INVESTIGATIONS INTO PULSED ULTRAHIGH MAGNETIC FIELD SINGLE TURN COIL SYSTEMS AND Θ-PINCH ELECTROMAGNETICALLY DRIVEN FLUX COMPRESSION DEVICES

by

Douglas Findlay Rankin

A Doctoral Thesis
submitted in partial fulfilment of the requirements for the award of
Doctor of Philosophy of Loughborough University

September 2006

Department of Electronic and Electrical Engineering
Loughborough University
Loughborough, UK.

© by Douglas F Rankin, September 2006
Magnetic flux densities exceeding 100 T are termed 'ultrahigh' magnetic flux densities and are necessarily developed using pulsed energies. Two particular laboratory techniques are commonly used to produce magnetic fields of this size; the single turn coil (STC) technique and the electromagnetically driven flux compression (EMFC) technique. Over recent years there has been a strong drive to improve both of these systems and to develop them further. This has primarily been achieved by analytical simulation as well as by innovative design solutions. This thesis investigates both techniques, and in particular details the development of an accurate finite element model used in predicting the behaviour of STC systems as well as detailing experimental advances made using Θ-pinch EMFC systems, including in particular the use of an insulator-metallic phase transition cascade.
ACKNOWLEDGEMENTS

...to all those that made this possible.
Sincerest thanks, Douglas.
# Table of Contents

Abstract  
Acknowledgements  
Table of Contents  
List of Figures and Tables

1. **Introduction** ................................................................. 1

2. **Pulsed Magnetic Fields** ................................................ 3
   2.1. Pulsed Magnets .......................................................... 4
   2.2. Single Turn Coil Systems ............................................ 6
   2.3. Magnetic Flux Compression ......................................... 9
      2.3.1. $\Theta$-Pinch Explosively Driven Flux Compression ....... 10
      2.3.2. $\Theta$-Pinch Electromagnetically Driven Flux Compression .... 15
      2.3.3. Z-Pinch Electromagnetically Driven Flux Compression ....... 18
   2.4. Flux Compression using Flux Concentrators ................. 20
   2.5. Flux Compression using Cascades ............................... 22
   2.6. Shock waves in Pulsed Ultrahigh Magnetic Field Systems ......................................................... 25
      2.6.1. *Equation of State in Shock waves* .......................... 26
      2.6.1.1. Shockwaves in Porous Metals ................................... 29
      2.6.2. *Equation of State using SESAME database* .................. 30
   2.7. Conclusion .................................................................... 32
3. FINITE ELEMENT ANALYSIS USING ANSYS

3.1. The Finite Element Method

3.1.1. Procedures taken in constructing an FEA solution

3.1.1.1. Discretise the continuum

3.1.1.2. Select interpolation functions

3.1.1.3. Implement the element properties

3.1.1.4. Assemble the matrices

3.1.1.5. Impose boundary conditions

3.1.1.6. Solve the systems of equations

3.1.1.7. Derive additional unknowns for computational results

3.1.2. Composing a FEA solution

3.1.3. Higher order elements

3.1.4. Non-linearity

3.1.5. Steady state, modal, or transient analysis

3.2. Using ANSYS code to solve FEA problems

3.2.1. Implementing the analysis

3.2.1.1. Implementing the analysis in batch mode

3.2.2. Using Multiphysics to solve complex engineering problems

3.2.2.1. Coupled Analysis

3.2.2.2. Sequential Analysis

3.2.2.2.1. One way sequential coupling

3.2.2.2.2. Full sequential coupling

3.2.2.3. Mesh Morphing

3.3. Errors in FEA

3.4. Conclusions

4. PULSED MAGNETIC FIELD SYSTEMS AT LOUGHBOROUGH

4.1. Experimental Configuration

4.1.1. Energy Supply Systems

4.1.2. High Voltage Closing Switches

4.1.2.1. Rail Gap Switches
5.3.1. Design A

- Current ................................................................. 104
- Flux Density ............................................................ 105

5.3.2. Design B

- Current ................................................................. 106
- Flux Density ............................................................ 107
- Deformation ......................................................... 108

5.4. Conclusions .......................................................... 110

6. FINITE ELEMENT ANALYSIS OF SINGLE TURN COIL SYSTEMS .......................................................... 111

6.1. Filamentary Analysis of pulsed power systems .................. 112

6.2. Multiphysical FEA model ........................................... 114

- Electromagnetic environment ...................................... 115
- Thermal environment ............................................... 116
- Structural environment ............................................. 118
- Combined Multiphysics ............................................. 119

6.3. Generating the STC model ........................................... 121

- Two Dimensional Model of STC .................................. 121
  - Generating the 2D solid model .................................. 122
  - Generating the 2D mesh ......................................... 123
- Three Dimensional Model of STC .................................. 124
  - Generating the 3D solid model .................................. 124
  - Generating the 3D mesh ......................................... 126
- Material Models ...................................................... 127
  - Semi-Destructive Material Model ................................ 127
  - Destructive Material Model ....................................... 129

6.3.4. Establishing boundary conditions, loads, and solution options ......................................................... 132

6.4. Results ...................................................................... 132

- Semi destructive simulation results ......................... 133
  - Discharge current .................................................. 133
6.4.1.2. Central flux density .................................................. 134
6.4.1.3. Peak temperature .................................................. 136
6.4.1.4. Coil Deformation .................................................. 137
6.4.2. Destructive simulation results ........................................ 141
   6.4.2.1. Design A ....................................................... 141
      6.4.2.1.1. Discharge current ....................................... 141
      6.4.2.1.2. Central flux density ................................... 143
      6.4.2.1.3. Peak temperature ....................................... 148
      6.4.2.1.4. Coil Deformation ....................................... 149
   6.4.2.2. Design B ....................................................... 150
      6.4.2.2.1. Flux Density ............................................. 150
      6.4.2.2.2. Coil Deformation ....................................... 151
6.5. Conclusions ..................................................................... 154

