A COMPUTER-INTERACTIVE, SINGLE SPECIMEN J-INTEGRAL FRACTURE TOUGHNESS TEST

D.S. Saunders and I.A. Burch

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ABSTRACT

This report outlines the development of a computer-interactive, single specimen J-integral fracture toughness test method. The test method was developed on a PDP 11/04 computer and MTS 810 servo-hydraulic test machine using compact tension specimens machined from a NiMoCr gun steel. The report discusses some of the theoretical concepts of the J-integral, particularly those which are relevant to the test method which involves the measurement of area under the load/load-line-displacement curve and the measurement of crack extension. The report also discusses in detail some of the errors within the computer-interactive, single specimen J-integral test method and how these can be reduced. It is concluded that the test method permits the evaluation of the J-integral fracture toughness of high strength steels in accordance with the existing (ASTM) standard.
This report outlines the development of a computer-interactive, single specimen J-integral fracture toughness test method. The test method was developed on a PDP 11/04 computer and MTS 810 servo-hydraulic test machine using compact tension specimens machined from a NiMoCr gun steel. The report discusses some of the theoretical concepts of the J-integral, particularly those which are relevant to the test method which involves the measurement of area under the load/load-line-displacement curve and the measurement of crack extension. The report also discusses in detail some of the errors within the computer-interactive, single specimen J-integral test method and how these can be reduced. It is concluded that the test method permits the evaluation of the J-integral fracture toughness of high strength steels in accordance with the existing (ASTM) standard.
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LIST OF SYMBOLS

\(a\)  =  crack length
\(a_0\)  =  initial crack length
\(a_f\)  =  final crack length
\(\Delta a\)  =  \(a_f - a_0\)  =  crack extension
\(A\)  =  area under load/load-line-displacement record
\(b\)  =  uncracked ligament length
\(B\)  =  specimen thickness
\(\text{CTOD}\)  =  crack tip opening displacement
\(E\)  =  Young's modulus
\(E'\)  =  \(E/(1 - \nu^2)\)
\(\text{Err}\%\)  =  error in measurements
\(\tilde{E}(\theta,n)\)  =  non-dimensional function of \(\theta\) and \(n\)
\(I_n\)  =  coefficient of strain hardening stress intensity
\(J\)  =  \(J\)-integral value
\(J_c\)  =  critical value of \(J\)
\(J_{\text{IC}}\)  =  critical value of \(J\) measured in Mode I opening
\(K\)  =  stress intensity factor
\(K_{\text{IC}}\)  =  critical value of \(K\) measured in Mode I opening and by definition is used as a measure of plane strain fracture toughness
\(K_Q\)  =  critical value of \(K\) measured under conditions which cannot be demonstrated to meet all criteria for a valid \(K_{\text{IC}}\) test.
\(L\)  =  half-span of a beam in three point bending
\(M\)  =  bending moment
\(n\)  =  work hardening exponent in the Ramberg-Osgood power hardening law
\(p\)  =  used to denote load-control
\(P\)  =  force
\(r\)  =  distance ahead of a crack tip in \(r,\theta\) polar co-ordinate system
\(ds\)  =  increment in the contour path
\( T \) = the outward fraction vector on \( ds \).

\( \bar{u} \) = the displacement vector at \( ds \).

\( u \) = potential energy of a cracked body under load.

\( v \) = used to denote displacement control.

\( V_{LL} \) = load-line-displacement.

\( W \) = loading work per unit volume.

\( a \) = constant in Ramberg-Osgood power hardening law.

\( r \) = the path of the integral which encloses the crack tip.

\( e \) = strain.

\( \dot{\epsilon}_y \) = yield strain.

\( \epsilon_{ij} \) = strain tensor.

\( \theta_T \) = total angular deflection of a beam.

\( \theta_{el} \) = elastic contribution to total angular deflection.

\( \theta_{pl} \) = plastic contribution to total angular deflection.

\( \theta \) = angular displacement ahead of a crack tip in \( r, \theta \) polar coordinate system.

\( k \) = a parameter of value = 1 for metals.

\( \nu \) = Poisson's ratio.

\( \sigma \) = stress.

\( \sigma_y \) = yield stress.

\( \sigma_{0.2} \) = 0.2\% proof stress.

\( \sigma_{UTS} \) = ultimate tensile stress.

\( \sigma_{eff} \) = \( \frac{\sigma_{0.2} + \sigma_{UTS}}{2} \) = an effective yield stress.

\( \sigma_{ij} \) = stress tensor.

\( \overline{E}(\theta,n) \) = non-dimensional function of \( \theta \) and \( n \).
A COMPUTER-INTERACTIVE, SINGLE SPECIMEN

J-INTEGRAL FRACTURE TOUGHNESS TEST

1. INTRODUCTION

In the fields of engineering and materials science, the concept of linear-elastic fracture mechanics is an accepted part of material testing. The use of plane strain fracture toughness as a material property is useful in engineering studies because it allows the prediction of critical crack sizes where the stresses in a body or structure are known. The measurement of plane strain fracture toughness, $K_{IC}$, is covered by ASTM Standard E 399 [1]. This test is relatively simple and, for the most part, easily understood. For plane strain fracture toughness to be measured in any test, a most important criterion which must be met is that the specimen size be sufficiently large to ensure that plane strain conditions prevail across most of the specimen thickness. This means that there is a minimum specimen size for each material tested. Thus, the specimen thickness and the crack length must both be greater than $2.5\left(\frac{K_{IC}}{\sigma_{0.2}}\right)^2$, where $K_{IC}$ is the measured plane strain fracture toughness and $\sigma_{0.2}$ is the 0.2% proof stress of the material.

In many instances, materials are tested from parent bodies which do not allow specimens large enough for the measurement of $K_{IC}$ to be taken from them. For example, some modern, large calibre gun barrels are of sufficiently high toughness that valid plane strain fracture toughness specimens cannot be taken from the walls of the gun tube. Tests using subsized specimens exhibit unacceptably high plasticity in their test records and hence alternative test techniques to the $K_{IC}$ test method must be used. One method which admits a degree of plasticity is the J-integral test method which is covered by ASTM Standard E 813 [2]. The test method predicts a critical value of $J$ at which the crack first begins to extend. By convention, this critical value of $J$ is denoted $J_{IC}$ because the test is predominantly in mode I opening.

Under most circumstances, the measurement of $J_{IC}$ for a high toughness material (such as gun barrel steel) is an involved, multiple specimen test method because the critical value of $J$ has to be inferred from the J-Δa behaviour obtained from a number of specimens. Δa is the increase
in crack length associated with each J measurement, and will be discussed in
the following section. However, now that computer-interactive test machines
are readily available to researchers it is possible to make use of the single
specimen J-integral test method which utilizes unloading compliance
measurements from which the extent of crack growth is inferred.

A short paper covering the initial development of the computer-
interactive single specimen J-integral test method at MRL has been published
[3]. The present work covers the same general aspects of the test method as
[3] but expands considerably on details of computer programs and error
analyses. This is facilitated by practical examples of the J-integral test
using a gun barrel steel.

2. THE J-INTEGRAL

The development of the concept of the J-integral as a parameter
which can describe the fracture toughness of a material is based on the
demonstration that a path-independent integral, J [4], can uniquely describe
the crack tip stress singularity in a material which obeys the Ramberg-Osgood
power hardening law of deformation plasticity. This power hardening law for
the case of simple tension can be stated,

\[
\frac{\bar{\sigma}}{\bar{\epsilon}} = \frac{\sigma}{\epsilon} + n \left( \frac{\sigma}{\bar{\epsilon}} \right)^n
\]

(1)

where

- \( \sigma \) = stress
- \( \epsilon \) = strain
- \( \bar{\sigma} \) = the yield stress
- \( \bar{\epsilon} \) = the yield strain, \( \bar{\epsilon} = \bar{\sigma}/E \)
- \( E \) = Young's modulus
- \( n \) = a material constant
- \( a \) = work hardening exponent

From the calculus of variations, Rice [5] showed that J, the path-
independent integral, could be formulated,

\[
J = \int_0^1 (Wd\epsilon - T.(\partial\bar{\sigma}/\partial x)dx) \quad (2)
\]
where \( T(\partial u/\partial x) \) = the rate of work input from the stress field into the area enclosed by \( \Gamma \).

\( \Gamma \) = the path of the integral which encloses the crack tip.

\( W \) = loading work per unit volume.

\( ds \) = increment in the contour path.

\( T \) = the outward traction vector on \( ds \).

\( \bar{u} \) = the displacement vector \( a \bar{r} \) \( ds \).

\( J \) can also be interpreted as the change in the potential energy of a cracked body with a small increment in crack length [6].

Using the path independent characteristics of the \( J \)-integral, Rice and Rosengren [7] and Hutchinson [8a,b] showed that the following equations for the stresses and strains at the crack tip apply:

\[
\sigma_{ij} = \frac{\bar{\sigma} y}{\bar{\sigma} y} \left[ \frac{J}{\bar{\sigma} y \bar{\varepsilon} y I_n} \right]^{1/n+1} \sum_{ij} \varepsilon_{ij} (\theta, n) \tag{3}
\]

\[
\varepsilon_{ij} = \frac{\bar{\sigma} y}{\bar{\sigma} y} \left[ \frac{J}{\bar{\sigma} y \bar{\varepsilon} y I_n} \right]^{n/n+1} E_{ij} (\theta, n) \tag{4}
\]

where \( \bar{\sigma} y \) = mean material yield stress

\( \bar{\varepsilon} y \) = mean material yield strain

\( \sigma \) = constant in the Ramberg-Osgood power hardening law

\( n \) = work hardening rate from the Ramberg-Osgood power hardening law.

\( I_n \) = coefficient of strain hardening stress intensity which has been evaluated numerically, [8a,b].

\( r, \theta \) = polar co-ordinates.

and \( J \) can be evaluated for a boundary removed from the crack tip.

The similarities between the above formulations in terms of \( J \) and those in terms of \( K \), the stress intensity factor [9], are readily apparent; see also Liu [10], and Figure 1 for a summary of the HRR model and the linear-elastic model of the stress-strain fields at the crack tip.
We see, above, that \( J \) can be used to describe the stress and strain singularities at the crack tip and, like \( K \), \( J \) can be measured by a mechanical test, thus \( J \) can be evaluated physically as the change in potential energy, \( U \), as the crack extends; see [11] and [12] for the following proof.

\[
J = \frac{\partial U}{\partial a_p} \quad \text{and} \quad J = -\frac{\partial U}{\partial a_v}
\]

(5)

where \( p \) and \( v \) denote load and displacement control respectively. For the linear-elastic case we write:

\[
J = \frac{1}{2} p \frac{\partial v}{\partial a} \quad \text{and} \quad J = -\frac{1}{2} v \frac{\partial p}{\partial a}
\]

(6)

and for the non-linear elastic case:

\[
J = \int_0^P \left( \frac{\partial v}{\partial a} \right)_p \, dp \quad \text{and} \quad J = -\int_0^V \left( \frac{\partial p}{\partial a} \right)_v \, dv
\]

(7)

If we deal with deeply cracked beams we can write the above in terms of the deflections of the beam, where:

\[
\theta_T = \theta_{el} + \theta_{pl}
\]

(8)

where

- \( \theta_T \) = total deflection
- \( \theta_{el} \) = elastic contribution to total deflection
- \( \theta_{pl} \) = plastic contribution to total deflection

When the ligament is fully plastic, \( \theta_T = \theta_{pl} \) and 

\[
\theta_T = \frac{v}{L}
\]

(9)

where \( v \) = back face displacement of the beam

\( L = 1/2 \) the loading span of the beam

\[
\text{thus} \quad \theta_{pl} = f\left( -\frac{M}{Bb^2 \sigma_y}, \frac{v}{E}, n \right)
\]

(10)
\[
M = \frac{Bb^2}{L} \sigma_y h \left( \frac{V}{L}, \frac{\sigma_y}{E}, n \right)
\]

and \( M = PL \)

\[
\text{thus } P = \frac{Bb^2}{L} \sigma_y h \left( \frac{V}{L}, \frac{\sigma_y}{E}, n \right)
\]

we know \( \frac{\partial P}{\partial a} = -\frac{\partial P}{\partial b} = -\frac{2bb}{L} \sigma_y h \left( \frac{V}{L}, \frac{\sigma_y}{E}, n \right) \)

and substituting \( L = \frac{M}{P} \) in (13) and (7)

\[
J = \frac{2}{b} \int_0^V pdv
\]

we note that \( \int_0^V pdv \) is the area, \( A \), under the load/load-point-displacement curve for the beam.

Equation 14 is the fundamental relationship which is used for the evaluation of \( J \) for small increments of crack length. This is used in the present ASTM standard for the measurement of \( J_{IC} \) [2].

There are two methods by which \( J \) can be measured, one using a multiple specimen technique where a series of specimens is tested covering a range of crack increments and the other using a single specimen where the length of the crack is continuously monitored as it extends during a test. The \( J \)-integral value is determined from the area under the load/load-line-displacement record using equation 14 above. This method is summarized diagrammatically in Figure 2. Both methods lead to the measurement of a \( J-A_a \) curve. This curve, in itself, does not determine the critical value of \( J \), \( J_C \), where the crack begins to extend. This is done by linearly back-extrapolating the \( J-A_a \) data to the "blunting line". The blunting line describes the apparent crack growth which occurs as the crack tip blunts during the initial development of the plastic zone. The blunting line is derived from the relation given by Rice and Johnson [13] where:

\[
J = \lambda \sigma_{eff} \text{CTOD}
\]
where \( \lambda = 1 \) for metals

\[ \sigma_{\text{eff}} = \text{effective yield strength of the material} \]

\[ \text{CTOD} = \text{crack tip opening displacement}. \]

The effective increment in the position of the crack tip, \( \Delta a \), can be considered to be about \( 0.5 \times \text{CTOD} \) and hence a simple relation for this blunting line can be written

\[ J = 2 \times \sigma_{\text{eff}} \times \Delta a \]

(16)

where \( \sigma_{\text{eff}} \) is often defined as \( \left( \frac{\sigma_{0.2} + \sigma_{\text{UTS}}}{2} \right) \).

The computer-interactive, single specimen J-integral test method described in the following sections permits the measurement of \( J_{\text{IC}} \) in accordance with the ASTM standard [2].

3. THE OBJECTIVES OF THE DEVELOPMENT OF THE COMPUTER-INTERACTIVE, SINGLE SPECIMEN J-INTEGRAL TEST METHOD

When all refinements are completed, (and this can only be achieved by the continued use of the test method developed here), the test method should permit the determination of \( J_{\text{IC}} \), i.e. fracture toughness, on a routine basis and in accordance with ASTM E 813 [2].

The objectives of the development of the computer-interactive single specimen J-integral test method are:

* The ASTM Standard, [2], suggests that "when estimating \( \sigma_{\text{eff}} \) influences of testing conditions such as loading rate and temperature should be considered."
(1) Accurately determine $J_{IC}$.

(2) Document all relevant calculations.

(3) Store all test data in a logical and retrievable form.

(4) Be flexible in a mathematical sense to allow compliance calibrations, Young's modulus, Merkle-Corten coefficient and other test parameters to be inserted into the program or readily changed.

(5) Ability to re-examine test data.

