A SUITE OF INTERACTIVE PROGRAMS
FOR
FUSE DESIGN AND DEVELOPMENT

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INTRODUCTION The design and development of power fuses requires considerable time and expense to be spent on testing. There is scope for savings in development effort if mathematical models can be used to predict the performance of proposed designs, and the possibility exists of using computers to help produce more effective products or optimise existing designs.

Compared with the equipment which it normally protects, the HRC fuse is a physically small item, yet extremely large generating plant with complex control and measuring facilities, is needed to prove the fuse's capability. When considering the cost of manufacturing all the necessary test samples, (and usually a number of alternative designs are included), together with the very high charges involved in the use of high-power testing plant, the ability to carry out meaningful tests 'on paper' becomes a very useful advantage.

Whilst computer-aided design procedures are well established now in many branches of engineering, application to power fuse design has been limited, owing to the complexity of the mathematical models which are needed to represent the various important physical phenomena which govern the performance of such fuses. For example, the calculation of the transient heating of a typical fuse element requires the computation by numerical methods of the temperature at a vast number of points on the element, which requires very large and fast computers to be used.

There has been considerable research world-wide on the modelling of the physical processes, which include heat transfer, arc physics, circuit modelling and the choice of the numerical methods most appropriate for obtaining solutions. Although many research workers have developed computer programs for the purpose of validating mathematical models, these programs have not been of general usefulness, often requiring to be run in an inconvenient batch-processed mode, and requiring an inordinate amount of time to be spent preparing data by the user, who needs specialised knowledge of the programs themselves.

However, with the increasing availability of interactive computing facilities with massive memory sizes, high speeds and relatively low costs, it is now feasible to implement CAD programs for fuses which are of reasonable accuracy at reasonable cost.

This paper describes a suite of programs which has been developed for use by design engineers and researchers and reports upon some initial

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experience of using the programs. A key requirement was that programs were user-friendly, so the user need have no detailed knowledge of the algorithms used to obtain solutions and that data input and output should be as simple as possible.

In designing the suite of programs attention has been paid to the facility of examining the effects of changing one or more design or test parameters, and in this respect it offers great assistance to the designer who previously, may have had to evaluate the 'remains' of a test sample before deciding upon the next step.

Computer simulations can never replace testing altogether, but the availability of these simulations should permit a reduction in the amount of testing done, by preliminary screening of designs using the engineer's judgement and the computed results as a guide. A second important application is that of simulating non-standard situations, which in some cases are almost impossible to reproduce in the test laboratory, for example the response of a fuse in one phase of a power converter subjected to a particular type of transient fault.

OVERVIEW OF SUITE Fig. 1 shows the arrangement of the suite of programs, in block diagram form. The type of fuse which can be accepted by the program is illustrated in Fig. 2. This fuse has a number of silver or copper elements in parallel within a sand-filled body. The element profile can be specified to be one of a number of standard shapes, or with some of the programs, a generalised profile specified by the user can be accommodated.

Data describing the fuse design is input via the data management program and then this is stored permanently in a named datafile. Simulated tests may then be carried out using one of the 'applications' programs, which at present are (i) temperature rise; (ii) time-current characteristic and (iii) short-circuit. The applications programs are designed so that the user 'tests' the fuse required, according to the IEC requirement appropriate for the fuse type (low voltage, semiconductor type, or high-voltage). Alternatively, if the user requires,non-standard test conditions can be specified and entered.

All the applications programs access the same bank of datafiles, which have a standard format. Thus, addition of new programs to the suite, or replacement of existing programs by more accurate versions, is simplified. The program are written in FORTRAN and mounted on a DEC-20 mainframe computer.

DATA MANAGEMENT PROGRAM Datafiles describing fuse construction are created by the very important data management program.

