NASA Technical Memorandum 4425

Computer Programs To Characterize Alloys and Predict Cyclic Life Using the Total Strain Version of Strainrange Partitioning

Tutorial and Users Manual

Version 1.0

James F. Saltsman
Lewis Research Center
Cleveland, Ohio

NASA

National Aeronautics and
Space Administration

Office of Management

Scientific and Technical
Information Program

1993

CONTENTS

COMPUTER PROGRAMS TO CHARACTERIZE ALLOYS AND PREDICT CYCLIC LIFE USING THE TOTAL STRAIN VERSION OF STRAINRANGE PARTITIONING — TUTORIAL AND USERS MANUAL

Version 1.0

James F. Saltsman
National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio 44135

INTRODUCTION

This manual presents computer programs for characterizing and predicting fatigue and creep-fatigue resistance of metallic materials in the high-temperature, long-life regime for isothermal and nonisothermal fatigue. The programs use the total strain version of Strainrange Partitioning (TS-SRP). The user should be thoroughly familiar with the TS-SRP method (ref.1) before attempting to use any of these programs. Improper understanding can lead to incorrect use of the method and erroneous life predictions. An extensive database has also been developed in a parallel effort. The database is probably the largest source of high-temperature, creep-fatigue test data available in the public domain and can be used with other life-prediction methods as well. This users manual, software, and database are all in the public domain and are available through COSMIC[1].

Two disks accompany this manual when received through COSMIC. The first disk contains the source code, executable files, and sample output from these programs. The second disk contains the creep-fatigue data in a format compatible with these programs.

SOFTWARE

Five computer programs have been developed for TS-SRP: The first four are written in Fortran 77, and the fifth is written in interpretive BASIC. The purpose of each program is summarized below.

TABLE: The high-temperature creep-fatigue datasets are in NAMELIST format and are difficult to read. TABLE is used to print a dataset in a reader friendly format.

INDATA: INDATA is used to create new or add to existing datasets (in NAMELIST format) used by the programs FAIL and FLOW.

FAIL: The program FAIL is used to characterize the *failure* behavior of an alloy as given by the constants in the inelastic strain-range–life relations used by both the total strain version of SRP (TS-SRP) and the inelastic strain-range-based version of SRP. The equation constants for the elastic strain-range–life relation for pure fatigue or PP cycles are also determined.

FLOW: The program FLOW is used to characterize the *flow* behavior (the constitutive response) of an alloy as given by the constants in the flow equations used by TS-SRP.

---

[1]COSMIC, 382 East Broad St., Athens, GA 30602; (404) 542-3265, FAX (404) 542-4807.

LIFE: This program is used to predict the life of a specified cycle and uses the constants characterizing the failure and flow behavior as determined by FAIL and FLOW. LIFE is written in interpretive BASIC to avoid compiling and linking every time the equation constants are changed.

The use of these programs is illustrated in figure 1. The programs TABLE, FAIL, and FLOW require an input dataset in NAMELIST format from the database in figure 1. Life predictions are made using LIFE and the equation constants determined by FAIL and FLOW. The program INDATA is used to create a new dataset or add to an existing dataset.

As an example, assume that an analyst wishes to use the dataset to predict the life of a particular component. The first step could be to print the appropriate dataset (or sets) in a reader friendly format using TABLE. The next step would be to characterize the failure and flow behavior of the component material using the FAIL and FLOW. Life predictions could now be made. The appropriate constants obtained from FAIL and FLOW would be entered in the program LIFE. The analyst could now make the desired life prediction(s) using the program LIFE.

These programs can be easily tailored to meet the needs of the user. One enhancement we have found useful with FAIL and FLOW is an on-line plotting capability using Fortran callable plotting software. There are many commercial and shareware plotting software products available. If the user chooses to change the source code, it will be necessary to recompile and then link to create an executable file.

The programs (source codes and executable files) are on the first disk in the directory PROGRAMS and are listed in table I. The subroutines used by FAIL and FLOW are in separate files and must be compiled and linked to the appropriate main program to create an executable file as shown in table I. Sample output from these programs is found on the first disk in the directory OUTPUT.

TABLE I.— TS-SRP PROGRAMS, SUBROUTINES, AND
EXECUTABLE FILES IN DIRECTORY PROGRAMS.

| TABLE.FOR	Source file, used to list SRP datasets in reader friendly format.
TABLE.EXE	Executable file.
INDATA.FOR	Source file, used to create SRP datasets in NAME-LIST format.
INDATA.EXE	Executable file.
FAIL.FOR	Source file: determines the generic SRP inelastic strain range-cyclic life relations.
FAIL_S1.FOR	Source file: contains subroutines used with FAIL.FOR
FAIL.EXE	Executable file created by linking object files created by compiling the above two files.
FLOW.FOR	Source file: determines cycle-dependent stress-strain-time relations.
FLOW_S1.FOR	Source file: contains subroutines used with FLOW.FOR.
FLOW.EXE	Executable file created by linking object files created by compiling above two files.
LIFE.BAS	Used to calculate cyclic life for a given duty cycle.
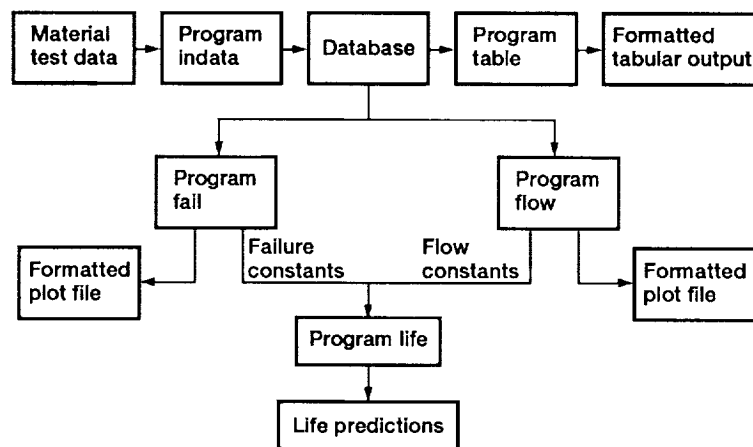
Figure 1.—Schematic of TS-SRP program organization.

TABLE II.— SUMMARY OF FULLY-
REVERSED, HIGH-TEMPERATURE,
LOW-CYCLE CREEP-FATIGUE DATA
IN DIRECTORY CFDATA

Alloy	Number of files	Temperature, °C
René 80	2	1000
IN-100	4	650, 732, 760, 900, 925, 1000
MAR M002	1	750, 850, 950, 1040
Nimonic 90	1	650, 810, 900
Waspaloy	2	700, 750
René 95	1	650
Amzirc	1	538
Narloy Z	1	538
TI6AL4V	1	450, 550,
2.25Cr-1Mo	6	316, 371, 427, 482, 538, 593
Hastelloy X	1	750
Haynes 188	1	316, 760, 316 ↔ 760, 760 ↔ 316
AF2-1DA	2	760
B1900+Hf	2	483, 871, 483 ↔ 871, 871 ↔ 483
Inconel 625	1	650, 815
Inconel 718	4	650
Inconel 738	3	750, 850
304 Stainless steel	2	650
316 Stainless steel	2	650, 705

The programs were developed using an IBM AT with a 80287 math co-processor, a hard drive, two floppy drives, MS-DOS (version 3.10), and advanced BASIC (version 3.0). The Fortran programs were compiled using the LAHEY compiler (version 4.0). If a Fortran compiler that does not support NAME-LIST is used, the datasets must be edited and the Fortran READ statements revised accordingly. The LINK software provided in MS-DOS version 3.10 was used to create these executable files.

The second disk accompanying this manual contains the creep-fatigue database in the directory CFDATA. The data are in six subdirectories under CFDATA: AGARD, ORNL, COBALT, NICKEL, STAINLES, and PUBLIC. Each subdirectory, with the exception of COBALT, contains several datasets. The COBALT subdirectory contains only one. All data are for fully reversed cycles, and in most cases for $R_\epsilon = -1$. The entire database contains data for 18 alloys in 38 files. The datasets are too numerous to list here, and the user should consult the README.DOC file in the directory CFDATA for details. A summary of the data is given in table II.

PROGRAM USAGE

The proper use of these programs will be illustrated by an example problem to predict the life of the nickel-based alloy AF2-1DA subjected to an isothermal (760 °C) compressive strain hold cycle (CHSC) test (ref. 4). The failure and flow relations needed in the prediction are obtained from two datasets (located on the second disk in the directory CFDATA\NICKEL), which contain the isothermal (760 °C) test results. These data were also used in reference 1. One dataset, AF21DA.NAS (ref. 2), features stress-hold creep-fatigue test data and will be used to determine the generic SRP failure relations. The second dataset, AF21DA.PWA (ref.3), features strain-hold creep-fatigue test data and will be used to determine the flow relations. Additional information on these datasets is found in the README.DOC file in the directory CFDATA on the data disk.

In discussing the use of these programs, the following convention will be used. Program prompts and output written to the screen will appear in typewriter type, and the response, if required, will be in bold type. A program is started by typing its name, which will also be shown herein in bold type. Please note that alphabetic input to these programs must be in CAPS. For simplicity, the following discussion assumes that the executable programs and the

4

input datasets are located on a disk in drive A and that program output is written to drive A. The programs will be discussed in the order given in the previous section.

TABLE

The input datasets to the Fortran programs FAIL and FLOW are in NAMELIST format and are difficult to read. TABLE is used to list the data in a reader friendly format. The output consists of two "pages" because there are too many columns to fit on a single page. Program output is sent to two files for subsequent printing. The program is written assuming that output will be in portrait mode with the printer set to print in compressed mode if a dot matrix printer is used or in 16.66 cpi (characters per inch) if a HP Laserjet II printer is used. The program can be easily changed to get output in landscape mode if desired.

The program is invoked by typing **TABLE**. The program then asks for the name of the input file:

ENTER DRIVE & FILENAME: **A:AF21DA.NAS**

The program then asks for the drive and filenames for the two "pages" of output.

