

Guidance on methodology for assessment of stress-rupture data —

Part 2: Computing methods

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Foreword

This Published Document has been prepared under the direction of the Engineering Sector Committee. It results from a programme of development and validation activity undertaken by the Creep Rupture Assessment Methodology Panel ISE/73/-/4, with financial support from the Department of Trade and Industry.

Guidance is given for assessment of multi-source, multi-cast, multi-temperature stress rupture data to determine reliable strength values for durations within and beyond the range of the data. The guidance is primarily intended for derivation of stress rupture strength values for inclusion in standards for steels for pressure purposes, and ultimately to form the basis of design strength values in relevant pressure vessel specifications and codes. However, the methodology is equally applicable to provision of rupture strength values for other purposes, and to a wider spectrum of ferrous and non-ferrous materials. The procedure allows for estimation of confidence limits about the predicted strength values.

The procedure exploits recent advances in statistical modelling and desktop computing technology, but requires metallurgical judgement to ensure that model predictions are physically realistic. A large part of the procedure may be implemented using the GLIM program utility macros supplied with this part of this Published Document.

Prior to issue, the procedure was subject to field trials by a number of independent organizations.

It has been assumed in the drafting of this Published Document that execution of its provisions is entrusted to appropriately qualified people.

Summary of pages

This document comprises a front cover, an inside front cover, pages i and ii, pages 1 to 27 and a back cover.

1 Scope

The main steps of the assessment procedure described in Part 1 of this Published Document may be implemented using a suite of GLIM¹⁾ program utility macros contained on the diskette accompanying this Published Document. This part of this Published Document provides background notes to support these macros. The code listings for the macros may be read in a text editor and converted to enable their implementation in other software packages. In addition to the macros, the diskette contains two data files to complement the worked example.

The macros may be revised from time to time, and users of this document may wish to consult the BS PD 6605 Web Page²⁾ to ensure that they have the latest version of the software.

2 Normative references

The following normative documents contain provisions that, through reference in this text, constitute provisions of this Published Document. For dated references, subsequent amendments to, or revisions of, any of these publications do not apply. For undated references, the latest edition of the publication referred to applies.

PD 6605-1:1998, *Guidance on methodology for assessment of stress rupture data — Part 1: Procedure for derivation of strength values.*

3 Guidance for working in GLIM on PC

3.1 Implementation

There are five sizes of GLIM that can be installed; GLIM-C (the middle size version) should be used for this application.

NOTE To check the size of GLIM, type *\$env u\$* within GLIM. GLIM-C has a data space of 1 000 000.

GLIM files should be run from DOS. They should be copied from the floppy disk into a directory on the hard drive. (GLIM can be accessed from this directory by typing *glim* after the DOS prompt, providing a path has been established in the configuration system file.)

3.2 Program operation

When the GLIM prompt *?* appears, the required file should be input by entering *\$in'filename'\$*. The filename should be enclosed by single quotation marks.

The user should then respond to the prompts given by the program, such as *name of data file?*, *model to fit?*, etc.

NOTE 1 No quotation marks are required for these responses.

The program should then run unless there is an error. When a graph is displayed, the user should press the return key to continue. When the program stops the user should exit GLIM by typing *\$stop*.

NOTE 2 GLIM is not case sensitive. Text printed is displayed as it is typed (e.g. in a graph heading). If the user makes a typing error so that the input is of the wrong type (e.g. a character instead of a number), GLIM stops with an error message. After the GLIM prompt *?*, the user may stop the GLIM session by typing *\$stop*, and then re-enter from DOS by typing *glim*. Alternatively, a new job may be started within GLIM by typing *\$new(c=y)\$*.

3.3 Data output

Output to the screen produced during an interactive GLIM session (which disappears at the end of the session) is written to a transcript file called GLIM.LOG (this file can be viewed, edited and printed if required). Graphs produced are stored in a file called GLIMPLOT.PS, which can be printed on a directly connected postscript printer using the DOS command: *copy/b GLIMPLOT.PSprn:.* For printers connected on a network, the user should refer to local documentation.

A new GLIM session should overwrite the GLIM.LOG and GLIMPLOT.PS files, and they should be renamed if the user wishes to preserve them (alternatively, by typing *GLIM.LOG=MYFILE.LOG* at the start of a session, the transcript file can be directed to the file MYFILE.LOG instead of the usual GLIM.LOG).

