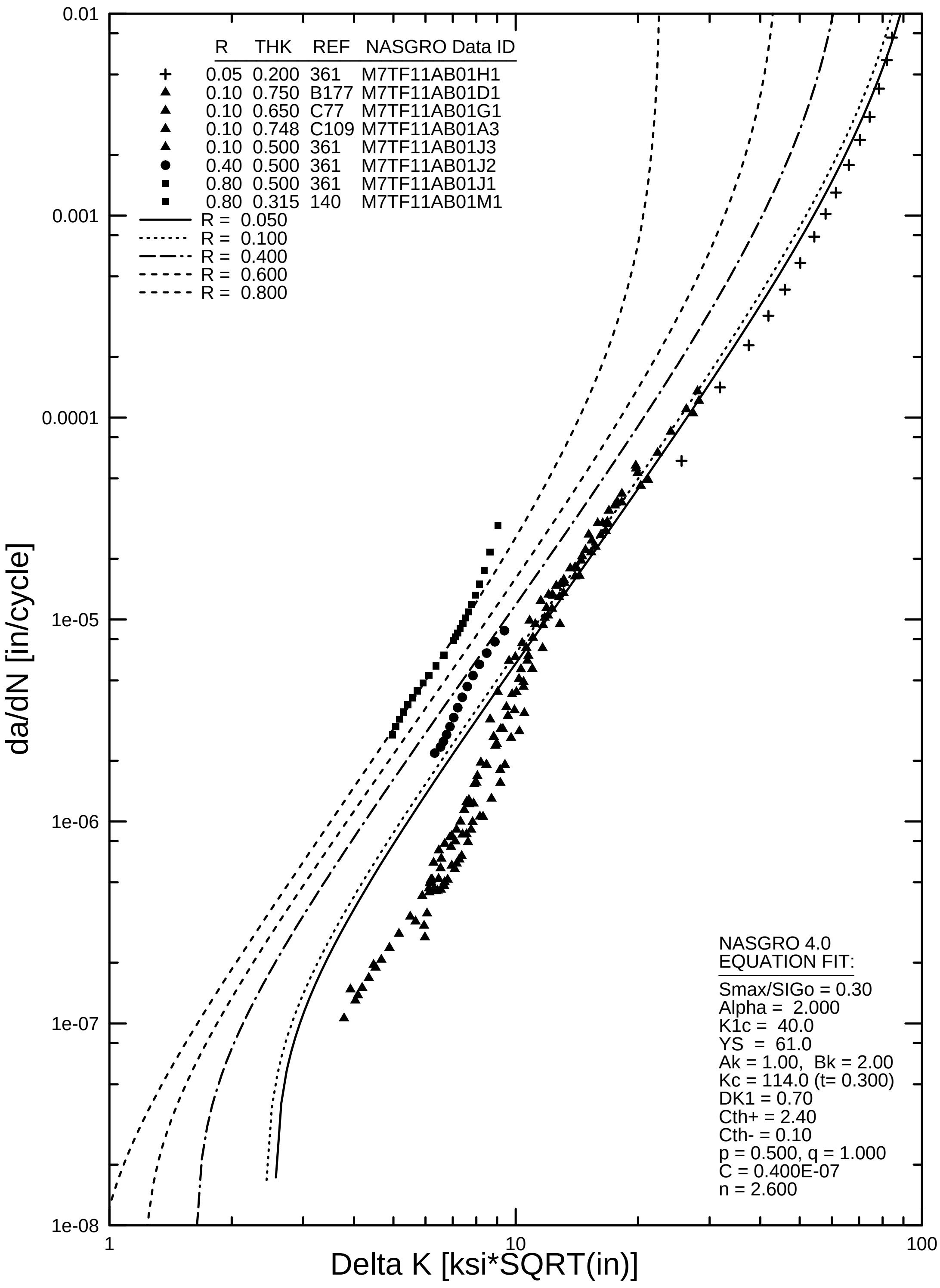


FIGURE B-31a. NASGRO EQUATION FIT FOR 7475-T7351 PLATE, L-T (M7TF11AB1) WITH POSITIVE *R* VALUES

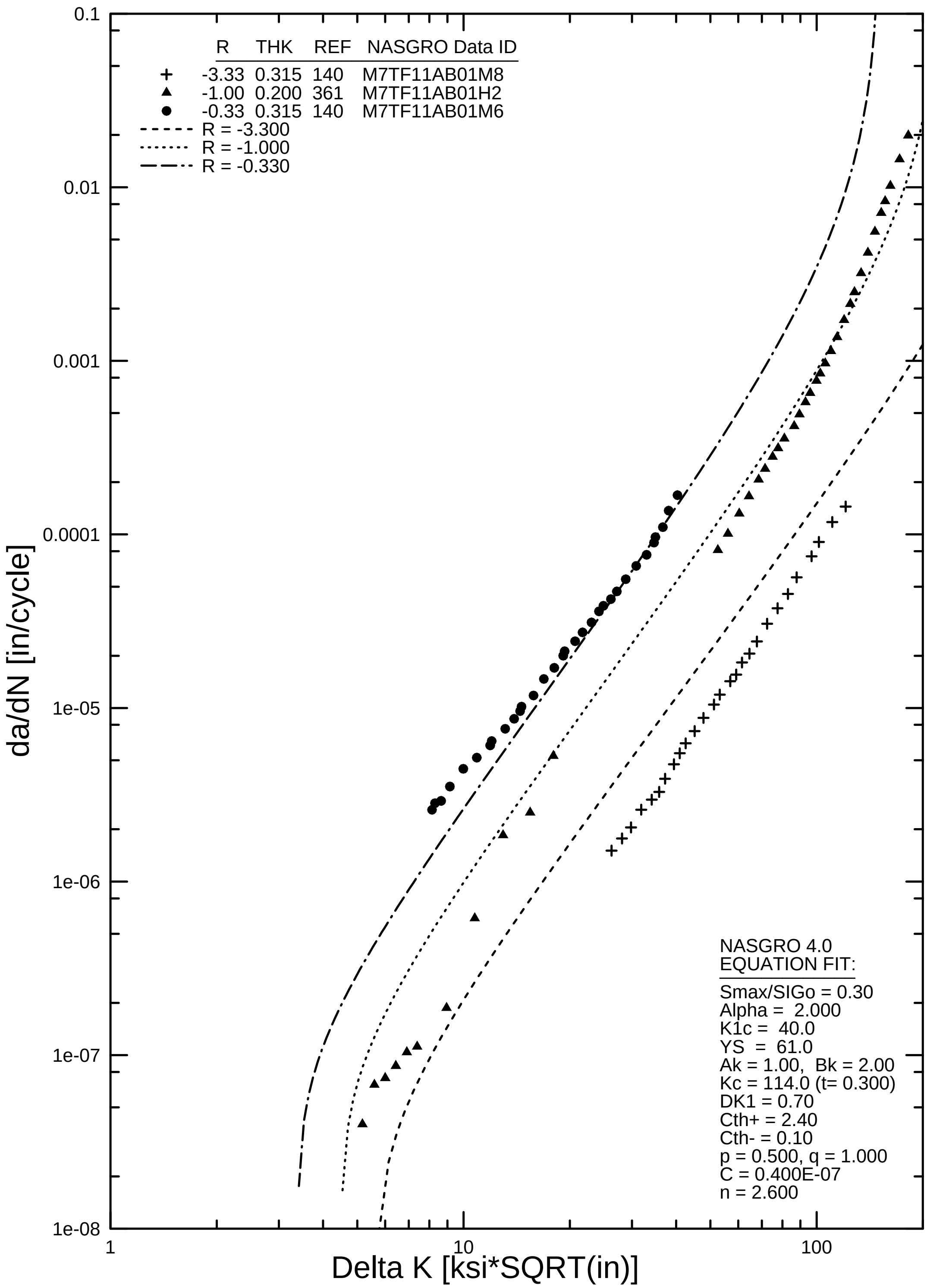


FIGURE B-31b. NASGRO EQUATION FIT FOR 7475-T7351 PLATE, L-T (M7TF11AB1) WITH NEGATIVE *R* VALUES

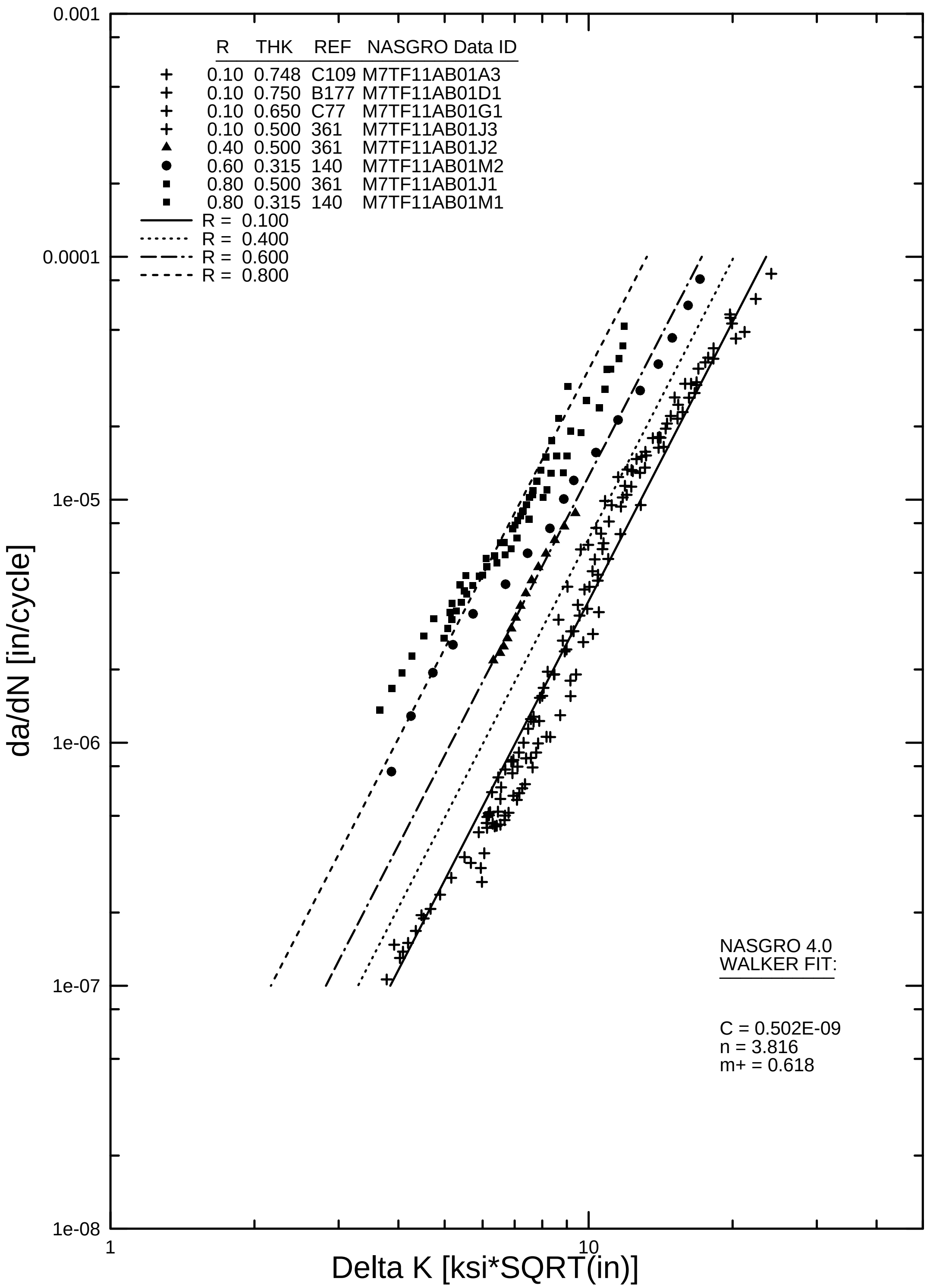


FIGURE B-32a. WALKER EQUATION FIT FOR 7475-T7351 PLATE, L-T (M7TF11AB1) WITH POSITIVE *R* VALUES

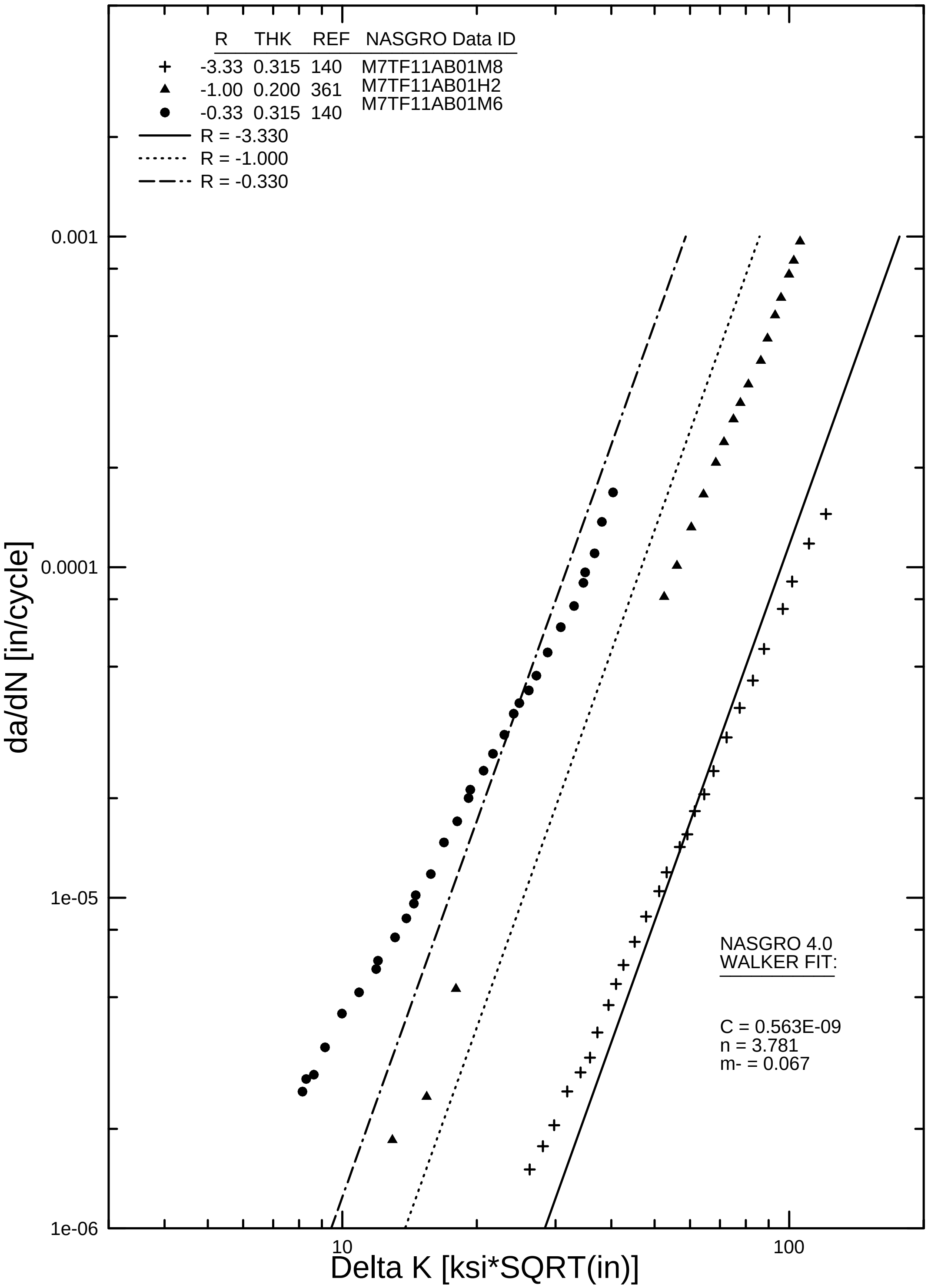


FIGURE B-32b. WALKER EQUATION FIT FOR 7475-T7351 PLATE, L-T (M7TF11AB1) WITH NEGATIVE *R* VALUES

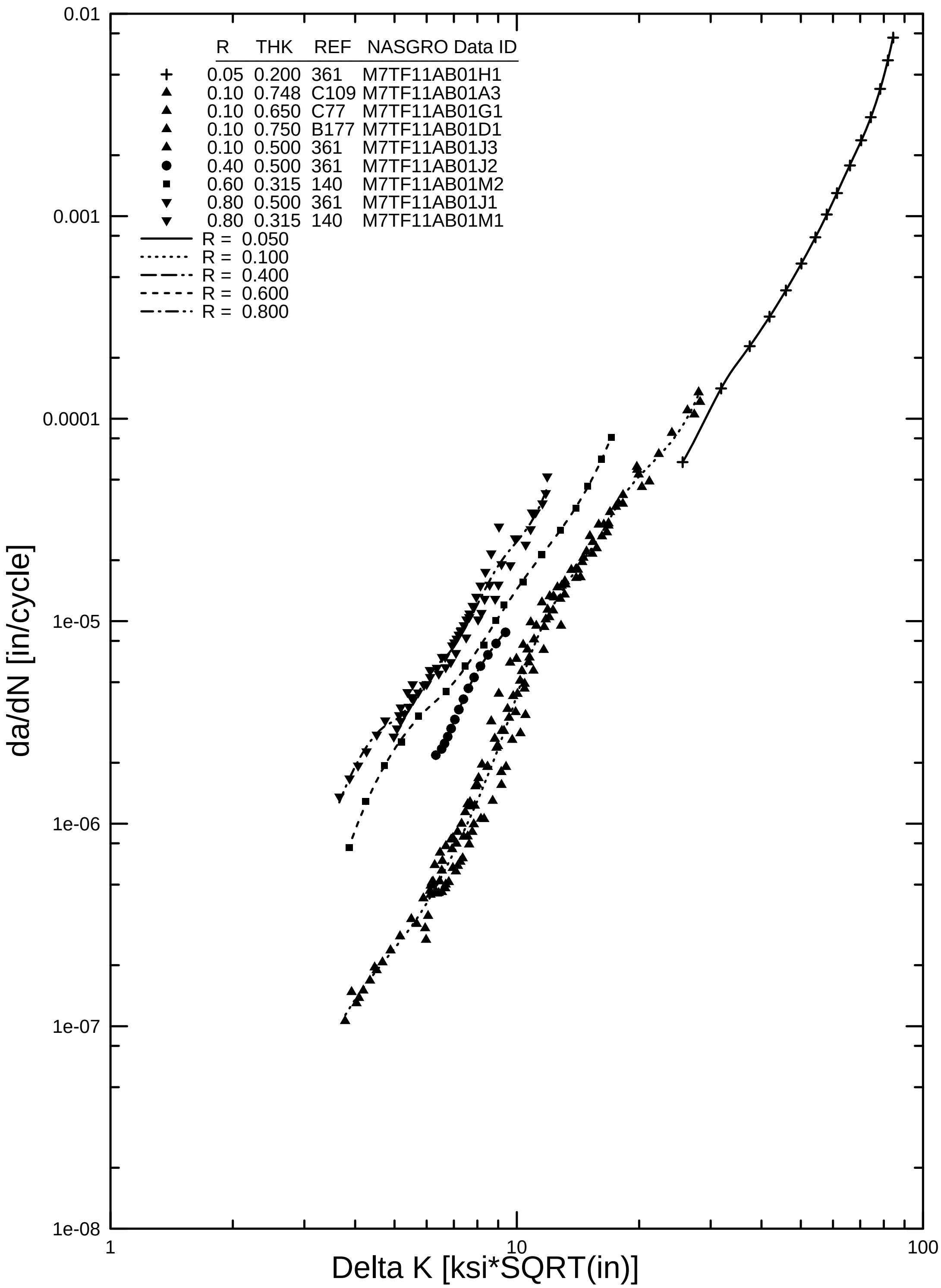


FIGURE B-33a. SPLINE FIT FOR 7475-T7351 PLATE, L-T (M7TF11AB1) WITH POSITIVE *R* VALUES

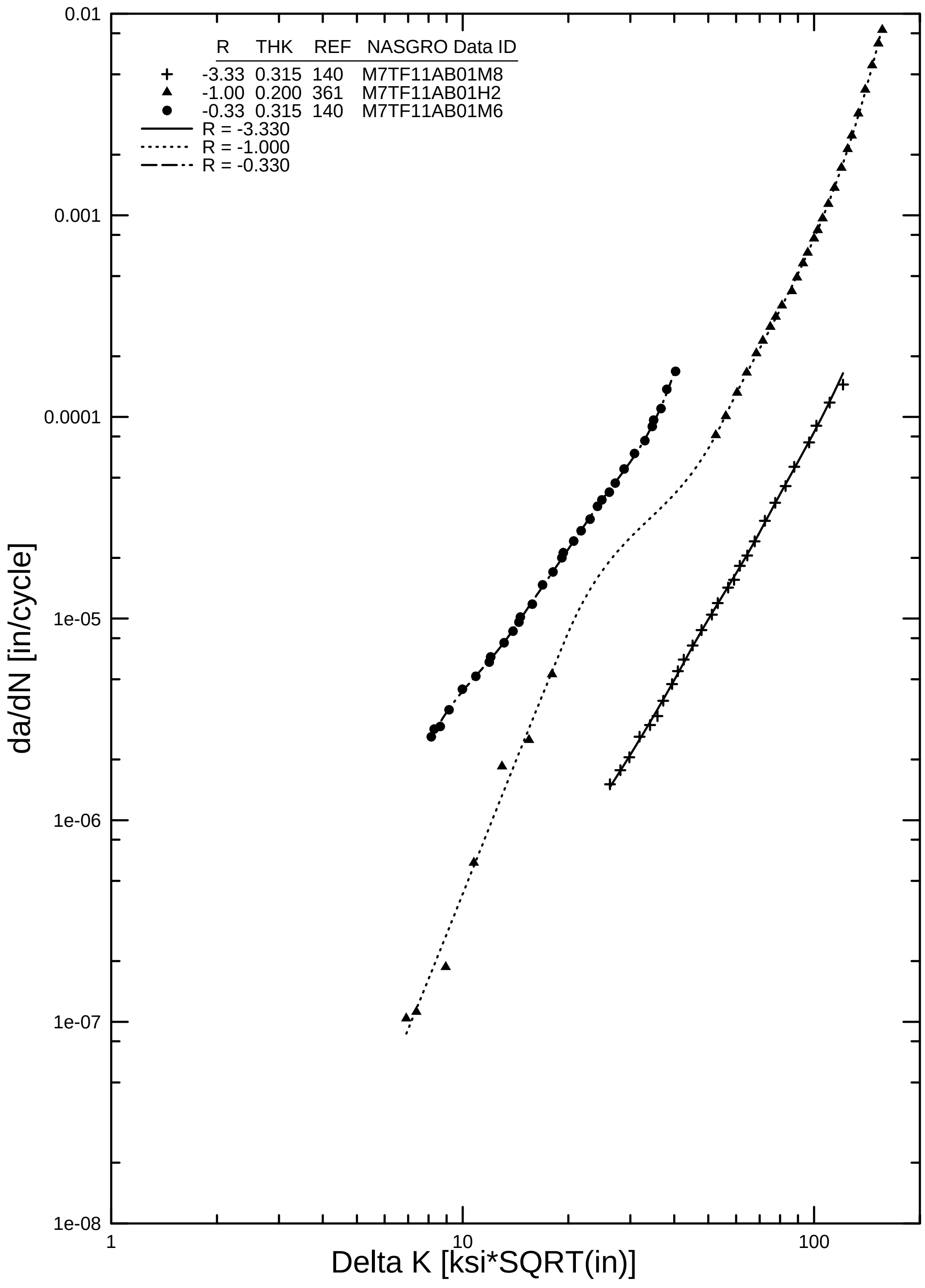


FIGURE B-33b. SPLINE FIT FOR 7475-T7351 PLATE, L-T (M7TF11AB1) WITH NEGATIVE *R* VALUES

TABLE B-22a. *da/dN*-Δ*K* SPLINE FIT FOR 7475-T7351 PLATE, L-T WITH POSITIVE *R* VALUES (M7TF11AB1)

ID Code = M7TF11AB1 *R* = 0.0500	
da/dN	Δ*K*
6.0976e-05	25.5859
1.0000e-04	29.1291
1.8000e-04	34.3384
3.2000e-04	41.9551
6.0000e-04	50.5506
1.0000e-03	57.7136
1.8000e-03	66.1325
3.2000e-03	74.9027
6.0000e-03	82.0848
7.6571e-03	84.3335

(a)

ID Code = M7TF11AB1 *R* = 0.100	
da/dN	Δ*K*
1.1281e-07	3.7757
1.8000e-07	4.4395
3.2000e-07	5.5572
6.0000e-07	6.6805
1.0000e-06	7.5536
1.8000e-06	8.5494
3.2000e-06	9.5128
6.0000e-06	10.5654
1.0000e-05	11.7300
1.8000e-05	14.0297
3.2000e-05	16.9336
6.0000e-05	21.4500
1.0000e-04	26.1917
1.3699e-04	28.2488

(b)

ID Code = M7TF11AB1 *R* = 0.400	
da/dN	Δ*K*
2.1311e-06	6.3241
2.5336e-06	6.6432
3.1203e-06	6.9783
3.9647e-06	7.3304
4.9129e-06	7.7002
5.8720e-06	8.0886
6.8358e-06	8.4967
7.8424e-06	8.9253
8.8749e-06	9.3756

(c)

ID Code = M7TF11AB1 *R* = 0.600	
da/dN	Δ*K*
7.7646e-07	3.8726
1.0000e-06	4.0583
1.8000e-06	4.6362
3.2000e-06	5.6268
6.0000e-06	7.5125
1.0000e-05	8.8901