Due to the limited transient programming area (TPA) of 32 K words available in the PDP11/04 computer at the time of the development of the program for the control of the J-integral test, the program may be regarded as incomplete because it does not undertake the linear regression through the $J-A$ data to the blunting line for the calculation of $J_{IC}$. This can be done using a plotting file created for this purpose.*

The objectives (1)-(4) are met by the current J-test program for the PDP11/04; JCTS.BAS, for the compact tension specimens. Objective 5 is met by programs written for both the VAX11/780 and the PDP11/04 which allow files written by the PDP11/04 under RT11 version 4.1 to be treated as data files for what is effectively another J-integral test. This program, JRERUN.BAS, re-examines the existing data but allows the insertion of accurate specimen dimensions and crack lengths and the use of alternative compliance calibrations in the calculations. Estimates of the accuracy of the linear regression analysis to infer crack-length are made by this program.

The programs are listed in Appendix 1 and details of these programs are given later in this report.

4. THE J-INTEGRAL TEST SPECIMENS

The present work was mainly undertaken for the "compact tension" specimen design and although the test method is readily applicable to beam specimens, it is not dealt with in detail in this report.

* This feature will be incorporated in the program when the computer is upgraded to a PDP11/34 which has a larger TPA.
Several specimen designs have been proposed for the compact tension specimen for J-integral testing [14]. The primary requirement from the specimen is the need for the measurement of the load-line-displacement, see equation 14 above.

For J-integral testing the present work used a modified compact tension specimen which conforms to the ASTM E 399 specimen geometry except that it has an integral knife edge machined at the load-line, see Figure 3. This specimen is similar to that proposed by Clarke et al [14], except that the pin holes are closer together. The advantage of utilizing specimens which are essentially common to the E 399 and E 813 test methods is that, where $K_{IC}$ cannot be measured, the specimens are readily converted to J-integral specimens. The MRL specimen design would probably preclude the use of clevises with roller bearings, however, there is no conclusive evidence that this is a necessary feature of J-integral tests using the compact tension specimen.

The J-integral specimen manufactured by MRL is designated MRL J03, [15].*

5. THE COMPLIANCE CALIBRATION FOR THE COMPACT TENSION J-INTEGRAL SPECIMENS

At the present time there are two elastic unloading compliance calibrations which are immediately applicable to the MRL J03 specimen. The first is an experimental unloading calibration using 13 mm thick MRL J03 specimens [16], and the second a theoretical compliance calibration developed from a finite element program, PAFEC, run on a VAX 11/780 computer [17a,b]. These compliance calibrations are plotted in Figures 4 and 5 together with the unloading compliance calibrations supplied in ASTM E 813 (see also Saxena and Hudak [18] and Newman [19]). These calibrations are used in Section 8 of this work. Listings of the compliance data for compact tension specimen designs are given in Appendix 2.

* This is a specific designation. The "03" refers to an $a/W$ of 0.3. Other starter crack lengths can be used.
6. THE HARDWARE FOR THE COMPUTER-INTERACTIVE SINGLE SPECIMEN $J_{IC}$-TEST

The single specimen $J$-integral tests were undertaken on a 250 kN servohydraulic testing machine (MTS 810 system), interactive with a PDP11/04 computer.*

The graph generated by the program, $J$-Aa, was plotted on a Tektronix 4010-1 VDU and dumped via a Tektronix thermal imager while the analogue output of load/load-line-displacement was plotted using a HP 7090A plotter. This plotter can be controlled by the PDP11 and hence could be used for the re-plotting of the data as stored by the program. More conveniently this is handled via the VAX11/780 and appropriate graphics terminals.

The load-line-displacement was measured using an MTS 632.02C.20 clip gauge. The locating edges on the clip gauge arms were modified slightly to accommodate the MRL $J_{03}$ integral knife edge design. The linearity and reproducibility of this clip gauge were tested experimentally and the data plotted in Figure 6. It was considered unnecessary to use any correction factors over the range used for the $J$-integral test of an MRL $J_{03}$ specimen.

7. THE SOFTWARE FOR THE COMPUTER-INTERACTIVE SINGLE SPECIMEN $J$-INTEGRAL TEST

The software written for the single specimen $J$-integral test method and the data analysis programs are largely interactive and self-explanatory, however brief descriptions of the programs are given in Appendix 3. Some documentation of the variables in the control program for the PDP 11/04, where relevant to the description of the software in this section, is given in Appendix 4.

The programs which undertake $J$-integral testing and data analysis are in two separate suites.

(1) The computer-interactive control program written for the PDP 11/04.

and

(2) The data analysis programs written for the VAX11/780 and PDP11/04 which utilize the data generated and stored on disc by the control program.

* This computer has a TPA of 32K words but is to be upgraded to a PDP11/34 with a TPA of 64K words.
7.1 The control program on the PDP11/04–MTS 810

The language used for the control program is DEC Multi-user BASIC with MTS and Tektronix enhancements for the Master Segment Generator and the graphics respectively [20a,b]. The Master Segment Generator (MSG) is used to generate, through a D/A converter, the offset signal to drive the servo-valve.

The single specimen J-integral test is conducted in stroke control, with the position of the ram being measured by its displacement transducer rather than using the displacement of the specimen as measured by the clip gauge. This makes the test fail safe should the clip gauge signal fail.

At the present time, for J-integral tests using the MRL J03 specimens, ± 2047 bits = ± 5 mm of ram travel. This stroke can be decreased to allow an increase in the number of data points acquired for any test using J03 specimens. Incrementing the stroke during the test results in a small increment in the load applied to the specimen, while displacement in the load-line of the notch is measured by the clip gauge where ± 2047 bits = ± 2 mm. For the MRL J03 specimen it is found that 2 mm movement of the clip gauge is ample for most J-integral tests. This calibration can be altered using the MTS 440.21 signal conditioner to increase the sensitivity of the test.

The software for the test method is summarised in the flow diagram, Figure 7.

The single specimen J-integral test method requires the collection of load/load-line-displacement data for each bit-wise increment (or decrement in the case of an unloading) produced by the Master Segment Generator, (MSG). Each bit-wise increment and decrement in stroke is accompanied by the sequential reading number and with each reading is recorded load, load-line-displacement, cumulative area under the load/displacement record and a switching integer (Z9), which has a value of 1, 2, 3, or 4 depending on the call to the MSG, i.e. the ramp control. These data are written sequentially into a large virtual file on disc as binary numbers. The switch, Z9, is the integer used to control the loading and the unloading sequences of the test and is incorporated in an "ON GOTO" statement to call the bit-wise output from the MSG, see Figure 7. The ramp control is shown schematically in Figure 8. The switch has an important secondary function in the JRERUN.BAS programs on the VAX11/780 and PDP 11/04 where this record is used to control the use of the load/load-line-displacement data in a manner analogous to the control program on the PDP11/04, viz., the switch designates data which are to be treated as unloading data for inferring crack length via the unloading compliance and the normalized compliance/normalized cracklength calibration such as those in Figures 3 and 4. JRERUN.BAS is discussed in detail in section 7.2.

The acquisition of the load/load-line-displacement data is undertaken as a separate (but common) subroutine (through a "GOSUB" statement) called by each of the ramp routines set by the ramp switch, i.e. the acquisition of data is always undertaken in the same manner. Thus, for each sequential bit-wise increment or decrement in stroke from the MSG, when the ram of the MTS has stopped moving, ten reading pairs of load and load-line-displacement are taken at 1 millisecond intervals and then averaged. These
average values are "written" into the record and used for the calculation of
the cumulative area under the load/displacement curve. Once all calculations
have been completed the ramp is re-activated, see Figure 8.

Initially the test behaves in a linear-elastic manner. A load, \( P_7 \), to
which the specimen can be loaded and still remain linear-elastic is used to
establish that the area calculation is correct. This is done by comparing the
cumulative area up to this elastic load with a geometric calculation using the
slope of the linear-elastic loading line and the elastic load; viz. the area
of a triangle. In the linear-elastic region the cumulative area should be to
within +2\% of the geometric calculation.

The test parameters such as specimen dimensions, Young's modulus,
elastic load for preliminary calculations, Merkle-Corten coefficients [21] and
the load cell calibration are inserted into the computer and also stored in
the data file ("name".DAT) at the start of the test. A plotting file
("name".PLT) is also set-up concurrently with the data file. The graphics for
the J-Aa plot are also set-up before the test. The test starts with an
initial loading in the linear-elastic range, the limit set by the elastic load
\( Z_9 \), and the area calculation is checked as described above. After a 20
bit increment in stroke when \( Z_9 = 2 \) (see next paragraph), a 10\% unloading \( Z_9 = 3 \)
allows the initial crack length \( a_0 \) to be established from the unloading
compliance calibration in the program.* To produce crack growth in a
controlled way the bit-wise increment in stroke \( Z_9 = 2 \) is limited to a pre-set
number of bits from the MSG. This can be changed readily within the program
but for a compact tension specimen geometry such as the MRL J03 it has been
found that 20 bits total output from the MSG for each loading ramp is
sufficient to produce measurable crack extension. As the stroke is increased
the cumulative area under the load/displacement curve is "written" into the
data and plotting files (VF1 and VF2 respectively). On attaining the total
number of bits of stroke increment the specimen is unloaded \( (Z_9=3) \) to 90\% of
the load in the preceding loading ramp and, using a linear regression analysis
on the data, the unloading compliance is calculated and normalized with
respect to \( E \) (Young's modulus) and \( B \) (specimen thickness). No area under the
curve is calculated in this section of the program. Through the compliance
calibration in the program (see Section 5), crack length is inferred and the
corresponding J-integral value calculated using equation 14. A summary of
these results is "written" into the plotting file (VF2). The J-integral test
then continues, firstly by restoring the specimen to the displacement at the
top of the unloading \( (Z_9=4) \) and then by bit-wise incrementing the stroke a
further 20 bits \( (Z_9=2) \) to promote further crack growth. The determination of
the area under the load/displacement curve is resumed at the point in the
program when \( Z_9=2 \).

* It has been found that \( a_0 \) is often better estimated if this first 10\%
unload is used for the calculation rather than the initial elastic loading
as specified in [2]. This unloading must occur in the linear-elastic
regime.
The data "written" into the virtual files (VF1 and VF2) can be retrieved using the program ACCESS.BAS. All details of the test including scaling factors are included in the printout of data from the PDP11/04 virtual files.

A typical analogue output from a single specimen J-integral test is given in Figure 9; this will be dealt with in detail in Section 8 when the test results from gun steel are discussed.

7.2 The data analysis programs on the VAX11/780 and PDP11/04

The main program in this suite of programs for the VAX11/780 and PDP11/04 is for the re-analysis of the test data for the purpose of arithmetic checks and the use of alternative calibrations or test details such as specimen dimensions etc. To use this program on the VAX the data file used by the JRERUN.BAS program must be in ASCII code. The data file created on the PDP11/04 and loaded into the VAX11/780 is in binary numbers and must therefore be re-written in ASCII code. This is achieved by a small program to create an ASCII code output file which can be utilised by the data analysis programs (see Appendix 2 for details). In the case of JRERUN.BAS for the PDP 11/04 the virtual files are read directly. In all other respects the programs are similar.

The data analysis program, JRERUN.BAS requires specimen details to be input again (should errors be discovered in the original measurement of the specimen) and also, with the accurate measurement of initial crack length now that the test specimen has been broken open after heat tinting, a correct value of the Merkle-Corten coefficient can be inserted for compact tension J tests. Similarly Young's modulus can be changed for the re-analysis of the test data. Most importantly, however, alternative compliance calibrations can be used if they are available for the specimen geometry tested. This should allow the eventual attainment of better correspondence between measured crack length values and those inferred by the unloading compliance technique. The standard, ASTM E 813 [2], requires "that the final crack extension value, as predicted by single-specimen techniques, must agree with the averaged heat tint values within 15%". Using the present re-analysis method this requirement can usually be met for the compact tension J-integral specimen (see Section 9). The JRERUN.BAS program also gives the correlation coefficients for linear regression analysis of the unloading data and also permits the examination of the load/load-line-displacement data pairs to decide if any should be discarded from the start of the unloading to allow for non-linear effects. Some computer-interactive J-integral test programs use a delay before an unloading to reduce non-linear effects and time-dependent, plastic recovery [22,23]. The control program on the PDP11/04 overcomes non-linear effects to some extent by discarding a fixed number of data points for the linear regression to establish the compliance. The data analysis program on the other hand allows the number of points which are discarded to be varied at each unloading.
The program prints a summary of all calculations together with all test details including the compliance calibration used to infer the crack extension in the J-integral test.

Another program, ACCESS1.BAS, for the VAX only, is a simple utility to allow the examination of any part of the load/load-line-displacement record (stored as load/load-line-displacement data pairs). This program "writes" a simple plotting file which can be used with MRL utility program GRAPH [24] so that the record between any two reading numbers can be replotted. The ACCESS1.BAS/GRAPH combination can be used to examine for any hysteresis in the unloading/reloading sequence and to obtain the slope of any unloading or reloading part of the record, should this be necessary (see Section 10).

8. COMPUTER-INTERACTIVE, SINGLE SPECIMEN J-INTEGRAL TESTS AND A MULTIPLE SPECIMEN J-INTEGRAL TEST ON A Ni-Cr-Mo GUN STEEL

The material used in this work was taken as MRL 103 compact tension specimens in the transverse orientation from a 4.5 inch Naval gun.* This material was used for the preliminary investigation of the J-integral test method [3] because limited fracture toughness data was available for this steel [25,26]. The chemical composition of the steel is given in Table 1.

A micrograph of the steel, with orientation transverse to the barrel wall, is shown in Figure 10.

The mechanical properties of this gun steel have been reported in earlier work [25] and are summarised in Table 2. Estimates of fracture toughness, using ASTM E 399 [1], were made from the load/displacement records of tests on the steel [26]; these are reproduced in reference 25. It should be noted, however, that the fracture toughness values reported in Table 2 are designated as $K_0$ values because the fracture toughness tests were invalid [26]. For the 51 mm thick compact 'C'-shaped specimens (51CC) and the 51 mm thick compact tension specimens (51CT) the $P_{max}/P_0$ ratios were approximately 1.12. It is considered, therefore, that the $K_0$ values reported in Table 2 approach the $K_{IC}$ of the material. Thus in the transverse orientation $K_{IC}$ is approximately 130 MN m$^{-3/2}$.

* MRL Reference, Barrel G1 (1971).
TABLE 1

Chemical Composition of Steel from a 4.5 inch Naval Gun (wt%)

<table>
<thead>
<tr>
<th></th>
<th>C</th>
<th>Mn</th>
<th>P</th>
<th>S</th>
<th>Si</th>
<th>Ni</th>
<th>Cr</th>
<th>Mo</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.32</td>
<td>0.62</td>
<td>0.009</td>
<td>0.011</td>
<td>0.20</td>
<td>2.56</td>
<td>0.84</td>
<td>0.57</td>
</tr>
</tbody>
</table>

TABLE 2

Mechanical Properties of Gun Steel

<p>| | | | | | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.2</td>
<td>691 MN m(^{-2})</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>UTS</td>
<td>932 MN m(^{-2})</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>K(_Q) 25CT (transverse)</td>
<td>133 MN m(^{-3/2})</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>K(_Q) 51CC (transverse)</td>
<td>130 MN m(^{-3/2})</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>K(_Q) 51CT (longitudinal)</td>
<td>150 MN m(^{-3/2}) (160 MN m(^{-3/2}) est. from COD)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Note: All properties are measured at 20°C.

