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Engineering Design File

ATR Vessel Specimen Irradiation Program

Idaho National Laboratory

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Idaho National Laboratory

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1. INTRODUCTION

An assessment of the Advanced Test Reactor (ATR) vessel and primary coolant system [1] was performed to evaluate the affects of aging on structural integrity including irradiation embrittlement of the reactor pressure vessel. In this analysis, data from the literature were used to estimate lower bound fracture toughness for irradiated 308 stainless steel weld material. The estimated toughness value was then used in a conservative approach for predicting fracture, and it was concluded in the report [1] that the ATR primary vessel would adequately perform its function.

However, the literature data sources used to estimate the minimum fracture toughness did not exactly match materials and conditions in ATR, and it was recommended that a test program be initiated to demonstrate the conservatism of the estimated material toughness. The results of the test program that was carried out and conclusions drawn from the results are presented here.

Revision 1 of this EDF corrects a misconception in the conclusions concerning operation beyond 2014, and updates reactor vessel fluence estimates based on current data.

2. BACKGROUND

The report by Durney et al. [1] found minimum fracture toughness values for the austenitic stainless steel to be J_{Ic} = 684 in•lb/in² for cracks with T-S orientation (see ASTM E 1820) or J_{Ic} = 889 in•lb/in² for cracks with T-L orientation. The Durney report further suggested that irradiation would not significantly degrade the fracture toughness of weld metal exposed to a fluence of 3.13E+18 n/cm² (E > 1 MeV).[a] A conservative fracture-mechanics-based analysis was applied using a conservative lower bound fracture toughness of J_{Ic} = 464 in•lb/in². Determination and justification of the critical crack sizes used in the analysis are presented in the report [1]. The report concluded that the ATR primary vessel would continue to perform its intended functions until at least an accumulated fast fluence of 3.13E+18 n/cm², but recommended the assumptions used in the analysis be verified by testing.

A vessel material test program initiated based on the recommendations of the Durney report [1] investigated both the validity of using J_{Ic} = 464 in•lb/in² as a lower-bound toughness and the relative reduction of fracture toughness due to neutron irradiation of the Type 308 weldments.

The methodology for measuring fracture toughness is provided in Graham et al. [2], and presents baseline fracture toughness data on unirradiated ATR vessel material. The vessel specimen irradiation program (VSIP) [3] was initiated to obtain fracture toughness specimens irradiated to a fluence of at least 3.2E+18 n/cm², with a target minimum of 1.5 x 10^{19} n/cm² (E > 1 MeV). Based on current projections, the target value of fluence for the irradiations is three times higher than the projected fluence in the ATR primary vessel weldment in 2060.

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[a] At that time, this fluence level was estimated to be greater than the ATR pressure vessel weldment accumulated fluence through at least 2014. A revised accumulated fluence is provided later in the report, and indicates 3.13E+18 n/cm² (E > 1 MeV) is a very conservative over-estimate.

Fracture toughness specimens and fluence monitor capsules were assembled by SWR-XX806 and placed in the ATR outer irradiation facility from June 1989 to May 1992. The specimens were then shipped to the B&W NES Inc. Lynchburg Technology Center for fracture testing, and the fluence monitors were taken to the INL Radiation Measurements Laboratory (RML) for isotopic measurement.

3. RESULTS

Fracture Toughness

The fracture toughness test data, and tensile properties measurements, collected by B&W NES are provided in the B&W report included as part of Appendix A. The B&W report documents the load-displacement data and calculated crack measurements used to determine the initial J-integral fracture toughness values. Review of the semi-automated analysis results generated by B&W per ASTM E 813, and then ASTM E 1737, showed that various acceptance criteria specified by these standards were not met. This invalidated the calculated fracture toughness values. Further review of the original data and test procedures identified various problems. Insufficient data were collected during the unload portions of the tests, and there was excessive scatter in the raw data (indeterminate causes). Both led to inconsistent calculated crack lengths, creating further perturbations in the data analysis.

In an effort to recover usable results form the raw test data, Bruce Young (MTI Inc., Alliance, OH) was tasked with analyzing the same raw data using an alternative approach. The approach used and his results were reported to INL, and are included as part of Appendix A. He used the "Normalization Data Reduction Technique." This analysis approach was under development at the time of his analysis, but since has been approved by ASTM and is included as Appendix A15 in Standard E 1820-08 [4]. This analysis method proved to be successful in providing valid fracture toughness results from the irradiated weldment test data. The technique, as applied, was documented in the MTI Inc. report to INL.

Valid fracture toughness measurements were obtained from most of the test specimen data, however it was not possible to obtain an acceptable fracture toughness value from specimen W-5 by any of the analysis techniques. Specimen W-5 data was inadmissible by the test standards validity tests, and thus was eliminated from the sample set.

Fluence Measurements

The fluence monitor capsules contained several flux wires which were each analyzed for radio-isotopic content at the INL RML. The fluence seen by the individual flux wires were then determined based on the measured isotopic content. The final results obtained by J.W. Rogers of INL RML are given in Appendix B. A table in Appendix B lists adjusted fluxes based on four different isotopic inventories, and then the average for the position, and finally the average fluence for the position. Appendix B also includes a figure that presents the average fluence by outer irradiation facility position. The specimens of interest for this EDF were loaded in VSIP

assemblies 2 and 5, which were irradiated in position OS-6 and 5 respectively. Data sheets from the VSIP assembly work order (XX806) show the loading orientation of the fluence monitor capsules relative to the fracture toughness specimens. Therefore, each test specimen can be identified with a fluence monitor capsule that was irradiated in the same position.

Summary of Results

Table 1 summarizes fracture toughness and fluence values for VSIP weld specimens. Irradiated and unirradiated specimens were removed from the same weldment. This weldment was fabricated using a procedure [see Appendix A in Ref. 2] to simulate the construction of the ATR primary vessel. The fracture toughness specimens were tested with the same T-L crack orientation for all conditions. Unirradiated toughness data are from Graham et al. [2], and irradiated toughness data are from the Bruce Young report in Appendix A. Fluences are from Appendix B.

Table 1. Fracture toughness and fast fluence results from Type 308 weldment tests

Specimen	J_{Ic} (in•lb/in²)	fluence (n/cm²) (E > 1 MeV)	irradiation position average fluence
W-1	737	1.32E+19	1.08E+19
W-5	invalid	9.47E+18	1.08E+19
W-9	769	8.55E+18	1.08E+19
W-10	781	1.18E+19	1.08E+19
W-6	699	1.20E+19	1.52E+19
W-11	573	1.64E+19	1.52E+19
W-7	721	1.85E+19	1.52E+19
W-2	629	1.37E+19	1.52E+19
wld-2	1100	0	0
wld-3	889	0	0

Figure 1 is a plot of these data. The line through the data is a least squares fit and the parallel line below the fit is the lower 95% confidence level. The vertical lines indicate the estimated fluence accumulated at the end of cycle 141A (1.34E+18 n/cm²) in March 2008 [5], and the projected total fluence in fifty more years of operation at 175 MW and 90% efficiency (4.82E+18 n/cm²). Note that current typical operation is about 105 MW and about 75% efficiency.

As Figure 1 shows, the mean value of toughness at the projected year-2060 fluence accumulation is about 880 in•lb/in², and the 95% confidence value of toughness at that fluence is about 730 in•lb/in². Compared to the measured unirradiated material toughness, the reduction in weldment fracture toughness in 2060 is only about 15% from the unirradiated condition. Comparing the 95% confidence level toughness in 2060 (730 in•lb/in²) with the estimated toughness value (464 in•lb/in²) used in the original analysis by Durney et al. [1], the primary vessel weldments will still have fracture toughness 35% higher. Based on the experimental results, the 95% confidence level toughness of the weldments does not degrade to the level used in the original analysis until accumulated fluence is four times higher than the projected year-2060 maximum.

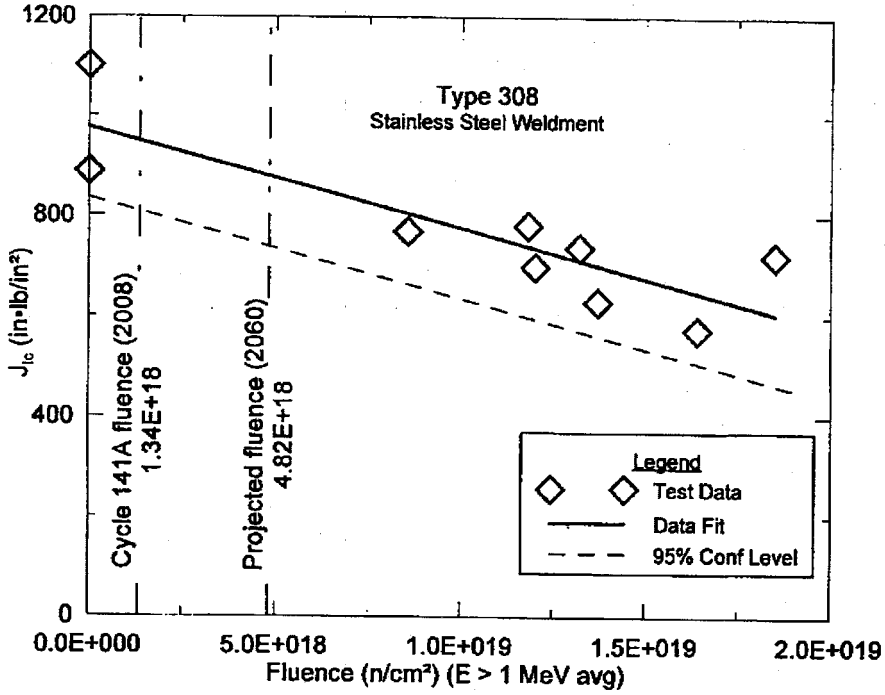

Figure 1. J_{Ic} fracture toughness measurements plotted verses fast fluence accumulation.

4. CONCLUSIONS

The original assessment [1] was directed toward showing irradiation and related aging effects through the year 2014, even though the mission of ATR was expected to extend well beyond that time. The VSIP fracture toughness assessment project showed the original assessment is safely conservative in several ways.

The 1986 estimated fluence accumulation for 2014 (3.13E+18 n/cm^2 ,E > 1 MeV) was very conservative, given that the fluence accumulated in 2008 (forty years of operation) is less than half of the 2014 assessment target.

The original fracture toughness test data also provide information on crack growth resistance (J vs. Δa curves) following the initiation of growth (by definition when J_{Ic} is reached). The crack growth resistance is continually and substantially increasing following initiation in the weldment specimens. This means that there could be substantial stable crack growth in the vessel weldments following crack growth initiation when $J = J_{Ic}$, hence there is additional conservatism beyond the original analysis results.

As shown in Figure 1, the value of fracture toughness used in the original assessment [1] of the primary vessel corresponds to more than 300 years of additional operation of ATR. Therefore,

the effects of irradiation embrittlement (reduction of fracture toughness) on the ATR vessel integrity will not be a concern for the foreseeable life of the facility.

The net result is that the assumptions made in the aging assessment [1] are conservative and that the assessment is, and will continue to be, valid.

5. REFERENCES

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6. APPENDICES

Appendix A – Irradiated Material Test Results and Analyses

Appendix B – VSIP Fast Neutron Fluxes and Fluences

Appendix A

Irradiated Material Test Results and Analyses

Appendix B

VSIP Fast Neutron Fluxes and Fluences

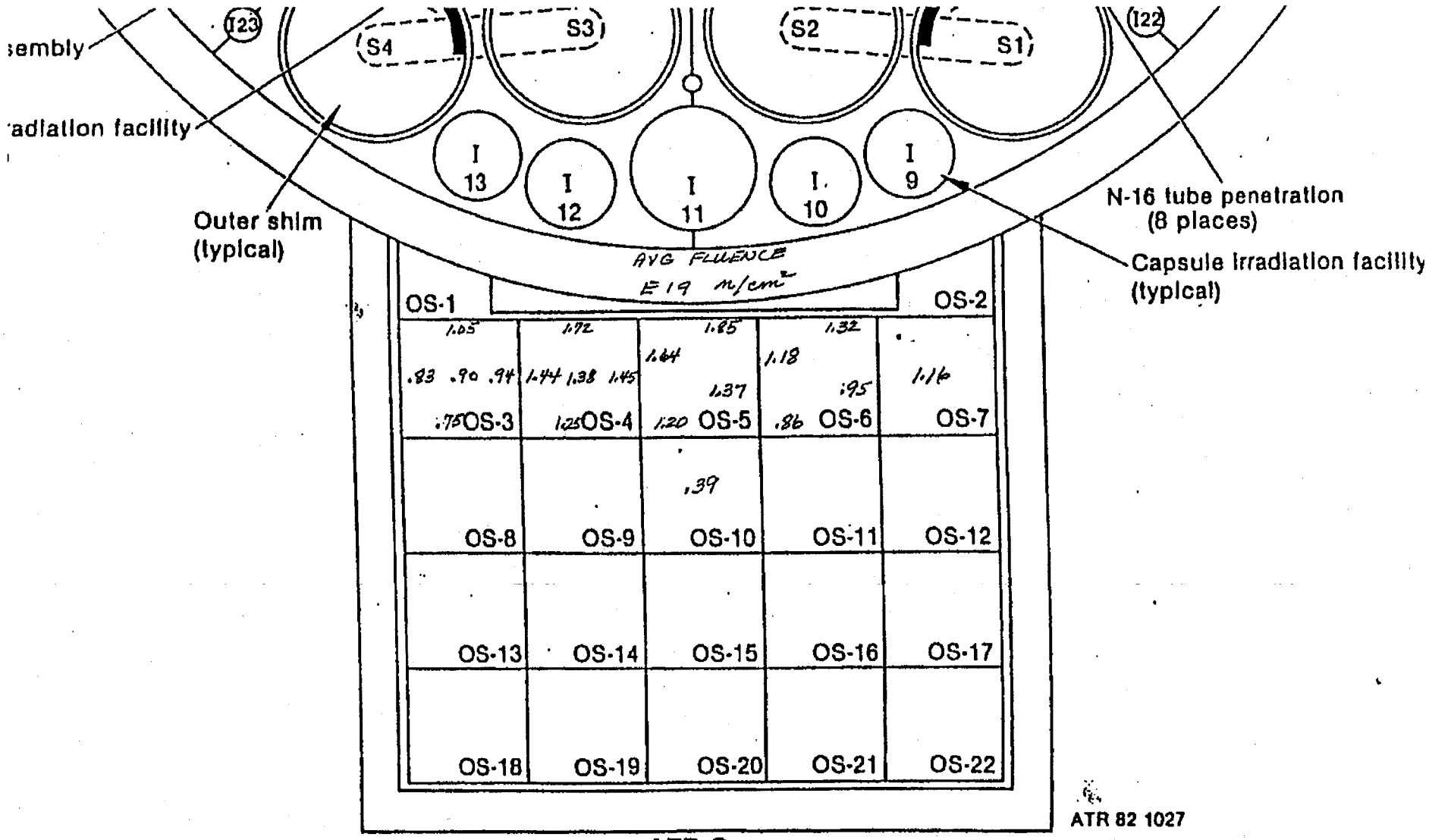
		Adjusted Flux					
		1.0	1.0	0.680	0.835		
	ID	^{54}Fe	^{93m}Nb	^{238}U	^{237}Np	Avg. Flux (10^9 n/cm²/s)	Avg. Fluence (10^{18} n/cm²)
1-A	OS3-A	211e9	190e9	184e9	201e9	196±12	7.55
	OS3-B	235e9	203e9	209e9	218e9	216±14	8.32
	OS3-E*	291e9	249e9	274e9	280e9	273±18	10.5
	OS3-F	255e9	233e9	239e9	250e9	244±10	9.39
	OS3-V	251e9	219e9	--	--	235±16	9.04
4-B	OS4-G	245e9	243e9	291e9	269e9	244±20	14.4
	OS4-H*	273e9	264e9	333e9	301e9	292±30	17.2
	OS4-I	228e9	230e9	265e9	260e9	246±19	14.5
	OS4-J	205e9	209e9	203e9	230e9	212±12	12.5
	OS4-W	235e9	234e9	--	--	234±10	13.8
5-B	OS5-K	193e9	193e9	212e9	214e9	203±12	12.0
	OS5-L	257e9	255e9	313e9	286e9	278±27	16.4
	OS5-M*	285e9	286e9	366e9	318e9	314±38	18.5
	OS5-N	219e9	222e9	248e9	241e9	232±14	13.7
2-A	OS6-P*	361e9	313e9	362e9	342e9	344±23	13.2
	OS6-Q	260e9	232e9	245e9	247e9	246±11	9.47
	OS6-R	241e9	214e9	214e9	220e9	222±13	8.55
	OS6-S	320e9	279e9	313e9	310e9	306±18	11.8
3-A	OS7-T	355e9	271e9	302e9	272e9	300±39	11.6
6-B	OS10-U	71.9e9	60.3e9	66.4e9	66.5e9	66.3±4.7	3.91

