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A Computer Program for the Interpolation and Extrapolation of Crack Propagation Data

by

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A COMPUTER PROGRAM FOR THE INTERPOLATION AND EXTRAPOLATION OF CRACK PROPAGATION DATA

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SUMMARY

A computer program has been written which extracts crack propagation rates from crack rate data, given mean and alternating stress intensity factors. Data required is a set of between 1 and 11 curves of crack rate against alternating stress intensity factor for a range of values of 'stress' ratio. The program then interpolates between the specified data points or extrapolates outside them in order to calculate the crack rate. An empirical correction for sheet thickness is included.

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CONTENTS

1 INTRODUCTION

This paper describes a computer program which extracts crack propagation rates from a set of crack propagation curves, given mean and alternating stress intensity factors.

Crack propagation rates in a wide range of materials are dependent upon mean stress intensity factor as well as on alternating stress intensity factor. When calculating crack rates for design purposes the most accurate method of taking both these factors into account is to read values from appropriate data sheets, e.g. from ESDU[1]. However this can be a tedious and time-consuming process where a large number of crack rate values are required. Additionally, where the crack rate values are to be processed by computer it is desirable that the computer be used to extract the rate values also. For both these reasons widespread use is made of empirical equations giving a best fit to crack propagation data. A number of equations of this type have been proposed, for instance those given in Refs.2 to 5, the most well-known and widely used being that of Forman, Kearney and Engles[2]

$$\frac{da}{dN} = \frac{C(\Delta K)^m}{[(1 - R)K_c - \Delta K]} \qquad (1)$$

where the constants C and m are selected to give a best fit to the crack propagation data for the material under consideration.

However, this equation is not suitable for predicting crack propagation rates at stress intensity factors close to the threshold of crack propagation, and does not in fact predict any low level threshold at all. Whilst other equations have been developed to take this particular limitation into account, for instance those of Hartman and Schijve[4] and Rice *et al.*[5], the fact remains that such equations are empirical and only give a 'best fit' to crack propagation data. Bearing in mind the considerable range of shapes of crack propagation curves in published data sheets, the use of such equations is likely to give significant errors for some situations. The design engineer however requires a tool that can be used with confidence and he is not likely to want to spend time checking whether or not the equation he is using is reliable in his particular situation.

The computer program described in this paper was written with the above requirement in mind. The program uses crack propagation data effectively for a range of values of mean and alternating stress intensity factor (in practice a set of curves for alternating stress intensity factor against crack rate, each curve being at a constant value of 'stress' ratio R). As described here it demands teletype input of mean and alternating stress intensity factors together with the fracture toughness value K_c for the thickness of material in question. The program then interpolates between the specified data points or extrapolates outside them in order to calculate the crack rate. In this way it is felt that the rates calculated are only limited in accuracy to any extent by the reliability and scope of the crack propagation data. An empirical correction for plate thickness is included which ensures that crack rates tend to infinity as K_c is approached.

Program listings are given in FORTRAN II and BASIC so that the program can be implemented on a wide range of computers and minicomputers with little modification. The operation of the program is demonstrated with sample data for a 4% copper-aluminium alloy.

2 FORM OF CRACK RATE DATA REQUIRED

An example of the form of rate data required is plotted in Fig.1 and the corresponding data tape is shown in Fig.2. As can be seen from Fig.1 it consists of a set of curves of alternating stress intensity factor against crack rate for a number of values of $K_{min}/K_{max} = R$. The data for crack rates above 2×10^{-5} mm/cycle was taken from work by Maddox[6] on BSL71 aluminium alloy. Below this crack rate the curves were extrapolated down to the assumed crack growth thresholds which were obtained by Frost, Pook and Denton[7] for the similar BSL65 aluminium alloy.

Alternating stress intensity factor was defined in the data and program as the semi-range value $K_a = \Delta K/2$. This was chosen instead of ΔK because it was felt to be slightly more convenient when using the program to calculate rates under random loading. The form of the stress intensity factor assumed in the data was $K = \sigma\sqrt{\pi a}$ for cracks in an infinite sheet.

In Fig.1, each symbol on the data curves corresponding to different values of R represents a data point defined in Fig.2. Data points were chosen to give a good representation of the crack rate data. This was assessed by joining adjacent points at the same R values using straight lines on a plot of log rate against log K_a (Fig.1), as assumed by the program. In the program as written the data are subject to the following conditions:

(a) the number of curves at constant R must be between 1 and 11. The maximum number of curves can be increased relatively easily (see section 4.3);

(b) the number of data points for each curve must be between 2 and 10. The maximum number of points per curve can also be increased relatively easily (see section 4.3);

(c) the rate values for the first points on each curve must be the same (e.g. 10^{-7}mm/cycle in Fig.1). The same applies to the last points. However, the intermediate points have no such restriction, and the number of points on each curve can be different;

(d) no two consecutive points on any curve can have identical values for alternating stress intensity since the program has to calculate slopes of lines joining adjacent points, and this would give a value of infinity. However, the values can be made as close as makes no difference in practice;

(e) no crack rate should ever be exactly unity since the log of this is zero, which is used as a flag in the program (see section 3.1).

Fig.2 shows the data tape corresponding to Fig.1. This can be used for both the FORTRAN and BASIC programs (NB most BASIC languages require commas between data values on the same line). The first value on the tape is the fracture toughness value for the data. Next is the lowest value of R in the data followed by the list of data points for that R value. Each point is defined by alternating stress intensity factor and rate values, and the data points are in ascending order of alternating stress intensity factor. The list of data points is terminated by a dummy data point having a negative value for alternating stress intensity factor. Then comes the next highest value of R, and so on. The data tape is terminated by any invalid value for R, i.e. greater than unity.

3 DESCRIPTION OF PROGRAM

The program was developed on a PDP 8E minicomputer in both FORTRAN II and BASIC using the OS 8 operating system. Flow charts for the program and explanatory diagrams are given in Figs.3 to 9 and listings are given in the Appendices. To facilitate comparison between the two versions of the program all the reference labels in the FORTRAN program are the same as those in the BASIC program, where the lines are equivalent. There is, in fact, a one to one correspondence of lines over the greater part of the two versions. The flow charts for both versions of the program are therefore virtually identical, except that the FORTRAN version uses mnemonic names for some variables and arrays, and whereas the FORTRAN arrays start from index 1, the BASIC arrays start from index 0 . Table 1 lists the names used for all variables and arrays in both programs. The flow charts, the text and the explanatory diagrams refer to the FORTRAN version, but BASIC line numbers are also included where appropriate.

3.1 Main segment

The main segment (Fig.3), first reads the rate data and then goes into a loop reading values of mean and alternating stress intensity factor, and current fracture toughness value CKC , after which the corresponding rate is calculated. If the current fracture toughness value CKC is greater than that associated with the value DKC associated with the rate data, CKC is set equal to DKC (see section 3.5).

Fig.4 shows the layout of the rate data for L65/L71 (see Figs.1 and 2) after being read in. In later parts of the program the number of data points in any curve at constant R is detected by looking in the AK array for the zero value which is in the store above the highest value of AK at the R value in question. For this reason the AK array has one more column than the CR array so as to accommodate the zero 'flag' when any row is full (10 data points).

3.2 Function 'CRATE':- Calculation of effective alternating stress intensity and R values and sort out into regions

In function CRATE the rate calculation is carried out assuming first that the data and current K_c values, DKC and CKC values, are equal. This part of the calculation follows one of three paths depending upon whether the value of R for which the calculation is required is less than the lowest defined value of R in the rate data (region A), higher than the highest defined value of R in the rate data (region B) or somewhere within the defined range of values of R (region C). Fig.1 shows the three regions for the data tabulated in Fig.2. If the calculated rate before the adjustment for K_c is higher than the highest defined rate in the data, the regions are given the suffix 1, i.e. A_1, B_1, C_1.

Flow chart 1 for CRATE (Fig.5) shows the sort out into the various regions. The mean and alternating stress intensity factors STK and ALK are used to find the curve or pair of curves from which the calculation is to be made. This culminates in a value of J which is the index of one of the data curves. Effective values of R and log of alternating stress intensity factor, ER and EK are also calculated. These are the values used subsequently in the rate prediction for the three regions. They are calculated from STK and ALK and are modified or not depending upon the assumptions made in the different regions. A more detailed description follows.

First STK and ALK are checked for magnitudes which would give error conditions or erroneous values of rate (lines 530 to 550) and appropriate values of crack rate are returned if such conditions are found (CRATE = 1E10 corresponds to specimen broken). The first value of ER is then calculated and is the value calculated directly from the input STK and ALK with no modification. If ER is less than the lowest value of R in the data then the required prediction is in region A (line 580).

For region A it is assumed that the peak value of stress intensity factor is as input to the computer (i.e. STK + ALK) but that ER is equal to R(1) the lowest value of R defined in the data. J is therefore set to 1 and EK is calculated from equation 2 below:

$$EK = \log \left[\left(\frac{STK + ALK}{2}\right)(1 - R(1))\right] \qquad (2)$$

which gives the log alternating stress intensity factor corresponding to a peak stress intensity factor of STK + ALK and a value of R equal to R(1) . The rate is then predicted from the data curve corresponding to R = R(1) as described in section 3.3. The effect of this is to ignore the part of the cycle which is more compressive than that at the lowest defined value of R for the same peak stress intensity factor, i.e. the assumption is made that the crack is closed for this part of the cycle. For instance, if the lowest defined value of R in the data were zero, and a rate were required for STK = 0 (R = -1) then the prediction would be made from the R = 0 curve for an alternating stress intensity factor of ALK/2 .