Using the computer-interactive test method described above, a series of standard, single specimen J-integral tests conforming to ASTM E 813 [2] was undertaken and the inferred and measured crack length data obtained from each test are given in Tables 3a and b. Table 3a summarizes the results from the actual test as controlled by the program on the PDP11/04, and this program incorporated the unloading compliance obtained using the finite element program, PAFEC, [17a,b] (see Figure 4). Table 3b summarizes the results from a re-run of the experimental data using JRERUN.BAS on the VAX 11/780. Errors in the measurement of a\(_0\), a\(_f\) and Aa are given in both tables.
Summary of J-Integral Test Data using PAFEC-Generated Compliance Calibration. 
Data from PDP11/04 Control Program, (1) (JCTS.BAS)

<table>
<thead>
<tr>
<th>Specimen No.</th>
<th>Specimen</th>
<th>$a_o$ meas. compl. mm</th>
<th>$a_f$ meas. compl. mm</th>
<th>Err% (2)</th>
<th>$a_f$ meas. compl. mm</th>
<th>$\Delta a$ meas. compl. mm</th>
<th>Err%</th>
</tr>
</thead>
<tbody>
<tr>
<td>B1</td>
<td>B1</td>
<td>30.14</td>
<td>30.74</td>
<td>+2.0</td>
<td>31.52</td>
<td>31.77</td>
<td>+0.88</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1.38</td>
<td>1.03</td>
<td>-25.4</td>
</tr>
<tr>
<td>B2</td>
<td>B2</td>
<td>30.43</td>
<td>31.07</td>
<td>+2.1</td>
<td>31.08</td>
<td>31.61</td>
<td>+1.7</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.65</td>
<td>0.54</td>
<td>-16.9</td>
</tr>
<tr>
<td>B3</td>
<td>B3</td>
<td>30.09</td>
<td>30.53</td>
<td>+1.5</td>
<td>31.38</td>
<td>31.76</td>
<td>+1.2</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1.29</td>
<td>1.23</td>
<td>-4.7</td>
</tr>
<tr>
<td>B4</td>
<td>B4</td>
<td>30.18</td>
<td>30.75</td>
<td>+1.9</td>
<td>30.47</td>
<td>31.01</td>
<td>+1.8</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
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<td></td>
<td>0.29</td>
<td>0.26</td>
<td>-10.3</td>
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<td>B6</td>
<td>B6</td>
<td>30.50</td>
<td>31.00</td>
<td>+1.6</td>
<td>31.13</td>
<td>31.58</td>
<td>+1.4</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.63</td>
<td>0.58</td>
<td>-7.9</td>
</tr>
<tr>
<td>B8</td>
<td>B8</td>
<td>29.94</td>
<td>30.92</td>
<td>+3.3</td>
<td>-</td>
<td>31.04</td>
<td>-</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>-</td>
<td>0.12</td>
<td>-</td>
</tr>
<tr>
<td>B9(3)</td>
<td>B9(3)</td>
<td>30.16</td>
<td>31.18</td>
<td>+3.4</td>
<td>-</td>
<td>30.60</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>-</td>
<td>0.0</td>
<td>-</td>
</tr>
<tr>
<td>B10(3)</td>
<td>B10(3)</td>
<td>30.19</td>
<td>30.69</td>
<td>+1.7</td>
<td>30.78</td>
<td>31.18</td>
<td>+1.3</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.59</td>
<td>0.49</td>
<td>-16.9</td>
</tr>
<tr>
<td>B11</td>
<td>B11</td>
<td>30.27</td>
<td>30.47</td>
<td>+0.7</td>
<td>30.40</td>
<td>30.60</td>
<td>+0.7</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.13</td>
<td>0.13</td>
<td>+0.0</td>
</tr>
</tbody>
</table>

Note:

(1) Young's modulus = 203 GPa, used in preliminary calculations.

(2) Err% is defined here as the error in the value inferred from the unloading compliance calibration.

\[
\text{Err\%} = \left( \frac{X_{\text{inferred}} - X_{\text{measured}}}{X_{\text{measured}}} \right) \times 100
\]

$X_{\text{measured}}$ is taken as absolutely correct. It is only subject to errors in physical measurement and this can be demonstrated to be ±0.01 mm ($\pm 10 \mu m$).

(3) No heat tinting results available for specimens B8 and B9.
### TABLE 3b

Summary of J-Integral Test Data using an Experimental Compliance Calibration. Data from VAX11/780 Computer Program, (JRERUN.BAS)

<table>
<thead>
<tr>
<th>Specimen</th>
<th>(a_0) meas. compl. mm</th>
<th>(a_f) meas. compl. mm</th>
<th>(\Delta a) meas. compl. mm</th>
<th>Specimen</th>
<th>(a_0) meas. compl. mm</th>
<th>(a_f) meas. compl. mm</th>
<th>(\Delta a) meas. compl. mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>B1</td>
<td>30.14</td>
<td>29.76(2)</td>
<td>-1.3</td>
<td>B2</td>
<td>30.43</td>
<td>30.09</td>
<td>-1.2</td>
</tr>
<tr>
<td></td>
<td>30.07(3)</td>
<td>30.38</td>
<td>-0.2</td>
<td></td>
<td>31.08</td>
<td>30.68</td>
<td>-1.3</td>
</tr>
<tr>
<td>B3</td>
<td>30.09</td>
<td>29.54</td>
<td>-1.8</td>
<td>B4</td>
<td>30.18</td>
<td>29.79</td>
<td>-1.3</td>
</tr>
<tr>
<td></td>
<td>29.86</td>
<td>31.08</td>
<td>-0.8</td>
<td></td>
<td>30.47</td>
<td>30.07</td>
<td>-0.3</td>
</tr>
<tr>
<td>B6</td>
<td>30.50</td>
<td>30.04</td>
<td>-1.5</td>
<td>B8(5)</td>
<td>29.96</td>
<td>30.27</td>
<td>+0.1</td>
</tr>
<tr>
<td></td>
<td>30.35</td>
<td>30.37</td>
<td>-0.5</td>
<td></td>
<td>30.08</td>
<td>30.39</td>
<td>-1.1</td>
</tr>
<tr>
<td>B9(5)</td>
<td>30.16</td>
<td>29.72</td>
<td>-1.5</td>
<td></td>
<td>29.72(6)</td>
<td>30.04</td>
<td>0.4</td>
</tr>
<tr>
<td></td>
<td>30.04</td>
<td>30.27</td>
<td>0.4</td>
<td></td>
<td></td>
<td>30.04</td>
<td>0.0</td>
</tr>
<tr>
<td>B10</td>
<td>30.19</td>
<td>29.76</td>
<td>-1.4</td>
<td>B11</td>
<td>30.27</td>
<td>29.51</td>
<td>-2.5</td>
</tr>
<tr>
<td></td>
<td>30.07</td>
<td>30.78</td>
<td>-0.0</td>
<td></td>
<td>30.40</td>
<td>29.64</td>
<td>-2.5</td>
</tr>
</tbody>
</table>

(1) \(Err\%\) as defined for Table 3a.
(2) Upper line are results calculated using Young's modulus = 203 GPa.
(3) Lower line are results calculated using Young's modulus = 210 GPa.
(4) This value is not the same as that given in Table 3 of [3], because in the present analysis the "next-to-final" unloading data pairs were used for linear regression analysis. More unloading data pairs are available and hence the estimate of \(\Delta a\) is possibly more accurate than in [3] despite the fact that a small amount of crack growth has occurred between unloads.
(5) No heat tinting results available for specimens B8 and B9.
(6) B9 showed no crack growth.
For specimens B1 to B11 different final crack extension values were attained for each individual test which means, therefore, that the series could also be treated as one multiple specimen J test. The final crack length for each of the tests was marked by heat tinting; some of the tinted specimens are shown in Figure 11. The final Δa values measured from the heat tinted specimens are included in the summary of the test results given in Tables 3a and 3b and were measured using an unweighted 11 point average* which included the two outer-surface locations. In some cases, where the final crack extensions are quite small, less than 0.20 mm, it is possible that the requirements for a valid (or even useful) J-integral test are not met (see [2] section 9.3).

From Table 3a it can be seen that the original PAFEC-generated compliance calibration used in the PDP11/04 control program gives what appears to be good estimates of a₀ and a₉, with maximum errors of up to ±3.4%. Further, the PAFEC compliance calibration results in consistent over-estimates of actual crack-length; thus the relative errors between any sets of a₀ and a₉ values are apparently very small. However the calculations of Δa (which use a₀ and a₉ values) are often subject to very large errors; indeed many of the estimates of crack extension using the present PAFEC compliance calibration do not meet the requirements of the ASTM standard for the J-integral test (2) where "the final crack extension value, as predicted by single specimen techniques, must agree with the averaged heat tint value within 15%". There are two possible reasons for this; (1) that the compliance calibration used initially in the control program on the PDP11/04 is not entirely appropriate for the test and (2) the number of points discarded from the start of the unloading for the linear regression analysis is not sufficient to avoid all non-linear behaviour. This program originally discarded 2 unloading data pairs. These data can be re-analysed, however, using alternative compliance calibrations and varying the number of discarded data pairs.

Using the program JRERUN.BAS on the VAX11/780 (or PDP11/04) an alternative compliance calibration is tested. The only other compliance calibration presently available for the MRL J03 specimen is the experimental unloading compliance calibration generated using 13 mm thick MRL J03 specimens [16], see Figure 4. Using this alternative calibration, and discarding 4 data points from the start of the unloading, gives slightly different estimates of a₀ and a₉; the results of the calculations are summarized in Table 3b.

The experimental compliance [16] tends to slightly under-estimate the values of crack lengths and this can be altered further by using a higher value of Young's modulus, although the value for the gun steel used in the present work has not been measured. A Young's modulus value of 203 GPa was

* It should be noted that ASTM E 813 uses nine inner points plus a weighted two outer points for the calculation of mean crack length. The present unweighted 11 point average appears to give better correspondence with crack length inferred from compliance than the 9 + 2 point average used in E 813.
used for the normalization of the data in the experimental determination of the unloading compliance calibration but a value of 210 GPa may be more appropriate for the thick specimens used in the J-integral testing of specimens B1-B11. Both Young’s modulus values are used for the calculations presented in Table 3b. While an E value of 210 GPa appears to give a closer correspondence with the heat tinting data there is a greater relative error between $a_0$ and $a_f$ values using this higher E and, as a result, slightly larger errors in the estimations of the $\Delta a$ values. Over-all the use of the experimental unloading compliance data [16] in the J-integral test offers a better correspondence (smaller Err% values) between the inferred crack length values and those measured from heat tinted specimens than is achieved using the original PAFEC-generated unloading compliance calibration.

Typical J-\Delta a plots for the single specimen test methods are shown in Figures 12, 13 and 14. These plots used J-\Delta a data pairs generated by JRERUN.BAS on the VAX11/780.

The blunting line used in all calculations is given by equation 16, and is included on all J-\Delta a plots.

As mentioned above, the series of specimens B1 to B11 can also be treated as one multiple specimen J-integral test on this gun barrel steel. The $a_f$ values used in this method are those obtained from the heat tinting experiments and the J values corresponding to each final $\Delta a$ value were calculated from the area under the load/load-line-displacement record at the start of the final unload of each test. The J-\Delta a plot for these data is shown in Figure 15.

An estimate of fracture toughness in terms of stress-intensity factor, $K$, is made using the relation

$$K_{JC} = \sqrt{E' J_{IC}}$$

(17)

where $K_{JC}$ = the fracture toughness derived from a multiple specimen or single specimen J-integral fracture toughness test.

$J_{IC}$ = value of J at the intersection of the blunting line and the linear regression through admissible J-\Delta a data points.

$E'$ = the value of Young’s modulus used in unloading compliance calculations. In the cases of relatively thick specimens this $E'$ value would approach $E/(1-\nu^2)$, where $\nu$ is Poisson’s Ratio.

The following table summarizes the results of the J-integral calculations using both multiple and single specimen test methods.
Summary of J-Integral Test Results for a NiCrMo Gun Steel at 20°C

<table>
<thead>
<tr>
<th>Specimen No.</th>
<th>( J_{IC}^{(1)} ) kN( \cdot )m(^{-1} )</th>
<th>( K_{JC}^{(1)} ) MN( \cdot )m(^{-3/2} )</th>
<th>( \Delta a_{max}^{(1)} ) mm</th>
<th>( J_{IC}^{(2)} ) kN( \cdot )m(^{-1} )</th>
<th>( K_{JC}^{(2)} ) MN( \cdot )m(^{-3/2} )</th>
<th>( \Delta a_{max}^{(2)} ) mm</th>
<th>( \Delta a_{max} ) measured mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>B1</td>
<td>80</td>
<td>127.4</td>
<td>1.04</td>
<td>73</td>
<td>121.6</td>
<td>1.18</td>
<td>1.38</td>
</tr>
<tr>
<td>B2</td>
<td>96</td>
<td>139.6</td>
<td>0.54</td>
<td>78</td>
<td>126.2</td>
<td>0.61</td>
<td>0.66</td>
</tr>
<tr>
<td>B3</td>
<td>85</td>
<td>131.3</td>
<td>1.23</td>
<td>80</td>
<td>127.5</td>
<td>1.23</td>
<td>1.30</td>
</tr>
<tr>
<td>B4</td>
<td>45</td>
<td>95.6</td>
<td>0.26</td>
<td>84</td>
<td>130.4</td>
<td>0.26</td>
<td>0.30</td>
</tr>
<tr>
<td>B6</td>
<td>80</td>
<td>127.4</td>
<td>0.60</td>
<td>76</td>
<td>124.2</td>
<td>0.60</td>
<td>0.64</td>
</tr>
<tr>
<td>B8(3)</td>
<td>78</td>
<td>125.6</td>
<td>0.12</td>
<td>71</td>
<td>120.3</td>
<td>0.12</td>
<td>-</td>
</tr>
<tr>
<td>B9(3)</td>
<td>&gt;60</td>
<td>0</td>
<td>&gt;60</td>
<td>&gt;60</td>
<td>&gt;0</td>
<td>0.13</td>
<td>0.0</td>
</tr>
<tr>
<td>B10</td>
<td>58</td>
<td>103.3</td>
<td>0.49</td>
<td>57</td>
<td>108</td>
<td>0.51</td>
<td>0.60</td>
</tr>
<tr>
<td>B11</td>
<td>&gt;61</td>
<td>-</td>
<td>0.13</td>
<td>&gt;70</td>
<td>-</td>
<td>0.13</td>
<td>0.13</td>
</tr>
</tbody>
</table>

\[ 121.5 \pm 15.9 \quad 122.6 \pm 7.3 \]

Multiple Specimen(4) \( J_{IC} = 93 \) kN/m \( K_{JC} = 137.4 \) MN\( \cdot \)m\(^{-3/2} \)

Notes:

1. From the original PDP11/04 data, see [3]. 2 discards from the start of an unloading; PAFEC-generated unloading compliance calibration; \( E = 203 \) GPa and a Merkle-Corten Coeff of 2.265, (too high).

2. From JRERUN.BAS on the VAX 11/780. 4 discards from the start of an unloading; experimentally determined unloading compliance calibration; \( E = 203 \) GPa and a Merkle-Corten Coeff of 2.216, (correct value).