The following data is input using a VDU terminal:-

Fusename
Type (low-voltage, semiconductor, high-voltage)
Nominal Current
Body material and dimensions
Number of bodies
Filler type

Dimensions of end-cap and tags
Fuse element material
Number of elements and PCD
Element profile (3 standard profiles plus 1 generalised)
M-spot type (if any)
M-spot location
Dimensions of element according to profile
(e.g. thickness, width of strip, notch length, etc.)

Data errors are trapped as far as possible at input time and each value is checked to ensure that it lies within a predetermined 'acceptable' range.

When data entry is complete a final series of checks is made to detect any internal inconsistency and then the dated datafile is saved on disc.

During input, the VDU mimics a pro-forma used by engineers to describe the fuse, and by means of a powerful screen editor, allows the alteration or correction of data. Among other features, this permits the ready creation of new datafiles describing fuses derived by slight modifications of existing designs.

As a consequence of the adoption of a standardised datafile format, each of the applications programs needs to process this data after input into a form suitable for the particular application. Whilst this front-end processing is trivial in some cases, it is very significant in others, notably in the short-circuit program.

TEMPERATURE RISE TEST   In the thermal steady-state, heat is generated within the fuse elements due to the passage of current and this heat is lost (i) radially by conduction through the sand and the body and thence by convection and radiation to the surrounding air, and (ii) axially by conduction to the endcaps and thence to the connecting cables and busbars. This complex 3-dimensional heat transfer problem cannot be solved efficiently by numerical solution of the partial differential equations involved and so a semi-analytical solution method has been developed and is described in another paper [1]. It is necessary to take into account the heat generation within the connecting cables and the fuse endcaps to achieve acceptable accuracy.

The temperature-rise program simulates a standard test, so that, according to the fuse rating and type, connecting cables and/or busbars are selected automatically corresponding to the sizes required by the appropriate IEC standard. A simple model of M-spot diffusion is included, so that the likely state of activity of an M-spot (if used) can be estimated. The program gives a simulated test report as output giving the following computed values:-

Cold resistance
Hot resistance
Power loss
mV drop
End-cap temperature rise
Body temperature
Hotspot temperature

plus a series of comments relating to the possibility of melting or M-spot activity. A graph of the temperature distribution along a fuse element can be output if requested.

If the applied current is too high there may be no possible steady-state solution. This condition, along with several others, is trapped by the program and an explanation is output.

Fig. 3 shows typical results which have been obtained using the temperature-rise program. The accuracy achievable at present is discussed in reference (1).

TIME-CURRENT CHARACTERISTIC The purpose of this program is to compute the prearcing time/current characteristic (TCC) of a given fuse design.

The first part of the program calculates the minimum fusing current, which is an asymptote to the TCC. This is achieved by repeated calls of the temperature rise program, according to the following procedure. Starting with the fuse rated current, the test current is increased consecutively by a factor $(1+q)$ until the melting temperature is exceeded. q is then halved and the procedure repeated until the maximum temperature is within $0.1^{o}C$ of the value required for melting. Since the temperature-rise calculations are very fast, computation of the minimum fusing current is achieved without excessive computing time; $q_o = 0.1$ gives good results. The computed m.f.c's. are very close to those expected from tests, bearing in mind the fact that the 'experimental' value cannot be directly measured, being between the conventional non-fusing current and the conventional fusing current.

The second part of the program calculates points on the TCC, starting from the short-time end, using the decoupled method to represent transient heat loss to the filler [2]. However, to reduce computing time, a simple one-dimensional model is used to represent the fuse elements. The elements are divided axially into a large number of strips and the resulting finite-difference equations are solved using the Crank-Nicholson method to obtain the transient temperature distribution. Use of a one-dimensional representation results in a tridiagonal matrix equation which can be efficiently solved at each time step.

The program outputs pairs of (current/time) values but stops when the time exceeds 10 seconds to save computing time. The remaining part of the curve can be sketched in by hand if required. Fig. 4 shows typical results. If the ratio of full to reduced section of the fuse element exceeds about 4.0 the one-dimensional model is inadequate. In these cases, if desired, the short-circuit program described in the next section can be used to obtain points at the short-time end, at the expense of greatly increased computer time.

