The Computer Simulation of Quenching in Superconducting Magnets

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The term 'quenching' describes the reversion of an operating superconducting magnet to its normally resistive state. This change involves the conversion of stored magnetic energy to heat. It is usually accompanied by the generation of high temperatures, voltages and stresses, because of the large amount of energy stored by such magnets. Since a magnet may be damaged by a quench, it is important to predict the behaviour of a design in this situation. However, the process involves a complex interaction of electromagnetic and thermal phenomena, so a computer-based simulation is necessary for the analysis of practical magnet designs.

It is shown how a quench in a magnet can be modelled using the concept of a 'propagation velocity' which defines how fast the normal region spreads throughout the magnet. A review of currently-available quench simulation software, much of which uses this approach, is then presented. Modifications are made to one such program, with the aim of widening the range of magnets it can model and improving its usability. This program is shown to give results comparable to those of earlier versions. However, it is still hard to use and further modifications would be difficult.

The development of a new program is then described. It makes use of an interactive command shell and has graphical display of input and output. This makes it easy to use, which is important in an engineering environment. The design of the program also allows for considerable flexibility in the description of the magnet and for easy modifications to satisfy future requirements. Several novel features in the analysis of the quench make the program considerably more efficient than its predecessors. A comparison of experimental and predicted results for a simple quench show that good results can be obtained.

CONTENTS

1. INTRODUCTION

It has been known for many years that most materials conduct electricity. The ease with which a current passes through a material is measured by the voltage drop across it. In 1838, Georg Simon Ohm found that, for many materials, the relationship between current and voltage is linear; the constant in this relationship is called the resistance of the material. Almost a century later, in 1911, Heike Kammerlingh Onnes discovered a class of materials which do not even approximately obey Ohm's law; in fact, they show <u>no</u> resistance to the passage of an electric current when cooled below a certain temperature [1]! These materials became known as 'superconductors'. The critical temperature required to sustain superconducting operation is usually very low (just a few degrees Kelvin in commercially available superconducting wires). Early superconducting materials could only carry small currents, and work in low magnetic fields, without reverting to a normally resistive state. However, since the 1960s, practical superconducting wires have been available and are now widely used.

The phenomenon of superconductivity has an obvious application in the generation of high magnetic fields, where large currents are required. Use of ordinary resistive conductors leads to wasteful dissipation of energy due to resistive losses. However, a superconducting wire will carry a current with no losses apart from those associated with refrigeration.

High magnetic fields are required in electrical machinery, particle and fusion physics research, magnetic levitation and nuclear magnetic resonance (NMR) spectroscopy. Superconductors have applications in all these fields, but the most commercially important is NMR spectroscopy [2]. This technique needs high, very homogeneous fields. High fields can be obtained by winding many layers of superconducting wire around a solenoidal former. Homogeneity is achieved by using several concentric coils to 'correct' the field.

Although such magnets are designed to operate in the superconducting mode, it is important to know how they will behave when part of the wire becomes normally resistive. This is quite a common occurrence, since the energy input needed to raise the temperature of part of a wire above its critical value is very small. Such an input could occur through refrigeration failure or a heat-generating process within the magnet, such as frictional heating due to wire motion.

Once the transition has taken place in part of the wire, then if resistive heating of this normal region exceeds the rate of energy loss to its surroundings, the temperature of the neighbouring superconductor will rise. This in turn will generate heat, and the entire magnet can rapidly revert to the normally resistive state. This transition from the superconducting to the normal state during operation of the magnet is known as 'quenching'.

During the quench, all the energy stored in the magnetic field of the magnet is converted into heat in the windings. Most energy, and hence the highest temperatures, occur at the quench initiation point. These peak temperatures can be very high, because of the large amount of stored energy in typical magnets. High temperatures can lead to damaged wire insulation and, in severe cases, melted windings. Thermal expansion due to temperature differentials can produce high stresses within the windings, which may also permanently damage the magnet. The large currents flowing through the normal region produce large voltage drops. These can cause insulation damage due to dielectric breakdown, and sparking to earthed components.

Since the effects of a quench may be severe enough to destroy a magnet, and because of the high cost of magnet systems, it is important to be able to predict how a magnet design will behave during a quench. This is not a trivial calculation; one has to consider the thermal and electromagnetic interaction of individual coils, and the behaviour of the electrical circuit in which the magnet is incorporated. The magnetic field- and temperature-dependence of wire properties such as resistivity and specific heat complicate the analysis. It is only possible to derive analytic expressions for the parameters of the quench for very simple cases [3]. For situations of interest to designers of real magnets, a computer simulation of the process is necessary.

Computer-based models of quenching have been available for some time; the first program was developed over twenty years ago [4]. However, experience of the programs [4,5,6] available at Oxford Instruments Ltd, a leading manufacturer of superconducting magnet systems, has shown that they have limitations which have prevented them from becoming widely used:

a) lack of generality; for example, the inability to model correctly the electrial circuits of which the magnets are part

b) slowness; run-times of several hours for complex systems

c) poor documentation (or no documentation!)

d) batch-oriented input and output; communication with the program via data files, with no graphical pre- or post-processing

e) use of unstructured or poorly-structured code, making modifications difficult

In many cases, the problems are due to the programs being developedas research tools, rather than as computer-aided design packages. However, in order to improve the quality of quench modelling of magnet designs, a new simulation is required. This report describes the development of a new program for use by magnet designers at Oxford Instruments Ltd. It addresses the problems listed above by:

a) developing algorithms which are sufficiently general to describe a wide range of magnet systems

b) paying attention to speed considerations when designing the model

c) providing comprehensive documentation for both users and future programmers

d) using a set of Fortran libraries [7] to provide flexible, interactive input and output for the program

e) coding in structured, ANSI-standard Fortran 77 [8]

The new program will make quench modelling of magnet designs much simpler and more accurate. More and better quench modelling of magnets should lead to a clearer understanding of the process and hence to designs which are more effectively protected against the effects of a quench. Expensive redesigns of magnets which are found to be damaged by quenching will thus be avoided.

It must be emphasised, however, that the process of quenching depends on many physical properties and involves many adjustable parameters. It is impossible, even in a very complex model on a powerful computer, to model all aspects of a quench accurately. For this reason, the predictions of any such program should be treated with suspicion until they are experimentally confirmed. Non-validated results should be used for comparative purposes only.

2. Theory

2.1 Quench Initiation

In order to start a quench in a magnet, part of the superconducting winding must become normally resistive. This happens when the temperature of the wire rises to a point at which the current carried by the wire is greater than the 'critical current' at which the superconducting state occurs. In other words, the operating point of part of the superconductor lies outside the 'critical surface' shown in figure 2.1.

The energy input needed to produce a temperature rise sufficient to drive the superconductor normal is very small, because at low temperatures the specific heats of the materials used in the windings are very small. If we assume that critical current falls linearly with temperature, as in figure 2.2, then the temperature at which the winding returns to the normal state, and starts generating heat, is given by

$$\theta_g = \theta_c + (\theta_0 - \theta_c)\, J_{op} / J_{c0} ,$$

where θ_c is the critical temperature at zero field and current, θ_0 is the operating temperature, J_{op} is the current density at which the magnet operates, and J_{c0} is the critical current at θ_0. Clearly, θ_g, and hence the energy needed to drive the conductor normal, fall as the operating current gets closer to the critical current. For a typical magnet operating in a field of 6 T and at an operating current of 90% of J_c, the energy input required to raise the temperature of the winding above θ_g is approximately 1000 Jm^{-3}. At room temperature, this would raise the temperature of the winding by just 0.3 mK!

The normal zone is continuously generating heat and losing it to its surroundings. In order to grow, the net heat generation must be positive; this means that the zone must exceed a certain critical volume. A simple calculation shows that this volume is very small. Consider a single superconducting wire, of cross-sectional area *A*, carrying the critical current density J_c, as in figure 2.3. Assume that a normal zone of length ℓ is initiated, and that the temperature of the zone is θ_g. For the zone to be stable, the heat loss along the wire must equal the resistive heat generation inside the zone. That is,

$$J_c^{\,2}\ \rho \ell A \;=\; 2\kappa A\ (\theta_g - \theta_o)\ /\ \ell\ ,$$

where ρ and κ are the normal resistivity and thermal conductivity respectively of the superconductor, or

$$\ell \;=\; \left\{ \frac{2\kappa\ (\theta_g - \theta_o)}{J_c^2\ \rho} \right\}^{\frac{1}{2}} .$$

Thus, any disturbance which results in a normal zone longer than ℓ will tend to grow. This smallest self-propagating volume is known as the 'minimum propagating zone' (MPZ) [10]. For a typical niobium-titanium superconducting wire, in a field of 6 T, the value of ℓ is $\frac{1}{2}$ μm. This is can be produced by a total energy input of only 10^{-9} J.

In practice, the conductor usually will be a composite of superconducting filaments in a copper matrix. A more complete analysis [3], taking into account the matrix material and transverse heat loss from the wire, shows that the energy input required is several orders of magnitude higher (around 10^{-5} J for the conditions described above). However, this is still small enough to be easily attainable, as will be seen below.

It is thought that the major source of energy input to the magnet is frictional heating due to wire motion. The winding carries a current in a magnetic field, and hence experiences a force. Since it is impossible to wind the wire in a magnet uniformly on a microscopic scale, wire motion is quite possible. Evidence that the wire does move is provided by observation of the acoustic emissions from operating magnets [11] and from transient voltages across coil terminals. For a single wire, the energy input due to wire motion is given by

$$E \;=\; (\mathbf{B} \times \mathbf{J})\ .\ \mathbf{d}$$

per unit volume, where **d** is the distance moved. For the figure of 1000 Jm^{-3} given above, this requires a movement of less than 1 μm. Clearly, this is a very demanding value. Although measures are often taken to limit wire motion [12], it can be seen that superconducting magnets are vulnerable to quenching, particularly when operating near the superconductor critical current.

2.2 Effects of Quenching

The main physical process of a quench is the conversion of magnetic energy to thermal energy. So, the first quench effect to consider is the temperature rise of the magnet winding. A typical magnet stores about 1 MJ of energy when at its operating current. If this were dissipated throughout the entire magnet, the temperature rise would be about 100 K, which would not damage any of the materials used in the magnet. However, section 2.1 showed that quenches can easily be initiated at specific points within the magnet. These points will experience higher temperatures, by virtue of the length of time for which they are normally resistive, and the large currents which are initially driven through them. The calculation of these peak temperatures is one of the most important tasks for any quench simulation program.

An estimate of the peak temperature achieved in a coil can be obtained from an analysis of the energy balance in a unit volume of magnet winding. Since many magnet designs become totally normal in a matter of milliseconds, it is reasonable to assume adiabatic heating. So, the temperature rise in an isothermal volume is obtained by equating the energy required to raise its temperature by $\Delta\theta$ to the power dissipation due to resistive heating by the current flowing through the normal resistance

$$\gamma C(\theta)\ \Delta\theta \ = \ J^2(t)\ \rho(\theta)\ \Delta t \ ,$$

where γC is the volumetric specific heat, and ρ the resistivity, averaged over the all the materials used in the conductor, including any material filling the gaps between wires. This leads to

$$\int_0^T J^2(t)\,dt = \int_0^{\theta_m} \frac{\gamma C(\theta)}{\rho(\theta)}\,d\theta \text{ , or}$$

$$\int_0^T J^2(t)\,dt = U(\theta) \text{ .}$$

The function $\int \gamma C/\rho \, d\theta$ is known as the 'generation function'. The equation linking $U(\theta)$ to $J(t)$ allows the peak temperature, θ_m, to be calculated very easily. In fact, a 'characteristic time' for the quench, T_Q, can be defined, such that

$$J_0^2 \, T_Q = U(\theta_m) \text{ ,}$$

where θ_m is the maxiumum temperature developed during the quench. Figure 2.4 shows $U(\theta)$ for some common materials. U for niobium-titanium, a commonly used superconductor, is too small to be shown, because of its high normal state resistivity. This means that magnet windings made of this material would develop very high temperatures during a quench. This is one reason why commercial superconducting wires are composed of filaments of superconductor in a copper matrix.

The fact that the temperature distribution is not uniform also means that the magnet, and the former on which it is wound, will undergo differential thermal expansion. This can produce stresses within the winding, and also between the winding and the former. High stresses are also experienced because, during the quench, the currents through individual coils are not equal. Different coils will experience different magnetic forces and large stresses may be developed at the coil-to-coil interfaces. These stresses may permanently distort the magnet.

A characteristic of quenching is rapid changes in the currents carried by the coils. Large values of dI/dt may induce large eddy currents in magnetically-coupled objects such as formers, which can then be damaged by the magnetic forces imposed on them.

Another major adverse effect of quenching is the development of high voltages, due to the rapidly-changing currents and the high inductances involved. Applying Kirchoff's second law to a single coil magnet gives

$$I(t)\ R(t) + L\,\frac{dI}{dt} = V_{supply}\ .$$

Clearly, the voltage which appears across the terminals of the magnet is equal to the voltage developed by the current supply. However, the 'internal' voltage across the normal zone, defined as IR, can be very large; 1 kV is quite common. This can cause breakdown of the insulation between turns of the winding, which would destroy the magnet.

2.3 Normal Zone Propagation

In order to predict how the normal zone spreads through the magnet after the start of a quench, it is necessary to solve the equation describing heat diffusion in three dimensions

$$\nabla\ .\ (\kappa A\ \nabla\theta) - \gamma C\,\frac{\partial\theta}{\partial t} - hP\ (\theta - \theta_0) + GA = 0\ ,$$

where h is the heat transfer coefficient to liquid helium for the wire, which has a wetted surface P, and G represents the heat generated in the wire. In this case, ρ and γC are averaged over the cross-section of the wire only, since the time constant for penetration of heat into any insulating material between the wires would be much longer than the characteristic time of the quench. This is a difficult and computationally intensive equation to solve for real problems, so a simplified model is appropriate. The treatment used here was developed by Cherry and Gittleman [13] and Broom and Rhoderick [14]; the notation is that of Wilson [3]. First, consider longitudinal propagation only. The heat diffusion equation can be written

$$\frac{\partial}{\partial x}\left[\kappa A\frac{\partial\theta}{\partial x}\right] - \gamma C\frac{\partial\theta}{\partial t} - hP(\theta - \theta_o) + GA = 0 .$$

Now assume that the temperature profile in the x-direction will be of the form shown in figure 2.5. and that it moves along the wire at a constant velocity, v. A new co-ordinate, ε, can be defined, such that $\varepsilon = x - vt$. (There is experimental evidence that, in the steady state, the normal zone will propagate along the wire with constant velocity.) Further, assume that the heat generation, $G(\theta)$, can be approximated by an abrupt transition at

$$\theta_s = (\theta_g + \theta_c) / 2 .$$

Then, G will have the value $G_c (= J_c^2 \rho)$, the heat generation at the critical temperature to the left of the boundary, and the value 0 to the right, giving

$$\frac{d^2\theta}{d\varepsilon^2} + \frac{v\gamma C}{\kappa}\frac{d\theta}{d\varepsilon} - \frac{hP}{\kappa A}(\theta - \theta_o) + \frac{G}{\kappa} = 0 .$$

The boundary conditions for the solution are

$$\theta = \theta_s \quad \text{at} \quad \varepsilon = 0 ,$$

$$\theta = \theta_1 \quad \text{as} \quad \varepsilon \rightarrow -\infty ,$$

$$\theta = \theta_o \quad \text{as} \quad \varepsilon \rightarrow \infty \quad \text{and}$$

$$- \kappa \left.\frac{d\theta}{d\varepsilon}_{\text{normal}}\right|_{\varepsilon=o} = \kappa \left.\frac{d\theta}{d\varepsilon}_{\text{super}}\right|_{\varepsilon=o} + vQ_L .$$

The last condition imposes continuity of heat flow across the normal-superconducting boundary; Q_L represents the transient effects in the transfer of heat to boiling helium.

Solving subject to these boundary conditions produces an equation for the propagation velocity

$$v = \frac{J}{\gamma C}\left\{\frac{\rho\kappa}{\theta_s - \theta_o}\right\}^{\frac{1}{2}} \frac{(1 - 2y)}{(yz^2 + z + 1 - y)^{\frac{1}{2}}} .$$

The first two factors represent the adiabatic propagation velocity, assuming no heat transfer to the liquid helium, where

$$y = \frac{hP\,(\theta_s - \theta_o)}{AJ^2\rho} \quad \text{and}$$

$$z = Q_L \,/\, \gamma C\,(\theta_s - \theta_o) .$$

Provided the longitudinal thermal conductivity is dominated by the normally-resistive metal (as it will be in a copper-matrix wire), the product $\rho\kappa$ can be found from the Wiedemann-Franz-Lorentz law at an average temperature

$$\rho\kappa = L_o\theta_s ,$$

where L_o is the Lorentz number, so that

$$v_{ad} = \frac{J}{\gamma C}\left\{\frac{\rho\kappa}{\theta_s - \theta_o}\right\}^{\frac{1}{2}} .$$

The normal zone will also propagate laterally from turn to turn. An expression for the lateral propagation velocity can be derived from the longitudinal velocity. The ratio of velocities is related to the ratio of longitudinal to lateral thermal conductivities,

$$\alpha = \frac{v_{trans}}{v_{long}} \left\{\frac{\kappa_t}{\kappa_l}\right\}^{\frac{1}{2}} .$$

(It should be noted that recent work [15], treating the transverse propagation as a diffusive process, suggests that it is not directly proportional to the longitudinal velocity. There is some experimental support for this belief [16].)

These expressions are for the adiabatic propagation velocities for uncooled windings (that is, windings which are not permeated by liquid helium). They give quick indications of the speed of propagation in a given situation, but are very approximate. The full expression, taking into account heat transfer to the liquid helium, is less reliable, since the parameters Q_L and h are very difficult to measure in practice. Other workers have developed similar formulae with corrections to improve the agreement with experimental results [17-20].

2.4 Protection Circuits

The adverse effects of a quench are due to the transfer of energy from the magnetic field to the magnet. It follows that the damage to the magnet can be reduced by diverting the energy away from the magnet. The easiest way to do this is to add external electrical components to the magnet system, which can carry the magnet current if a quench occurs. This external circuitry is known as the 'protection circuit'. Several distinct types of circuit are commonly used.

Consider the single coil magnet system shown in figure 2.6. If the value of the resistance R is correctly chosen, then as the resistance of the magnet grows during the quench, the resistor current will rise significantly and energy will be dissipated in the resistor instead of the magnet. (In practice, resistances of the order of 1 Ω are needed.)

Section 2.2 showed that the maximum temperature developed during a quench is related to the characteristic time, T_Q. For a magnet system consisting of many coils - a common situation - the total inductance may be hundreds of henries. This means that the time constant (L_{total}/R) of a system protected by a single dump resistor, as shown in figure 2.7(a) may be very large. In this situation, the magnet can be protected by connecting a resistor in parallel with each coil, as in figure 2.7(b). Now, if a single coil quenches, the time constant is determined by the inductance of that coil alone, and hence the current decay will be much faster, and the maximum temperature will be lower. This technique is called 'protection by subdivision'.

Another way of diverting energy away from the magnet is to make use of a magnetically coupled secondary. Then, after the onset of a quench, the changing current will induce a current in the secondary. If this circuit contains a normally resistive component, then it will dissipate energy which would otherwise be deposited in the magnet. This technique can also be used to shorten the quench time. If the secondary is in contact with the quenching coil, then as its temperature rises, it will heat up the coil and assist the spread of the normal zone in it. The energy dissipated in the coil will thus be spread over a larger volume. As noted in section 2.2, this will help to reduce the peak temperature developed in the magnet. The heating of a coil due to induced currents in a coupled secondary is known as 'quench-back' [21].

Constraints on the design of a magnet sometimes lead to the possibility of damaging quenches, even when the optimum protection circuit is added. In this case, 'active protection' can be used. This relies on external circuitry sensing the start of a quench and activating some device to limit its effects. At its simplest, this consists of a circuit breaker and resistor, as shown in figure 2.8. In this case, the quench detector closes a switch and the magnet current flows through the resistor instead of the coil. The quench detector must be resistant to spurious signals, so a voltage difference detector is usually used. Figure 2.9 shows a circuit in which the difference in the voltage drop across two parts of a coil is monitored. If a quench starts, the voltage drops will be unequal, and the switch is closed.

Active protection is effective, but relies on the correct operating of quench detectors and switches. For this reason, passive protection is usually used. An active protection scheme is added in parallel if high voltages or temperatures are predicted in spite of the passive protection.