NOTE Installing the public domain graphics program GHOSTVIEW allows inspection of individual postscript graphs and printing to any Windows driven printer.

4 Model fitting

NOTE A suite of GLIM files are supplied on diskette for model fitting, using the standard procedures, assuming a Weibull error distribution (these are listed in Table 1). The file MODELm.LLG is supplied for fitting models with a log-logistic error distribution, for cases in which there is concern about the Weibull lower confidence interval (see 4.6).

¹⁾ GLIM is a statistical software package supplied by Numerical Algorithms Group Ltd., Wilkinson House, Jordan Hill Road, Oxford OX2 8DR. The copyright for GLIM is owned by the Royal Statistical Society.

²⁾ Details of Web Page: <http://www.cas.lancs.ac.uk/bsi6605/>.

Table 1 — List of files supplied on diskette

File name ^a	Description	Relevant clause
VARHETm.INP	Model fitting: variance heterogeneity macros	
GLIM.INI	for initialization in graph plotting	
FITMHm.HET	for determination of T_0 , MHn models	4.2, 4.3.2
FITMRm.HET	for determination of T_0 , MRn models	4.2, 4.3.2
FITMHm.AUT	automatic search for T_0 , MHn models	4.2
FITMRm.AUT	automatic search for T_0 , MRn models	4.2
MODELm.HET	for model fitting with Weibull error distribution and variance heterogeneity	4.3 , Figures 1 and 2
MODELm.BTC	for model fitting in batch mode	4.4
BATCH.INP	example of an input file for MODELm.BTC	4.4.3
MODELm.LLG	for fitting models with log-logistic error distribution in cases where there is concern about the Weibull confidence interval	4.5
PATm.HET	implements PAT-1 tests	4.6 , Figure 3
CMOVNB.DAT	Example data: example creep-rupture data file	4.1, 9 , annex A
CMOVNB.MET	example metallurgical data file	9 , annex D
CMOVNBm.INP	input file to merge and to process data	9
CULLm.HET	Robustness in extrapolation: for implementing robustness in extrapolation	5.2
CULLm.BTC	for batch mode implementation	5.3
CASTm.HET	Influential casts: implements influential cast analysis	6.2
CASTm.GRA	graphical summary of CASTm.HET output	6.3 , Figure 4
INFCASTm.GRA	provides isothermal plot to illustrate influential role of specific cast for a given model	6.4 , Figure 5
KEYS.MAC	for providing key for graphs	
PREDm.HET	Strength predictions: for standard table of predicted values	7.1
PREDAm.HET	user defined table of strengths (linear increment)	7.2
PREDBm.HET	user defined table of strengths (log increment)	7.3
PREDm.LLG	log-logistic version of PREDm.HET	7.4
PREDAm.LLG	log-logistic version of PREDAm.HET	7.4
PREDBm.LLG	log-logistic version of PREDBm.HET	7.4

^a "m" defines the version number of the GLIM macro.

4.1 Data files

Prior to data assessment, the appropriate data files should be prepared.

NOTE 1 A typical results data file is given in CMOVNB.DAT on the diskette³⁾.

Blank entries should be replaced by “-1”. The file should read in a number of data records (specified by **\$slength**) comprising: country code (*I*), material code (or cast number *J*), temperature, stress, unbroken time and failure time.

NOTE 2 A consequence of making the data file format consistent with other creep rupture data file structures (see for example ECCC-WG1 [1] Vol. 4) is that there are columns that are not needed for the present analysis (see annex A). A line of code at the end of the file deletes these to save space.

The code should redefine the cast number to include the country code (this is only necessary for data that originate from more than one country: for example, country code = 20, material code = 17 becomes cast number *J* = 2017).

When fitting the MHn or MRn models, the constant T_0 should be defined. This should be estimated using the program FITMHm.HET or FITMRm.HET as appropriate (see 4.2.2, 4.3.1 and 4.3.5).

To avoid confusion, different identifiers should be assigned for T_0 for each MRM model, i.e.:

- ‘**\$num to=**’ sets T_0 for MH4 model (fourth order polynomial);
- ‘**\$num tom=**’ sets T_0 for MR4 model (fourth order);
- ‘**\$num to3=**’ sets T_0 for MH3 model (cubic);
- ‘**\$num tom3=**’ sets T_0 for MR3 model (cubic);
- ‘**\$num to2=**’ sets T_0 for MH2 model (quadratic);
- ‘**\$num tom2=**’ sets T_0 for MR2 model (quadratic).