* Nearest to core.

VSIP FAST NEUTRON FLUXES / FLUENCES

FORM EG&G-656
(Rev. 8-77)

VSIP	ID	^{54}Fe (1.0)	^{93m}Nb (1.0)	^{238}U (0.650)	^{237}Nb (0.835)		AVG FLUX		AVG FLUENCE		
	053-A	2.11E11	1.90E11	1.84E11	2.01E11		1.96±.12E11		7.55E18		
	B	2.35E11	2.03E11	2.09E11	2.18E11		2.16±.14E11		8.32E18		
(1) A	* E	2.91E11	2.49E11	2.74E11	2.80E11		2.73±.18E11		1.05E19		
	F	2.55E11	2.33E11	2.39E11	2.50E11		2.44±.10E11		9.39E18		
	V	2.51E11	2.19E11	—	—		2.35±.16E11		9.04E18		
	054-G	2.45E11	2.43E11	2.91E11	2.69E11		2.44±.20E11		1.44E19		
	* H	2.73E11	2.64E11	3.31E11	3.01E11		2.92±.30E11		1.72E19		
(4) B	I	2.28E11	2.30E11	2.65E11	2.60E11		2.46±.19E11		1.45E19		
	J	2.05E11	2.09E11	2.03E11	2.30E11		2.12±.12E11		1.25E19		
	W	2.35E11	2.34E11	—	—		2.34±.10E11		1.38E19		
	055-K	1.93E11	1.93E11	2.12E11	2.14E11		2.03±.12E11		1.20E19		
	L	2.57E11	2.55E11	3.13E11	2.86E11		2.78±.27E11		1.64E19		
(5) B	* M	2.85E11	2.86E11	3.66E11	3.18E11		3.14±.38E11		1.85E19		
	N	2.19E11	2.22E11	2.48E11	2.41E11		2.32±.14E11		1.37E19		
	056-P	3.61E11	3.13E11	3.62E11	3.42E11		3.44±.23E11		1.32E19		
	Q	2.60E11	2.32E11	2.45E11	2.47E11		2.46±.11E11		9.47E18		
(2) A	R	2.41E11	2.14E11	2.14E11	2.20E11		2.22±.13E11		8.55E18		
	S	3.20E11	2.79E11	3.13E11	3.10E11		3.06±.18E11		1.18E19		
(3) A	057-T	3.55E11	2.71E11	3.02E11	2.72E11		3.00±.39E11		1.16E19		
(6) B	0510-U	7.19E10	6.03E10	6.64E10	6.65E10		6.63±.47E10		3.91E18		
	*	missed dose									



ATR Core
Cross-sectional Diagram

McDermott Technology, Inc.

Research and Development Division Alliance, Ohio

To: Ken Mayo – BWXT Services, Lynchburg (4)	
From: Bruce Young (640) – Materials Engineering – ARC	
Customer: BWXT Services	File No.: RDD:CY00:43805-001-000:01 SVR
Subject: Fracture Toughness Analysis Using the Normalization Technique on Data Provided by INEEL.	Date: November 1, 2000

SUMMARY

This report presents the results obtained from a fracture toughness analysis on data provided to BWXT by Idaho Nuclear Engineering and Environmental Laboratory (INEEL). The analysis was completed using the normalization technique to determine the J fracture toughness value for each data set. A previous report issued by B&W Nuclear Environmental Services, Inc. indicates the data was obtained from tests conducted on irradiated 308 Stainless Steel weld metal. The analysis results will be used to evaluate the conservatism of the toughness value used in the Advanced Test Reactor's (ATR) structural integrity analysis.

Analysis was attempted on eight data sets using the normalization technique. Seven of the data sets gave results that were consistent with the analysis technique. One data set, specimen identity W-5, was unable to be analyzed using this method. In discussions with B&W Nuclear Environmental Services, this specimen was suspect in the original analysis. A suggestion was made that further metallurgical analysis was needed to determine if the material tested was actually weld-metal. To the knowledge of the investigator, no further examination was completed.

Using the seven data sets that gave consistent J results, a statistical analysis was performed. The mean J value was 701 (in-lbs/in^2) with a standard deviation of 75.6 (in-lbs/in^2). Taking the mean minus three standard deviations, a value of 474.3 (in-lbs/in^2) was obtained. The original assessment of ATR used a value of 464 (in-lbs/in^2), which is conservative with respect to the three-sigma lower bound value obtained from the normalization analysis. However, it is recommend that further investigation of specimen W-5 be completed.

KEY WORDS:

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INTRODUCTION

In August 1995, B&W Nuclear Environmental Services, Inc. (B&W NES) issued a report[1] detailing test results for tensile and bend type fracture specimens. This report included fracture toughness results for 308 stainless steel weld metal tested at 125°F that had been irradiated to fluence levels of 1. X 10^{18} and 1.2 x 10^{19} n/cm^2. The fracture toughness data in the B&W NES report was analyzed to ASTM E813-89 and ASTM E1152-87.

In the discussion portion of the B&W NES report (Section 5), it was stated that there were not many data points collected during the unload portion of the test. The lack of sufficient data points can lead to crack length measurements having a large amount of scatter. As seen in the results of the J-R curves, the calculation of an initial a_0 from the first three data points (in accordance with ASTM E813-89) is inaccurate. In addition, there was significant backup in the J verses Δa data.

Upon further review of the initial report issued by B&W NES, it was determined that another approach to analyzing the data was needed. B&W NES contracted with Westmoreland Mechanical Testing and Research, Inc. (WMT&R) to analyze the data in accordance to ASTM E1737-96. The reasoning for re-analyzing the data to ASTM E1737-96 was the inclusion of a new approach for calculating the initial a_0 from the test data.

In October 1998, WMT&R issued a report[2] that included the fracture toughness results for the eight weld specimens. The results included the new approach in determining the initial a_0, but the data in the unload portion of the set was still sparse. The newer analysis technique was valid, but the data was still scattered due to insufficient load-cod data points in the compliance unload portion of the test.

In November 1998, B&W NES contracted McDermott Technology, Inc. (MTI) to review the results provided by WMT&R and to make recommendations. Upon MTI's review of the data, it was noted that the regression data from compliance used to determine the crack lengths were too sparse and another approach to analyzing the data was needed. In a subsequent discussion between MTI, B&W NES, and INEEL, MTI recommend that the normalization[3] approach be applied to the data set.

In July 2000, INEEL contracted with BWXT Services which in turn contracted with MTI to provide the normalization analysis. This report details the results of the normalization approach that was applied to the data of the eight weld specimens.

BACKGROUND ON THE ANALYSIS APPROACH[4]

Landes[3] first proposed a normalization procedure based on the Key-Curve principle originally proposed by Ernst et al.[5]. The development of the procedure has been described in a number of papers by Landes and co authors [6,7,8]. Recently, this normalization procedure was used in an ASTM round robin testing program for determining a dynamic J-R curve. Joyce[9] developed the procedure used in that round robin. Porr[10] has suggested some modifications to the Joyce procedure, which Porr successfully used in very slow strain rate J tests in an aggressive environment[11]. The analysis in this report has made use of the procedure developed by Joyce and the modifications by Porr.

The advantage of the normalization procedure is the J-R curve can be obtained from the load-displacement record and the initial and final physical crack lengths, without the need for a remote crack-length measurement approach such as unloading compliance or potential drop. This procedure is a significant advantage when the testing conditions are such that unloading compliance or potential drop is difficult or impossible to apply. It is particularly useful in dynamic fracture testing and testing in aggressive environments such as corrosion crack-growth testing in high temperature water or fracture testing of irradiated materials.

DESCRIPTION OF THE NORMALIZATION PROCEDURE[4]

The load and the load-line displacement records from the experiment are each normalized using the following equations.

$$P_{Ni} = \frac{P_i}{WB\left(\frac{W - a_{bi}}{W}\right)^{\eta_{pl}}}$$

P_{Ni} – Normalized Load
W – Specimen Width
B – Specimen Thickness
P_i – Load for a given Load-Displacement Pair
a_{bi} – Blunting Corrected Crack Length
η_{pl} – Plastic eta Factor

$$v'_{pli} = \frac{v_{pli}}{W}$$

v'_{pl} – Normalized Plastic Displacement
v_{pli} – Plastic Displacement for a give Load-Displacement Pair

The crack length used in this normalization procedure is the initial physical crack length corrected for the crack tip blunting for all the load displacement pairs with the exception of the final load point. For the final load point, the crack length is the final physical crack length. The points for the purpose of curve fitting are then chosen between the normalized plastic load line displacement cutoff and the estimate of the last point before crack initiation. A curve is then fit through these points and the final point calculated from the final physical crack length. The crack length is then adjusted for all the load displacement pairs between the normalized plastic displacement cutoff and the final point, such that the normalized load displacement points fall on the curve fitted line.

The analysis procedure used in this study was incorporated into a customized computer program. This program used the equations described by Joyce[9] to determine the normalized load and normalized data pairs. An iteration routine was used to determine estimate of the last point prior to crack initiation. Porr[10] developed a method to estimate the point. This method uses the final data point and fits secant lines between that point and the rest of the data. The point at which the tangency occurs is the estimated point prior to the onset of cracking. Next, the function proposed by Joyce was curve fit using the data between the normalized displacement cutoff and the estimated point prior to the onset of cracking plus the data point from the final crack length. The curve fit was developed using a predicted-corrected solution method. Since this method is a predicted-corrected method, an initial guess for the fit coefficients needed to be made. The data was reduced in such a manner that the initial guesses were all the same.

The function, used in curve fitting the data, is the following form.

$$P_N = \frac{a + bv'_{pl} + cv'^2_{pl}}{d + v'_{pl}}$$

P_{Ni} – Normalized Load
v'_{pl} – Normalized Plastic Displacement

Once the curve fit was established for the initial data set, a goodness of fit determination was made between the data and the curve fit. If the goodness of fit was lower than minimum value specified by the user of the software, the estimated crack initiation point was reduced by one data-pair and the curve fit process repeated. Iteration continued until the desired goodness of fit was achieved.

Once the goodness of fit was met, the data after the normalized load displacement cutoff was moved to the fitted line by an iteration process on crack length. This iteration process continued until the data was within the deviation permitted. The permitted deviation was some given percent of normalized load between the data point and the curve fit. Once all of the data had been moved to the curve, the known data triplet; crack length, Load Line Displacement, and Load were used to obtain a J-R curve.

SPECIFIC PARAMETER VALUES USED IN THIS ANALYSIS

As noted in the description of the procedure, certain parameters that require values before the procedure can be executed. The four parameters are data spacing, normalized plastic displacement cutoff, goodness of fit limit, and deviation allowance. All of these parameters remained constant for all eight specimens.

The data spacing parameter sets the spacing between each load - load line displacement data pair. This parameter is based on the load-line displacement. Data spacing was set to .001" between data points. The normalized plastic displacement cutoff sets a lower bound for the curve fit, that is, it ensures there is some plasticity in the data. This parameter is set such that the lower bound for the curve fit is still in the blunting region. The normalized plastic displacement cutoff for all the data sets was set at .001 in/in.

The goodness of fit parameter measures how well the curve matches the data. If the goodness of fit parameter is not met, then the data set used in the curve fit is reduced by one data point as described in the previous section. The goodness of fit value, for the data analyzed in this report, was set to 0.99. The deviation allowance parameter describes how close the data point must be to the curve fit during the crack length iteration stage of the analysis. The deviation between the normalized load in the curve fit and the normalized load for the data point had to be less than 0.1%.