3. No heat tinting results for these specimens.

4. All data for \( \Delta a_{max} \) measured (viz B1,B2,B3,B4,B6,B9 (\( \Delta a = 0 \)), B10,B11).
The results of the calculations of $J_{IC}$, given in Table 4, for two methods of analysis show that the control program, JCTS.BAS and the arithmetically more accurate JRERUN.BAS produce similar $J_{IC}$ values. Some tests such as B9 and B10 give measurably lower $J_{IC}$ values than the remaining bulk of the tests. The reason for this is not apparent because the same test method and data analysis was applied to these specimens, and hence it must be concluded that specimens B9 and B10 are representative of the lower toughness values in what may be normal scatter for this material, viz. $K_{JC} = 122.6 \pm 7.3$ MN m$^{-3/2}$.

From the results summarized in Table 4 it can be seen that the multiple specimen test gives a higher $J_{IC}$ value than the series consisting of single specimen tests. This difference arises because of distribution of the $J$-Aa data points between the 0.15 and 1.50 mm exclusion lines. The multiple specimen test has these points evenly distributed between the exclusion lines, but in the cases of the single-specimen tests these data are often closer to the blunting line, thus producing lower $J_{IC}$ values. Despite limited multiple specimen $J$-integral data both the single specimen and multiple specimen $K_{JC}$ values agree well with the known $K_0$ values of the gun steel. Unfortunately, there are no $K_{IC}$ values, but because the $P_{max}/P_5$ values for the test are approximately 1.12 (26), then the comparison between the $K_{JC}$ values measured in the present work and the known $K_0$ values is not unreasonable.

These preliminary $J_{IC}$ tests using the gun steel highlight some deficiencies in the computer-interactive single specimen $J$-integral test method, but these can be overcome by the use of JRERUN.BAS. The first deficiency is that JCTS.BAS should discard more than two unloading data pairs for the linear-regression analysis since there is evidence of non-linear behaviour within the first four data pairs. This contributes to errors in crack length measurement, although this would not readily be apparent in the "rounding off" of data to 2 decimal points. Another deficiency is that within JCTS.BAS the correlation coefficient for the linear regression analysis should be calculated and documented.* At the present stage of development this is only handled by JRERUN.BAS. A further limitation of the JCTS.BAS program is its lack of generality; certain lines within the program have to be edited if test parameters are changed; e.g. discards of data pairs in the linear regression, compliance calibration and displacement calibration. At a later stage of development the program could be expanded for these to be written into the program interactively.

Those factors which influence the accuracy of the measurements and calculations are discussed in Section 10.

* Limited TPA of PDP 11/04 does not permit these calculations to be undertaken.
9. FURTHER APPLICATIONS OF THE COMPUTER-INTERACTIVE, SINGLE SPECIMEN J-INTEGRAL TEST METHOD

At its present level of development this test method has been used for the measurement of the fracture toughness, $J_{IC}$, of 6 mm thick MRL J03 specimens of a precipitation hardened martensitic stainless steel, STA60, [27]. The results presented in [27] were found to behave similarly to those data reported for 17/4 PH, [22]. The greatest difficulty encountered with the test method was that the unloading compliance calibrations used in the work, PAFEC-generated in JCTS.BAS and experimentally measured in JRERUN.BAS, could not accommodate the large degree of crack tunnelling which occurred in the testing of the STA60. This problem is one which has not been addressed by the developers of unloading compliance J-integral test methods.

A second application of the computer-interactive, single specimen J-integral test method was in the measurement of the fracture toughness, $J_{IC}$, of a 105 mm gun tube (non-autofrettaged) of NiCrMo steel. In this work [28] it was possible to determine the plane-strain fracture toughness, $K_{IC}$, of the steel, with which to compare the $J_{IC}$ value obtained from JCTS.BAS, as $K_{IC}$. The agreement between $K_{IC}$ and $K_{IC}$ was particularly good. Crack tunnelling in this series of tests was minimal, and hence agreement between inferred and measured $\Delta a$ values generally conformed to ASTM E 813 [2].

These applications of the computer-interactive, single specimen J-integral test method have demonstrated its suitability for the testing of high strength steels.

10. DISCUSSION

The limited TPA of the PDP11/04 used in the present experiments meant that error and accuracy checks as specified in [2] could not be undertaken during the test. Thus most of the accuracy checks have to be undertaken retrospectively using the JRERUN.BAS program and this makes the J-integral test method developed in this work similar to the $K_{IC}$ test [1], where a completed test can be declared invalid on the basis of retrospective analysis.

The standard [2] requires that the initial linear-elastic slope be used as a guide for the accuracy of the initial test set-up. If the PDP11/04 control program were to check the loading compliance following the elastic load-up ($Z_F=1$), then it would be essential for the elastic load limit of the test to be set to the maximum final pre-cracking load of the specimen. This means that if the test were found to be progressing incorrectly then it could be stopped and re-started without the need for further pre-cracking, i.e. the specimen would still satisfy the final pre-cracking requirements for a valid test. Unfortunately, this load is relatively low. For example, in the case of the gun steel (Section 8) the elastic load limit would be 25 kN or lower.
In the present method the specimens are checked for dimensional accuracy and so it can be assumed that if the clip gauge seats correctly in the specimen then errors in the load/load-line-displacement record will be minimal. (Correct seating of the clip gauge can be checked using very small pre-loads and unloads.) The alignment of the test machine is also checked prior to starting a series of J-tests. It is considered, therefore, that the preliminary check of the compliance is not necessary. Any discrepancies in compliance with the experimentally-determined value can probably be accommodated by small changes in Young's modulus in JRERUN.BAS (see below). This check of the initial linear elastic compliance is done indirectly by the JRERUN.BAS program. It can be shown that a ± 7% variation in normalized compliance at a/W = 0.60 produces a ± 2.3% variation in inferred a/W value, or, for a 25 mm thick specimen, a crack length of 30.60 mm ± 0.70 mm. With the exception of specimens B8 and B9, the initial crack length estimates in Table 3(a) fall within this range suggesting that most tests were correctly set-up.

The area calculation check in the linear-elastic loading region is considered more important than the linear-elastic loading compliance (above) because it will give an indication of the errors in the area under the load/displacement curve introduced by the area calculation. This can be checked further against the analogue plot (see below). To undertake this numerical check, it is desirable that the elastic load limit, P7, be set as high as possible at the start of the test so that a relatively large area is measured and checked against a calculated area (area of a triangle in the elastic region). In the present form of the test control program this elastic load limit is usually set higher than the maximum fatigue load (for the final 7.6 mm of crack growth) and this precludes the re-use of the specimen if a test does not proceed for any reason. Experience with steels has shown, however, that with the present instrumentation and level of development of the test method, preliminary compliance checks are unnecessary, and that once started the test should not be interrupted. The preliminary J-integral tests conducted on the gun steel revealed a slight error in the calculation of the area under the load/load-line-displacement record, producing an over-estimate of this area in the linear elastic region up to load P7 (see Table 5 below). This has been modified and now most MRL J03 specimens give an error in the elastic region of less than +2.0% (27, 28). The magnitude of error is calculated by the ACCESS.BAS program on the PDP 11/04. This particular error check gives a good indication of the accuracy of the area measurement in the initial stages of the test where, because of the slope of the load/load-line-displacement record, the calculation errors should be the largest of the test. This may also give a measure of the non-linearity which is observed at the start of most fracture toughness tests.

A check against the area under the analogue load/load-line-displacement records for specimens B1-B11, using a Kontron Bildanalyse Mini-MOP for area determination, shows good agreement between the calculated and measured areas. These are summarized in Table 5. It is not possible to determine errors for the computer-calculated areas because there are no measured areas which are absolutely correct. The areas measured from the analogue plots are subject to undetermined errors (but which are likely to be small anyway). These are, for example, the accuracy of the analogue plot (pen thickness, linearity of scales calibration, etc.) and the accuracy of usage of the Mini-MOP, see Table 5. Within these limitations, the agreement
between the calculated and the measured areas for specimens B1-B11 demonstrates that the JCTS.BAS program produces acceptable estimates of area under the load/load-line-displacement record from which J values can be determined.

TABLE 5

Area Calculations for Single Specimen J-Integral Tests

<table>
<thead>
<tr>
<th>Specimen No.</th>
<th>Measured Area (1) kN mm</th>
<th>Calculated Area kN mm</th>
<th>Error to Elastic (2) Load Limit %</th>
<th>Elastic Load Limit kN</th>
</tr>
</thead>
<tbody>
<tr>
<td>B1</td>
<td>35.97 ± 0.233</td>
<td>34.92</td>
<td>1.58</td>
<td>35</td>
</tr>
<tr>
<td>B2</td>
<td>32.07 ± 0.035</td>
<td>32.68</td>
<td>2.31</td>
<td>35</td>
</tr>
<tr>
<td>B3</td>
<td>39.84 ± 0.093</td>
<td>39.14</td>
<td>4.60</td>
<td>35</td>
</tr>
<tr>
<td>B4</td>
<td>23.20 ± 0.066</td>
<td>23.63</td>
<td>2.45</td>
<td>35</td>
</tr>
<tr>
<td>B6</td>
<td>27.07 ± 0.072</td>
<td>27.21</td>
<td>2.05</td>
<td>35</td>
</tr>
<tr>
<td>B8</td>
<td>18.42 ± 0.060</td>
<td>19.51</td>
<td>4.11</td>
<td>35</td>
</tr>
<tr>
<td>B9</td>
<td>13.90 ± 0.037</td>
<td>19.25</td>
<td>3.54</td>
<td>30</td>
</tr>
<tr>
<td>B10</td>
<td>29.71 ± 0.032</td>
<td>29.97</td>
<td>1.21</td>
<td>35</td>
</tr>
<tr>
<td>B11</td>
<td>19.85 ± 0.052</td>
<td>18.82</td>
<td>2.48</td>
<td>35</td>
</tr>
</tbody>
</table>

Notes:

(1) Measured using Mini-MOP; standard deviations reflect reproducibility of area measurements using a minimum of 4 determinations.

\[
\text{Err}\% = \frac{A_{\text{measured}} - A_{\text{calc}}}{A_{\text{calc}}} \times 100; \text{ results from ACCESS.BAS.}
\]

One limitation of the test procedure at the present level of development is in the limited number of load/load-line-displacement pairs used for the calculation of the unloading compliance \([29=3] \). Dependent on the displacement calibration of the system, the number of admissible data pairs should be in excess of 20 (see [29] for a discussion of unloading compliance instrumentation). Some computer-interactive test methods use more than 60 data pairs and to obtain such a large number of points both those from the unloading and the re-loading are used \([30] \). At the present time it is not possible to determine the optimum number of data pairs for determination of
the unloading compliance of the specimens; however, to assist in the assessment of the over-all acceptability* of data, the linear regression calculations within JRERUN.BAS also give the coefficient of determination, $r^2$, for each estimate of unloading compliance. Ideally, this value should be in excess of 0.9999, [22], however, for the B1-B11 series undertaken in this work most of the linear regression calculations for each unloading give values in excess of 0.999. A typical output from JRERUN.BAS is given in Appendix 5, where it can be seen that the coefficients of determination for unloading compliance data are in excess of 0.999. If an increase in the number of data pairs for the unload is found to be desirable then, in the cases of specimen geometries for which the present J-integral test control program has been developed, this can be achieved simply by changing the span control of the MTS-810 system so that the number of bits from the MSG results in a smaller increment in stroke.

Another potential source of error in the single-specimen J-integral test method is in the non-linear unloading effects which occur with some materials. This can introduce significant errors in the calculation of unloading compliance [29] and also small errors in the estimation of area under the load/load-line-displacement curve. To allow for these non-linear effects (time-dependent line recovery) a "hold" in the displacement is often desirable before unloading see [22 and 29]. The material tested in this preliminary work was a high strength steel and as a result the non-linear effects at the start of an unload are small. This can be seen in Figure 16, where several unloads are re-plotted by GRAPH [24] after running the data through ACCESS1.BAS on the VAX 11/780. It is noted that a very small degree of non-linearity is evident at the top (start) of the unloading record. To overcome the possibility that any data pairs which may constitute the non-linear part of the record are admitted to the regression analysis the control program (JC11S for example) now discards the first 4 load/load-line-displacement data pairs. In the case of the data analysis programs, JRERUN.BAS on the VAX 11/780 and the PDP 11/04, all data pairs are listed prior to linear regression analysis, and the data can be re-examined and the number to be discarded input before the calculations begin. The number of data pairs which are discarded can vary for successive unloads in the JRERUN.BAS program and hence is listed in the summary of the calculations produced by the program.

Errors in the estimations of $\Delta a$, and to a lesser extent the calculation of $J$, can also arise as a result of electrical and mechanical hysteresis in the load and displacement measurement systems. Using a 250 kN load cell, the load can be measured to within $\pm 1.0\%$ and the displacement clip gauge has a maximum error of $\pm 0.1\%$. Electrical noise is minimised because each load/load-line-displacement data pair is an average of 10 readings taken over 0.01 second.

Looking back to the data in Tables 3(a and b), generated by

* The acceptability of the data can be tested quantitatively on the basis of the accuracy of predicted versus measured $a_0$ and $a_f$ values.
JRERUN.BAS, it can be seen that the agreement between measured and calculated crack length values is closer than those obtained using the PAFEC-generated compliance calibration for the MRL J03 specimens. The sensitivity of the calculated results to the compliance calibration and Young’s modulus value used for the normalization of raw compliance data has been demonstrated in Section 8, and is clearly an important aspect of the appraisal of the test procedure.

It is difficult to assess the accuracies to which the J-integral value and corresponding Aa value are measured. All aspects of the calculations and error analyses must be documented during a test or in the re-run of the raw data through JRERUN.BAS.

The final point to be discussed is the accuracy to which the $J_{IC}$ value can be determined from a set of admissible J-Aa data pairs. It is usual to fit a straight line through all admissible data pairs whereby $J_{IC}$ is calculated at the point of intersection of this linear regression line and the blunting line [2]. This method has been used in the present work. However, it is instructive to re-examine some of the results given in Table 4 in more detail. The $J_{IC}$ values under consideration are those obtained from JRERUN.BAS using the experimentally-determined unloading compliance calibration. The calculations for the $J_{IC}$ values are summarized in Table 6.

From the ± 95% confidence limits on the estimation of $J_{IC}$ for each of the specimens tested in this work it can be seen that some of the $J_{IC}$ values are poor estimates of fracture toughness. Appreciable errors in the estimation of $J_{IC}$ arise when

(i) the number of admissible J-Aa data pairs is low.

(ii) the J-Aa data pairs are grouped away from the 0.15 mm exclusion line and towards the 1.50 mm exclusion line, [2].

(iii) the J-Aa data pairs exhibit scatter within a single specimen test.