7. Θ-PINCH ELECTROMAGNETICALLY DRIVEN FLUX COMPRESSION ........................................................................ 155
   7.1. Cnare Effect .................................................................. 155
      7.1.1. Experimental Configuration .................................... 158
      7.1.2. Magnetic Field Production ..................................... 164
   7.2. With seed field ........................................................... 166
      7.2.1. Experimental Configuration .................................... 169
      7.2.2. Magnetic Field Production ..................................... 172
      7.2.3. Implosion Dynamics .............................................. 174
   7.3. EMFC using an Insulator-Metallic Phase transition cascade ..................................................................... 180
      7.3.1. Experimental Configuration .................................... 182
   7.4. EMFC using an Insulator-Metallic Phase transition cascade, and implementing Copper liners ................................................................ 189
      7.4.1. Experimental Configuration .................................... 189
      7.4.2. Experimental Results ............................................. 191
   7.5. Conclusion ..................................................................... 194
8. FEA MODELLING OF Ω-PINCH ELECTROMAGNETICALLY
DRIVEN FLUX COMPRESSION........................................... 196

9. PUBLICATIONS................................................................. 198
  9.1. List of Journal Publications........................................... 198
  9.2. List of Conference Publications..................................... 198

10. CONCLUSIONS. ............................................................ 202

11. FUTURE WORK............................................................ 204

12. REFERENCES............................................................. 206

13. APPENDICES............................................................... 214
  13.1. Appendix A – Implementing the analysis in batch mode........ 214
  13.2. Appendix B – Batch code........................................... 221
  13.3. Appendix C – Integrator circuit..................................... 224
  13.4. Appendix D – 2D STC FEA Batch Code.......................... 226
  13.5. Appendix E – 3D STC FEA Batch Code.......................... 242
  13.6. Appendix F – Semi Destructive Materials Library............. 258
  13.7. Appendix G – Destructive Materials Library.................... 267
LIST OF FIGURES AND TABLES

FIGURES

Chapter 2 – Pulsed Magnetic Fields

2.1. Topography of a pulsed magnet
2.2. Experimental STC arrangement
2.3. Cross-section of Θ-pinch explosively driven flux compression
2.4. Cross-section of Θ-pinch explosively driven flux compression, using Helmholtz coils for initial field
2.5. Explosively driven flux implosion: (a) initial configuration (b) during implosion
2.6. Electromagnetically driven flux compression arrangement
2.7. Z-pinch Flux compression
2.8. Axial view of Θ-pinch flux compression with non-uniformity of liner due to feed gap (a) axial image at start of experiment, (b) axial image during compression
2.9. Cylindrical Flux Compression concentrators
2.10. Final stages of compression, (a) distorted inner, (b) ideal inner
2.11. Flux compression with cascades
2.12. Shock wave in material

Chapter 3 – Finite Element Analysis using ANSYS®

3.1. Finite element discretisation
3.2. Interpolation functions
3.3. Newton-Raphson non-linear iteration
3.4. FE code stages
3.5. ANSYS GUI Window
3.6. Multiphysics representation

Chapter 4 – Pulsed Magnetic Field Systems at Loughborough

4.1. Capacitor charging circuit schematic
4.2. Capacitor bank configuration
4.3. Closing switching
4.4. Cross section of a Spark Gap
4.5. Cross section of a Rail Gap
4.6. TITAN Rail-gap switch, model 40302
4.7. TITAN Rail-gap switch arrangement
4.8. Operating curve
4.9. Pin closing switch
4.10. Pin closing switch
4.11. RLC circuitry
4.12. Flat transmission plates
4.13. Inductance and correction factor for parallel plate
4.14. Flashover
4.15. Mylar breakdown characteristics
4.16. Inductive magnetic pick-up loop
4.17. Cross section of pick-up probe construction
4.18. Faraday rotation arrangement
4.19. Rogowski Coil
4.20. Rogowski coil equivalent circuit
4.21. Rogowski coil second equivalent circuit
4.22. Hadlen IMACON 486 high speed camera configuration
4.23. 150 kV Flash X-ray configuration

Chapter 5 – Single Turn Coil Technique
5.1. Semi-destructive STC load
5.2. Semi-destructive STC set-up
5.3. Semi-destructive STC current discharge
5.4. Semi-destructive STC magnetic flux density
5.5. Pictures of deformed STC
5.6. Area of most deformation
5.7. Destructive STC load
5.8. Destructive STC Set-up, (a) Design A, (b) Design B
5.9. Design A - Current discharge
5.10. Design A - Magnetic flux Density, (a) Faraday Signal, (b) extrapolating axial field
5.11. Design B - Current discharge
5.12. Design B – Central Flux Density
5.13. X-Ray images of Design B, (a) 0 µs, (b) 0.82 µs
5.14. X-Ray images of Design B at 1.2 µs

Chapter 6 – Finite Element Analysis of Single Turn Coil Systems

6.1. Filamentary resolution of STC
6.2. Equivalent circuit of filamentary STC
6.3. Electrical representation
6.4. Multiphysical flow chart
6.5. 2D simplification (a) complete model, (b) cross-section (c) simplified cross-section
6.6. Solid Model
6.7. Meshed Model
6.8. Simplified STC solid model
6.9. (a) ¼ model STC, (b) extruded surrounding air, (c) extruded farfield
6.10. 3D mesh of coil
6.11. Material properties used over temperature in Kelvins (a) resistivity, (Ω/m), (b) thermal conductivity, W/(m-K) (c) density, (kg/m3) (d) specific heat, (J/(kg-K))
6.12. Bilinear kinematic hardening Stress (N/m²) v Strain (%)
6.13. Electrical resistivity used over temperature in Kelvins, (Ω/m)
6.14. Enthalpy function used (K/m³)
6.15. Discharge current Comparison with results
6.16. Simulated Discharge current over 150 µs
6.17. 2D Magnetic flux density comparison with results
6.18. 2D Simulated magnetic flux density over 150 µs
6.19. 3D Magnetic flux density comparison with results
6.20. Temperature variation
6.21. Deformed semi-destructive STC (a) recovered test piece (b) predicted shape - vector displacement in m
6.22. Predicted dynamics of semi-destructive STC
6.23. 3D FEA spatial distribution within semi-destructive STC (a) temperature - K (b) Joule heating - J (c) current density – A/m²
6.24. Discharge current comparison with results over 2.4 µs
6.25. Current density in the coil at (a) 0.25 µs (b) 1.42 µs.
6.26. 2D Axial flux density
6.27. 3D Axial flux density
6.28. 2D Spatial magnetic flux density in Teslas (a) 0.025 µs (b) 1.15 µs
6.29. 2D Axial flux density comparison with no movement over 1.45 µs
6.30. 2D Spatial temperature distribution after 1.15 µs
6.31. Temperature variation with time
6.32. 2D Displacement vector sum at 1.15 µs after beginning of discharge, meters
6.33. 3D Axial magnetic flux density of Design B
6.34. X-ray dynamics Design B (a) images at 0 ns and 820 ns (b) corresponding predicted shapes - scale indicates vector displacement in meters
6.35. 3D Predicted dynamics of Design B