RESULTS

In previous analysis[1,2], J values were invalid due to certain invalidity of the remote crack length measurements (i.e.: compliance) with the actual physical crack lengths. Since there is no remote crack length measurements used in this analysis, the J values should be considered valid for the crack lengths. The only reason for invalidity would be if the specimen size criteria was violated. The largest J value in the data set is 780.6 (in-lbs/in^2). Using this value the uncracked ligament and the thickness must be greater than 0.2 inches to be valid. Thus all of the specimens are valid and the J values should be considered J_{IC}.

Comparisons were made between the initial physical crack length and the compliance derived crack lengths. For each specimen, the compliance derived crack length was obtained by regressing on the initial portion of the load vs. load line displacement data. This regression slope was inverted to obtain the initial load line compliance. The compliance was then used to calculate an initial crack length. The error between the physical crack length and the compliance crack length was less than ten percent.

The compliance calculated crack lengths under-estimate the physical crack lengths. Also, the pre-crack shape of each specimen was irregular and thumb-nailed as can be seen in the original report[1]. The under-estimation of the physical crack length by the compliance of the specimen is not unusual since the compliance function tends to favor the non-cracked portions of the crack front.

The results of data analysis are summarized in Table 1.

Table 1 – Results Summary

Specimen	J (in-lbs/in^2)	C_1 (in-lbs/in^2)	C_2	a_0 Physical (in)	Load Line Compliance (in/lb) x 10^{-6}	Compliance a_0 (in)	Error in a_0 (Absolute %)
W-1	737.2	1372.1	0.5096	0.6316	6.88459	0.6135	3.0
W-2	628.7	1076.3	0.4242	0.6240	6.18743	0.6050	3.1
W-6	698.9	1232.8	0.4589	0.6425	5.96506	0.5980	7.4
W-7	720.6	1320.7	0.4946	0.6828	9.33376	0.6760	1.0
W-9	768.6	1333.9	0.4581	0.6271	6.15729	0.6040	3.8
W-10	780.6	1359.0	0.4605	0.6066	5.55920	0.5810	4.4
W-11	572.7	971.3	0.4074	0.6103	4.98967	0.5610	8.8

The results were obtained from the re-analysis of the raw data using the normalization technique. The analyzed data and curve fits, for the analysis technique, can be found in Appendix I. Appendix I is only data and results from the normalization procedure; the Appendix contains no data from the past reports.

The formula for the J-R curve is as follows:

$$J = C_1 * \left(\frac{\Delta a}{k}\right)^{C_2}$$

$$k = 0.0394 \text{ in.}$$

Data graphs, with detailed results, are in Appendix I.

Using the seven data sets that gave J results, a statistical analysis was performed. The mean J value was 701 (in-lbs/in^2) with a standard deviation of 75.6 (in-lbs/in^2). Taking the mean minus three standard deviations, a three-sigma lower bound value of 474.3 (in-lbs/in^2) was obtained.

CONCLUSIONS

1. Using the seven data points obtained from the analysis in this report, the ATR value of 464 used in their analysis is considered to be conservative.
2. The normalization technique shows reasonable statistical variation between specimens.
3. Specimen W-5 needs further investigation, which is outside the scope of this report.

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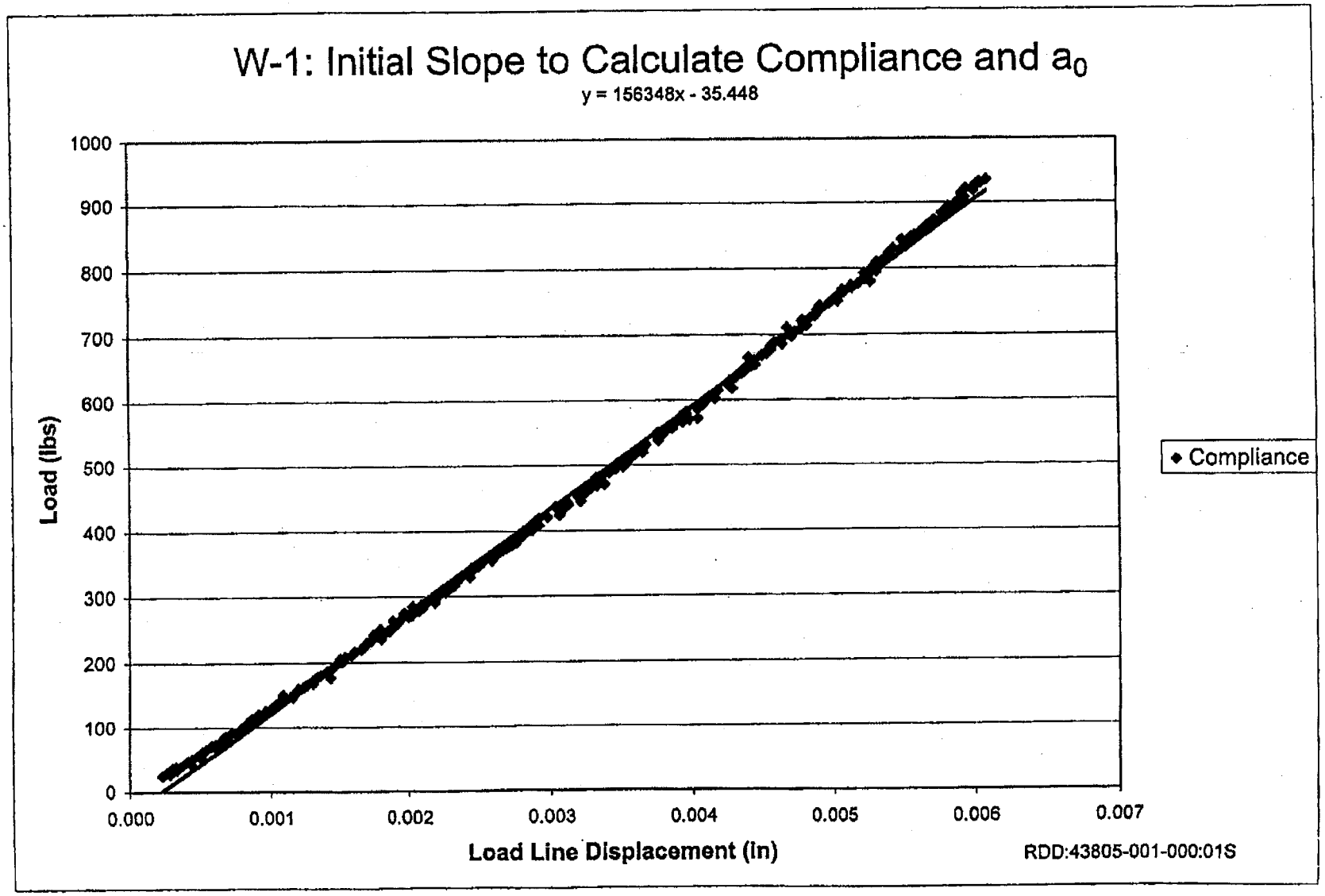
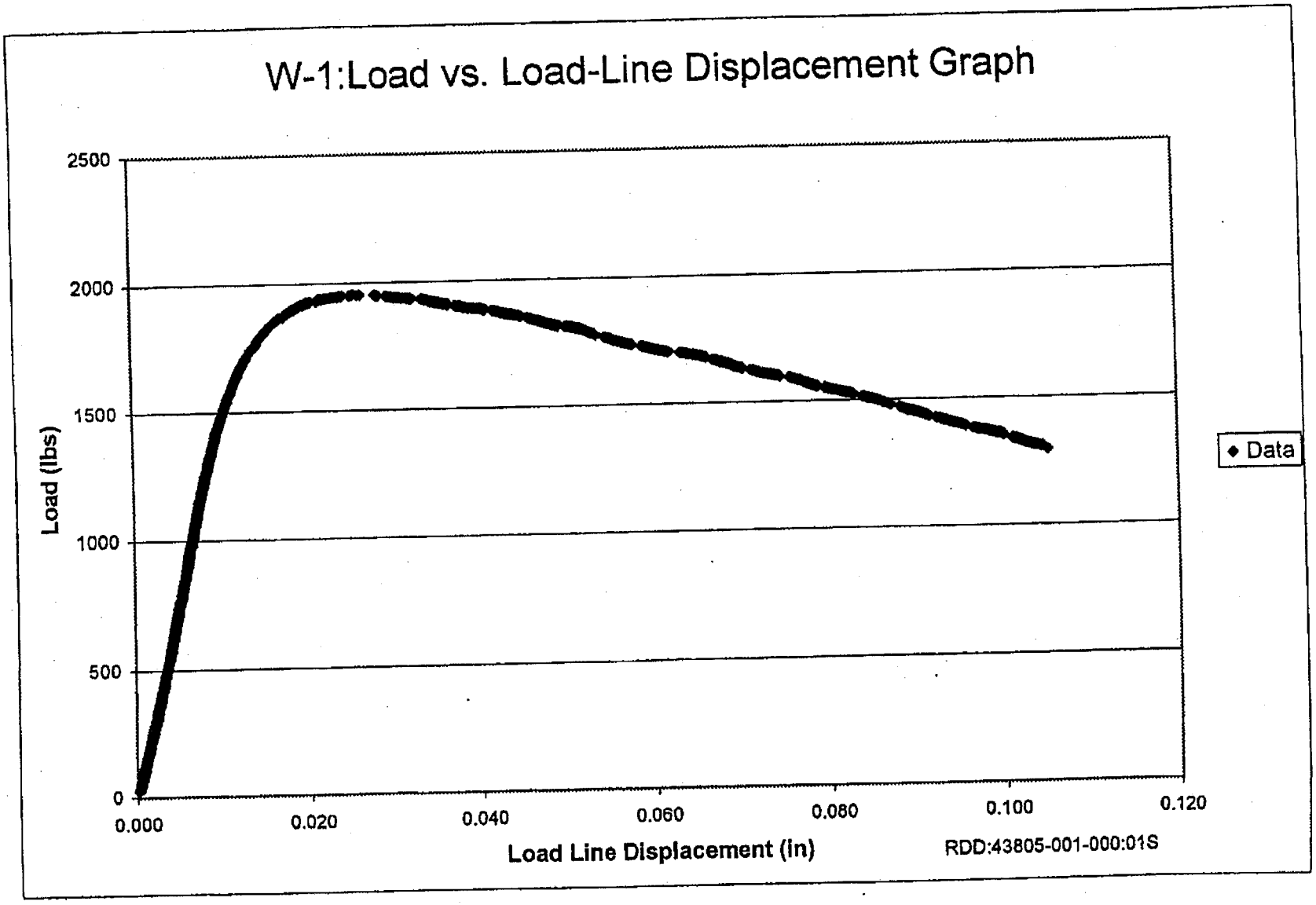
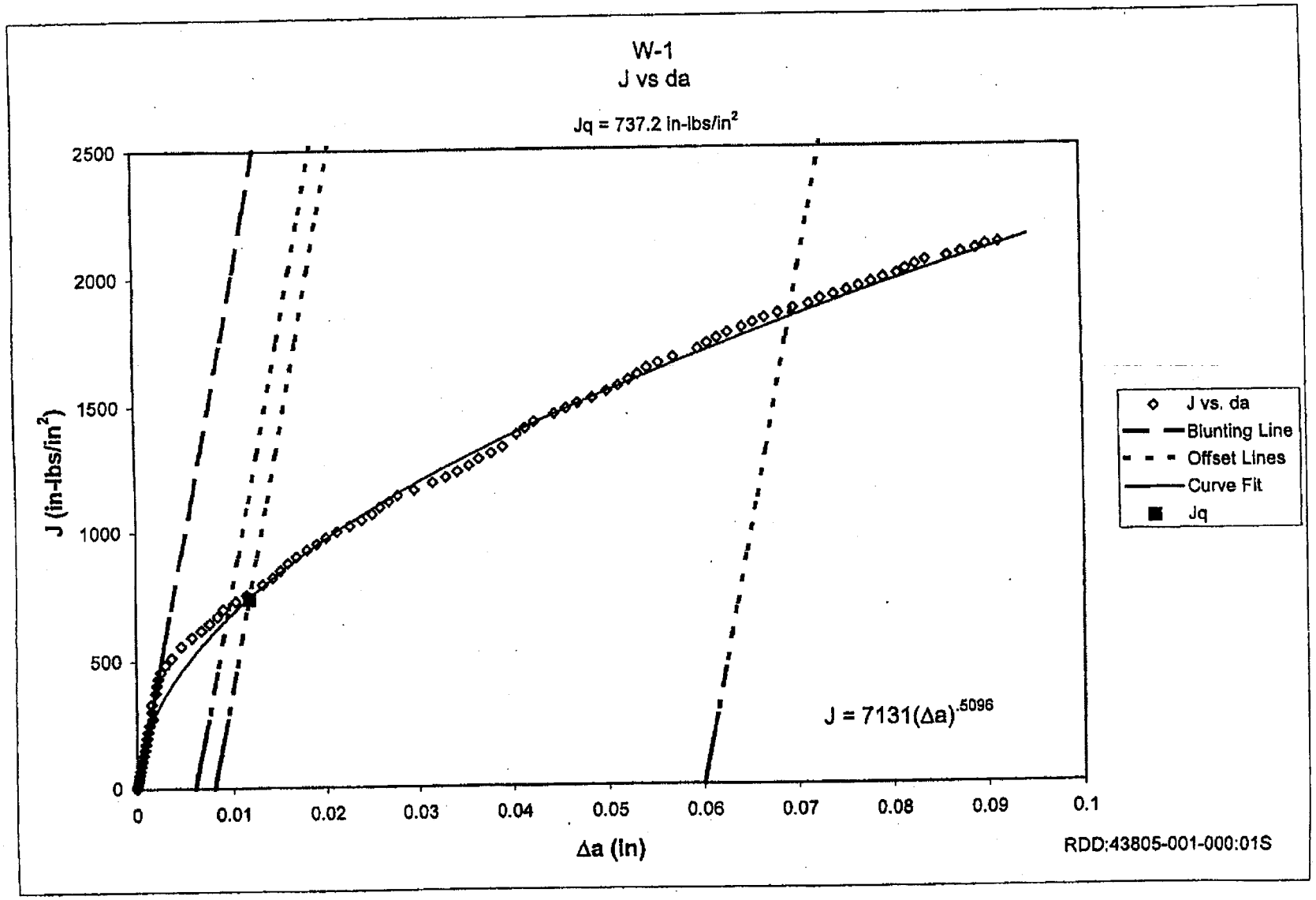
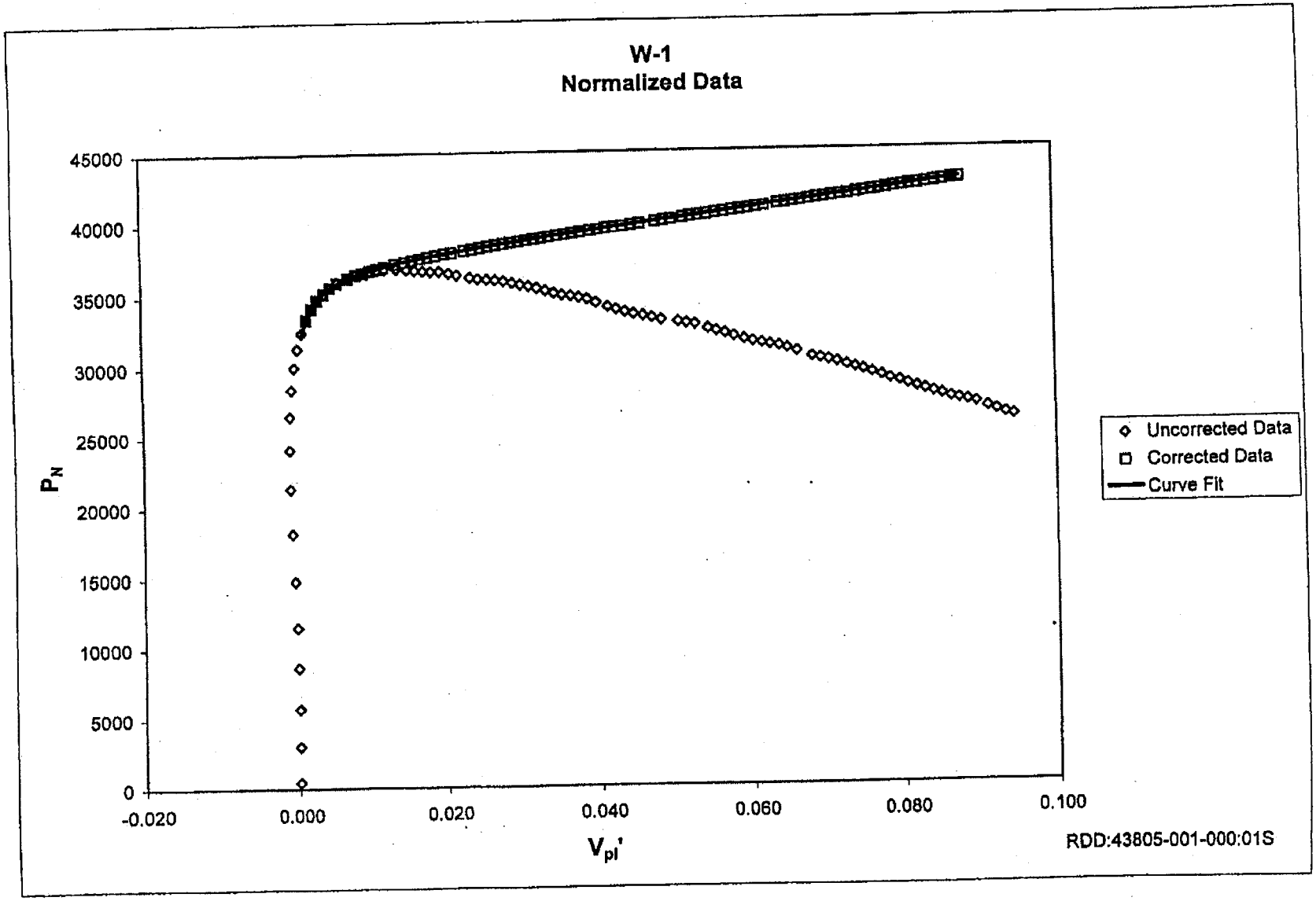
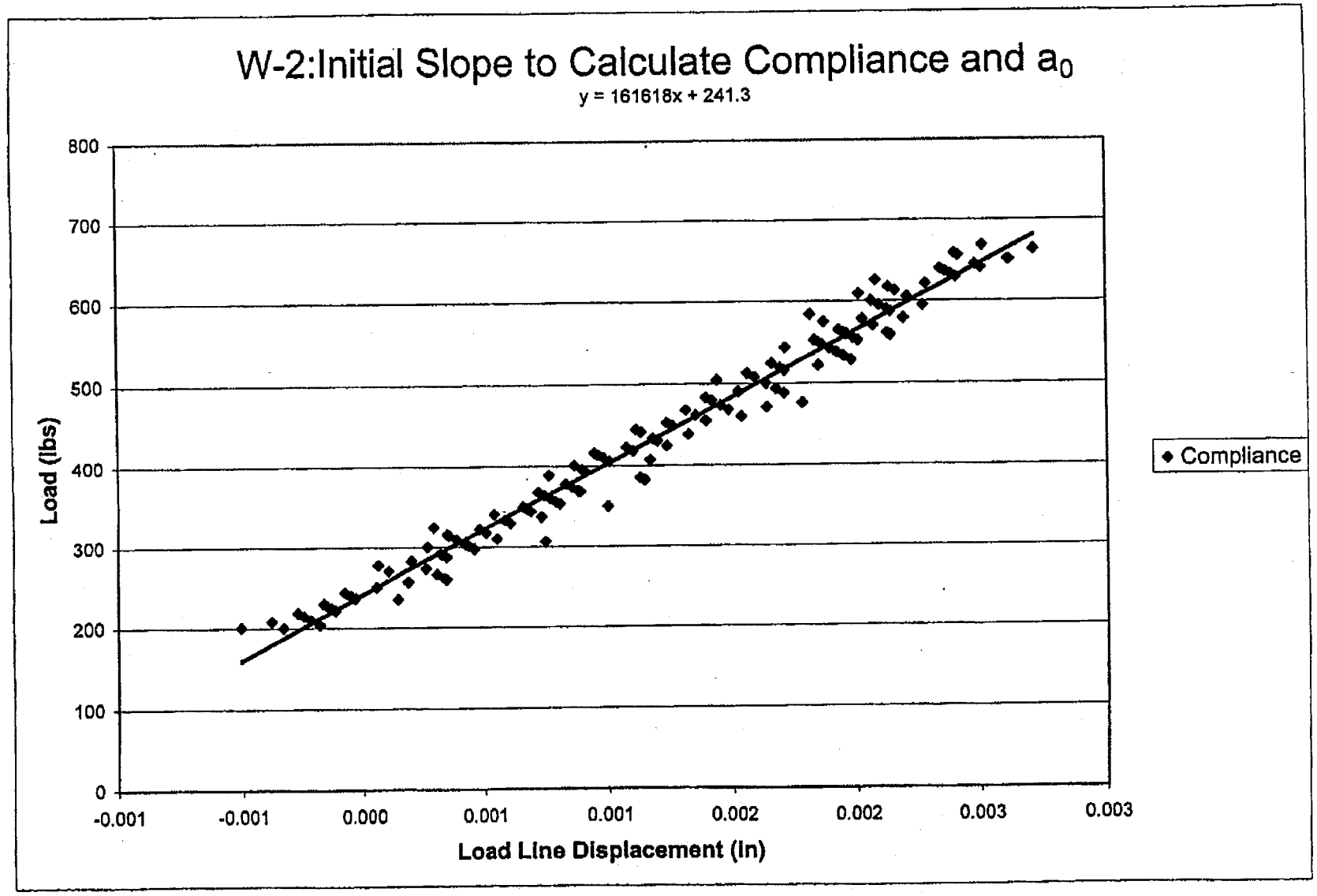
Appendix I
Detailed Data and Curves