1.8000e-05	10.8345
3.2000e-05	13.3851
6.0000e-05	15.9949
8.1597e-05	17.1002

(d)

ID Code = M7TF11AB1 *R* = 0.800	
da/dN	Δ*K*
1.3987e-06	3.6559
1.8000e-06	3.9536
3.2000e-06	5.0058
6.0000e-06	6.3986
1.0000e-05	7.5841
1.8000e-05	9.0106
3.2000e-05	10.9275
4.6122e-05	11.8850

(e)

TABLE B-22b. *da/dN*-Δ*K* SPLINE FIT FOR 7475-T7351 PLATE, L-T WITH NEGATIVE *R* VALUES (M7TF11AB1)

ID Code = M7TF11AB1 *R* = -3.330	
da/dN	Δ*K*
1.5109e-06	26.2422
1.8000e-06	28.3202
3.2000e-06	34.7824
6.0000e-06	42.4357
1.0000e-05	50.0292
1.8000e-05	61.7240
3.2000e-05	74.0434
6.0000e-05	89.4125
1.0000e-04	105.2751
1.4422e-04	120.7814

(a)

ID Code = M7TF11AB1 *R* = -0.330	
da/dN	Δ*K*
2.6351e-06	8.1470
3.2000e-06	8.8192
6.0000e-06	11.6842
1.0000e-05	14.6625
1.8000e-05	18.3595
3.2000e-05	23.1285
6.0000e-05	29.9840
1.0000e-04	35.4084
1.6771e-04	40.3645

(c)

ID Code = M7TF11AB1 *R* = -1.000	
da/dN	Δ*K*
8.6815e-08	6.9024
1.0000e-07	7.1356
1.8000e-07	8.1828
3.2000e-07	9.3438
6.0000e-07	10.7922
1.0000e-06	12.1310
1.8000e-06	13.8829
3.2000e-06	15.8568
6.0000e-06	18.3672
1.0000e-05	20.8197
1.8000e-05	25.4103
3.2000e-05	34.5305
6.0000e-05	47.3349
1.0000e-04	55.7073
1.8000e-04	66.0374
3.2000e-04	78.5636
6.0000e-04	93.8108
1.0000e-03	106.4446
1.8000e-03	120.6893
3.2000e-03	134.1643
6.0000e-03	148.3574
8.6206e-03	156.3148

(b)

TABLE B-23. MATERIAL DESCRIPTION AND SPECIMEN TESTING INFORMATION FOR 7475-T761 CLAD SHEET, L-T

Material ID Code	M7TI01AB1
Alloy Type	7475 Al
Alloy Condition/HT	T761
Product Form	0.04″-0.09″ Clad Sheet
Test Environments	Laboratory Air, High-Humidity Air
Specimen Types	C(T), M(T)
Crack Orientation	L-T
Specimen Thickness (in.)	C(T): 0.09 M(T): 0.04-0.125
Specimen Width (in.)	C(T): 1.5 M(T): 6-36
Yield Strength (ksi)	60-65
Ultimate Strength (ksi)	69-73
Cyclic Frequency, Hz	2-30

Data References for Table B-23.