Chapter 7 – Θ-Pinch Electromagnetically Driven Flux Compression
7.1. EMFC using the Cnare effect
7.2. Titan Corp, Model 40302 rail gap schematic
7.3. EMFC load
7.4. EMFC set-up
7.5. Magnetic flux density recordings, Design M, (a) dB/dt (108 T/s), (b) Flux density (T)
7.6. Seed field central Magnetic Flux density
7.7. Initial coils in situ
7.8. System set-up with initial field coils
7.9. Dynamics diagnostic set-ups (a) IMACON High Speed Camera, (b) X-Ray
7.10. Magnetic Flux density with Initial field
7.11. dB/dt of magnetic flux density
7.12. High speed imaging
7.13. High-speed imaging post-peak field
7.14. X-Ray imaging
7.15. High-speed imaging post-peak field
7.16. Aluminium cascade, (a) empty, (b) full
7.17. Magnetic flux density of (i)
7.18. Magnetic flux density of (ii), with comparison of experiment without powder
7.19. Design M with and without cascade
7.20. X-ray images corresponding to (a) without powder and (b) with powder shown in Figure 7.18
7.21. Magnetic Flux Density produced by Experiment 3 of Table 7.5
7.22. Magnetic Flux Density produced by Experiment 5 of Table 7.5
7.23. X-ray pictures of Experiment 3 taken at 6.03 μs and 9.14 μs
7.24. X-ray pictures of Experiment 3 taken at 5.6 μs and 10.75 μs
Chapter 2 – Pulsed Magnetic Fields

2.1. Performance of experimental STC to date
2.2. Performance of EMFC without seed field
2.3. Performance of EMFC with seed field

Chapter 5 – Single Turn Coil Technique

5.1. Destructive STC parameters

Chapter 7 – 0-Pinch Electromagnetically Driven Flux Compression

7.1. Cnare effect geometric arrangements
7.2. Typical Magnetic Flux density produced
7.3. Magnetic Flux density with Initial field
7.4. Aluminium cascade
7.5. Aluminium cascade with Copper liners
1. INTRODUCTION

The harnessing and application of magnetic fields plays a pivotal role in many modern day situations. Recent research has shown strong interest in the application of relatively intense magnetic fields in both solid state physics (Muira et al. 1984, Matsuda et al. 2002) as well as in recent proposals for magnetised plasma target fusion (Frese et al. 2004) and possibly in high-energy nuclear physics (Herlach et al. 1971). Further recent developments have detailed an interest in using such magnetic fields as a basis for the development of unconventional radiation emitters (radio, microwave and X-ray) (Novac and Smith, 1997, 2002) primarily for the use in defence projects.

The production of magnetic flux densities exceeding 100 T are termed 'ultrahigh' magnetic flux densities and are always developed using pulsed energies. Two particular laboratory techniques are often used to develop magnetic fields in this region; the single turn coil (STC) technique and electromagnetically driven flux compression (EMFC) technique. Over recent years there has been a strong drive to improve these systems and develop them further. This has primarily been achieved by analytical simulation as well as innovative design solutions.

With regards to the simulation of such systems being pulsed and or producing ultrahigh fields, previous analytical methods have developed a simple and efficient filamentary model. This model however has current limitations which may hinder future development and it is therefore a requirement that an alternative technique is adopted if these limitations are to be overcome. Within this thesis there is detailed the initial development of a finite element model developed in ANSYS for such pulsed power systems, which acts to indicate the potential for possible future development in this area, highlighting some of the benefits of the proposed technique over the existing filamentary analysis. The work in this area was
conducted during a limited licence agreement window with ANSYS and as such the results detailed here are those which were best achieved to date.

In addition, this thesis details experimental work investigating EMFC techniques, and in particular a flavour known as Θ-pinch EMFC. The work investigates the geometric considerations of such systems and highlights the benefits of one geometric set-up in particular. The work also investigates the use of supplementary fields, used to increase the final ultrahigh magnetic field produced within such systems. Furthermore, detailed here is the development and implementation of an insulator-metallic phase transition cascade that can be used to improve the effectiveness of the technique. Within the work detailed, the production of ultrahigh magnetic fields is detailed using a compact system, powered from a fast capacitor bank. The work details a system with high efficacy when compared to other published results as well as developing a new pulsed shape of fields from such system, and in addition perhaps capturing an image with evidence of the turn around effect known in such systems.

The work described was supported by the EPSRC and the MoD through their Joint Grant Scheme (Research Grant GR/R 44645).
The harnessing and application of magnetic fields plays a pivotal role in many modern day situations, from simple stepper motors used in the vast majority of mechatronic equipment through to the power generators and high voltage AC transformers employed in power supply systems. Magnetic fields also find application in many further sectors, such as Magnetic Resonance Imaging (MRI) within the medical industry, or more recently in the utilisation of Pulsed Electric Fields (PEF) as a treatment in the inactivation of microorganisms within the food production sector (Beveridge et al. 2003).