SHORT-CIRCUIT TEST A previous paper [3] has described methods for modelling the performance of current-limiting fuses under short-circuit conditions. These methods involve simulation of the transient two-dimensional heating in the elements during the prearcing period, the initial voltage step upon the appearance of arcs, burnback of the unmelted parts of the elements, fusion of the sand surrounding the arcs, which affects the axial arc gradient and the interaction of these processes with the electric circuit.

The short-circuit program incorporates all these models and again the input/output is arranged as if the user were conducting a test in a high-power short-circuit test laboratory. Thus the user is asked to supply the values of test voltage, prospective current, source type (a.c./d.c.) source circuit power factor (or time constant) and with a.c., the frequency and making angle. The program computes and prints out if desired the complete course of voltage and current transients, indicating the instants at which melting occurs, series arcs merge, arcs burn back to the end-caps and finally the arcs extinguish.

A simulated test report is then output giving the following:-

Prearcing time
Arcing time
Total operating time
Prearcing I^2t
Arcing I^2t
Total operating I^2t
Arcing angle
Current at start of arcing
Peak let-through current
Peak arc voltage
Total arc energy

Accurate simulation of the prearcing transient requires the use of two-dimensional finite-difference modelling of the thermal and electric fields within the fuse elements. The short-circuit program uses sub-routines after data input to automatically generate the required finite-difference meshes for the different types of element which the program can handle.

Fig. 5 compares predicted values of cut-off current, for fuses of several different types under a variety of source-circuit conditions, with values measured in high-power tests. Similar accuracies are obtained in the computation of prearcing time and total operating time.

DISCUSSION   The table below gives a rough comparison of the program sizes and run times (per complete test).

Program	Source code (k bytes)	Data (reals)	Typical C.P.U. time (sec)
data management	25	small	N.A.
temp. rise	24	8000	1
TCC	26	10000	30
short-circuit	30	90000	40

This shows that the heavy computing demands of the short-circuit program requires the use, at present, of a mainframe computer although this situation may change suddenly with the introduction of 32-bit processors for microcomputers.

Experience with the usage of the programs by design engineers and researchers has shown that the usage can be divided into three categories.

(1) The programs may be used in parallel with the design and development activity. This type of usage has been limited by the natural uncertainty about the accuracy of the computer simulations, and the restricted number of element profiles which the programs can handle. For example, the short-circuit program requires notches to be identical and uniformly spaced. However, as the accuracy of the program may be increased by the incorporation of improved models and the range of application increased by extending their capability, this class of usage is likely to increase.

(2) The programs may be used to investigate general aspects of fuse performance, which although possible to determine experimentally would be prohibitively expensive and time consuming. Such investigations have included a study of the variation of arc energy with prospective current and making angle for several different fuse designs.

(3) The programs are frequently used to supply quick answers to day-to-day problems of the 'what-if' type. For example, if test values are available for a fuse tested at 0.1p.f. it might be required to know how much the arc energy would be reduced if the power factor were raised to 0.2, all other conditions remaining the same. Whilst the absolute accuracy in predicting the value of arc energy may be only ± 20%, the effect of deviations from a given test condition can be calculated with much higher accuracy. This type of usage has to date probably proved the most useful for the industrial user, since the equipments encountered nowadays in everyday or 'shop-floor' applications are more complex, and sensitive to fault conditions. The versatility of the programs in the suite is a clear advantage when evaluating problems of this nature.

CONCLUSIONS The paper has described the philosophy and design of a suite of programs for simulation of tests on current-limiting power fuses for low-voltage, semi-conductor and high-voltage applications, and some initial experiences have been described.

With the increased availability of cheap computing power and with improved models of the physical processes, use of computer-aided design in this field is bound to increase. The suite described can be extended to include simulations of overcurrent breaking, pulsed loading and cyclic loading tests.