112 Data of 2014-T6, 7475-T61, 2024-T62, 7475-T761, 2124-T851, 7475-T7351 - Materials received from L. Schwarmann, MBB Transport, Germany.

362 Kahandal, R.S., "C-17 Material Specimen Tests for Fracture Mechanics Data," Phase I, Lot 2 Aluminum Alloys.

B266 Cervay, R.R., AFML-TR-72-173, 1972.

C80 McCarty, J.E., et al., "Materials Fracture Data From the Advanced Metallic Structures."

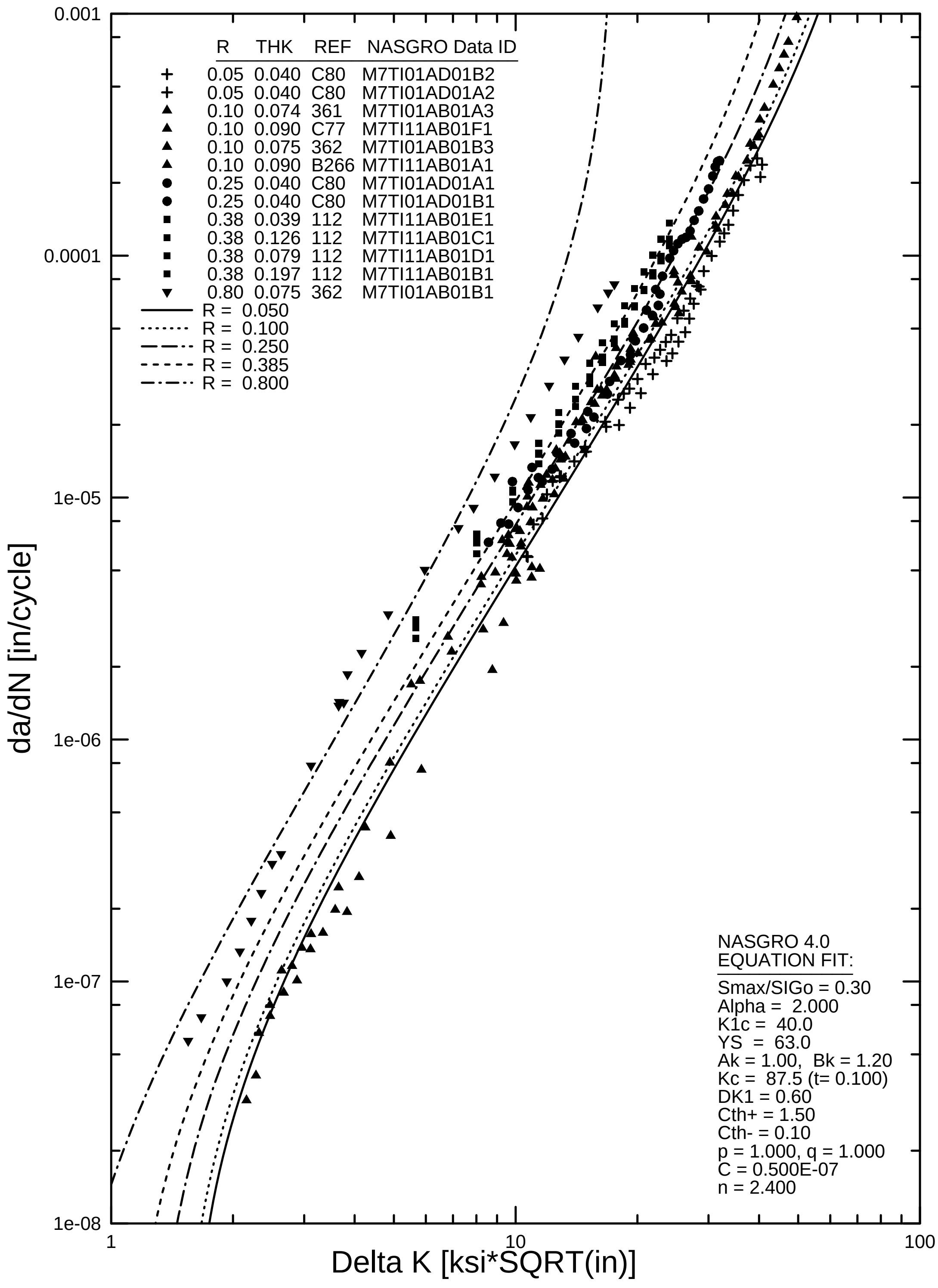


FIGURE B-34. NASGRO EQUATION FIT FOR 7475-T761 CLAD SHEET, L-T (M7TI01AB1)

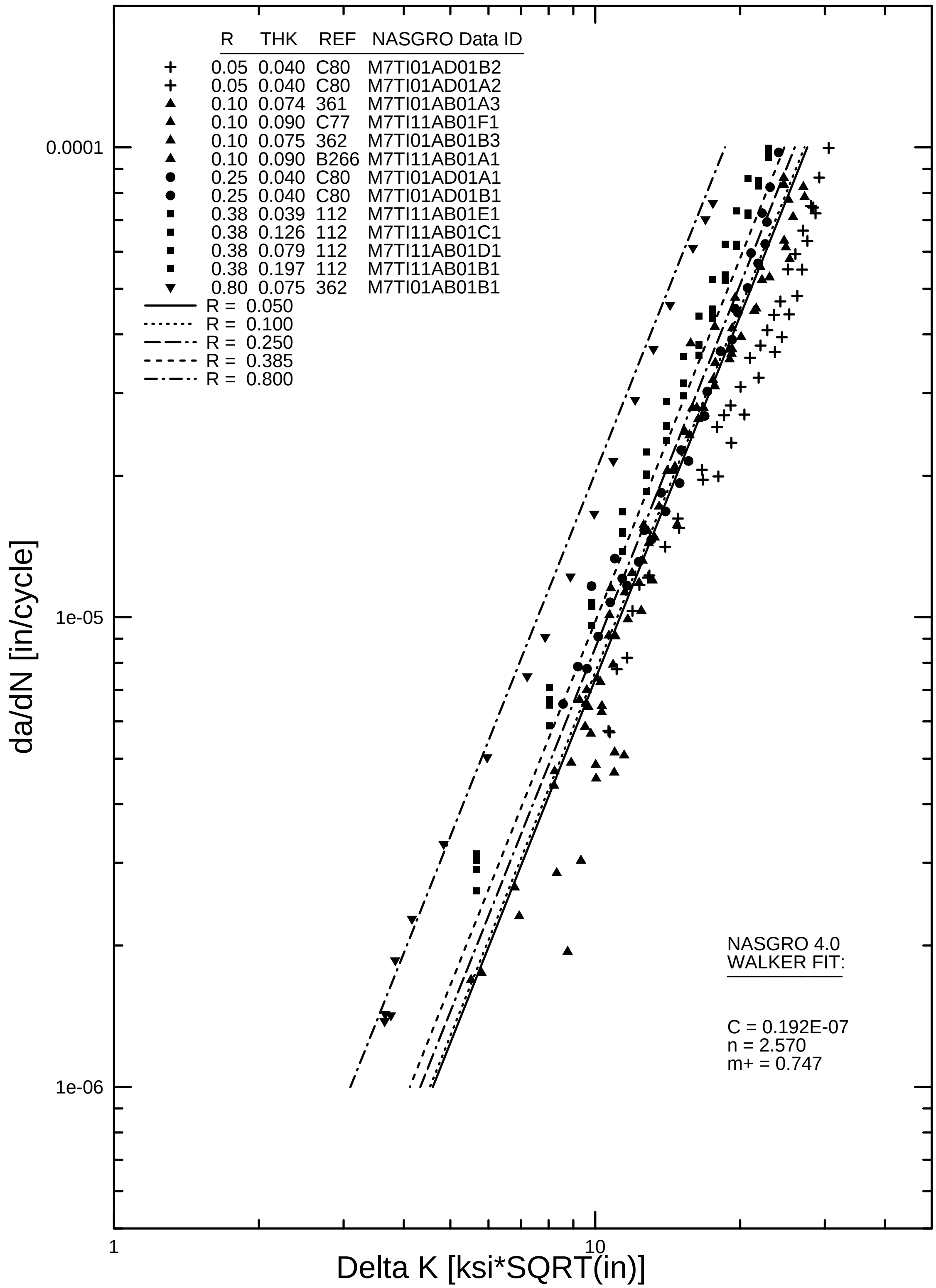


FIGURE B-35. WALKER EQUATION FIT FOR 7475-T761 CLAD SHEET, L-T (M7TI01AB1)

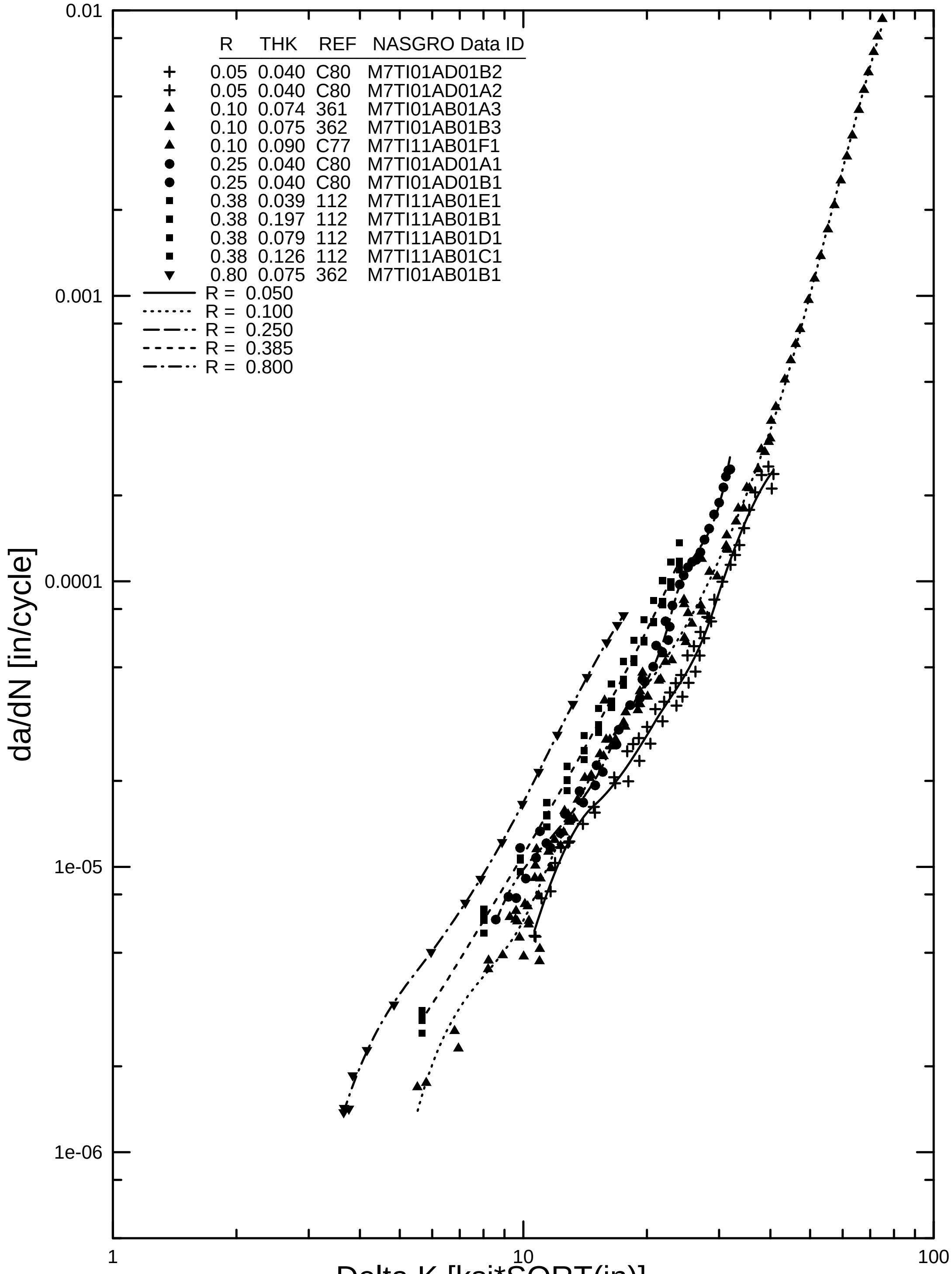


FIGURE B-36. SPLINE FIT FOR 7475-T761 CLAD SHEET, L-T (M7TI01AB1)