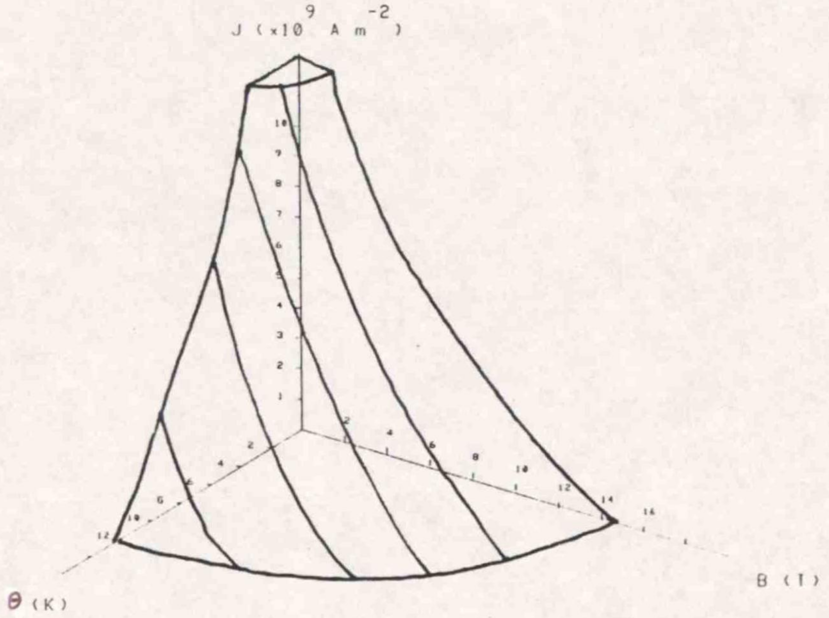

Figure 2.1

Critical surface for a typical niobium-titanium superconductor

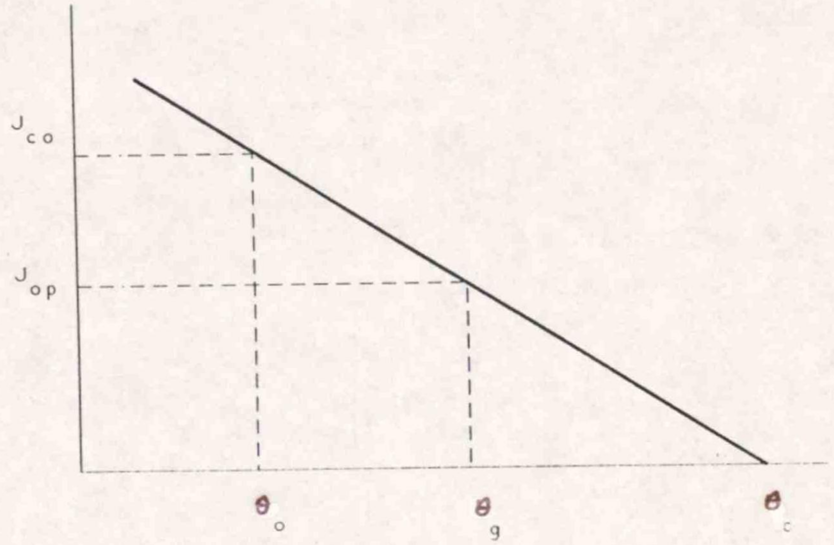

Figure 2.2

Approximate linear variation of critical current with temperature

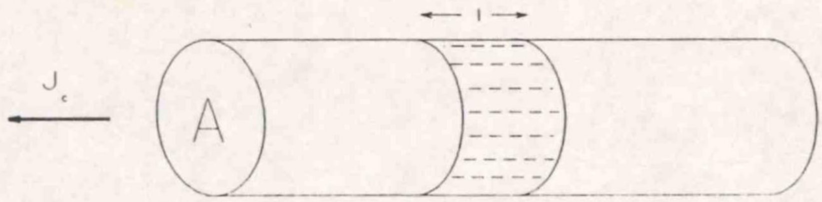

Figure 2.3

Initial quench point in a superconducting wire

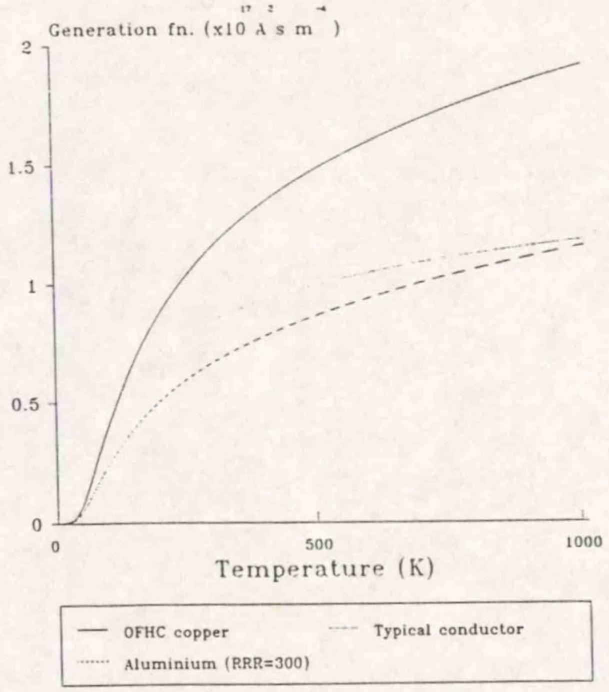

Figure 2.4

Generation function for some common cryogenic materials

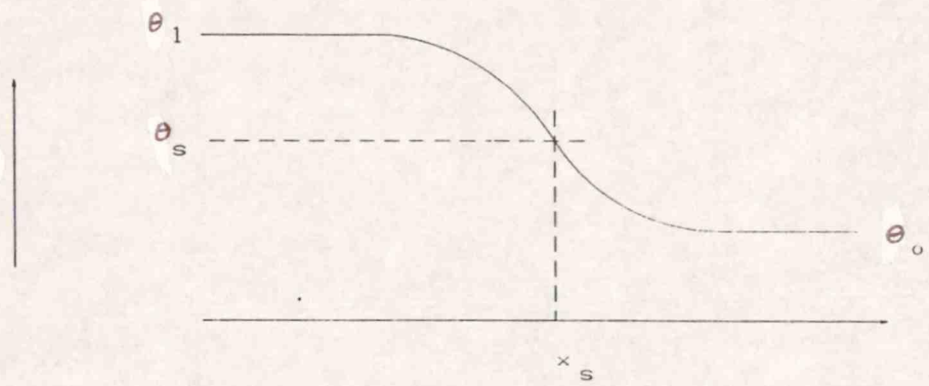

Figure 2.5

Temperature profile along a quenching wire

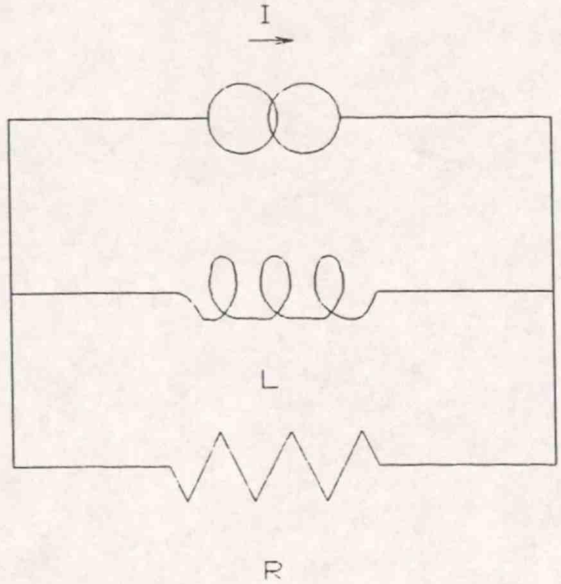

Figure 2.6

Simple magnet protection circuit

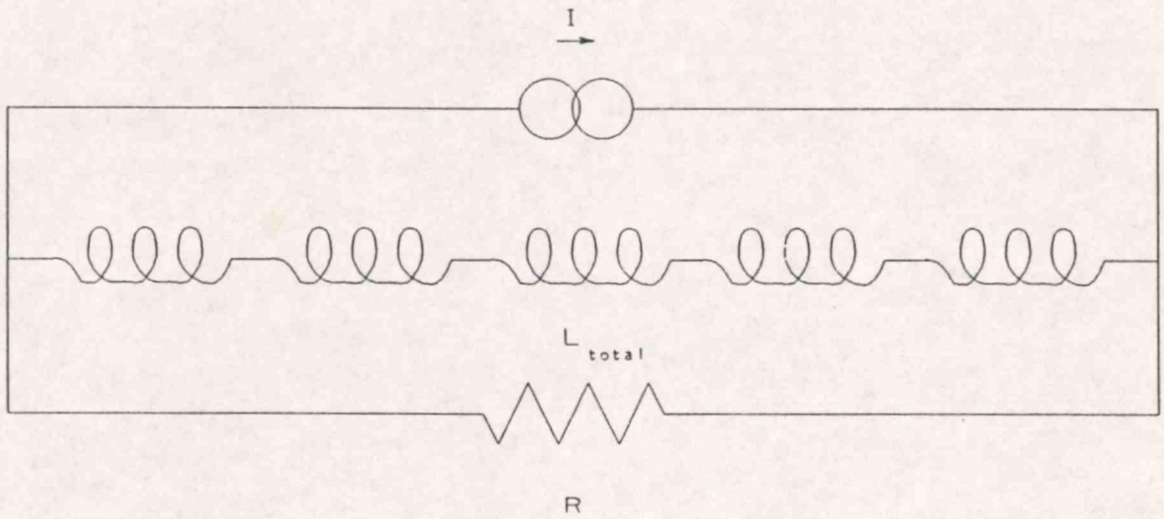

Figure 2.7(a)

Protection of several coils by a single resistor

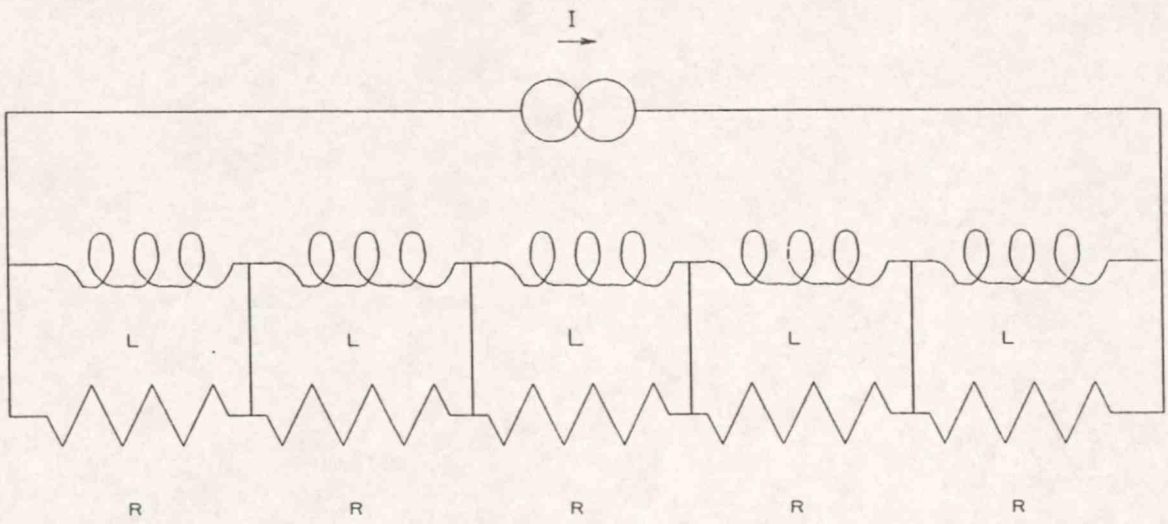

Figure 2.7(b)

Protection of several coils by subdivision

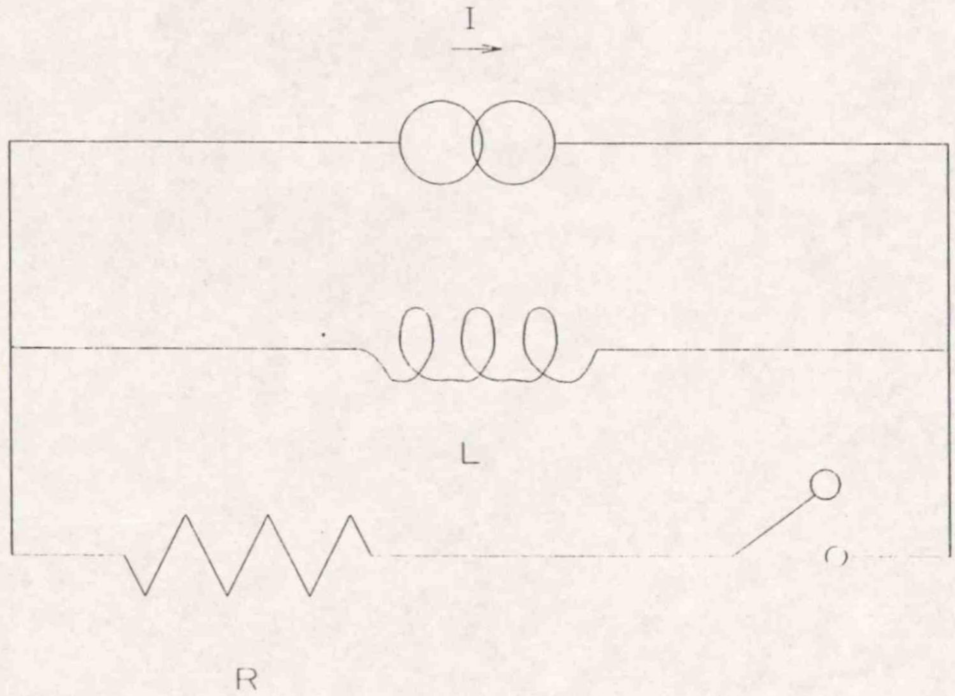

Figure 2.8
Active quench protection

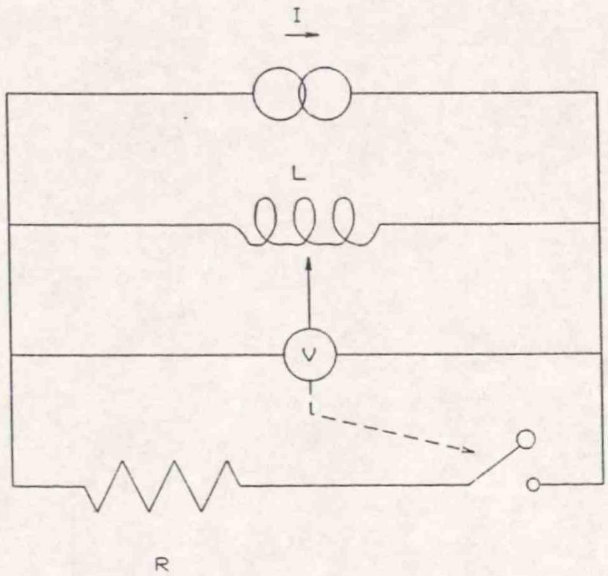

Figure 2.9
Quench detection by voltage offset

3. Review of current work

3.1 Purpose and Method of Review

The programs available at Oxford Instruments were largely based on work done over ten years earlier. Clearly, it was important to examine the work done in the previous decade. This review was in the form of a literature search over the period 1977 to 1988. References came from sources in the company and conference proceedings, but primarily from a computerised literature search. Almost all the references obtained from the manual review were also produced by the computer search, so it seems likely that the computer search found the majority of the relevant papers.

3.2 Description of Current Programs

Papers covering a total of ten models were examined [4-6,9,22-31]. Three of the programs available at Oxford Instruments were examined in greater detail; they are described more fully in Chapter 4. There are two common approaches to the analysis of the spread of a normal zone:

a) solution of the full three dimensional heat diffusion equation (see section 2.3) using a finite difference method [9,25,28,33]

b) use of the concept of quench propagation velocity (see section 2.3) to drive the normal zone expansion [4-6,22-24,26,27,29-31]

The finite difference models have the advantage of not requiring any knowledge of the quench propagation velocity, which is difficult to calculate and measure. They can work with complex coil shapes [25] and can include effects such as heat transfer to boiling helium. They were found to produce good agreement with experimental results (although in one paper [9], it is noted that the predictions are very similar to those of the original, simple program QUENCH [4]!). However, they appear to suffer from the problems of all software of this type:

a) a large amount of work is required to set up the model

b) to obtain accurate results, the models must be very large. This leads to long run times or the use of an expensive supercomputer [30]

c) these size, run-time and programming effort constraints mean that the programs tend to be developed for particular magnets containing only a few coils (often only one!)

In general, these models appear to be best suited to the analysis of large, one-off magnet designs, where very accurate results are required and extensive resources are available.

The velocity-driven models are smaller - one model [27] runs on an IBM PC. Run time and model complexity are less of a problem, and in many cases [5,23,24,29] systems containing tens of coils can be analysed. All the programs appear to be very similar and have much in common with QUENCH [4]. At each time step, a new normal zone is added via the propagation velocity. These incremental normal volumes are assumed to be at a constant temperature; they are known as 'isothermals'. Knowledge of the specific heat of the coil and the energy generated in each isothermal allows their temperatures to be calculated. The resistances of the normal zones are updated from the resistivity of the coil data and the isothermal temperatures. These are used in the circuit analysis to find the new currents flowing in the coils. New fields and propagation velocities are then calculated and the process is repeated for the next time step. Materials data is user-supplied, sometimes as polynomial approximations. Propagation velocities are calculated or user-supplied. The programs generally calculate the temperatures, currents and voltages in the system as functions of time.

In most programs, however, it appears that some simplifying assumptions have been made that limit the applicability of the programs to certain magnet designs. Examples of the restrictions are:

a) only one coil, or one coil plus a former, can be modelled

b) normal zones are assumed to propagate infinitely fast in the axial and/or longitudinal directions, so that the normal zone propagates in only one or two dimensions, rather than all three, as shown in figures 3.1(a-c). This places restrictions on the aspect ratio of the coils. For example, assuming two dimensional propagation implies infinitely fast propagation along the wire, which means that the circumference of the coil must not be too large compared to its thickness

c) only a few types of wire can be used. This is not the case in many modern designs, where there may be many coils, each containing many types of wire

d) limited freedom in the protection circuit design. For example, in some programs each coil must be protected by a parallel resistor

Whilst these restrictions may be trivial in a research situation, or where only a limited set of magnet designs are used, they would be unacceptable in a program which was to be used in an environment such as that at Oxford Instruments, where many, varied designs must be analysed.

In the cases in which comparisons with experimental results are given, the predictions are acceptably accurate; usually, agreement to within 10-15% is obtained. However, in most cases, only a few coils are used and it is noticeable that the predictions become less accurate as the sizes of the models increase. The worst results are obtained when the limitations of the program conflict with the system being modelled. For example, violation of the restrictions on coil geometry will cause the field calculations to be inaccurate.

The models examined are summarised in table 3.1.

Authors	Ref	Model	Comments
WILSON	4	Velocity driven	First single-coil quench program.
SIMKIN	5	Velocity driven	Multiple-coil extension to [4].
APTAKER	22	Velocity driven	Longitudinal propagation only; for specific magnet design with one coil plus former.
ECKERT et al.	23,24	Velocity driven	Radial propagation only; similar to [5].
CAROSIO et al	9	Finite difference	Single-coil simulation; results similar to those from [4] in case considered.
O'LOUGHLIN and CHRISTENSEN	25	Finite difference	Developed for particular magnet design.
MORI and NOGUCHI	26	Velocity driven	Developed for particular single-coil magnet design. Quench-back from former simulated by increased propagation velocity.
MILLS	6	Velocity driven	Multiple-coil simulation.
WILLIAMS, JOSHI and IWASA	27, 30, 31	Velocity driven	Limited to 10 touching, concentric coils. Assumes round wire is used.
KADAMBI and DORRI	28	Finite difference	Large model running on a supercomputer.
GROSS	29	Velocity driven	Good agreement with experimental results
KURODA et al.	32	Finite difference	Single-coil simulation. Developed in conjunction with an experimental quench study.

Table 3.1

Summary of the Review of Quench Simulation Programs

3.2 Conclusions from the Review

The papers on finite difference-based models show that they are not well suited to use in an engineering environment. They are usually applied to single-coil magnets, or are written to model one particular design. They give good, accurate results, but will require fast computers or run-times of many hours.

Velocity-driven models appear to be able to model magnets containing large numbers of coils of varying design and to produce acceptably accurate results. The simplified thermal analysis which results from the propagation velocity concept can be solved quickly. However, few of the programs examined above could be used at Oxford Instruments without major modifications to remove limitations. It is clear that a reliable model can be developed using the same techniques as these programs, but it must avoid any unrealistic restrictions on the magnet design.

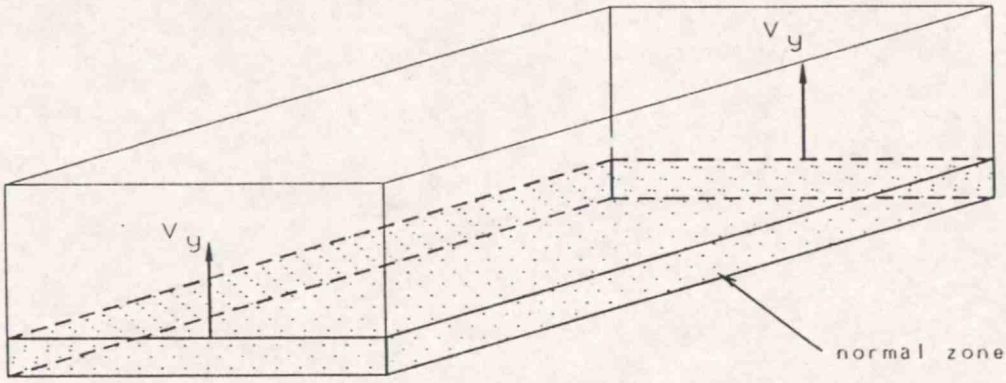

Figure 3.1(a)

One dimensional quench propagation

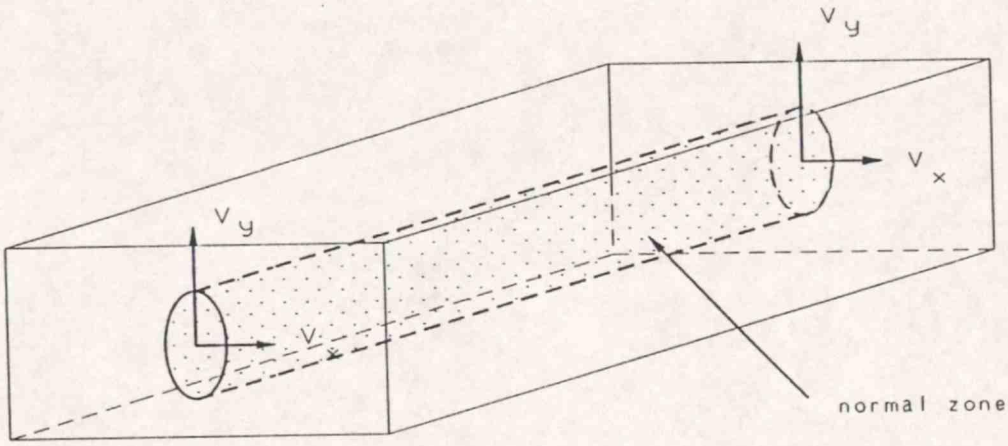

Figure 3.1(b)

Two dimensional quench propagation

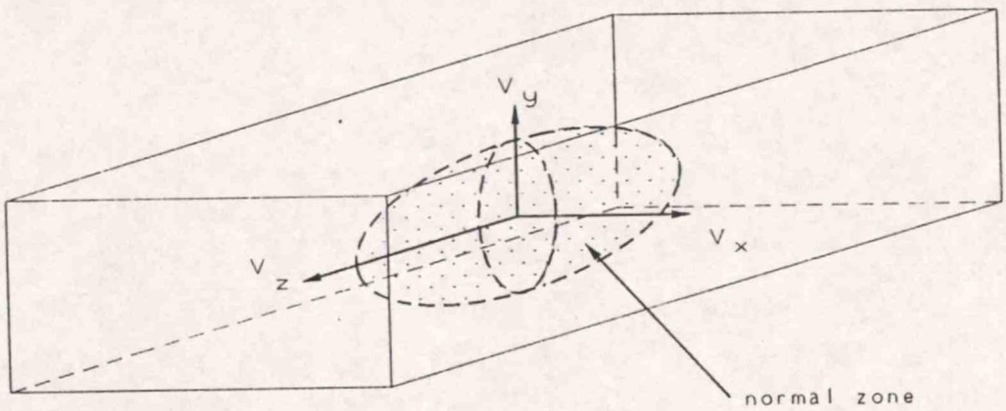

Figure 3.1(c)

Three dimensional quench propagation

4. Modifications to an Existing Program

4.1 Reasons for Modifying an Existing Program

Despite the problems discussed in the previous chapter, a significant amount of quench modelling was done with the existing programs. However, several new, very large magnet designs were being developed in the company at this time [33,34], so it was important that a workable quench program should be made available quickly. Since a completely new program, able to satisfy all the requirements of all the magnet designers, was estimated to require $1\frac{1}{2}$ to 2 man years of work, a modified program was the best solution to the problem.

Modifying an existing program was also attractive as a way of gaining experience in the production, documentation and user support of engineering software in general, and quench simulations in particular. It was expected that this experience would be extremely valuable during the development of a new program.

4.2 Choice of Existing Program

Source code was available to the company for three programs: QUENCH [4], MCQUENCH [5] and 2QUENCH [6]. QUENCH is limited to the analysis of single coil magnets, which form a very small fraction of modern superconducting magnet designs. The choice was thus reduced to MCQUENCH or 2QUENCH. As discussed in the previous chapter, they are based on the same model and calculate the same parameters. The two programs were used to analyse a particular magnet design and compared for ease of use and flexibility.