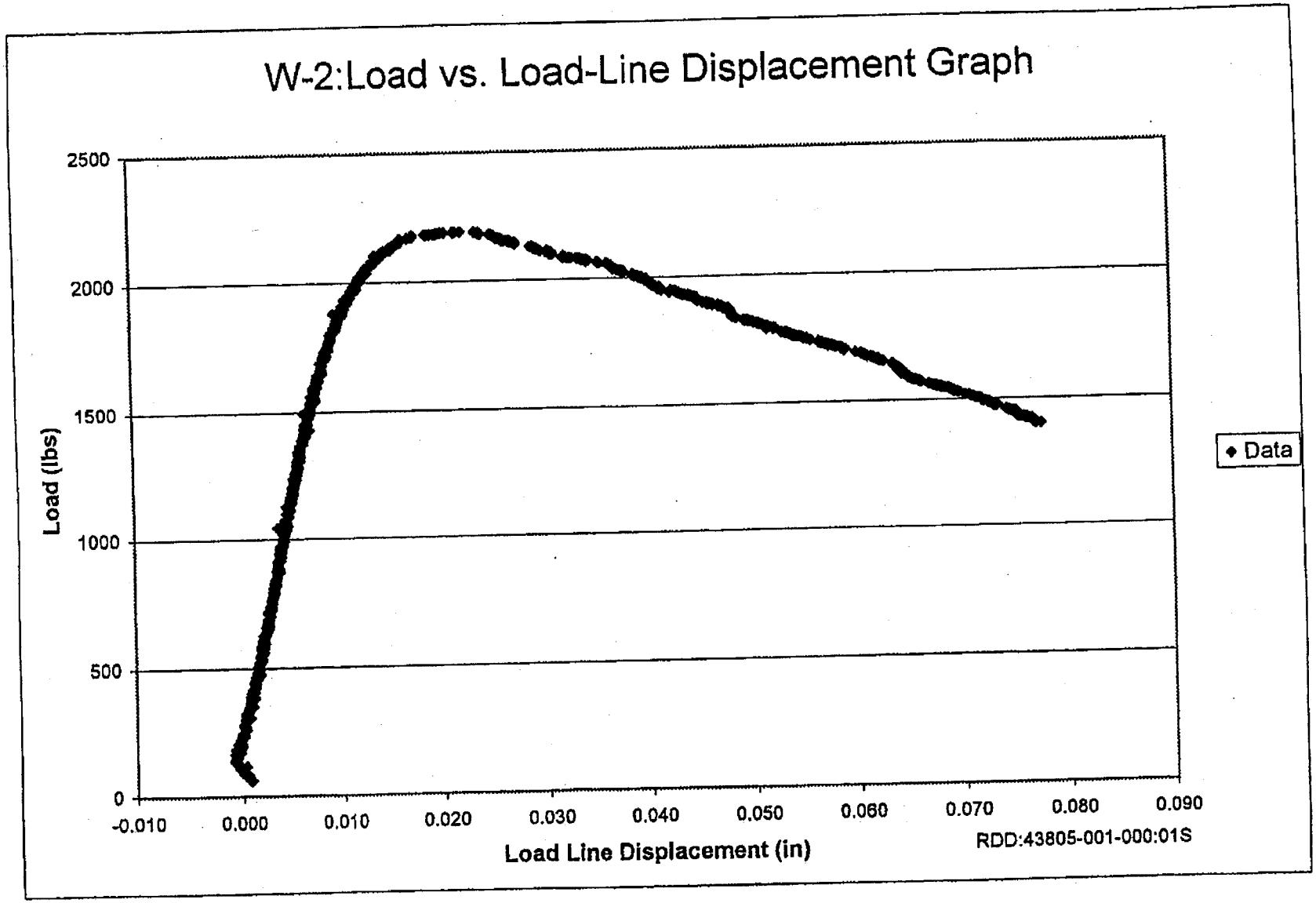

W-1: Initial Slope to Calculate Compliance and a_0
y = 156348x - 35.448
Load (lbs)
1000
900
800
700
600
500
400
300
200
100
0
0.000
0.001
0.002
0.003
0.004
0.005
0.006
0.007
Load Line Displacement (in)
Compliance
RDD:43805-001-000:01S

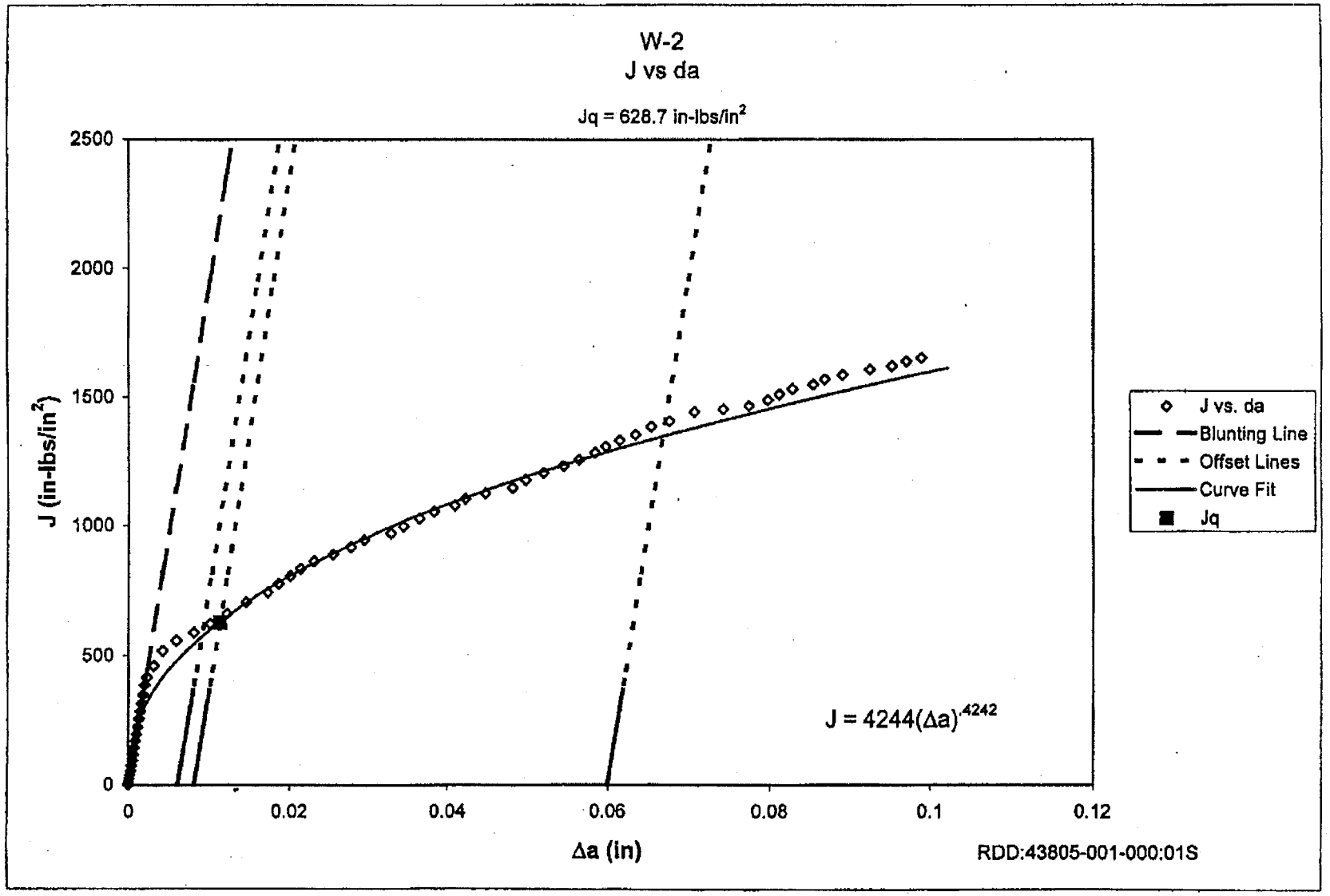

W-1:Load vs. Load-Line Displacement Graph
2500
2000
1500
1000
500
0
Load (lbs)
0.000
0.020
0.040
0.060
0.080
0.100
0.120
Load Line Displacement (in)
RDD:43805-001-000:01S
Data