TABLE B-24. *da/dN*-Δ*K* SPLINE FIT FOR 7475-T761 CLAD SHEET, L-T (M7TI01AB1)

ID Code = M7TI01AD1 R = 0.0500	
da/dN	Δ*K*
6.4211e-06	10.6414
1.0000e-05	12.3039
1.8000e-05	15.3166
3.2000e-05	21.1370
6.0000e-05	26.8593
1.0000e-04	30.9441
1.8000e-04	36.1085
2.5595e-04	40.7380

(a)

ID Code = M7TI01AD1 R = 0.100	
da/dN	Δ*K*
1.7069e-06	5.5208
1.8000e-06	5.7600
3.2000e-06	7.8798
6.0000e-06	9.9990
1.0000e-05	11.7692
1.8000e-05	13.9868
3.2000e-05	17.3330
6.0000e-05	23.2501
1.0000e-04	28.5579
1.8000e-04	34.0576
3.2000e-04	39.2800
6.0000e-04	45.0994
1.0000e-03	50.0057
1.8000e-03	55.9171
3.2000e-03	62.0367
6.0000e-03	69.1641
9.7196e-03	74.9894

(b)

ID Code = M7TI01AD1 R = 0.250	
da/dN	Δ*K*
6.7295e-06	8.5704
1.0000e-05	10.2070
1.8000e-05	14.2093
3.2000e-05	17.5303
6.0000e-05	21.7555
1.0000e-04	24.6244
1.8000e-04	29.2023
2.2532e-04	31.9154

(c)

ID Code = M7TI01AD1 R = 0.385	
da/dN	Δ*K*
2.9083e-06	5.6624
3.2000e-06	5.9110
6.0000e-06	7.7464
1.0000e-05	9.6016
1.8000e-05	12.2024
3.2000e-05	15.2651
6.0000e-05	19.2019
1.0000e-04	22.7799
1.1779e-04	23.9883

(d)

ID Code = M7TI01AD1 R = 0.800	
da/dN	Δ*K*
1.3790e-06	3.6475
1.8000e-06	3.8928
3.2000e-06	4.7450
6.0000e-06	6.5211
1.0000e-05	8.1918
1.8000e-05	10.2472
3.2000e-05	12.5215
6.0000e-05	15.8410
7.5988e-05	17.5388

(e)

TABLE B-25. MATERIAL AND SPECIMEN TESTING INFORMATION FOR 7475-T7651 PLATE, L-T

Material ID Code	M7TJ11AB1
Alloy Type	7475 Al
Alloy Condition/HT	T7651
Product Form	0.25″-1.5″ Plate
Test Environments	Laboratory Air
Specimen Types	C(T), M(T)
Crack Orientation	L-T
Specimen Thickness (in.)	C(T): 0.25 M(T): 0.19-0.25
Specimen Width (in.)	C(T): 2 M(T): 12
Yield Strength (ksi)	68-69
Ultimate Strength (ksi)	78-79
Cyclic Frequency, Hz	5-30

Data References for Table B-25.

361 Larson, B.F., "C-17 Material Specimen Tests for Fracture Mechanics Data," Phase I, Lot 1 Aluminum Alloys.

362 Kahandal, R.S., "C-17 Material Specimen Tests for Fracture Mechanics Data," Phase I, Lot 2 Aluminum Alloys.

B140 Cervay, R.R., AFML-TR-75-220, 1975.

C222 Ferguson, C.W., et al., "Hypervelocity Impact Effects on Liquid Hydrogen Tanks," NASA CR-54852, Douglas Aircraft Co. Inc., March 1966.

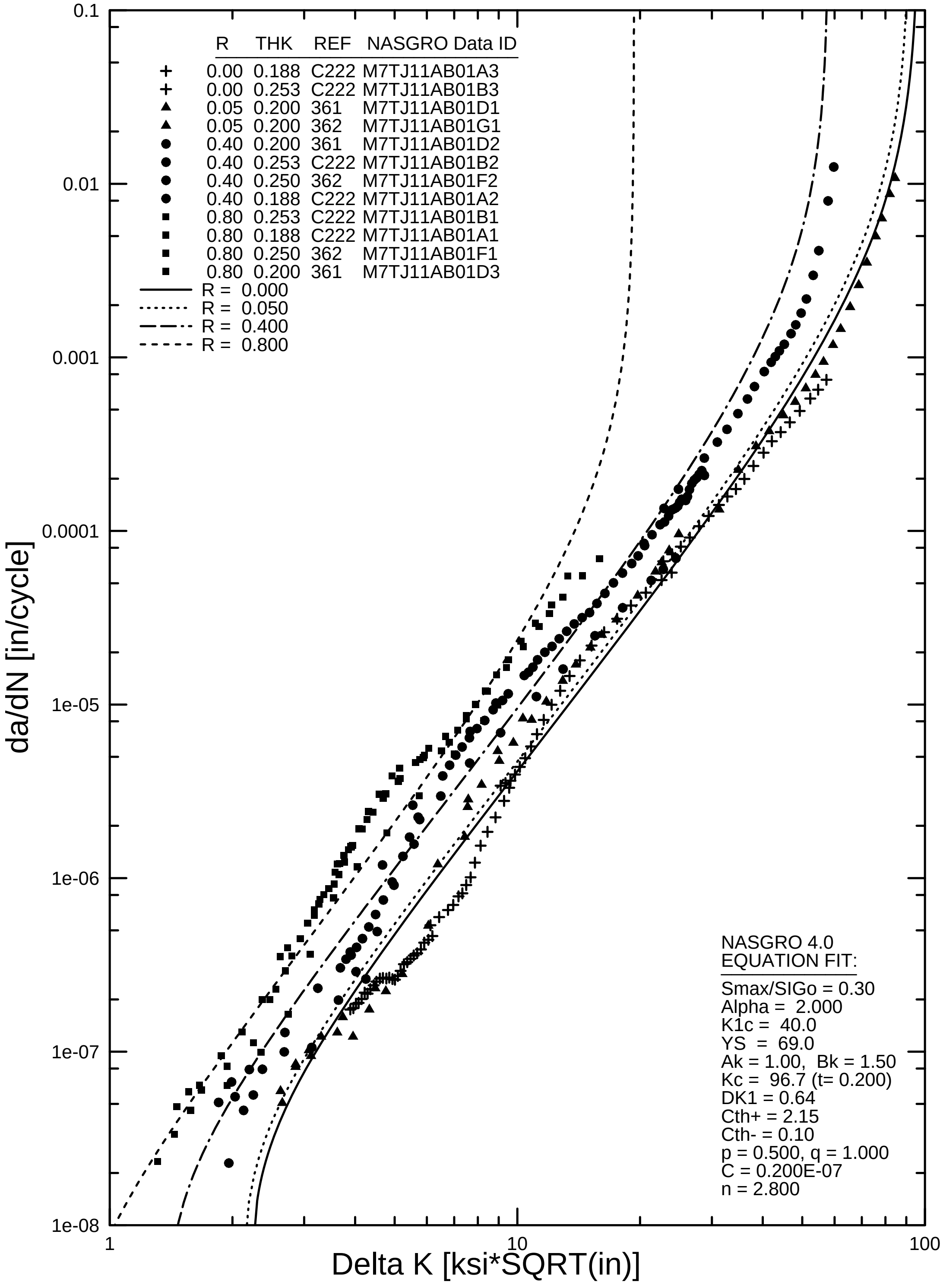


FIGURE B-37. NASGRO EQUATION FIT FOR 7475-T7651 SHEET AND PLATE, L-T (M7TJ11AB1)

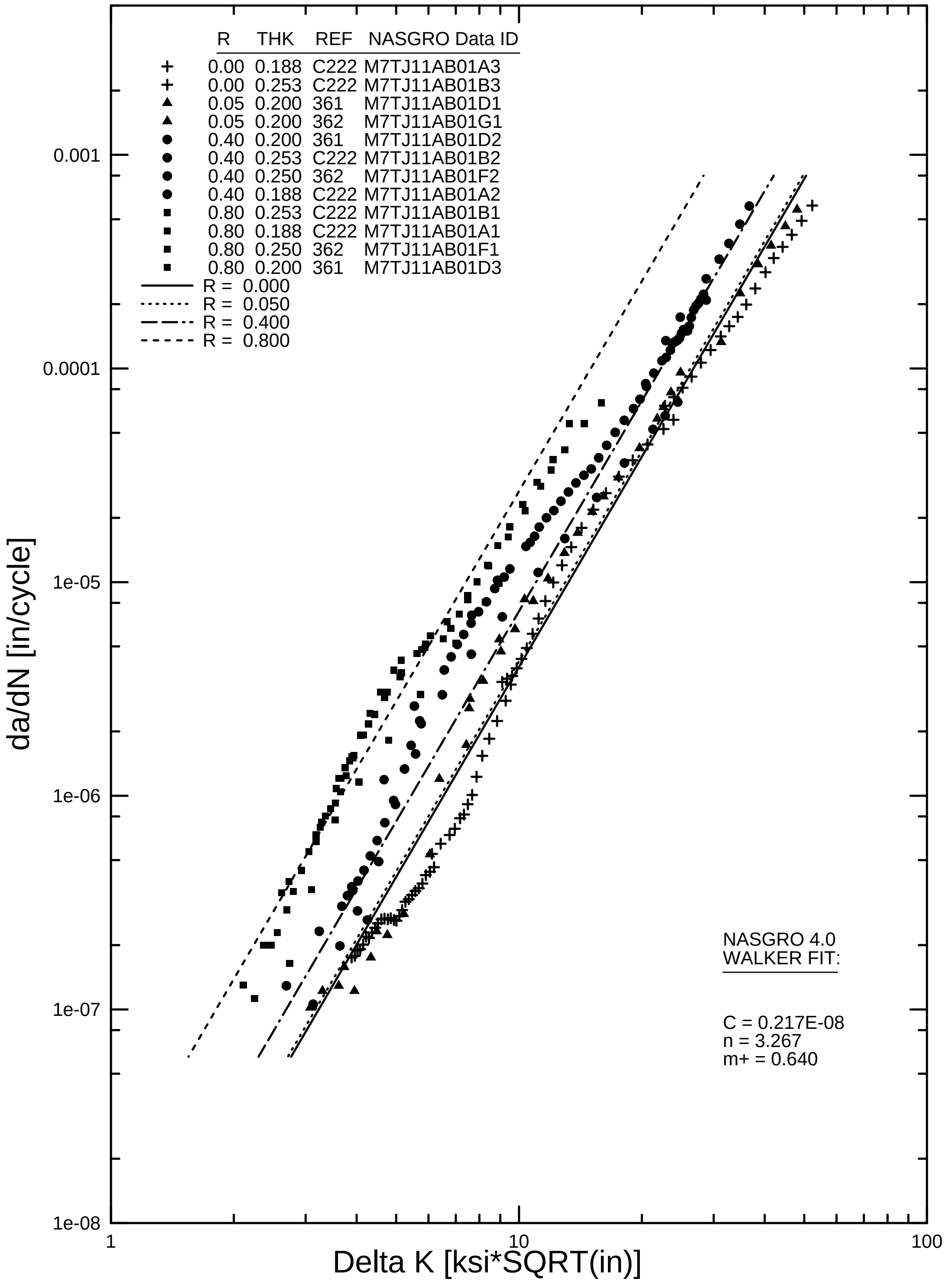


FIGURE B-38. WALKER EQUATION FIT FOR 7475-T7651 SHEET AND PLATE, L-T (M7TJ11AB1)