It is clear that the ideal grouping of the J-Aa data points for the purposes of the linear regression analysis is equi-spaced between the exclusion lines and that the number of data pairs should be in excess of 12. This is not satisfied by some of the tests conducted in this work. Where the above criteria are met, as in the cases of specimens B1 and B2, the ± 95% confidence interval is small. The data for specimen B4 have been analysed by successively using more J-Aa data in the regression analysis. Unfortunately, where 6 and 9 data points are used the extra data points are to the left of the 0.15 mm exclusion line. However the result demonstrates the need for sufficient data points of optimum spacing. Whether or not the scatter of J-Aa points can be reduced for a single specimen J-integral test is difficult to assess. If all physical aspects of the J-integral test are correct (see above) then any scatter observed in the test data must be regarded as a result of the response of the material to the loading (and unloading) of the J-integral test procedure. The effects of scatter on the estimation of $J_{IC}$ can be reduced by keeping the number of admissible data pairs high and this can be done quite simply using computer-interactive test methods.
### TABLE 6

Summary of Linear Regression Calculations for $J_{IC}$ Determinations

<table>
<thead>
<tr>
<th>Specimen No.</th>
<th>$J_{IC}$ value $\text{kJ m}^{-1}$</th>
<th>No. of Admissible Data Points</th>
<th>$Y$ Intercept $\text{kJ m}^{-1}$</th>
<th>$\pm$ 95% Confidence limits $\text{kJ m}^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>B1</td>
<td>72.8</td>
<td>13</td>
<td>70.2</td>
<td>$\pm$ 5.5</td>
</tr>
<tr>
<td>B2</td>
<td>78.4</td>
<td>9</td>
<td>73.0</td>
<td>$\pm$ 9.1</td>
</tr>
<tr>
<td>B3</td>
<td>80.1</td>
<td>11</td>
<td>71.0</td>
<td>$\pm$ 22.7</td>
</tr>
<tr>
<td>B4</td>
<td>not calculated</td>
<td>5</td>
<td>41.9</td>
<td>$\pm$ 75.3</td>
</tr>
<tr>
<td>B4</td>
<td>83.8</td>
<td>6</td>
<td>79.5</td>
<td>$\pm$ 32.2</td>
</tr>
<tr>
<td>B4</td>
<td>not calculated</td>
<td>9</td>
<td>48.8</td>
<td>$\pm$ 8.8</td>
</tr>
<tr>
<td>B6</td>
<td>75.9</td>
<td>7</td>
<td>72.6</td>
<td>$\pm$ 6.8</td>
</tr>
<tr>
<td>B8</td>
<td>71.3</td>
<td>no values</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>B9</td>
<td>&gt; 60</td>
<td>no values</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>B10</td>
<td>57.4</td>
<td>9</td>
<td>55.4</td>
<td>$\pm$ 22.5</td>
</tr>
<tr>
<td>B11</td>
<td>&gt; 70</td>
<td>no values</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

(1) On the blunting line

(2) On the $Y$ axis

In summary it can be seen that most of the errors discussed above are approximately the same for each test using the MRL J03 specimen. The calculated error in the area under the elastic portion of the load/load-line-displacement curve is consistently $\pm 2\%$ (but never negative), $a_0$ and $a_f$ are usually estimated to within $\pm 2\%$ (but if similar unloading compliance calibrations are used the test-to-test variations in crack-length estimates are even smaller) and $Aa$ is usually estimated to within $\pm 15\%$. Thus under most circumstances the computer-interactive single specimen $J$-integral test using MRL J03 specimens satisfy the standard test method for the measurement of $J_{IC}$. 
11. CONCLUSIONS

A computer-interactive, single specimen J-integral test method has been developed for the PDP11/04-MTS 810 system, and tested using the MRL J03 specimen. The material under test was a Ni-Cr-Mo 4.5 inch gun steel.

(1) The control program on the PDP11/04 has been shown to conduct a single specimen J-integral test which produces $K_{IC}$ values which agree well with known plane-strain fracture toughness values.

(2) The inferred increments in crack length, $\Delta a$, obtained using the unloading compliance method incorporated in the control program are usually found to agree within $\pm 15\%$ of that obtained by direct measurement. Alternative calibrations and slight changes to the Young's modulus value used in the calculations can be used to improve the correspondence between measured and inferred values of crack length.

(3) The computer-interactive single specimen J-integral test conforms to the requirements of ASTM standard E 813 for the measurement of $J_{IC}$.

12. ACKNOWLEDGEMENTS

The authors are indebted to Mr R. Farrara [27] of US Army Armament Research and Development Command, Benet Weapons Laboratory, for valuable discussions which led to the refinement of the control program for the single specimen J-integral test.

We are also indebted to Mr T.V. Rose for his pioneering program development for this work [3].
\[ \sigma_{ij} = \frac{K}{\sqrt{2\pi r}} \sum_{ij} \delta(\theta) \]

\[ \epsilon_{ij} = \frac{K}{\sqrt{2\pi r}} \sum_{ij} \delta(\theta) \]

\[ W_1 = \frac{1}{n} \left( \frac{K}{\sigma_y} \right)^2 \]

\[ W_2 \leq 2 \frac{J}{\sigma_y} \]

**FIGURE 1** Schematic representation of crack-tip stress and strain fields.
FIGURE 2  ASTM E 813 method for the measurement of $J_{ic}$. 

**Diagram Description:**
- **Force, kN.** vs. **Load-point displacement, $\delta$.**
- **J-Integral Value, kN/m.** vs. **Crack Extension, mm.**
- Shaded area represents the integral of the load-displacement curve.
- Blunting line indicates the offset for crack extension measurements at 0.15 mm and 1.5 mm.

**Legend:**
- $0.15\text{mm offset}$
- $1.5\text{mm offset}$
Experimentally determined compliance for MRLJ03 specimen.

Normalized compliance from ASTM E 813.

FIGURE 4  An experimental unloading compliance calibration for an MRL J03 specimen, data from [16].
An analytical unloading compliance calibration for an MRL J03 specimen, data from [17a].
FIGURE 6

The opening and closing voltage output from an MTS 632.02C.20 clip gauge.
FIGURE 7  Flow diagram for a computer interactive, single specimen J-integral test.
FIGURE 8  Loading, unload and re-load ramps in a single specimen J-integral test.
FIGURE 9  A typical force/load-line-displacement analogue output for a single specimen J-integral test.
FIGURE 10  Micrograph of a transverse section through a 4.5 inch Naval gun.  
1000X  2% nital etch.
FIGURE 11  Heat tinted specimens to mark final crack lengths in specimens from a 4.5 inch gun barrel of NiCrMo steel.
FIGURE 12 A single specimen J-Δa plot for specimen B1.

Data from JRERUN.BAS, see Appendix IV.
File B1.DAT
Experimental compliance calibration. E = 203 GPa.
MCC = 2.216.
FIGURE 13  A single specimen J-Δa plot for specimen B3.
FIGURE 14 A single specimen J-Δa plot for specimen B10.

Data from JRERUN.BAS
File B10.DAT
Experimental compliance calibration
E=203 GPa
MCC=2.216
Final J-integral values from JRERUN.BAS
All data files (B1-B11)
\( \Delta a \) values from heat tinting
Experimental compliance calibration:
- \( E = 203 \)
- \( \text{MCC} = 2.216 \)

FIGURE 15 The multiple specimen J-\( \Delta a \) plot for all specimens, B1-B11.
FIGURE 16  An example of the hysteresis in successive unloads and reloads for a NiCrMo gun steel.
13. REFERENCES


2. Ibid., E813-81 Standard Test Method for $J_{IC}$, A Measure of Fracture Toughness.


APPENDIX 1

COMPUTER PROGRAM LISTINGS FOR SINGLE SPECIMEN
J INTEGRAL FRACTURE TOUGHNESS TESTS

(a) Program listings for PDP 11/04 Computer.

(1) JCTS.BAS

100 REM ...AUSTRALIAN GOVERNMENT DEFENCE SCIENTIFIC AND TECHNOLOGY ORGANIZATION
110 REM ...MATERIALS RESEARCH LABORATORIES
120 REM JCTS.BAS
130 TIME(10)
140 EDUMP / BUTN("S", LINE 2260 )
150 ERASE
160 PRINT
170 PRINT 'THIS PROGRAM CONDUCTS A SINGLE SPECIMEN J TEST'
180 PRINT / PRINT 'THE TEST COMPLIES WITH ASTM 813 '
190 PRINT / PRINT 'NOTE: READ THE QUESTIONS CAREFULLY'
200 PRINT 'FOR A LISTING OF ALL PARAMETERS RUN "JLIST.BAS"
210 PRINT '<CR>; / INPUT Z$
220 ERASE / PRINT ***** MTS ANALOG SET UP ROUTINE ***** / PRINT
230 PRINT 'ENSURE:-'
240 PRINT 'STRAIN CHANNEL IS CONNECTED TO COMPUTER'
250 PRINT 'STROKE CTRL ***** RANGE MUST BE +/-.10 MM *****
260 PRINT '- SPECIMEN OUT'
270 N7=N7+1
280 PRINT '- HYDRAULICS ON'
290 PRINT '- PROGRAM CTRL IS LOCAL'
300 PRINT / PRINT 'MASTER CLEAR (CHNL 4 MUST = 000),<CR>''
310 INPUT Z$ / PRINT
320 PRINT 'SET PROGRAM CTRL TO REMOTE, <CR> ';
330 INPUT Z$ / PRINT
340 PRINT 'ADJUST SET POINT TO GIVE ZERO DISP (CHNL3=000)'
350 PRINT ***** WARNING *****
360 PRINT ' RAM WILL MOVE SO ENSURE CLEARANCE WITH STROKE ZERO'
370 PRINT '<CR> '; / INPUT Z$ / PRINT
380 PRINT ' INSERT SPECIMEN USING STROKE ZERO, <CR> ';
390 INPUT Z$ / PRINT
400 PRINT 'SPAN 1 TO 1000,<CR> ' ; / INPUT Z$ / PRINT
410 PRINT 'INSTALL CLIP GAUGE (632.02C.20) AND ZERO OUTPUT'
420 PRINT 'COARSE ZERO IS ON THE INPUT BOX AND FINE ZERO IS ON THE AMPLIFIER UNIT'
430 PRINT '<CR> ' ; / INPUT Z$ / PRINT
440 PRINT 'SET UP X-Y RECORDER FOR LOAD/DISP RECORD'
450 PRINT 'USING CALIBRATED 10V POT ON 442 CONTROLLER'
460 PRINT '1MM = 25 CM (HDR12) = 5.0 V'
470 PRINT '<CR> WHEN SET UP ' / INPUT Z$
480 ERASE / PRINT ***** RANGE SELECTION ***** / PRINT
490 PRINT 'LOAD RANGE (kn) '; / INPUT RO
500 RO=2047/RO / REM RO NOW = BITS/KN
510 PRINT 'ENSURE 75% STRAIN RANGE IS SELECTED,<CR> ';

A1.1
INPUT

R1=1011 / REM 1011 BITS IS 1.0MM ON THE 75% STRAIN RANGE
F1=80 / REM RAMP RATE=80
QUIT

ERAS / PRINT TO STOP TEST <BREAK> "S" WILL DUMP THRU LINE15460
ERAS / PRINT <CR> TO CONTINUE / INPUT Z$

PRINT ***** D/A ZERO READINGS ***** / PRINT
PO-0 / DO-0
GOSUB 1760 / REM DACQ
PRINT
AVE LOAD - PO/(10*R0); KN (OR ';PO/10;' BITS)
AVE LPD - ;DO/(10*R1); MM (OR ';DO/10;' BITS)
PRINT 'ZERO RESPECTIVE AMPLIFIER. REPEAT READINGS (Y/N)
INPUT Z$
IF Z$='Y' THEN

ERAS / PRINT ***** DATA STORAGE ***** / PRINT
PRINT 'ENSURE DISK IS IN D1:
PRINT 'SPECIMEN TITLE'; INPUT T$
OPEN 'DYI: *T$ '.DAT' FOR OUTPUT AS FILE VF1(20000)
FOR Z-0 TO 20000 / VF1(Z)-0 / NEXT Z
OPEN 'DYI: T$ .PLT' FOR OUTPUT AS FILE VF2(300)
FOR Z-0 TO 300 / VF2(Z)-0 / NEXT Z
OPEN LS: FOR OUTPUT AS FILE #1
ERAS / PRINT ';TS; DIMENSIONS ***** / PRINT
PRINT 'SPEC WIDTH (METRES) -'; INPUT W
PRINT 'SPEC THICKNESS (METRES) -'; INPUT B
PRINT 'E (GPA) -'; INPUT E
PRINT 'PROOF STRESS (MPA) -'; INPUT U
PRINT 'MERKLE-CORTEN CO-EFFIC.'; INPUT Q
M=M+1.00000E+09 / REM IN N/M 2
PRINT / PRINT 'TO RETRIEVE ';T$; J DATA, RUN <ACCESS>
COPY VF1(0)-B / VF1(1)-W / VF1(2)-M / VF1(3)-R0 / VF1(4)-R1
PRINT 'ELASTIC LIMIT (KN)'; INPUT P7
PRINT 'MAX. # OF UNLOADS'; INPUT U7
PRINT '# OF BITS STROKE INCR'; INPUT M7
VF2(1)-P7
P7-INT(P7*R0)
N-0 / N1=0 / Z9=1 / Z-0 / D2=0 / N7=0
ERAS / PRINT *** RAMP TO ';P7/RO;' KN THEN J TEST'
PRINT / PRINT 'X-Y READY, <CR> TO START TEST'; / INPUT Z$
REM PRINT OF DATA FILE
PRINT #1,TAB(10)'PRINTING DATA FOR THE 10% UNLOAD J INTEGRAL TEST FOR SPECIMEN ';T$
PRINT #1,TAB(5)'READING #';TAB(20)'AREA';TAB(35)'A/W';TAB(50)'DELTA CNGKLNHT';TAB(75)'J';TAB(85)'ES';TAB(100)'V'
PRINT #1,TAB(21)'KNM';TAB(54)'METRES':TAB(72)'KN/M'
REM SET UP GRAPHICS
ERAS / GRON
SCALE(0.0,2.000000E-03,0.350)
AXES(0.0) / AXES(2.000000E-03,350)
LABEL(TS" DELTA A. METRES. " J VALUE,KN/M",5.000000E-04,25,0)
INVEC / PLOT(0.03) / PLOT(200/(2*U*1000),250) / INVEC
INVEC / PLOT(1.500000E-03,0.0) / PLOT((200/(2*U*1000))+1.500000E-03,250) / INVEC
GOSUB 1130 / REM RAMP ROUTINE
IF Z9=3 THEN GO TO 1040
IF Z9=5 THEN GO TO 1040