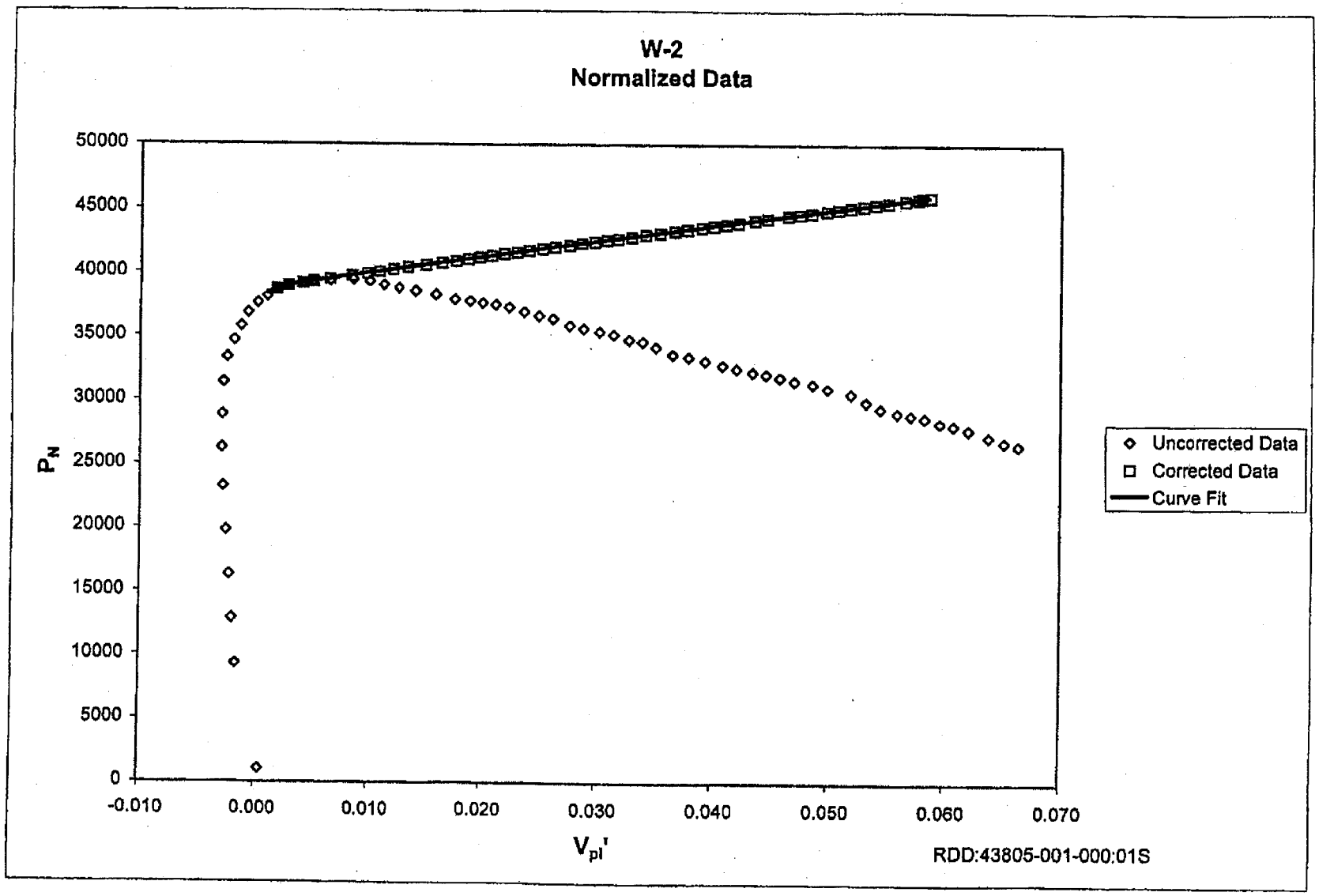

W-1
J vs da
Jq = 737.2 in-lbs/in²
J (in-lbs/in²)
2500
2000
1500
1000
500
0
0
0.01
0.02
0.03
0.04
0.05
0.06
0.07
0.08
0.09
0.1
Δa (in)
J = 7131(Δa)^.5096
J vs. da
Blunting Line
Offset Lines
Curve Fit
Jq
RDD:43805-001-000:01S

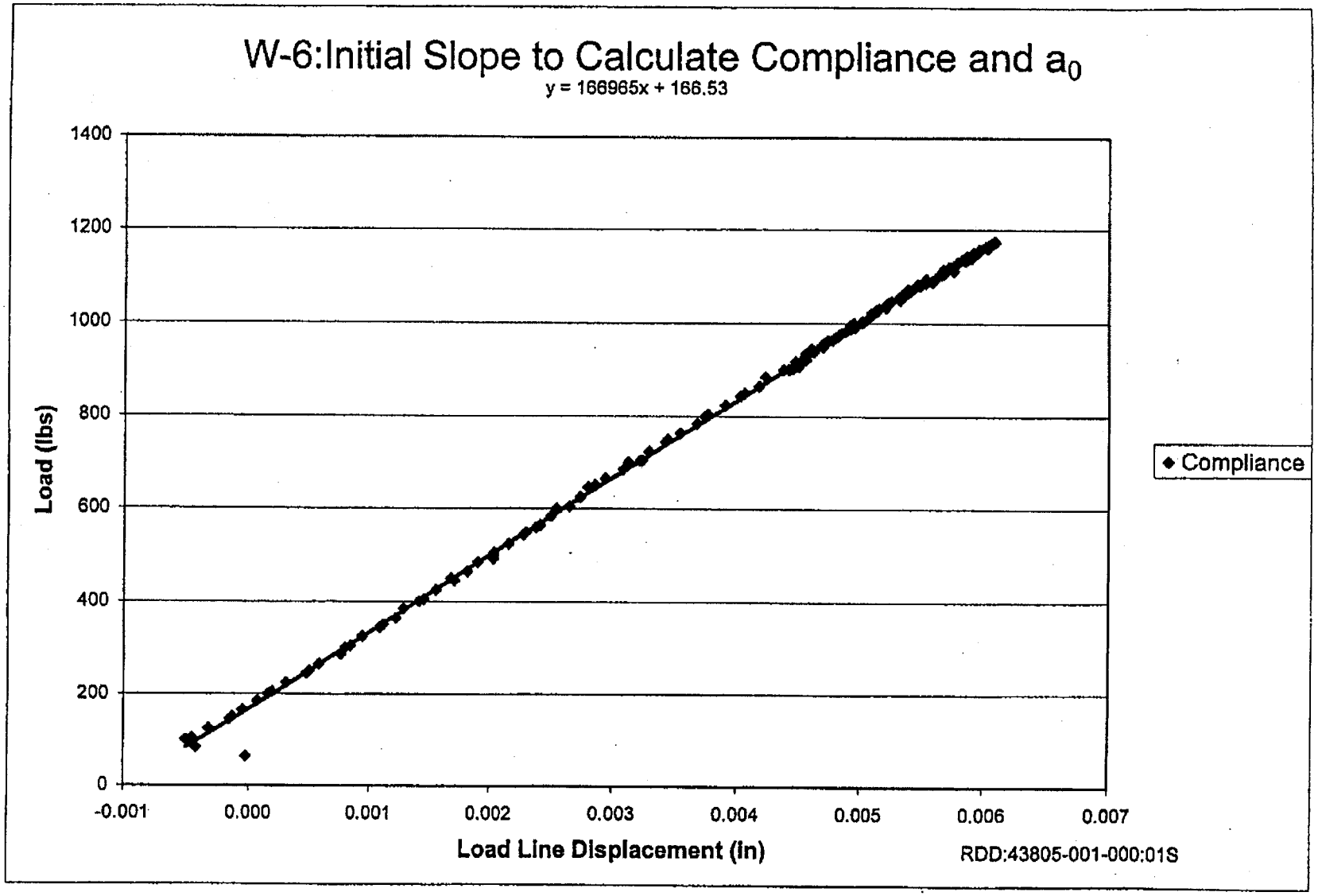

W-1
Normalized Data
45000
40000
35000
30000
25000
20000
15000
10000
5000
0
P_N
-0.020
0.000
0.020
0.040
0.060
0.080
0.100
V_{pl}'
Uncorrected Data
Corrected Data
Curve Fit
RDD:43805-001-000:01S

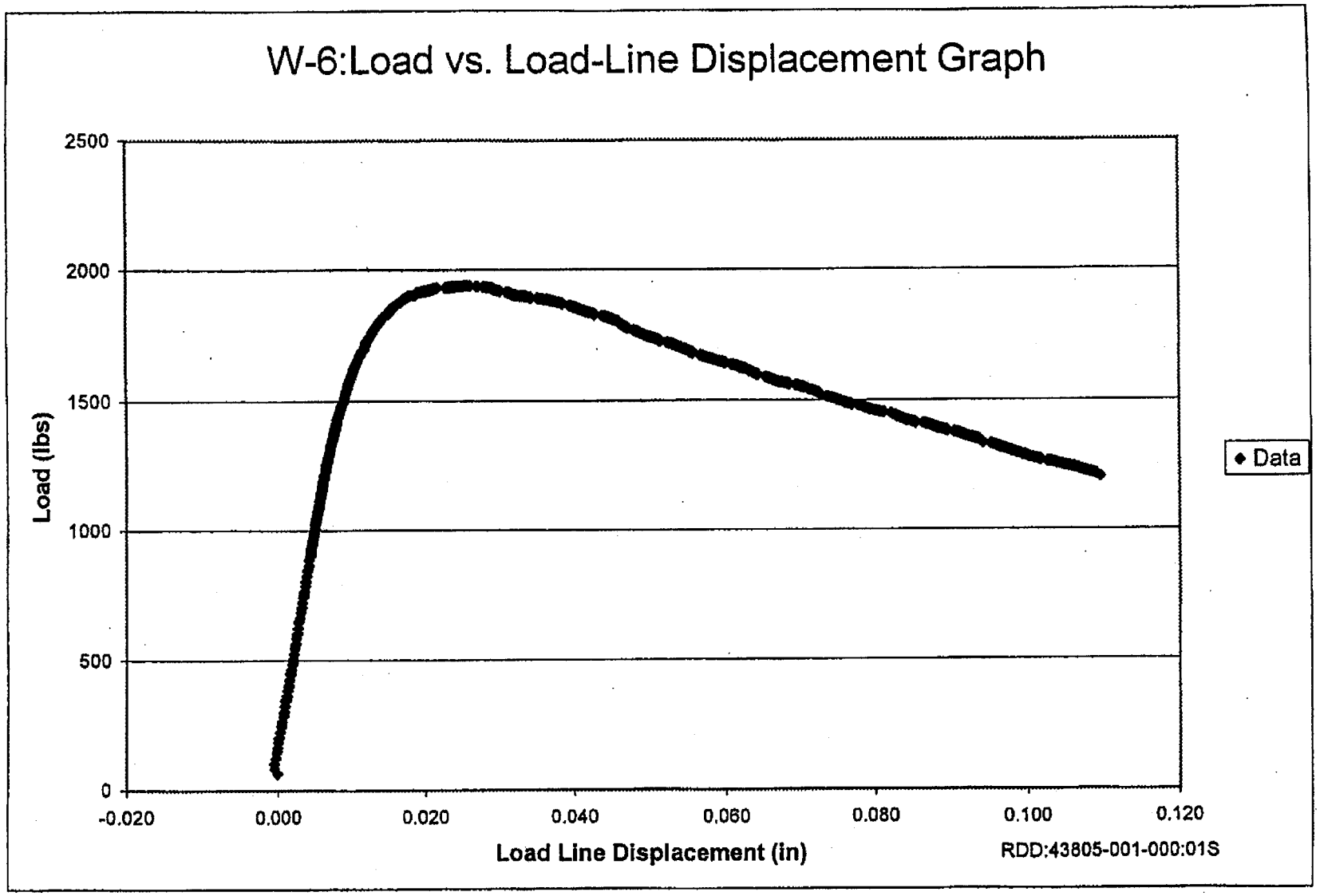

W-2:Initial Slope to Calculate Compliance and a_0
y = 161618x + 241.3
800
700
600
500
400
300
200
100
0
Load (lbs)
-0.001
-0.001
0.000
0.001
0.001
0.002
0.002
0.003
0.003
Load Line Displacement (in)
Compliance