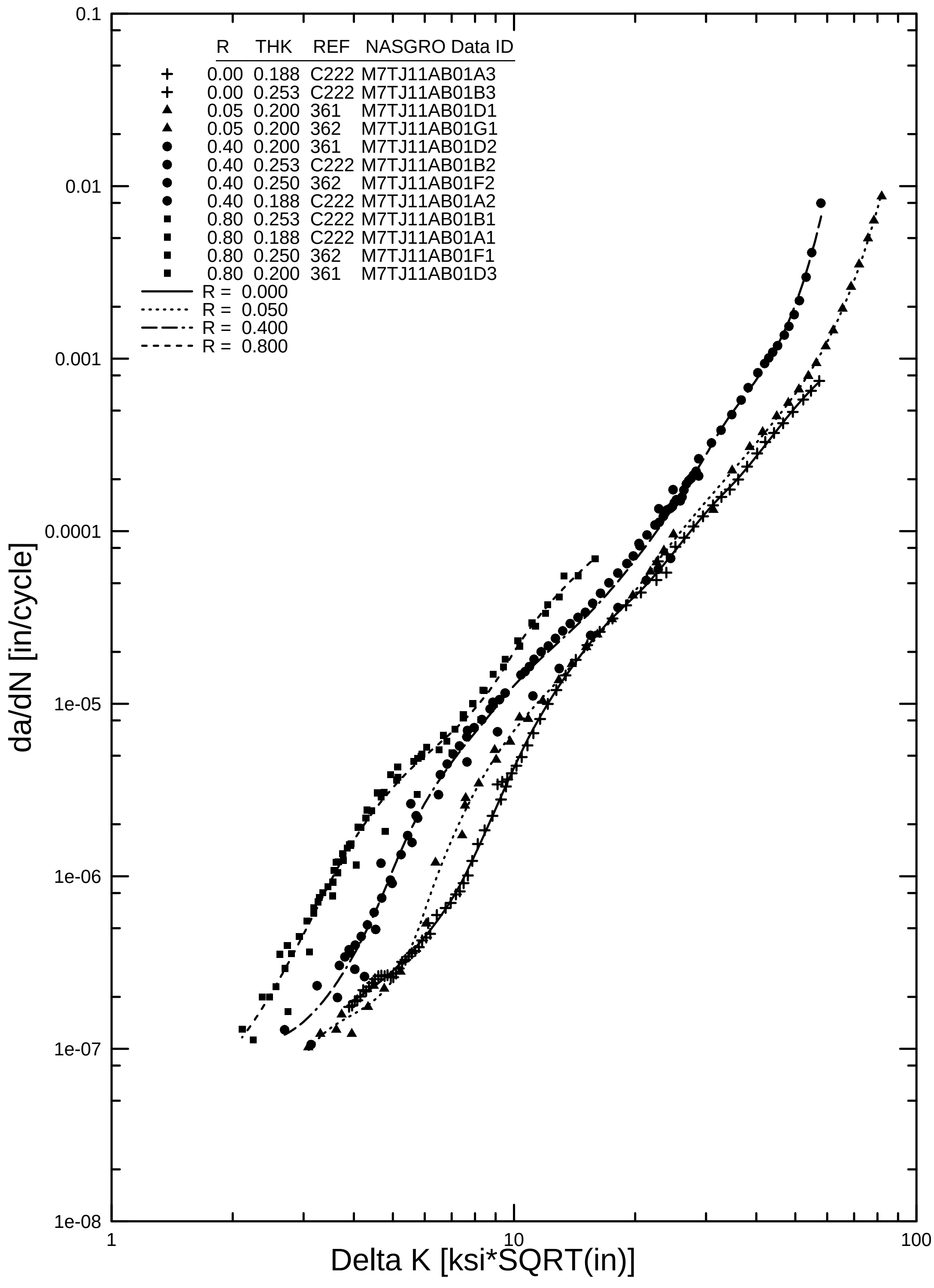


FIGURE B-39. SPLINE FIT FOR 7475-T7651 SHEET AND PLATE, L-T (M7TJ11AB1)

TABLE B-26. *da/dN*-Δ*K* SPLINE FIT FOR 7475-T7561 CLAD SHEET, L-T (M7TJ11AB1)

ID Code = M7TJ11AB1 R = 0.0000	
da/dN	Δ*K*
1.8481e-07	3.8905
3.2000e-07	5.2775
6.0000e-07	6.6140
1.0000e-06	7.5311
1.8000e-06	8.4826
3.2000e-06	9.4618
6.0000e-06	10.7314
1.0000e-05	12.1336
1.8000e-05	14.3660
3.2000e-05	17.6823
6.0000e-05	23.0121
1.0000e-04	27.4649
1.8000e-04	34.3773
3.2000e-04	42.3049
6.0000e-04	52.6966
7.3479e-04	57.4116

(a)

ID Code = M7TJ11AB1 R = 0.050	
da/dN	Δ*K*
9.7848e-08	3.0832
1.0000e-07	3.1049
1.8000e-07	4.3472
3.2000e-07	5.3300
6.0000e-07	5.9547
1.0000e-06	6.4360
1.8000e-06	7.1359
3.2000e-06	8.0568
6.0000e-06	9.5316
1.0000e-05	11.3905
1.8000e-05	14.3418
3.2000e-05	17.7553
6.0000e-05	21.9446
1.0000e-04	26.0137
1.8000e-04	32.1934
3.2000e-04	39.7875
6.0000e-04	49.3327
1.0000e-03	56.9240
1.8000e-03	64.6548
3.2000e-03	71.3356
6.0000e-03	77.9134
9.1696e-03	82.0352

(b)

TABLE B-26. *da/dN*-Δ*K* SPLINE FIT FOR 7475-T7561 CLAD SHEET, L-T (M7TJ11AB1) (Continued)

ID Code = M7TJ11AB1 R = 0.400	
da/dN	Δ*K*
1.2078e-07	2.6915
1.8000e-07	3.2988
3.2000e-07	3.9084
6.0000e-07	4.4853
1.0000e-06	4.9264
1.8000e-06	5.4994
3.2000e-06	6.3044
6.0000e-06	7.6562
1.0000e-05	9.1601
1.8000e-05	11.5761
3.2000e-05	15.0749
6.0000e-05	19.1702
1.0000e-04	22.6213
1.8000e-04	26.7859
3.2000e-04	31.0723
6.0000e-04	37.2407
1.0000e-03	43.2472
1.8000e-03	48.9027
3.2000e-03	53.2963
6.0000e-03	57.3154
6.6786e-03	57.9429

(c)

ID Code = M7TJ11AB1 R = 0.800	
da/dN	Δ*K*
1.1626e-07	2.1086
1.8000e-07	2.3549
3.2000e-07	2.8021
6.0000e-07	3.2007
1.0000e-06	3.5366
1.8000e-06	4.0855
3.2000e-06	4.9071
6.0000e-06	6.7696
1.0000e-05	8.0711
1.8000e-05	9.7494
3.2000e-05	11.5677
6.0000e-05	14.7456
7.0066e-05	15.9221

(d)

APPENDIX C— FATIGUE CRACK GROWTH DATABASE SOFTWARE OPERATION

C.1 FATIGUE CRACK GROWTH DATABASE SOFTWARE INSTALLATION.

The Fatigue Crack Growth Database (FCGD) software and its graphical user interface (GUI) were developed under Microsoft Windows 98 and would be compatible on most Windows platforms. The FCGD software is installed by executing a setup file (setup.exe). The default directory for the installation is c:\program files\fcgd, but may be changed to a different one if desired. An FCGD icon to run the software is automatically created on the computer's desktop during the FCGD installation process.

This version of the FCGD software and database require approximately 10 MB of hard disk space. As data for additional materials are added to the database, this will increase. Microsoft® PowerPoint is also required to display the plots for the materials included in the database.

C.2 OPENING WINDOW.

The opening window of the FCGD software is shown in figure C-1. Clicking the Agree button to accept the displayed disclaimer opens the window shown in figure C-2. Through this window, the database of materials could be accessed or an option to input user's own set of data can be selected.

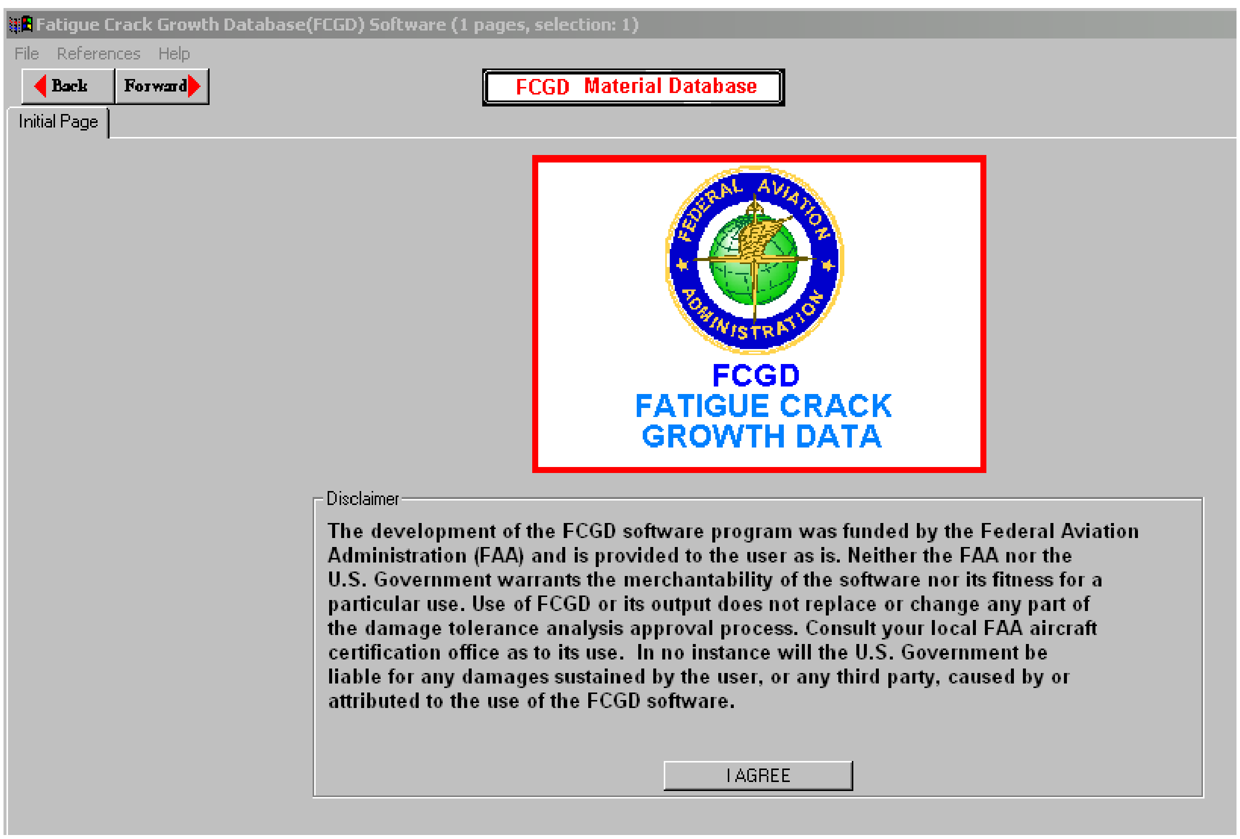


FIGURE C-1. OPENING WINDOW FOR THE FCGD SOFTWARE

C.3 MATERIAL SELECTION.

Curve fits for specific materials in the database can be displayed by selecting the Choose Material menu tab. An example display window is shown in figure C-2. There are currently 13 materials in the database. Selecting a material automatically displays the ID code in the standard material identification box for reference. Choosing any of the buttons labeled NASGRO Equation, Walker Equation, or Spline under the blue-highlighted text Plot Std Data with Std Curve Fits, displays the respective curve fit and opens a PowerPoint file displaying a table of the material description and color plot(s) of the data. These plots are displayed in U.S. customary units (ksi√in and in/cycle) and may be printed directly from PowerPoint or copied into another document using the copy and paste functions of Windows.

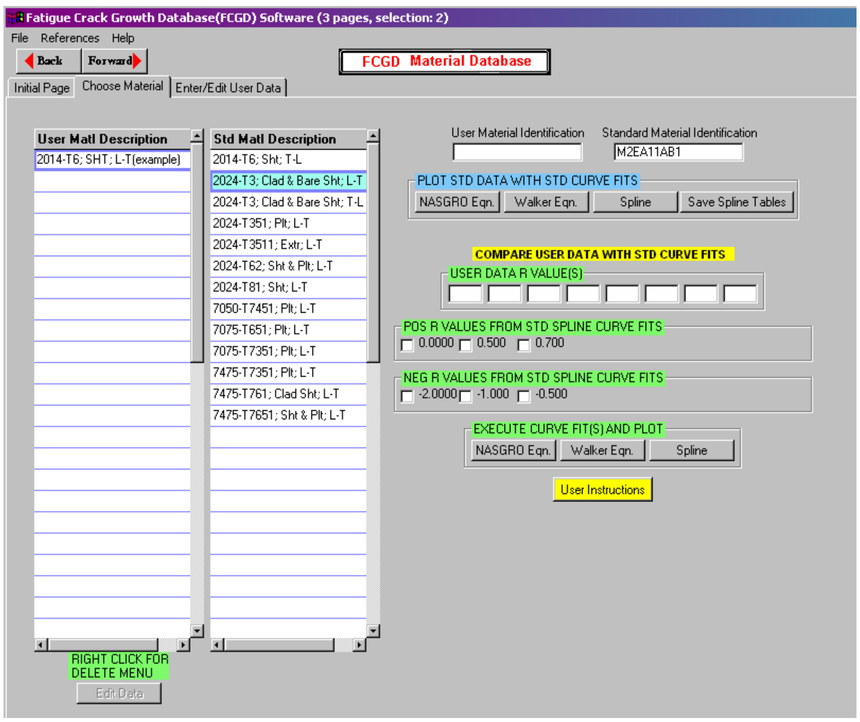


FIGURE C-2. MATERIAL SELECTION WINDOW FOR PLOTTING STANDARD DATA AND CURVE FITS

Spline data points can be saved into a text file by choosing the Save Spline Tables button. This file is stored in the default directory c:\program files\fcgd under the default name material ID.tbl. Both the default file name and location can be changed during this operation if desired.

C.4 ENTERING USER DATA.

Choosing Enter/Edit User Data from the menu tab in figure C-2 displays an input window, as shown in figure C-3, for a set of fatigue crack growth data, which can be compared with the standard curve fits in the database. With this window, the material characteristics can be specified, a material ID code created, and the information saved to a file. The data source input types that are available are direct keyboard input and text file. Data from spreadsheets such as

Microsoft Excel, can be entered by using the copy and paste functions of Windows. Data from scanned graphical images in bitmap format as well can be digitized and imported into the FCGD software.