Recent research has shown strong interest in the application of relatively intense magnetic fields in solid state physics (Muir et al. 1984, Matsuda et al. 2002) as well as in recent proposals for magnetised plasma target fusion (Frese et al. 2004) and possibly high-energy nuclear physics (Herlach et al. 1971). Further recent developments have detailed an interest in using such magnetic fields as a basis for the development of unconventional radiation emitters (radio, microwave and X-ray) (Novac and Smith, 1997, 2002) primarily for the use in defence projects. Significant limitations however exist when the production of continuously high magnetic fields are attempted; both thermal effects due to Joule heating and large magnetically induced pressures inevitably lead to structural deterioration of the system. In certain circumstances the effect of excessive heating can be alleviated by the use of heat sinks or overcome by employing superconducting technology to minimise the resistance (Wood and Montgomery, 1967, Herlach and Jones, 1994, Maeda et al. 1996). Furthermore, new composite materials and reinforced structures can be used to increase structural integrity (Foner, 1986). However in the quest for very high flux densities, the magnetic pressure induced in any given component has the potential to exceed its constitutive yield strength and hence lead to failure of the system. For this reason, only pulsed...
magnets can constantly extend the boundaries and achieve 'ultrahigh' magnetic fields.

2.1 Pulsed Magnets

Pulsed electromagnets can loosely be separated into two categories; destructive and non-destructive. In their simplest form they generally share a common toroidal topography, whereby large currents are passed around a loop as a means to establish a central axial magnetic field, as highlighted in Figure 2.1.

![Figure 2.1. Topography of a pulsed magnet](image)

The power supply for the current is generally either a battery on a rectified AC source or the stored energy in a capacitor, whereby the volume of utilisation is substantially the bore at the centre of the coil. Either multiple turns of the conductor, reinforced for insulation and structural resilience, or a simple single turn of conductor, or coil, provide a path for the current $I_C$. The magnetic pressure impressed upon the inner surface of the coil is a function of the axial flux density, and can be expressed simply as:
\[ p = \frac{B_z^2}{2\mu_0} \quad \text{Eq. 2.1} \]

At a flux density of 100 T, the pressure exerted on the inner surface of the magnet reaches almost 4 GN/m². This is close to the yield strength of the strongest known materials and, as such, this level of flux density marks the boundary between destructive and non-destructive systems. As a point of reference AISI® 1050 Steel, as rolled, has a yield strength around 415 MN/m² and an ultimate strength of 620 MN/m², corresponding to magnetic flux densities of 32.3 T and 39.5 T respectively. Clearly achieving high magnetic fields in a repetitive pulsed system (i.e. non-destructive) is extremely difficult and in order to make headway in such high field developments, repetitive pulsed systems must take advantage of both structural and thermal inertia. The pulse duration in such systems will therefore generally be of the order of a few milliseconds, with the hope of a lifespan of several hundred discharges being targeted.

Success in producing repetitive pulsed magnetic systems has come from the development of composite coils, constructed for robustness with multiple layers and employing the latest materials and engineering aids. Such coils are often used to produce magnetic field in the region of 70 T in experiments (Helrach, 1999).

In contrast to these "repetitively" pulsed magnetic systems, with a pulse duration of perhaps milliseconds, pulsed magnets that can develop over 100 T are always destructive and flux densities above this threshold are termed 'ultrahigh' magnetic fields. Due to the extreme magnetic pressures induced, it is important again to rely on structural and thermal inertia to ensure that the 'ultrahigh' magnetic field is developed before the arrangement has had time to destroy itself. Pulse durations of 'ultrahigh' magnetic field systems tend to be much less than those of repetitive systems, with durations often in the region of microseconds rather than

* American Iron and Steel Institute – a trade association.
milliseconds. In each instance, pulsed magnetic that produce over 100 T are generally termed "single shot" magnets, surviving only one discharge.

2.2 Single Turn Coil Systems

The Single-Turn Coil (STC) technique is possibly the simplest pulsed ultrahigh magnetic field system, and consists of a single turn of conductor in the topography of Figure 2.1. In order to achieve a very large current, and as a consequence an ultrahigh magnetic flux density, only a single turn of coil is used so as to minimise the inductance, with the energy for the system being supplied from a large capacitor bank with a transmission system designed to deliver in the order of millions of amps into the coil. Figure 2.2 presents a typical STC arrangement, as initially first developed by Furth et al (1956, 1957) and further developed by Herlach and McBroom, 1973, Portugall et al, 1999, Novac and Smith, 2002.

In this arrangement switch S is closed when the high energy capacitor bank C is charged to an initial high voltage $V_0$, which discharges the electrostatically stored energy into the coil through the flat parallel-plate transmission line of inductance $L_T$ and resistance $R_T$. The resulting current $I_C$ rises very rapidly, and eventually produces an ultrahigh magnetic flux density at the centre of the STC. Insulation, which may be provided by
Mylar polyester film, separates the two plates of the transmission line and powerful clamps restrict their movement during the capacitor discharge. Either magnetic pick-up probes or Faraday rotation sensors are used to provide a signal recording the time change of the flux density along the central axis of the STC.

If we assume firstly that the STC is constructed from a homogenously conductive material, then the discharge current \( I_C \) will have a tendency to travel along a path in which it can travel the least distance, i.e. the inner surface of the coil. The height (i.e. the axial length) of the coil must be assumed to be sufficiently short for the current to be assumed uniform along this inner surface, and there must be negligible change in the radius of the coil during the time up to peak field. The magnetic flux density \( B_z \) at the centre of the coil can then be approximately evaluated from:

\[
B_z = \frac{\mu_0 I_C}{2r} \quad \text{Eq. 2.2}
\]

where \( r \) is the inner radius of the coil and \( \mu_0 \) is the permeability of free space. As can be seen, the maximum central flux density is directly proportional to the current circulating in the coil, and inversely proportional to the radius of the bore. In order to achieve ultrahigh magnetic fields it is clearly important that the overall inductance remains extremely low during initial discharge, so that the time rate-of-change of current is as high as possible and the ultrahigh magnetic field is produced before the system has an opportunity to destroy itself.