ENTER DRIVE & FILENAME FOR PAGE 1 OF OUTPUT: **A:AF21DA.PG1**
ENTER DRIVE & FILENAME FOR PAGE 2 OF OUTPUT: **A:AF21DA.PG2**

This completes the input to TABLE.

FINISHED

The two output files are printed using the DOS command PRINT or TYPE as shown below or by using one's favorite ASCII text editor. Note that these two files will not appear on the screen in a reader friendly format because screen output does not recognize printer carriage control code.

TYPE **A:AF21DA.PG1>PRN**
TYPE **A:AF21DA.PG2>PRN**

The above two output files are in the directory OUTPUT of the first disk. The user should now use TABLE to list the dataset AF21DA.PWA.

INDATA

The program INDATA is used to ease the burden of generating datasets in NAMELIST format for the programs FAIL and FLOW. These programs require data from fully reversed tests with a negative value of R_ϵ. As an example, three tests (7, 16, and 52) from the dataset AF21DA.PWA located on the data disk in CFADTA\NICKEL will be used to generate a dataset named AF21DA.DAT. This example will illustrate the input for a PP cycle (HRSC), a CP strain-hold cycle (THSC), and a PC stress-hold (CCCR) cycle. Procedures for partitioning the σ-ϵ hysteresis loop are given in references 5 and 6. The types of cycles accepted by the FAIL and FLOW programs are listed in table III and are illustrated in figure 2. Data input will begin with test 7.
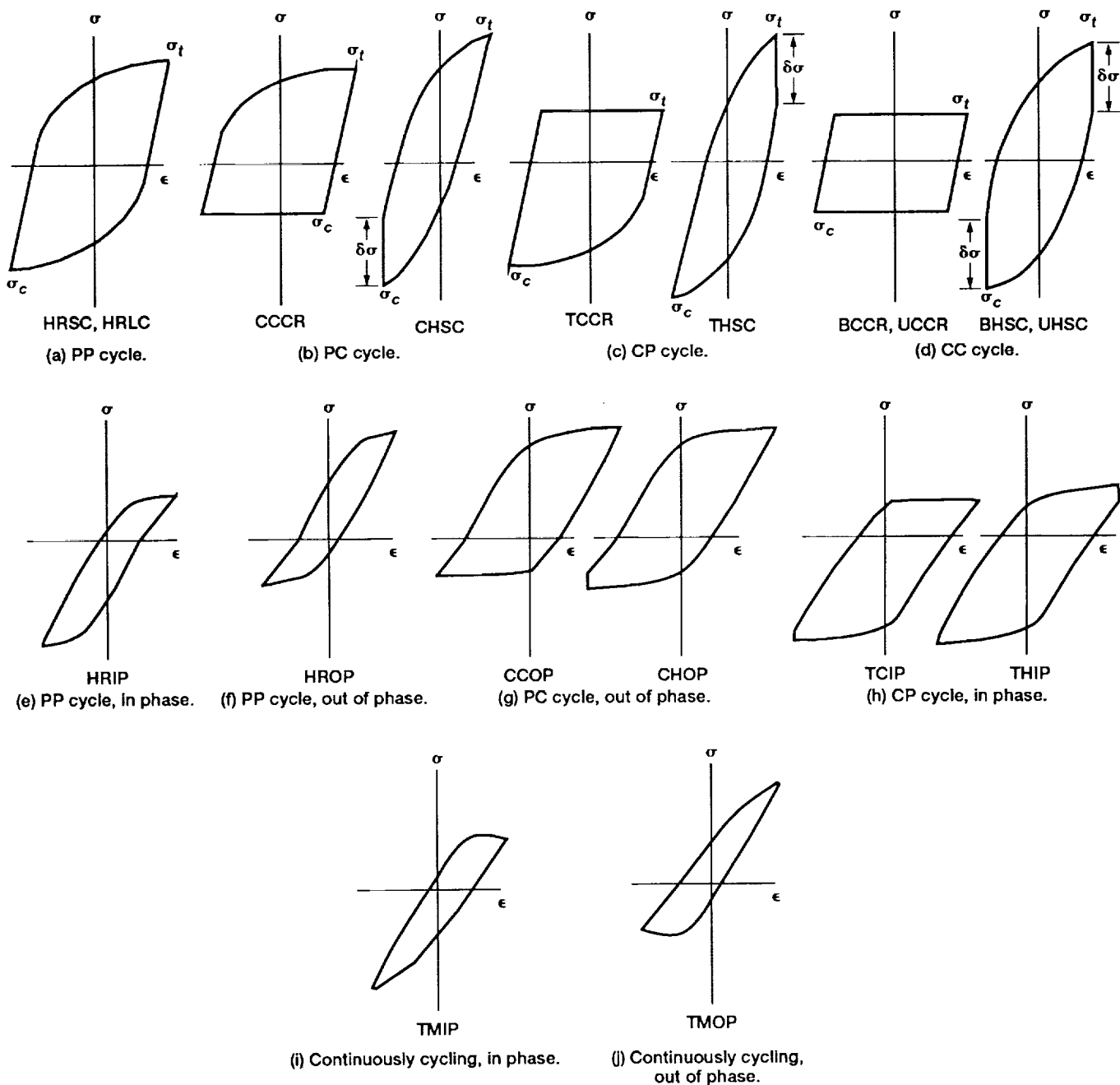
Figure 2.—Generic SRP hysteresis loops: isothermal (parts (a) - (d)), bithermal (parts (e) - (h)), and thermomechanical (parts (i) - (j)). (See table III.)

TABLE III. — FLOW.TYPES OF CYCLES ACCEPTABLE TO
PROGRAMS FAIL AND FLOW

Isothermal	PP cycle	HRLC high rate load cycle HRSC high rate strain cycle
	PC cycle	CCCR compressive cyclic creep rupture CHSC compressive strain-hold strain cycle FSSC fast-slow strain cycle[a]
	CP cycle	TCCR tensile cyclic creep rupture THSC tensile strain-hold cycle SFSC slow-fast strain cycle[a]
	CC cycle	BHSC balanced strain-hold strain cycle LRSC low rate strain cycle[a]
Bithermal	PP cycle	HRIP high rate in phase HROP high rate out of phase
	PC cycle	CCOP compressive cyclic creep rupture out-of-phase CHOP compressive hold strain cycle out-of-phase
	CP cycle	TCIP tensile creep in phase THIP tensile strain-hold in phase
Thermo- mechanical	PP cycle	None
	PC cycle	TMOP thermomechanical out-of-phase[a]
	CP cycle	TMIP thermomechanical in phase[a]
	CC cycle	None

[a]These cycles are accepted only by the program FLOW.

The program is invoked by typing **INDATA**. The following prompts result:

ENTER FILENAME OF DATASET TO BE CREATED: **A:AF21DA.DAT**

The filename can include the drive and directory, if required.

IS A NEW DATASET BEING CREATED? Y/N: **Y**

A new dataset is being created, so the appropriate response is **Y**(YES). The response here should be **N**(NO) if a dataset is being created to be appended to an existing dataset. A response of **N** causes the program to skip the next three prompts and asks for the units of the input stress values.

A NEW DATASET IS BEING CREATED
ENTER NAME OF DATA SOURCE: **PWA;NAS3-22387**

Note that there can be no imbedded blanks or commas in the data source name because those characters act as delimiters.

ENTER MATERIAL NAME: **AF2-1DA**

Again, there can be no imbedded blanks or commas in the input.

ENTER NUMBER OF DATA POINTS: **3**

As noted above, data for three tests are to be entered for this example.

ARE STRESS UNITS FOR INPUT DATA MPa(M) OR KSI(K)? **M**

The program is written to accept stress values in either megapascals (MPa) or kips per square inch (ksi) units. Output is in megapascals.

ENTER SPECIMEN No. AND TEST TYPE: 7 HRSC

In this case the blank is a delimiter between the specimen number and test type and is required. The test type HRSC (see fig. 2(a)) indicates that the test is isothermal with no time-dependent cyclic strains present in the hysteresis loop. Note that the prompts that follow will vary somewhat depending on the test type. Additional information may be added at this line to provide for the printing of footnotes when running TABLE. The user will have to modify the source code TABLE.FOR to print the desired footnotes.

ENTER TENSILE TEMP(TTEN) AND COMPRESSION TEMP(TCOMP)
FOR ISOTHERMAL CASE, ENTER "0" FOR TCOMP: 760 0

For isothermal and bithermal cycles the temperature in the tensile-half of the hysteresis loop is TTEN, and the temperature in the compressive-half of the loop is TCOMP. For an isothermal test a "0" entry for TCOMP reduces the amount of user input. The program then calculates TCOMP, which in this case is 760 °C. For a thermomechanical cycle, TTEN is the temperature at the tension strain limit of the loop, and TCOMP is the temperature at the compressive strain limit. Both temperatures must be entered. The program assumes that the temperature is in degrees centigrade.

ENTER CYCLE FREQUENCY, HZ: .5

Note that for cycles that contain only time-independent inelastic strains (PP cycles), the program calculates the cyclic strain rate assuming a triangular wave form and using the cycle frequency and the total strain range.

ENTER HALF-LIFE MAX STRESS, MIN STRESS, & STRESS RANGE
IF ALL THREE VALUES ARE KNOWN, ANY ONE MAY BE
ENTERED AS "0": 1077.9 1130.6 0

The <u>absolute</u> value of the stresses are entered. If all three values are known, it is only necessary to enter any two of them. The unknown value must be entered as "0," and the program will calculate that value, thus reducing user input. If only one value is known, enter that value in the appropriate sequence with the unknown values entered as "0." Note that the minimum stress will be compressive in a fully reversed test with a negative value of R_ϵ. (See fig. 2(a).)

ENTER % CHANGE (+/-) IS STRESS RANGE FROM
FIRST TO HALF-LIFE CYCLE: 7.7

Cyclic strain hardening or softening is defined as the percent change in the stress range from the first to the half-life cycle. Softening is indicated by a negative value. This value is not used by FAIL or FLOW but is included to better characterize the cyclic mechanical properties of the alloy.

ENTER HALF-LIFE STRAINRANGE VALUES - %
TOTAL, ELASTIC & INELASTIC: 1.485 1.150 0

It is necessary to enter only any two of these values. The remaining value may be entered as "0," and the program will calculate it.