REFERENCES

1. Wilkins, R. "Simulation of fuselink temperature rise tests. Int. Conf. on Electric Fuses and their Applications. Trondheim, 13-15 June 1984.

2. Wilkins, R. and McEwan, P.M. "A decoupled method for predicting time-current characteristics of HRC fuses." Int. Conf. on Electric Fuses and their Applications, Liverpool Polytechnic, 7-9 April 1976.

3. Wilkins, R. and Gnanalingam, S. "Digital simulation of fuse breaking tests." Proc. IEE, 127, part C, No. 6, 1980.

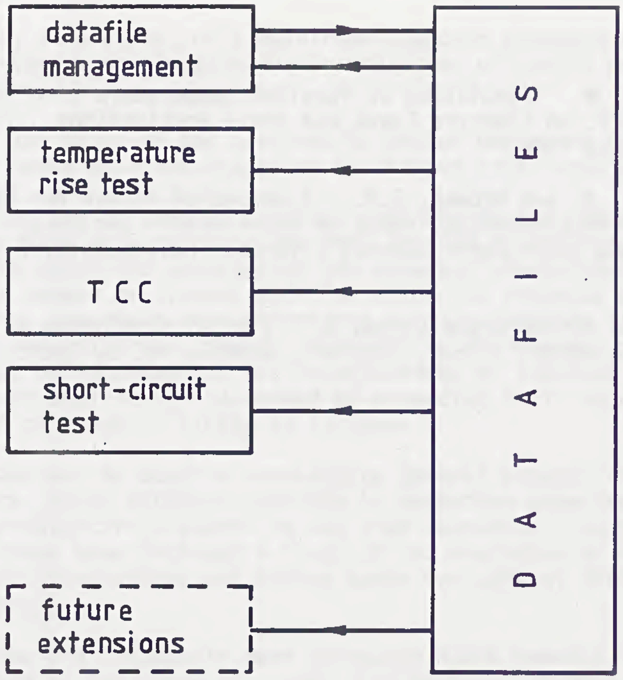

Fig 1. General arrangement

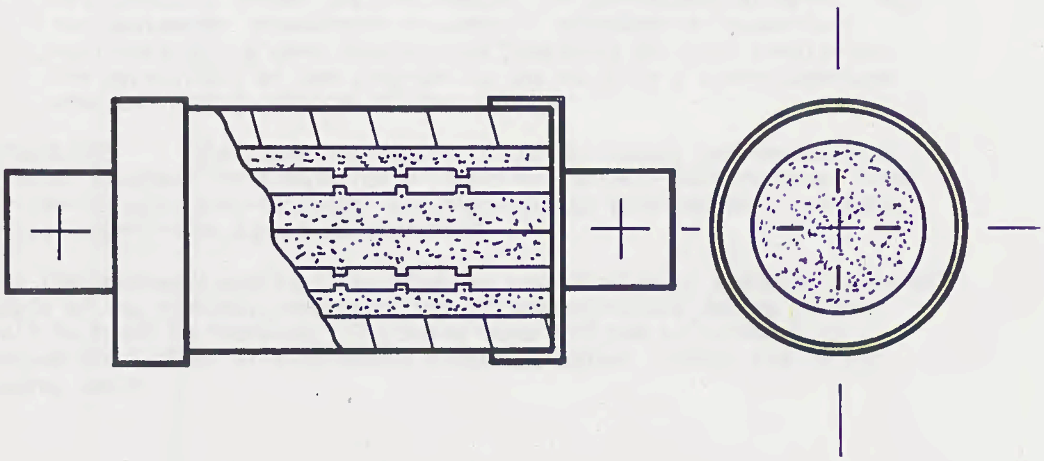

Fig 2. Basic construction

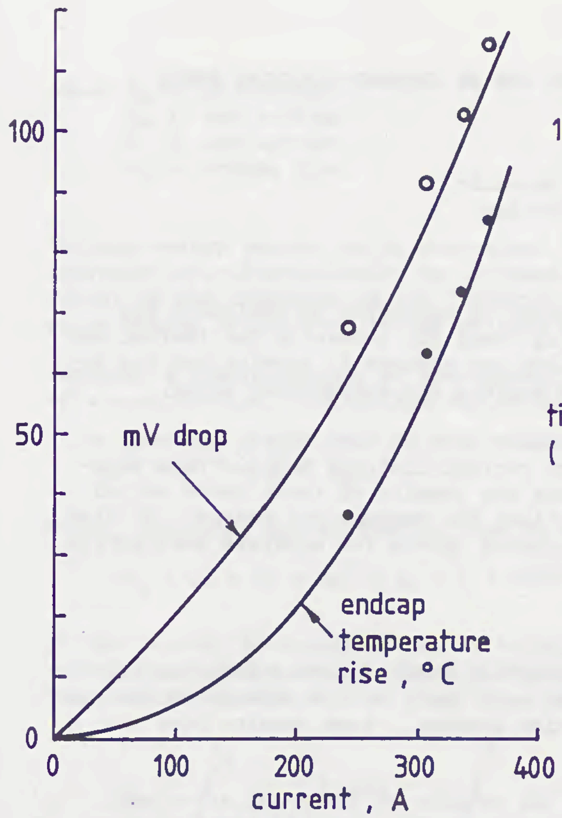

Fig 3 . Temperature-rise tests on 315A LV fuse

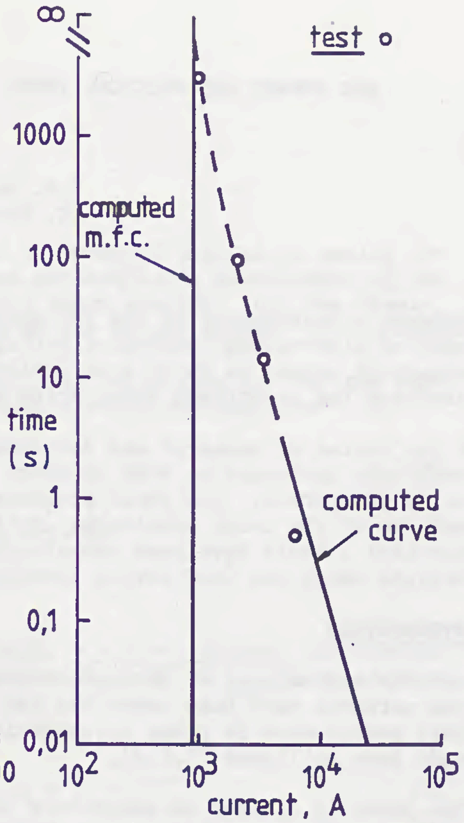

Fig 4. Typical TCC

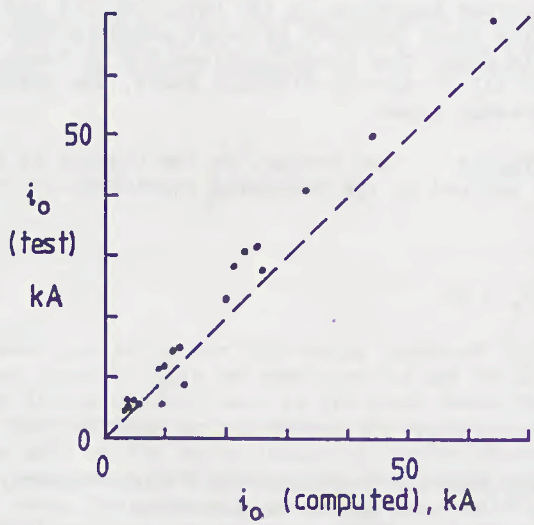

Fig 5. Cut-off currents