At line 780 a check is made as to whether ER is greater than the highest value of R defined in the data, R(JMR) . If this is so then the prediction is required for region B. In this case the prediction is as for region A except that the alternating stress intensity factor used is the same as that input to the computer, ALK, and

$$EK = \log (ALK) \quad . \qquad (3)$$

Prediction for region B is carried out as described in section 3.3 for ER = R(JMR) , (J = JMR) . This effectively ignores the mean stress effect for

R values greater than R(JMR) . However, the adjustment for K_c (section 3.5) subsequently makes some allowance for this.

If the calculation is not required for regions A and B only region C remains. Equation 3 applies for this region also. Lines 830 to 850 find the index J corresponding to the defined value of R immediately above ER , after which region C calculation as described in section 3.4 is carried out.

On exit from this part of the program EP is the peak stress intensity factor assumed by the predictions, as described in sections 3.3 and 3.4. For region B this is less than STK + ALK , and is equal to this value for regions A and C. EP is required by the routine which adjusts for K_c (section 3.5).

Table 2 gives examples of predictions for the various regions together with the corresponding values of ER , EP and EXP(EK) .

3.3 Function CRATE:- Calculation of log rate from single curve (regions A and B)

The calculation of log rate from a single curve is shown in flow chart form in Fig.6 and diagrammatically in Fig.7. The inputs required for this routine are values of EK and ER , the effective log alternating stress intensity factor and R value respectively, together with a value for J , the index defining the particular curve required. If the rate is not zero the routine returns a value of Z , the log rate before adjustment for K_c . If the rate is zero the routine returns a value of zero for crack rate (CRATE) directly and the adjustment for K_c is by-passed. For regions A and B the routine calculates rate assuming that the defined data points are joined by straight lines on a log-log plot. For regions A_1, B_1 the log rate is calculated on a curve which starts at the boundary between the upper and lower regions with a slope equal to that of the last linear section of the lower region. The curve then becomes vertical at the point where the maximum value of stress intensity factor is equal to DKC , the K_c value associated with the crack rate data. A more detailed description follows.

At line 620 a check is made of whether EK is below the threshold value of alternating stress intensity, in which case the function returns a zero value for rate. Over lines 630 to 660 the data-defined value of AK immediately above EK is found and index K set to the corresponding value. If EK is above the highest value of AK , K is set for the highest value of AK . TK , the difference between EK and the value of AK returned above is then calculated at line 670. TK is negative for regions A, B and positive for regions A_1, B_1. A first value of Z is calculated at line 680 by similar triangles as the log rate value corresponding to EK on a straight line joining the points above and below EK . This is the final value required for regions A, B. For regions A_1, B_1 this first value of Z corresponds to the intercept of EK with a line extrapolated from the last linear section of the data curve (see Fig.7). By looking at the sign of TK , line 690 decides whether or not the prediction is in regions A_1, B_1. If it is ΔZ is added to Z at line 700 where

$$\Delta Z = \frac{TK^2}{\log\left[\frac{DKC(1 - ER)}{2} - EK + TK\right]^2 - TK^2} \quad . \qquad (4)$$

This is a purely empirical expression which has a slope of zero at TK = 0 and which is infinite where the maximum stress intensity factor is equal to DKC. Its purpose is to give a reasonable extrapolation beyond the end of crack propagation curves in regions where there are no data.

3.4 Function CRATE:- Calculation of log rate in region C

The calculation of log rate for region C is flow charted in Fig.8 and shown diagrammatically in Fig.9. The inputs required for this routine are a value for EK , the log alternating stress intensity factor, ER , the effective value of R , and J , the index defining the data curve for the value of R immediately above ER . If the rate is not zero the routine returns a value of Z , the log rate before adjustment for K_c . If the rate is zero the routine returns a value of zero for crack rate (CRATE) directly and the adjustment for K_c is by-passed. Prediction is similar to that for a single curve (section 3.3) except that the curve used is derived from the curves at R values above and below ER by interpolating horizontally. For region C the interpolated curve is derived as shown in Fig.9 which demonstrates the process for ER = -0.75 . From each defined data point on both curves a horizontal line is drawn to intersect the other curve. A point is then drawn on each of the horizontal lines such that the horizontal distance to the curve on each side is proportional to the difference between ER and the R value for that curve. The interpolated curve is then obtained by joining all such points. Therefore in Fig.9 the interpolated curve for R = -0.75 is horizontally equidistant from the curves for R = -1 and R = -0.5. For region C_1 the curve is derived as for regions A_1 and B_1 (section 3.3). A more detailed description follows.

Line 860 calculates F , the parameter defining the magnitude of ER relative to the data-defined values above and below (R(J) and R(J-1)). This is used at line 870 to calculate H3, the threshold log alternating stress intensity factor for ER and at line 880 a check is made as to whether it is greater than EK . If it is, a value of zero is returned for crack rate (CRATE). If not, indices K and L which define data points on the data curves for R values above and below ER are set to unity thus defining the lowest points A' and B' (Fig.9). H4 is then set to the value of threshold log rate.

At this point, H3 and H4 are the log stress intensity factor and log rate coordinates of C' , the lowest point on the interpolated curve (Fig.9). From this point the procedure is to calculate the coordinates of successive points on the curve, D' , E' , F' , etc. As each next set of coordinates is calculated, H5 and H1, the previous values, are transferred to H3 and H4 (lines 1110, 1120). Calculation of coordinates stops when either H5 is greater than EK (line 1000) or the highest point in the data is reached (line 990 or 1100). From line 1120 the calculation of rate is virtually identical to that from line 670 in Fig.6 for a single curve.

The coordinates for points D' , E' , etc. are calculated opposite each defined data point and the calculation follows a different branch depending upon whether the defined data point is on the left hand or right hand curve (Fig.8). The only purpose of lines 940 and 1050 is to save time by ensuring that the coordinates of points like D' are not calculated twice. Without these lines this would happen once for each of the data points on either side of D' . The inset on Fig.9 shows the key values calculated when following the path 1010, 1020, 920, 930 - 1000, 1110, 1120.

3.5 Function CRATE:- Adjustment for K_c

This is one line of the program (710) which converts the log rate Z to rate, and multiplies it by the factor below, derived from the denominator of the Forman, Kearney and Engles equation (1).

$$K_c \text{ factor} = \left[\frac{1 - \dfrac{EP}{DKC}}{1 - \dfrac{STK + ALK}{CKC}} \right]^{0.5} . \tag{5}$$

This purely empirical factor fulfils two functions. First it adjusts the crack rate curves such that they become vertical at the current K_c value CKC rather than at the K_c value for the crack rate data DKC *.

Secondly, it adjusts crack rates in region B so that the crack rate curve becomes vertical at a point appropriate to the value of R as input to the computer - it was assumed in section 3.2 for region B that R was equal to the highest defined value in the rate data. Since the actual value of R is greater than this then the crack rate curve must become vertical at a lower alternating stress intensity factor than calculated earlier.

The K_c factor adjusts only the crack rates and not the threshold stress intensity factors. Its effect is greatest at the highest values of alternating stress intensity factor. Its accuracy has been assessed by predicting thick sheet crack propagation data from thin sheet data for three classes of aluminium alloy, 4% Cu-Al, artificially aged; 2.5% Cu - 1.5% Mg-Al, artificially aged, and 5.5% Zn-Al, artificially aged. The three alloys were chosen as the only ones in the ESDU data sheets for which comparable thin and thick sheet data existed at peak stress intensity factors approaching K_c. K_c values for the thick sheet were given with the data sheets. The values of K_c for the thin sheet were derived from extrapolation of the crack propagation curves. This is perhaps a rather debatable procedure for the thin sheet case where K_c varies with crack length. It is justified here on the grounds that in all the cases so far tried, the gross differences in shape of crack rate curve between thin and thick sheet data at high values of peak stress intensity factor were predicted well. Typical examples are shown in Figs.10 and 11 for the artificially aged 4% copper-aluminium alloy at R values of 0.5 and 0.05 respectively.

Fig.12 illustrates the second function of equation 5, namely the adjustment of predictions in region B such that crack rate progressively approaches infinity as the peak stress intensity factor approaches K_c.

On the left hand side of the diagram can be seen the curves for R = 0.8 and 0.9 predicted by equation (5) from the data curve for R = 0.5 (i.e. assuming that the highest defined data curve was that for R = 0.5). Although the differences between the predicted and data curves are quite large, equation (5) normally underestimates the true difference since it only adjusts the upper

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* Its use is restricted in the program to the case where CKC is less than DKC (predictions of thick sheet data from thin sheet data). This is because in the reverse case the equation can give unreliable predictions where the peak stress intensity factor is close to DKC . Also the program would need substantial modification for predictions where the peak stress intensity was above DKC .

portions of the rate curves to any great extent and does not change the crack propagation threshold at all. This can be seen in Fig.12 by comparing the data curve for $R = 0.5$ with that predicted from the data curve for $R = 0$ using equation (5). Further development of equation (5) was considered to improve the predictions in region B but this was decided against for the following reasons. Firstly, if a method of extrapolation were used without additional data the program would become very much more complicated in order to cope with the wide range of types of rate data which could be envisaged. Secondly, empirical constants could be used to define behaviour in region B, but these would require derivation and checking for each set of rate data. It was concluded that by far the most flexible and convenient method of improving the accuracy of prediction in region B if required would be to extend the rate data to cover anticipated behaviour in that region.