ENTER VALUES FOR No, Ni, AND N5: 0 0 0

Because these values were not determined for this test, all three values must be entered as unknowns. These values define the number of cycles required to produce defined changes in the cyclic stress-strain hysteresis loop. They are not used by any of the programs but are recorded to better characterize the cyclic behavior of the alloy. They are defined in reference 7 as follows:

8

No   Number of cycles to first indication of cracking

Ni   Number of cycles when ratio of maximum tensile to maximum compressive stress decreases 10 percent from half-life or stabilized value.

N5   Number of cycles when stress range decreases 5 percent from half-life or stabilized value

The user can change these definitions if so desired.

```
ENTER CYCLES TO FAILURE (NF) TOTAL TEST TIME, HRS
ENTER NEGATIVE VALUE FOR NF IF SPECIMEN DNF: 114 .07
```

The program FAIL ignores data from tests where the specimen did not fail (DNF). However, data from DNF tests can be used by FLOW. The definition of failure is left to the user.

```
QUIT? ,Y/N N
```

All of the data for specimen 7 have been entered. You are given the choice of quitting or entering data for another test. The appropriate response here is N so that data for the second test can be entered. The following values are for test 16, a tensile hold strain cycle (THSC) test as shown in figure 2(c).

```
ENTER SPECIMEN No. AND TEST TYPE: 16 THSC
ENTER TENSILE TEMP(TTEN) AND COMPRESSION TEMP(TCOMP)
FOR ISOTHERMAL CASE, ENTER"0" FOR TCOMP: 760 0
ENTER CYCLE FREQUENCY, HZ: .033
```

This value is determined by the tension hold time of 30 sec and the cyclic strain rate.

```
ENTER TEST TYPE
1 = STRAIN HOLD
2 = STRESS HOLD
3 = CONTINUOUS CYCLING          1
```

Because data for a strain hold test are being entered, the appropriate response is 1. A continuous cycling test is defined as one where the tension-going and/or compression-going strain rates are slow enough to produce time-dependent inelastic strains (see table III).

```
ENTER TEN.-GOING & COMP-GOING STRAINRATES - %/SEC
FOR EQUAL RATES, ENTER "0" FOR COMP-GOING RATE: 1.2 0

ENTER TEN. AND/OR COMP. STRAIN HOLD TIME, SEC: 30 0
```

Since this is a tensile strain-hold strain cycle, the hold time in compression is zero (see fig. 3).

```
ENTER HALF-LIFE MAX STRESS, MIN STRESS, & STRESS RANGE
IF ALL THREE VALUES ARE KNOWN, ANY ONE MAY BE
ENTERED AS "0": 997 1221.8 0

ENTER TEN. & COMP. STRESS RELAXATION: 166.7 0
```

This is the amount of stress relaxation during the tensile strain-hold time. There is no compressive stress relaxation during a THSC test (see figs. 2(c) and 3).

```
ENTER % CHANGE (+/-) IN STRESS RANGE FROM
FIRST CYCLE TO HALF-LIFE CYCLE:5.16
```

The specimen experienced cyclic hardening.

```
ENTER HALF-LIFE STRAINRANGE VALUES - %
TOTAL, ELASTIC, & INELASTIC STRAINRANGE: 1.245 1.007 0

ENTER HALF-LIFE VALUES OF INELASTIC STRAINRANGE - %
EPP, EPC, ECP ECC: .145 0 .093 0
```
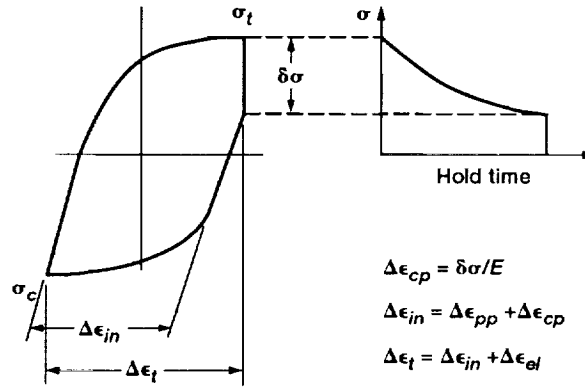These are the PP, PC, CP, and CC components of the inelastic strain range. All four values

$$\Delta\epsilon_{cp} = \delta\sigma/E$$

$$\Delta\epsilon_{in} = \Delta\epsilon_{pp} + \Delta\epsilon_{cp}$$

$$\Delta\epsilon_t = \Delta\epsilon_{in} + \Delta\epsilon_{el}$$

Figure 3.—Partitioning of tensile hold strain cycle (THSC).

$$\Delta\epsilon_t = \Delta\epsilon_{in} + \Delta\epsilon_{el}$$

$$\Delta\epsilon_{in} = \Delta\epsilon_{pp} + \Delta\epsilon_{cp}$$
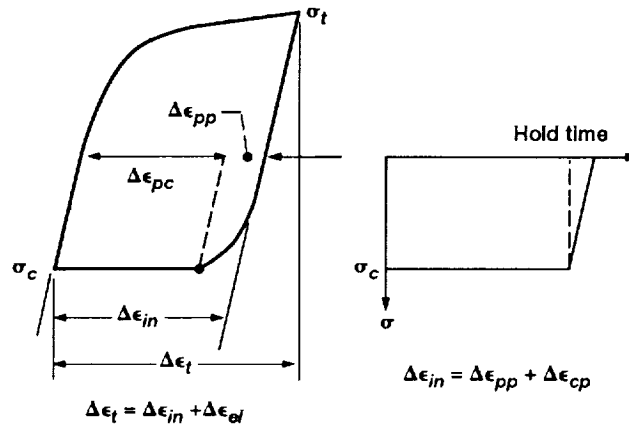
Figure 4.—Partitioning of compressive cyclic creep rupture cycle (CCCR).

10

must be entered and must sum up to the inelastic strain range. If they do not, the program will prompt the user to check the input values.

```
ENTER VALUES FOR No, Ni, AND N5: 0 0 0

ENTER CYCLES TO FAILURE (NF) AND TOTAL TEST TIME, HRS
ENTER NEGATIVE VALUE FOR NF IF SPECIMEN DNF: 395 3.52

QUIT? ,Y/N N
```

All of the data for test 16 have been entered, and we now enter the data for test 52. This is a cyclic compressive creep rupture test (CCCR) as shown in figure 2(b).

```
ENTER SPECIMEN No. AND TEST TYPE: 52 CCCR

ENTER TENSILE TEMP(TTEN) AND COMPRESSION TEMP(TCOMP)
ENTER ISOTHERMAL CASE, ENTER "0" FOR TCOMP: 760 0

ENTER CYCLE FREQUENCY, HZ: 1.1E-04

ENTER TEST TYPE
1 = STRAIN HOLD
2 = STRESS HOLD
3 = CONTINUOUS CYCLING            2

ENTER TEN-GOING & COMP-GOING STRAINRATES - %/SEC
FOR EQUAL RATES, ENTER "0" FOR COMP-GOING RATE: 1.2 0

ENTER TEN. AND/OR COMP. STRESS HOLD TIME, SEC: 0 8760
```

There is no tension stress-hold time for this type of cycle (see fig. 4).

```
ENTER HALF-LIFE MAX STRESS, MIN STRESS, & STRESS RANGE
IF ALL THREE VALUES ARE KNOWN, ONE MAY BE
ENTERED AS "0": 1092.9 620.6 0

ENTER % CHANGE (+/-) IN STRESS RANGE FROM
FIRST TO HALF-LIFE CYCLE: -2.35
```

The specimen experienced cyclic softening.

```
ENTER HALF-LIFE STRAINRANGE VALUES - %
TOTAL, ELASTIC,AND INELASTIC STRAINRANGE: 1.200 .925 0

ENTER EPP, EPC, ECP, ECC VALUES - %: .100 .175 0 0

ENTER VALUES FOR No, Ni, AND N5: 0 0 0

ENTER CYCLES TO FAILURE (NF) AND TOTAL TEST TIME, HRS
ENTER NEGATIVE VALUE FOR NF IF SPECIMEN DNF: 69 18.25

QUIT?, Y/N Y
FINISHED
```

This completes the data entry for this example. A copy of this example is in the directory OUTPUT on the first disk. A comparison of the values in datasets AF21DA.PWA and AF21DA.DAT will reveal some superficial differences in format. This is because AF21DA.PWA was generated manually; numerically the values are identical.

FAIL

This Fortran program is used to determine the four generic SRP inelastic strain-range–cyclic life relations and the time-independent elastic strain-range–cyclic life relation for PP cycles. All equation constants are determined by a log-log linear regression analysis of the

appropriate data. The program will accept data from either isothermal or bithermal tests as listed in table III. The life relations to be determined are

$$\Delta\epsilon_{in} = C_{ij}(N_{ij})^c \tag{1}$$

$$\Delta\epsilon_{el} = B(N_{pp})^b \tag{2}$$

where $ij = pp$, pc, cp, or cc. The notation used here is the same as that in reference 1.

The user also has the option of determining the time-dependent elastic strain range-life relations for cycles with time-dependent inelastic strains (PC, CP, and CC cycles).

$$\Delta\epsilon_{el,ij} = B(N_{f0})^b \tag{3}$$

where $B = B(t)$ and N_{f0} is the life under theoretical zero mean stress conditions. This option can be used when the hold time per cycle is a controlled variable. This relation is generally not used to make life predictions but can be used to verify the calculated elastic strain range-life relation intercept (eq. (7) in ref. 1)) if the wave shape of the data used to determine the life relation is appropriate for the duty cycle being predicted.

As recommended in reference 1, data from stress-hold tests are preferred when determining the constants in equation (1) for cycles involving creep ($ij = pc$, cp, and cc) because this type of cycle can impart a large amount of cyclic creep damage to the material. The dataset AF21DA.NAS contains this type of data and will be used here. Other types of tests, such as strain-hold, which impart much less cyclic creep damage can be used, but it may be more difficult to observe the default damage fraction criterion of 0.50 (ref. 1) when determining the PC, CP, and CC life relations.