Although Equation 2.2 is a good general rule of thumb, it is true that the reality of the situation is somewhat different. As this current \( I_C \) flows, the heat capacity or thermal absorption of the coil plays a role in assisting current migration due to magnetic diffusion from hotter areas to cooler (less resistive) areas as Joule heating takes effect. The current then moves away from the inner surface, and thus effectively increases the radius of the current circulating in the STC even if the geometry of the STC
remains unchanged. Moreover, as the discharge continues the electromagnetic stress associated with the magnetic diffusion process causes the STC to expand rapidly outwards, resulting normally in the maximum central flux density being achieved before the maximum discharge current has been reached. In this circumstance the STC is said to be over-driven, whereas one in which the current and flux density peak at the same time is considered as under-used (Herlach, 1999).

It is clear that complicated analytical tools are necessary in order to understand the complex interactions that occur within any STC experiment. Various computer modelling techniques have been developed for such situations (Nakao et al., 1985, Muira and Nakao, 1990), with perhaps the most successful to date being refined at Loughborough (Novac [1] et al., 2004) However even with these techniques certain assumptions and simplifications are required that limit the development of future STC systems.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Voltage, kV</td>
<td>20</td>
<td>40</td>
<td>60</td>
<td>25</td>
</tr>
<tr>
<td>Energy, kJ</td>
<td>55</td>
<td>100</td>
<td>180</td>
<td>18</td>
</tr>
<tr>
<td>Inductance, mH</td>
<td>14</td>
<td>18</td>
<td>14</td>
<td>18</td>
</tr>
<tr>
<td>Resistance, mΩ</td>
<td>6</td>
<td>3</td>
<td>2</td>
<td>7</td>
</tr>
<tr>
<td>Inner Rad, mm</td>
<td>1.25</td>
<td>1.5</td>
<td>2.5</td>
<td>1</td>
</tr>
<tr>
<td>Outer Rad, mm</td>
<td>3.35</td>
<td>3.5</td>
<td>5.5</td>
<td>2</td>
</tr>
<tr>
<td>Height, mm</td>
<td>5</td>
<td>4.1</td>
<td>5</td>
<td>2</td>
</tr>
<tr>
<td>Material</td>
<td>Cu</td>
<td>Ta</td>
<td>Cu</td>
<td>Cu</td>
</tr>
<tr>
<td>Peak Current, MA</td>
<td>1.3</td>
<td>1.75</td>
<td>2.9</td>
<td>0.9</td>
</tr>
<tr>
<td>Rise Time, µs</td>
<td>1.6</td>
<td>1.6</td>
<td>1.2</td>
<td>1.1</td>
</tr>
<tr>
<td>Flux Density, T</td>
<td>200</td>
<td>275</td>
<td>310</td>
<td>245</td>
</tr>
<tr>
<td>Efficiency², 10² Jb/s</td>
<td>1.78</td>
<td>1.94</td>
<td>3.58</td>
<td>4.28</td>
</tr>
</tbody>
</table>

* Magnetic flux produced per Joule of electrostatic energy

Table 2.1. Performance of experimental STC to date

Since studies were initially reported in the early 1950’s (Furth et al. 1956, 1957) STCs have been used in experimental applications at various

As has been demonstrated by Forster and Martin (1967) the ability to reduce the overall inductance and the resistance of the system is as important, if not more so, than the total initial energy in the capacitor banks. It was furthermore shown that the general construction of the coil played an influential role in the effectiveness, with smaller, flimsier coils being more productive than larger, heavier ones. This was believed to be due primarily to spreading of the current in the sidewalls of the coil. In 1969 Shearer showed that 355 T could be produced in such a manor.

As an interesting comparative tool, the efficacy of each systems serves to indicate the magnetic flux produced as a function of the energy input, which in the results detailed in Table 2.1 is by stored capacitive means. As can be seen, the efficacy of the system developed at Loughborough is almost 27% higher than the alternative results.

2.3 Magnetic Flux Compression

An alternative to the STC technique for the production of ultrahigh magnetic fields is to employ magnetic flux compression devices, and in particular magnetic pinch systems. All magnetic flux compression devices work on the same principal, and rely on a conducting, moving actuator to
compress an existing magnetic field. By (ideally) using a material with an infinite conductivity, magnetic diffusion will not occur through the actuator and the initial magnetic field will compress, thus giving rise to the possibility of ultrahigh magnetic flux densities. However, there are no such materials, and finite resistivity is a property of every conductor. As a result, flux compression is only possible when the speed of the moving actuator exceeds that of the magnetic diffusion back through the device. Numerous magnetic pinch systems are based on this approach and succeed in producing ultrahigh magnetic flux densities.

2.3.1 Θ-Pinch Explosively Driven Flux Compression

In the early 1960s magnetic flux compression by explosively driving an actuator was reported as a research tool by Fowler et al (1960). This implosive technique was achieved by using a metallic cylinder with an initial radius of $r_0$, a thickness $d$, and an axial height $h$, with the outside of the cylinder being surrounded by explosives that, once detonated, were arranged to cause the inward implosion of the metal liner; the cylinder being given the term 'liner' as it lined the inside of the explosive package. In addition, an initial axial field was generated by discharging a current into a coil located along the axis of the liner.
Figure 2.3 details the experimental set-up that was used and for clarity only a cross section of the complete cylindrical liner and corresponding explosives is illustrated. In this Figure the initial axial magnetic flux density, $B_z$, is produced by discharging the capacitor bank $C$ by triggering a three-electrode spark gap, although any switching mechanism may be used. At some predetermined time (after the initial field has reached its desired value) the cylindrical ring of explosives is detonated, with the subsequent implosion causing the liner to accelerate inwards and compress the initial magnetic flux $B_z$. The rate-of-change of magnetic flux density at the centre of the liner may be recorded, for example by means of magnetic pick-up probe, whereby the magnitude of the final field produced is indicative of the initial field, or 'seed field' used in the arrangement. As an alternative to using a wound coil to generate the seed field along the centre axis, it is also possible to generate an initial axial field by using a pair of Helmholtz coils. Figure 2.4 details the cross-section of such a configuration.
This configuration clearly has the advantage that the implosion may continue until a lesser radius, as the liner is not hindered by the initial field coil used in Figure 2.3 as it compresses toward the central axis. In either case, the initial magnetic fields are generally transient, with associated build up times before the explosive detonation. A machined slot along the length of the liner prevents the built-up of transient currents occurring within the liner before the implosion. This slot is generally insulated by tape, and effectively opens the closed loop circuit of the liner. However during the implosion the insulation is overcome by the force of compression between the two edges of the gap and perfects a conductive path around the liner.