Until T_0 is estimated these identifiers should be set to -1 in the data file for each model.

Text following ! on any line is commentary and is not read by GLIM; all the directives beginning with \$ are important and should be written into the data file.

Specifically, the user should insert:

- a) a number after **\$slength** to indicate the number of lines of data to be read;
- b) a list of identifiers after **\$data** in the order they appear in the data listings;
- c) **\$read**;
- d) **\$delete ‘identifiers of data not needed’** to save space;
- e) **\$calc $J=I*100+J$** to redefine the cast number (see above);
- f) **\$num to= ‘value of T_0 estimated’** or -1 if not yet known, followed by \$ (similarly for all MRM model T_0 parameters);
- g) **\$print(store=steel) ‘name of steel to be used for graph headings’\$**;
- h) **\$num option=‘1, 2 or 3’\$** (parameter for left censoring option⁴⁾; and
- i) **\$num fileout=‘0 or 1’\$**.

If **fileout** is set to 1, MODELm.HET and MODELm.BTC should send the parameter estimates and other information from model fitting to a separate output file.

4.2 Determination of T_0

4.2.1 FITMHm.HET

FITMHm.HET estimates T_0 for the MHn models (see Table 2); estimation should be performed by:

- a) assuming a range of values for T_0 ;
- b) fitting the model; and
- c) finding the deviance, the best estimate of T_0 corresponding to the minimum deviance.

The recommended range of values of T_0 that should be investigated is between $\pm T_0$, where T_0 is the maximum temperature in the dataset in Kelvins.

Ranges of T_0 for which aliasing occurs are discounted when evaluating T_0 ; a warning message is output if this happens in the temperature range selected. The user should then examine the output and select a new range of T_0 .

³⁾ The diskette also includes the CMOVNB.MET material pedigree data file used, in conjunction with CMOVNB.DAT, for the worked example in annex C of PD 6605-1.

⁴⁾ For **\$option=1\$**, all the data are used (except in rare cases in which failure time is given as 0). For **\$option=2\$**, tests with a failure time of ≤ 10 h are excluded. For **\$option=3\$**, all data with a failure time of ≤ 10 h together with data at the same temperature and at greater or equal stress are excluded.

Table 2 — Choice of models

Model	Code	Comment
Algebraic: 1) Soviet Model 1 $\ln [t_T^*] = \beta_0 + \beta_1 \log [T] + \beta_2 \log [\sigma_0] + \beta_3/T + \beta_4 \sigma_0/T$ 2) Soviet Model 2 $\ln [t_T^*] = \beta_0 + \beta_1 \log [T] + \beta_2 \log [\sigma_0]/T + \beta_3/T + \beta_4 \sigma_0/T$ 3) Minimum Commitment Model $\ln [t_T^*] = \beta_0 + \beta_1 \log [\sigma_0] + \beta_2 \sigma_0 + \beta_3 \sigma_0^2 + \beta_4 T + \beta_5/T$	SM1 SM2 MC	
TTP: a) Mendelson–Roberts–Manson (MRM) $\ln [t_T^*] = f(\sigma_0)(T - T_0)^r/\sigma_0^{-q} + \beta_5$, where $f(\sigma_0) = \beta_0 + \beta_1 \log [\sigma_0] + \beta_2 \log [\sigma_0]^2 + \beta_3 \log [\sigma_0]^3 + \beta_4 \log [\sigma_0]^4$ b) MRM with $r = -1$, $q = 0$ $\ln [t_T^*] = f(\sigma_0)/(T - T_0) + \beta_5$ (T_0 determined using FITMRm.HET) c) Larson–Miller (MRn with $T_0 = 0$) $\ln [t_T^*] = f(\sigma_0)/T + \beta_5$ d) Manson–Haferd (MRM with $r = 1$, $q = 0$) $\ln [t_T^*] = f(\sigma_0)(T - T_0) + \beta_5$ (T_0 determined using FITMHm.HET) e) Manson–Haferd (with $T_0 = 0$) $\ln [t_T^*] = f(\sigma_0)T + \beta_5$ f) Orr–Sherby–Dorn $\ln [t_T^*] = f(\sigma_0) + \beta_5/T$	MR4 MR3 MR2 LM4 LM3 LM2 MH4 MH3 MH2 MH04 MH03 MH02 OSD4 OSD3 OSD2	 $\beta_4 = 0$ $\beta_4, \beta_3 = 0$ $\beta_4 = 0$ $\beta_4, \beta_3 = 0$ $\beta_4 = 0$ $\beta_4, \beta_3 = 0$ $\beta_4 = 0$ $\beta_4, \beta_3 = 0$
Own: a) user defined	OWN	