The program first determines the inelastic and elastic strain-range–PP life relations (eqs. (1) and (2)). The PC, CP, and CC strain–life relations (eq. (1)), are then determined, if adequate data are available in the dataset, in this order. The program requires a minimum of two points for the log-log linear regression analysis determining the equation constants. Note that results may be questionable when only a few data points are used in the regression analysis.

This program is invoked by typing **FAIL,** and the following screen prompts occur:

ENTER DRIVE & FILENAME FOR INPUT: **A:AF21DA.NAS**

As noted above, this dataset contains the preferred stress-hold data and is assumed for this example to reside on a disk in drive A.

SEND OUTPUT TO PRINTER(P) OR FILE(F)? **F**

A response of **F** permits the creation of a file for program output.

ENTER DRIVE & FILENAME FOR OUTPUT: **A:AF21DA.FAL**

This prompt appears if the response to the above prompt was **F**.

THE DEFAULT VALUE OF MIN INELASTIC STRAIN IS 0.10000E-3
DO YOU WANT TO CHANGE IT?, YES(Y) OR NO(N): **N**

The default value is the smallest inelastic strain range that can be experimentally determined with satisfactory accuracy. All tests with an inelastic strain range less than the minimum value are rejected with the exception of PP tests. Test data with an inelastic strain range less than the minimum are used to determine the elastic PP failure relation (eq. (2)).

DO YOU WANT TO WRITE X-Y DATA FILES FOR OFF-LINE
PLOTTING? YES(Y) OR NO(N): **Y**

12

This response permits the creation of a file for off-line plotting using appropriate commercially available software.

DRIVE & FILENAME FOR OUTPUT: **A:AF21DAXY.FAL**

This prompt appears if the response to the above prompt was **Y**.

ISOTHERMAL (ISO) OR BITHERMAL (BTH) CYCLES? **ISO**

A life prediction is to be made for an isothermal test at 760 °C, so the appropriate response is **ISO**.

INPUT ISOTHERMAL TEMP C: **760**

DO YOU WANT TO USE THE MEAN STRESS CORRECTION OF
HALFORD & NACHTIGALL ? YES(Y) OR NO(N): **Y**

This method of accounting for mean stress effects on cyclic life was developed for nickel-based alloys and is appropriate in this example. However, it may not be appropriate for other nickel-based alloys as noted in (ref. 1). Generally, each alloy should be considered separately when evaluating mean stress effects. The PP line should be determined using data from tests with a $R_c = -1$. A small negative mean stress develops for this loading condition and is ignored.

INPUT ELASTIC LINE SLOPE "B", ABSOLUTE VALUE: **.117**

This prompt appears only if the response to the previous prompt was **Y**. If the value of b is not known, it can be determined with this program with a response of **N** to the preceeding prompt. The program is then terminated at the end of the PP section and run again. Note that the mean stress correction procedure requires the *absolute* value of b. The program is coded to ensure that the absolute value of b is used in determining the mean stress correction.

The program now displays the number of data points available for each type of SRP cycle.

```
NUMBER OF PP POINTS =      9
NUMBER OF PC POINTS =      6
NUMBER OF CP POINTS =      3
NUMBER OF CC POINTS =      3
DATA POINTS FOR CURVE FITTING
Press Enter to Continue
```

Note that each type of SRP cycle has more than two points available for determining the constants in equations (1) and (2).

```
              CRUNCHING PP DATA
++++++++++++++++++++++++++++++++++++++++++++++++++
PP CONSTANTS DETERMINED, DO YOU WANT
TO CONTINUE? YES(Y) OR NO(N): Y
```

The program terminates if the response is **N**. The constants in the $\Delta\epsilon_{in} - N_{pp}$ and $\Delta\epsilon_{el} - N_{pp}$, relations are now determined (eqs. (1) and (2)). The program then determines the PC, CP, and CC life relations in this order if sufficient data are available in the dataset.

```
              CRUNCHING PC DATA
**************************************************
```

At this point the program will display the calculated damage fraction for each data point (if it is less than the default value of 0.50) and ask the user if this test is to be included in the analysis. This gives the user the choice of including a test when data are limited or when the damage fraction is sufficiently close to the default value. In this example the damage fraction for each test is ≥0.50. The program now checks again for the minimum number of acceptable data

points (two points) required for determining the constants in the $\Delta\epsilon_{in} - N_{pc}$ relation (eq. (1)). Since all the data points have a damage fraction ≥ 0.50, all six data points are used. If fewer than two points are acceptable, the program skips to the next (CP) section.

Note that two $\Delta\epsilon_{in} - N_{ij}$ life relations are determined for each type of cycle (PC, CP, and CC). The first is obtained from a log-log linear regression of the data, as noted earlier. The second relation is obtained by forcing a line through the centroid of the $\Delta\epsilon_{in} - N_{ij}$ data parallel to the PP inelastic line. This second relation is used in TS-SRP.

```
DETERMINE ELASTIC LINE AS A FUNCTION OF
HOLD TIME? YES(Y) OR NO(N): N
```

This option determines the $\Delta\epsilon_{el} - N_{f0}$ relation for cycles where the hold time per cycle is a controlled variable. The appropriate response is N because this dataset contains only stress-hold tests where the creep time per cycle at half-life varies for each test. The response could be Y if strain-hold tests, for example, were being analyzed where the hold time per cycle is a controlled variable. Note that the SRP inelastic strain-range–life relations for cycles with time-dependent inelastic strains are assumed to be insensitive to the wave form (stress hold, strain hold) used to generate the data. However, the intercept, B, of the elastic strain range-life relation (eq. (3)), is a function of both failure and flow terms and thus is sensitive to wave form.

This completes the analysis of the PC data, and the program will now analyze the CP data if sufficient data (number of CP points ≥ 2) are available.

```
              CRUNCHING CP DATA
**********************************************************
```

The damage fraction for all three tests is ≥ 0.50, and the constants in the two $\Delta\epsilon_{in} - N_{cp}$ relations (eq. (1)) are now determined as noted previously.

```
DETERMINE ELASTIC LINE AS A FUNCTION OF
HOLD TIME ? YES(Y) OR NO(N): N
```

This completes the analysis of the CP data, and the program will now analyze the CC data if sufficient data are available (number of CC points ≥ 2).

```
              CRUNCHING CC DATA
**********************************************************
CC DAMAGE FRACTION =    0.409752
DAMAGE FRACTION LESS THAN 0.50. DO YOU WANT
TO INCLUDE THIS POINT? YES(Y) OR NO(N): Y
```

The damage fraction is fairly close to the desired value of 0.50, and we choose to include it because of the paucity of data CC (three points). The constants in the two $\Delta\epsilon_{in} - N_{cc}$ relations (eq. (1)) are now determined as noted earlier.

```
DETERMINE ELASTIC LINE AS A FUNCTION OF
HOLD TIME ? YES(Y) OR NO(N): N
FINISHED
```

This completes the terminal session for FAIL. Two output files have been generated during this terminal session, AF21DA.FAL and AF21DAXY.FAL. These files can be found in the directory OUTPUT of the first disk, and the user should study these output files to enhance his/her understanding of the program. The former file contains the constants for the SRP life relations and the data used to determine them in a reader friendly format. The latter file contains these same data but in an X-Y format suitable for plotting using commercially available software. This file will undoubtedly have to be edited before submitting it to the plotting software because it contains additional information to help identify the X-Y data.

A plot of the relations determined by FAIL is shown in figure 5. A comparison of the results shown in figure 5 with those shown in figure 7 of reference 1 will reveal small differences in the equation constants. There are two reasons for this: First, the results in reference 1 were obtained on a totally different machine (a mainframe); and second, minor changes have been made in the program.

FLOW

This Fortran program is used to obtain the time and wave-shape dependent flow variables that are used to determine the intercepts B and C' in equation (4) and the stress and strain values required for the Halford-Nachtigall mean-stress-correction equation (ref. 1).

$$\Delta \epsilon_t = B(N_{f0})^b + C'(N_{f0})^c \tag{4}$$

The value of B and C' are obtained from the following equations:

$$B = K_{ij}(C')^n \tag{5}$$

$$C' = \left\{ \Sigma F_{ij}(C_{ij})^{1/c} \right\}^c \tag{6}$$

where K_{ij} is the cyclic strain coefficient, n is the cyclic strain hardening exponent, F_{ij} is the strain fraction and $ij = pp$, pc, cp, or cc. The constants C_{ij} and c are defined in equation (1). The value of n can be determined in two ways: The first is by a regression analysis using PP test data and the equation

$$\Delta \epsilon_{el,pp} = K_{pp}(\Delta \epsilon_{in})^n \tag{7}$$

The second is by using the relation $n = b/c$, where the fatigue exponents b and c in equations (1) and (2) are determined from the PP failure tests (ref. 6). The user must determine which approach is more appropriate. In this example, we choose to determine the strain hardening exponent n by a log-log linear regression analysis using equation (7) and the dataset AF21DA.NAS. Note that n is related to the failure terms b and c and that this dataset was used to characterize failure behavior. The remaining flow variables are determined by a log-log linear multiple regression analysis using equation (8):