If it is considered for analytical purposes that the axial length of the liner is much greater than the uniformly imploding radius, it is possible to derive an expression for the magnetic flux compression with the change in radius of the liner.
By considering the compression shown in Figure 2.5, the magnetic flux density at time $t$ can be shown to be:

\[ B_z(t) = B_{z,\text{init}} k \left( \frac{r_{\text{init}}}{r(t)} \right)^2 \]  

where the liner radius is $r(t)$ and $k$ can be termed the flux conversion coefficient - a coefficient used to account for losses in the system and thus to indicate the efficiency of the compression. As discussed above, flux compression will in reality only take place while the time rate of change of radius is greater than the rate of diffusion back through the liner. Thus an effective cylindrical flux compression device will have a compressive speed very much in excess of the diffusion speed. The magnetic flux lost in such an implosion can be derived from the diffusion speed (Knoepfel, 1970):

\[ v_{\text{diff}} = \frac{E_\theta}{B_z} = \frac{J_\phi}{\sigma B_z} = \frac{1}{\mu_0 \sigma} \frac{1}{B_z} \frac{\partial B_z}{\partial r} \]  

where $E$ is the electric field, $J$ is the current density and $\sigma$ is the conductivity. The speed of implosion can be simply deduced from the time rate of change of radius:

\[ v_{\text{imp}} = -\frac{dr}{dt} \]
and the total magnetic flux confined by the cylindrical liner is:

$$\Phi = B_z \cdot \pi \cdot r^2$$  \hspace{1cm} Eq. 2.6

The time rate of change of flux is therefore:

$$\frac{d\Phi}{dt} \cdot \frac{d}{dt} \left( B_z \cdot \pi \cdot r^2 \right) = -E_\theta \cdot 2 \cdot \pi \cdot r$$  \hspace{1cm} Eq. 2.7

giving the time rate of change of flux density as:

$$\frac{dB_z}{dt} = -\frac{2}{r} \left( \frac{dr}{dt} \frac{E_\theta}{B_z} \right) B_z$$  \hspace{1cm} Eq. 2.8

If we now introduce the rate of implosion from Equation 2.5 and the rate of diffusion from Equation 2.4 we obtain:

$$\frac{dB_z}{dt} = \frac{2}{r} \left( v_{imp} - v_{diff} \right) B_z$$  \hspace{1cm} Eq. 2.9

While the inward implosion velocity exceeds the diffusion speed, the RHS of Equation 2.9 will remain positive, and hence magnetic flux compression will occur.

The rate at which the magnetic flux diffuses will vary as current is induced, due to the diffusion process itself. As this occurs Joule heating will inherently take place, altering the conductivity of the liner and therefore the rate of diffusion. In cylindrical geometry the rate of diffusion is (Herlach, 1968):

$$\frac{\partial B}{\partial t} = \frac{1}{\mu_0 r} \frac{\partial}{\partial r} \left( \frac{r}{\sigma} \frac{\partial B}{\partial r} \right)$$  \hspace{1cm} Eq. 2.10
During an implosion, the speed of compression will vary due to the fact that the liner is being accelerated by an explosive force, and the acceleration is limited by the inertia of the cylinder and the structural integrity. Furthermore if we consider again Equation 2.1, it is evident that as the field is compressed, and magnetic diffusion induces a current on the inner surface of the liner, an outer radial magnetic pressure will begin to oppose this inward implosion. It is possible that at some point in the final stages of the implosion the compressed field will reach such a value as to overcome entirely the motion of the liner. This compressed field thus causes the liner to decelerate and, if forces continue to act to a suitable extent, potentially change the direction and begin to expand back outwards radically, with the change in direction of motion being termed 'turn-around'. (Knoepfel, 1970)

Explosively driven flux compression devices have achieved the record magnetic flux densities in the order of 2800 T (Bykov et al, 2001). However this was produced by a configuration involving a system of 'cascades' as discussed later in section 2.5.

2.3.2 θ-Pinch Electromagnetically Driven Flux Compression

Although explosively driven flux compression devices have been demonstrated as being very good at generating ultrahigh magnetic fields, they can prove awkward to use in many laboratory conditions, primarily as explosives are required. Special facilities are often required in order to accommodate such experiments, as well as a continuing supply of new components to replace those inevitably destroyed during each experiment.

In 1966, Cnare (1966) became the first to report that ultrahigh magnetic fields could be developed by using an Electromagnetically Driven Flux Compression (EMFC) technique. A typical EMFC system is shown in Figure 2.6.
Figure 2.6. Electromagnetically driven flux compression arrangement

As before, a capacitor bank is used to supply energy to the coil via a transmission system similar to that described for the STC, wherein large flat transmission plates provide a low inductance path for the discharge current. Figure 2.6 shows the EMFC comprising Helmholtz coils arranged to provide the seed field. The coils as shown can be energised by a high-powered battery system, or by a supplementary capacitor bank. In either case it is common for the seed field produced to be considered as constant when compared to the duration of the experiment. In a manner similar to that of the STC system, the large capacitor bank is charged to an initial voltage $V_0$. Switch $S$ is then closed and a large current $I_C$ circulates around the outer 'driving coil'. Placed concentrically with this driving coil is a conducting liner, similar to that described for explosive compression. When the capacitor bank is discharged, the transient current $I_C$ in the driving coil induces a current $I_L$ in the opposite direction in the inner liner. These two opposing currents give rise to a repulsive force, and with the inner liner being structurally weaker than the outer coil it collapses inwards. This mechanical action is analogous to that which occurs in the explosive arrangement detailed above, although it is the repulsive force induced by opposing currents that assists the compression.