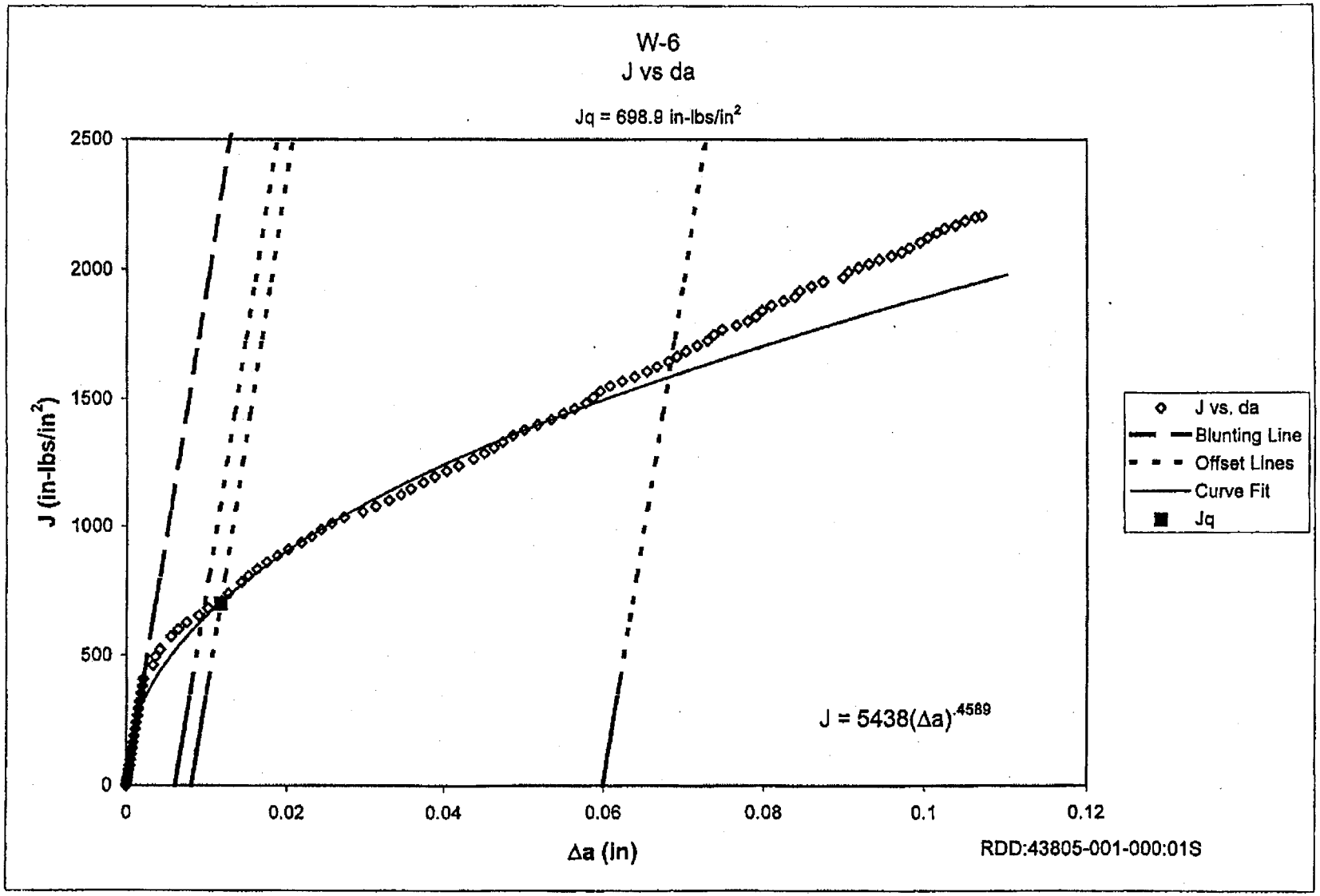

W-2:Load vs. Load-Line Displacement Graph
Load (lbs)
2500
2000
1500
1000
500
0
-0.010
0.000
0.010
0.020
0.030
0.040
0.050
0.060
0.070
0.080
0.090
Load Line Displacement (in)
Data
RDD:43805-001-000:01S

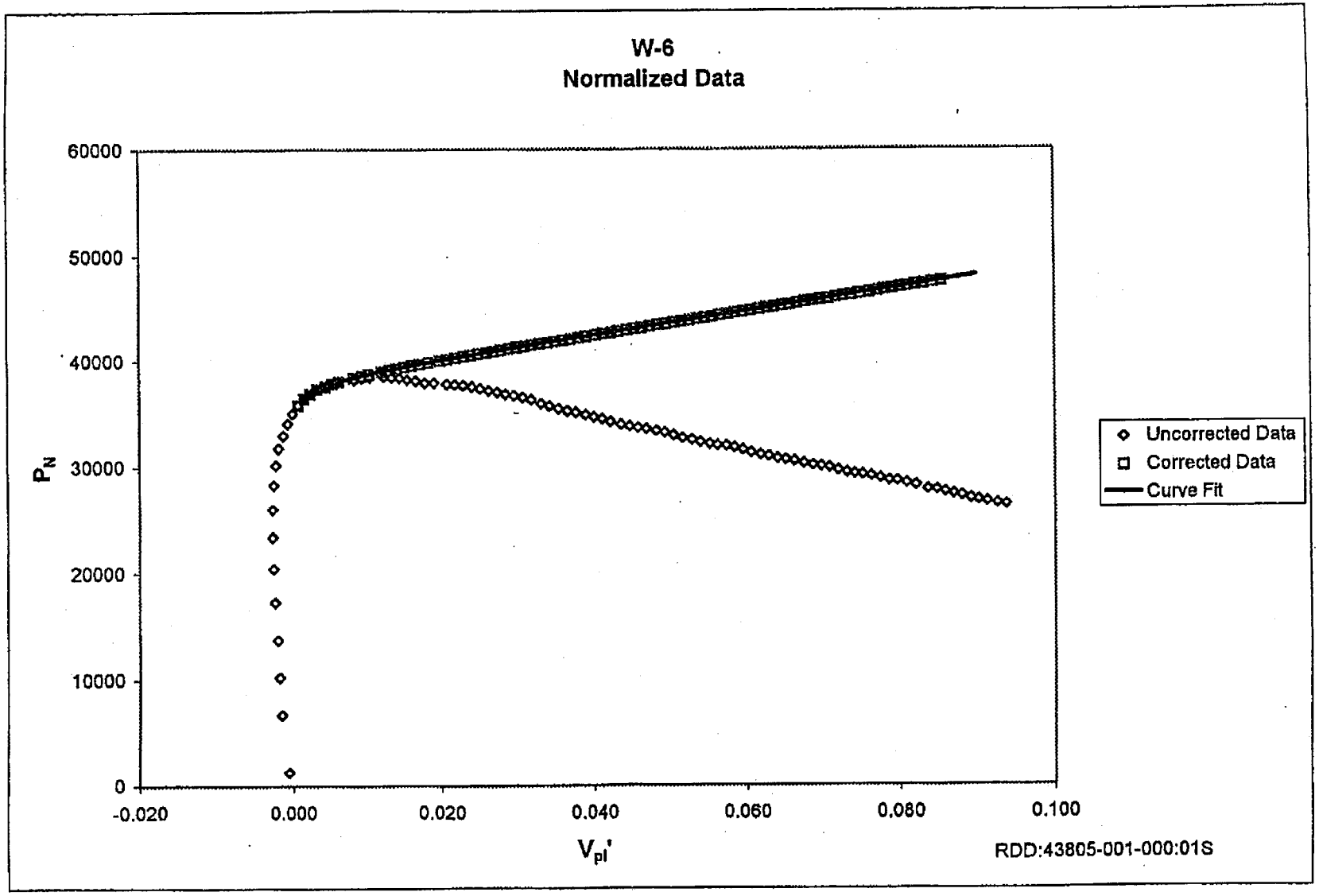

W-2
J vs da
Jq = 628.7 in-lbs/in²
J (in-lbs/in²)
2500
2000
1500
1000
500
0
0
0.02
0.04
0.06
0.08
0.1
0.12
Δa (in)
J = 4244(Δa)^.4242
J vs. da
Blunting Line
Offset Lines
Curve Fit
Jq
RDD:43805-001-000:01S

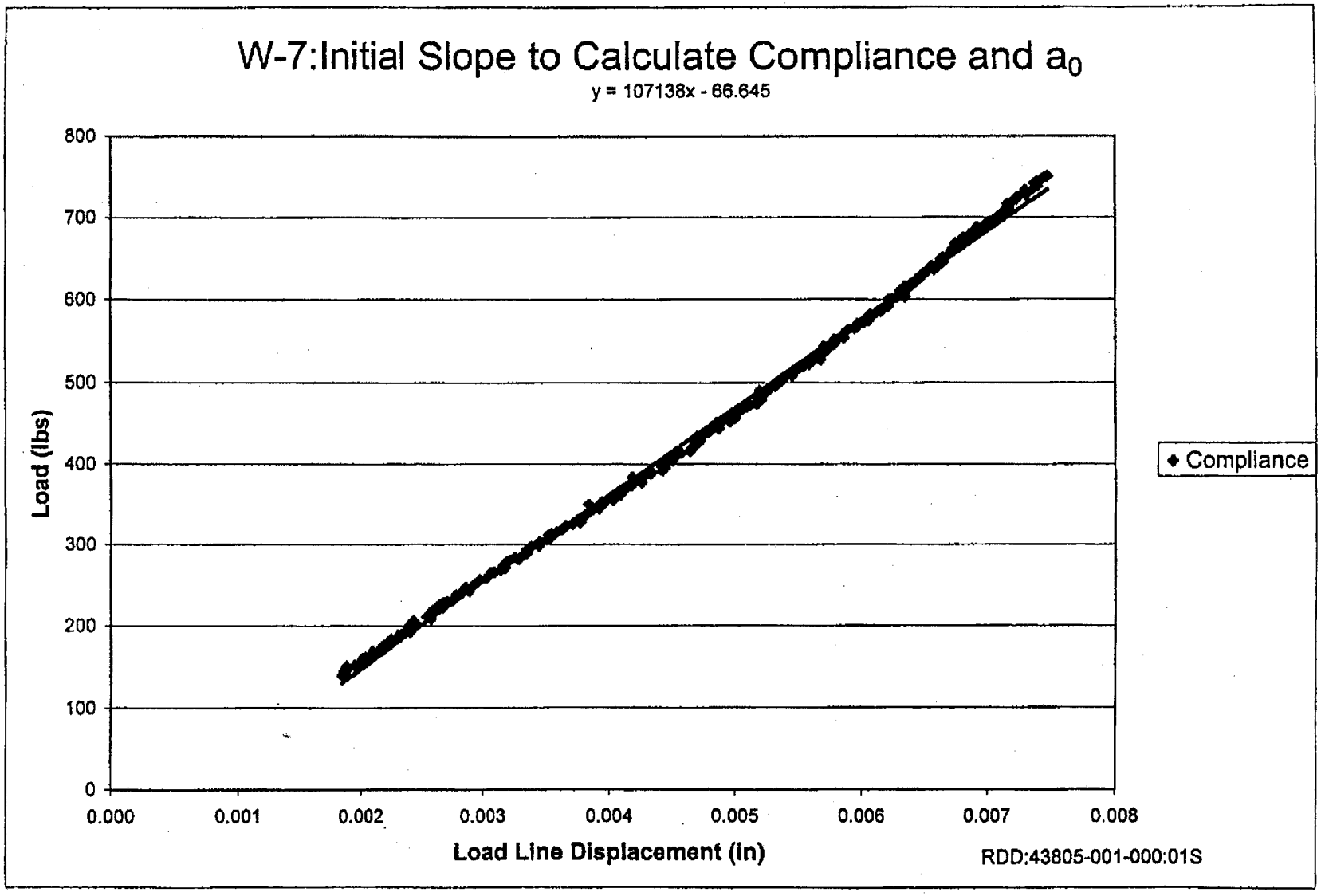

W-2
Normalized Data
50000
45000
40000
35000
30000
25000
20000
15000
10000
5000
0
P_N
-0.010
0.000
0.010
0.020
0.030
0.040
0.050
0.060
0.070
V_{pl}'
Uncorrected Data
Corrected Data
Curve Fit
RDD:43805-001-000:01S