4.2.2 Input to FITMHm.HET

The program prompts for:

- a) the name of the data file;
- b) the model to be fitted (MH4, MH3 or MH2);
- c) the minimum value of T_0 to be tried in the fit;
- d) the maximum value of T_0 to be tried in the fit;
- e) the incremental value; and
- f) the option to fit the model over a new range of T_0 .

4.2.3 Output from FITMHm.HET

The program outputs:

- a) the left censoring option selected;
- b) the parameter estimates from model fitting;
- c) a table showing how the deviance and “aliased model indicator” (set to 1 if aliasing occurs) vary with T_0 ; and
- d) a plot of deviance against T_0 in the range of T_0 specified, for fits without aliasing (there is a warning if the fourth order term is “aliased”).

4.2.4 Model fitting strategy

As model fitting can be time consuming, a large range of T_0 and a large increment should be tried first, and then the range of values of T_0 that gives the smallest deviance fitted again using smaller increments. This should be repeated to give T_0 to the required accuracy (see also 4.2.6); the deviance values are listed and plotted. Users therefore should have both a visual and a more precise numerical picture of how the deviance varies with T_0 .

NOTE Experience indicates that near to the minimum deviance, the absolute value of deviance is not very sensitive to T_0 . It is therefore sufficient to estimate T_0 to the nearest 10 K.

4.2.5 FITMRm.HET

FITMRm.HET estimates T_0 for the MRn models (see Table 2); it is used in exactly the same way as FITMHm.HET and gives an estimate of T_0 for these models. If both the MHn and MRn models have a minimum of deviance as T_0 is varied, the model with the lower minimum deviance should be chosen.

4.2.6 FITMHm.AUT and FITMRm.AUT

FITMHm.AUT and FITMRm.AUT are programs in which the search for T_0 has been automated. The programs:

- fit the chosen model with T_0 in the temperature range $-T_{\max}$ to $+T_{\max}$ (with $T_{\max}$ in Kelvins); and
- find the value of T_0 corresponding to the minimum deviance.

Model fitting should be carried out within two ranges of temperature; first between $-T_{\max}$ and $+T_{\max}$ (rounded up to the nearest 100 K), in increments of 100 K, to find the 200 K temperature span within which the minimum deviance is located. The routine is then repeated within the 200 K range identified, in increments of 10 K, to find T_0 to the nearest 10 K.

4.2.7 Use of FITMHm.AUT and FITMRm.AUT

4.2.7.1 Input to the programs

Each program prompts for:

- the name of the data file; and
- the model to be fitted.

4.2.7.2 Output from the programs

Each program outputs:

- the left censoring option selected;
- the parameter estimates from model fitting;
- two lists of T_0 , deviance and “aliased model indicator” (set to 1 if aliasing occurs); and
- two plots of deviance against T_0 in the selected ranges of T_0 , for fits without aliasing.

NOTE There is a warning if the fourth order term is “aliased” or if model fitting has not yet reached the convergence criterion. There is also a message if no minimum of deviance has been found in the range $-T_{\max}$ to $+T_{\max}$.

4.2.7.3 Program limitations

The search method assumes that the deviance varies smoothly with T_0 and that there is only one minimum of deviance as T_0 is varied in the selected temperature range; the validity of the output value of T_0 should be checked by examining the list and plot of deviances after both sections of output.

NOTE 1 The appropriate part of the output can be found quickly by searching for the “plot of deviances”.

NOTE 2 Very occasionally, model fitting may fail for a dataset with T_0 at a particular temperature. If this occurs, use of FITMHm.HET or FITMRm.HET is recommended, because ranges of temperature to be searched can be entered from the keyboard, thereby avoiding the problem temperature.

4.3 Modelm.HET

4.3.1 General

NOTE 1 MODELm.HET fits a number of models to the dataset and draws graphs showing the trend lines, confidence intervals, and failed and censored data points at temperatures chosen by the user.