It was found that 2QUENCH, the more modern program, was somewhat easier to use, since it has a pre-processor program to help the user prepare the input data file. It is also more flexible in its input of the material properties data; it uses tables of '$f(\theta)$ versus θ' data, whereas MCQUENCH requires polynomial approximations to the data to be supplied. The MCQUENCH documentation, although concise, was more detailed than that for 2QUENCH. However, these problems were quite minor and in the other categories considered above, the programs were found to be similar.

Since the programs were outwardly comparable, the ease with which the software could be modified was the most important factor in deciding which to work on. Examination of the source code showed that MCQUENCH is written in unstructured Fortran 66 [35], using many deprecated constructs, such as arithmetic IFs. Such code is notoriously difficult to maintain and extend [36]. 2QUENCH, developed in the mid-1980s, was written in Fortran 77 with VAX/VMS extensions [37] and some awareness of modular design [38]. It was decided that the programming style and structure of 2QUENCH meant that modifications to it would be less difficult than to MCQUENCH, and so it was chosen as the basis of an interim quench program, which (inevitably!) became known as 3QUENCH.

4.3 Description of Existing Program

2QUENCH was designed to simulate the quenching of multiple-coil magnet systems. The user specifies the geometry of the coils, the temperature dependence of the physical properties of the magnet materials and the quench initiation point. The quench is modelled over a specified time interval and the following quantities are calculated as functions of time:

a) peak temperature developed in each coil
b) current through each coil
c) voltages across each coil
d) resistance of each coil
e) volume of the normal zone in each coil
f) magnetic field in the centre of the magnet

The algorithm used to analyse the spread of the normal zone through a magnet is similar to that of QUENCH and MCQUENCH. The concept of a quench propagation velocity is used to compute the growth of the normal zone. The normal zone spreads through the coil from the quench initiation point. At each time step, the zone expands a distance $v\Delta t$ in each direction, where v is the propagation velocity in that direction. So, at each time step, an ellipsoidal 'shell' is added to the outside of the normal zone, as shown in figure 4.1. Each shell is considered to be an isothermal volume. Furthermore, there is assumed to be no heat transfer between isothermals; this is an adiabatic model. Since many magnet systems quench in a few seconds, this is a reasonable assumption. For longer quenches, where heat transfer between isothermals will be significant, it will produce pessimistically high values for the isothermal temperatures.

This assumption of adiabaticity allows the temperature of an isothermal to be calculated from a simple differential equation, which relates the temperature rise to the Ohmic energy dissipation (in fact, the generation function could have been used; it is a better-behaved function than $\gamma C(\theta)$ for most materials and would have been more suitable)

$$\frac{d\theta}{dt} = \frac{J^2(t)\ \rho(\theta)}{\gamma C\ (\theta)} .$$

2QUENCH uses a Runge-Kutta method [39] to solve this equation. The isothermal temperatures can then be used to calculate isothermal resistances, and hence coil resistances, from the resistivity data and the geometry of the isothermals. The coil resistances are used in an analysis of the electrical circuit, of which the magnet is a part, to find the currents flowing through each coil and the voltages across each coil. The propagation velocities for each coil, which are dependent on coil currents, are then recalculated using the method described in [18,19] and the process is repeated for the next time step. The program outline is shown in figure 4.2.

4.4 Required Modifications

4.4.1 Circuit analysis modifications

The most important alteration required was in the circuit analysis section of the program. 2QUENCH uses the method of mesh analysis [40], in which a set of simultaneous differential equations are obtained by applying Kirchoff's second law to each current loop, or mesh, in the circuit (that is, the total voltage drop around the loop must be zero). Figure 4.3 shows the law applied to a general current loop. This is conceptually very simple, but cannot easily be adapted for the computerised analysis of a general circuit. This was not a problem for 2QUENCH, which was intended to be used with the standard protection circuit shown in figure 4.4. Since there will only be two current loops in this circuit, only the position of the magnet coils in the circuit and the values of the protection resistors need to be known for the two circuit equations to be set up.

However, to be of widespread use, 3QUENCH had to be able to analyse magnets using many different protection circuit schemes. This requires a different approach to the circuit, known as 'nodal analysis' [40]. In this method, Kirchoff's first law is applied to each component junction, or 'node', in the circuit. This requires that the sum of all the component currents flowing into a node must be equal to the sum of all the component currents flowing out of the node, as shown in figure 4.5. This allows the circuit description to be easily reduced to a set of matrices, which are very well suited to computer analysis. The approach used is described well by Staudhammer [40].

Consider the general circuit element shown in figure 4.6. It consists of a resistance and a current supply. The current leaving the component is called the branch current, I_b, whilst the current flowing through the resistance is the element current, I_e. These are related by

$$I_b = I_e - I_{gen},$$

where I_{gen} is the current produced by the current generator in the element. There is a similar relation for the voltages associated with the element

$$V_b = V_e - V_{gen} .$$

The 'nodal voltages' for the element are defined as the voltages of the ends of the component, relative to a ground node.

For a circuit consisting of many connected elements, the currents and voltages can be represented by vectors. Branch and nodal voltages can be related by the 'incidence matrix', **A**, which defines how the components are connected:

$$A_{ij} = \begin{cases} +1 & \text{if the first node of component } j \text{ is connected to node } i \\ -1 & \text{if the second node of component } j \text{ is connected to node } j \\ 0 & \text{otherwise} \end{cases}$$

(Note that this definition of the incidence matrix defines the convention for positive current flow as being from node 1 to node 2. To reverse this convention, the signs of the elements of **A** should be exchanged.)

Given this definition of **A**, the branch and nodal voltages can be related by

$$\mathbf{V}_b = \mathbf{A}^t \mathbf{V}_n .$$

Branch currents and nodal voltages can also be related. Let the resistance of the i^{th} component be R_i. We can define an admittance matrix, **Y**, where

$$Y_{ij} = \begin{cases} 1/R_i, & i = j \\ 0, & i \neq j \end{cases} .$$

Then,

$$\mathbf{I}_e = \mathbf{Y} \mathbf{V}_e .$$

So, combining this with the equation linking branch and element currents,

$$\mathbf{I}_b = \mathbf{Y} \mathbf{V}_e - \mathbf{I}_{gen} \text{, or}$$

$$\mathbf{I}_b = \mathbf{Y} (\mathbf{V}_b + \mathbf{V}_{gen}) - \mathbf{I}_{gen} \text{, or}$$

$$\mathbf{I}_b = \mathbf{Y} (\mathbf{A}^t \mathbf{V}_n + \mathbf{V}_{gen}) - \mathbf{I}_{gen} .$$

Applying Kirchoff's second law to these definitions gives

$$\mathbf{A}\,\mathbf{I}_b = \mathbf{0}\ ,\ \text{so that}$$

$$\mathbf{A}\,\mathbf{Y}\,\mathbf{A}^t\,\mathbf{V}_n + \mathbf{A}\,\mathbf{Y}\,\mathbf{V}_{gen} - \mathbf{A}\,\mathbf{I}_{gen} = \mathbf{0}\ ,\ \text{or}$$

$$\mathbf{V}_n = \mathbf{G}^{-1}\,\mathbf{A}\,(\mathbf{I}_{gen} - \mathbf{Y}\,\mathbf{V}_{gen})\ ,$$

where $\mathbf{G} = \mathbf{A}\,\mathbf{Y}\,\mathbf{A}^t$ is known as the 'nodal admittance matrix'. The equation above allows the nodal voltages to be calculated from a knowledge of the values of the resistances and power supplies in the circuit, and their interconnections. The branch currents can then be obtained from

$$\mathbf{I}_b = \mathbf{Y}\,(\mathbf{A}^t\,\mathbf{V}_n + \mathbf{V}_{gen}) - \mathbf{I}_{gen}\ .$$

The equations above are sufficient for a dc analysis of a static circuit. However, the electrical circuits encountered in a quenching magnet are anything but static! To analyse a time-varying system, the differential equations describing the inductors must be included (capacitors have no applications in magnet protection circuits at present and so are neglected in this analysis). For a single inductor,

$$V_L = L\,\frac{dI_L}{dt}\ .$$

A very simple analysis [40], involving trapezium rule integration of this differential equation, was used in 3QUENCH. Integrating the above equation to obtain I_L gives

$$I_L = \frac{1}{L}\int_0^t V_L\,dt + I_{L0}\ .$$

Applying the trapezium rule to the kth time step gives

$$I_{Lk} = \frac{1}{L}\,\frac{\Delta t}{2}\,(V_{Lk} + V_{Lk-1}) + I_{Lk-1}\ ,\ \text{or}$$

$$I_{Lk} = \frac{\Delta t}{2L} V_{Lk} + \frac{\Delta t}{2L} V_{Lk-1} + I_{Lk-1} ,$$

where V_k and V_{k-1} are the voltages across the inductor for the k^{th} and $(k-1)^{th}$ time steps respectively. This equation can be rewritten

$$I_L = V_{Lk} / R^* + constant .$$

Thus, the transient analysis can be reduced to a series of dc analyses, with the inductors replaced by resistors with values of $2L/\Delta t$. The (time-dependent) constant represents the 'history' of the current flowing through the inductor.

This analysis was successfully implemented in 3QUENCH. It uses a circuit description similar to that of the circuit analysis program SPICE [41], with linear time-dependence of circuit values if required. It was validated by comparison with SPICE for several example circuits.

4.4.2 Other modifications

The other major flaw with the (then) latest version of 2QUENCH was its output. It is a non-interactive program; input is via data files and output is also directed to a file. Since a large amount of data can be generated when analysing a quench in a complex magnet system, some ability to process this data is necessary. Graphical display would be very useful. Unfortunately, the output from 2QUENCH consisted of a page of data for each time step in the analysis, with numeric data 'buried' in explanatory text, as shown in figure 4.7. This is almost impossible to process graphically without first re-arranging the data manually. It was decided that the output routines should be re-written to provide data in columns, with one line per time step, to allow easy transfer to graph-plotting programs. Discussions with engineers and experience with the use of the current quench programs showed that the most useful format for the data would be one table of ASCII data for each coil in the magnet. This layout has several advantages:

a) it is relatively easy to extract trends from the data without resorting to graph plotting

b) it is also easy to find peak values of parameters without plotting

c) it is portable to almost any graph-plotting program

The format chosen was that used by an in-house software library of data manipulation routines (see section 5.1.2) and is shown in figure 4.8. Each table is written to a separate file, whose name is specified by the user. Later, two more tables were added. These store the data on nodal voltages and branch currents in the protection circuit, which could not logically be added to the coil data files.

4.5 Required Extra Features

Some extra features were added to 3QUENCH as a result of user demands. The ability to initiate a quench in a coil at a specified coil current is useful in many cases, since exceeding the critical current in a coil has the same effect as exceeding the critical temperature. The original program used user-supplied critical surface data, but only to warn if initial coil currents were unrealistically high. A simple modification enabled the user to give coil currents above which quenching would be initiated at specified points.

An important addition to the program was the provision of much more comprehensive documentation. The original 'user guide' consisted of instructions on the use of the pre-processor for preparation of the input data files, with no indication of how the program worked. This guide was rewritten in several sections:

a) introduction, covering the capabilities and limitations of the program

b) reference section, describing each category of data in the input data files

c) example section, showing all the input and output data for a sample quench run

d) description of the circuit analysis used in the program and guide to the preparation of the circuit model

This new layout was well received by users. Perhaps the best proof of its usefulness is that some users ran quench simulations using the manual alone, without any help from the author!

4.6 Testing of the Modified Program

Since the new program had a limited lifetime, and no suitable experimental data was available at the time, it was decided that only minimal testing should be performed. The first stage was a form of regression testing. A set of test data for a single coil system was input to both 2QUENCH and 3QUENCH and the predictions for coil current, maximum temperature, normal zone resistance and normal zone volume as functions of time were compared. The results agreed to within 1-2%, as can be seen in figures 4.9(a-d). For such a complex phenomenon, involving so much data of varying reliability, this is acceptable.

Having ensured that no major inaccuracy had been introduced to the program as a result of the modifications, it was necessary to check the model in some way, since it was believed that no validation of 2QUENCH had taken place. In the absence of experimental data, the 3QUENCH predictions were compared with those of QUENCH, which has been extensively checked against experimental results [3]. Figures 4.10(a-d) show that the agreement on normal zone resistance and normal volume was poor. The worst discrepancy was in the prediction of normal zone growth. These predictions were examined more closely by comparing both models with an analytic solution for two idealised quenches.

A very simple situation is the case of a spherical normal zone, which occurs when the three propagation velocities are equal. In a situation in which the current, and hence the velocity, is constant, the time at which the coil becomes 100% normal can be calculated from the velocity and the distance of the furthest point in the coil from the quench origin. The time predicted by 3QUENCH agreed with the theory, whilst QUENCH predicted a 100% normal zone earlier and a final normal zone of 106% of the coil volume. This shows that its normal volume calculator is capable of errors of at least 6%.

A further test was to set very large transverse velocities, to simulate the effect of a planar normal front moving along the wire. The coil should become 100% normal when the zone meets itself on the opposite side of the coil from the quench initiation point. Again, 3QUENCH predicted the 'correct' time for 100% normality, whilst QUENCH predicted a final normal volume of 4800% of the coil volume!

Examination of the QUENCH source code showed that a large proportion of it was concerned with geometrical formulae for the calculation of the volume of ellipsoidal sections. Such complex three-dimensional geometry is obviously subject to errors. It was concluded that the normal volume calculations in 3QUENCH were more reliable than those of QUENCH and so, given the approximate agreement of the two programs, 3QUENCH was likely to be at least as accurate.

Despite the discrepancy in normal zone growth, the predictions for final maximum temperature, probably the most important single parameter, are remarkably similar; they agree to within 10 K! With this agreement, the validation of 3QUENCH was ended. Clearly, much more rigorous testing is required for the new program.

4.7 Critique of the Modified Program

It was intended that the modification of 2QUENCH should be quite a short exercise. Consequently, the program that was released was known to be still deficient in many respects. However, it was used by several engineers and its strengths and weaknesses soon became apparent.

The major problem was that the program was very unreliable; it crashed frequently and a lot of work was necessary to fix bugs discovered after its release. Some were due to problems in the original software, but the majority occurred in the modified code. Many of these were due to poor program structure in the original code, which was exacerbated by the extensive modifications. It was noticeable that where all the code was new, such as in the circuit analysis routines, fewer bugs were found. The program gradually became more robust as the bugs were removed.

The frequently-occurring crashes made the program difficult to use. This was exacerbated by the difficulty in compiling correct input data files. The batch-proccessing nature of the program meant that removing errors from the input data was a slow and frustrating task. However, once a set of input data had been prepared, the magnet design being studied could be 'tuned' easily by making small modifications to the input files, so the design process was not too difficult.

Once a model had been set up, the slow speed of the program was a drawback. This was a weakness of the original code, since the new circuit analysis routines were very fast by comparison with the thermal analysis routines. There were many opportunities for optimisation of the program. In particular, the calculation of isothermal temperatures was carried out for each isothermal at each time step. Had the generation function been used, it would only have been necessary to carry out one integration per coil, starting at the time at which the quench began in that coil. Then

$$U_{iso}(t) = U_{coil}(t) - U_{iso}(t_o) ,$$

where t_o is the time at which this particular isothermal went normal. This modification would have considerably increased the speed of the program.

The new circuit analyser described in section 4.4.1, although fast, was found to be quite inefficient. This was due to the use of the trapezium rule, rather than a higher-order algorithm, in the integration of coil currents. However, the speed of the analysis allowed several 'circuit time steps' to be made inside each thermal analysis time step, so in practice, this inefficiency was only a minor problem. A more serious deficiency was its inability to handle non-linear components, such as diodes, in the protection circuit. Provision was made for iteration to take account of non-linear resistances. Unfortunately, diodes used at cryogenic temperatures change their characteristics rapidly as they heat up. The effect of this is that they exhibit negative resistance in their current-voltage characteristics [42]. This made the circuit analysis unstable and was only solved by substituting low resistances for the diodes. This is valid approximation, since the diodes turn on very quickly after the onset of a quench, and the diode action has no effect on the operation of the protection circuit.

Despite all these drawbacks, the program was used quite heavily, whereas the previously available programs had only been rarely used. Although they were not much more difficult to use than 3QUENCH, it is much more flexible and its documentation is much more detailed. Its flexibility, in particular the generalised description of the protection circuit, meant that it could be used to model any magnet system in which adiabatic quenching might take place. The main restriction proved to be the availability of data on material properties as functions of temperature for all the materials that are used in a magnet system.

Although it can model quenching in many magnet systems, 3QUENCH ignores some important effects. The main one is quench propagation between coils. To simulate the effect of a normal zone spreading from one coil to an adjacent one, a quench must be initiated at the appropriate time at the coil interface in the second coil. This requires a knowledge of the speed of the quench in the first coil which, since it is current-dependent, cannot be known in advance and must be estimated. Further, the quench in the second coil is initiated at a point, whereas the broad front of the normal zone in the first coil would initiate a quench over the whole face of the second coil, is shown in figure 4.11. An associated problem is that of modelling quench-back from formers. Formers can be approximated to 'coils' made of a single material, which quench very quickly at t=0. In this way, the temperature of the former due to eddy current heating can be calculated, but there is no provision for the propagation of normal zones via the former. These problems are fundamental; they are due to the assumption of elliptical normal zones within the coils. To model these effects requires a different approach to quench simulation; this is described in the following chapters, which cover the development of an entirely new program.