In 1966 Cnare (1966) also discovered that flux compression occurred even if no initial field was used, and that ultrahigh magnetic fields could be generated even without using a seed field. Experiments of this simplified
type are known as Cnare Effect experiments. As the capacitor is discharged, current is again induced in the liner, but before the liner has accelerated, some of the field generated by the outer coil has diffused through the liner into the inner bore of the experiment. As the inner cylinder then begins to implode, and is imploding at an increasing rate, it is this field that is compressed by the moving liner to result in a pulsed ultrahigh magnetic field.

Various laboratories have reported the generation of pulsed ultrahigh magnetic field by means of EMFC, both without production of an initial seed field (Cnare, 1966, Alikhanov et al [1], 1967, Kachilla et al, 1970, Mikhkel’soo et al, 1974, Muira et al, 1975, Novac et al [2], 2004) and with production of an initial seed field (Cnare, 1966, Muira et al, 1984, Muira et al, 2001, Novac et al [2], 2004). Table 2.2 details some of the highest published results to date without seed field, while Table 2.3 shows the best of the published result with seed field. The table also includes the combined capacitive energy requirements for each system, i.e. the combined energy of the driving coil bank and the seed field bank.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Capacitor Energy, kJ</td>
<td>136</td>
<td>700</td>
<td>27</td>
<td>92</td>
<td>285</td>
<td>63</td>
</tr>
<tr>
<td>Magnetic Probe Diameter, mm</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>1.6</td>
<td>2</td>
<td>2.45</td>
</tr>
<tr>
<td>Flux Density, T</td>
<td>210</td>
<td>143</td>
<td>120</td>
<td>340</td>
<td>120</td>
<td>230</td>
</tr>
<tr>
<td>Efficacy*, 10^4 mTms/3</td>
<td>0.49</td>
<td>0.06</td>
<td>1.39</td>
<td>0.74</td>
<td>0.13</td>
<td>1.72</td>
</tr>
</tbody>
</table>

* Magnetic flux produced per Joule of electrostatic energy

Table 2.2. Performance of EMFC without seed field
Electromagnetically driven flux compression devices have achieved the highest indoor magnetic flux densities (i.e. in laboratory applications) of over 620 T. These were produced as part of a program undertaken by the Institute of Solid State Physics (ISSP) in Tokyo, and are detailed in column 3 of Table 2.3.

Again, in both Table 2.2. and Table 2.3 the efficacy of the systems has been evaluated. In each case the results provide by Loughborough show a substantial increase over the next closest results.

2.3.3 Z-Pinch Electromagnetically Driven Flux Compression

Although in the early 1960s it was common to use explosively driven flux compression techniques, as discussed these were obviously unsuitable for laboratory experiments. In contrast, as presented above, flux compression by using magnetic pressure can be applicable as a laboratory tool in the production of ultrahigh magnetic fields. This style of magnetically driven compression detailed above was termed Θ-pinch, derived from the direction of the circulating currents in the driving coil and liner.
However, in 1967 Alikhanov (1967 [2]) detailed an alternative laboratory arrangement in which axial currents drive the compression. This type of flux compression system is termed Z-pinch, with this name again derived from the direction of current acting in the system. Figure 2.7 shows a typical Z-pinch EMFC.

![Z-pinch Flux compression diagram](image)

Figure 2.7. Z-pinch Flux compression

In contrast to the $\Theta$-pinch experiment, a large capacitor bank is discharged to cause a large current to flow through an outer cylinder or coil and then back through an inner liner, with the coil and the liner separated axially by a layer of insulation.

The outer coil is constructed such that it retains its structural and electrical integrity during the discharge, however the liner is considerably more flimsy. During the experiment current flows in the opposite sense in the outer coil and the inner liner resulting in the implosion of the liner. As the compression occurs, the liner slides down the angled electrodes to maintain the circuit. In Figure 2.7 the initial seed field is supplied by the external initial field coil, with the current producing the seed field circulating around the central axis of the implosion.
In order to assist the compression and to maintain contact with the electrodes, it is often preferred that the liner is in a plasma state during the compression. This requires considerable energy, as the plasma formation has to be achieved under extreme magnetic pressures. In order to assist this an exploding array of wires often replaces the complete liner to improve this process during implosion.

The principle application of Z-pinch flux compression is predominantly used in investigated such activities as inertial confinement fusion (Frese et al, 2004). Such compression experiments have also been conducted at various American National laboratories as a continuing part of the National Ignition Project (NIP) (Lawrence Livermore National Laboratory, 2006)

### 2.4 Flux Compression using Flux Concentrators

During implosion of metal liners, whether explosively or electromagnetically driven, deformation of the liner and the resulting compression of the magnetic field liner play an important role in the maximum field that can be generated. In many implosions, liner instabilities arise as a result of the large magnetic pressures that are generated and the extreme temperatures which may cause localised melting and possibly vaporisation. It has been well documented that during Θ-pinch EMFC the lack of complete symmetry of the driving coil can cause 'jetting' of the liner in the final stages (Matsuda et al, 2002). That is to say that the gap in the driving coil, however small, may give rise to an inhomogeneous magnetic field distribution between driving coil and liner. This results in a non-uniform compression of the liner with the area near to the gap not having the same compression as elsewhere. The resultant, non-uniform, compression potentially reduces the flux compression effect. The axial view of Figure 2.8 illustrates a typical problem where clearly the liner has become deformed due to the lack of symmetry of the driving coil.
To overcome this and to improve the implosion characteristics of the liner, flux concentrators as illustrated in Figure 2.9 have been employed.

A flux concentrator works by introducing a conductor into a specific region where it is desirable that the field is shaped. The orientation of the flux concentrator in Figure 2.9 matches that in which it would be used in Figure 2.6, although the images are not to scale.