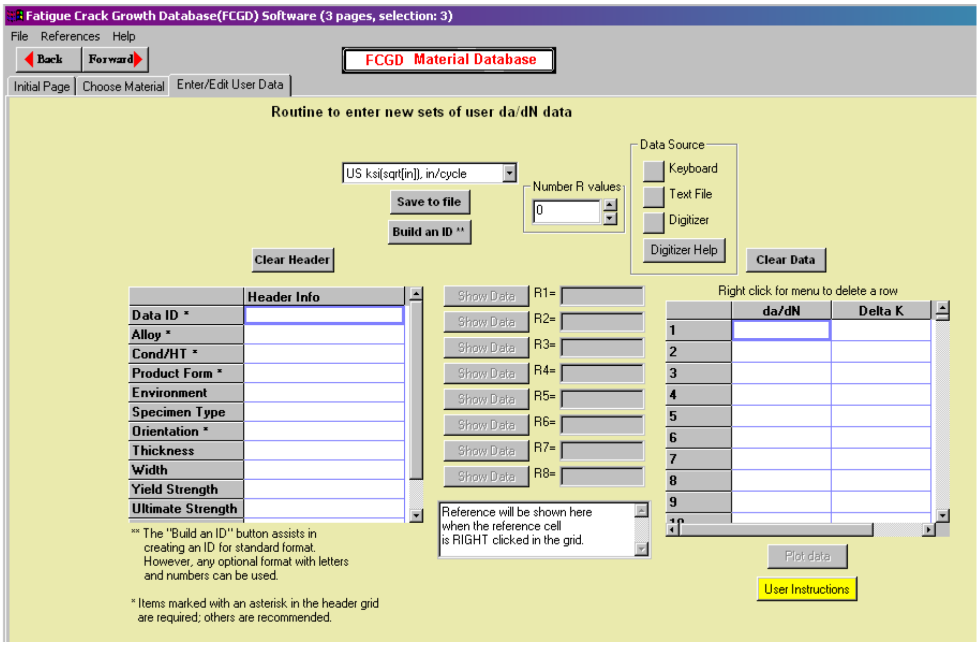


FIGURE C-3. INPUT WINDOW FOR USER-DEFINED FATIGUE CRACK GROWTH DATA

Besides the standard U.S. customary units, the FCGD software has the flexibility to accommodate data input in SI units (MPa√m and m/cycle) and other nonstandard units by the Choose Units pull-down menu. The units of the data are then converted by the software to U.S. customary units for comparison to the database curves.

The first step in specifying a set of user data is to supply the characteristics of the material. By clicking on the Build an ID button, the user has the option of creating a material characteristic and ID code for the data consistent with the material ID nomenclature used in the database and NASGRO. Alternatively, the Header Info box provides a list of items that the user can fill in to identify the material characteristics in terms that the user is familiar with. Note that items marked with an asterisk are required, others are recommended.

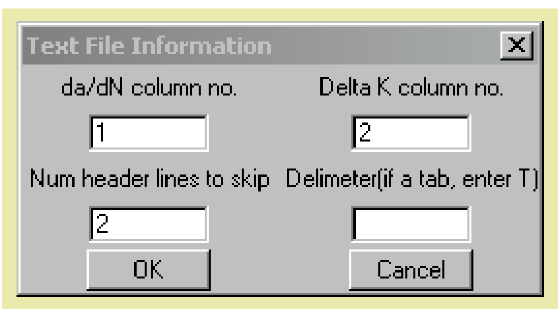
Next, the data units, the Number of *R* Values, and the Data Source must be identified in the small inset windows of the Enter/Edit User Data window. Each of the various input data sources mentioned above are described below in detail.

<u>C.4.1 KEYBOARD</u>.

To use the keyboard for data input, the number of *R* values *n* for the data set must be entered under the label Number of *R* values. Empty boxes adjacent to the labels R1 through Rn automatically open up and are ready for data entry. For example, specifying four *R* values activates boxes R1 through R4, for which the *R* values can be entered. Each of the *da/dN* and *ΔK* data can now be entered in the grid to the right by clicking on the Show Data button of the respective *R* value.

C.4.2 TEXT FILE.

Clicking on the Text File button under the data source label brings up a small dialog box (shown in figure C-4(a)) for description of the format of the text data file. In this dialog box, the column numbers containing the *da/dN* and *ΔK* data, the type of delimiter, and the number of header lines to skip can be specified. In figure C-4(a), *da/dN* and *ΔK* data are in columns 1 and 2, respectively, the number of header lines to skip is 2 (space is used as the delimeter) and, it is assumed that the data for each *R* value are in a separate file. A sample text file is shown in figure C-4(b). Clicking on OK confirms the specified data format and displays a matrix by which the user can specify the file names and their corresponding *R* values. This matrix is shown in figure C-5, along with the help window describing the details of its operation.



(a) Format Utility

Wing *da/dN* vs Δ*K* Data
7075-T351 Aluminum at *R* = 0.0

1.0000E-10	1.25
4.0000E-09	1.50
9.9400E-09	2.00
4.8800E-08	3.00
1.5100E-07	4.00
3.6200E-07	5.00
9.7100E-07	6.00
2.6300E-06	7.00
4.7400E-06	9.00
6.4300E-06	10.00
6.9600E-06	11.00
9.6700E-06	12.00
1.3600E-05	13.00
1.7800E-05	14.00
2.1800E-05	15.00
3.5400E-05	18.00
6.7800E-05	22.00
1.1600E-04	25.00
1.4100E-04	26.00
2.4100E-04	28.00

(b) Sample Text File

FIGURE C-4. UTILITY TO SUPPLY FORMAT OF TEXT DATA FILE

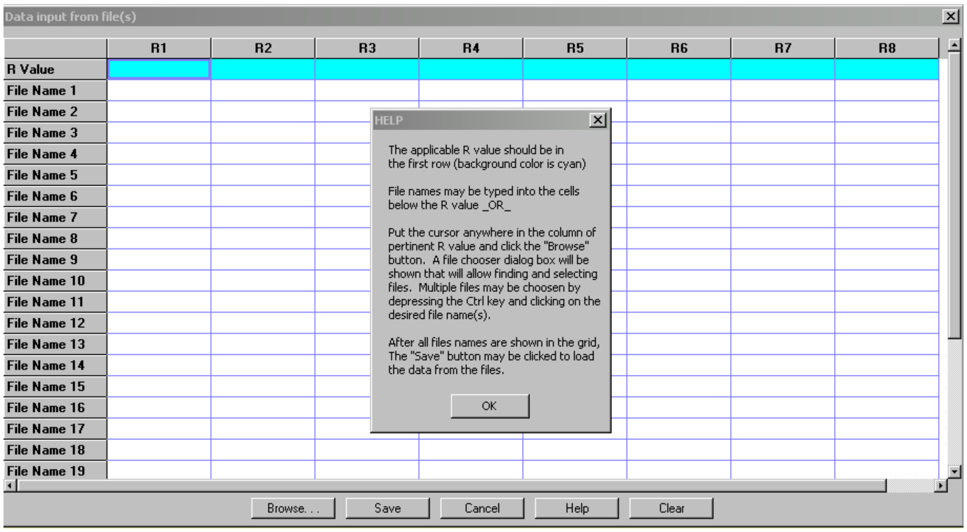


FIGURE C-5. INPUT MATRIX TO SPECIFY FILE NAMES FOR DIFFERENT SETS OF CRACK GROWTH RATE DATA AS A FUNCTION OF *R* VALUE

C.4.3 SPREADSHEET.

It is also possible to copy data for each *R* value directly from a spreadsheet into the data grid using the copy and paste functions of Windows. For a given *R* value, highlight and copy the data of interest from an open spreadsheet. With the Show Data button activated for the *R* value of interest, right click on the data grid and a pop-up menu is displayed to paste the copied data, as shown in figure C-6. The user may copy and paste a column of data at a time or both columns simultaneously.

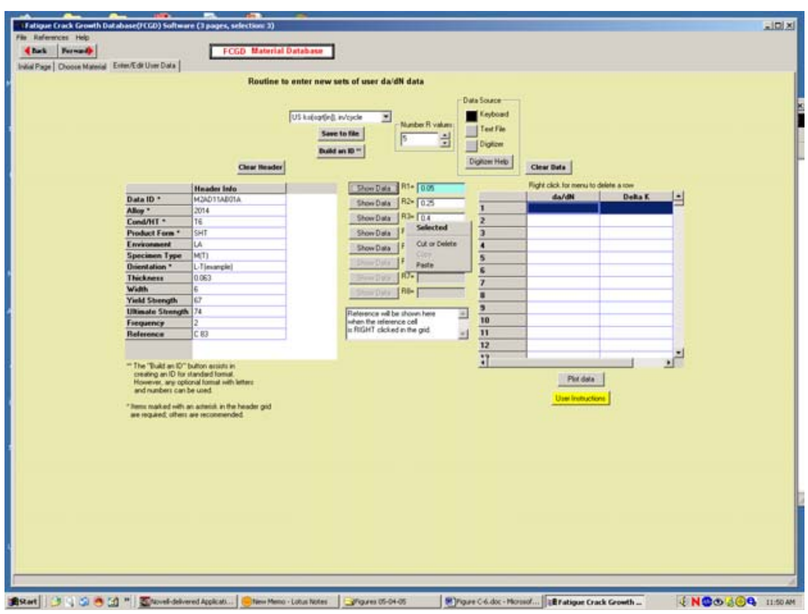


FIGURE C-6. THE FCGD KEYBOARD INPUT WINDOW SHOWING THE USE OF WINDOW'S COPY AND PASTE FUNCTIONS

C.4.4 DIGITIZER.

A utility is provided to digitize a bitmap (.bmp) file of a scanned graphical image or other sources. Detailed instructions for this data input can be accessed by clicking on the button labeled Digitizer Help. The contents of the Digitizer Help button are reproduced in figure C-7.


```
1. The file to be digitized must be a bitmap(.bmp) obtained
   from a scanner or other method.

2. From the File menu of the digitizer screen:  Choose "Open"
   and open the file that is to be digitized.

3. From the Scale menu:
   -Choose Log X scale and Log Y scale if appropriate.
    Do not use the keyboard shortcut Crtl X!
   -Choose Define 3 Pts.
    For point 1, click on the top of the Y axis and enter
    X and Y values.
    For point 2, click on the axes intersection and enter
    X and Y values.
    For point 3, click on the end of the X axis and enter
    X and Y values.

4. DIGITIZE THE FIRST POINT ANYWHERE ON THE Y AXIS.
   (i.e., place the cross hair on the Y axis and double click)
   This will provide a minimum X value to be used later.

5. Digitize the values of a data set by DOUBLE CLICKING on
   each point.

6. If more than one data set is to be digitized:
   After each data set is digitized, MOVE THE CROSSHAIR TO
   THE LEFT OF THE Y AXIS AND DOUBLE CLICK TO DIGITIZE A POINT.
   This will provide a separator for the data sets by recording
   a point which is smaller than the minimum X value.

7. After all points are digitized; From the Data menu choose
   "Save" and save the file, using a name of your choice. Then
   close the digitizer program.

8. When control returns from the digitizer program, you will
   be prompted for the name of the file which was saved in
   step 7.  Select the file and click the “Open” button.
   Choose the number of R values and enter the values into
   the text boxes provided in the same order that the
   digitizing was done.
```

FIGURE C-7. INSTRUCTIONS TO USE THE DIGITIZER UTILITY

C.5 COMPARING USER DATA WITH FCGD CURVES.

The data in the user-defined database can be compared to curve fits in the standard database (FCGD) by going to the choose material screen (figure C-2), selecting one material from the Std Matl Description column and material from the User Matl Description column and one of the standard crack growth equations under plot Std Data with Std Curve Fits. The *R* values to plot are automatically displayed in the data boxes below the green-highlighted text of figure C-2. For the spline fit, negative and/or positive *R* values (at least one *R* value) must be selected before the data may be plotted and compared. A plotting utility automatically appears that provides options to send the plot to the screen or to save it to a file for later use.

Note that the user's crack growth data can only be compared to the curve fits in the material database FCGD. The FCGD software does not have the capability to produce NASGRO, Walker, or Spline fits to user-supplied crack growth data.

D.1 KEYBOARD ENTRY OF USER DATA.

In this example, a set of fatigue crack growth data of three different *R* values (0.0, 0.50, and 0.72) is assumed for a 7000 series aluminum plate material, and will be compared to the 7075-T7351 plate material data in the fatigue crack growth database (FGCD) software.

Figure D-1 shows the display of the Enter/Edit User Data window. The Data Source has been checked as keyboard, and 3 has been specified as the number of *R* values. Adjacent and to the right of each of labels R1-R3 are the entered *R* values. By clicking on the Show Data button, located to the left of the labels R1-R3, the grid on the right under the *da/dN*-Δ*K* labels is activated for data entry from the keyboard. Figure D-1 shows the data entered for *R* = 0.0. (Generally, there would be more data points than those shown in this hypothetical example.) The required material information under the Header Info box on the left has been filled in for this example. Clicking on the Plot Data button located at the lower right of the screen displays the *da/dN*-Δ*K* plot for this example, as shown in figure D-2.

Clicking on the Save to file button enters the data into the User Material database under the created material ID code's name (7xxx-T7yy Plate), as shown in the left-hand column of figure D-3. At the Choose Material window, the material (7xxx-T7yy Plate) can be selected and compared to the FCGD standard curve fits.