$$y = A'(\Delta \epsilon_t)^\alpha (t)^m \tag{8}$$

where the dependent variable y represents the flow variable to be determined and is a function of two independent variables, total strain range, $\Delta \epsilon_t$, and time per cycle, t. For a given alloy the constants A', α, and m are dependent on temperature, and wave shape and must be determined for each flow variable. For nonisothermal cycles the constants depend on the maximum and minimum temperatures and the phase relation between mechanical load and temperature. The flow variables determined using equation (8) are
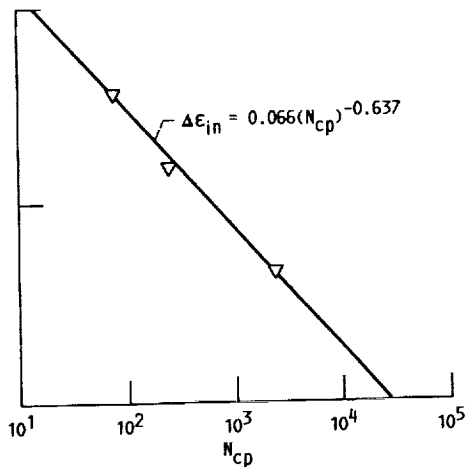
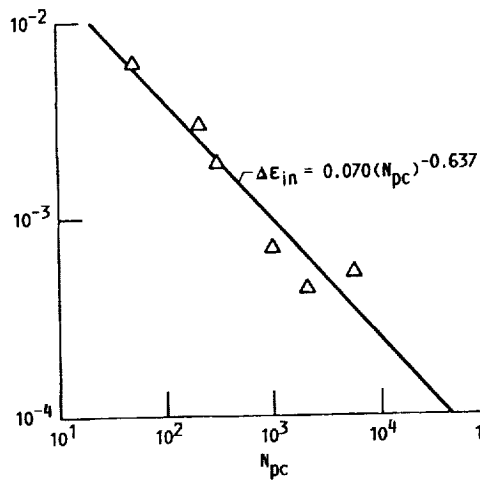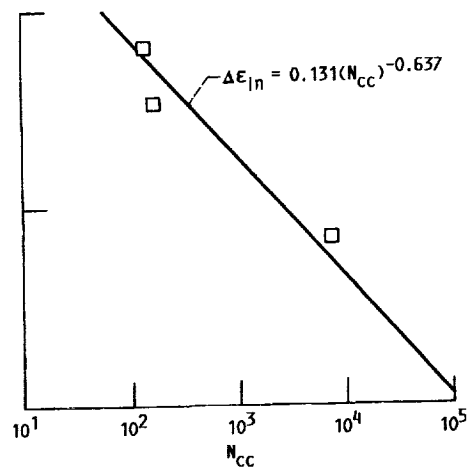|	
σ_t	stress at positive strain limit of cycle
σ_c	stress at negative strain limit of cycle
$\Delta \sigma$	stress range, $\sigma_t + \sigma_c$
$\Delta \epsilon_{el}$	elastic strain range
F_{ij}	strain fraction, $\Delta \epsilon_{ij}/\Delta \epsilon_{in}$
K_{ij}	cyclic strain coefficient

$$\Delta\varepsilon_{el,pp} = 0.022(N_{pp})^{-0.117}$$

(a) Elastic PP line.

$$\Delta\varepsilon_{in} = 0.103(N_{pp})^{-0.637}$$

(b) Inelastic PP line.

$$\Delta\varepsilon_{in} = 0.066(N_{cp})^{-0.637}$$

(d) Inelastic CP line.

$$\Delta\varepsilon_{in} = 0.070(N_{pc})^{-0.637}$$
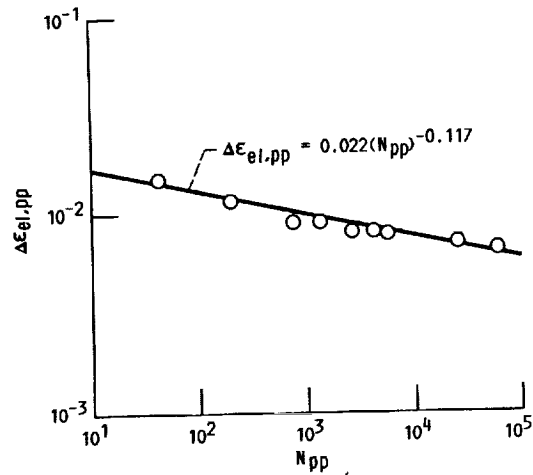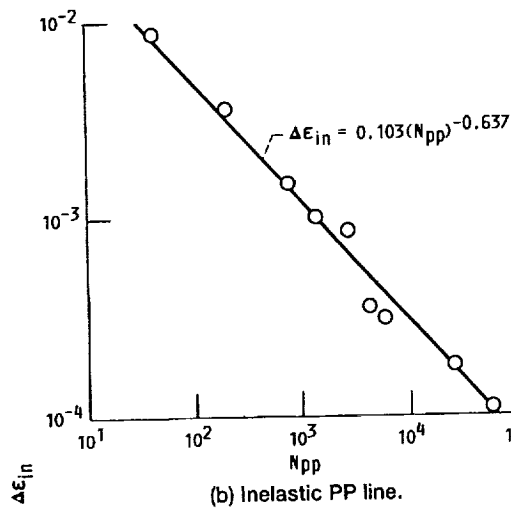
(c) Inelastic PC line.

$$\Delta\varepsilon_{in} = 0.131(N_{cc})^{-0.637}$$

(e) Inelastic CC line.

Figure 5.—Example of graphical depiction of output from program FAIL. Material, AF2-1DA; temperature, 760 °C (data from ref. 2).

16

The variables K_{ij} and F_{ij} are used to determine the intercepts B and C' in equation (4), and the remaining variables are used to determine the Halford-Nachtigall mean-stress correction. A word of explanation is in order regarding the correlations used in determining the mean stress. We have found it best to use the compressive stress correlation (σ_c) and the stress range correlation ($\Delta\sigma$) for PC cycles, and the tension stress correlation (σ_t) with the stress range correlation ($\Delta\sigma$) for CP cycles. For CC cycles either the tension or compression stress correlation may be used along with the stress range correlation. The mean stress can then be determined.

The data used to determine the mean-stress correlations can come from both failure tests or flow tests where the specimen is cycled until the stress-strain hysteresis loop satisfies the criteria for stability (ref. 1). Note that the type of cycle used to determine the constants in equation (8) must be appropriate to the duty cycle to be predicted.

The program is invoked by typing **FLOW**, and the following screen prompts occur:

DRIVE & FILE NAME FOR INPUT: **AF21DA.NAS**

As noted earlier, this dataset is used to determine the value of n in equation (7).

SEND OUTPUT TO PRINTER (P) OR FILE (F)? **F**

This response permits the creation of a file for output.

DRIVE & FILE NAME FOR OUTPUT: **A:AF21DA.N**

This prompt appears only if the response to the previous prompt was **F**.

DO YOU WANT TO WRITE X-Y DATA FILES FOR OFF-LINE
PLOTTING? YES(Y) OR NO(N): **Y**

A response of **Y** permits a file to be created for off-line plotting using appropriate commercially available software.

DRIVE & FILENAME FOR OUTPUT: **A:AF21DAXY.N**

This response appears if the response to the previous prompt was **Y**.

THE DEFAULT VALUE OF MINIMUM INELASTIC S.R. IS 0.1000E-3
DO YOU WANT TO CHANGE IT? YES(Y) OR NO(N): **N**

The default value will not be changed. Note that three flow variables are functions of the inelastic strain range. They are the cyclic strain hardening exponent n, the strain fraction F_{ij}, and the cyclic strain coefficient K_{ij}. If a test has an inelastic strain range value less than the minimum, it is not used to determine the equation constants for these three flow variables. However, such a test can be used to determine the stress and elastic strain range correlations.

ENTER TYPE OF DATA FOR ANALYSIS
1 = FLOW DATA ONLY
2 = FAILURE DATA ONLY
3 = FLOW AND FAILURE DATA **2**

The user has the option of using data from flow tests only, failure tests only, or both. This dataset contains only failure data, so the appropriate response is **2**.

ISOTHERMAL (ISO) OR BITHERMAL (BTH)
OR THERMOMECHANICAL (TMF) CYCLES? **ISO**

Life predictions are to be made for isothermal data at 760 °C, so the appropriate response is **ISO**.

INPUT ISOTHERMAL TEMP: **760**

The program now displays the number of data points available for each type of SRP cycle.

```
BCCR - NOT PROGRAMMED FOR THIS CYCLE TYPE
BCCR - NOT PROGRAMMED FOR THIS CYCLE TYPE
BCCR - NOT PROGRAMMED FOR THIS CYCLE TYPE
NUMBER OF PP POINTS =     9
NUMBER OF PC POINTS =     6
NUMBER OF CP POINTS =     3
NUMBER OF CC POINTS =     0
NUMBER OF DATA POINTS FOR CURVE FITTING
Press Enter to Continue

ANALYZE PP DATA ?, YES(Y) OR NO(N):  Y
```

The value of the cyclic strain hardening exponent n in equation (7) is to be determined from the PP test data.

```
CRUNCHING PP DATA
```

The constants in equation (7) are now determined and are shown in figure 6.

```
TERMINATE PROGRAM ? YES(Y) OR NO(N):  Y
```

```
FINISHED
```

The desired correlation has been obtained, and the program is stopped. Two output files have been created: The first, AF21DA.N, contains the correlation for the strain hardening coefficient. The second, AF21DAXY.N, contains the same information but in an X-Y format for plotting. These files are on the first disk in the directory OUTPUT.