4 CONCLUDING DISCUSSION

This section discusses some practical points in using the program.

4.1 Rate data

The minimum data required by the program is one curve for one value of R. However, although this is perfectly adequate for the calculation of rates at values of R equal to the data value, the effect of varying R would be only partially predicted by the program, i.e. for R values above the data value the effect of varying R (or mean stress intensity factor) would be ignored except in the adjustment for K_c (section 3.5); for R values below the data value the part of the cycle more compressive than that in a cycle having the same maximum stress intensity factor and an R value equal to the data value, would be ignored (section 3.2).

Since the assumptions for variation of crack rate with R values below the lowest in the data imply that the crack is closed for part of the cycle (section 3.2) it is recommended that crack rate data should include curves at R values down to $R = 0$. If this is not done the effect of R on crack rate will be exaggerated between the lowest value of R in the data and $R = 0$. In general it is recommended that crack rate data should cover as wide a range of values of R as possible - even if the data are not available 'pseudo data' can be used to cover expected behaviour.

4.2 Compatibility of languages

The FORTRAN II program should be compatible with most other FORTRAN systems except that the second DIMENSION statement will not normally be required. There is no mixed mode arithmetic whatsoever.

For the BASIC program the input of data from paper tape (lines 170-270) contains input statements which are particular to PDP 8 BASIC. Line 17 will not be required for most systems and INPUT # 1: should be replaced by the appropriate input command for paper tape. The variable Q in lines 180, 200 and 230 is needed in PDP 8 BASIC to read line feeds on the data tape, and will not normally be required for other systems.

4.3 Possible changes to program

The number of data curves can be increased by changing lines 160 (Fig.4) and 190.

The number of points per data curve can be increased by changing lines 160 (Fig.4) and 220.

Appendix A

FORTRAN II LISTING

```
      COMMON R,AK,CR,JMR,DKC
110   FORMAT(2E12.3)
120   FORMAT(16H MEAN K         =,F9.3)
130   FORMAT(16H ALTERNATING K =,F9.3)
140   FORMAT(16H KC             =,F9.3)
150   FORMAT(6H RATE=,E10.4,9H MM/CYCLE//)
      DIMENSION R(12),AK(11,11),CR(11,10)
      READ (2,110) DKC
      DO 280 JMR=1,12
      READ (2,110) R(JMR)
      IF (R(JMR)-1.) 220,220,300
220   DO 260 K=1,12
      READ (2,110) X,Y
      IF (X) 280,250,250
250   AK(JMR,K)=ALOG(X)
260   CR(JMR,K)=ALOG(Y)
280   AK(JMR,K)=0
300   JMR=JMR-1
340   READ(1,120) STK
      READ(1,130) ALK
      READ(1,140) CKC
      IF (CKC-DKC) 420,400,400
400   CKC=DKC
420   WRITE(1,150) CRATE(STK,ALK,CKC)
      GO TO 340
      END
      FUNCTION CRATE(STK,ALK,CKC)
      COMMON R,AK,CR,JMR,DKC
      DIMENSION R(12),AK(11,11),CR(11,10)
      IF (STK+ALK-CKC) 540,750,750
540   IF (ALK) 730,730,550
550   IF (STK+ALK) 730,730,560
560   ER=(STK-ALK)/(STK+ALK)
      EP=STK+ALK
      IF (ER-R(1)) 590,590,770
590   ER=R(1)
      EK=ALOG(EP/2.*(1.-ER))
      J=1
620   IF (EK-AK(J,1)) 730,630,630
630   DO 660 K=2,10
      IF (AK(J,K)-EK) 650,650,670
650   IF (AK(J,K+1)) 660,670,660
660   CONTINUE
670   TK=EK-AK(J,K)
      Z=CR(J,K)+TK*(CR(J,K)-CR(J,K-1))/(AK(J,K)-AK(J,K-1))
690   IF (TK) 710,700,700
700   Z=Z+TK*TK/((ALOG(DKC*(1.-ER)/2.)-EK+TK)**2.-TK*TK)
```

```
710    CRATE=EXP(Z)*((1.-EP/DKC)/(1.-(STK+ALK)/CKC))**.5
       RETURN
730    CRATE=0
       RETURN
750    CRATE=1E10
       RETURN
770    EK=ALOG(ALK)
       IF (R(JMR)-ER) 790,790,830
790    ER=R(JMR)
       J=JMR
       EP=2.*ALK/(1.-ER)
       GO TO 620
830    DO 850 J=2,JMR
       IF (R(J)-ER) 850,850,860
850    CONTINUE
860    F=(ER-R(J-1))/(R(J)-R(J-1))
       H3=F*AK(J,1)+(1.-F)*AK(J-1,1)
       IF (EK-H3) 730,890,890
890    K=1
       L=1
       H4=CR(J,1)
920    IF (CR(J,K+1)-CR(J-1,L+1)) 930,930,1040
930    K=K+1
       IF (CR(J,K)-CR(J-1,L)) 950,920,950
950    H1=CR(J,K)
       G=(CR(J-1,L+1)-CR(J-1,L))/(AK(J-1,L+1)-AK(J-1,L))
       H2=AK(J-1,L)+(CR(J,K)-CR(J-1,L))/G
       H5=F*AK(J,K)+(1.-F)*H2
       IF (AK(J,K+1)) 1000,1120,1000
1000   IF (EK-H5) 1120,1010,1010
1010   H3=H5
       H4=H1
       GO TO 920
1040   L=L+1
       IF (CR(J,K)-CR(J-1,L)) 1060,920,1060
1060   H1=CR(J-1,L)
       G=(CR(J,K+1)-CR(J,K))/(AK(J,K+1)-AK(J,K))
       H2=AK(J,K)+(CR(J-1,L)-CR(J,K))/G
       H5=F*H2+(1.-F)*AK(J-1,L)
       IF (AK(J-1,L+1)) 1000,1120,1000
1120   TK=EK-H5
       Z=H1+TK*(H1-H4)/(H5-H3)
       GO TO 690
       END
```

Appendix B

BASIC LISTING

```
160 DIM R(11),K(10,10),S(10,9)
170 FILE#1:"PTR:"
180 INPUT#1: K1,Q
190 FOR I=0 TO 10
200 INPUT#1: R(I),Q
210 IF R(I)>1 THEN 300
220 FOR K=0 TO 10
230 INPUT#1: X,Y,Q
240 IF X<0 THEN 280
250 K(I,K)=LOG(X)
260 S(I,K)=LOG(Y)
270 NEXT K
280 K(I,K)=0
290 NEXT I
300 I=I-1
310 PRINT
320 PRINT
330 PRINT"MEAN K",
340 INPUT U
350 PRINT"ALTERNATING K",
360 INPUT W
370 PRINT"KC=",
380 INPUT K2
390 IF K2<K1 THEN 410
400 K2=K1
410 GOSUB 530
420 PRINT"RATE =";R2;"MM/CYCLE"
430 GOTO 310
530 IF U+W>=K2 THEN 750
540 IF W<=0 THEN 730
550 IF U+W<=0 THEN 730
560 R3=(U-W)/(U+W)
570 P=U+W
580 IF R3>R(0) THEN 770
590 R3=R(0)
600 W1=LOG(P/2*(1-R3))
610 J=0
620 IF W1<K(J,0) THEN 730
630 FOR K=1 TO 9
640 IF K(J,K)>W1 THEN 670
650 IF K(J,K+1)=0 THEN 670
660 NEXT K
670 K3=W1-K(J,K)
680 Z=S(J,K)+K3*(S(J,K)-S(J,K-1))/(K(J,K)-K(J,K-1))
690 IF K3<0 THEN 710
700 Z=Z+K3*K3/((LOG(K1*(1-R3)/2)-W1+K3)↑2-K3*K3)
```

```
710 R2=EXP(Z)*((1-P/K1)/(1-(U+W)/K2))↑.5
720 RETURN
730 R2=0
740 RETURN
750 R2=1E10
760 RETURN
770 W1=LOG(W)
780 IF R(I)>R3 THEN 830
790 R3=R(I)
800 J=I
810 P=2*W/(1-R3)
820 GOTO 620
830 FOR J=1 TO I
840 IF R(J)>R3 THEN 860
850 NEXT J
860 F=(R3-R(J-1))/(R(J)-R(J-1))
870 H3=F*K(J,0)+(1-F)*K(J-1,0)
880 IF W1<H3 THEN 730
890 K=0
900 L=0
910 H4=S(J,0)
920 IF S(J,K+1)>S(J-1,L+1) THEN 1040
930 K=K+1
940 IF S(J,K)=S(J-1,L) THEN 920
950 H1=S(J,K)
960 G=(S(J-1,L+1)-S(J-1,L))/(K(J-1,L+1)-K(J-1,L))
970 H2=K(J-1,L)+(S(J,K)-S(J-1,L))/G
980 H5=F*K(J,K)+(1-F)*H2
990 IF K(J,K+1)=0 THEN 1120
1000 IF W1<H5 GOTO 1120
1010 H3=H5
1020 H4=H1
1030 GOTO 920
1040 L=L+1
1050 IF S(J,K)=S(J-1,L) THEN 920
1060 H1=S(J-1,L)
1070 G=(S(J,K+1)-S(J,K))/(K(J,K+1)-K(J,K))
1080 H2=K(J,K)+(S(J-1,L)-S(J,K))/G
1090 H5=F*H2+(1-F)*K(J-1,L)
1100 IF K(J-1,L+1)=0 THEN 1120
1110 GOTO 1000
1120 K3=W1-H5
1130 Z=H1+K3*(H1-H4)/(H5-H3)
1140 GOTO 690
1150 END
```