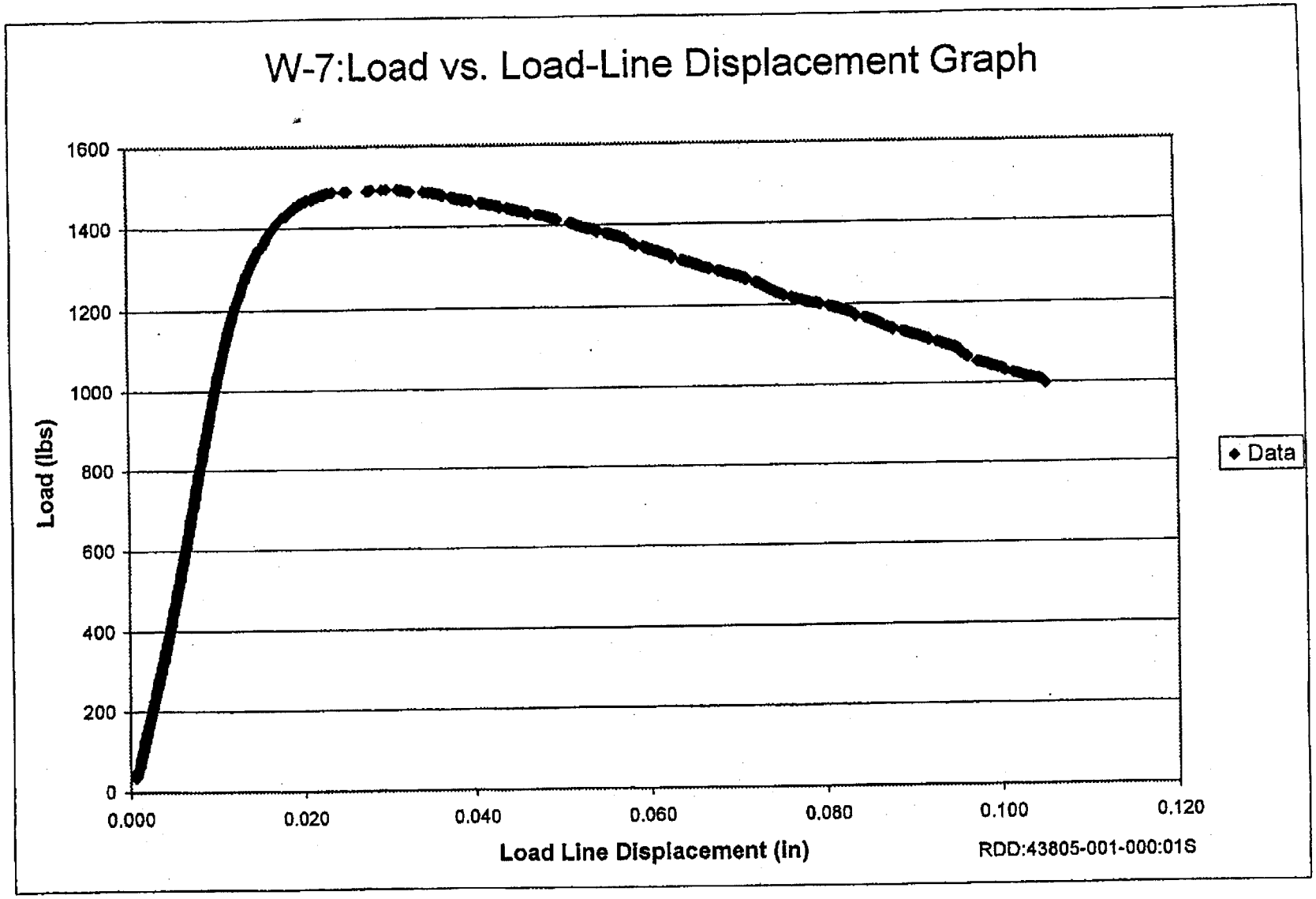

W-6:Initial Slope to Calculate Compliance and a_0
y = 166965x + 166.53
1400
1200
1000
800
600
400
200
0
Load (lbs)
-0.001
0.000
0.001
0.002
0.003
0.004
0.005
0.006
0.007
Load Line Displacement (in)
Compliance
RDD:43805-001-000:01S

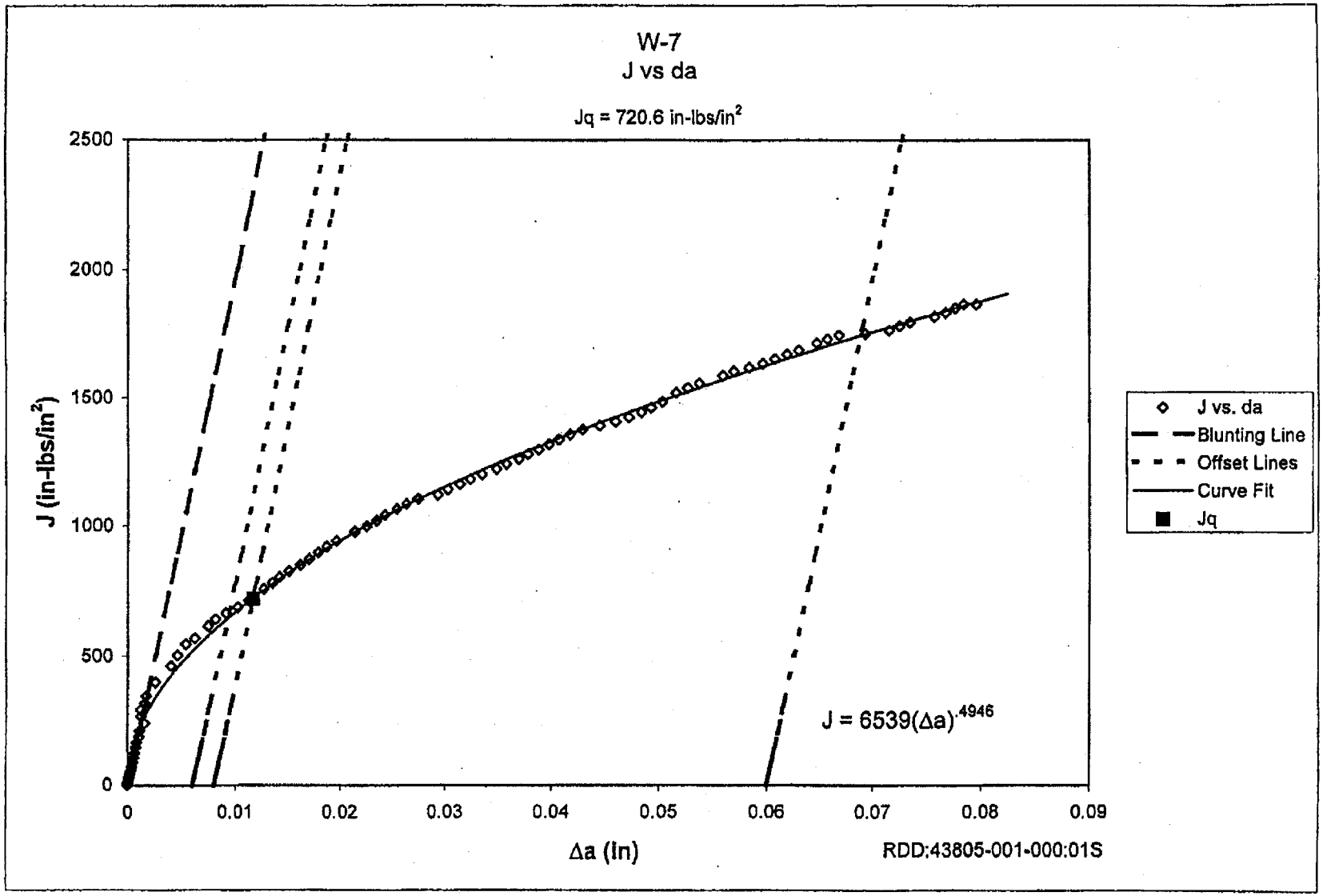

W-6:Load vs. Load-Line Displacement Graph
2500
2000
1500
1000
500
0
Load (lbs)
-0.020
0.000
0.020
0.040
0.060
0.080
0.100
0.120
Load Line Displacement (in)
Data
RDD:43805-001-000:01S

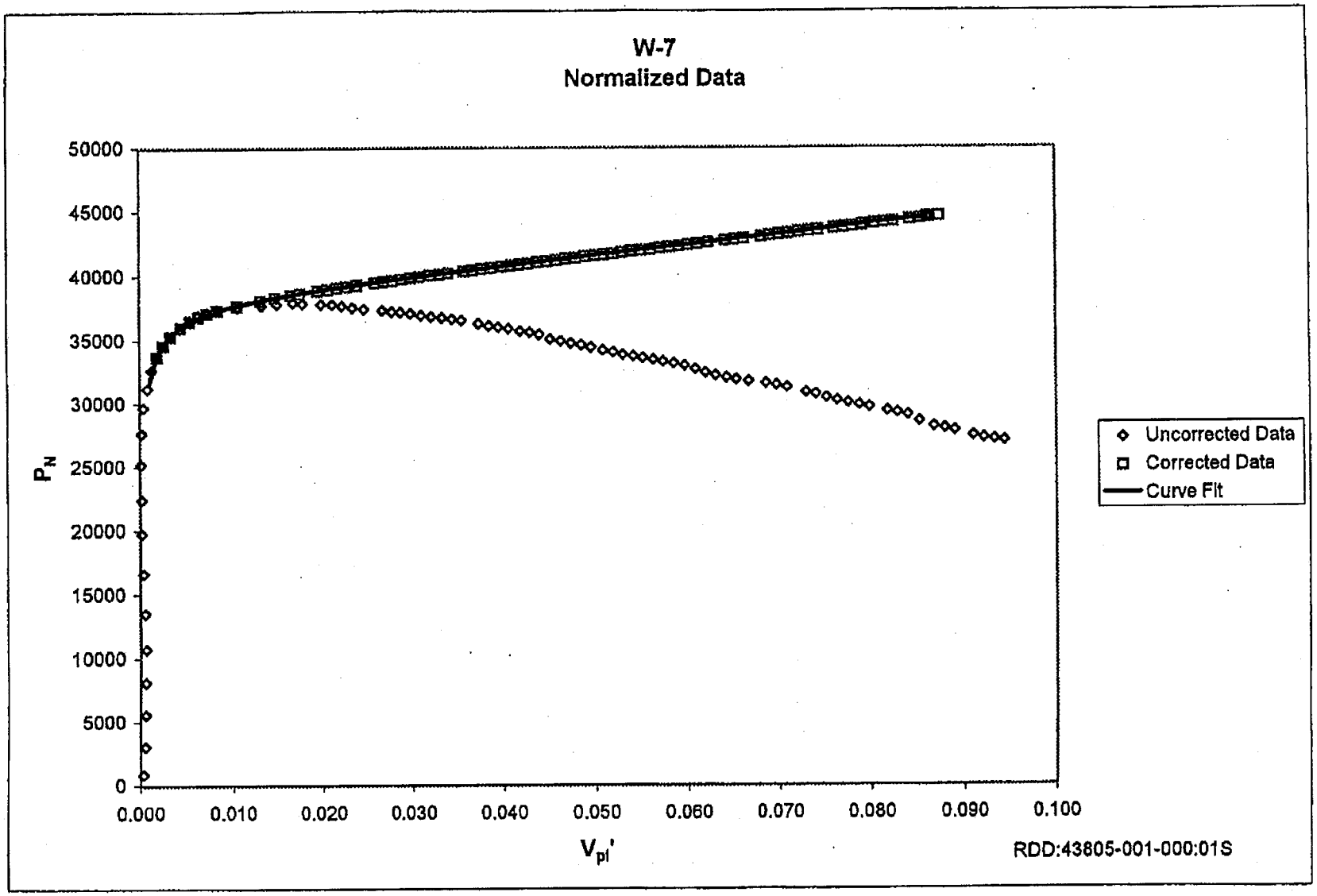

W-6
J vs da
Jq = 698.9 in-lbs/in²
J (in-lbs/in²)
2500
2000
1500
1000
500
0
0
0.02
0.04
0.06
0.08
0.1
0.12
Δa (in)
J = 5438(Δa)^.4589
J vs. da
Blunting Line
Offset Lines
Curve Fit
Jq
RDD:43805-001-000:01S

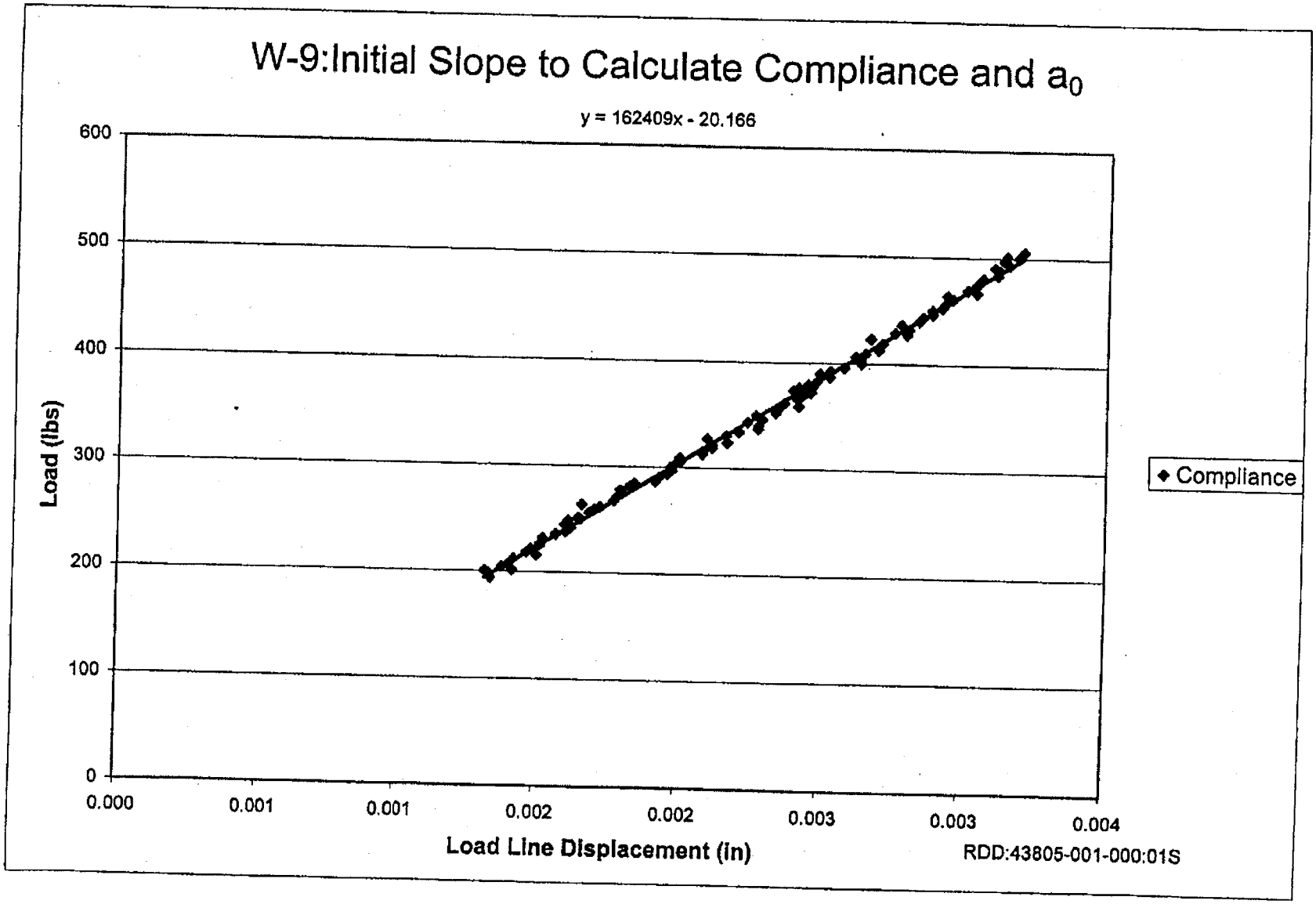

W-6
Normalized Data
60000
50000
40000
30000
20000
10000
0
P_N
-0.020
0.000
0.020
0.040
0.060
0.080
0.100
V_{pl}'
Uncorrected Data
Corrected Data
Curve Fit
RDD:43805-001-000:01S