A1.2
1070 GOSUB 1870 / REM FIT ROUTINE
1080 MARK("");VF2(5*N1+3),J
1090 PRINT
D1,TAB(7);VF2(5*N1);TAB(22);VF2(5*N1+1);TAB(37);VF2(5*N1+2);TAB(52);VF2(5*N1+3);TAB(70);VF2(5*N1+
4);TAB(85);VF2(5*N1+100);V
1100 IF VF2(5*N1+3)>1.80000E-03 THEN 2260 / REM OUT OF PROG
1110 IF N7>U7 GO TO 2260
1120 GO TO 1040
1130 REM ** RAMP SUB-Routine **
1140 IF Z9=5 THEN Z9=2
1150 DIM S(3)
1160 ON Z9 GO TO 1180,1340,1500,1630
1170 REM
1180 REM RAMP STROKE UP ON LOAD WATCH (Z9-1)
1190 S3=S0 / REM S0 IS PRESENT STROKE POSITN
1200 t=n-0 / D0=0
1210 S=2 / S(o)-0 S(1)-F1 / S(2)=S9
1220 FG(1,S,1,7,4)
1230 FOR Z=0 TO 1000 / NEXT Z / REM WAIT
1240 N=N+1
1250 GOSUB 1760 / REM DACQ
1260 VF1(5*N)-N / VF1(5*N-1)-PS / VF1(5*N-2)-DS / VF1(5*N-4)-Z9
1270 IF N=1 THEN VF1(5*N-3)-PS / GO TO 1300
1280 PS=((P5+P4)/2)
1290 VF1(5*N)+VF1(5*N-2)*(P8)*(D5)-D7
1300 D7-D5 / P4-P5
1310 IF PS>P7 THEN 1740
1320 S9=S9+1 / GO TO 1200
1330 REM
1340 REM RAMP STROKE UP ON DELTA DISPL. WATCH (Z9-2)
1350 D9=D5+M7 / REM D9=DISPLACEMENT END LEVEL
1360 P0-0 / D0=0
1370 S=2 / S(o)-0 / S(1)-F1 / S(2)=S9
1380 FG(1,S,1,7,4)
1390 FOR Z=0 TO 1000 / NEXT Z / REM WAIT
1400 N=N+1
1410 GOSUB 1760 / REM TO DACQ
1420 PS=((P5+P4)/2)
1430 VF1(5*N)-N / VF1(5*N-1)-PS / VF1(5*N-2)-DS / VF1(5*N-3)-VF1(5*N-2)*(P8)*(D5)-D7
VF1(5*N-4)-Z9
1440 A3=VF1(5*N-3)
1450 D7-D5 / P4-P5
1460 N5=N / REM LAST READING NUMBER AT LOAD UP
1470 IF D9>D5 THEN 1740 / REM D9=NEW DISP LIMIT
1480 S9=S9+1 / GO TO 1360
1490 REM
1500 REM RAMP DOWN ON LOAD WATCH (Z9-3)
1510 N7=N7+1
1520 P9=.9*(P5) / D9=D5 / REM D9 IS DISP AT START OF UNLOAD
1530 P0-0 / D0=0
1540 S=2 / S(o)-0 / S(1)-F1 / S(2)=S9
1550 FG(1,S,1,7,4)
1560 FOR Z=0 TO 1000 / NEXT Z / REM WAIT
1570 N=N+1
1580 GOSUB 1760 / REM DACQ
1590 VF1(5*N)-N / VF1(5*N-1)-PS / VF1(5*N-2)-DS / VF1(5*N-3)-A3 / VF1(5*N-4)-Z9
1600 IF P5<P9 THEN 1740
1610 S9=S9-1:GO TO 1530
1620 REM
1630 REM RAMP UP TO PRIOR LEVEL ON DISP WATCH (Z9=4)
1640 P0=0:D0=0
1650 S2=S(0)=0:S(1)=F1:S(2)=S9
1660 FG(1,5,1,7,4)
1670 FOR Z=0 TO 1000:NEXT Z:REM WAIT
1680 N=N+1
1690 GOSUB 1760:REM DACQ
1710 IF D5>D9 THEN 1740
1720 S9=S9-1:GO TO 1640
1730 REM
1740 Z9-Z9-1 / REM RAMP SWITCH
1750 RETURN
1760 REM ** DACQ **
1770 DIM P(10),D(10)
1780 FOR Z=0 TO 10 / P(Z)=0 / D(Z)=0 / NEXT Z
1790 DACQ(3,P,0,10) / DACQ(3,D,1,10)
1800 START
1810 IF P<10 THEN 1810
1820 IF D<10 THEN 1820
1830 QUIT
1840 FOR Z=0 TO 9 / P0=P0+P(Z) / D0=D0+D(Z) / NEXT Z
1850 P5=P0/10 / D5=D0/10
1860 RETURN
1870 REM STRAIGHT LINE FIT
1880 X0=.074877 / X1=.0178943 / X2=-2.30639E-04
1890 X3=1.50663E-06 / X4=3.78693E-09
1900 K=LOG(R1*1.000000F+06) / REM SCALING FACTOR FOR VFI/P IN MW/KN
1910 REM SET SUMMATIONS TO ZERO
1920 E1=0 / E2=0 / E3=0 / E4=0 / E5=0 / E6=0 / F=0
1930 IF N1>-1 THEN 2000
1940 REM USING DATA FROM 1ST LOAD
1950 FOR C=INT(.5*N) TO INT(.5*N) STEP -1
1960 E1=E1+VFI(5*C+1) / E2=E2+VFI(5*C+2) / E3=E3+VFI(5*C+1)*VFI(5*C+2)
1970 E4=E4+VFI(5*C+2) 2
1980 F=F+1
1990 NEXT C / GO TO 2060
2000 REM USING DATA FROM 10% UNLOAD
2010 FOR C=(N5-5) TO N STEP +1
2020 E1=E1+VFI(5*C+1) / E2=E2+VFI(5*C+2) / E3=E3+VFI(5*C+1)*VFI(5*C+2)
2030 E4=E4+VFI(5*C+2) 2
2040 F=F+1
2050 NEXT C
2060 REM CALC OF SLOPE
2070 E5=(E3-((E1*E2)/F))/(E4-(E2+2)/F)
2080 V=(K*M*E)/E3 / REM NORM. COMPL.
2090 R=X0*X1*V+X2*V 2+X3*V 3+X4*V 4
2100 Y1=R*W
2110 IF N1>-2 THEN 2210
2120 VFI(3)=Y1
2130 IF N1>-1 THEN 2210
2140 VFI(0)=Y1 / REM ORIGINAL CRACK LENGTH
2150 REM CALC OF Y INTERCEPT

A1.4
2160 E6-E1/F-E5*E2/F
2170 REM D8 IS DISPL AFTER ALLOW FOR NONLINEAR EFFECTS
2180 D8--E6/E5
2190 REM PRELIM ESTIMATE OF AREA (ELASTIC)
2200 VF2(2)=(VF1(S*N+2)-D8)*VF1(S*N+1)/2
2210 N1-N1+1
2220 REM CALC OF J (KIN/M)
2230 J-Q*VF1(S*N+3)/(B*(W-Y1)*R0*R1*1000)
2240 VF2(S*N1)-N / VF2(S*N1+1)-VF1(S*N+3)/(R0*R1) / VF2(S*N1+2)-R / VF2(S*N1+3)-Y1-VF2(S)
VF2(S*N1+4)-J
2250 RETURN
2260 DUMP / MSWPG(1,2)
2270 COPY
2280 ERASE / PRINT "END OF TEST ...PROGRAM BY T.V. ROSE AND D.S. SAUNDERS, 1984"
2290 CLOSE / STOP / END
100 REM ...AUSTRALIAN GOVERNMENT DEFENCE SCIENTIFIC AND RESEARCH ORGANIZATION
110 REM ...MATERIALS RESEARCH LABORATORIES
120 REM JRERUN... THIS PROGRAM WILL RE-RUN THE JTEST DATA
130 ERASE
140 PRINT "+++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++

150 PRINT "JRERUN. A PROGRAM TO RE-RUN THE J TEST USING THE DATA FILES"
160 PRINT "FROM THE PDP11 ...EDIT LINES 1650-1740 TO CHANGE"
170 PRINT "THE COMPLIANCE CALIBRATION FOR THE MEASUREMENT OF CRACK"
180 PRINT "LENGTH FROM THE UNLOADS (Z9=3"
IN THE TEST DATA FILE)"
190 PRINT "+++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++

200 PRINT "<CR> TO CONTINUE " INPUT Z$
210 PRINT "+++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++

220 PRINT "SPECIMENS FOR WHICH UNLOADING COMPLIANCE CALS. ARE AVAILABLE"
230 PRINT "SPEC GEOMETRY";TAB(40)"TYPE"
240 PRINT "MRL J03...PAFEC 1984";TAB(40)"1"
250 PRINT "MRL J03...EXPA TAL CHP";TAB(40)"2"
270 PRINT "+++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++

280 PRINT "INPUT SPECIMEN TYPE " / INPUT Y
290 GOSUB 1650, 1700
300 PRINT N9
310 PRINT / PRINT
320 PRINT "WHAT IS THE OUTPUT DATA FILE NAME? VIZ NAME " / INPUT T$
330 OPEN 'DY1:'.T$. '.DAT' FOR INPUT AS FILE VF1(10000)
350 OPEN 'LS:.' FOR OUTPUT AS FILE #1
360 PRINT "HOW MANY READINGS IN THE FILE " / INPUT Q
370 PRINT "WHAT IS THE MERKLE-CORTEN COEF FOR THIS SPEC. " / INPUT M5
380 DIM P(40), L(40), A(40),
N(40)
390 DIM R5(40), QS(40), JS(40), US(40), JS(40)
400 DIM F5(40), VS(40), JS(40), TS(40)
410 Z9=2 / N7=0
420 PRINT VF1(2);"BITS/KN"
430 PRINT VF1(4);"BITS/MM"
440 PRINT "SPECIMEN DIMENSIONS SHOULD BE MEASURED WITH A MICROMETER"
450 PRINT "SPECIMEN THICKNESS (METERS) " / INPUT B
460 PRINT "SPECIMEN WIDTH (METERS) " / INPUT W
470 ERASE
480 PRINT "YOUNG'S MODULUS IS ";VF1(2);"PA"
490 M=VF1(2)
500 PRINT "DO YOU WISH TO CHANGE YOUNG'S MODULUS Y/N " / INPUT S$ 
510 IF S$="N" GO TO 540
520 PRINT "WHAT IS THE NEW VALUE,... IN GPA " / INPUT M
530 M=M*1.00000E+09
540 PRINT / PRINT
550 PRINT "CHECK OF VARIABLES"
570 PRINT "OK? <Y/N> " INPUT S$
580 IF S$<"Y" THEN GO TO 440

A1.6
590 N3=VF1(3)
600 N4=VF1(4)
610 K=N3/(N4*1.00000E-06)
620 FOR I=2 TO Q=1
630 Z=VF1(S*I-1)
640 IF Z=1 GO TO 680
650 IF Z=2 THEN N=0
660 IF Z=(Z9+1) THEN COSUB 880
670 IF Z=3 THEN COSUB 710
680 NEXT I
690 IF Z=3 THEN GO TO 880
700 GO TO 1290
710 REM DATA ACQUISITION
FROM PDP11 DATA FILE
720 IF N<0 THEN GO TO 760
730 PRINT
740 PRINT "UNLOADING COMPLIANCE DATA" / PRINT
750 PRINT "READING", "LOAD", "DISPL.", "AREA"
760 N6=VF1(S*I-5)
770 P=VF1(S*I-4)
780 L=VF1(S*I-3)
790 A=VF1(S*I-2)
800 P(N)=P
810 L(N)=L
820 A(N)=A
830 N(N)=N6
840 PRINT N(N),P/N3,L/N4,A/(N3*N4)
850 N=N+1
860 Z9=Z / N5=N
870 RETURN
880 PRINT / PRINT / PRINT
890 PRINT "UNLOADING COMPLIANCE RETURN"
900 REM SET SUMMATIONS TO ZERO
910 E1=0 / E2=0 / E3=0 / E4=0 / E5=0 / E6=0
920 E7=0 /
E8=0 / E9=0 / V1=0 / F=0
930 PRINT "MAX. NO OF UNLOADING POINTS IS:";N5
940 PRINT "HOW MANY TO BE DISCARDED" / INPUT O
950 IF (N5-O)<3 THEN PRINT "ERROR... NOT ENOUGH DATA POINTS!" / GO TO 940
960 FOR C=0 TO (N5-1)
970 E1=E1+P(C) / E2=E2+L(C) / E3=E3+P(C)*L(C)
980 E4=E4+L(C) / E5=E5+P(C) / E6=E6+P(C)
990 F=F+1
1000 NEXT C
1010 REM CALC OF SLOPE
1020 E8=E3-((E1+E2)/F) / E9=E4-((E2 2)/F)
1030 E5=E8/E9
1040 REM CALC OF CORR COEFF
1050 V1=E6-((E1 2)/F)
1060 E7=(E8 2)/(E9*V1)
1070 V=(K*W*B) / E5 REM NO
RM COMPLIANCE
1080 V5(N7)=V / C5(N7)=E7
1090 R-X0-X1*V-X2*V 2+X3*V 3+X4*V 4
1100 IF N7>1 GO TO 1120
1110 Y1=R*W / Y0=Y1 / GO TO 1130

A1.7
1120 Y1=R*W
1130 PRINT "CHECK OF UNLOADING POINTS \";F;\" SHOULD BE \";N5-O
1140 PRINT "CRACKLENGTH \";Y1;\" METRES"
1150 PRINT "READING", "DATA POINTS", "NORM COMPL", "CORR COEFF", "AREA", "A/W", "DELTA A", "J VALUE
1160 J=M5*A(C)/(B*(W-Y1)*N3*N4*1000)
1170 U=N6-N5+1
1180 PRINT U,F,V,E7,A(C)/(N3*N4),R,Y1-Y0,J
1190 Z9-Z
1200 US(N7)=U / AS(N7)=A(C)/(N3*N4) / RS(N7)=R
1210 QS(N7)=Y1-Y0 / JS(N7)=J / FS(N7)=F / TS(N7)=N5
1220 PRINT "<CR> TO CONTINUE TO NEXT UNLOADING SET" / INPUT X5
1230 N7=N7+1
1240 IF I<=Q THEN GO TO 1280
1250 PRINT "LAST UNLOADING DATA SET"
1260 PRINT "<CR> TO CONTINUE...PRINT OUT ON LS:" / INPUT X5
1270 GO TO 1290
1280 RETURN
1290 CLOSE VFl
1300 PRINT #1,"*******;T5;*******;T5;*******;T5;*******
1310 PRINT #1 / PRINT #1
1320 PRINT #1,"SUMMARY OF UNLOADING COMPLIANCE CALCS"
1330 PRINT #1,"USING PDP11/04 DATA FILES AND RUN ON THE PDP11/04"
1340 PRINT #1,"FOR FILE ";T5
1350 PRINT #1 / PRINT #1
1360 PRINT #1,"YOUNG'S MODULUS FOR THESE CALCULATIONS \";M;\"PA"
1370 PRINT #1,"SPECIMEN THICKNESS \";B;\"METRES"
1380 PRINT #1,"SPECIMEN WIDTH \";W;\"METRES"
1390 PRINT #1 / PRINT #1
1400 PRINT #1,N3
1410 PRINT #1,"POLYNOMIAL FIT COEFFS"
1420 PRINT #1,"X0-\";X0;\" X1-\";X1;\" X2-\";X2
1430 PRINT #1,"X3-\";X3;\" X4-\";X4;\" X5-\";X5
1440 PRINT #1 / PRINT #1
1450 PRINT #1,"MEKKE-CERTEN COEFF- \";M5
1460 PRINT #1 / PRINT #1
1480 PRINT #1,"TOP OF UNL",TAB(14),"DATA POINTS";TAB(28),"USED"
1490 FOR N=0 TO N7-1
1500 PRINT #1,US(N),TS(N),FS(N),YS(N),CS(N),AS(N),RS(N),QS(N),JS(N)
1510 NEXT N
1520 PRINT #1 / PRINT #1
1540 GO TO 1800
1550 REM
1560 N5=\"JO3 CAL. FROM PAFEC 1984\"
1570 X0=-.0748577 / X1=-.0178943 / X2=-2.30639E-04
1580 X3=-1.50063E-06 / X4=-3.78693E-09
1590 RETURN
1700 REM
1710 N5=\"JO3 CAL. FROM CLARK EXPT DATA, 1983\"
1720 X0=-106976 / X1=-.0147547 / X2=-1.62423E-04
1730 X3=-8.73445E-07 / X4=-1.77957E-09
1740 RETURN
1750 REM
1800 PRINT #1,"END OF JERUN.BAS... PROGRAM BY D.S.SAUNDERS AND I.A.BURCH....1986"
1805 CLOSE
1810 END