Table 1

NAMES OF ARRAYS AND VARIABLES

ARRAYS

FORTRAN	BASIC	DESCRIPTION
R(11)	R(10)	List of values of $\frac{K_{min}}{K_{max}}$ in rate data.
AK(11,11)	K(10,10)	Lists of log (alternating K values) in rate data.
CR(11,10)	S(10,9)	Lists of log (crack rates) in rate data corresponding to values in array AK .

INTEGER VARIABLES

FORTRAN	BASIC	DESCRIPTION
JMR	I	Index of max value of R in rate data (after data has been read in).
K or L	K or L	Index of alternating K and crack rate values at constant R .
J	J	Index of R values in rate data.

REAL VARIABLES

FORTRAN	BASIC	DESCRIPTION
DKC	K_1	K_c value associated with rate data.
X	X	Temporary stores used when reading rate data.
Y	Y	
-	Q	Temporary store needed to read 'carriage returns' in rate data (particular to PDP 8 'BASIC')
STK	U	Mean (steady) K value for which rate is to be calculated.
ALK	W	Alternating K value ($K_{max} - K_{mean}$) for which rate is to be calculated.
CKC	K2	Value of K_c for current prediction.
ER	R3	Effective value of R used by 'CRATE' to calculate crack rate.
EK	W_1	Effective log alternating K value used by 'CRATE' to calculate crack rate.
EP	P	Peak K value assumed in 'CRATE' before adjustment for K_c .

Table 1 (concluded)

FORTRAN	BASIC	DESCRIPTION
TK	K3	Difference between EK and a data - derived value of log alternating K .
F	F	Factor defining the value of ER relative to the data values of R above and below ER (region C only).
G	G	Slope of log alternating K vs. log rate data curve opposite data point on adjacent curve (region C only).
H1, H2 H3, H4	H1, H2 H3, H4	Coordinates of points on interpolated curve (region C only).
Z	Z	Log (CRATE) before adjustment for K_c .
CRATE	R2	Crack rate returned by function.

Table 2

SAMPLE VALUES OF RATE CALCULATED BY PROGRAM

STK $(N\ mm^{-\frac{3}{2}})$	ALK $(N\ mm^{-\frac{3}{2}})$	CKC $(N\ mm^{-\frac{3}{2}})$	R as input	ER	EP $(N\ mm^{-\frac{3}{2}})$	EXP (EK) $(N\ mm^{-\frac{3}{2}})$	Region	Crack rate (CRATE) (mm/cycle)
-62	124	1860	-3	-2	62	93	A	0
-200	400	1860	-3	-2	200	300	A	3.45×10^{-5}
-1600	3200	1860	-3	-2	1600	2400	A_1	6.01×10^{-2}
-2000	4000	1860	-3	-2	2000	3000	A_1	1.00×10^{10}
-62	124	1000	-3	-2	62	93	A	0
-200	400	1000	-3	-2	200	300	A	3.65×10^{-5}
-1600	3200	1000	-3	-2	1600	2400	A_1	1.00×10^{10}
7.86	55	1860	-0.75	-0.75	62.86	55	C	0
14.29	100	1860	-0.75	-0.75	114.29	100	C	4.24×10^{-6}
214.3	1500	1860	-0.75	-0.75	1714.3	1500	C_1	1.29
285.7	2000	1860	-0.75	-0.75	2285.7	2000	C_1	1.00×10^{10}
7.86	55	1000	-0.75	-0.75	62.86	55	C	0
14.29	100	1000	-0.75	-0.75	114.29	100	C	4.36×10^{-6}
214.3	1500	1000	-0.75	-0.75	1714.3	1500	C_1	1.00×10^{10}
61.63	20	1860	0.51	0.5	80	20	B	0
154.1	50	1860	0.51	0.5	200	50	B	3.16×10^{-6}
1233	400	1860	0.51	0.5	1600	400	B_1	0.127
1541	500	1860	0.51	0.5	2000	500	B_1	1.00×10^{10}
61.63	20	1000	0.51	0.5	80	20	B	0
154.1	50	1000	0.51	0.5	200	50	B	3.35×10^{-6}
1233	400	1000	0.51	0.5	1600	400	B_1	1.00×10^{10}
113.3	20	1860	0.7	0.5	80	20	B	0
283.3	50	1860	0.7	0.5	200	50	B	3.3×10^{-6}
2267	400	1860	0.7	0.5	1600	400	B_1	1.00×10^{10}

See Figs.1 and 2 for data.

SYMBOLS

a	half plane crack length
C	constant in Forman, Kearney and Engles equation
K	stress intensity factor
K_a	semi-range alternating stress intensity factor
K_{max}	maximum stress intensity factor
K_{min}	minimum stress intensity factor
ΔK	range of alternating stress intensity factor
K_c	fracture toughness
m	constant in Forman, Kearney and Engles equation
N	number of cycles
R	'stress' ratio $= \frac{K_{min}}{K_{max}}$
σ	stress at infinity

CONVERSIONS

$$1\ \mathrm{N/mm^{\frac{3}{2}}} = 0.0316\ \mathrm{MN/m^{\frac{3}{2}}}$$
$$= 28.8\ \mathrm{lb/in^{\frac{3}{2}}}$$

NB Names of variables and arrays used in computer programs are given in Table 1.

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No.	Author	Title, etc.
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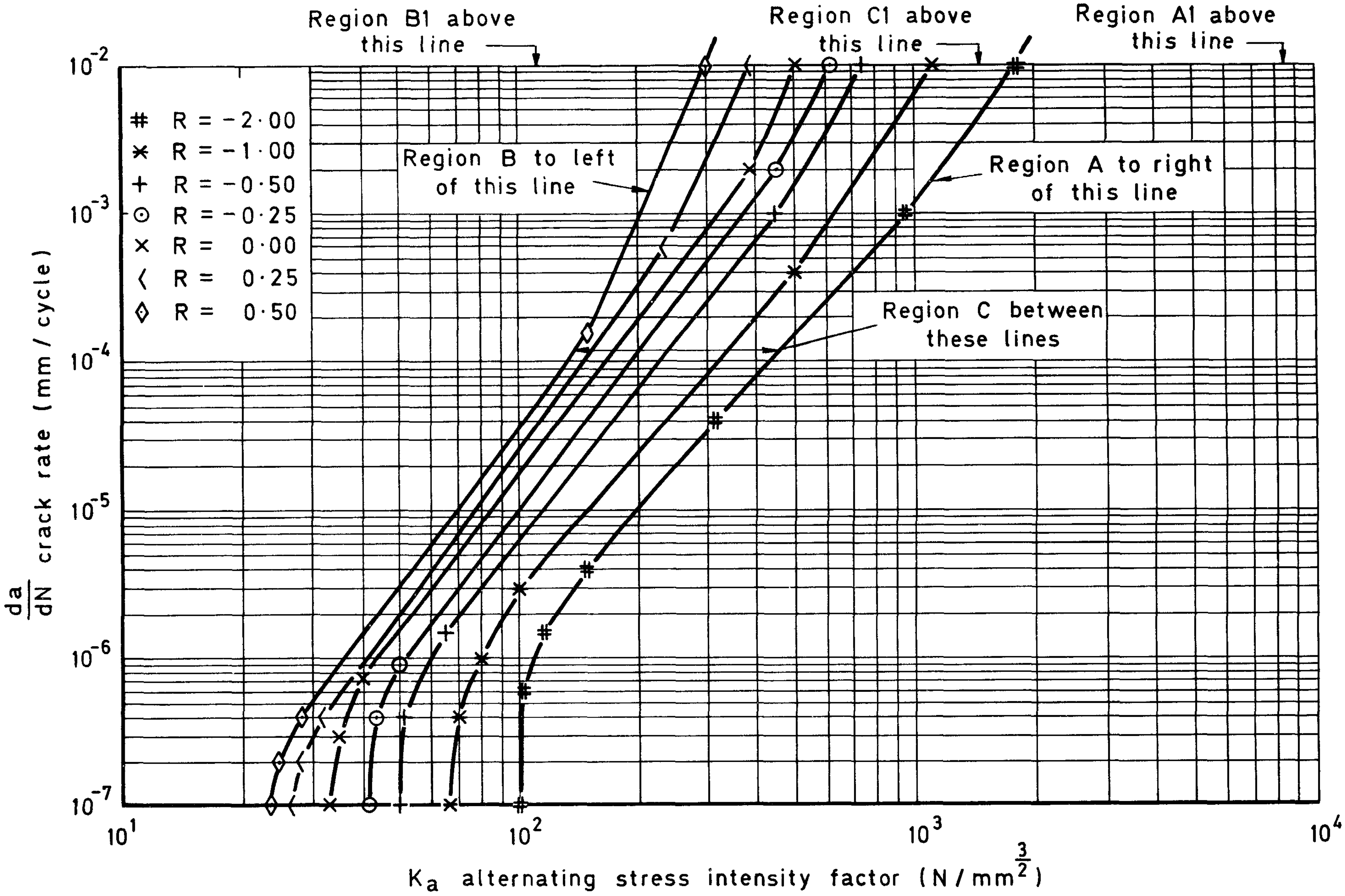