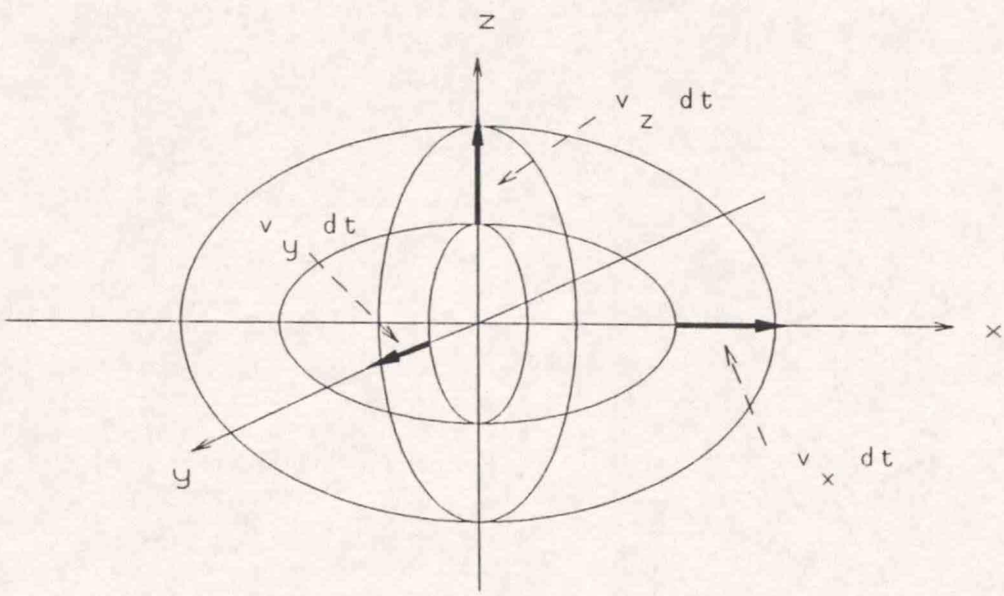

Figure 4.1

Addition of ellipsoidal shells during quench propagation

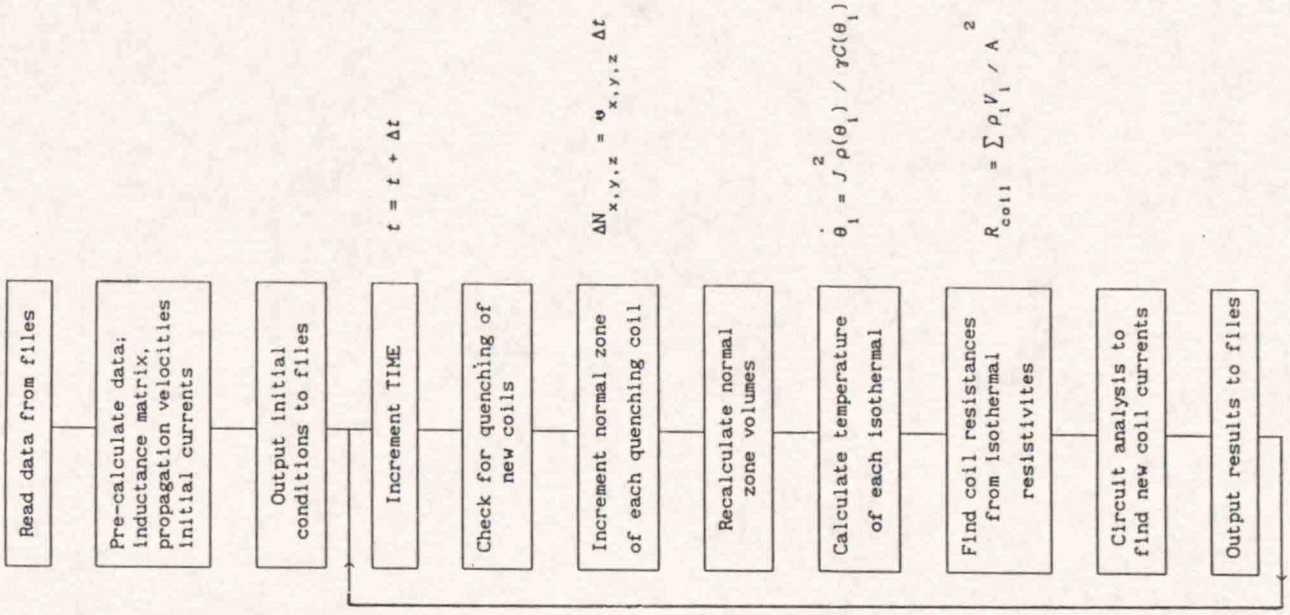

Figure 4.2

2QUENCH program outline

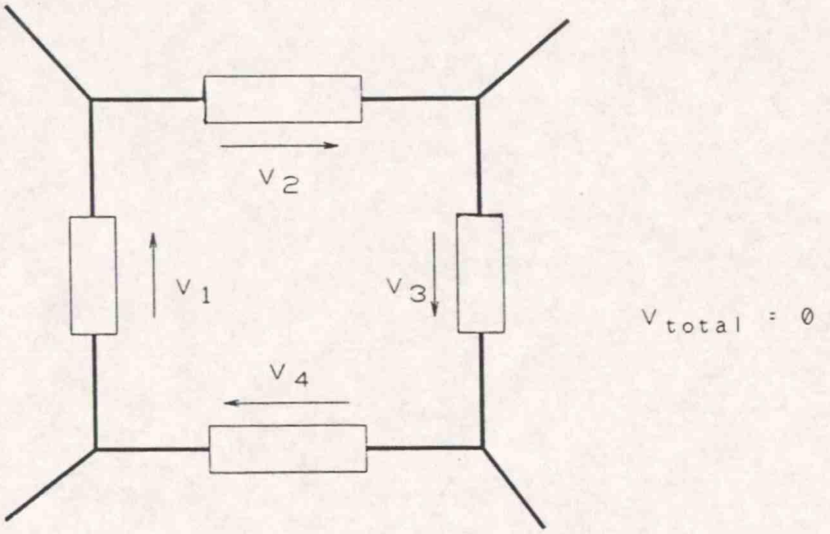

Figure 4.3

Application of Kirchoff's second law

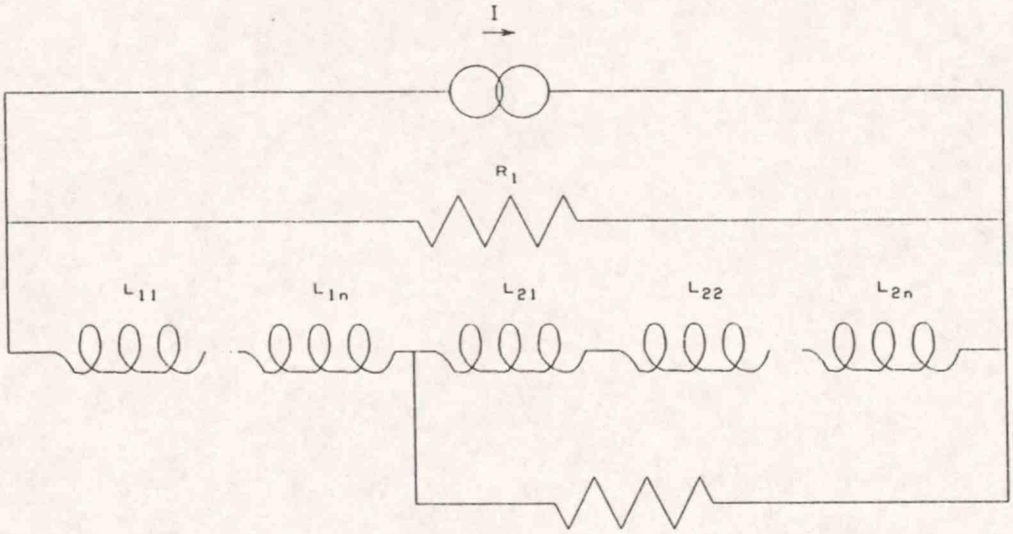

Figure 4.4

2QUENCH standard protection circuit

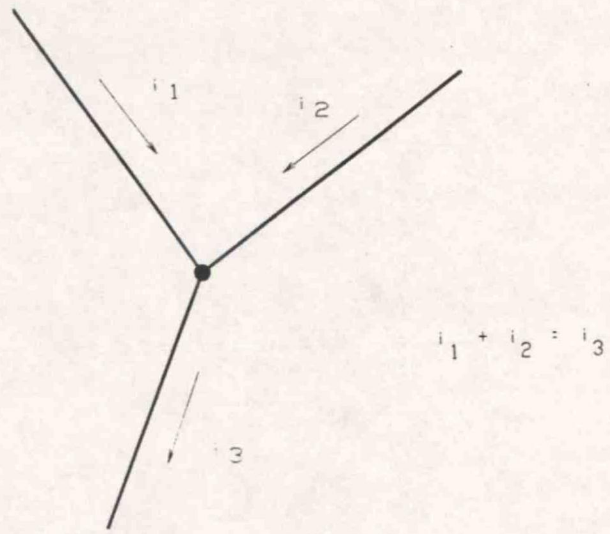

Figure 4.5
Application of Kirchoff's first law

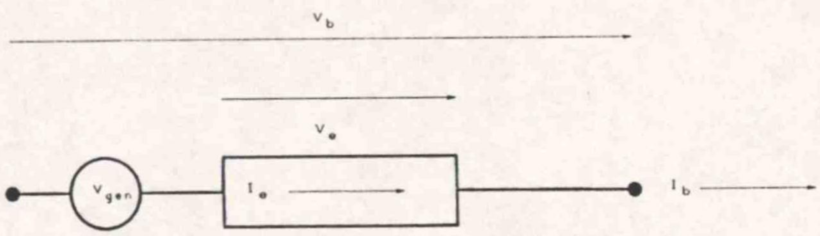

Figure 4.6
Generalised circuit element

```
COIL INFORMATION :

Coil       A1        A2        B1        B2          TD
 £        (cm)      (cm)      (cm)      (cm)    (turn/cm/cm)

  1       5.00      7.00    -10.00     10.00        19.30
  2       7.00      9.00    -10.00     10.00        19.30

Time =    0.150 seconds
Centre field = 0.307 T
Stored energy =    110 J.

Response of circuit 1 :

Current in coils =  33.987 A
Current in switch protection resistor =    0.000 A
Current in switch =  33.987 A

Coil    Resistance   Temperature   Voltage      Voltage     Normal
 £        (Ohms)         (K)       (Normal)   (Terminal)    Volume
                                     (V)          (V)         (%)

  1       0.0001        6.09         0.00        -7.70       0.39

Response of circuit 2 :

Current in coils =  43.815 A
Current in protection resistor =  -9.828 A

Coil    Resistance   Temperature   Voltage      Voltage     Normal
 £        (Ohms)         (K)       (Normal)   (Terminal)    Volume
                                     (V)          (V)         (%)

  2       0.0000        4.20         0.00       -10.66       0.00
```

Figure 4.7

2QUENCH output

```
TABLE  COIL  1  'Response of coil 1'
!--------------------------------------------------------------------------
TIME      IL_1       VL_1       TL_1       NV_1       NR_1
.         .          .          .          .          .
S         A          V          K          %          OHM
!--------------------------------------------------------------------------
0         250        2.5E-07    4.2        0          0
0.1       249.912    -0.002     33.2554    0.60748    0.0120517
0.2       244.53     -0.0024    48.6804    34.0675    0.6785316
0.3       228.48     -0.002     64.8563    59.9554    1.828296
0.4       197.933    -0.0019    81.0334    90.5680    3.4339053
0.5       158.034    -0.0015    93.689     100.050    4.9655932
!--------------------------------------------------------------------------
$$
```

TIME	- time from start of quench
IL_1	- current in 1st coil
VL_1	- voltage across coil
TL_1	- maximum temperature in coil
NV_1	- volume of coil which is normally resistive
NR_1	- resistance of coil

Figure 4.8

3QUENCH output

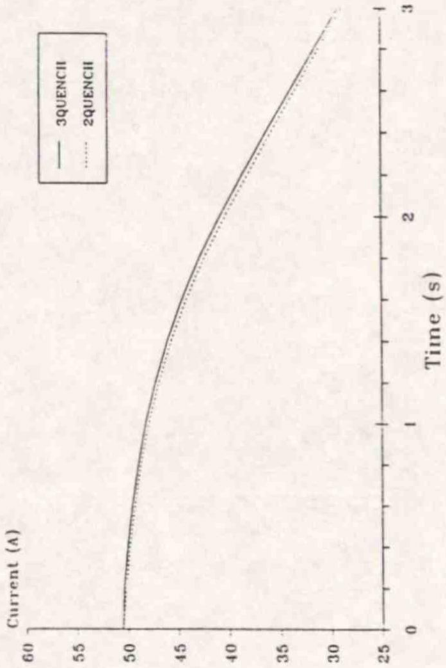

Figure 4.9(a)

2QUENCH/3QUENCH current decay

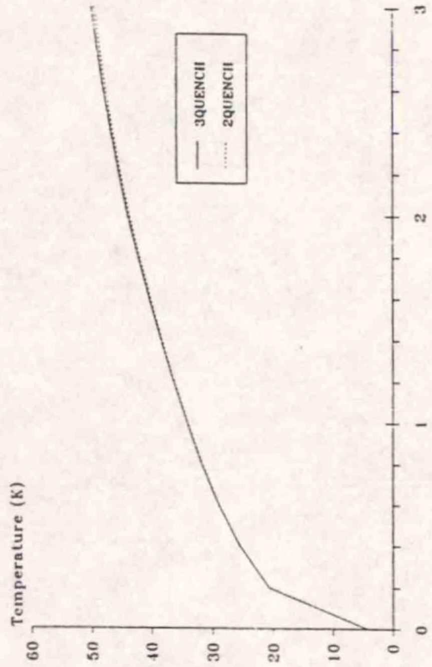

Figure 4.9(b)

2QUENCH/3QUENCH temperature rise

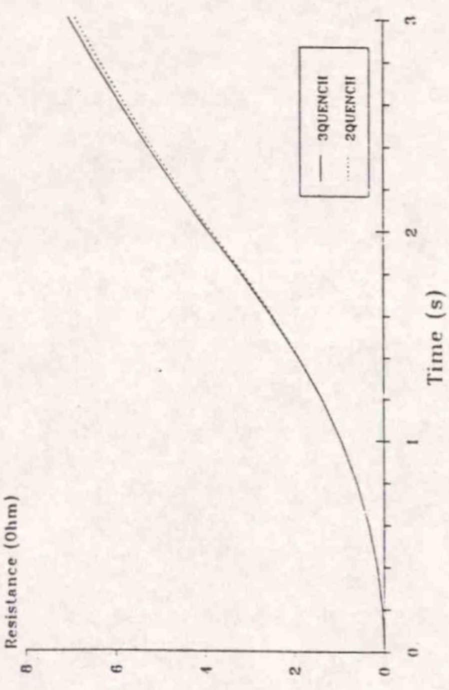

Figure 4.9(c)

2QUENCH/3QUENCH resistance rise

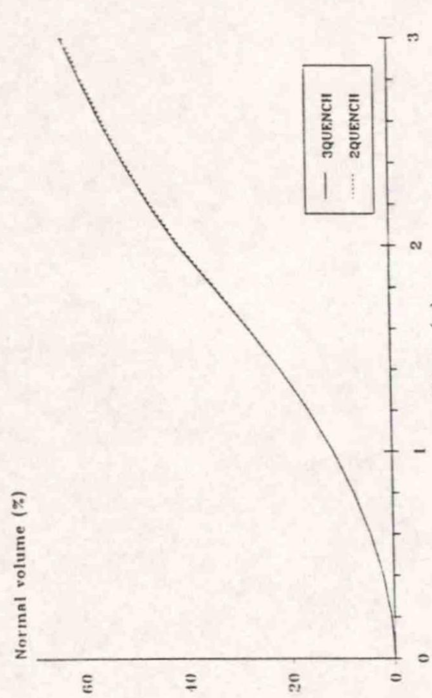

Figure 4.9(d)

2QUENCH/3QUENCH normal volume growth

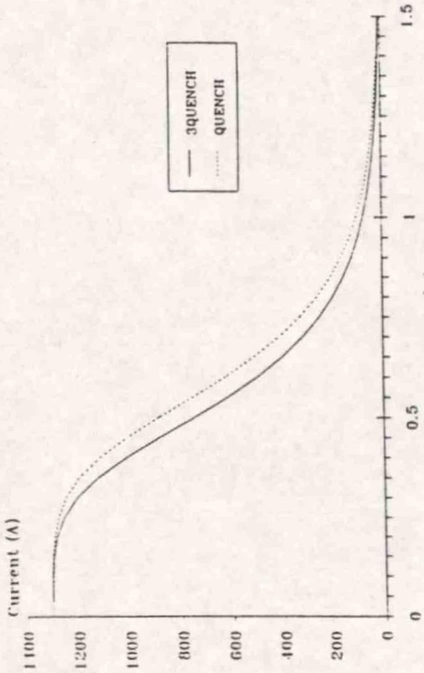

Figure 4.10(a)

QUENCH/3QUENCH current decay

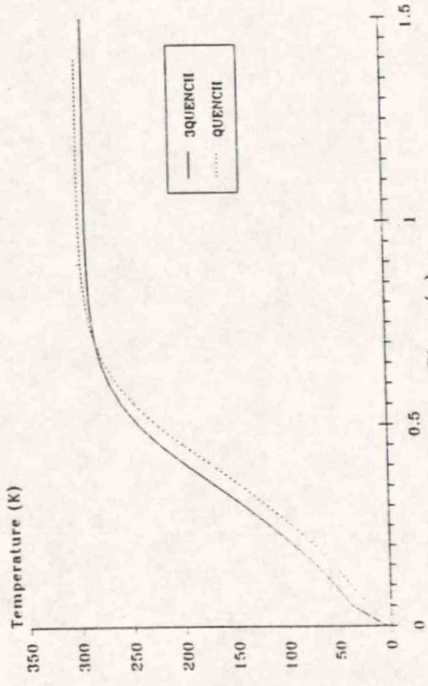

Figure 4.10(b)

QUENCH/3QUENCH temperature rise

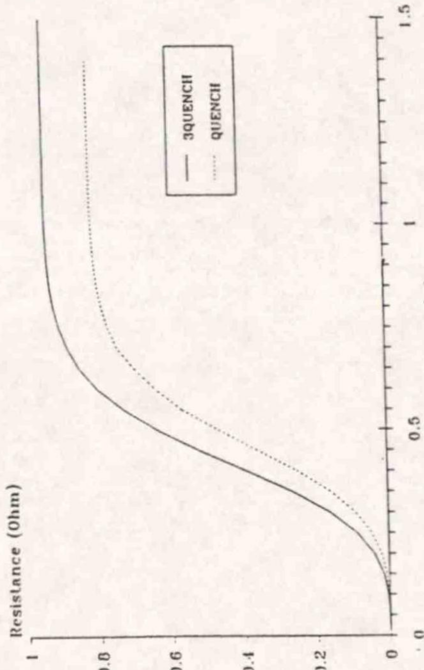

Figure 4.10(c)

QUENCH/3QUENCH resistance rise

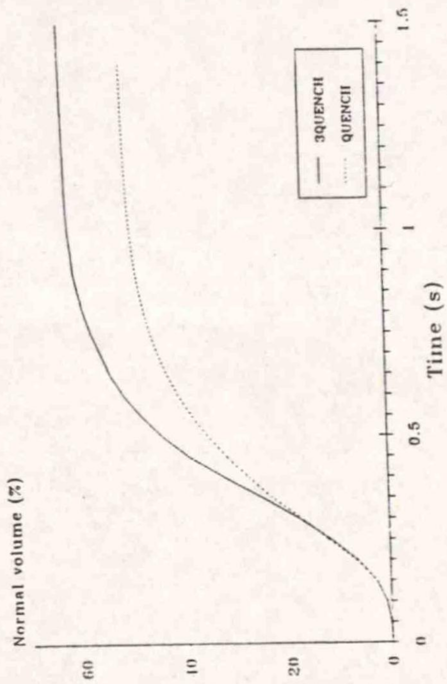

Figure 4.10(d)

QUENCH/3QUENCH normal volume growth

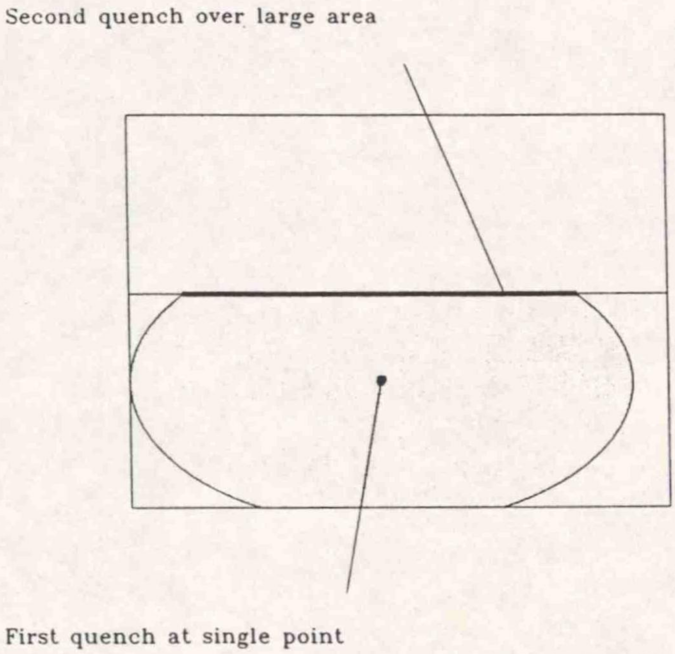

Figure 4.11

Quench initiation over large area in second coil

5. Development of a new program

5.1 Specification of the New Program

5.1.1 Requirements

The requirements of the new program were developed from experience in the writing of 3QUENCH, discussions with engineers who had used 3QUENCH and, equally importantly, discussions with engineers who had not used 3QUENCH because it did not address their needs. It became clear that it was important to extend the range of effects that could be modelled. In particular, thermal interaction between coils and other objects was seen to be important. The major areas in need of attention were

a) propagation of quenches between coils. The previous section showed that this could only be achieved in 3QUENCH in a difficult and unrealistic manner.

b) the inclusion of the formers on which the magnets are wound in the quench analysis. This suffers from the same problems as a) when modelled by 3QUENCH.

c) calculation of extra information, such as power dissipated in coils, formers and cryogen, and the forces on the components as the coil currents change during the quench

The other major factor governing the effectiveness of a program is its ease of use. In common with most modern software, it was intended that the new program should be interactive; commands and data could be given to the program directly, rather than via a file which is read by the program. Users can experiment with the effects of varying a parameter by rerunning the simulation with different values and comparing the predictions with previous ones at each stage. Graphical display of input and output data is also essential in a simulation requiring a large amount of information, such as this. These abilities were provided by the use of the library routines described in the next section.

5.1.2 Software considerations

Some decisions about the software were made quite early on. Choice of language was an important one. Pascal [43], C [44] and, increasingly, Ada [45] are used in the development of engineering software, but Fortran 77 [8] was chosen despite its many drawbacks, including

a) weak data typing and the lack of a RECORD data structure

b) static memory management, requiring the specification of large arrays of data even when almost all of it is unused

c) lack of a complete set of control structures, particularly the DO..WHILE, REPEAT..UNTIL and CASE statements

Many of these inadequacies will be remedied by the proposed standard for Fortran 8x [46], which will be 'backwards compatible' with Fortran 77. The reasons for accepting the deficiencies were

a) The age of Fortran (it was introduced as the first 'high-level' programming language in 1957) means that a huge amount of software is available. Libraries of numerical analysis and graphics routines are widely available. In particular, the full range of routines in the Numerical Algorithms Group libraries [47,48] are only available in Fortran

b) Fortran benefits from a rigorous specification [8]. Adherence to this standard makes the porting of software to other computers much easier. It is likely that the new program will outlast any one operating system (as QUENCH [4] did - it was run on at least 3 machines running 3 different operating systems), so the existence of a 'standard' language is very valuable. (It should be noted that most compilers, such as the one running under VAX/VMS [37], offer extensions which provide many of the features missing from Fortran 77, but of course they all implement them differently!)

The user-friendly interface discussed in section 5.1.1 was provided by a set of in-house library routines [7]. These provide menus of commands, command parameters, a simple help system, automatic logging of all commands, tabular storage and display of data, an interactive Fortran expression analyser and other features which provide a powerful 'shell' for any engineering software. The libraries and their relationship are shown schematically in figure 5.1.

The naming of the program was also considered! Following QUENCH, 2QUENCH and 3QUENCH, it became known, rather unimaginatively, as 4QUENCH.

5.2 Input and Analysis of Materials Properties

5.2.1 Input and display of data

The user-supplied data on the dependence of materials properties on temperature (and, in some cases, magnetic field) forms the basis of the simulation. Knowledge of these properties is required for the calculation of propagation velocity, temperature rise and normal zone resistivity. The tabular format used in 3QUENCH was successful and was also adopted for 4QUENCH, with the data being handled via the TABLE library routines. A sample set of data, as displayed by the program, is shown in figure 5.2.

Data will usually be loaded from pre-prepared files. However, it can also be input via the program; points can also be edited and deleted, and revised tables can be saved in files. Graphical display of the data is available, and the effect of interpolating using various methods (see the next section) can also be examined. Figure 5.3 shows a plot of the data of figure 5.2.

The properties required by the program are shown in table 5.1.

Property	Comments	Symbol
Volumetric specific heat	No field dependence (slight dependence for superconductors, which is neglected)	$\gamma C(\theta)$
Volumetric enthalpy	Usually obtained as $\int \gamma C \, d\theta$ (again, slight field dependence for superconductors)	$H(\theta)$
Resistivity	Often field dependent in metals	$\rho(\theta[,B])$
Thermal conductivity	Often field dependent in metals. Can be related to resistivity by the Wiedemann-Franz-Lorentz law for pure metals.	$\kappa(\theta[,B])$
Critical current density	Superconductor critical surface, inside which the conductor must operate.	$J_c(\theta,B)$

Table 5.1

Physical Properties Required for the Quench Analysis

5.2.2 Use of data in the simulation

The main considerations in the design of the materials handling routines were storage and method of interpolation. Since no interpolation method is satisfactory under all circumstances, three user-selectable methods are offered. Linear interpolation between data points is available, since it is fast and easy to check. A NAG spline routine [47] is also included. A spline fit is relatively fast and, in this case, allows least-squares fitting to points, which is very useful for experimental data. Unfortunately, splines have a tendency to oscillate in areas where data points are sparse or close together, as shown in figure 5.4. A spline curve cannot be considered to be reliable for use with a particular set of data until the fit has been viewed graphically (which can be done in 4QUENCH). Since viewing every data set fit before a quench run would be very tedious, another method, known as rational interpolation [49], can also be used (and is the default method). This guarantees that the fitted curve will contain no more extrema than are implied by the data. A routine based on this method was written and proved to be satisfactorily fast and accurate.

Since some of the properties are functions of two variables, it was also necessary to fit surfaces. A bicubic spline fit from the NAG library is available and fits some functions satisfactorily. It also has the advantage of being able to handle scattered data; that is, for a function $f(x,y)$, x and y can take any values. However, it was found to be unable to cope with a typical set of critical surface data, due to the instabilities inherent in splines. A two-dimensional version of the rational interpolation method was developed to solve this problem.

Consider a function $f(x,y)$, which is to be interpolated at (x_o, y_o). Assuming that the data points lie on lines of constant y, a simple rational interpolation can be performed at each available value of y, so that

$$f_i = f(x_o, y_i) .$$

A further rational interpolation can be performed on the f_i points at $x=x_o$, and hence $f(x_o, y_o)$ is obtained, as shown in figure 5.5. Routines using this algorithm were written and were found to produce a good fit to the critical surface data. The restriction that data points must lie on lines of constant y is not a problem in this application, since critical surface data is generally supplied as $J(\theta)$ data for a set of magnetic field (y) values.

Having developed appropriate routines for fitting and evaluating the material properties, their storage had to be considered. The method chosen was to hold all data and fitting information in a single three-dimensional array. An associated cross-reference array held information on each data set, such as type of data, number of points, fitting method and title. The two arrays and their interaction is shown diagrammatically in figure 5.6.

This arrangement was found to be effective, but suffers from the presence of large amounts of 'white space'. Each data set contains the same number of entries, regardless of how many data points it holds, and the maximum number of points must be large enough to hold sufficient three dimensional critical surface data. An alternative method would be to have a two dimensional array and maintain pointers to the start of each data set, as in figure 5.7. However, this would require quite sophisticated data management. For example, it would be necessary to ensure that the materials array was regularly 'defragmented' to avoid large amounts of white space appearing as the size of the individual data sets changed dynamically under user control.

Since so much data manipulation and storage is involved in a quench analysis, it may be that the incorporation of a database program into the software would have been useful. However, since most scientific workstations and mini- and mainframe computers have memory address ranges of several megabytes, the simple, memory-inefficient system descibed above was adequate and the use of a database was not examined in detail.

Now that fitted data was available, stored in an appropriate form, a high-level routine was added. This returns the value of the specified property at the required values of temperature and, optionally, magnetic field. It effectively insulates the program from the raw materials data, which can now be used in the abstract. The relationship between data, mathematics routines, the high-level materials function and the quench analysis is shown in figure 5.8.