A1.8
100 REM ... AUSTRALIAN GOVERNMENT DEFENCE SCIENTIFIC AND TECHNOLOGY ORGANIZATION
110 REM ... MATERIALS RESEARCH LABORATORIES
120 REM ACCESS PROGRAM TO ACCESS DATA IN THE * * * * .DAT FILE AND THE * * * * .GRA FILE FOR THE 10% UNLOAD J TEST
130 PRINT "WHAT IS THE DATA FILE NAME?" INPUT T$ */
140 OPEN 'DY: (*.T$*.DAT' FOR INPUT AS FILE VF1(30000)
150 OPEN 'LS: (*.T$*.PLT' FOR INPUT AS FILE VF2(500)
160 OPEN 'DY: (*.T$*.DAT' FOR OUTPUT AS FILE #1
170 PRINT 'TEXT REQUIRED? Y/N' INPUT Z$ */
180 IF Z$='N' GO TO 270
190 PRINT "THE DATA STORED IN THIS PDP/11 VIRTUAL FILE IS IN BINARY FORMAT*****
200 PRINT 'FILE';VF(0);' M'
210 PRINT 'MEASURE WIM';VF1(1);' M'
220 PRINT 'DO YOU REQUIRE A PRINTOUT FROM THE DATA FILE? (Y/N)'
230 PRINT 'DO YOU WANT TO ACCESS ALL THE DATA Y/N' / INPUT Z$ */
240 IF Z$='Y' GO TO 440
250 PRINT 'WHAT VALUE DO YOU WANT TO START AT?' / INPUT V
260 PRINT 'WHAT VALUE DO YOU WANT TO FINISH AT?' / INPUT W
270 GO TO 450
280 GO TO 440
290 PRINT 'THE DATA FILE IS STORED IN BITS'
300 PRINT 'DO YOU WANT THE DATA FROM (*.T$*.DAT) IN KN,MM AND MKM? (Y/N)'/ INPUT YS
310 IF YS='N' THEN 610
320 IF YS='Y' THEN 345
330 PRINT 'THE DATA FILE IS STORED IN BITS'
340 PRINT 'DO YOU WANT THE DATA FROM (*.T$*.DAT) IN KN,MM AND MKM? (Y/N)'/ INPUT YS
350 IF YS='N' THEN 610
360 IF YS='Y' THEN 345
370 PRINT 'THE DATA FILE IS STORED IN BITS'
380 PRINT 'DO YOU WANT THE DATA FROM (*.T$*.DAT) IN KN,MM AND MKM? (Y/N)'/ INPUT YS
390 IF YS='N' THEN 610
400 IF YS='Y' THEN 345
410 PRINT 'THE DATA FILE IS STORED IN BITS'
420 PRINT 'DO YOU WANT THE DATA FROM (*.T$*.DAT) IN KN,MM AND MKM? (Y/N)'/ INPUT YS
430 IF YS='N' THEN 610
440 IF YS='Y' THEN 345
450 PRINT 'THE DATA FILE IS STORED IN BITS'
460 PRINT 'DO YOU WANT THE DATA FROM (*.T$*.DAT) IN KN,MM AND MKM? (Y/N)'/ INPUT YS
470 IF YS='N' THEN 610
480 IF YS='Y' THEN 345
490 PRINT 'THE DATA FILE IS STORED IN BITS'
500 PRINT 'DO YOU WANT THE DATA FROM (*.T$*.DAT) IN KN,MM AND MKM? (Y/N)'/ INPUT YS
510 PRINT 'THE DATA FILE IS STORED IN BITS'
520 PRINT #1, TAB(3) "READING \#" ; TAB(23) "LOAD" ; TAB(37) "DISPL" ; TAB(50) "UNCORR. AREA" ; TAB(65) "SWITCH"
530 PRINT #1, TAB(25) "KN" ; TAB(39) "MM" ; TAB(56) "KN/M"
540 PRINT #1
550 FOR Z = V
560 TO W
570 IF VF1(5*Z) = 0 THEN 590
570 PRINT #1, TAB(7); VF1(5*Z); TAB(22); VF1(5*Z+1)/R0; TAB(35); VF1(5*Z+2)/R1; TAB(52); VF1(5*Z+3)/(R0*R1) ; VF1(5*Z+4)
580 NEXT Z
590 PRINT #1 / PRINT #1 / PRINT #1
600 GO TO 740
610 REM THIS PART PRINTS OUT DATA FROM THE JTEST.DAT VF
620 PRINT #1, TAB(18) "TEST DATA FOR THE 10% UNLOAD J INTEGRAL TEST"
630 PRINT #1, TAB(32) "DATA FOR \#5; TEST"
640 PRINT #1.
650 PRINT #1, TAB(5) "READING \#" ; TAB(20) "LOAD" ; TAB(35) "DISPL" ; TAB(50) "UNCORR. AREA" ; TAB(65) "SWITCH"
660 PRINT #1, TAB(20) "BITS" ; TAB(36) "BITS" ; TAB(52) "BITS" ; TAB(52) "BITS"
670 PRINT #1
680 FOR Z = V TO W
690 IF VF1(5*Z) = 0 THEN 740
700 PRINT #1, TAB(7); VF1(5*Z); TAB(22); VF1(5*Z+1); TAB(35); VF1(5*Z+2); TAB(52); VF1(5*Z+3); TAB(67); VF1(5
710 NEXT Z
720 PRINT #1 / PRINT #1 / PRINT #1 / PRINT #1
730 GO TO 840
740 REM THIS PART PRINTS OUT DATA FROM THE JTEST.GRA VF
750 PRINT "THIS PROGRAM WILL NOW ONLY PRINT OUT DATA FROM THE J CALCULATION FILE (VF2)"
760 PRINT #1, TAB(20) "INITIAL CRACK LENGTH FROM ELASTIC LOADING" ; VF2(0) ; "M"
770 PRINT #1, TAB(20) "ELASTIC LOAD LIMIT FOR THE TEST" ; VF2(1) ; "KN"
780 PRINT #1, TAB(20) "CRACK LENGTH CALCULATED FROM THE FIRST UNLOADING" ; VF2(3) ; "M"
790 IF VF2(5*Z) = 0 THEN 840
800 A1 = VF2(6) / A2
810 IF VF2(5*Z) = 0 THEN 840
820 IF VF2(5*Z) = 0 THEN 840
830 IF VF2(5*Z) = 0 THEN 840
840 IF VF2(5*Z) = 0 THEN 840
850 IF VF2(5*Z) = 0 THEN 840
860 PRINT #1.
870 PRINT #1, TAB(5) "READING \#" ; TAB(20) "AREA" ; TAB(37) "A/W" ; TAB(53) "DELTA" ; TAB(72) "J"
880 PRINT #1, TAB(52) "CRACK LENGTH"
890 PRINT #1, TAB(53) "MM" ; TAB(73) "METRES" ; TAB(71) "KN/M"
900 PRINT #1.
910 FOR Z = 1 TO 100
920 IF VF2(5*Z) = 0 THEN 940
930 PRINT #1, TAB(7); VF2(5*Z); TAB(18); VF2(5*Z+1); TAB(36); VF2(5*Z+2); TAB(30); VF2(5*Z+3); TAB(67); VF2(5
940 NEXT Z
950 CLOSE #1 / CLOSE #2
960 PRINT #1, "END OF ACCESS.BAS....PROGRAM BY D. S. SAUNDERS"
970 END
(b) Program listings for VAX 11/780 Computer

(1) V.BAS

100 REM ...AUSTRALIAN GOVERNMENT DEFENCE SCIENTIFIC AND TECHNOLOGY ORGANIZATION
110 REM ...MATERIALS RESEARCH LABORATORIES
120 REM PROGRAM TO READ BINARY FILE OF THE RT11 FORMAT
130 INPUT "INPUT FILENAME [SSSS.DAT;?] IS A PDP11 VIRTUAL FILE := ",FILENS
140 INPUT "OUTPUT FILE NAME [SSSS.OUT;?] := ",FILENAME2
150 MAP (A) REAL VT2(127)
160 OPEN FILENAME FOR INPUT AS FILE #1%, &
   VIRTUAL,
   RECORDSIZE 512%,
   MAP A
170 OPEN FILENAME2 FOR OUTPUT AS FILE #2%, RECORDSIZE 132%
180 K%=0%
190 FOR J%=1% TO 79%
200 FIND #1%, RECORD J%
210 GET #1%
220 FOR I=0 TO 127
230 K%=K%+1%
240 IF K%<5% THEN
   PRINT #2%,VT2(I),
   ELSE
   K%=0%
   PRINT #2%,VT2(I)
END IF
250 NEXT I
260 NEXT J%
270 PRINT "END OF V.BAS......PROGRAM BY D.WALKER 1984".
280 END
(2) JERERUN.BAS