Fig.1 Plot of crack rate data for L65/L71 aluminium alloy

```
 0.186E+04                ---- Kc
-0.200E+01                ---- Lowest R in data
 0.989E+02   0.100E-06  ┐
 0.102E+03   0.600E-06  │
 0.115E+03   0.150E-05  │
 0.147E+03   0.400E-05  ├── Ka and da/dN values
 0.315E+03   0.400E-04  │
 0.950E+03   0.100E-02  │
 0.180E+04   0.100E-01  ┘
-0.100E+01   0.000E+00    ---- Terminator
-0.100E+01                ---- Next value of R
 0.659E+02   0.100E-06
 0.690E+02   0.400E-06
 0.800E+02   0.100E-05
 0.101E+03   0.300E-05
 0.495E+03   0.400E-03
 0.112E+04   0.100E-01
-0.100E+01   0.000E+00
-0.500E+00
 0.495E+02   0.100E-06
 0.510E+02   0.400E-06
 0.650E+02   0.150E-05
 0.450E+03   0.100E-02
 0.750E+03   0.100E-01
-0.100E+01   0.000E+00
-0.250E+00
 0.413E+02   0.100E-06
 0.430E+02   0.400E-06
 0.500E+02   0.900E-06
 0.450E+03   0.200E-02
 0.620E+03   0.100E-01
-0.100E+01   0.000E+00
 0.000E+00
 0.330E+02   0.100E-06
 0.350E+02   0.300E-06
 0.400E+02   0.730E-06
 0.390E+03   0.200E-02
 0.510E+03   0.100E-01
-0.100E+01   0.000E+00
 0.250E+00
 0.266E+02   0.100E-06
 0.280E+02   0.200E-06
 0.320E+02   0.400E-06
 0.235E+03   0.600E-03
 0.390E+03   0.100E-01
-0.100E+01   0.000E+00
 0.500E+00
 0.234E+02   0.100E-06
 0.245E+02   0.200E-06
 0.280E+02   0.400E-06
 0.149E+03   0.155E-03
 0.300E+03   0.100E-01
-0.100E+01   0.000E+00
 0.200E+01                ---- Final terminator for data
 ↑Z
```

Fig.2 Data tape for L65/L71 aluminium alloy

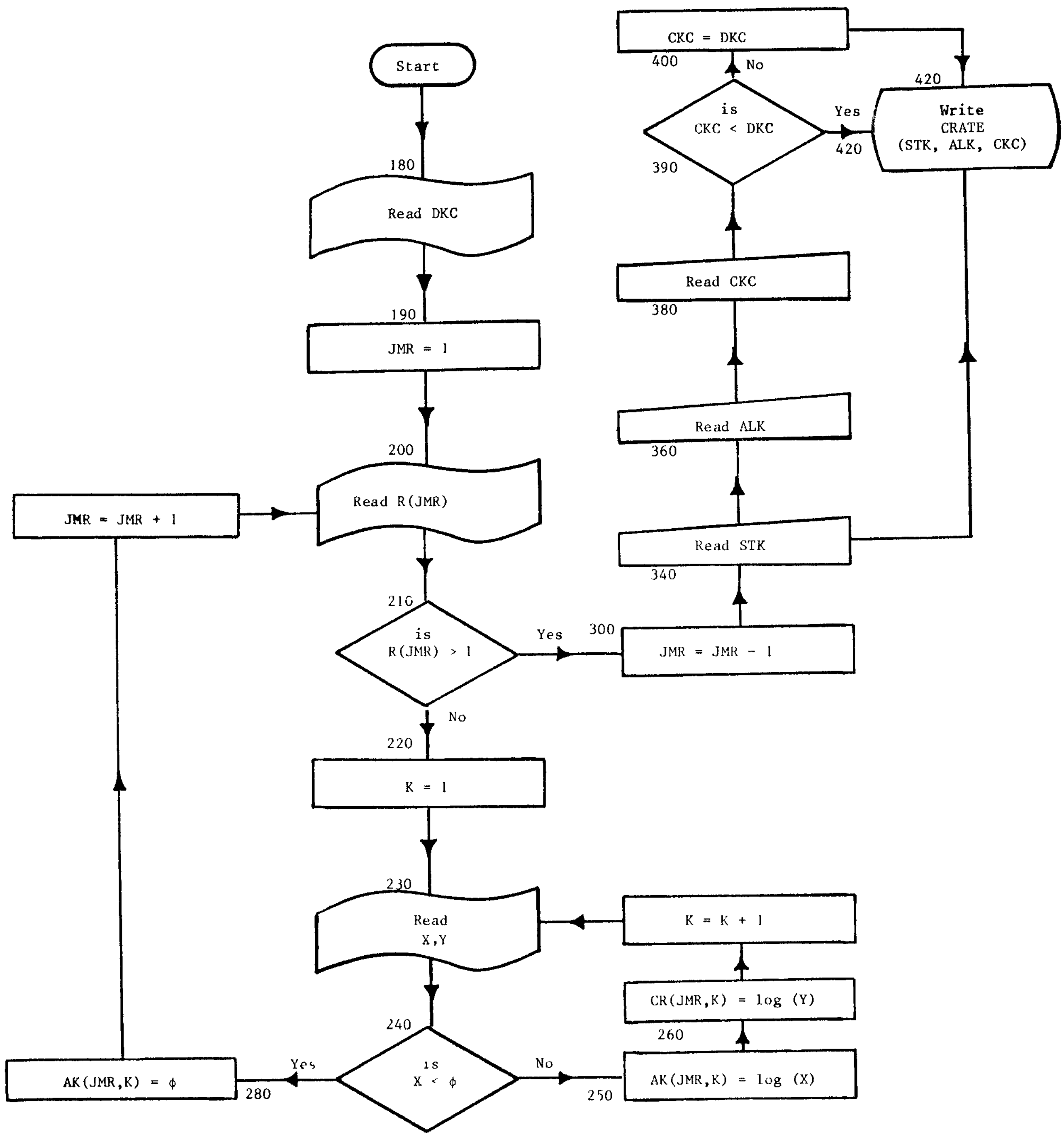

Fig.3 Flow chart for main segment

J	R
1	-2.0
2	-1.0
3	-0.50
4	-0.25
5	0.00
6	0.25
7	0.50
8	X
9	X
10	X
11	X
12	X

RATIO (R) ARRAY

J	K or L: 1	2	3	4	5	6	7	8	9	10	11
1	log (98.9)	log (102.0)	log (115.0)	log (147.0)	log (315.0)	log (950.9)	0.0	X	X	X	X
2	--- LISTS OF ------						0.0	"	"	"	"
3	ALTERNATING STRESS ----					0.0	X	"	"	"	"
4	--- INTENSITY -----					0.0	"	"	"	"	"
5	--- FACTORS -----					0.0	"	"	"	"	"
6	----------					0.0	"	"	"	"	"
7 (=JMR)	log (23.4)	log (24.5)	log (28.0)	log (149.0)	log (300)	0.0	"	"	"	"	"
8	X	X	X	X	X	X	"	"	"	"	"
9	"	"	"	"	"	"	"	"	"	"	"
10	"	"	"	"	"	"	"	"	"	"	"

ALTERNATING STRESS INTENSITY FACTOR (AK) ARRAY

Stores 1–7 contain natural logs of stated values

J	K or L: 1	2	3	4	5	6	7	8	9	10
1	0.10 E-6	0.60 E-6	0.15 E-5	0.40 E-5	0.40 E-4	0.10 E-2	X	X	X	X
2	------ LISTS OF RATES ------						X	"	"	"
3	------ CORRESPONDING --					X	"	"	"	"
4	------ TO K VALUES ---					X	"	"	"	"
5	------ IN AK ARRAY ---					X	"	"	"	"
6	----------------					X	"	"	"	"
7 (=JMR)	0.10 E-6	0.20 E-6	0.40 E-6	0.16 E-3	0.10 E-1	X	"	"	"	"
8	X	X	X	X	X	"	"	"	"	"
9	"	"	"	"	"	"	"	"	"	"
10	"	"	"	"	"	"	"	"	"	"
11	"	"	"	"	"	"	"	"	"	"