5.3 Input and Analysis of Other Data

5.3.1 Coil geometry data

The dimensions and positions of the coils which make up the magnet are clearly important. They provide boundaries for the normal zone growth and are required for the calculation of a mutual inductance matrix and magnetic fields. Magnet coils are conventionally described by their inner and outer radii and axial length, and are usually viewed in cross-section, as in figure 5.9. 4QUENCH, in common with most other quench programs, 'unwraps' the coils and treats them as rectangular blocks (figure 5.10). This overestimates the coil circumference at its inner radius, and underestimates it at its outer radius. However, this would only be a problem for thick solenoids. These are often made up of several layers of different wire, which because of their different properties, must be treated as separate coils anyway, so the assumption is usually valid.

A problem arises in the analysis of magnets which are not solenoidal, such as fusion containment devices. In this case, a set of 'equivalent solenoids' must be developed, in which the average coil circumferences and coil volumes are equal to those of the originals. This solution also requires a user-supplied inductance matrix and field coefficients, since their calculation by 4QUENCH assumes a solenoidal system.

This data set also includes the actual turns density of each coil (as opposed to the theoretical turns density, calculated from the wire dimensions), the wire type, the filler material (used to fill interstices in the winding), and several other parameters which are not required in a quench analysis, but are used in other programs which share these routines. A sample coil data set is shown in figure 5.11.

As with the materials data, tables of coils can be edited, loaded from a file, saved in a file, listed on screen and displayed graphically (figure 5.12).

5.3.2 Electrical circuit data

The electrical circuit data was stored in the same form as 3QUENCH, since it was found to be effective. Each lumped circuit element has the form

TYPE NAME NODE1 NODE2 VALUE1 VALUE2 TIME1 TIME2

Available circuit types are shown in table 5.2. The element name uniquely identifies components of the same type and the node numbers define the connection of elements, as described in section 4.4.1. Each component can have two values; the value starts at **VALUE1** and changes linearly with time to **VALUE2** between **TIME1** and **TIME2**. This allows power supplies to be switched off when a quench is detected and resistor values to change, simulating the action of a switch. The 4QUENCH circuit analysis cannot handle nodes connected only to inductors (see section 5.4.2), so series coils are amalgamated into blocks, which are treated by the circuit analyser as single coils. The inductor names consist of a list of coils to identify the contents of each block.

Again, editing and display of the table is available, and a 'CHECK' command tests the data for some of the common faults experienced in the input of circuit data in 3QUENCH, such as floating nodes. Figures 5.13(a-b) shows a sample circuit for a small magnet.

Symbol	Element type	Example
V	Voltage source	V source 0 1 100 (100V d.c voltage source)
I	Current source	I supply 2 0 1100 0 0.1 (1100A current source, switched off at 0.1 seconds)
L	Inductor	L 1..3 3 2 (inductance containing coils 1 to 3)
R	Resistor	R main 4 2 0.25 (constant resistance of 0.25Ω)

Table 5.2

Available Circuit Element Types

5.3.3 Inductance data

Calculation of a mutual inductance matrix for a set of coils is quite straightforward and the Oxford Instruments libraries contain routines to produce an inductance matrix from the coil geometry data. The matrix is calculated only if none is supplied, or if one is supplied and the coil geometry data is subsequently changed. A sample matrix is shown in figure 5.14.

5.3.4 Propagation velocity data

It was noted in section 2.3 that the calculation of propagation velocity is very approximate, so a variety of ways to specify the propagation velocity are offered in 4QUENCH. Any number of velocities can be specified; each one is linked to a quench initiation point (see section 5.3.5). The user can specify either the adiabatic velocity formula of section 2.3, or the full equation, incorporating the cooling effects of liquid helium, which is appropriate in systems in which helium can impregnate the magnet windings.

The most accurate propagation velocities are those obtained from experimental data. This could be available in a very large, expensive system for which very accurate quench data is required. 4QUENCH allows the input of experimentally-determined velocities as functions of current density and magnetic field.

Finally, for use in theoretical quench studies and validation of the program, the ability to specify the velocity as an analytic function of current density and magnetic field was expected to be useful. This facility was made available by using the expression analysis facilities of the ALGEBRA library routines (see figure 5.1).

Most quench programs incorporate functions which calculate propagation velocities as required during the quench analysis. However, calculation of complex functions such as propagation velocity formulae, involving the evaluation of material properties, is time-consuming. Any 'improved' formula, which incorporates extra effects to obtain a more accurate figure, is likely to be more so. It was decided that the most efficient method for the calculation of velocity was to treat it as another material property. A set of velocities are calculated at (currently) 64 points in (J,B) space at the start of the run. These are then approximated by a two dimensional rational function (see section 5.2.2) which can be evaluated relatively quickly during the quench analysis. Of course, if less than 64 evaluations of velocity are required, this method is actually slower than 'in-line' velocity calculations, but for such a relatively short run, timing is less important anyway. Figure 5.15 shows a set of velocity specifications.

5.3.5 Quench trigger data

4QUENCH makes no attempt to predict likely positions for the start of the quench in a magnet (although it is a possible future addition - see section 6.3.4). Users must specify a 'quench trigger'. This consists of a trigger type, a name, a position in cylindrical polar co-ordinates, an associated velocity from the velocity table and a value. The trigger initiates a quench when the parameter associated with the trigger type exceeds the specified value. Table 5.3 shows the available trigger types. The 'dI/dt' trigger is supplied to simulate the effect of heating due to rapidly changing fields, and hence currents, which can cause quenching in some situations.

Symbol	Trigger type	Example
V	Voltage	value = 100 (quench initiated when voltage across coil exceeds 100V)
I	Current	value = 1100 (quench initiated when coil current exceeds 1100A)
TIME	Time	value = 0.1 (quench initiated at t = 0.1s)
DIDT	Rate of change of current	value = 10000 (quench initiated when $\|dI/dt\|$ exceeds 10,000A/s)

Table 5.3

Available Trigger Types

5.3.6 Conductor data

Data on the conductor used in each coil is also required. The relevant parameters are wire name, cross-sectional area of the wire and cross-sectional shape (which affects the packing factor of the wound conductor). It is also necessary to know the composition of the wire, in terms of the volume fractions of superconductor, copper matrix, insulation and filler. This is stored in a separate 'wire fractions' table. The two sets of data are shown in figures 5.16 and 5.17.

5.3.7 Data checking

Since such a large amount of data must be input before starting a quench simulation, mistakes are inevitable. In order to avoid crashes due to missing or invalid data, all categories of data are checked at the start of a run. Typical checks are for the existence of data in all categories, agreement about the number of coils between the geometry table and the electrical circuit table, the existence of overlapping coils and that the quench triggers lie inside coils.

The program also uses sensible defaults for missing data where possible. For example, the resistivity of insulator materials is set to be high, the thermal conductivities of metals can be derived from their resistivities using the Wiedemann-Franz-Lorentz law and a missing inductance matrix is automatically calculated. Further, since materials data on wires is not readily available, it can be calculated from the data on the materials of which the wire is made, as stored in the 'wire fractions' table (section 5.3.6). The calculated data is stored and is then available for future runs without any recalculation.

5.4 Circuit Analysis

5.4.1 Selection of a new circuit analysis method

The problems encountered with the 3QUENCH circuit analysis were discussed in section 4.6. It was clear that a new analyser was required for 4QUENCH. The choice lay between the development of a new in-house analyser or the use of third-party software. A computer literature search, similar to the one described in section 3.1, produced references to a library of circuit analysis routines known as SPICE-PAC [51,52]. This is a set of Fortran or C routines which emulate the circuit analysis program SPICE and are designed to be incorporated in other software. They enable the behaviour of a circuit to be simulated, with software control of circuit parameters and output data.

Inspection of the code and documentation showed that SPICE-PAC was a very powerful tool for the analysis of electrical circuits. For example, it could be interfaced to an optimiser routine to provide fine-tuning of circuit parameters to obtain a desired effect [53]. An interface to Oxford Instruments' software would produce a powerful, interactive circuit analysis program with graphical output, which is noticeably lacking from version 2 of SPICE.

The requirements of the 4QUENCH circuit analyser are very modest by the standards of SPICE-PAC. No semiconductor or capacitative elements are required and only a transient analysis of the circuit is required. It was decided that the time required to become familiar with the use of SPICE-PAC was likely to be greater than the time taken to write a customised circuit analyser of the type needed in 4QUENCH. So, with some reluctance, SPICE-PAC was dropped and a set of circuit analysis routines were written especially for the program.

5.4.2 Development of a new circuit analysis method

The new analysis was based on a state-space [40] approach, in which the state variables are inductor currents. The differential equations describing the inductor currents are

$$\frac{dI_L}{dt} = \mathbf{M}^{-1}\, \mathbf{V}_L \,.$$

This set of equations is solved at each time step using an appropriate NAG routine (the user can select a Runge-Kutta-Merson method, an Adams multistep method or a Backward Difference Formula method if the system is believed to be stiff). The inductor currents obtained are then used to calculate branch currents and nodal voltages for the protection circuit as a whole. The inductors in the circuit are replaced by current sources with values equal to the calculated inductor currents. A simple dc nodal analysis, as described in section 4.4.1, is then performed to obtain the currents and voltages.

This approach is limited in that it does not allow nodes to be connected only to inductors, since this is equivalent to connecting a node only to current sources, which leads to a singular nodal admittance matrix (see section 4.4.1). Of course, series inductors with no parallel resistive components are commonly found in magnet circuits. This restriction was avoided by requiring users to specify 'inductor blocks' in the circuit description. Each block can contain several series inductors. Ideally, this circuit reduction should be automatic, but it proved difficult to implement and was not felt to be important enough to warrant further effort.

The normal zone resistances can easily be included in the analysis as an additional term in the differential equations, so that

$$\frac{dI_L}{dt} = \mathbf{M}^{-1} \mathbf{V}_L - I_L R_L .$$

This treatment of normal zone resistance can cope with zero normal zone resistance in coils which have not quenched. If the normal zone resistance were included in the circuit as a separate component, divide-by-zero errors would occur.

5.4.3 Testing of the new method

The algorithm described above was coded and performed well. It is easy to check the circuit analysis in isolation from the rest of the program, and this was done, using SPICE as the benchmark, for three simple circuits. Agreement with SPICE to less than 0.1% was obtained using all three differential equation solver routines. CPU timings were also compared. It was found that SPICE was between one and six times as fast as 4QUENCH. This is quite acceptable, considering the amount of effort spent on SPICE and the fact that critical SPICE routines are written in assembler.

5.5 Thermal Analysis and Normal Zone Propagation

5.5.1 Fundamentals of thermal analysis

The approach to the analysis of the normal zone in a coil was the same as that of previous programs; the zone is approximated by a set of isothermal volumes, whose temperatures are calculated separately at each step. If the quench is assumed to be adiabatic, then the temperature of the *i*th isothermal can be obtained from the differential equation

$$\frac{dU_i}{dt} = J^2, \text{ or}$$

$$\frac{dH_i}{dt} = J^2 \rho(\theta_i) ,$$

combined with the 'inverse material function'

$$\theta_i = U^{-1}(U_i), \text{ or}$$

$$\theta_i = H^{-1}(H_i) .$$

However, if heat transfer between isothermals is allowed, then the generation function cannot be used, and

$$\frac{dH_i}{dt} = J^2 \rho(\theta_i) + \Sigma \text{ (power input from adjacent isothermals)} .$$

Since it was intended that 4QUENCH should be able to model a wide range of magnets, some of which were known to quench in minutes, rather than seconds, the ability to model heat diffusion, at least in the future, was important. For this reason, the thermal analysis was based on enthalpy, rather than generation function, even for the adiabatic case.

Most previous programs set up isothermals as the analysis progresses. This approach, used by 3QUENCH, is described in section 4.3. A problem with this method is that many isothermals are required in a slow quench with many time steps, so that the analysis becomes progressively slower as the number of isothermals, and hence the number of differential equations which must be solved, increases linearly with time. Increasing the length of the time step to decrease the number of isothermals is only useful if the decrease in resolution can be tolerated. However, experience with a previous quench program which allowed the user to specify the number and size of the isothermals at the start of the run [22], showed that a large number of isothermals was not necessary. In fact, the number of isothermals in the normal zone could be drastically reduced with no loss of accuracy.

It was decided that this approach should be adopted in 4QUENCH. Consideration of the simulation process, described in section 4.3, shows that there is no reason why the position and volume of all the isothermals in each coil cannot be defined at the start of the simulation; this is done in 4QUENCH. The user specifies the number of isothermals in each coil and the isothermal positions and volumes are calculated automatically before the analysis starts.

5.5.2 Isothermal definition

Pre-definition of isothermals allows the user to specify in advance the shape to be used. Clearly, concentric ellipsoidal shells should be allowed, since they have been used successfully in previous programs. However, this arrangement has some drawbacks. For example, it is very difficult to analyse the effect of two independent quenches in a single coil, since a set of ellipsoidal isothermals must be based on a single quench initiation point. There are two ways in which this could be achieved, but they both present fundamental problems. If a single set of isothermals is specified for a coil, but more than one quench trigger is allowed, then a second quench could appear to cause a very large volume of the coil to go normal instantaneously, as shown in figure 5.18. Alternatively, if a set of isothermals is defined for each quench point, then the calculation of isothermal volumes is complicated by the complex intersection of ellipsoidal shells (figure 5.19).

A further problem is the assumption that material properties are constant within an isothermal. A large ellipsoidal isothermal will occupy parts of the winding in a high magnetic field, and parts in a much lower field, as shown in figure 5.20. Clearly, this will lead to inaccurate predictions for materials properties which are field dependent. This inaccuracy extends to the calculation of propagation velocity, which means that different parts of the zone will grow at different rates. Figure 5.21 shows that, in the long term, an ellipsoidal normal zone will grow in such a way that it is no longer ellipsoidal!

Many other cases in which ellipsoidal normal zones are not a good approximation can be described and it becomes clear that an accurate model must offer an alternative type of thermal analysis. Hence, 4QUENCH also provides isothermals which are small solenoids, arranged in a rectangular grid in the coil cross section, as shown in figure 5.22. These can have independent field calculations and can be triggered by any one of several disturbances in a coil, since their shape and position are independent of the quench initiation points.

Both types of isothermal are treated by the software in exactly the same way, so that, once prepared, isothermals can be considered in the abstract. This approach to the analysis is very important, since it allows for the addition of a new isothermal type (for example, a three dimensional array of isothermal cubes) without any changes to the analysis. Equally importantly, it allows users to specify their own sets of isothermals. This provides a way to model quenching in arbitrarily complex magnet shapes without resorting to inaccurate approximations.

5.5.3 Isothermal triggering

Users specify the start of a quench by defining a single trigger type and position (see section 5.3.5). These are related to the isothermals by a set of 'isothermal triggers', which are generated by the program. In general, a 'quench trigger' fires a 'velocity trigger', which is associated with a previously-defined velocity model (see section 5.3.4). Firing this trigger causes the differential equation describing the spread of the normal zone along the x-axis,

$$\frac{dx}{dt} = v_x ,$$

to be evaluated in parallel with the inductor currents. The relationship between the triggers and isothermals is shown schematically in figure 5.23.

The 'isothermal triggers' define the values of x, relative the the quench trigger, at which the isothermal will become normal. The simplest way of calculating x for an isothermal is to assume that the ratios v_z/v_x and v_y/v_x are constant and use Pythagoras' theorem to calculate the 'effective distance' along the x-axis which corresponds to the normal zone reaching the isothermal. When the value of x exceeds that for a given isothermal trigger. the isothermal goes normal and the differential equation describing its temperature rise for adiabatic quenching,

$$\frac{dH_i}{dt} = J^2 \rho(\theta_1) ,$$

is added to the set of differential equations to be integrated at each time step. This reduction of isothermal positions to single points on the x-axis is shown for each type of isothermal in figures 5.24(a-b)

If more than one quench trigger is present in a coil, each isothermal has more than one trigger associated with it, and of course a different velocity model can be used with each quench trigger.

However, for ellipsoidal isothermals, only the first quench trigger in each coil which fires is evaluated; later ones are ignored because of the difficulty in calculating normal zone volumes.

Since only a small number of isothermals are used in any coil, the jump in normal volume when an isothermal is triggered would lead to corresponding jumps in normal resistance and hence artefacts in the solution. This is avoided by a different treatment of the isothermals to that used in any previous model. Isothermals are allowed to become partially resistive! Their temperatures are taken to be those of the normal part of the isothermal volume and the resistances are calculated from the fractional normal volumes.

Partially normal isothermals are obtained by specifying 'start' and 'finish' values of x for each isothermal trigger. These values correspond to the normal zone just touching the point in the isothermal nearest to the quench trigger and reaching the furthest point from the trigger. Hence, the normal volume of the isothermal is a fraction of the total isothermal volume, calculated from x_{start}, x_{finish} and x, the current value of the normal zone extent. This allows a smooth normal voume growth, even if the coil is approximated by a single isothermal. The extended propagation algorithm is shown in figures 5.25(a-b).

Although this is a departure from the description of an isothermal as a volume of equal temperature, it is a very useful concept. It offers the smooth growth in normal volume of a system which adds one isothermal at each time step, whilst retaining the computational efficiency of a making small number of temperature calculations.

5.5.7 Program structure

The structure of the data input software is shown in figure 5.26. Figures 5.27-28 show the structure of the quench analysis section.

5.6 Output from the Program

The categories of data generated by 3QUENCH (see section 4.3) were found to be sufficient in almost all quench simulations. The only data sometimes required that were not available were the isothermal temperatures. These are available as output from 4QUENCH.

All output is in TABLE library format, as for 3QUENCH. Since so much data can be generated, users can specify what they require. Standard tables of data are automatically generated, and each can be directed by the user to the screen or a file, or neither if it is not required. The tables available are

a) coil data, containing coil current, terminal voltage, maximum temperature, normal volume and normal resistance at each time step (one per coil)

b) branch currents table, containing the current through each circuit component defined in the circuit table

c) nodal voltages table, containing the voltage at each node defined in the circuit table

d) isothermal temperatures table, containing the temperature of each isothermal

Additional tables are automatically produced if there is too much data to fit in a single table. Users can specify additional tables containing these variables in any order, and other variables which are functions of these, such as power generated in a coil ($P = I^2R$). Output is in the same format as for 3QUENCH (see figure 4.8). Tables produced during a run can later be loaded from file and displayed graphically.