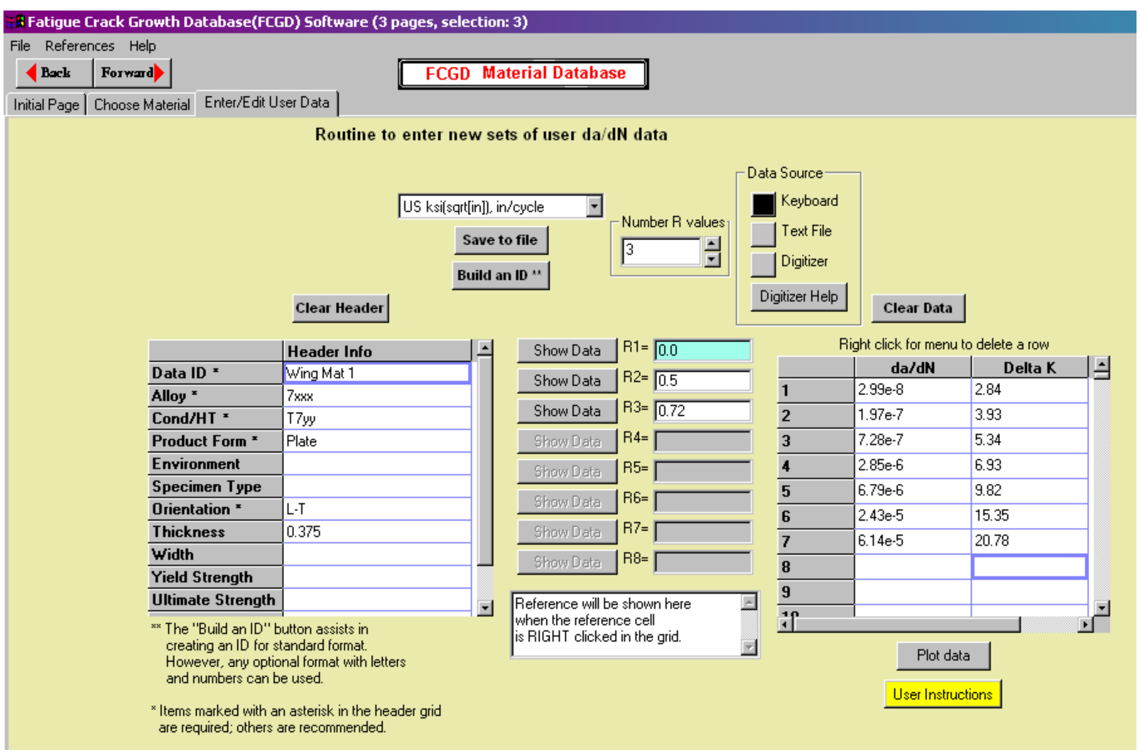


FIGURE D-1. KEYBOARD ENTRY OF USER DATA

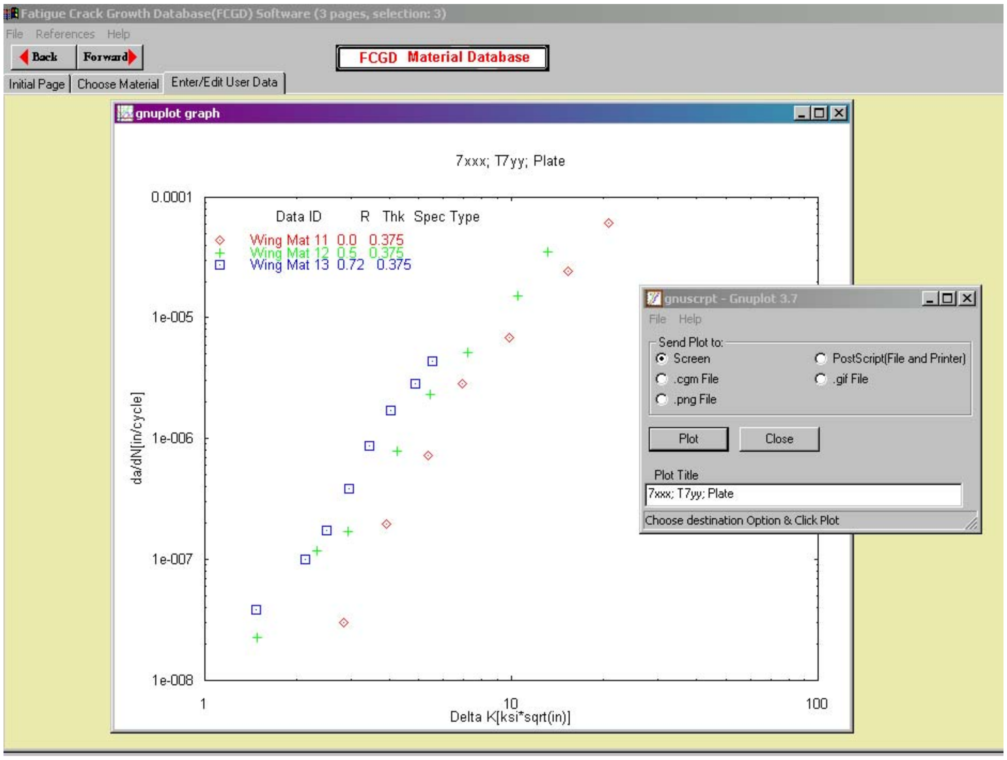


FIGURE D-2. DISPLAY OF USER-ENTERED DATA

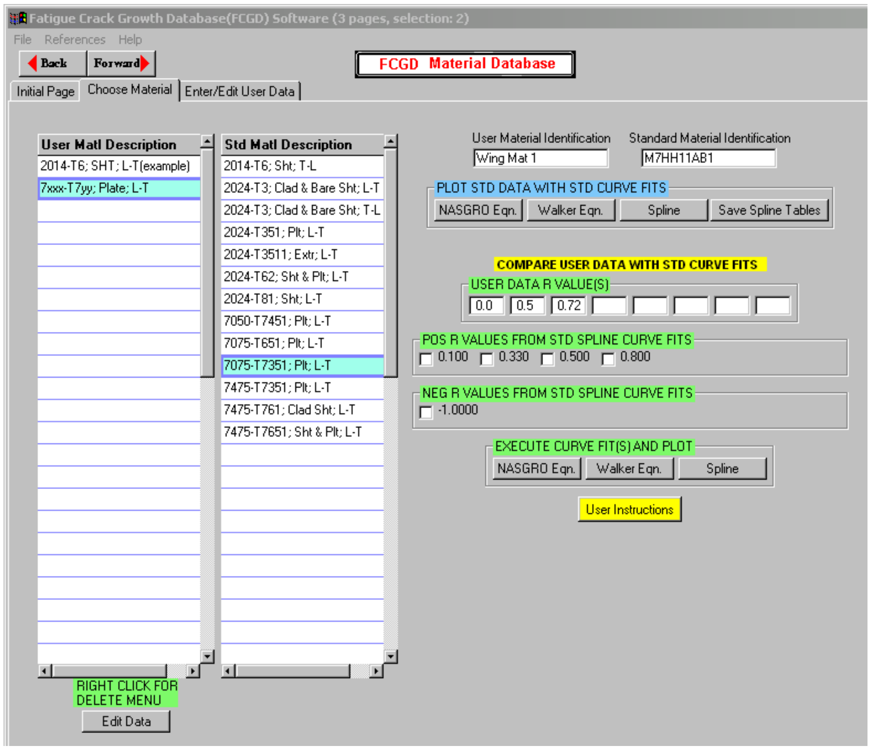


FIGURE D-3. SELECTION OF USER MATERIAL AND FCGD MATERIAL FOR COMPARISON PLOTTING

Figure D-4 shows a comparison of the user-entered data (7xxx-T7yy Plate) with the NASGRO curve fit for 7075-T7351 Plate from FCGD standard material database at the three *R* values. This plot was obtained by clicking on the user material under User Matl Description and the standard material under Std Matl Description (highlighted in figure D-3) followed by clicking the NASGRO Eqn button under the Plot Std Data with Std Curve Fits. Note that this is a comparison, not a curve fit of the user data. Similar plots are possible for the Walker equation and the Spline fits as shown in figures D-5 and D-6, respectively. In the case of the Spline fits however, the user must also select at least one *R* value of the available Spline fits to compare against.