CRACK RATE (CR) ARRAY

X = Value immaterial

Fig.4 Layout of rate data for L65/L71 after being read in

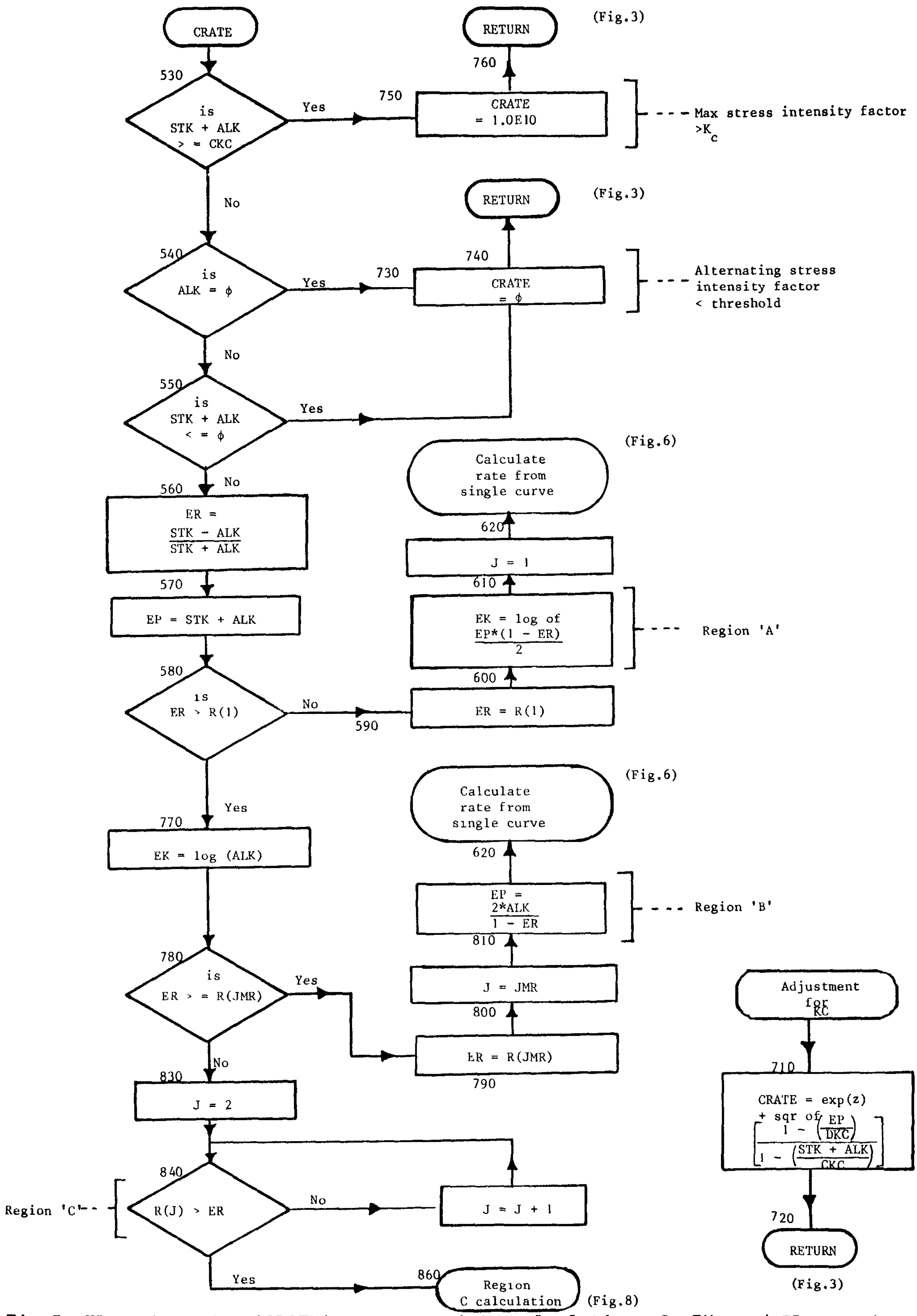

Fig.5 Flow chart for 'CRATE' - entry point, calculation of EK and ER, sort out of regions, and adjustment for K_C

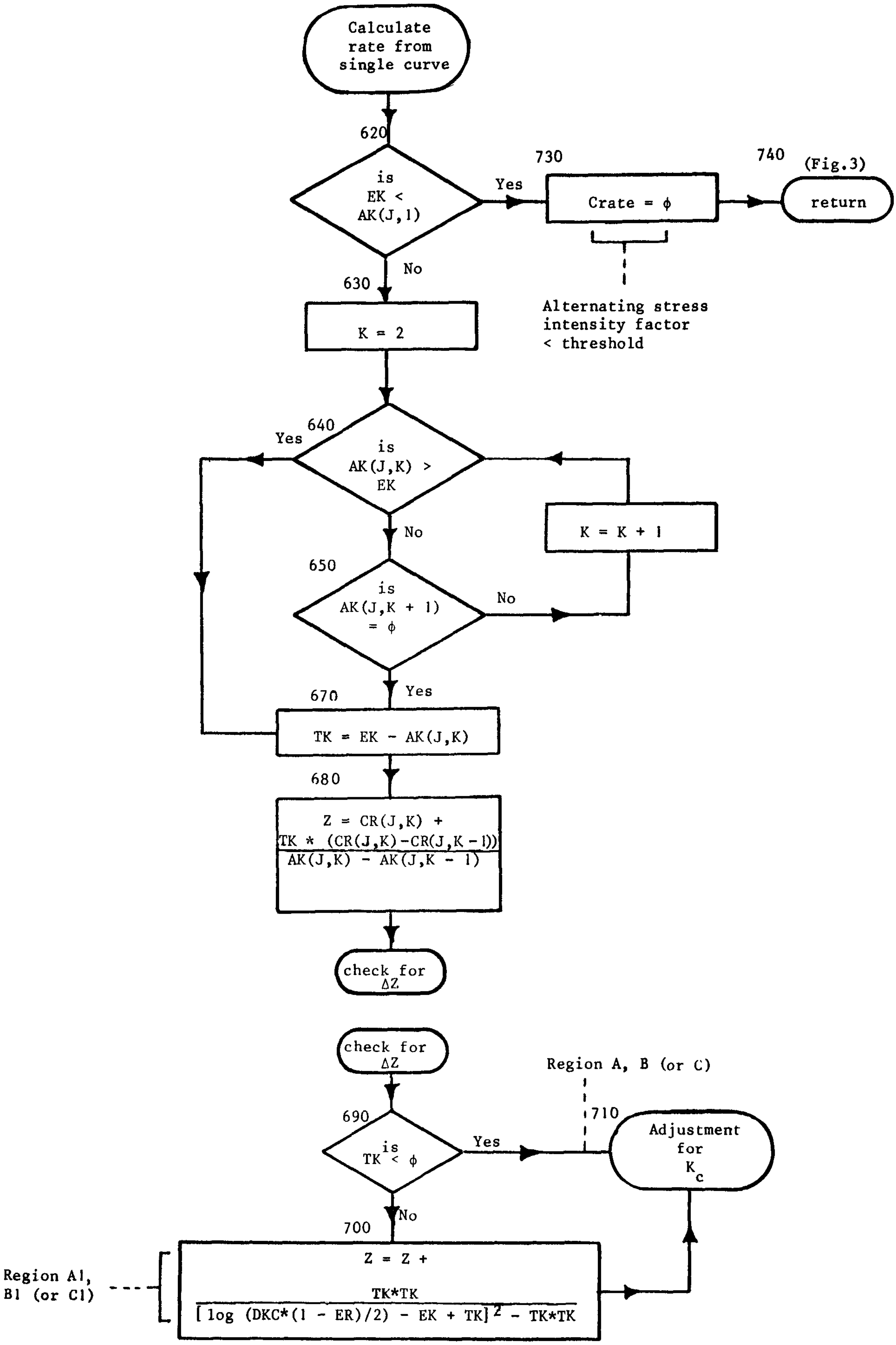

Fig.6 Flow chart 2 for 'CRATE' - calculation of log rate from single curve before adjustment for K_C