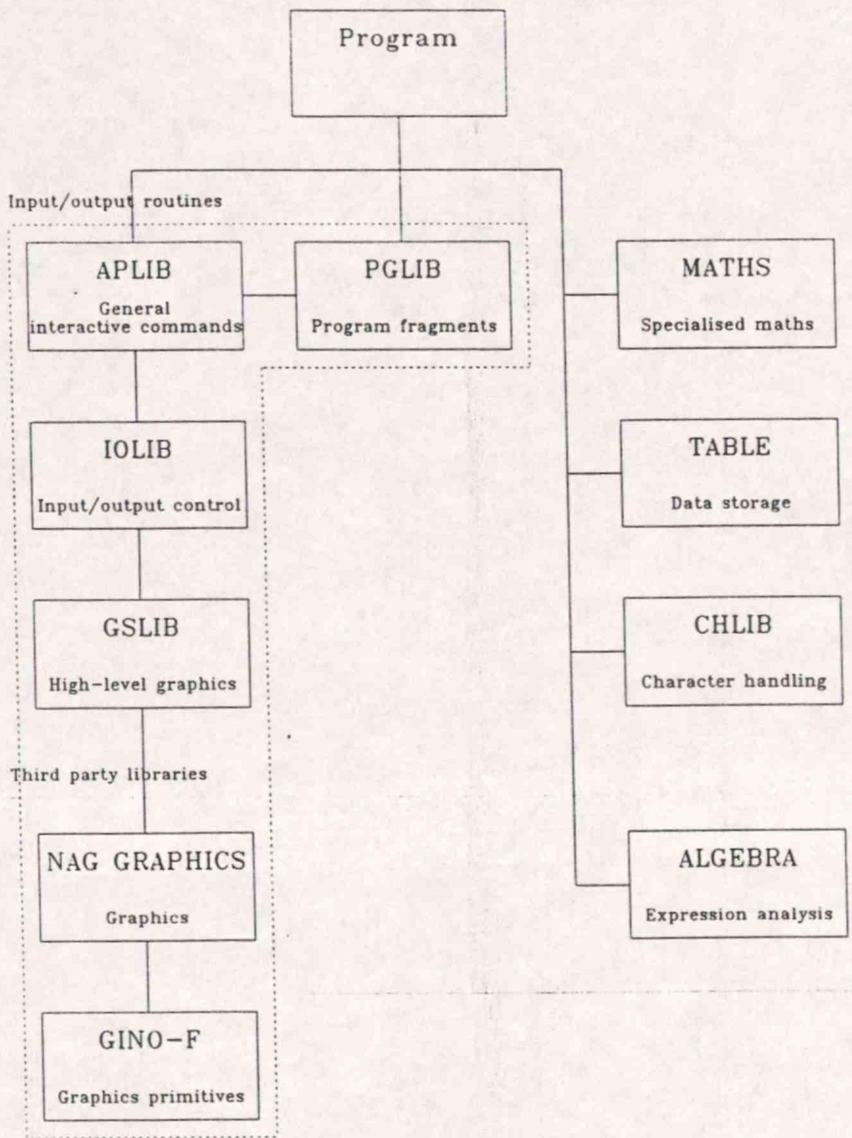

Figure 5.1
Oxford Instruments Software Libraries

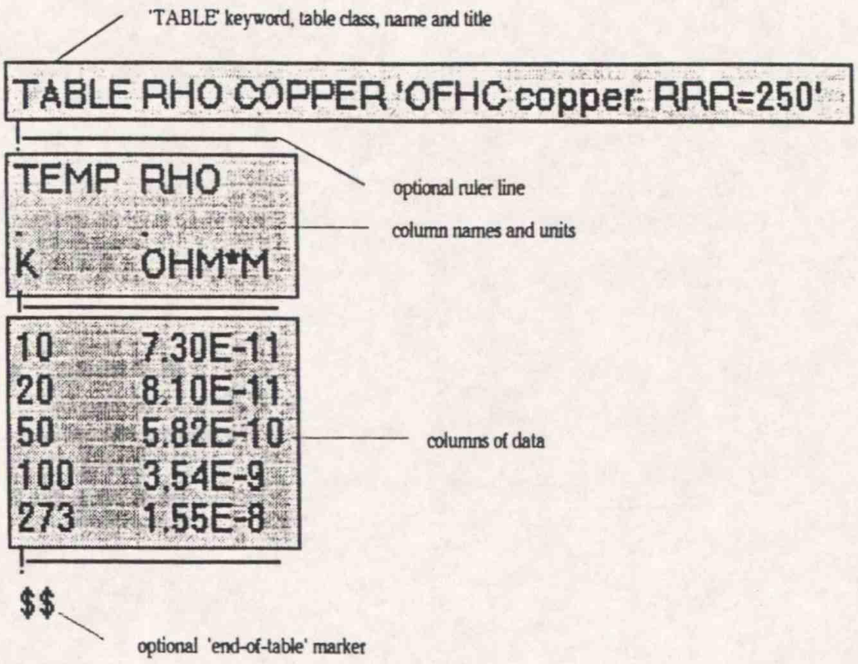

Figure 5.2

Sample 4QUENCH data set

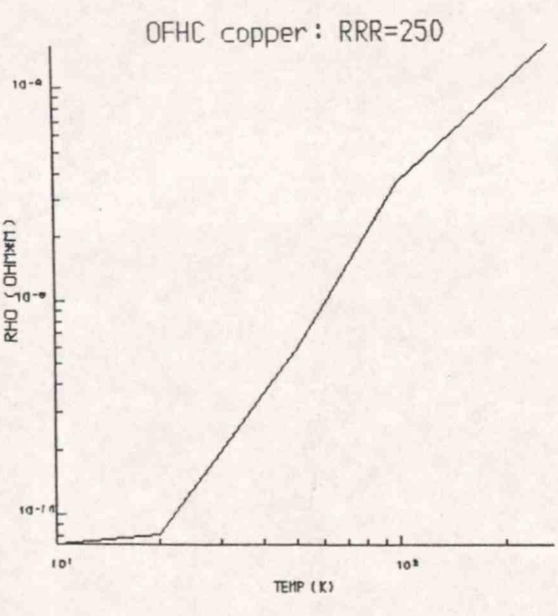

Figure 5.3

4QUENCH graphical display of figure 5.2

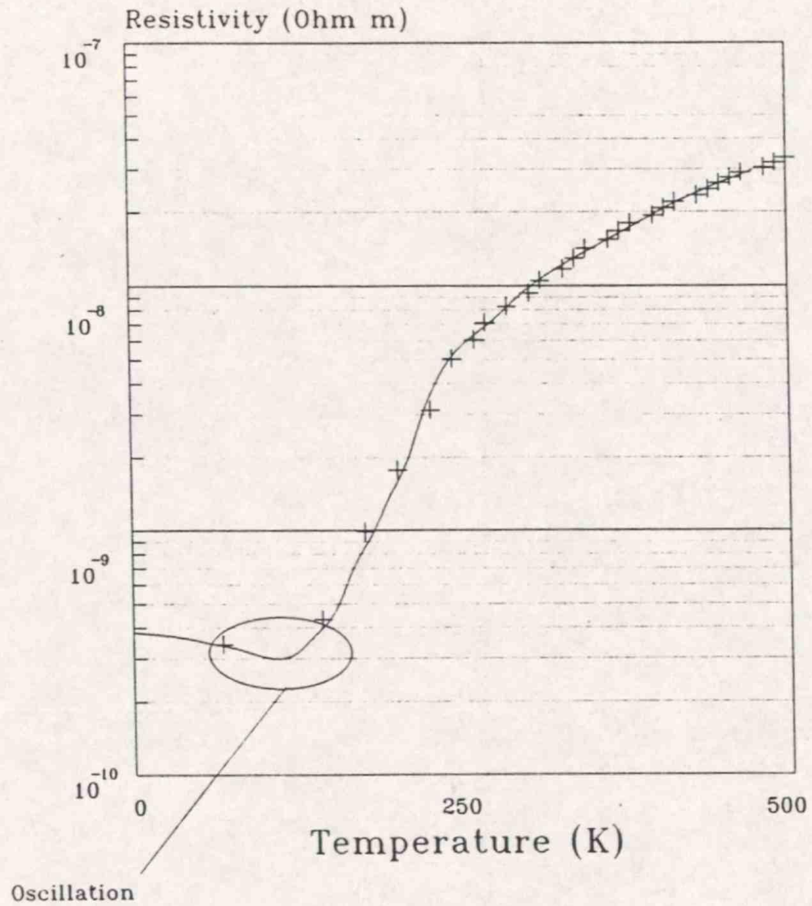

Figure 5.4

Spline fit oscillations

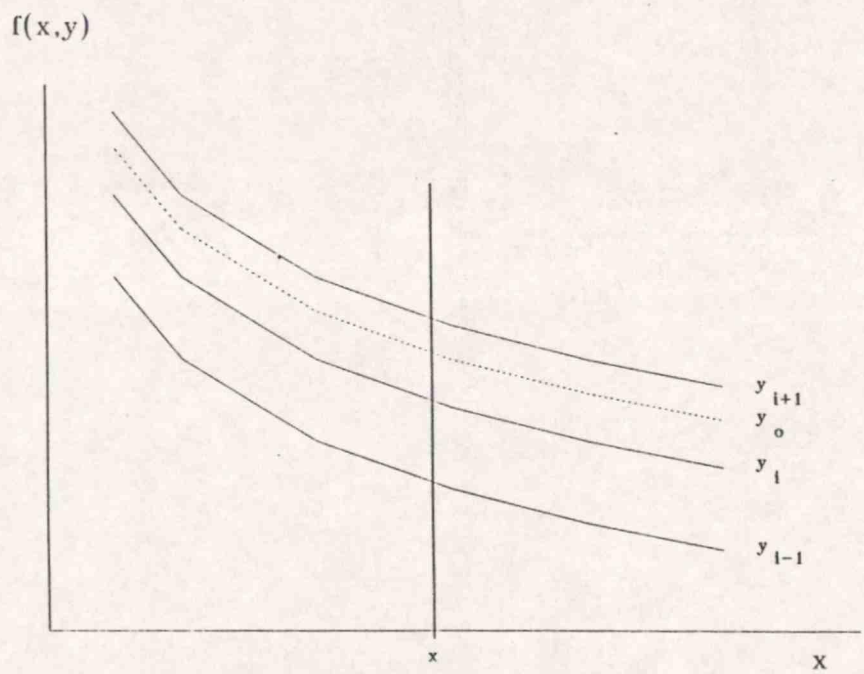

Figure 5.5

Application of rational interpolation to two dimensional functions

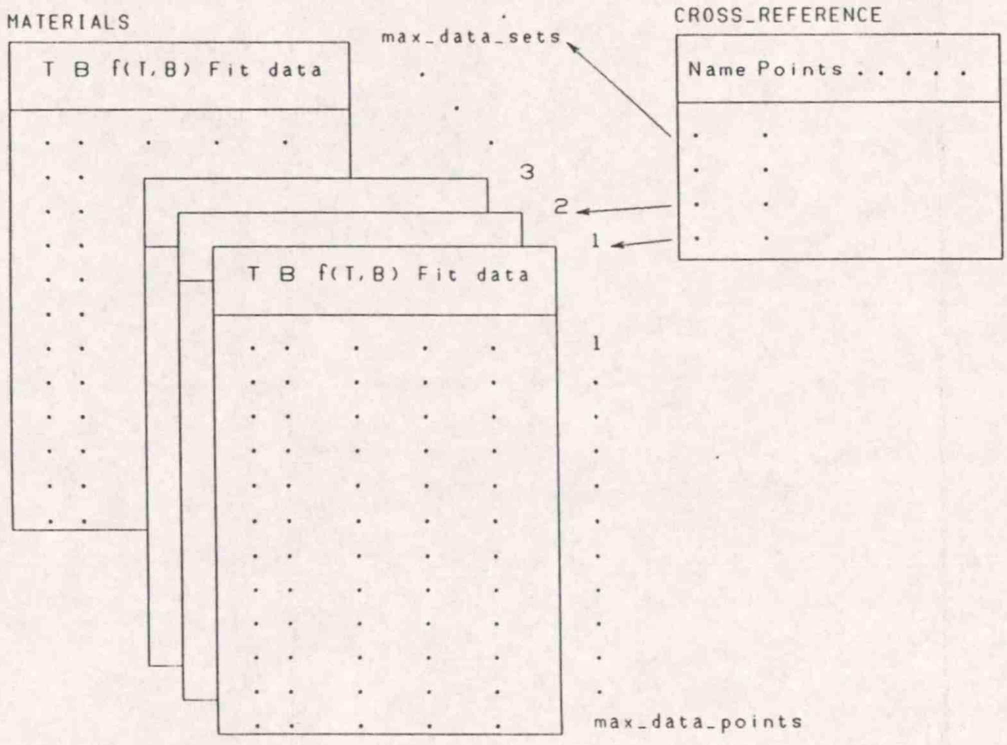

Figure 5.6

Storage of material properties data in 4QUENCH

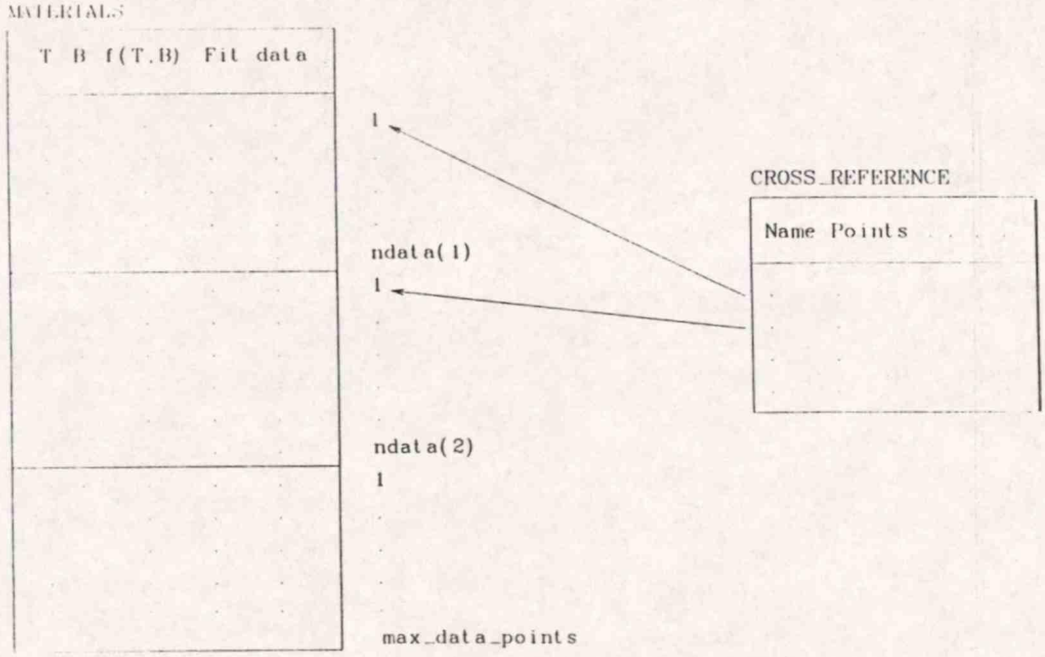

Figure 5.7

Alternative storage of material properties data

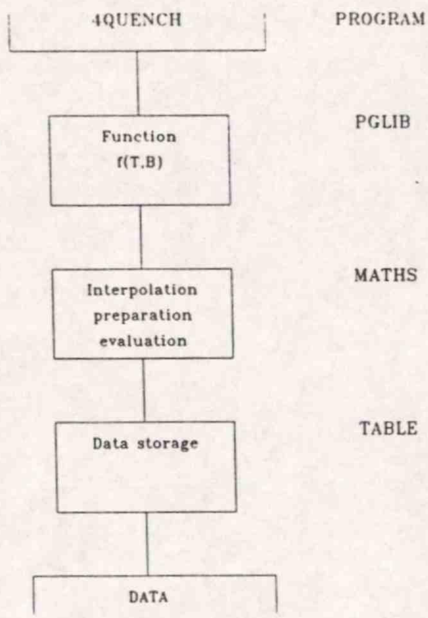

Figure 5.8

Relationship between 4QUENCH, interpolation software and data

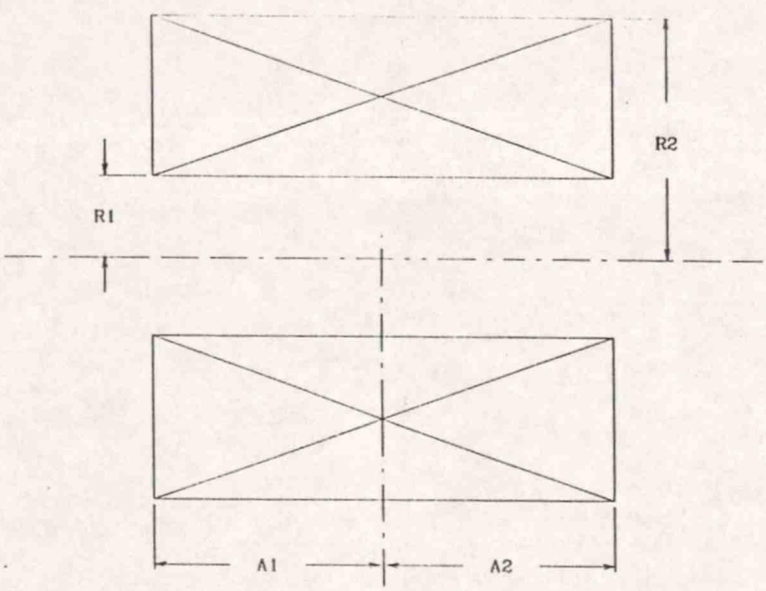

Figure 5.9

Cross-sectional view of a single coil magnet

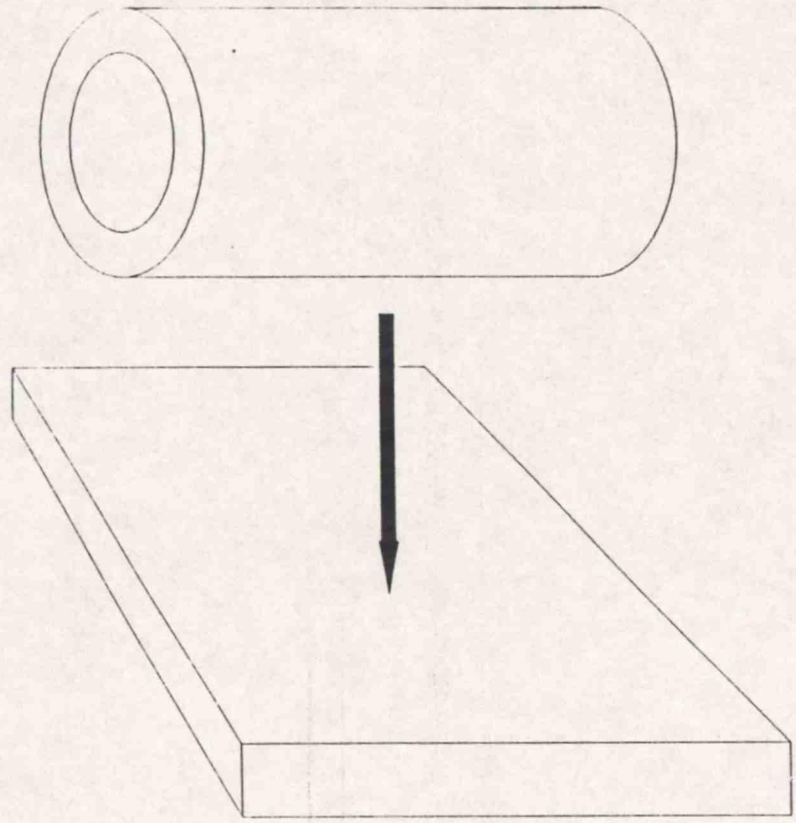

Figure 5.10
'Unwrapping' of a solenoid for quench analysis

TABLE COIL * 'Coil geometry data'

CN	SY	R1	R2	A1	A2	TD	CU	WIRE	FILLER
*	.	.	.	.	.	.	.	*	*
.	.	CM	CM	CM	CM	1/(CM**2)	A	.	. .
1	0	5	6	-10	10	843.4	100	S20/33	EPOXY
2	0	6	8	-10	10	843.4	100	S20/33	EPOXY
3	1	14	16	8	10	843.4	100	S20/33	EPOXY

$$

CN	- coil number
SY	- axial symmetry
R1, R2, A1, A2	- dimensions
TD	- turns density
CU	- initial current
WIRE	- wire type
FILLER	- filler material

Figure 5.11

Example magnet geometry table

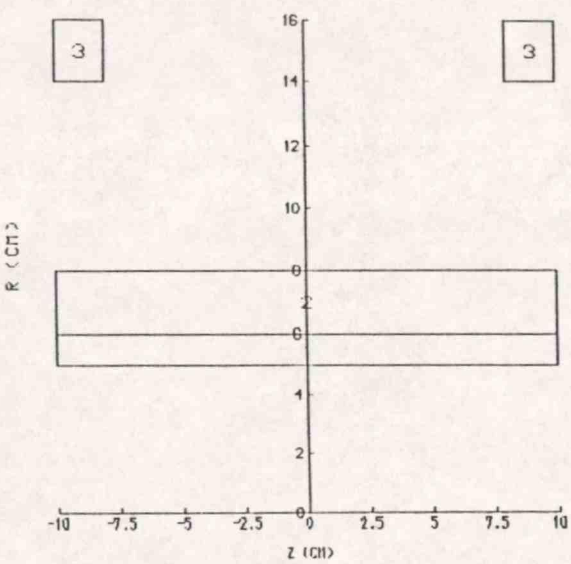

Figure 5.12

4QUENCH display of data of figure 5.11

```
TABLE   ELEC     *    'Protection circuit network'
!--------------------------------------------------------------------------
TYPE          NAME          N1     N2     V1     V2     T1     T2
*             *             .      .      .      .      .      .
.             .             .      .      SI     SI     S      S
!--------------------------------------------------------------------------
L             1..3          1      0      0      0      0      0
R             PROTECT       1      0      0.25   0.25   0      0
I             SUPPLY        0      1      100    0      0      0
!--------------------------------------------------------------------------
$$
```

TYPE	- component type
NAME	- component name
N1, N2	- node numbers
V1	- initial component value
V2	- final component value
T1	- start time for change V1 - V2
T2	- end t ime for change V1 - V2

Figure 5.13(a)

Example protection circuit table

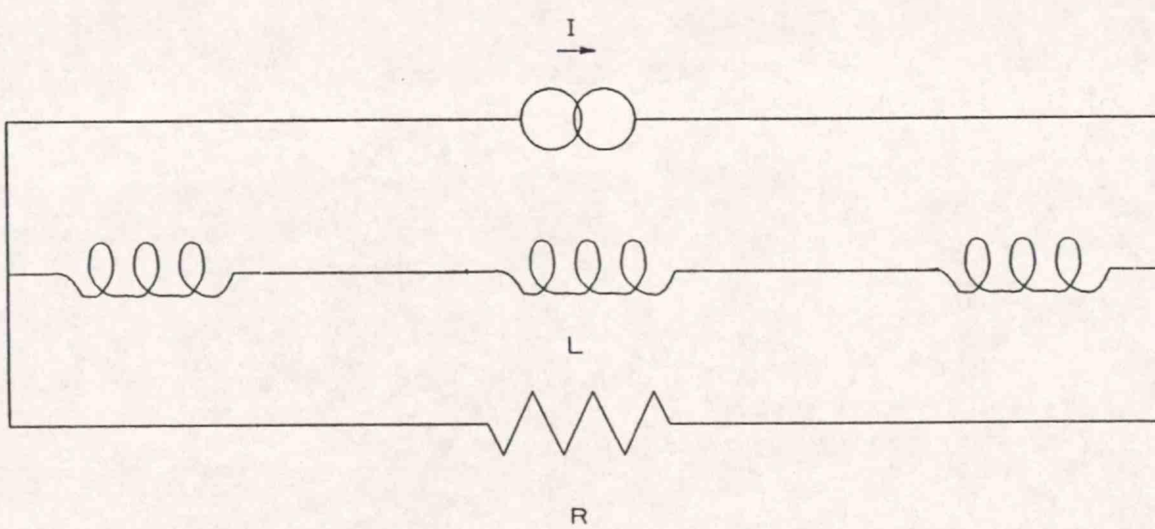

Figure 5.13(b)

Protection circuit described by the table of figure 5.13(a)

```
TABLE INDC * 'Coil inductance matrix'
!------------------------------------------------------------
COIL        L_1         L_2         L_3
.           .           .           .
.           H           H           H
!------------------------------------------------------------
1           1.075       0.51        0.11
2           0.51        0.775       0.098
3           0.11        0.098       0.65
!------------------------------------------------------------
$$
```

COIL	- coil number
L_n	- nth column of inductance matrix

Figure 5.14

Example mutual inductance matrix table

```
TABLE  VELS  *  'Quench propagation velocities'
!------------------------------------------------------------------------------------------------
NAME      COIL  METHOD    H           ETA       FZ          FX          FY
*         .     *         .           .         *           *           *
.         .     .         W/M**2*K .  .         .           .
!------------------------------------------------------------------------------------------------
VEL1      1     WILSON    0           0         .           .           .
VEL2      2     WILSON    0           0         .           .           .
VEL3      3     FORMULA   0           0         0.115*CD    0.019*VZ    0.013*VZ
!------------------------------------------------------------------------------------------------
$$
```

NAME	- name of velocity specification
COIL	- number of coil to which this specification applies
METHOD	- calculation method (e.g. WILSON - Wilson's formula, FORMULA - analytic formula)
H, ETA	- extra parameters for WILSON-type calculation
FZ, FX, FY	- formulae for Vz, Vy and Vx in Fortran notation

Figure 5.15

Example propagation velocity specification table

```
TABLE   WIRE   DATA   'IMI NIOMAX-S from manufacturers data sheets'
!-----------------------------------------------------------------------------------------------
NAME       DIMX       DIMY        MASSL       XSHAPE      TD          THICK
*                                             *
           .          .           .                       .           .
.          MM         MM          KGM/KM      .           MM**-2      MM
!-----------------------------------------------------------------------------------------------
S20/33     0.37       0.3204      0.7         ROUND       8.434       0.02
S20/40     0.44       0.3811      1.1         ROUND       5.694       0.02
S25/40     0.44       0.3811      1.04        ROUND       5.964       0.02
!-----------------------------------------------------------------------------------------------
$$
```

NAME	- wire name
DIMX	- x-axis thickness of unit cell
DIMY	- y-axis thickness of unit cell
MASSL	- mass per unit length
XSHAPE	- cross-sectional shape of wire
TD	- turns density
THICK	- insulation thickness

Figure 5.16

Example wire data table

```
TABLE   FRAC   DATA   'IMI NIOMAX-S fractions data from manufacturers data sheets'
!-----------------------------------------------------------------------------------------
WNAME      FNAME         FRAC            FTYPE       RRR
*          *             .               *           .
.          .             .               .           .
!-----------------------------------------------------------------------------------------
S20/33     COPPER        0.419763        METAL       180
S20/33     NBTI          0.269074        SUPER       0
S20/33     PVA           0.177102        INS         0
S20/40     COPPER        0.536763        METAL       180
S20/40     NBTI          0.178921        SUPER       0
S20/40     PVA           0.150255        INS         0
!-----------------------------------------------------------------------------------------
$$
```

WNAME	- name of wire containing fraction
FNAME	- name of fraction
FRAC	- fraction of FNAME in WNAME by volume
FTYPE	- type of material (e.g. metal, insulator)
RRR	- ratio $\frac{\text{resistivity(room temp)}}{\text{resistivity (4.2K)}}$ (metal only)