The remaining flow correlations are determined using the dataset AF21DA.PWA, which features strain-hold test data. This is necessary because we intend to predict the life of a compressive strain-hold (CHSC) cycle. Typing **FLOW** restarts the program, and the following prompts appear:

```
DRIVE & FILENAME FOR INPUT:  A:AF21DA.PWA
```

```
SEND OUTPUT TO PRINTER (P) OF FILE (F)?  F
```

```
DRIVE & FILENAME FOR OUTPUT:  A:AF21DA.FLO
```
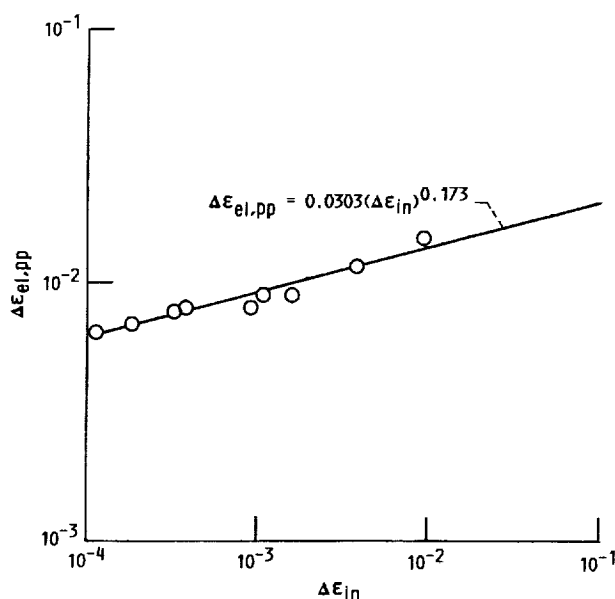

Figure 6.—Example of graphical depiction of output from program FLOW showing correlation to obtain strain hardening exponent. Material, AF2-1DA; temperature, 760 °C (data from ref. 3).

```
DO YOU WANT TO WRITE X-Y DATA FILES FOR OFF-LINE
PLOTTING YES(Y) OR NO(N):  Y

DRIVE & FILENAME FOR OUTPUT:  A:AF21DAXY.FLO

THE DEFAULT VALUE OF MINIMUM INELASTIC S.R. IS 0.10000E-3
DO YOU WANT TO CHANGE IT? YES(Y) OR NO(N):  N

ENTER TYPE OF DATA FOR ANALYSIS
1 = FLOW DATA ONLY
2 = FAILURE DATA ONLY
3 = FLOW AND FAILURE DATA  2
```

This dataset contains only failure data for the strain-hold tests.

```
ISOTHERMAL (ISO) OR BITHERMAL (BTH)
OR THERMOMECHANICAL (TMF) CYCLES?  ISO
```

We intend to predict the life of an isothermal cycle, so **ISO** is the appropriate response.

```
INPUT ISOTHERMAL TEMP:  760
```

The program now displays the number of data points available for each type of SRP cycle. Note that a limited number of cycle types is built into the program at this time. The user can easily modify the program to accept other cycle types. If a test cycle is of a type not coded into the program, it will be rejected. In this case three tensile creep extension ratcheting (TCER) tests are rejected. A TCER cycle is a tension stress-hold cycle with a fixed hold time per cycle, and the maximum strain limit is not controlled. A list of the cycle types coded into the program is given in table III.

```
BCCR - NOT PROGRAMMED FOR THIS CYCLE
BCCR - NOT PROGRAMMED FOR THIS CYCLE
TCER - NOT PROGRAMMED FOR THIS CYCLE TYPE
TCER - NOT PROGRAMMED FOR THIS CYCLE TYPE
TCER - NOT PROGRAMMED FOR THIS CYCLE TYPE
NUMBER OF PP POINTS =      8
NUMBER OF PC POINTS =     12
NUMBER OF CP POINTS =     12
NUMBER OF CC POINTS =      3
NUMBER OF DATA POINTS FOR CURVE FITTING
Press Enter to Continue
ANALYZE PP DATA ? YES(Y) OR NO(N):  N
```

The appropriate response here is **N** because the cyclic strain hardening exponent has already been determined.

```
ANALYZE PC DATA, YES(Y) OR NO(N)?  Y
CRUNCHING PC DATA:
ENTER WAVE SHAPE FOR CORRELATION,
CHSC, CCCR, FSSC:  CHSC
```

For isothermal conditions, three cyclic wave shapes are currently built into the program for PC cycles: CHSC, CCCR, and FSSC (see table III). Since we intend to predict the life of a compressive strain-hold test, **CHSC** is the appropriate choice.

```
SET LIMITS ON TOTAL STRAINRANGE?, YES(Y) OR NO(N):  N
```

There are occasions where a good correlation is not obtained over the entire span of the data as measured by the total strain range (ref. 9). This option gives the user the opportunity to limit data to tests within a specified maximum and minimum total strain range. For this example there is no need to set limits on the total strain range.

```
DETERMINE ALPHA BY TRIAL(T)
OR MULTIPLE REGRESSION(M):  M
```

As noted earlier, three constants in equation (8) are to be determined by a log-log multiple linear regression analysis. When the span of the total strain range data are limited either by choice or by circumstances, a better curve fit can usually be determined if the value of α is estimated by trial and error using the **T** option rather than by the log-log linear multiple regression option **M**. The α that gives the best correlation coefficient is the best value. When the **T** option is used, the dependent variable in equation (8) becomes a function of only one independent variable, time, and the program requires a minimum of two points with different time values for the log-log linear curve fit. The program will ask for the value of α to be used. In some cases, the total strain range may be a constant, and the **T** option is required with the value of α set equal to zero.

When the **M** option is used, the dependent variable is a function of two independent variables, total strain range and time, and is the preferred option when adequate data are available. The program requires a minimum of four points (two values of total strain range and two values of time) for the curve fit but does not contain a criteria to determine if the data are adequate. Adequate data are available in this example, and we choose the **M** option.

In order to make a life prediction using equation (4), the elastic line intercept B (eq. (5)) and the equivalent inelastic line intercept C' (eq. (6)) must be determined. These intercepts are determined using the correlations for the strain fraction F_{ij} and the cyclic strain coefficient K_{ij}. The value of the cyclic strain hardening exponent n must be known before determining K_{ij}.

Since we intend to account for mean stress effects on life for a CHSC test, correlations for compressive stress, σ_c, stress range, $\Delta\sigma$, and elastic strain range, $\Delta\epsilon_{el}$, are required. The two stress correlations are used to calculate the mean stress present in the cycle. As noted earlier, the correlation for σ_c is appropriate when determining the mean stress in a PC cycle. The flow correlations can be determined in any sequence. We choose to proceed in numerical order starting with the σ_c correlation. We are now presented with the following menu:

```
SELECT TYPE OF CORRELATION
OPTION 2: TENSION STRESS VS HOLD TIME
OPTION 3: COMPRESSION STRESS VS HOLD TIME
OPTION 4: STRESS RANGE VS HOLD TIME
OPTION 5: ELASTIC STRAINRANGE VS HOLD TIME
OPTION 6: Fij VS HOLD TIME
OPTION 7: Kij VS HOLD TIME
OPTION 8: TRANSFER TO NEXT SECTION
OPTION 9: QUIT PROGRAM
ENTER VALUE: 3
No. OF POINTS FOR CURVE FIT =    9
```

The constants A', α, and m in equation (8) for the σ_c correlation are determined.

```
NEW CORRELATION OR NEW ALPHA? YES(Y) OR NO(N): Y

CRUNCHING PC DATA:

ENTER WAVE SHAPE FOR CORRELATION,
CHSC, CCCR, FSSC: CHSC

SET LIMITS ON TOTAL STRAINRANGE? YES(Y) OR NO(N): N

DETERMINE ALPHA BY TRIAL(T)
OR MULTIPLE REGRESSION(M)? M
```

The program presents the menu for the next correlation.

```
SELECT TYPE OF CORRELATION
OPTION 2: TENSION STRESS VS HOLD TIME
OPTION 3: COMPRESSION STRESS VS HOLD TIME
OPTION 4: STRESS RANGE VS HOLD TIME
OPTION 5: ELASTIC STRAINRANGE VS HOLD TIME
OPTION 6: Fij VS HOLD TIME
OPTION 7: Kij VS HOLD TIME
```

```
OPTION 8: TRANSFER TO NEXT SECTION
OPTION 9: QUIT PROGRAM
ENTER VALUE: 4
No. OF POINTS FOR CURVE FIT =        9
```

The constants A', α, and m in equation (8) are now determined for $\Delta\sigma$ correlation.

```
NEW PC CORRELATION OR NEW ALPHA? YES(Y) OR NO(N): Y
```

Input to the program continues in the above manner determining the constants for the correlations for $\Delta\epsilon_{el}$ and F_{pc}. The last correlation is for K_{pc}.

```
CRUNCHING PC DATA:

ENTER WAVE SHAPE FOR CORRELATION,
CHSC, CCCR,FSSC: CHSC

SET LIMITS ON TOTAL STRAINRANGE? YES(Y) OR NO(N): N

DETERMINE ALPHA BY TRIAL(T)
OR MULTIPLE REGRESSION(M)? M
```

Nominally, K_{ij} is not a function of total strain range, and the **T** option is appropriate with the value of α set equal to zero. For some alloys the value of K_{ij} may be a weak function of total strain range, and the **M** option would be appropriate. In this example we choose to use the **M** option.

```
SELECT TYPE OF CORRELATION
OPTION 2: TENSION STRESS VS HOLD TIME
OPTION 3: COMPRESSION STRESS VS HOLD TIME
OPTION 4: STRESS RANGE VS HOLD TIME
OPTION 5: ELASTIC STRAINRANGE VS HOLD TIME
OPTION 6: Fij VS HOLD TIME
OPTION 7: Kij VS HOLD TIME
OPTION 8: TRANSFER TO NEXT SECTION
OPTION 9: QUIT PROGRAM
ENTER VALUE: 7

ENTER VALUE OF STRAIN HARDENING EXPONENT: .173
```

This is the value of n determined earlier. Note that this value of n must be used when calculating the value of the elastic line intercept B using equation (5).

```
No. OF POINTS FOR CURVE FIT =        8
```

The constants A', α, and m in equation (8) for the K_{ij} are now determined. Note that one data point has been rejected because the inelastic strain range is less than the default value of EMIN.

```
NEW PC CORRELATION OR NEW ALPHA? YES(Y), NO(N): N
```

All of the necessary PC correlations have been determined. A response of **N** terminates analysis of the PC data, and we now have the option of correlating the CP data.

```
ANALYZE CP DATA? YES(Y) OR NO(N): Y
```

The CP data can be analyzed in a similar manner, and the proper wave shape for this example is TIISC because the data in reference 4 are from strain-hold tests. The screen prompts will be identical to those shown above.

```
ANALYZE CC DATA? YES(Y) OR NO(N): N
```

The CC flow correlations cannot be determined because of insufficient data (three points and only one hold-time value), so the appropriate response is **N**.

Note that the program will accept only balanced CC cycles where the hold times (BHSC) or straining rates (LRSC) are equal in both tension and compression. These balanced cycles generally contain only PP and CC ($\Delta\epsilon_{pp} + \Delta\epsilon_{cc}$) inelastic strain components. Any PC or CP ($\Delta\epsilon_{pc}$, $\Delta\epsilon_{cp}$) inelastic strain range component present will usually be small and can be ignored. Procedures for analyzing cycles containing unbalanced hold time and/or inelastic strains are not fully developed at this time.