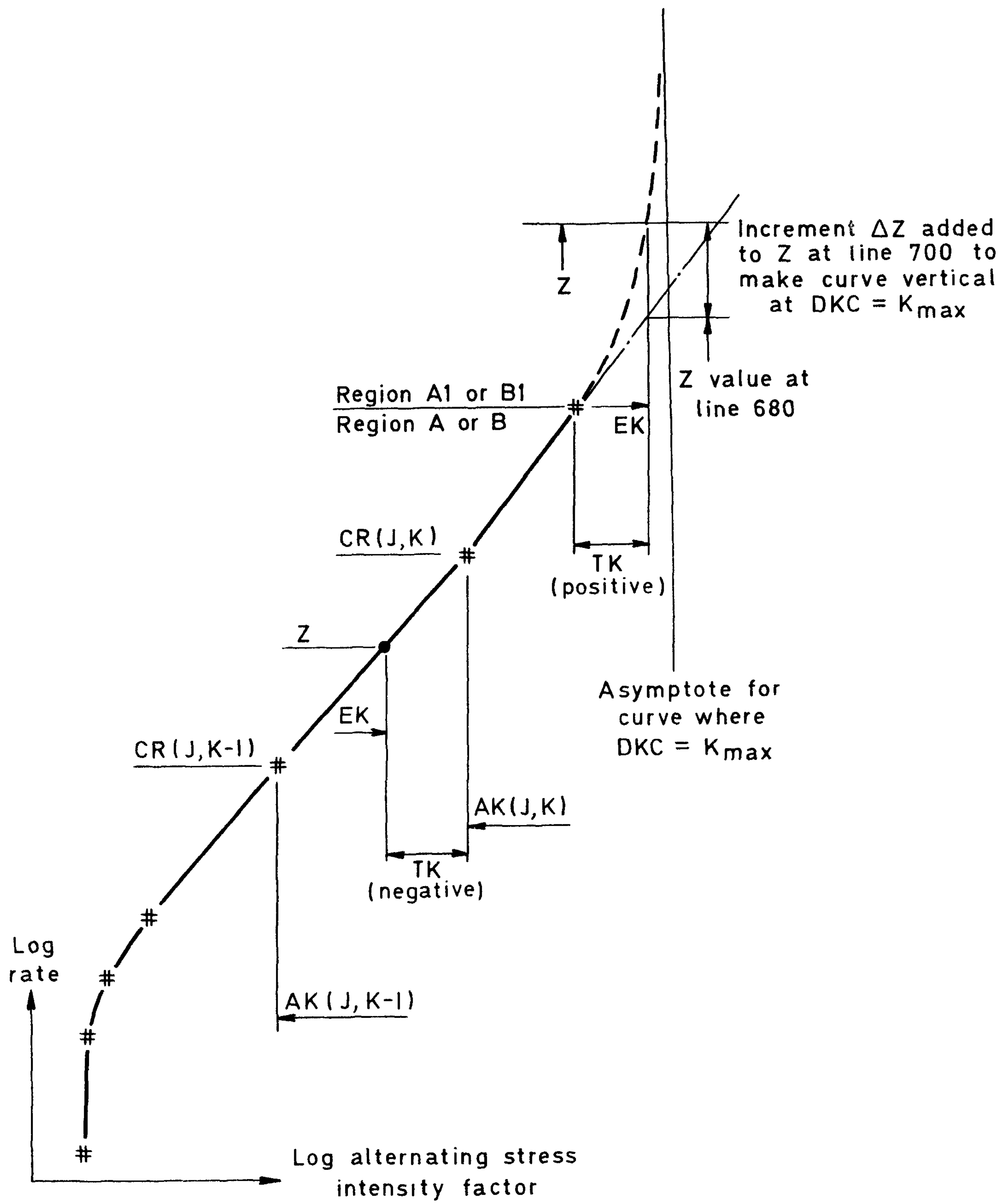

Fig.7 Calculation of log rate before ajustment for K_c-regions A and B

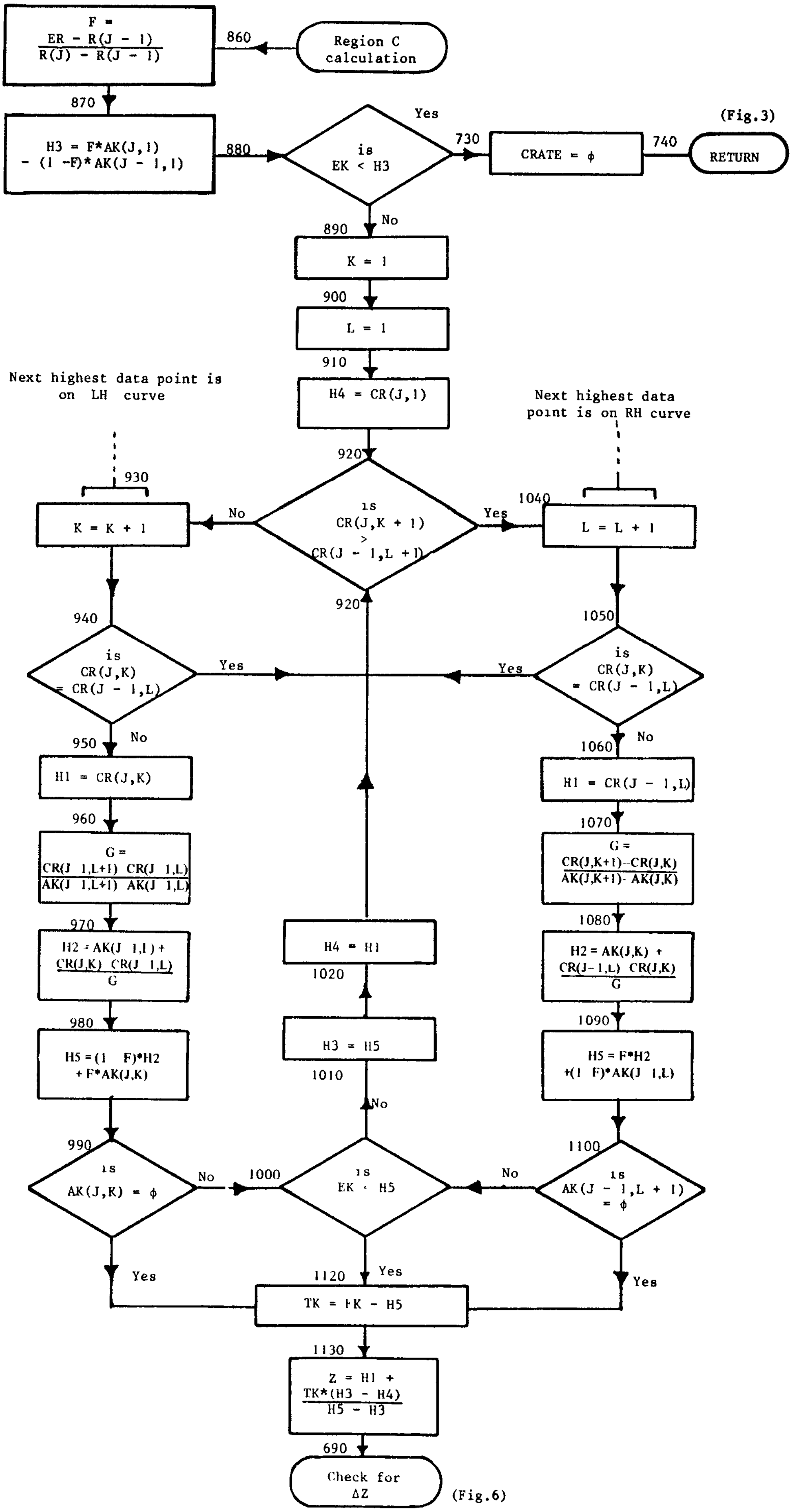

Fig.8 Flow chart 3 for 'CRATE' Region C - prediction before adjustment for K_c

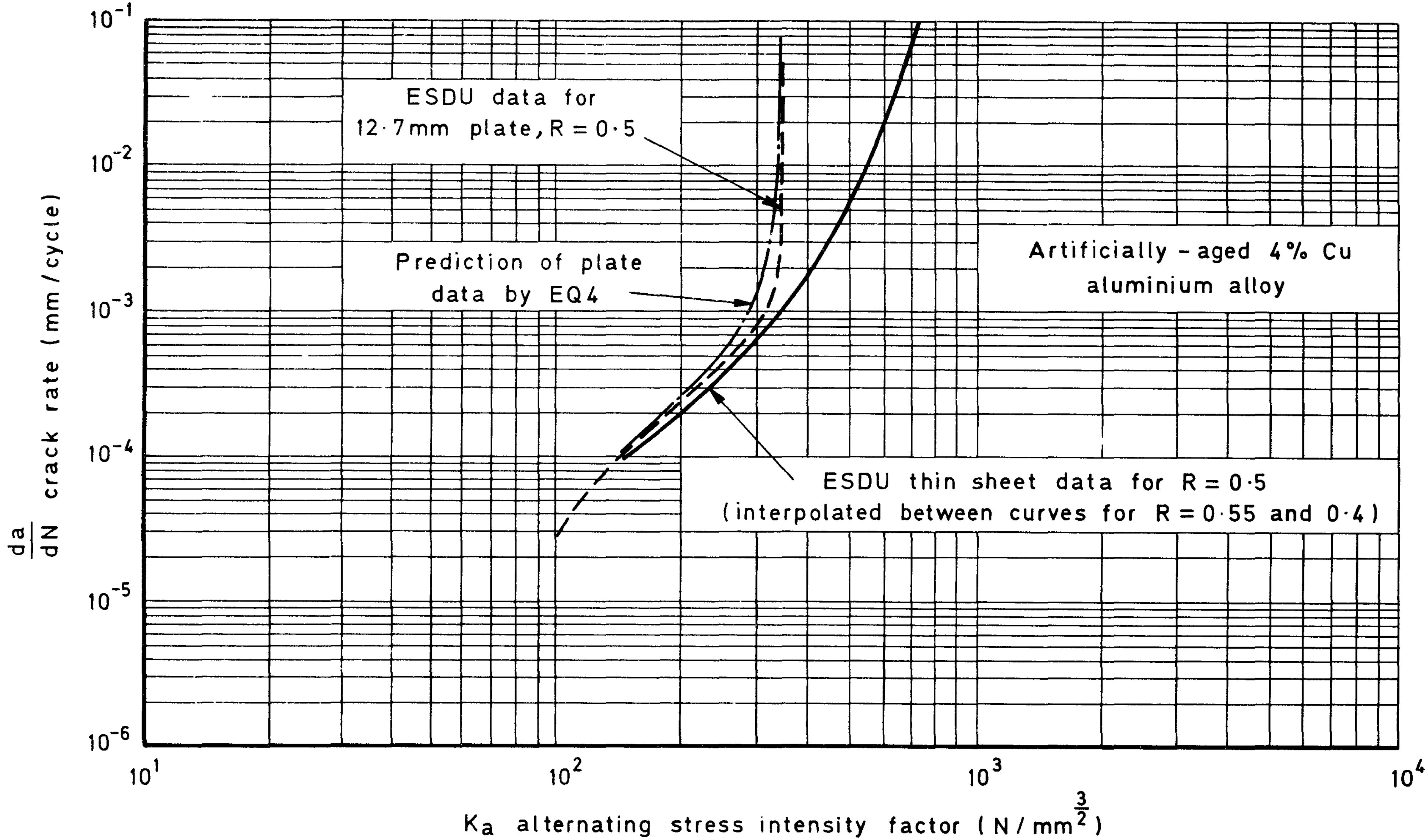

Fig.10 Prediction of crack rate data for thick sheet from that for thin sheet (R = 0·5)