Figure 5.17

Example wire composition table

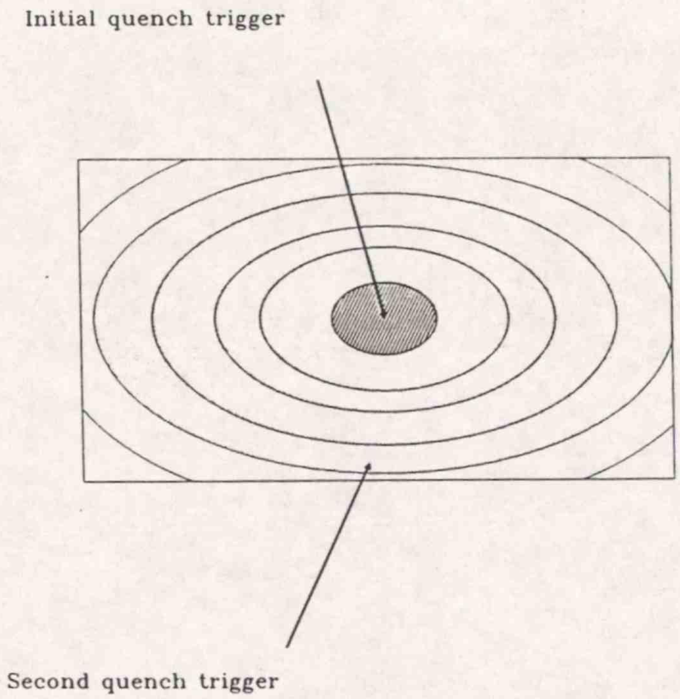

Figure 5.18
Large initial normal volume due to second quench
in ellipsoidal analysis scheme

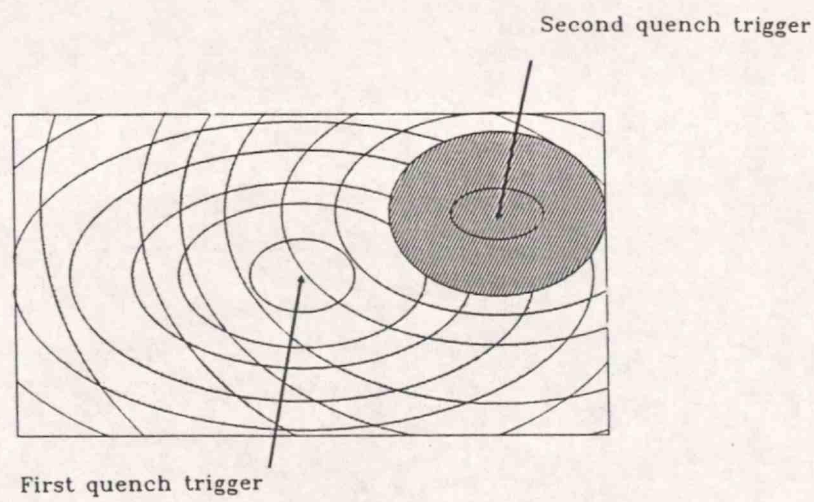

Figure 5.19
Complicated normal volume calculations due to intersection
of multiple ellipsoids

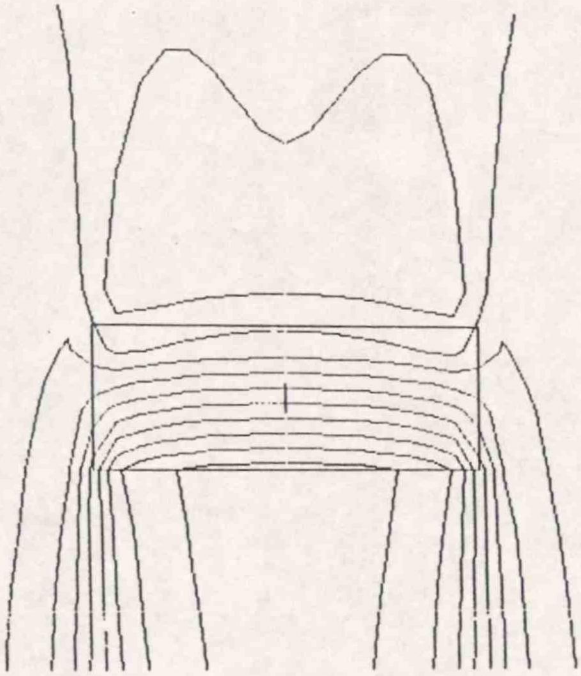

Figure 5.20

Varying magnetic field over coil cross-section

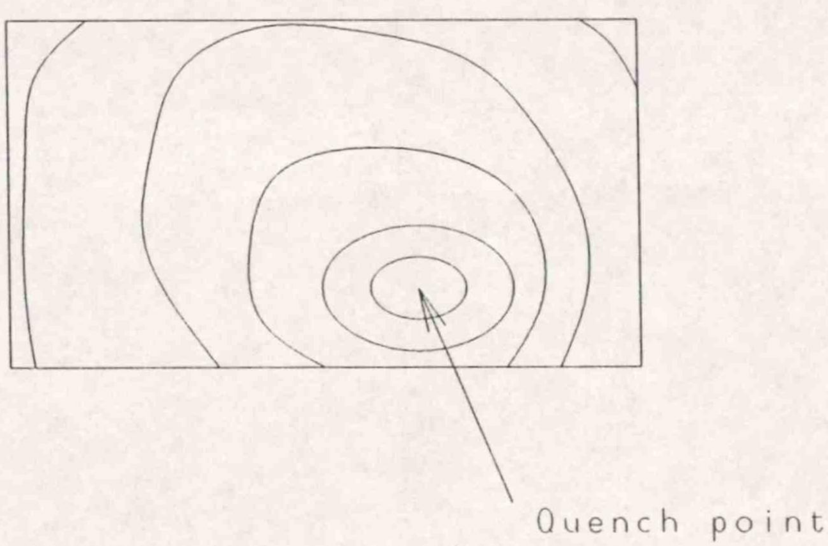

Figure 5.21

Non-ellipsoidal normal zone growth due to variation of propagation velocity over coil cross-section

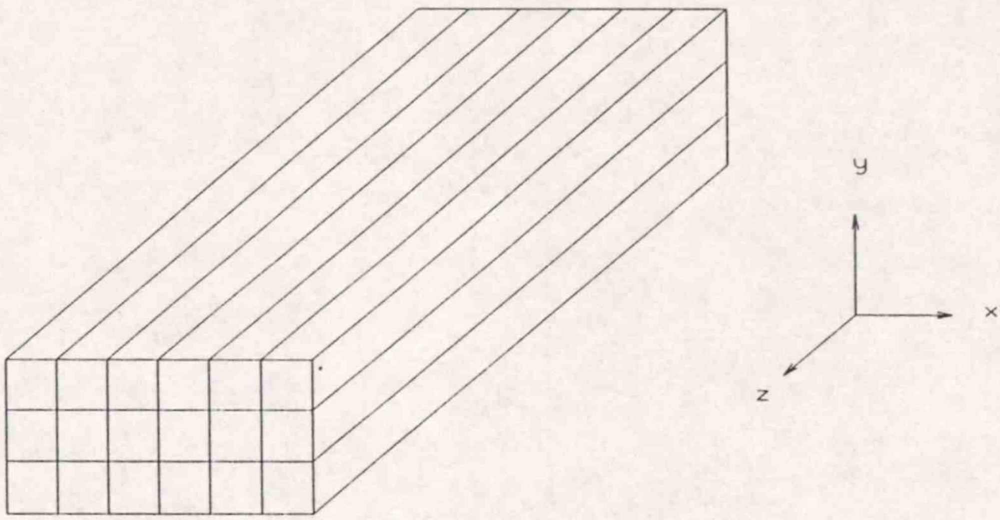

Figure 5.22

Rectangular grid of isothermals

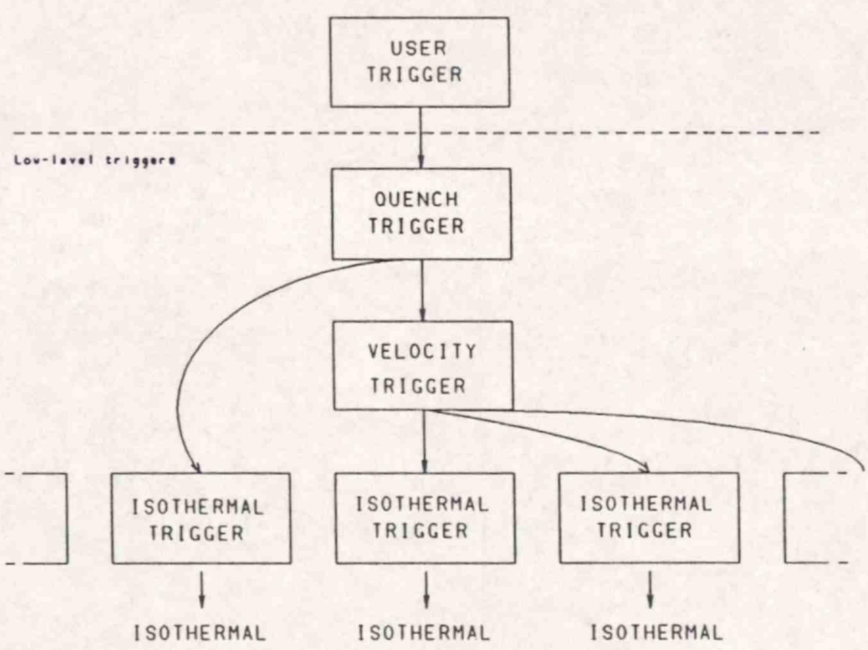

Figure 5.23

Relationship between triggers and isothermals

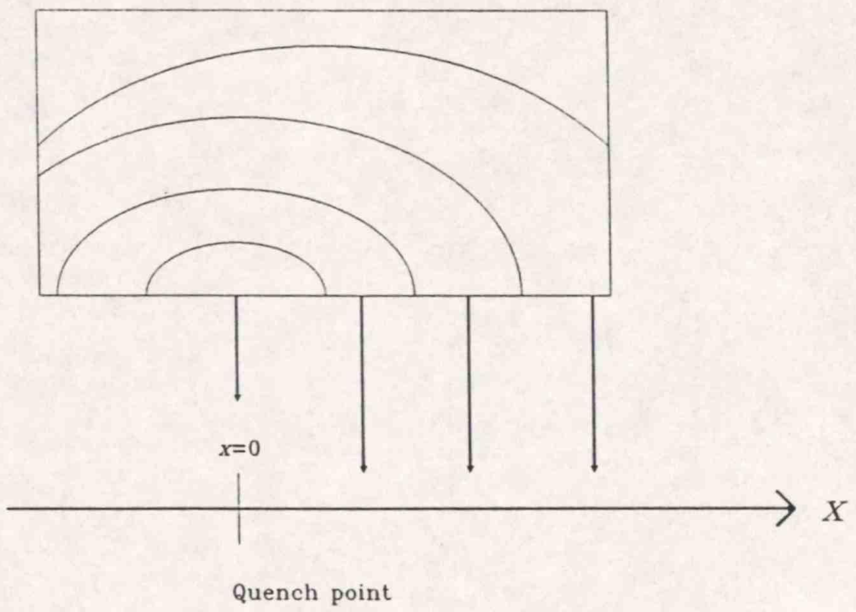

Figure 5.24(a)

Reduction of ellipsoidal isothermals to one dimension

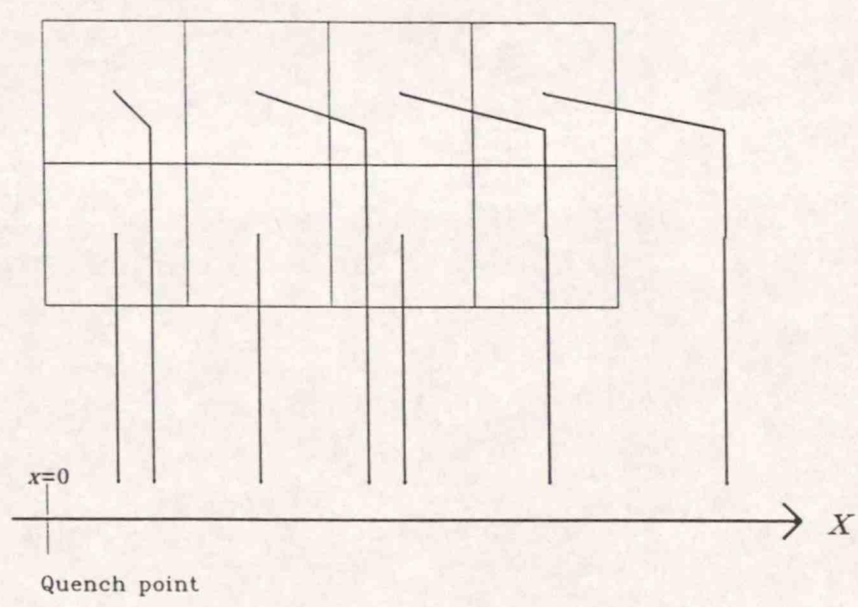

Figure 5.24(b)

Reduction of rectangular isothermal array to one dimension

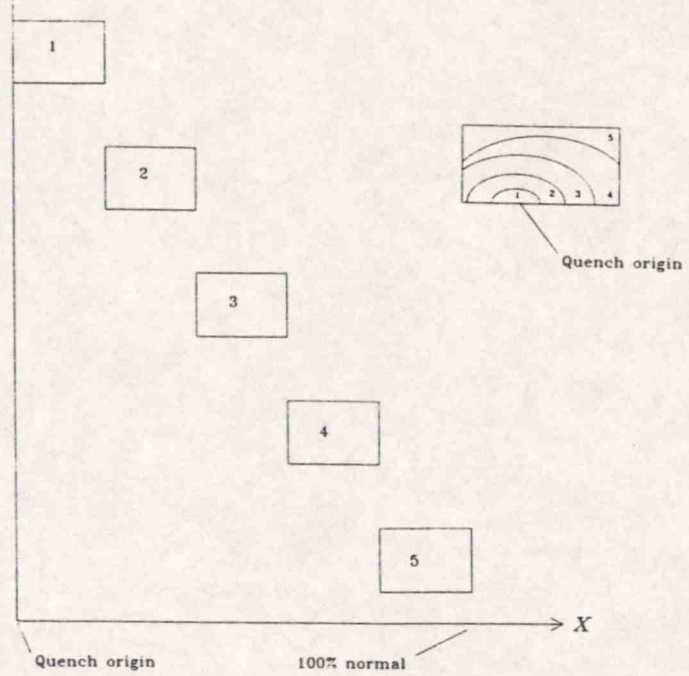

Figure 5.25(a)

Extended quenching of ellipsoidal isothermals

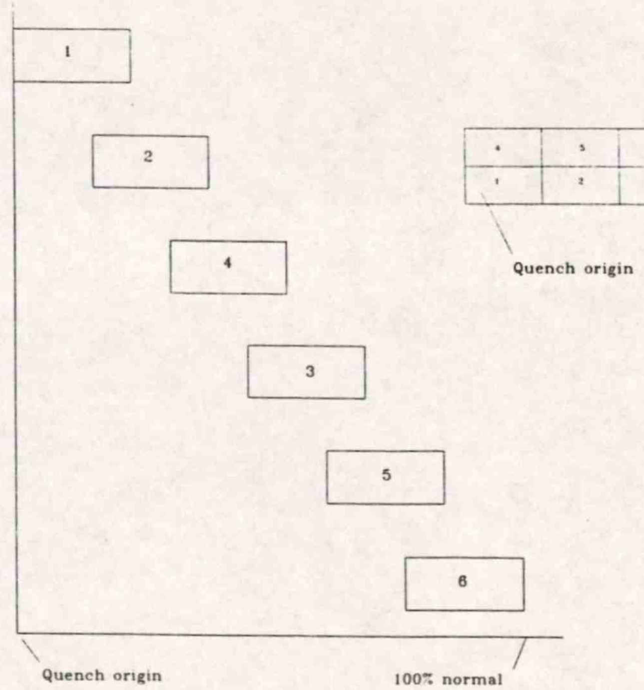

Figure 5.25(b)

Extended quenching of rectangular array of isothermals

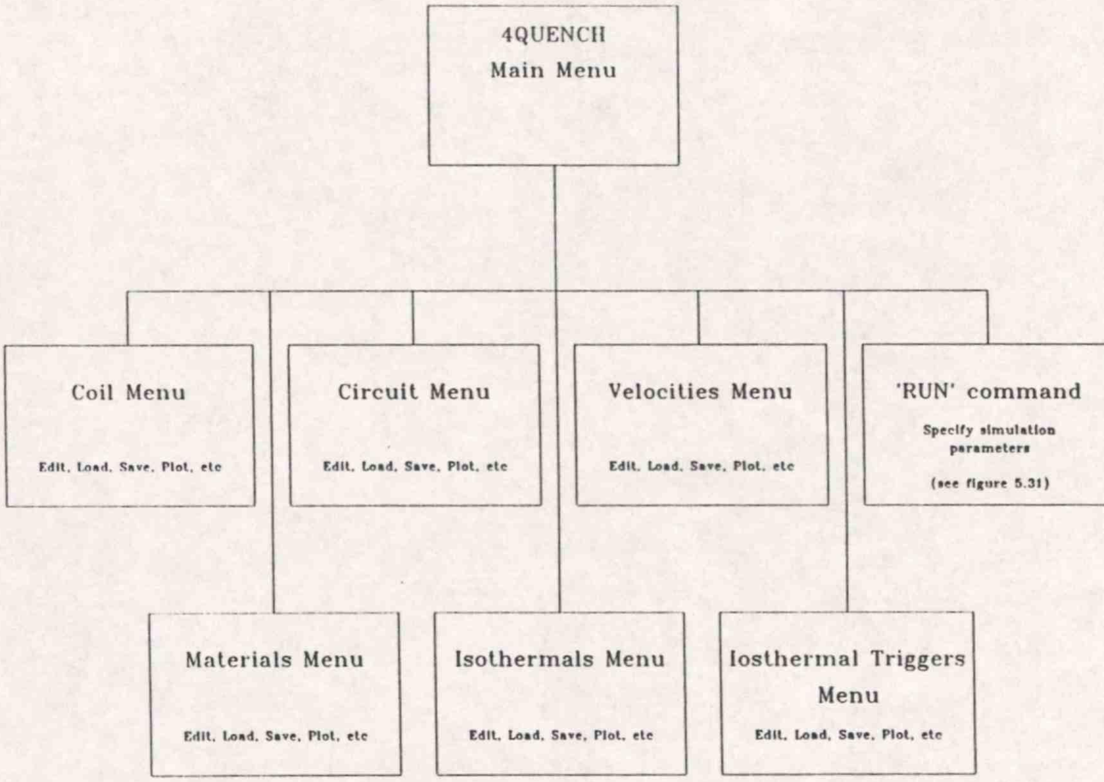

Figure 5.26

Structure of 4QUENCH data input software

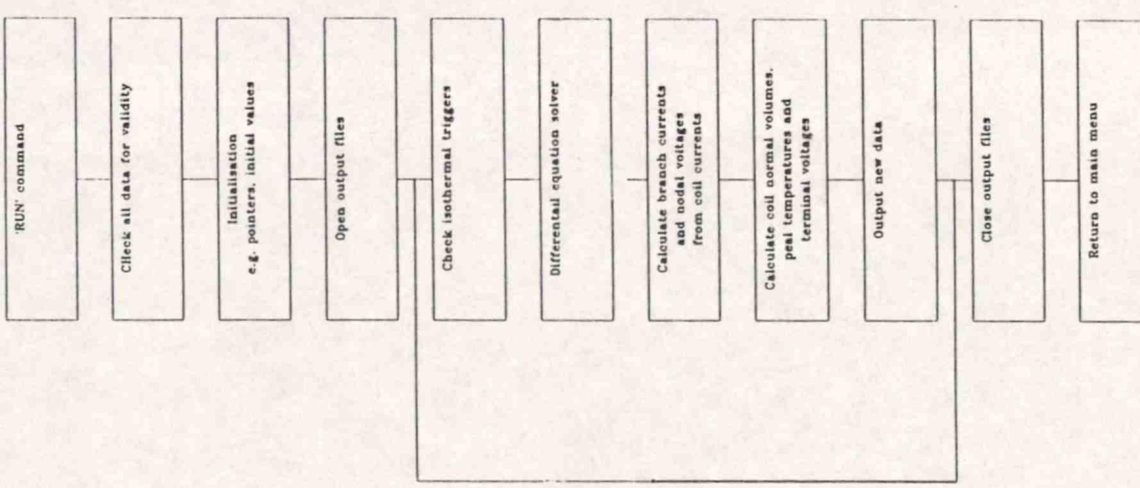

Figure 5.27

Structure of 4QUENCH quench analysis

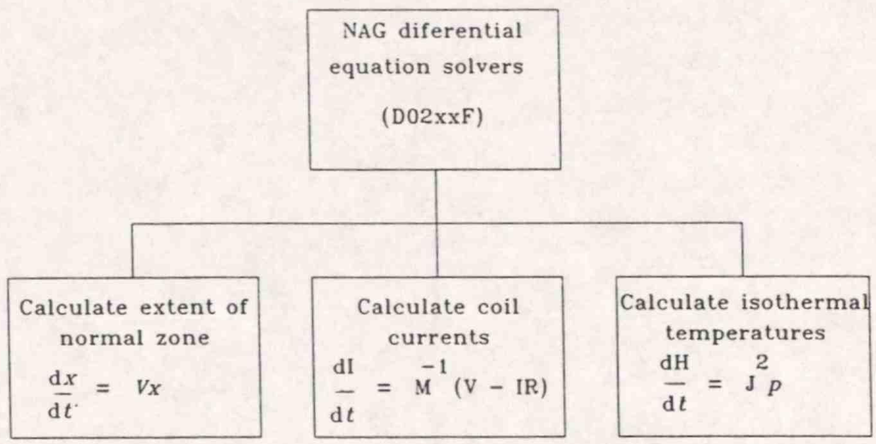

Figure 5.28

Structure of 4QUENCH differential equation solver

6. Program Documentation, Validation and Future Work

6.1 Documentation

Such a complex program must be well-documented. The 4QUENCH documentation was similar to that accompanying 3QUENCH, which was well received by the users. However, it was felt that a 'reference section', in which all the program commands were described in order, would be useful. Experience in supporting 3QUENCH showed that users often asked about features of the program which had not been presented in a consistent order. The final format was consistent with the recommendations of several sofware engineering texts, such as [54]

a) introduction - scope of the program, organisation of the documentation

b) overview, describing the features and limitations of the program

c) tutorial section, containing a complete program session; user input, program output and comments

e) reference section, covering all the commands available in the program, arranged by data input category

f) technical notes, describing how the program works and how to formulate a quench model for solution by the program

6.2 Program Validation

At the time of writing, the validation of the program using experimental quench data is incomplete. The only test that has been made is the quenching of a single coil magnet described by Wilson [3] and used for the validation of QUENCH [4]. However, the agreement with both QUENCH and the experimental results are encouraging. The runs made are shown in table 6.1.