This completes the terminal session for FLOW. Two output files have been generated during this terminal session: The first file, AF21DA.FLO, contains the flow correlations and the data used to determine them in a reader friendly format. The second file, AF21DAXY.FLO, contains these same data but in an X-Y format suitable for plotting. This file will have to be edited before plotting because it contains additional information to help identify the X-Y data. These files are found on the first disk in the directory OUTPUT.

Plots of the relations determined by FLOW and their representation of the data are shown in figures 7 to 11. As with the failure relations, the constants in these figures differ slightly from those shown in figures 9, 11, 13, 15, and 17 of reference 1 for reasons cited earlier. Our experience has shown that equation (8) generally gives satisfactory correlations for all flow variables with the exception of F_{ij}. The F_{ij} correlation typically has the most scatter and the lowest correlation coefficient, probably because equation (8) does not model F_{ij} as well as it models the other flow variables.

LIFE

This program is used to predict cyclic life using information generated by the programs FAIL and FLOW. Note that LIFE is written for the case where the cycle to be predicted contains time-independent PP strain and one type of time-dependent strain (PC, CP, or CC). Procedures have not been developed at this time for predicting the life of a cycle containing an unbalanced inelastic strain component (PP + CC + {PC or CP}). As an example of how this program is used, the life of a PC test (test 243 from ref.4) will be predicted. This example is also used in reference 1. In order to predict the life of this or any other PC strain-hold cycle (in this case for the alloy AF2-1DA), the constants for the appropriate failure and flow relations must be entered into the program before it can make a prediction. As noted earlier, LIFE is written in BASIC, so either the BASIC program editor or an ASCII text editor can be used to enter the constants.

The constants for the PP and PC failure relations and the strain hardening exponent are required and are found between lines 190 and 300.

```
190 REM *** failure constants & strain hardening exponent ***
200 REM
210 REM *** CPP is PP line intercept ***
220 CPP = .103
230 REM *** C is fatigue exponent for PP line ***
240 C = -.637
250 REM *** B is PP elastic line fatigue exponent ***
260 B = -.117
270 REM *** N is strain hardening exponent ***
280 N = .173
290 REM *** CIJ is intercept of PC, CP, or CC line ***
300 CIJ = .07
```

In this case, CIJ is the intercept of the PC inelastic failure line.

The appropriate constants A', α, and m in equation (8) for the flow correlations must be entered into the program and are found in the subroutine section starting at line 1420.
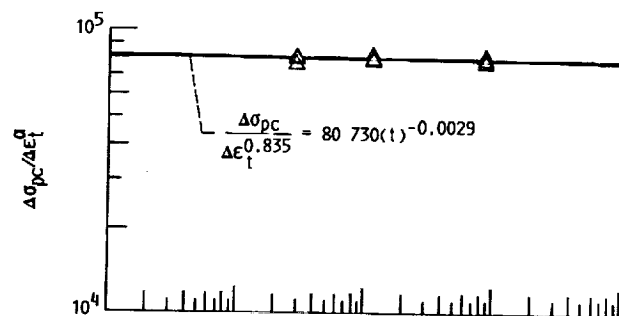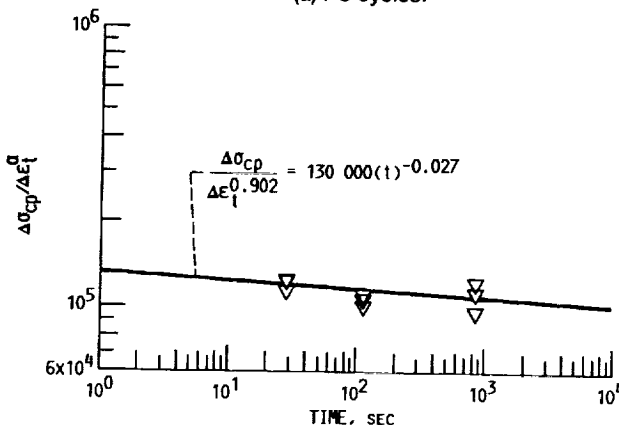
22
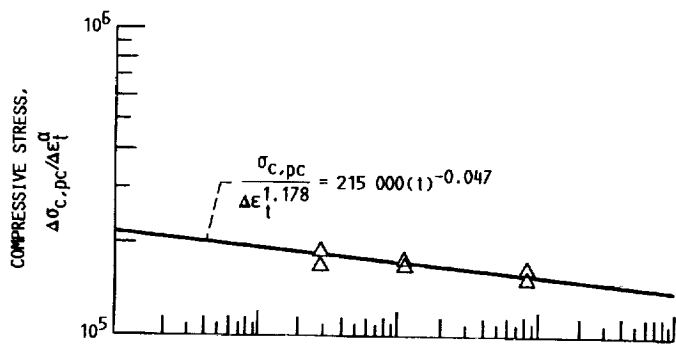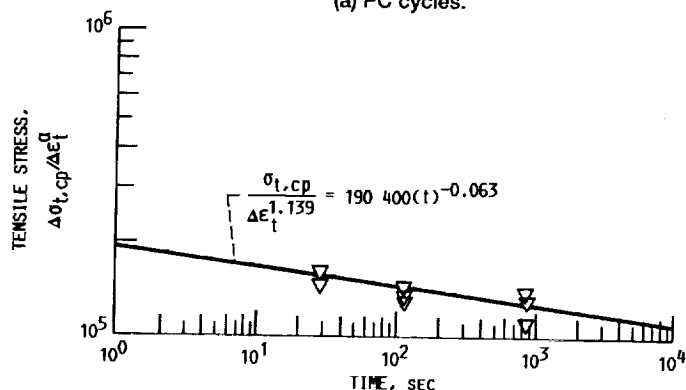
Figure 7.—Example of graphical depiction of output from program FAIL showing relation between stress, normalized by total strain range, and hold time for strain-hold cycles. Material, AF2-1DA; temperature, 760 °C (data from ref. 3).
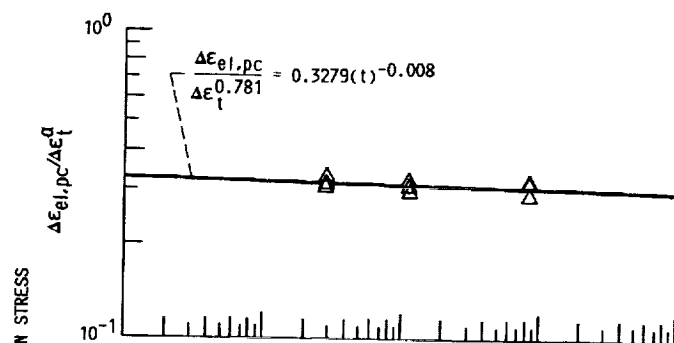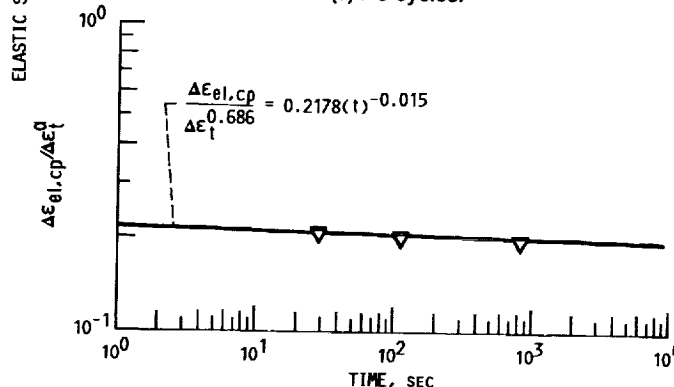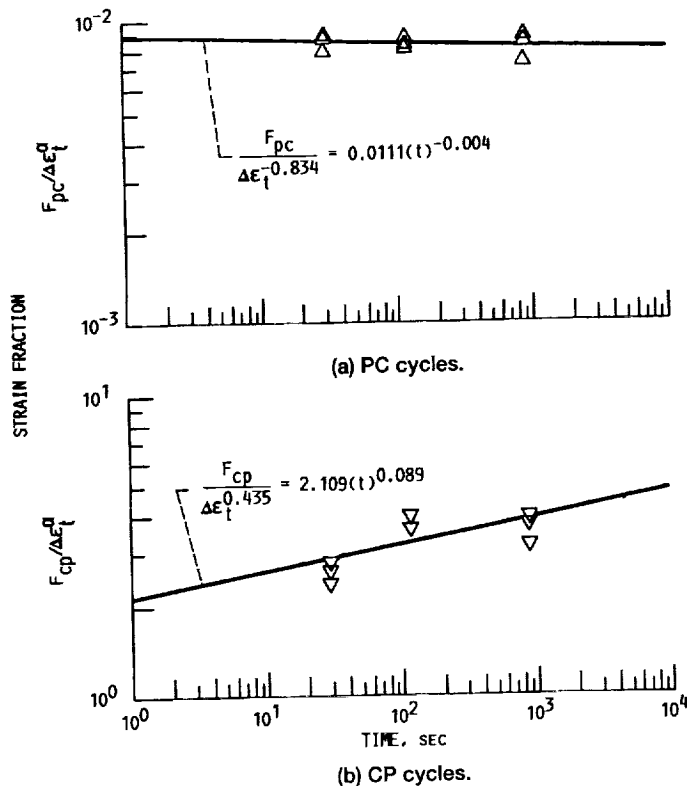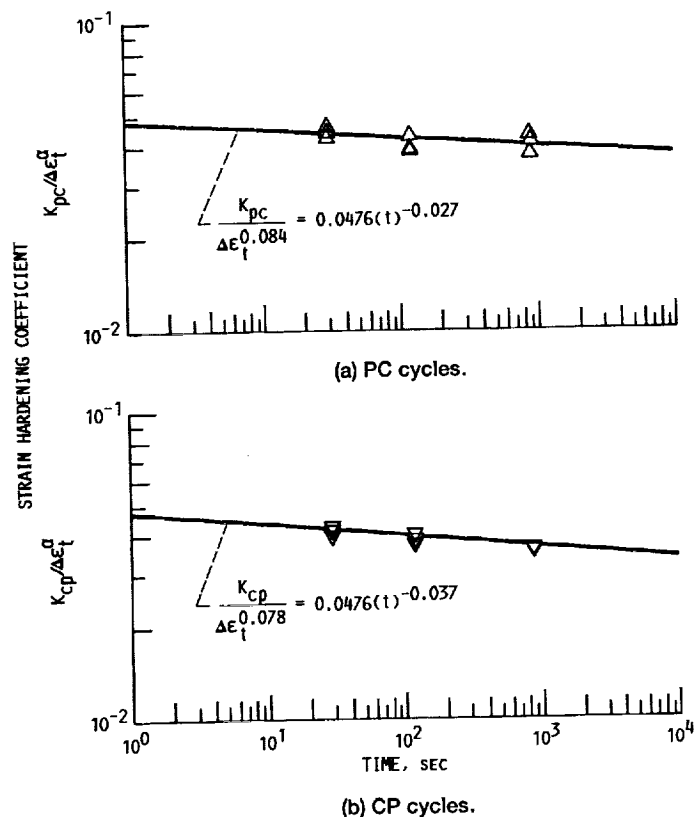
Figure 8.—Example of graphical depiction of output from program FAIL showing relation between stress range, normalized by total strain range, and hold time for strain-hold cycles. Material, AF2-1DA; temperature, 760 °C (data from ref. 3).