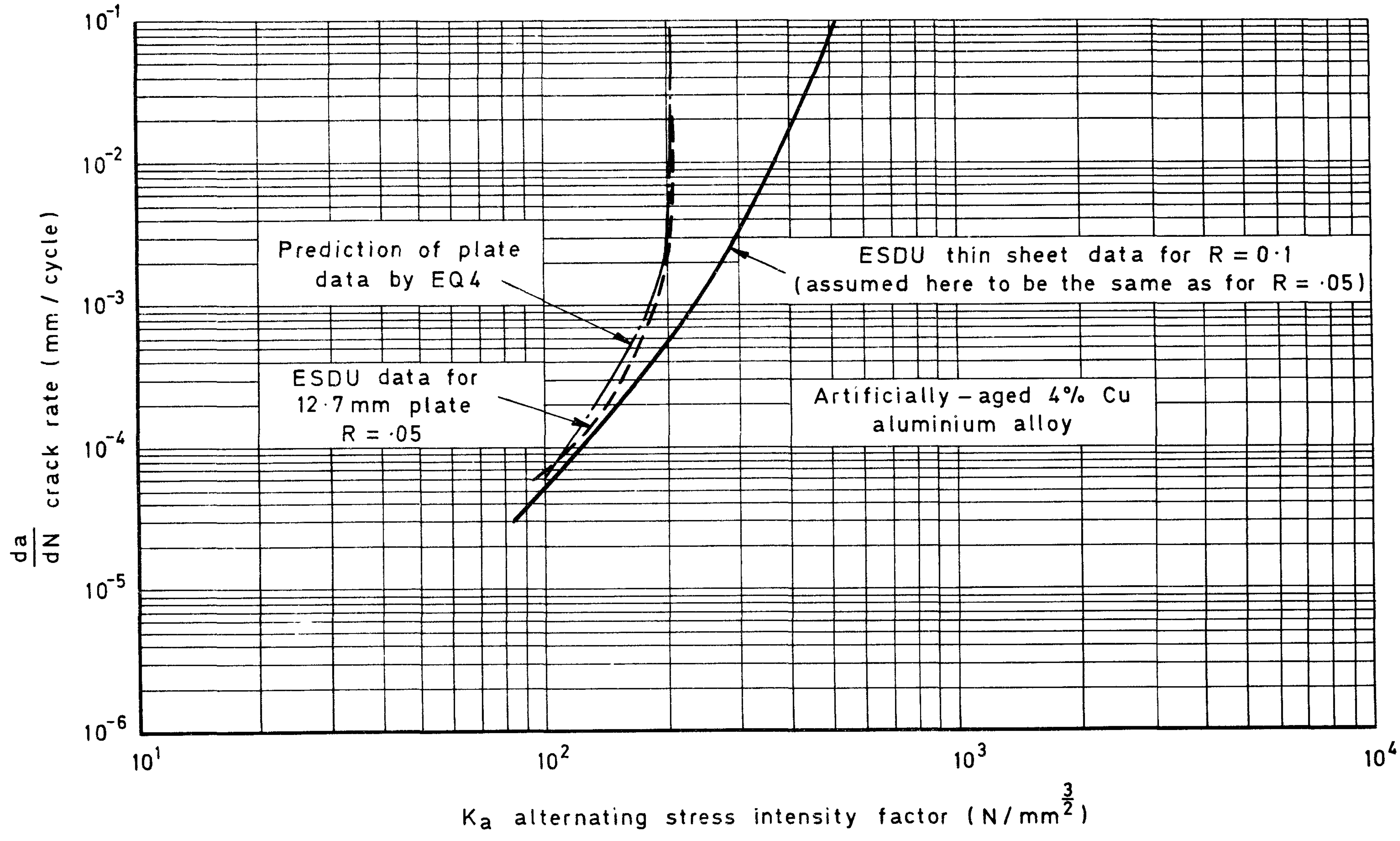

Fig. 11 Prediction of crack rate data for thick sheet from that for thin sheet ($R = 0{\cdot}05$)

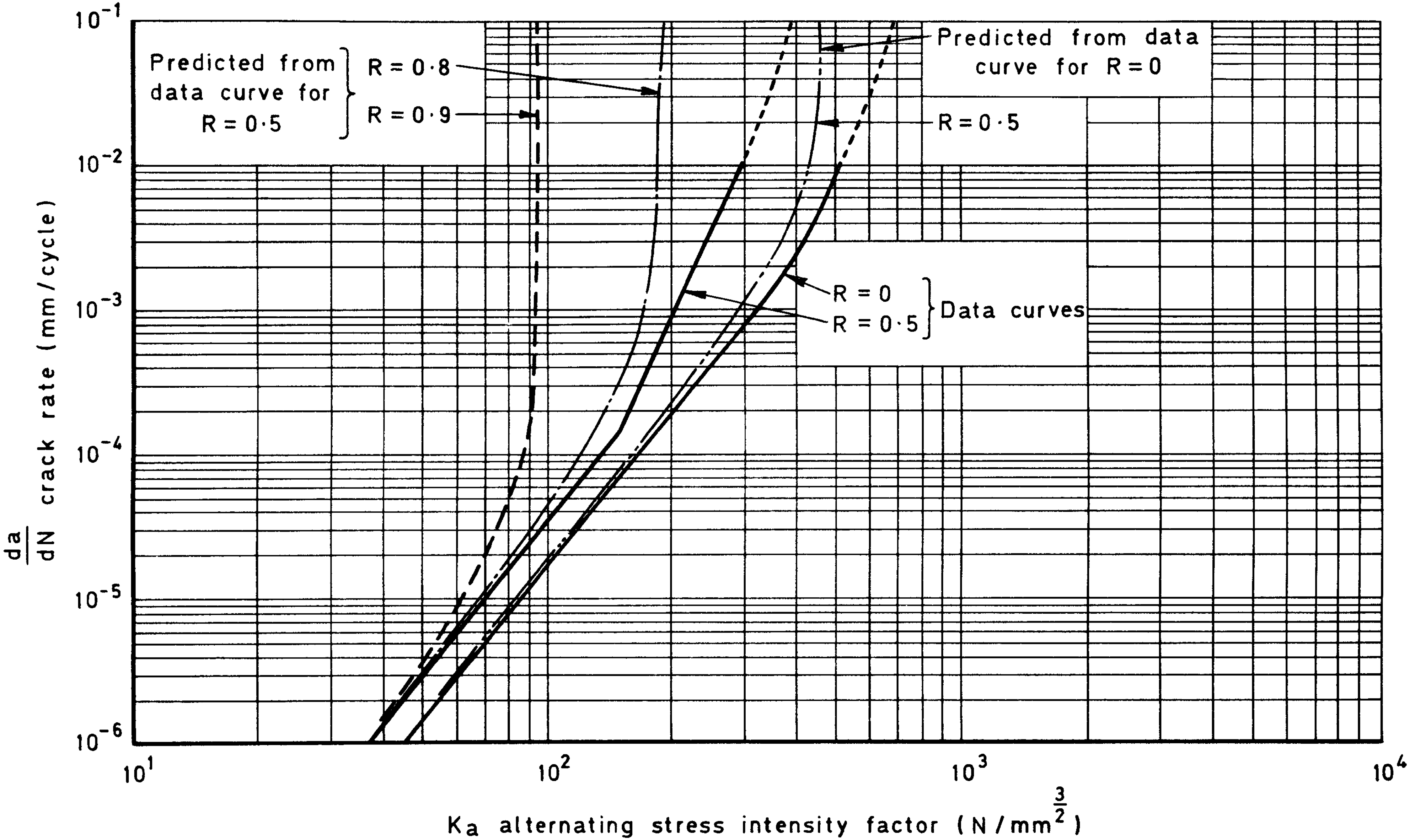

Fig.12 Adjustment of predictions in region B

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