Run number	Description	Figures
1	Simulation of single coil quench using 1 ellipsoidal isothermal	6.1(a-d)
2	As 1, 5 isothermals	6.1(a-d)
3	As 1, 10 isothermals	6.1(a-d)
4	As 1, 20 isothermals	6.1(a-d)
5	As 1, 100 isothermals	6.1(a-d)
6	Simulation of single coil quench using 1 rectangular isothermal	6.2(a-d)
7	As 6, 6 isothermals	6.2(a-d)
8	As 6, 12 isothermals	6.2(a-d)
9	As 6, 20 isothermals	6.2(a-d)
10	As 6, 100 isothermals	6.2(a-d)
11	As 9, isothermals arranged in a grid of $10(x) \times 2(y)$	6.3(a-d)
12	As 9, isothermals arranged in a grid of $2(x) \times 10(y)$	6.3(a-d)
13	As 9, isothermals arranged in a grid of $20(x) \times 1(y)$	6.3(a-d)
14	As 9, isothermals arranged in a grid of $1(x) \times 20(y)$	6.3(a-d)
15	As 9, isothermals arranged in a grid of $5(x) \times 4(y)$	6.3(a-d)
16	As 9, isothermals arranged in a grid of $4(x) \times 5(y)$	6.3(a-d)

Table 6.1

Summary of Single Coil Quench Simulation Runs

The runs with ellipsoidal isothermals (1-5) show good agreement with experiment and QUENCH when 20 isothermals are used. (It is noticeable that the predictions obtained with a single isothermal are very similar to those of Wilson using an approximate analytic method [3]). Most importantly, the 4QUENCH predictions converge as more isothermals are used; the results using 10, 20 and 100 isothermals are very close. This supports the idea that is is not necessary to use a large number of isothermals. By contrast, QUENCH used 100 time steps, and hence up to 100 isothermals, to obtain very similar results. The number of isothermals used also affects the time taken to perform the simulation; in practice, 4QUENCH is over 5 times faster than either QUENCH or 3QUENCH in comparable situations.

The results using rectangular isothermals (6-10) confirm these findings. However, the convergence with increasing numbers of isothermals is less regular. An explanation for this is that the relative numbers of isothermals on the *x*- and *y*-axes is varying as the number of isothermals is increased. Experiments with a constant number of isothermals but a varying ratio $N_x:N_y$ (11-16) support this. The aspect ratio of the coil is $x:y$ = 7.69:1 and the *x*- and *y*-axis propagation velocities are similar. Coil arrangements with $N_x:N_y$ ratios of between 5:1 and 20:1 (11,13) give good agreement with experiment, but ratios of 1.25:1 to 0.05:1 (12,14-16) give progressively poorer results.

From the single coil quench test, we can conclude that both the ellipsoidal and rectangular isothermal methods give good agreement with experiment, and require an order of magnitude less isothermals than a conventional, 1-isothermal-per-time-step quench model. However, work on a more complex system, containing several coils, is required before the program can be used with confidence on typical magnet designs.

6.3 Future Work

6.3.1 Automatic inter-coil quench propagation

This is a very important extension to this basic program. It can be implemented quite easily using the isothermal triggers described in section 5.5.3. If the user specifies a set of coils which are thermally linked, then the isothermal triggers in the 'secondary coils' are simply linked to the quench trigger in the 'primary coil', as shown in figure 6.4. The effect of having different velocities in different coils can be modelled by using different velocities in different coils, firing isothermal triggers which are all linked to a single quench trigger.

6.3.2 Non-adiabatic quenching

The ability to analyse slow quenches, in which there is time for significant heat transfer between isothermal regions to take place, is very important. 4QUENCH is prepared for this, since it uses enthalpy in the calculation of isothermal temperature. The necessary extension is to add the power input from neighbouring isothermals to the internal Joule heating when calculating the rate of change of enthalpy for each coil. The energy input from neighbouring isothermals can be calculated using a circuit analysis analogous to that for the protection circuit, with electrical conductivity replaced by (temperature-dependent) thermal conductivity, capacitance by heat capacity, voltage by temperature and current by power.

6.3.3 Calculation of forces

Since coil currents can change rapidly during a quench, and different coils will carry different currents, it is often important to consider the forces on the coils during a quench. These could be calculated from the coil currents after the run, but the ability to calculate them in the simulation would be very useful. Since magnetic force calculations are quite complex, it would be possible for the user to switch off the calculations when required, by disabling the output table containing the force information.

6.3.4 Prediction of quench origin

The ability to evaluate material properties as a function of field means that 4QUENCH could be developed to calculate a specified function of material properties over the cross-section of the coil(s). For example, evaluation of J/J_c would show the point in the coil at which the conductor was closest to its critical surface, and hence the point at which a quench would be likely to occur. Similarly, Stekly's parameter [50]

$$\alpha = \frac{\lambda^2 J_c^2 \rho A}{(1-\lambda)Ph(\theta_c - \theta_o)}$$

where λ is the volume fraction of superconductor in the wire and the other variables are as before, gives an indication of how near a superconductor is to quenching ($\alpha < 1$ for stability). This too could be evaluated at a grid of points on the coil cross-section and used to suggest likely places for a quench to occur.

6.3.5 Free quench propagation

In a quench model allowing diffusion, as described in section 6.3.1, energy transfer is only allowed between normal, or partly normal, isothermals. However, it is more realistic to allow diffusion to isothermals outside the normal zone, too. This leads to a method of solving the heat diffusion equation of section 2.3 without imposing a standing wave solution. All the isothermals in the system are analysed from the start, and heat can transfer freely between isothermals. When an isothermal temperature rises above θ_c, it starts to generate heat. No velocity calculations or iosothermal triggers are involved. This has the advantage of not requiring the use of (possibly inaccurate) velocity calculations and places no restrictions on how the normal zones propagate; normal zones need not be ellipsoidal, for example.

Simple, one-dimensional models based on an electrical circuit analysis program show that this approach can give reasonable results, with propagation at speeds close to the predicted values [55]. However, a three dimensional grid of isothermals would be required, since no assumptions about the propagation along the z-axis can be made. The large number of isothermals necessary for a three dimensional model mean that this would be computationally expensive.

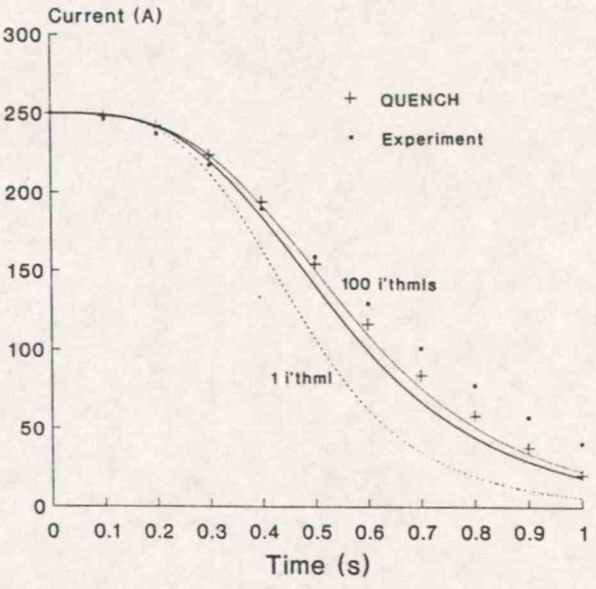

Figure 6.1(a)
4QUENCH current decay -
ellipsoidal isothermals

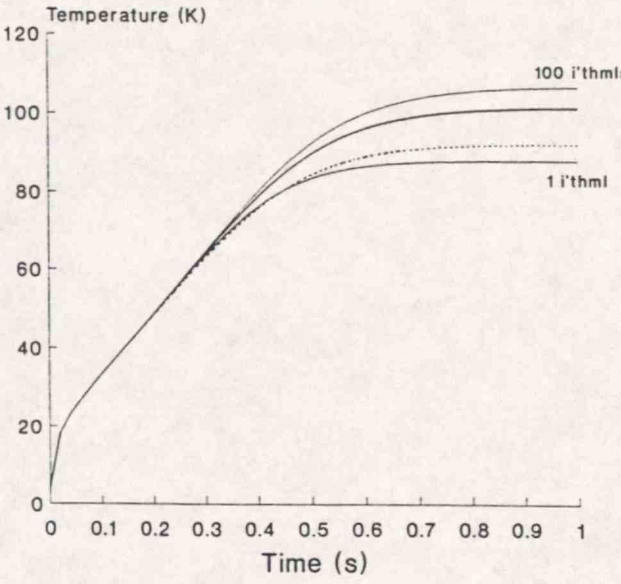

Figure 6.1(b)
4QUENCH temperature rise -
ellipsoidal isothermals

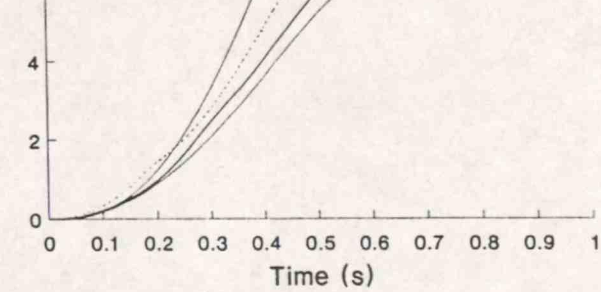

Figure 6.1(c)
4QUENCH resistance rise -
ellipsoidal isothermals

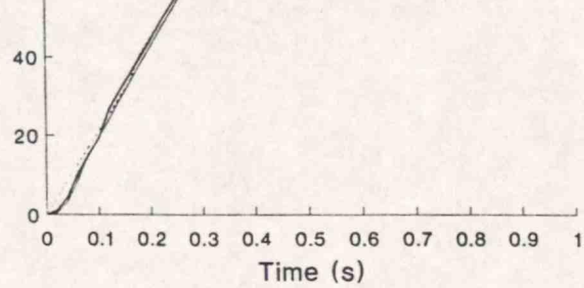

Figure 6.1(d)
4QUENCH normal zone growth -
ellipsoidal isothermals

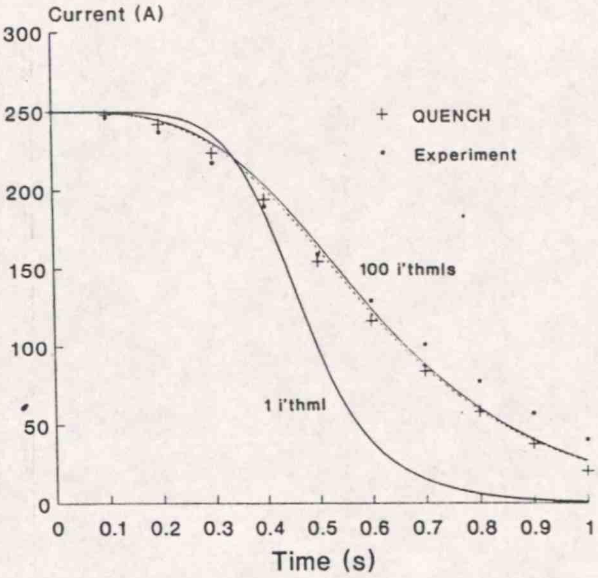

Figure 6.2(a)
4QUENCH current decay - rectangular isothermals

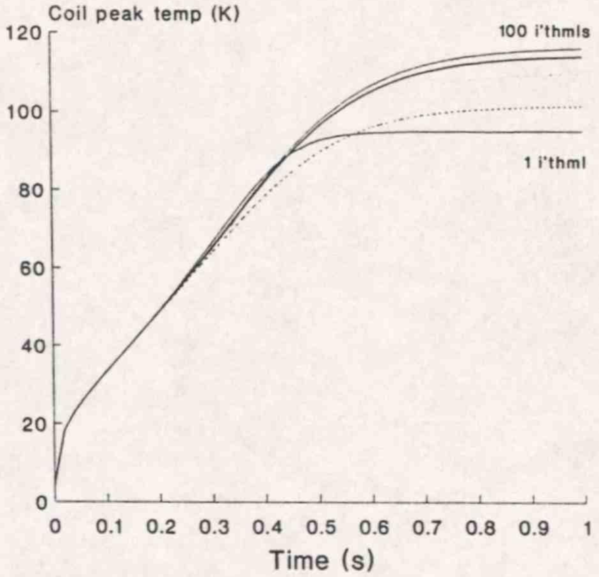

Figure 6.2(b)
4QUENCH temperature rise - rectangular isothermals

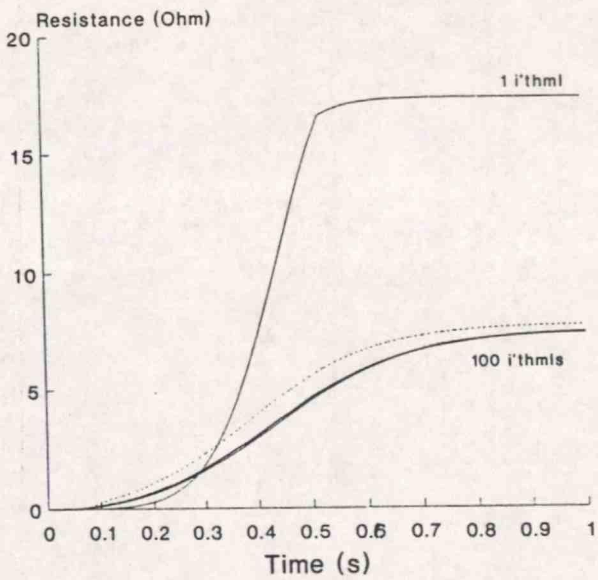

Figure 6.2(c)
4QUENCH resistance rise - rectangular isothermals

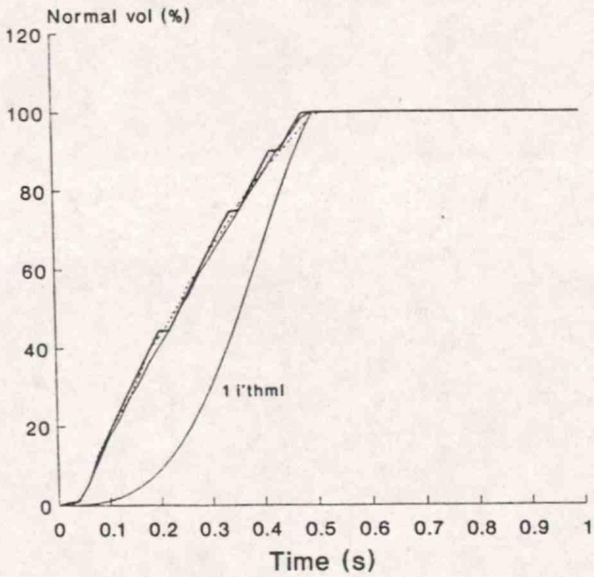

Figure 6.2(d)
4QUENCH normal zone growth - rectangular isothermals

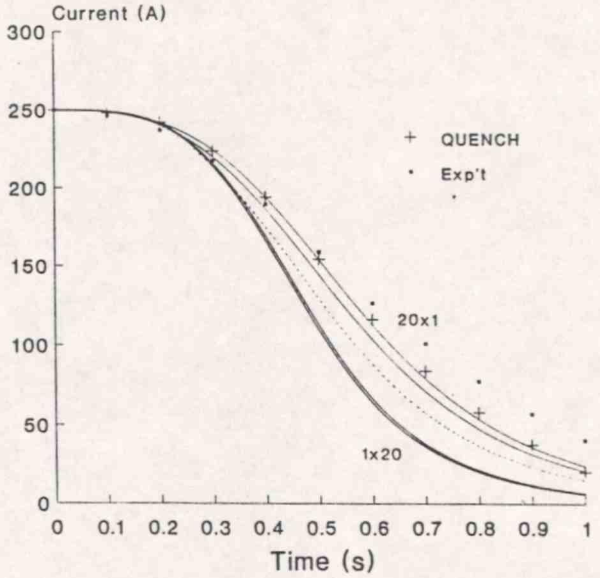

Figure 6.3(a)
4QUENCH current decay -
rectangular isothermals

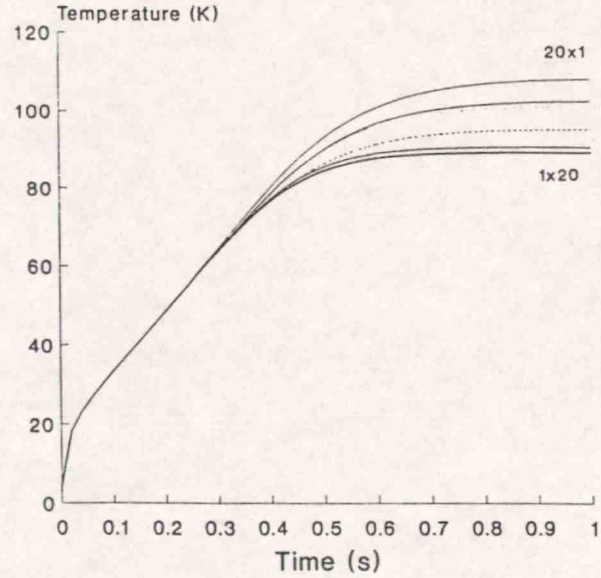

Figure 6.3(b)
4QUENCH temperature rise -
rectangular isothermals

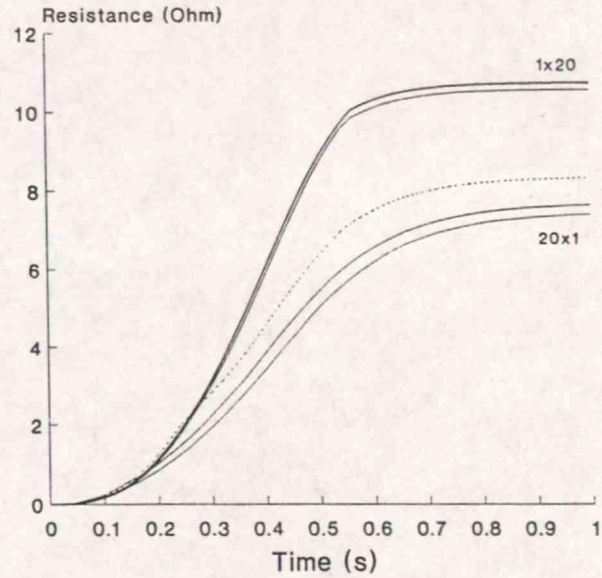

Figure 6.3(c)
4QUENCH resistance rise -
rectangular isothermals

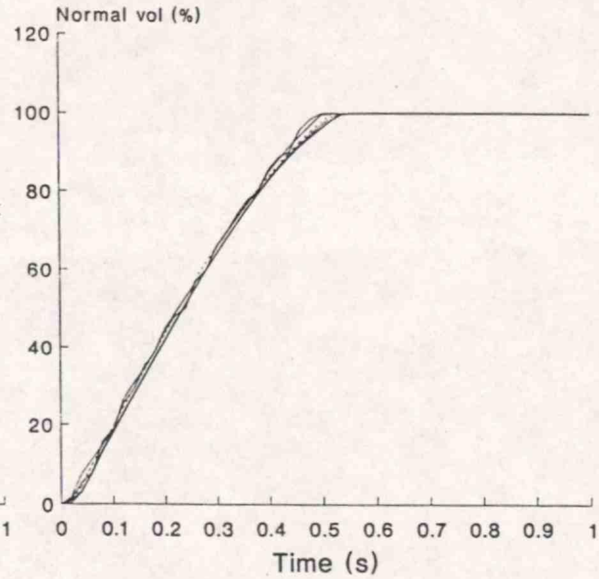

Figure 6.3(d)
4QUENCH normal zone growth -
rectangular isothermals

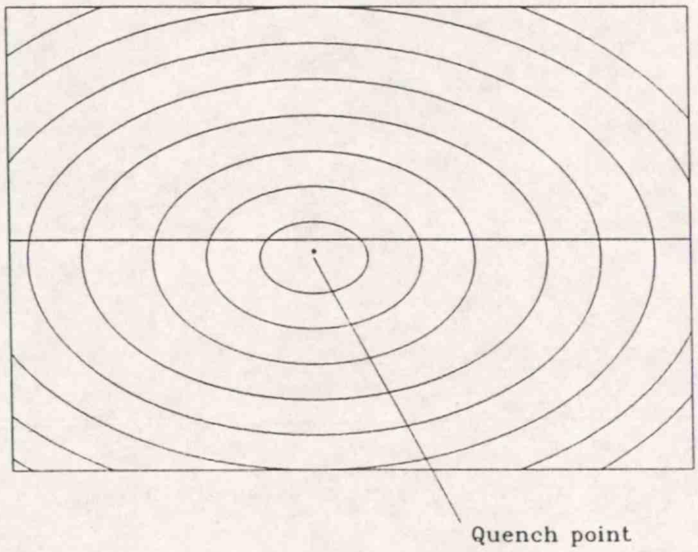

Figure 6.4

Inter-coil quench propagation using pre-defined isothermals

7. Conclusions

The catastrophic switch to normality of a superconducting magnet, known as 'quenching', and its consequences, have been described. A study of the theory of quenching shows that the spread of the normal zone through a magnet can be described by a 'propagation velocity'. However, the complexity of the process means that, to analyse the behaviour of a magnet during a quench, a computer-based simulation is necessary. This thesis describes the development of such a simulation, which is intended to meet the needs of magnet design engineers at Oxford Instruments Ltd. and answer some of the criticisms of previous quench programs.

First, a review of the literature on quench modelling was performed. Several programs which use the concept of propagation velocity to predict the outcome of a quench were found. In general, they produced acceptable results when compared with experiment, but tended to have limitations which restricted their application to a subset of all the common magnet designs. The programs which were available at Oxford Instruments were assessed in more detail and were also found to be difficult to use, largely due to the non-interactive nature of their input and output.

The program 2QUENCH, for which source code was available, was modified to handle a larger range of magnet designs by changes which made its electrical circuit analysis more general. Its ouput was also re-written to provide data in a form which could be easily displayed graphically. This modified program, 3QUENCH, was used successfully on several designs, but was still inflexible and hard to use.

In order to make quench simulation easier, and to produce more accurate predictions by modelling a wider range of quench effects, an entirely new program, 4QUENCH, was developed. The user interface of 4QUENCH is an improvement over the previous programs. It uses a previously developed 'command shell' which provides menus of commands, graphical display of data, command macros and expression analysis. This makes the input of data and the analysis of the quench predictions very easy; an important consideration for a program that is expected to be used in an engineering environment. The construction of the software was designed to make maintenance and the addition of new features straightforward.

4QUENCH also differs from previous programs in its novel approach to the thermal analysis of the quench. Isothermal regions within the magnet are defined before the analysis starts, instead of being generated as it progresses. These pre-defined isothermals are linked by a network of triggers which 'fire' isothermals to simulate the effect of the quench spreading through the magnet. In order to obtain good results with a limited number of isothermals, they are allowed to become partially normal, thus obtaining the smooth increase in normal volume associated with a large number of isothermals, whilst lowering the amount of computation required.

An important feature of 4QUENCH is that it treats the isothermals and triggers as abstract modelling elements. Using these elements, and calculated or user-supplied propagation velocity data, quench models of very high complexity can be prepared. In order to make the use of the program as simple as possible, a layer of software is included which prepares these elements from simple user specifications. This is appropriate for many simple magnet designs, where the full power of the model is not necessary and ease of use is more important.

The program has been documented and tested against experimental data and another quench simulation for the case of a quench in a single coil magnet. It is shown that accurate predictions can be made using as few as 20 isothermals in a coil, where previous programs may have used 100 or more. Agreement with experiment and the other program is good; this is a preliminary confirmation that the concept of a thermal analysis using pre-defined elements is valid.

8. Acknowledgements

The development of a piece of software of the size and complexityof a full quench simulation is a very demanding project. I am grateful for the assistance of many people and in particular Dr. Peter Aptaker of Oxford Instruments Ltd. His experience of quench modelling and flair for the development of engineering software have been invaluable.

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Last, but not least, the users! The Oxford Instruments engineers, particularly Dr. Steve Milward, who have used the quench software described, sometimes in its early, unreliable days, have made many contributions to the development of a usable engineering program.

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