The defined models listed in Table 2 should be fitted using a Weibull error distribution with variance heterogeneity, where t_r^* is the predicted failure time in hours, σ_0 is stress in megapascals, T is temperature in Kelvins, and $\beta_0, \beta_1, \beta_2, \beta_3, \beta_4, \beta_5$ and T_0 are parameters to be estimated⁵⁾.

NOTE 2 In Table 2, $\ln []$ is logarithm to the base e (GLIM uses natural logarithms). The equations may be transformed to the more conventional logarithm to base 10 formulation by dividing by $\ln [10] = 2.302\ 585\ 1$ throughout.

The variance of the error distribution for each model should be assumed to be a function of T and $\log [\sigma_0]$, and is defined in annex B of PD 6605-1.

⁵⁾ The notation used in this Published Document is listed in clause 3 of PD 6605-1.

4.3.2 Estimation of T_0 for MHn and MRn models

The MHn and MRn models are not linear in parameters and before they can be fitted in GLIM, the T_0 parameter should be estimated. This should be done using the programs FITMHm.HET or FITMRm.HET (see 4.2); these assume a range of values for T_0 , fit the model and find the deviance. The best estimate of T_0 for a given model should correspond to the minimum deviance determined using the appropriate program. The recommended range of values of T_0 to be investigated should be between $\pm T_{\max}$, where $T_{\max}$ is the maximum absolute temperature in the dataset.

NOTE 3 Values of T_0 vary according to whether $f(\sigma_0)$ is a quadratic, cubic or fourth order expression.

4.3.3 Input to MODELm.HET

The program prompts for:

- a) the name of the data file;
- b) the model (see Table 2, noting that the LMn and MH0n models are entered as MRn and MHn in this macro, with the T_0 parameters in the data file set to -1)⁶⁾;
- c) T_0 , if needed for the model and not already declared in the data file⁷⁾;
- d) the selected option to draw a graph of $\log [\sigma_0]$ against $\log [t_r]$;
- e) the temperature of the graph; and
- f) the selected option to draw further graphs at different temperatures.

The return key should be pressed after each graph is displayed with the label written on the graph.

If the variable **fileout** is set to "1" in the data file, indicating that output to a separate file is required, the program should also prompt for the name of the output file and for the date.

4.3.4 Output from MODELm.HET

The program outputs:

- a) the left censoring option selected;
- b) the deviance and parameter estimates from model fitting; and
- c) a message if the parameters suggest possible turn-back at low stresses (for the SM1, SM2 or MC models).

NOTE The parameter estimates are output first for the main model (prefixed by M_) and then for the variance model (prefixed by A_), in each case starting with the constant term (see for example Figure 1). For SM1, SM2, MC and OSDn, the main model parameters are output in the order $\beta_0, \beta_1, \beta_2, \beta_3, \beta_4$ and β_5 , followed by the variance model parameters γ_0, γ_1 and γ_2 . In the case of MRn, LMn, MHn and MH0n, the main model parameters are output in the order $\beta_0, \beta_1, \beta_2, \beta_3$ and β_4 , followed by the variance model parameters γ_0, γ_1 and γ_2 .

Information should also be given on the number of data points at different temperatures. As a feature of GLIM syntax, frequencies (i.e. number of data points) are labelled "TOTAL_WT" in the output (see Figure 1).

Graphs of $\log [\sigma_0]$ against $\log [t_r]$ are output at chosen temperatures, showing the trend line and 95 % confidence intervals together with failed and censored data points. The value of stress corresponding to 80 % of the lowest stress in the failed data should also be indicated on the graphs (see for example Figure 2).

NOTE 2 Macro MODELm.BTC is available for performing several MODELm.HET analyses in batch mode (see 4.4).

Confidence intervals are sensitive to the accuracy of the Weibull assumption and should be interpreted with care [log-logistic routines are available for cases in which there is concern about the Weibull lower confidence interval; see 4.5, also 7.2.2a) and 7.4 of PD 6605-1].

⁶⁾ GLIM is not case sensitive, but the graph headings display the model as typed. Upper case is recommended.

⁷⁾ T_0 should be set to zero to fit the LMn and MH0n models (respectively input as MRn and MHn in the MODELm.HET macro). If T_0 is not already set to a value obtained from FITMRm.HET or FITMHm.HET (i.e. $T_0 = -1$ in the data file for the appropriate model), it can be entered at the prompt for T_0 . Otherwise, T_0 should be temporarily changed to zero in the data file. The original directive setting T_0 may be prefixed by "!", and this is not read by GLIM (see 4.1).