* *

100 REM . . .AUSTRALIAN GOVERNMENT DEFENCE SCIENTIFIC AND TECHNOLOGY ORGANIZATION
110 REM . . .MATERIALS RESEARCH LABORATORIES
120 REM . . .THIS PROGRAM WILL RE-RUN A J TEST USING THE DATA FILES FROM THE PDP11
130 PRINT TAB(5);************
140 PRINT TAB(5);"JERERUN, A PROGRAM TO RE-RUN THE J TEST USING THE DATA FILES"
150 PRINT TAB(5);"FROM THE PDP11....EDIT LINES 1860-1960 TO CHANGE"
160 PRINT TAB(5);"THE COMPLIANCE CALIBRATION FOR THE MEASUREMENT OF CRACK"
170 PRINT TAB(5);"LENGTH FROM THE UNLOADS (Z9-3 IN THE TEST DATA FILE)"
180 PRINT TAB(5);************
190 INPUT "<CR> TO CONTINUE":X$  
200 PRINT TAB(5);************
210 PRINT TAB(5);"THE PROGRAM TAKES THE DATA FILE CREATED FROM THE PDP11/04"
220 PRINT TAB(5);"DISC. AS FILE name.OUT;#, AND READS EACH LINE TO DETERMINE"
230 PRINT TAB(5);"THE Z9 VALUE. WHEN Z9-3 DATA IS EXTRACTED FROM THE FILE AND"
240 PRINT TAB(5);"UNLOADING COMPLIANCE CALIBRATION IS USED TO MEASURE DELTA A"
250 PRINT TAB(5);"THE J VALUES ARE CALCULATED FROM THE DATA STORED IN THE FILE"
260 PRINT TAB(5);************
270 INPUT "<CR> TO CONTINUE":X$  
280 PRINT TAB(5);************
290 PRINT TAB(5);"SPECIMENS FOR WHICH UNLOADING COMPLIANCE CALS. ARE AVAILABLE"
300 PRINT TAB(5);"SPECIMEN GEOMETRY AND CALIBRATION":TAB(55);"TYPE"
310 PRINT TAB(5);"MRL J03 / PAPEC 1984":TAB(57);"1" / PRINT
320 PRINT TAB(5);"MRL J03 / EXPERIMENT":TAB(57);"2" / PRINT
330 PRINT TAB(5);************
340 INPUT "INPUT THE SPECIMEN TYPE ":TYPES / PRINT
350 IF TYPES<2 GOTO 430
360 PRINT "INVALID SPECIMEN TYPE "/ PRINT
370 GOTO 280
380 ON TYPES GOSUB 1860,1910
390 PRINT "POLYNOMIAL COEFFS FOR TYPE ":TYPES;" SPECIMEN"
400 PRINT NOTES:
410 PRINT "X0- ";X0 / PRINT "X1- ";X1 / PRINT "X2- ";X2
420 PRINT "X3- ";X3 / PRINT "X4- ";X4 / PRINT
430 INPUT "IS THIS CALIBRATION THE ONE REQUIRED? Y/N ";A$  
440 IF A$<"N" GOTO 280
450 IF A$="N" GOTO 280
460 PRINT / PRINT
470 PRINT ******************* STARTING TO RERUN THE DATA *******************
480 PRINT / PRINT
490 MAP (A) STRING NN = 132%
500 INPUT "IS THE OUTPUT DATA FILE NAME, VIZ name ":T$  
510 OPEN T$".OUT" FOR INPUT AS FILE #1% SEQUENTIAL,RECORDTYPE ANY & RECORDSIZE 132%, MAP A
520 INPUT "HOW MANY READINGS IN THE FILE":Q%  
530 INPUT "WHAT IS THE MERKLE-CORTEN COEFF FOR THIS SPECIMEN ";MCC
540 DIM P(50%),L(50%),A(50%),N(50%)  
550 DIM R$5(50%),DAS5(50%),AS5(50%),US5(50%),JS5(50%)  
560 DIM S5(50%),VS5(50%),CS5(50%)  
570 DIM Z9(2%),N7(-2%)
580 DIM %5(2%),S5(80%),X5(80%),A5(80%),N5(80%)
590 DIM Z9(2%),N7(80%)
600 DIM Z9(2%),N7(80%),CS5(50%)  
610 Z9(-2%)/ N7(0%)
620 GET ¥%
630 SNS;SEG5(NN,43,51)
640 PRINT SNS;" BITS/KN"
650 RNS;SEG5(NN,57,61)
660 PRINT RNS;" BITS/Km"
670 TNNS-SEGS(NN,1,13)
680 TNNS-TRMS(TNNS)
690 PRINT "SPECIMEN THICKNESS AND WIDTH SHOULD BE MEASURED WITH A MICROMETER."
700 INPUT "SPECIMEN THICKNESS (METRES)";B
710 UNS-SEGS(NN,14,19)
720 INPUT "SPECIMEN WIDTH (METRES)";W
730 VNS-SEGS(NN,28,37)
740 PRINT "YOUNG'S MODULUS=";VNS;"Pa"
750 M=VAL(VNS)
760 INPUT "DO YOU WISH TO CHANGE YOUNG'S MODULUS, Y/N ";SS
770 IF SS="N" GO TO 800
780 INPUT "WHAT IS THE NEW YOUNG'S MODULUS, ... IN GPa ";M
790 M=M*1E+09
800 PRINT B,W,M
810 N3-VAL(SNS)
820 N4%=-VAL(SNS)
830 K=N3/(N4%*1.0E+06)
840 FOR 1%-1% TO 9%
850 GET 01%
860 SNS-SEGS(NN,58,58)
870 Z%-VAL(SNS)
880 IF Z%<1% GO TO 920
890 IF Z%<2% THEN N%-0%
900 IF Z%<(29%-1%) THEN GOSUB 1200
910 IF Z%<3% THEN GOSUB 950
920 NEXT 1%
930 IF Z%<3% THEN GOTO 1200
940 GO TO 1620
950 REM DATA ACQUISITION FROM PDP11 DATA FILE VFI
960 IF N%-0% THEN GOTO 1000
970 PRINT PRINT PRINT
980 PRINT "UNLOADING COMPLIANCE DATA" PRINT
990 PRINT "READING","LOAD","DISPL."","AREA"
1000 N1S-SEGS(NN,1,5)
1010 N2S-TRMS(N1S)
1020 N6%-VAL(N2S)
1030 P1S-SEGS(NN,10,23)
1040 P2S-TRMS(P1S)
1050 P=VAL(P2S)
1060 L1S-SEGS(NN,23,35)
1070 L2S-TRMS(L1S)
1080 L=VAL(L2S)
1090 A1S-SEGS(NN,38,53)
1100 A2S-TRMS(A1S)
1110 A=VAL(A2S)
1120 P(N%-)=P
1130 L(N%-)=L
1140 A(N%-)=A
1150 N(N%-)=N6%
1160 PRINT N(N%),P/N3,L/N4%,A/(N3*N4%)
1170 N%-N%-1%
1180 Z9%-Z%/ N5%-N%
1190 RETURN
1200 PRINT / PRINT / PRINT
1210 PRINT "UNLOADING COMPLIANCE RERUN"
1220 REM SETTING SUMMATIONS TO ZERO
A1.13
1230 E1=0 / E2=0 / E3=0 / E4=0 / E5=0 / E6=0
1240 E7=0 / E8=0 / E9=0 / E10=0 / P%=0
1250 PRINT "MAX. NO. OF UNLOADING POINTS IS ";N5%
1260 INPUT "HOW MANY OFF THE MAX. LOAD ARE TO BE DISCARDED ";N%
1270 IF O%>(N%-10%) THEN PRINT "ERROR IN INPUT, TRY AGAIN" / GOTO 1250
1280 IF O%=0 THEN PRINT "DISCARD OF ZERO POINTS IS OK? <Y/N > / INPUT Z$ IF Z$<"Y" GOTO 1290
1290 FOR C%=0% TO (N%-1)% STEP 1%
1300 E1= E1+P(C%) / E2=E2+L(C%) / E3=E3+P(C%)*L(C%)
1310 E4=E4+L(C%) 2% / E6=E6+P(C%) 2%
1320 P%=P%+1%
1330 NEXT C%
1340 REM CALCULATION OF SLOPE
1350 E8=E8-((E1*E2)/P%) / E9=E4-((E2 2%)/F )
1360 ES=ES/E9
1370 REM CALCULATION OF CORRELATION COEF.
1380 E10=E6-((E1 2%)/F%)
1390 E7=(ES 2)/(E9*E10)
1400 V=(K*M*B)/E5 / REM NORMALIZED COMPLIANCE
1410 V5(N7%)=V / CS(N7%)=E7
1420 R=O*O*O"V=O*O*O"V 2%*O*O"V 3%*O*O"V 4%
1430 IF N7%>1% GOTO 1450
1440 Y1=R"W / Y0=Y1 / GOTO 1460
1450 Y1=R"W
1460 PRINT "CHECK OF NO. OF UNLOADING POINTS ":P%;" SHOULD BE ";N5%-N%
1470 PRINT "CRACK LENGTH- ";Y1;" METRES"
1480 PRINT "READING", "DATA POINTS", "NORM. COMPL.", "CORR. COEF.", "AREA", "A/W", "DELTA A", "J"
1490 J-MC"A(C%)/(B*(W-Y1)*N3%N4%)1000)
1500 UN-N6%-N5%+1%
1510 PRINT UN,P%,V,E7,A(C%)/(N3%N4%) R,Y1-Y0,J
1520 25%-2%
1530 US(N7%)=U% / AS(N7%)=A(C%)/(N3%N4%) / RS(N7%)=R
1540 DAS(N7%)=Y1-Y0 / JS(N7%)=J / FS(N7%)=P%
1550 INPUT <CR> TO PROCEED TO NEXT UNLOADING SET ";X3
1560 N7%-N7%+1%
1570 IF 1%<2% THEN GOTO 1610
1580 PRINT "LAST UNLOADING DATA SET"
1590 INPUT "SET PRINTER AND <CR> FOR PRINT OUT OF UNLOADING COMPLIANCE CALCS";X3
1600 GOTO 1620
1610 RETURN
1620 CLOSE #1%
1630 PRINT / PRINT / PRINT
1640 PRINT "SUMMARY OF UNLOADING COMPLIANCE CALCULATIONS"
1650 PRINT "RUN USING JERIN.BAS ON THE VAX11/780"
1660 PRINT "USING PDP11/04 DATA FILE ";T5;" (RUN THROUGH V.BAS)"
1670 PRINT
1680 PRINT "YOUNG'S MODULUS FOR THESE CALCULATIONS ";M;"Pa"
1690 PRINT "SPECIMEN THICKNESS-";B;"metres"
1700 PRINT "SPECIMEN WIDTH ";W;"metres" / PRINT
1710 PRINT NOTES
1720 PRINT "POLYNOMIAL FIT COEFFS"
1730 PRINT "X0- ";X0; "X1- ";X1; "X2- ";X2
1740 PRINT "X3- ";X3; "X4- ";X4
1750 PRINT
1760 PRINT "MORLE-CORTI COEFF- ";MCC
1770 PRINT / PRINT
1790 FOR N%-0% TO N%-1%
1800 PRINT US(N%),FS(N%),VS(N%),CS(N%),AS(N%),RS(N%),DS(N%),JS(N%)
1810 NEXT N%
1820 PRINT / PRINT
1830 PRINT "THIS FILE WILL BE STORED AS ";TS;".DAT"
1840 PRINT "RUN JPRINT TO RETRIEVE THIS FILE"
1850 GOTO 2110
1860 REM COMPLIANCE CALIBRATIONS (POLYNOMIAL FITS)
1870 NOTES="J03 CAL. FROM PAFEC 1984"
1880 X0=-7.48577272E-02 / X1=1.7894292E-02 / X2=-2.3063905E-04
1890 X3=1.506292E-06 / X4=-3.7869343E-09
1900 RETURN
1910 REM
1920 NOTES="J03 CAL. FROM CLARK EXPT. DATA"
1930 X0=1.0697574E-01 / X1=1.4754694E-02 / X2=-1.6242350E-04
1940 X3=8.7544527E-07 / X4=-1.7795666E-09
1950 RETURN
1960 REM
2110 REM PROGRAM TO WRITE A SUMMARY OF THE JRIJN CALCULATIONS AS A FILE name.DAT
2120 OPEN TS=".DAT" FOR OUTPUT AS FILE #2%, ORGANIZATION SEQUENTIAL, RECORDTYPE ANY
2130 PRINT #2%, TS
2140 PRINT #2%, M
2150 PRINT #2%, B
2160 PRINT #2%, W
2170 PRINT #2%, NOTES
2180 PRINT #2%, X0 / PRINT #2%, X1 / PRINT #2%, X2 / PRINT #2%, X3 / PRINT #2%, X4
2190 PRINT #2%, MCC
2200 N%=N%-1%
2210 PRINT #2%, N%
2220 FOR N%-0% TO N%
2230 PRINT #2%, US(N%)
2240 PRINT #2%, FS(N%)
2250 PRINT #2%, VS(N%)
2260 PRINT #2%, CS(N%)
2270 PRINT #2%, AS(N%)
2280 PRINT #2%, RS(N%)
2290 PRINT #2%, DS(N%)
2300 PRINT #2%, JS(N%)
2310 NEXT N%
2320 CLOSE #2%
2330 PRINT / PRINT
2340 PRINT "END OF JRIJN.BAS.........program by D.S.Saunders and I.A.Burch 1985"
2350 END
REM AUSTRALIAN GOVERNMENT DEFENCE SCIENTIFIC AND TECHNOLOGY ORGANIZATION
110 REM MATERIALS RESEARCH LABORATORIES
120 REM THIS PROGRAM WILL ACCESS OUTPUT FILES FOR TEST DATA FOR THE VAX 11/780
130 PRINT TAB(5);"ACCESS1, A PROGRAM TO CONVERT A JJ INTEGRAL TEST DATA FILE"
140 PRINT TAB(5);"INTO A PLOTTING DATA FILE FOR USE WITH THE KENNETT PLOT ROUTINE"
150 PRINT TAB(5);"THE PROGRAM TAKES THE DATA FILE CREATED FROM THE PDP11/04"
160 PRINT TAB(5);"DISK, AS FILE $$$$., AND WRITES A NEW FILE (FORCE/DISPL.)"
170 PRINT TAB(5);"THE PROGRAM WILL RECORD THE VAX DATA FILE FROM WHICH $$$$., IS CREATED"
180 PRINT TAB(5);"THE PROGRAM WILL ACCESS OUTPUT FILES FOR TEST DATA FOR THE VAX 11/780"
190 PRINT TAB(5);"WHAT IS THE OUTPUT FILE NAME, VIZ $$$$., AND WRITE A NEW FILE (FORCE/DISPL.)"
200 PRINT TAB(5);"WHAT IS THE PLOTTING FILE NAME, VIZ $$$$., "NAME THIS FILE $$$$.,"
210 PRINT TAB(5);"WHAT IS THE FIRST READING NUMBER YOU WANT TO ACCESS";P
220 PRINT TAB(5);"WHAT IS THE LAST READING NUMBER YOU WANT TO ACCESS";Q
230 GET @1%
240 SNS=SEG$(NN,43,51)
250 PRINT SNS
260 RNS=SEG$(NN,57,61)
270 PRINT RNS
280 N3=VAL(SNS)
290 N4=VAL(RNS)
300 PRINT TAB(20);"SELECTED FORCE/DISPLACEMENT DATA FROM";TS
310 PRINT TAB(20);"WRITTEN INTO PLOTTING FILE ";S$
320 PRINT TAB(20);"SCALING CONSTANTS FOR THE TEST"
330 PRINT TAB(20);"FOR LOAD, RO=",N3;TAB(50);"BITS/KN"
340 PRINT TAB(20);"FOR DISPL, RL=",N4;TAB(50);"BITS/MM"
350 PRINT / PRINT
360 PRINT #2%,DISPLACEMENT IN MM
370 PRINT #2%,1%;
380 PRINT #2%,-DATA FROM ORIGINAL ON PDP11/04 DISK AS "US;..DAT"
390 PRINT TAB(5);"READINGS NO";P%;" TO ";Q%;" INCLUSIVE"
400 PRINT / PRINT
410 B% = ((Q%-P%)+1)
420 PRINT #2%,"PLOTTING DATA FROM";TS;"READING NO: P% TO Q%; INCL" FOR 1% TO 2000%
430 GET @1%
440 NNWS=RIGHT$(NN,7)
450 N1S=LEFT$(NNWS,17)
460 N2S=SEG$(NNWS,18,33)
470 N1=VAL(N1S)
480 N2=VAL(N2S)
490 IF 1%<P% THEN 640
500 IF 1%>Q% THEN 650
510 IF 1%<P% THEN 640
520 IF 1%>Q% THEN 650
620 PRINT N2/N4%,N1/N3
630 PRINT #2%.N2/N4%;"",";N1/N3
640 NEXT 1%
650 CLOSE #1% / CLOSE #2%
660 PRINT "END OF ACCESS.BAS......Program by D.S.Saunders" 
670 END
APPENDIX 2

Listings of Elastic Unloading Compliance for a Range of Specimen Geometries

(A) MRL J03 (Compact Tension Specimen)

(1) PAFEC – generated (1984) [1]

<table>
<thead>
<tr>
<th>$E_B$</th>
<th>$V_{LL}/P$</th>
<th>$a/W$</th>
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<tbody>
<tr>
<td>18.0958</td>
<td>0.3</td>
<td></td>
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<tr>
<td>19.0547</td>
<td>0.32</td>
<td></td>
</tr>
<tr>
<td>20.3028</td>
<td>0.34</td>
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<tr>
<td>21.7481</td>
<td>0.36</td>
<td></td>
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<tr>
<td>22.563</td>
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<td>25.4099</td>
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<td>27.4611</td>
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<tr>
<td>29.7407</td>
<td>0.44</td>
<td></td>
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<tr>
<td>32.4349</td>
<td>0.46</td>
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<tr>
<td>35.3034</td>
<td>0.48</td>
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<td>38.5184</td>
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<tr>
<td>42.1361</td>
<td>0.52</td>
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<td>46.2305</td>
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<td>50.2362</td>
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<td>62.4079</td>
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<td>69.5932</td>
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<td>78.0284</td>
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<td>88.0301</td>
<td>0.66</td>
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<td>100.013</td>
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<td>113.907</td>
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<td>131.604</td>
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<td>153.631</td>
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<td>181.487</td>
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<td>217.361</td>
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<tr>
<td>264.575</td>
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(2) PAFEC-generated (1985) [2], Point Pin Loading

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<th>$E_B$</th>
<th>$V_{LL}/P$</th>
<th>$a/W$</th>
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<tbody>
<tr>
<td>22.76</td>
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</tr>
<tr>
<td>26.62</td>
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<tr>
<td>31.39</td>
<td>0.44</td>
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<tr>
<td>37.34</td>
<td>0.48</td>
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</table>
The second PAFEC-generated compliance calibration is now considered to be more accurate than (1), above. For this calibration the original mesh was modified slightly and the normalised compliance data is close to the experimental data given in (31) and reproduced below.

(ASTM E 399 (Compact Tension Specimen), [4], [5])

V

VLL

EB

a/W.

P

24.78

0.378

26.64

0.393

29.58

0.419

40.76

0.493

41.6

0.495

41.65

0.497

40.58

0.498

41.63

0.498

42.76

0.507

44.5

0.517

53.41

0.544

55.15

0.561

57.75

0.565

59.43

0.567

90.6

0.644

110.3

0.670

154.0

0.722

167.0

0.735

209.0

0.763

212.1

0.764

215.9

0.767

225.7

0.768

224.9

0.773

242.5

0.778

251.9

0.784

278.0

0.793

(B) ASTM E 399 (Compact Tension Specimen), [4], [5]
22.86 0.40
28.96 0.45
36.99 0.50
47.90 0.55
63.35 0.60
86.36 0.65
122.80 0.70
185.40 0.75
304.6 0.80
578.36 0.85
1389.07 0.90
5952.20 0.95

References


<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Notes</th>
</tr>
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<tr>
<td>A1</td>
<td>Area</td>
<td>This is the area under the linear-elastic part of the load/load-line-displacement record and is calculated as the area of the P/D triangle to P7.</td>
</tr>
<tr>
<td>A3</td>
<td>Area</td>
<td>This area is continuously updated for each displacement increment, viz Z9=1, Z9=2, but not when Z9=3 or Z9=4. A3 at the final load increment before the unload is written into the virtual files VFl, VF2. A3 is not increased again until Z9 returns to a value of 2.</td>
</tr>
<tr>
<td>E5</td>
<td>Raw compliance</td>
<td>This value from the linear regression of the unloading data.</td>
</tr>
<tr>
<td>V</td>
<td>Normalized compliance</td>
<td>$E5 \times E \times B \times P \times \frac{R_T}{R_O}$</td>
</tr>
<tr>
<td>R</td>
<td>a/W</td>
<td>This value is calculated from the unloading compliance calibration polynomial ($f(v)$).</td>
</tr>
<tr>
<td>Y1</td>
<td>Crack length</td>
<td>$R \times W$</td>
</tr>
<tr>
<td>D5</td>
<td>Displacement (bits)</td>
<td>Average of 10 values</td>
</tr>
<tr>
<td>P5</td>
<td>Load (bits)</td>
<td>Average of 10 values</td>
</tr>
<tr>
<td>D9</td>
<td>Displacement (bits)</td>
<td>Displacement at the commencement of unloading.</td>
</tr>
</tbody>
</table>

(1) See listing 3
END
11-87
DTIC