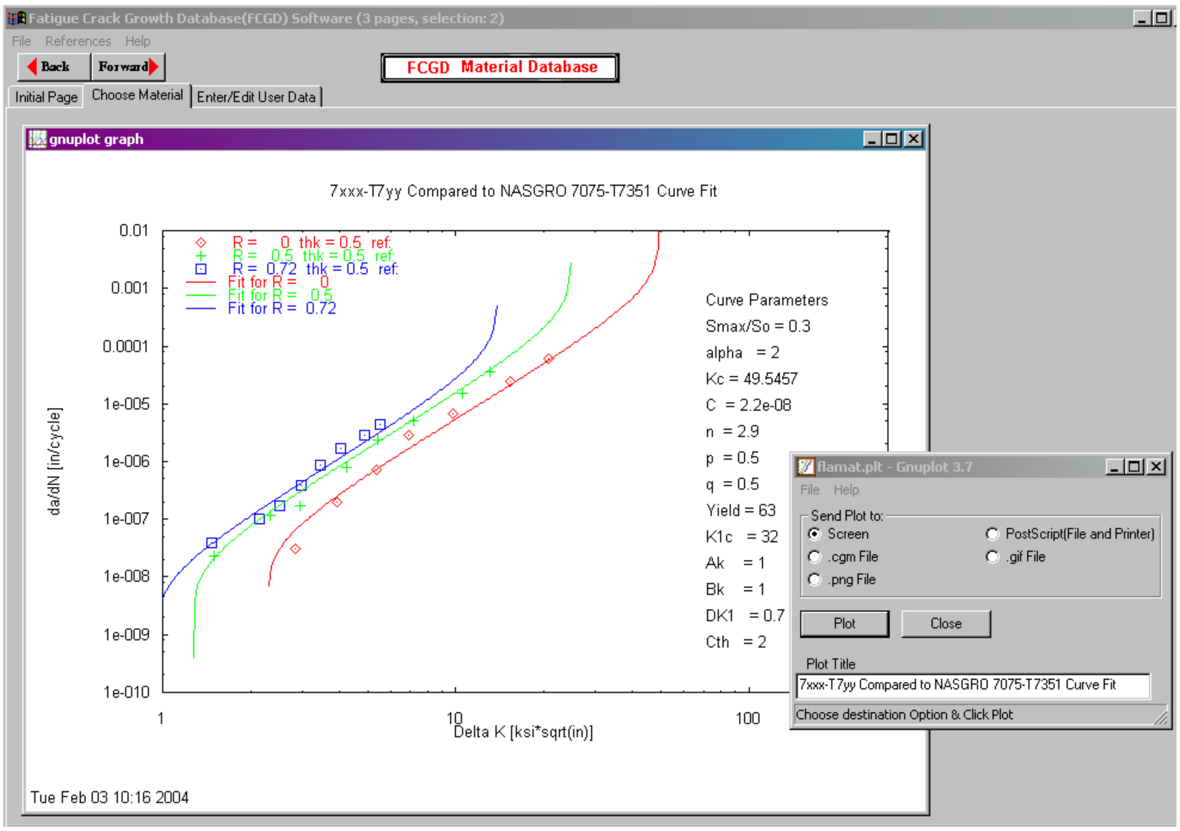


FIGURE D-4. COMPARISON OF USER-ENTERED DATA WITH 7075-T7351 NASGRO CURVE FIT AT *R* = 0, 0.5, AND 0.72

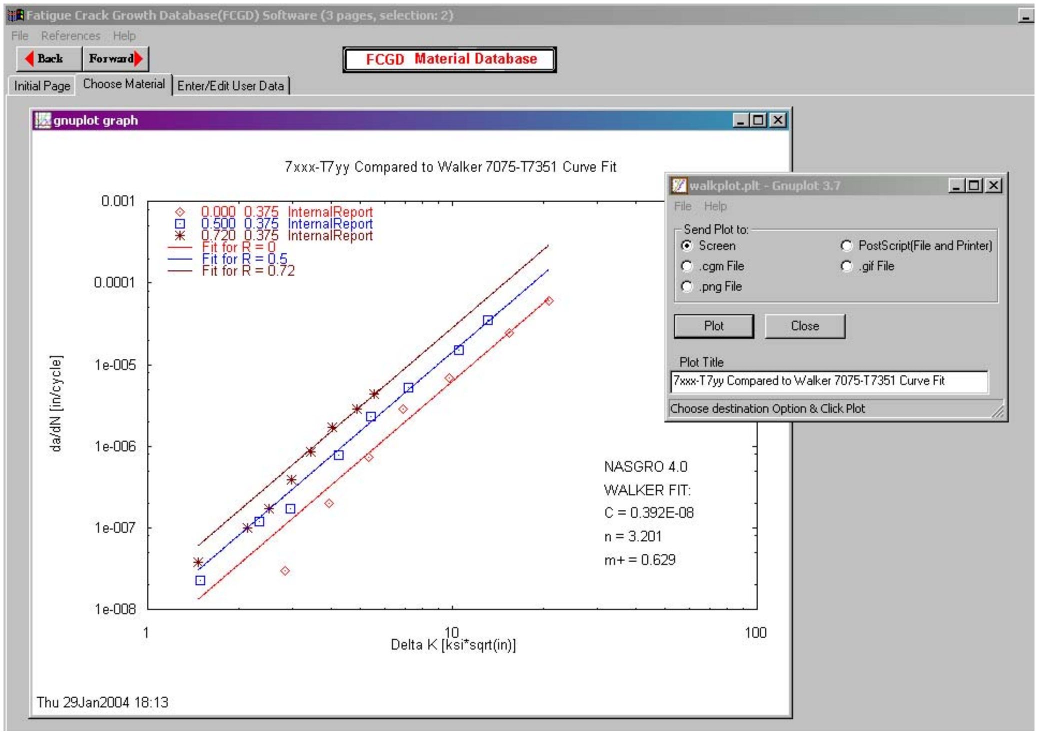


FIGURE D-5. COMPARISON OF USER-ENTERED DATA WITH 7075-T7351 WALKER CURVE FIT AT $R = 0$, 0.5, AND 0.72

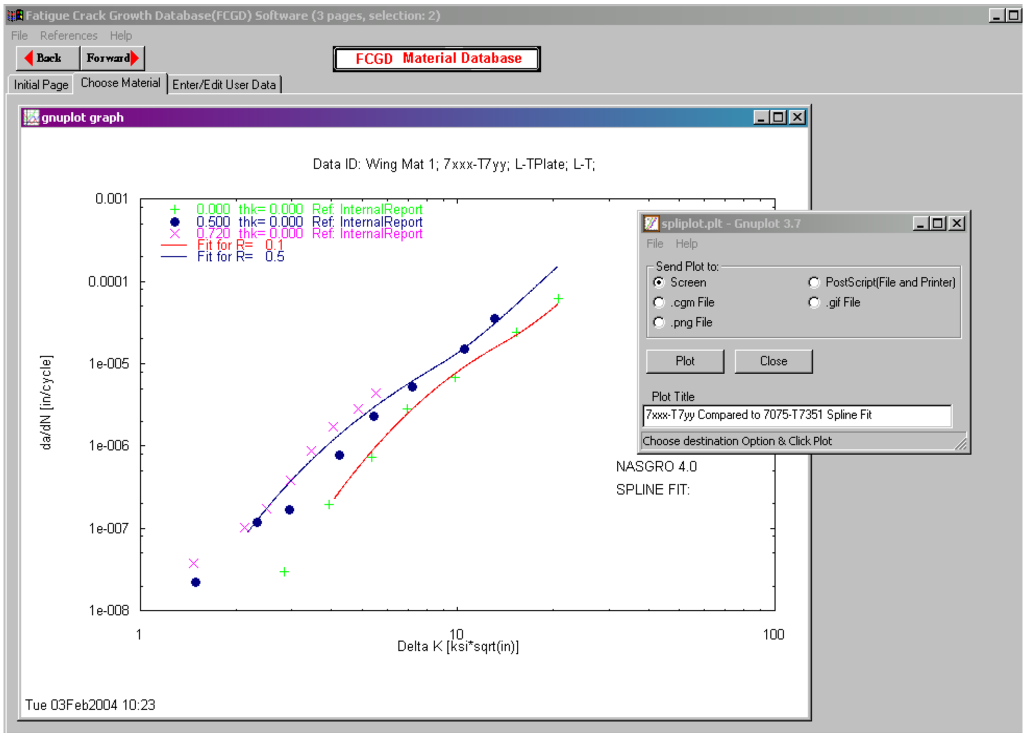
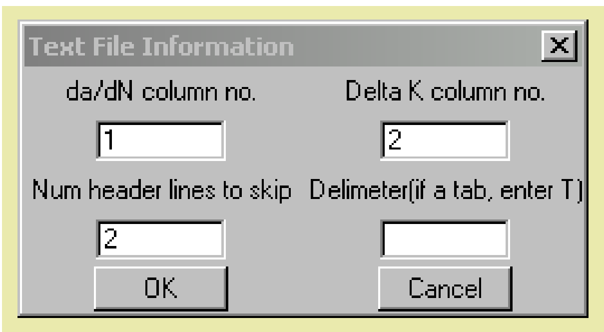


FIGURE D-6. COMPARISON OF USER-ENTERED DATA WITH 7075-T7351 SPLINE CURVE FIT AT $R = 0.1$ and 0.5

D.2 FILE ENTRY OF USER DATA.

It is more likely that the sets of *da/dN*-Δ*K* data would be in files. Therefore, the FCGD software accommodates input of data by text file. By clicking Text File under Data Source of the Enter/Edit User Data window (figure D-1), the Text File Information window shown in figure D-7(a) is displayed. In this window, the user is able to describe to the FCGD software the format of the fatigue crack growth rate data files by specifying the number of header lines to skip, the appropriate columns containing specific data (*da/dN or ΔK*), and a delimiter. It is assumed, however, that data for the individual *R* value are contained in separate files, as shown in figure D-7(b). With the format of the data files specified, an input matrix to specify file names is displayed by clicking the OK button, as shown in figure D-8.



(a) Format Utility

Wing *da/dN* vs Δ*K* Data
7075-T351 Aluminum at *R* = 0.0

1.0000E-10	1.25
4.0000E-09	1.50
9.9400E-09	2.00
4.8800E-08	3.00
1.5100E-07	4.00
3.6200E-07	5.00
9.7100E-07	6.00
2.6300E-06	7.00
4.7400E-06	9.00
6.4300E-06	10.00
6.9600E-06	11.00
9.6700E-06	12.00
1.3600E-05	13.00
1.7800E-05	14.00
2.1800E-05	15.00
3.5400E-05	18.00
6.7800E-05	22.00
1.1600E-04	25.00
1.4100E-04	26.00
2.4100E-04	28.00
3.9500E-04	30.00
7.7800E-04	33.00

(b) Format Utility

FIGURE D-7. UTILITY TO SUPPLY FORMAT OF TEXT DATA FILE

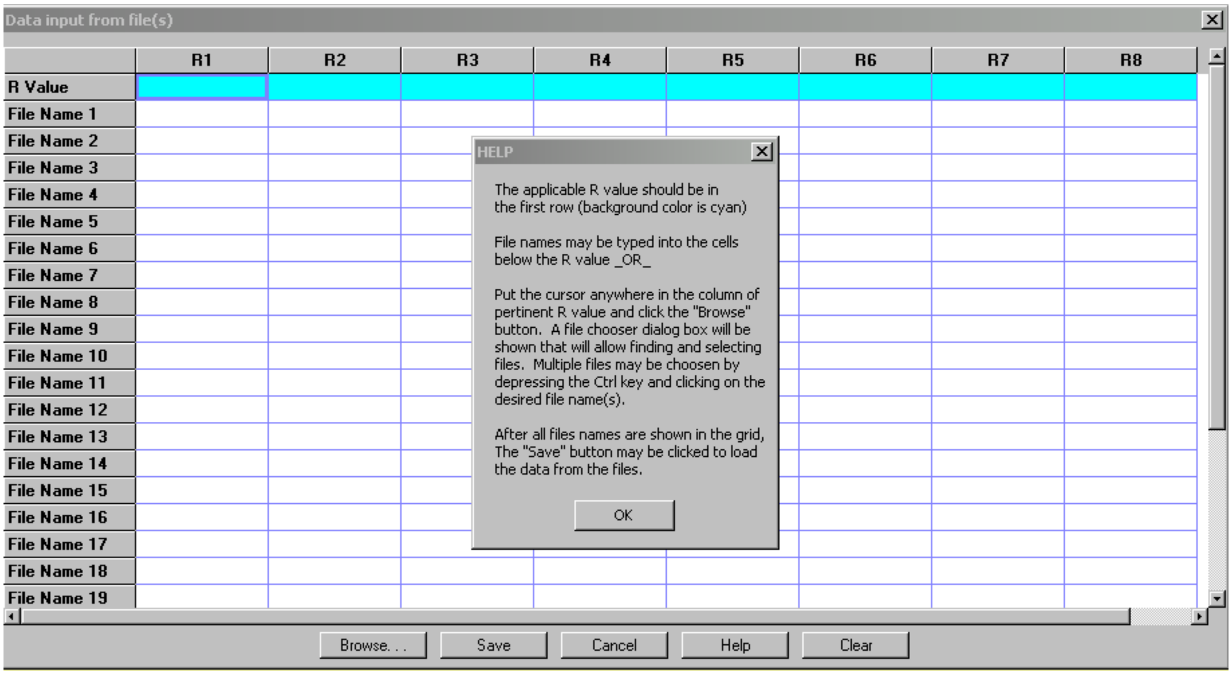
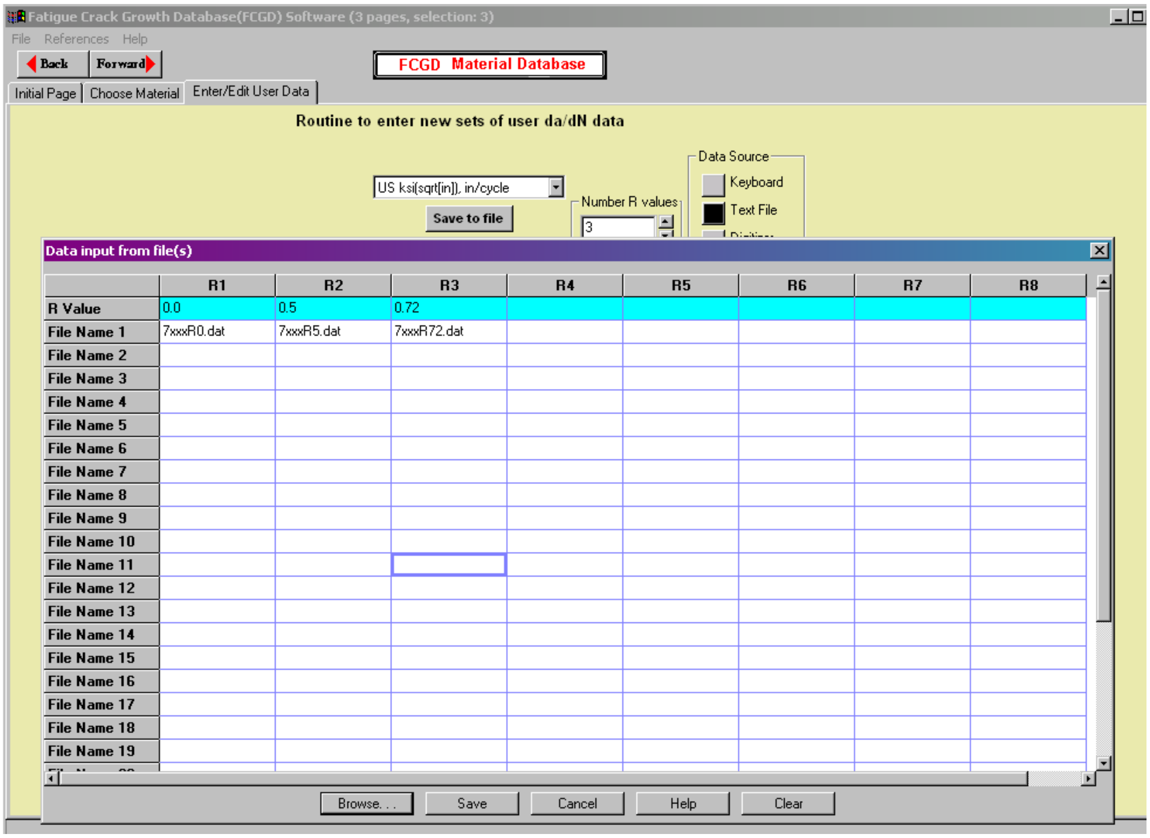


FIGURE D-8. INPUT MATRIX TO SPECIFY FILE NAMES FOR DIFFERENT SETS OF CRACK GROWTH RATE DATA AS A FUNCTION OF *R* VALUE

For the example discussed in section D.1, the *da/dN*-ΔK data were in three separate files. Figure D-9 illustrates how these files would be specified for each *R* value. A file name is specified for each *R* value for the case of equal number of file names and *R* values. In the event that there are multiple files for a given *R* value (e.g., more than one fatigue crack growth rate test), the file names could be entered in the rows under the *R* value column as appropriate. The *R* values and file names in the matrix may now be saved into the user material database by clicking on the Save button. Plotting and comparisons to the FCGD curve fits can then be performed, as outlined above for the keyboard input example.



Example data files:

Wing Material $R = 0.0$	
2.99e-08	2.84
1.97e-07	3.93
7.28e-07	5.34
2.85e-06	6.93
6.79e-06	9.82
2.43e-05	15.35
6.14e-05	20.78

7xxxR0.dat

Wing Material $R = 0.5$	
2.25e-08	1.49
1.18e-07	2.32
1.70e-07	2.94
7.80e-07	4.25
2.32e-06	5.43
5.18e-06	7.2
1.51e-05	10.5
3.52e-05	13.1

7xxxR5.dat

Wing Material $R = 0.72$	
3.81e-08	1.47
1.01e-07	2.13
1.74e-07	2.5
3.88e-07	2.97
8.66e-07	3.44
1.70e-06	4.04
2.85e-06	4.87
4.40e-06	5.54

7xxxR72.dat

FIGURE D-9. FILE ENTRY OF USER DATA

D.3 ENTERING USER DATA FROM A DIGITIZER.

Use of the digitizer requires that the *da/dN*-Δ*K* data to be digitized must be from a bitmap (.bmp) file obtained from a scanner or other method. Figure C-7 provides detailed instructions to use the digitizer utility. The digitizer incorporated in the FCGD software is WinDIG 2.0; additional instructions are available from the help button within the WinDIG window.