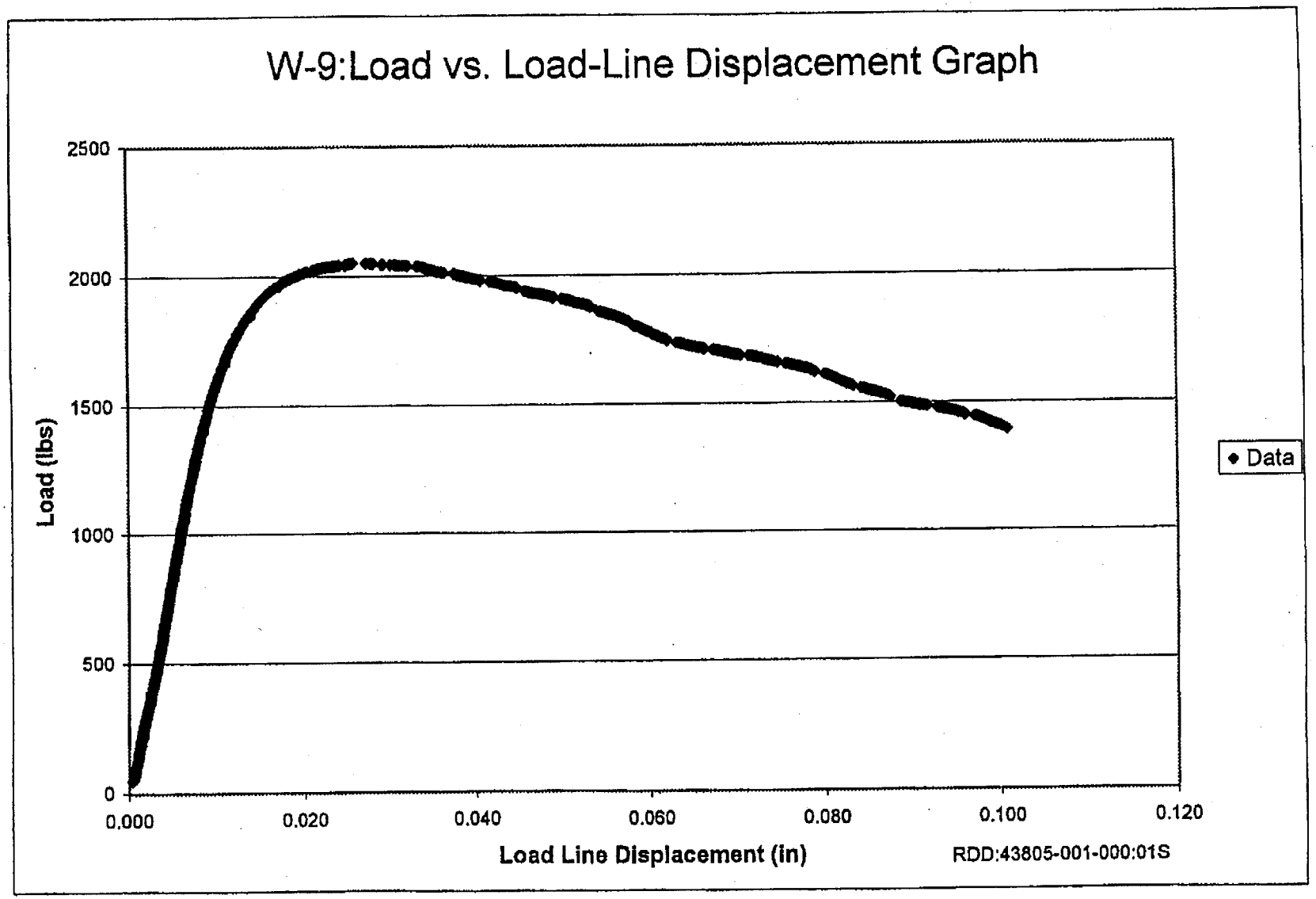

W-7:Initial Slope to Calculate Compliance and a_0
y = 107138x - 66.645
800
700
600
500
400
300
200
100
0
Load (lbs)
0.000
0.001
0.002
0.003
0.004
0.005
0.006
0.007
0.008
Load Line Displacement (in)
Compliance
RDD:43805-001-000:01S

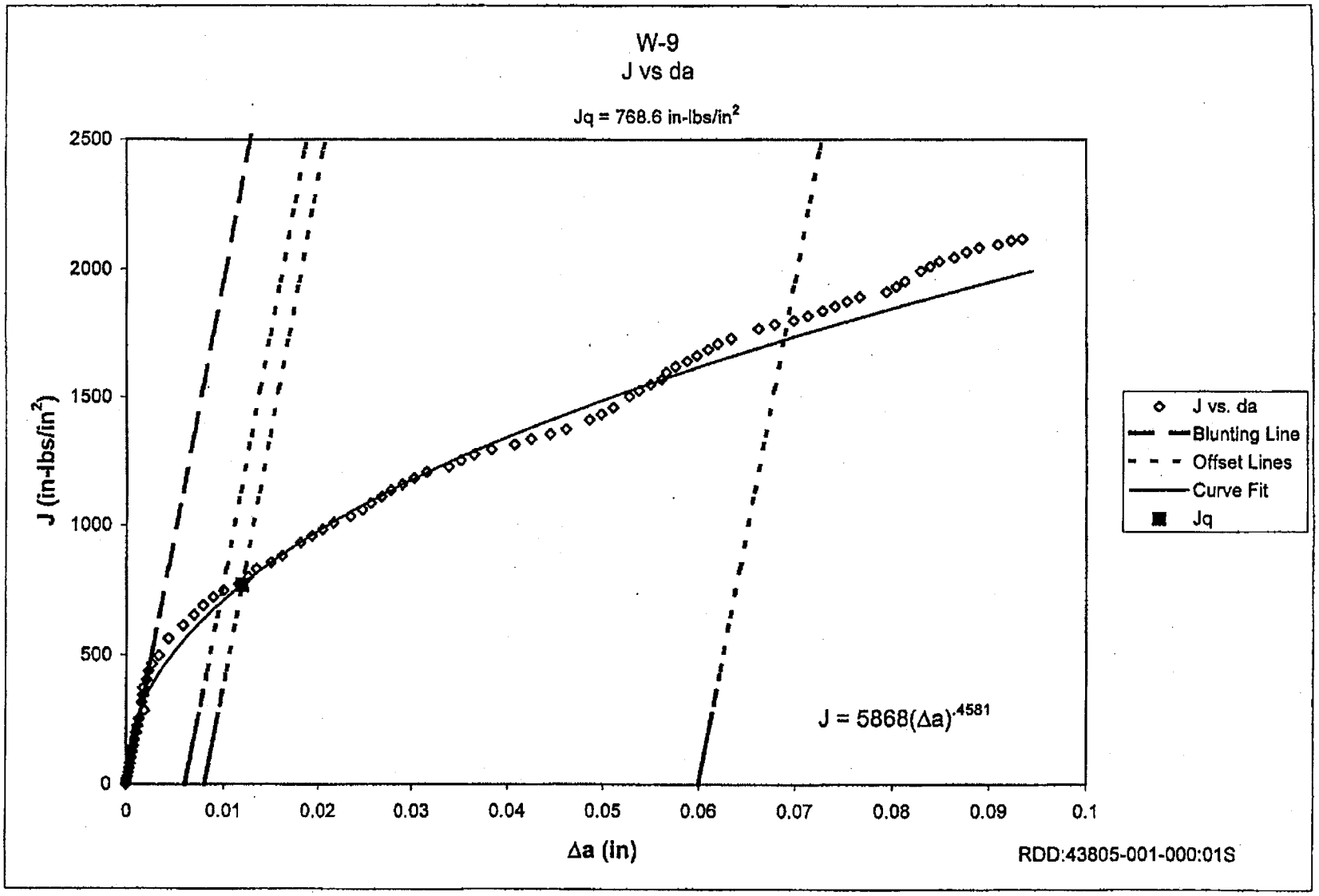

W-7:Load vs. Load-Line Displacement Graph
Load (lbs)
1600
1400
1200
1000
800
600
400
200
0
0.000
0.020
0.040
0.060
0.080
0.100
0.120
Load Line Displacement (in)
Data
RDD:43805-001-000:01S

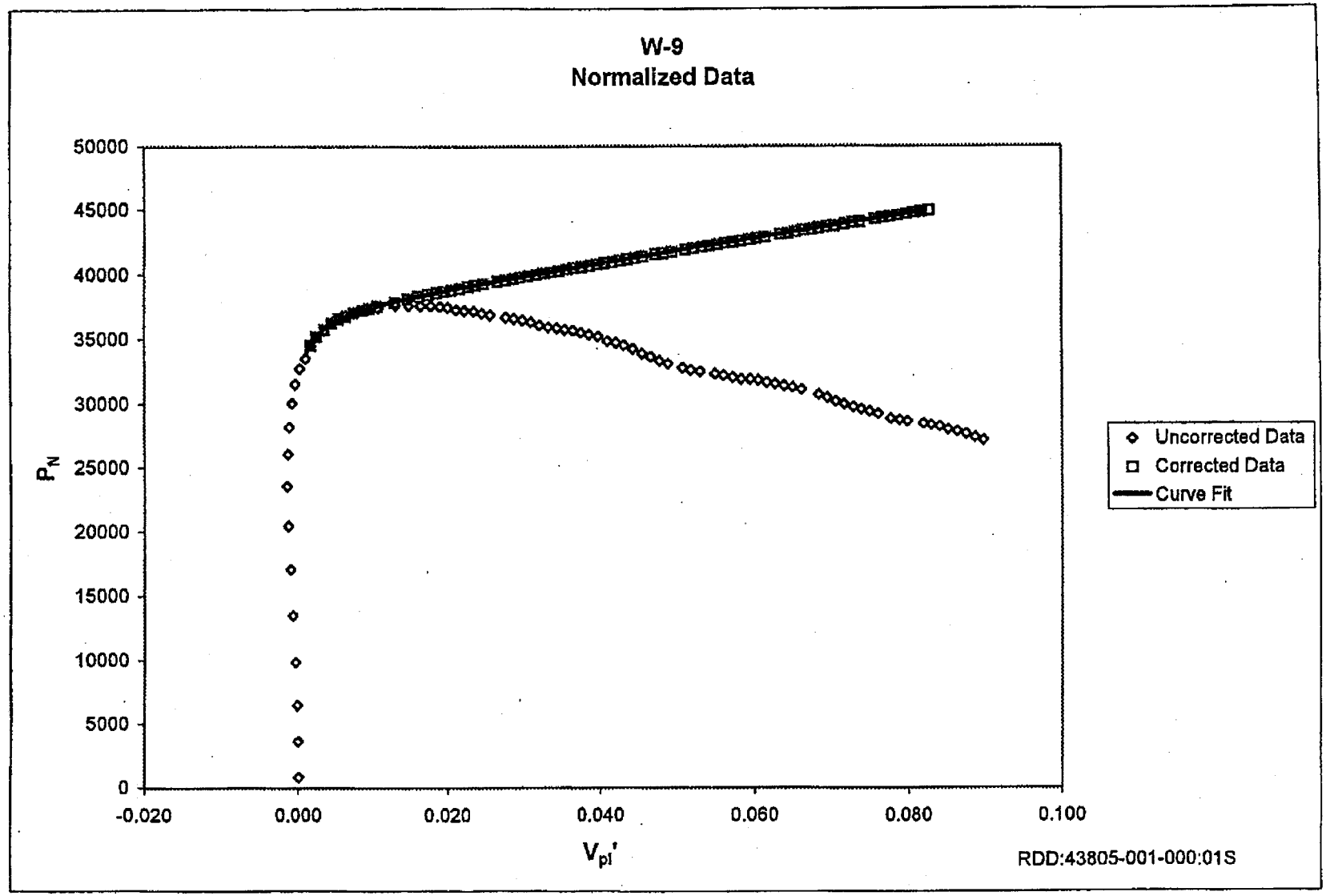

W-7
J vs da
Jq = 720.6 in-lbs/in²
J (in-lbs/in²)
2500
2000
1500
1000
500
0
0
0.01
0.02
0.03
0.04
0.05
0.06
0.07
0.08
0.09
Δa (in)
J = 6539(Δa)^.4946
J vs. da
Blunting Line
Offset Lines
Curve Fit
Jq
RDD:43805-001-000:01S


W-7
Normalized Data
50000
45000
40000
35000
30000
25000
20000
15000
10000
5000
0
P_N
0.000
0.010
0.020
0.030
0.040
0.050
0.060
0.070
0.080
0.090
0.100
V_{pl}'
Uncorrected Data
Corrected Data
Curve Fit
RDD:43805-001-000:01S


W-9:Initial Slope to Calculate Compliance and a_0
y = 162409x - 20.166
600
500
400
300
200
100
0
Load (lbs)
0.000
0.001
0.001
0.002
0.002
0.003
0.003
0.004
Load Line Displacement (in)
Compliance
RDD:43805-001-000:01S


W-9:Load vs. Load-Line Displacement Graph
2500
2000
1500
1000
500
0
Load (lbs)
0.000
0.020
0.040
0.060
0.080
0.100
0.120
Load Line Displacement (in)
Data
RDD:43805-001-000:01S


W-9
J vs da
Jq = 768.6 in-lbs/in²
J (in-lbs/in²)
Δa (in)
J = 5868(Δa)^.4581
J vs. da
Blunting Line
Offset Lines
Curve Fit
Jq
RDD:43805-001-000:01S


W-9
Normalized Data
50000
45000
40000
35000
30000
25000
20000
15000
10000
5000
0
P_N
-0.020
0.000
0.020
0.040
0.060
0.080
0.100
V_{pl}'
Uncorrected Data
Corrected Data
Curve Fit
RDD:43805-001-000:01S