Figure 9.—Example of graphical depiction of output from program FAIL showing relation between elastic strain range, normalized by total strain range, and hold time for strain-hold cycles. Material, AF2-1DA; temperature, 760 °C (data from ref. 3).

Figure 10.—Example of graphical depiction of output from program FAIL showing relation between strain fraction, normalized by total strain range, and hold time for strain-hold cycles. Material, AF2-1DA; temperature, 760 °C (data from ref. 3).

Figure 11.—Example of graphical depiction of output from program FAIL showing relation between strain coefficient and hold time for strain-hold cycles. Material, AF2-1DA; temperature, 760 °C (data from ref. 3).

```
1420 REM *** Fij correlation ***
1430 REM Fij = A1*(TSR^ALPHA1)*(TIME^M1)
1440 A1 = .0111
1450 ALPHA1 = -.834
1460 M1 = -.004

1580 REM *** Kij correlation ***
1590 REM Kij = A2*(TSR^ALPHA2)*(TIME^M2)
1600 A2 = .0476
1610 ALPHA2 = .084
1620 M2 = -.027

1650 REM *** mean stress correlation terms ***
1660 REM *** stress range correlation ***
1670 REM SRANGE = A3*(TSR^ALPHA3)*(TIME^M3)
1680 A3 = 80730
1690 ALPHA3 = .835
1700 M3 = - .0029

1740 REM *** Sten or Scomp correlation ***
1750 REM STRESS = A4*(TSR^ALPHA4)*(TIME^M4)
1760 REM STRESS IS STEN FOR A CP CYCLE;SCOMP FOR PC CYCLE
1770 A4 = 215000
1780 ALPHA4 = 1.178
1790 M4 = -.047

1850 REM ***elastic strainrange correlation ***
1860 REM ELAS = A5*(TSR^ALPHA5)*(TIME^M5)
1870 A5 = .3279
1880 ALPHA5 = .781
1890 M5 = -.0077
```

24

With the appropriate equation constants entered into the program, we are able to make the desired cyclic life prediction for test 243 (ref.4). Two input values are required: total strain range (0.0085) and compressive hold time (300 sec). The program is invoked by typing **BASICA A:LIFE.BAS**. Note that this applies to advanced IBM BASIC, version 3.0; other versions of BASIC may be different. The following prompts appear on the screen.

```
SEND OUTPUT TO PRINTER(P) OR FILE(F) F
ENTER FILENAME: A:PREDICT
ENTER SPECIMEN NUMBER: 243
ENTER TOTAL STRAIN RANGE: .0085
ENTER HOLD TIME, sec: 300
ENTER CYCLE TYPE-PC, CP, CC: PC
CORRECT FOR MEAN STRESS EFFECTS, Y/N: Y
MORE PREDICTIONS?, Y/N: N
```

A response of **N** terminates the life prediction. A comparison of the prediction in the output file PREDICT will reveal slight differences with the results in (ref. 1). Again, this is due to the small differences in the constants in the failure and flow equations in AF21DA.FAL and AF21DA.FLO and reference 1.

The program can be easily modified if estimates of maximum and minimum cyclic life are desired (ref. 1). Maximum life occurs when creep effects are not present, and cyclic life is calculated on a PP basis. This is done by forcing the elastic line intercept B_{ij} to be equal to the PP elastic line intercept (0.022) and C' to be equal to the PP inelastic line intercept (0.103). This requires only two additional lines of code as shown below. The first line is the existing code, and the second line is the added code.

PP elastic line:

```
480 BIJ = KIJ*(CPRIME)^N
481 BIJ = .022
```

PP inelastic line:

```
1560 CPRIME = (PART1 + PART2)^C
1561 CPRIME = .103
```

Minimum cyclic life occurs when all of the inelastic strain is time dependent ($F_{pp} = 0$) and C' is equal to (in this example) the PC inelastic line intercept of 0.07. The time dependent elastic line intercept is calculated using this value of C'. The only change to the program is to force C' equal to the PC inelastic line intercept adding one line of code as shown below.

```
1561 CPRIME = .07
```

In all cases, mean stress effects are accounted for as indicated in the original prediction given in the output file PREDICT.

CONCLUDING REMARKS

A set of five computer programs for characterizing an alloy and predicting cyclic life using the updated total strain version of Strainrange Partitioning (TS-SRP) has been presented along with an extensive high-temperature creep-fatigue database. The programs were developed on an IBM personal computer and should run on any IBM compatible personal computer. The Fortran programs read data using the NAMELIST format statement. Not all PC Fortran compilers support NAMELIST input. For those that do not, the READ statement must be

changed, and the datasets modified. Probably the easiest revision to make is to use a list-directed READ statement.

Lewis Research Center
National Aeronautics and Space Administration
Cleveland, Ohio, August 11, 1992

REFERENCES

1. Saltsman, J.F.; and Halford, G.R.: Procedures for Characterizing an Alloy and Predicting Cyclic Life With the Total Strain Version of Strainrange Partitioning. NASA TM-4102, 1989.
2. Halford, G.R.; and Nachtigall, A.F.: The StrainrangePartitioning Behavior of an Advanced Gas Turbine Disk Alloy, AF2-1DA. J. Aircraft, vol. 17, no.8, 1980, pp. 598-604.
3. Thakker, A.B.; and Cowles, B.A.: Low Strain, Long Life Creep-Fatigue of AF2-1DA and INCO 718.(FR-15656,Pratt & Whitney Aircraft, NASA Contract NAS3-22387) NASA CR-167989, 1983.
4. Hyzak, J.M.: The Effects of Defects on the Fatigue Initiation Process on Two P/M Superalloys. AFWAL-TR-80-4063, 1980. (Avail. NTIS, AD-A093509).
5. Hirschberg, M.H.; and Halford, G.R.: Use of Strainrange Partitioning To Predict High-Temperature Low-Cycle Fatigue Life of Metallic Materials. NASA TN D-8072, 1976.
6. Saltsman, J.F.; and Halford, G.R.: Application of Strainrange Partitioning to the Prediction of Creep-Fatigue Lives of AISI Types 304 and 316 Stainless Steel. ASME Trans., vol. 99, May 1977, pp. 264-271.
7. Characterization of Low Cycle High Temperature Fatigue by the Strainrange Partitioning Method. AGARD CP-243, 1978 (Avail. NTIS,AD-A059900).
8. Halford, G.R.; Saltsman, J.F.; Verrilli, M.J.; and Arya, V.K.: Application of Thermal Life Prediction model to High-Temperature Aerospace Alloys B1900+Hf and Haynes 188. ASTM 1122, 1991, pp. 107-119 (also NASA TM-4226, 1990).
9. Saltsman, J.F.; and Halford, G.R.: Life Prediction of Thermomechanical Fatigue Using the Total Strain Version of Strainrange Partitioning (SRP); A Proposal. NASA TP-2779, 1988.

26

INDEX

1. AGENCY USE ONLY (Leave blank)	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	December 1992	Technical Memorandum

4. TITLE AND SUBTITLE

Computer Programs To Characterize Alloys and Predict Cyclic Life Using the Total Strain Version of Strainrange Partitioning *Tutorial and Users Manual*—Version 1.0

5. FUNDING NUMBERS

WU–590–21–11

6. AUTHOR(S)

James F. Saltsman

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio 44135–3191

8. PERFORMING ORGANIZATION REPORT NUMBER

E–6906

9. SPONSORING/MONITORING AGENCY NAMES(S) AND ADDRESS(ES)

National Aeronautics and Space Administration
Washington, D.C. 20546–0001

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

NASA TM–4425

11. SUPPLEMENTARY NOTES

Responsible person, James F. Saltsman, (216) 433–3318.

12a. DISTRIBUTION/AVAILABILITY STATEMENT

Unclassified - Unlimited
Subject Category 39

12b. DISTRIBUTION CODE

13. ABSTRACT (Maximum 200 words)

This manual presents computer programs for characterizing and predicting fatigue and creep-fatigue resistance of metallic materials in the high-temperature, long-life regime for isothermal and nonisothermal fatigue. The programs use the total strain version of Strainrange Partitioning (TS-SRP). An extensive database has also been developed in a parallel effort. This database is probably the largest source of high-temperature, creep-fatigue test data available in the public domain and can be used with other life prediction methods as well. This users manual, software, and database are all in the public domain and are available through COSMIC (382 East Broad Street, Athens, GA 30602; (404) 542-3265, FAX (404) 542-4807). Two disks accompany this manual. The first disk contains the source code, executable files, and sample output from these programs. The second disk contains the creep-fatigue data in a format compatible with these programs.

14. SUBJECT TERMS

Fatigue (metal); Creep-fatigue; Strainrange partitioning; Constitutive modeling creep; Plasticity; Strain fatigue

15. NUMBER OF PAGES

32

16. PRICE CODE

A03

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	