The two semicylindrical components of Figure 2.9(a) (*Herlach and Knoepfel, 1965*) are placed round the pick-up probe at the centre of the
implosion, ensuring that there are no paths for eddy currents to be induced in the seed field. As the liner compresses, its edges become distorted due to pressure and heating effects, whereby the concentrator is intended to alleviate the corresponding inhomogeneous field by providing a region in which in the final stages of implosion the inner surfaces are smooth. However in practice the concentrator failed to improve the peak field attained, possibly due to flux being trapped between the rippled edges of the liner and the concentrator.

By contrast, Figure 2.9(b) (Matsuda et al, 2002) shows a flux concentrator specifically designed for use with electromagnetic driven flux compression. It is positioned between the liner and the driving coil and smoothes the magnetic field between them. It is important that it is isolated from both and also that it is constructed so as not to generate circulating current by induction in the presence of the magnetic field. When employing such flux concentrators, flux densities over 620 T were achieved in a volume 26.5 mm².

2.5 Flux Compression using Cascades

During flux compression experiments, containment of the axial magnetic field plays a destructive role on the inner surfaces of the liner. As diffusion occurs, Joule heating will often result in plasma formation, i.e. melting. Combining these thermal effects with the extreme structural transient pressures means that the inner region of the coil may deteriorate dramatically, with the severity of these instabilities playing a role in the uniformity of compression during the later stages. In many instance this can lead to a 'petalling' effect on the inner edges, which has dramatic results on the effectiveness of the system. These instabilities are often referred to as Magneto-Raleigh-Taylor perturbations (Knoepfel, 1970).
If the inner edge of the liner is dramatically ragged then, as the compression reaches its final stages, the magnetic flux will not be as centrally concentrated as expected. Figure 2.8 contrasts an ideal implosion, complete with one in which the inner edge has become typically distorted.

![Figure 2.10. Final stages of compression, (a) distorted inner, (b) ideal inner](image)

As can been seen from Figure 2.10(a), as the instabilities intrude into the final volume, and subsequently cause the destruction of the central probe or test piece, the overall area remain larger than that shown in Figure 2.10(b). When we consider Equation 2.3 it is immediately apparent that Figure 2.10(b) is the more effective.

In order to overcome this problem, a solution using cascaded liners has been employed (Pavlovskii et al, 1980, Bykov et al, 2001). Figure 2.11 shows the cross section skeleton of an explosively driven flux compression experiment, using two cascades. For clarity, the initial field arrangement is omitted from Figure 2.11.
In the above diagram the liner begins to collapse due to the pressure created by the explosives, resulting in the magnetic flux compressing. After some time the inner surface of the liner makes contact with the first cascade, a metal conductor, which has the effect of smoothing the inner surface while continuing to compress the flux. The new inner area of the liner also gives a path of good conductivity, as it has yet to be heated. After further compression, contact is made with the second metallic cascade. This alleviates any instabilities now arising in on the inner side of the first cascade, and again improves conductivity.

The ability of the cascade system to achieve a more uniform implosion produces an approximation to the liner shown in Figure 2.10(b). As detailed earlier, the largest magnetic flux density of 2800T produced to date has been by explosively systems employing cascades (Bykov et al, 2001). In this instance each cascade was provided by an array of thin axially positioned wires embedded in epoxy resin, in which circulating currents were prevented until the driving force of the outer liner compacted the cascade into a conducting item.
2.6 Shock waves in Pulsed Ultrahigh Magnetic Field Systems

In many ultrahigh magnetic field systems steep pressure gradients are inevitable. This is especially true during explosively driven flux compression, wherein the driving actuator relies upon the progression of a rapidly moving pressure gradient within an explosive substance, which in turn causes the chemical reaction under pressure that propagates the explosion. Velocities developed by explosive means however are inherently restricted by the rate of reaction within the explosive, although special techniques such as shape charges have enabled this to be exceeded.

Similarly, experiments intended to develop ultrahigh magnetic fields can also generate very large pressure gradients. Consideration of the results given in column 1 of Table 1 enables a simple analytical deduction to be made as to the transient pressure gradient experienced on the inner surface of the STC. Use of Equation 2.1 shows that the transient pressure would potentially have reached 16 GN/m$^2$ in a time probably less than a microsecond, and it is extremely probable that as a consequence shock waves were developed within the STC.

Shock waves only occur in compressible materials, and they rely on the fact that the speed of sound within a material is dependant on the change in density of a material with a change in pressure, or:

$$c_0 = \sqrt{\frac{dP}{d\rho}} \quad Eq. \ 2.11$$

Where $c_0$ is the speed of sound within the medium, $P$ is the pressure and $\rho$ is the density. As a pressure gradient is applied to a compressible material, the pressure wave is propagated at the speed of sound in the material. However, application of this pressure will normally take the form
of a pulse, so that initially the material experiences a low actuating pressure that progressively increases. As the speed of sound is larger for a greater difference in pressure, the tail of this wave may 'catch up' at some point into the material with the previously propagated wave produced by the lower pressure. When this occurs a large pressure and density front is established, termed a shock wave.

2.6.1 Equation of State in Shock waves

The equation of state for any material can be approximated by consideration of a perfect gas under quasistatic load conditions by the expression:

\[ PV = mRT \]  \hspace{1cm} \text{Eq. 2.12}

where \( P \) indicates pressure, \( V \) is volume, and their product equates to the temperature \( T \) of the material times the gas constant, \( R \) and the molar mass, \( m \). That is to say that the pressure, specific volume, temperature, and specific internal energy of any given material are interrelated. For many material tables have been established to predict the behaviour under these conditions.

Hawke et al (1972) detailed the criteria under which a shock wave is likely to exist and it is possible to determine the equation of state in these instances using the Rankine-Hugoniot shock jump equations (Herlach, 1968) that rely on the conservation of three fundamental properties; mass, momentum and energy. When the pressure wave shown if Figure 2.2 is applied to a surface a material a shock wave is produced that propagates with a shock velocity, \( v_s \) with the material behind having a particle velocity \( v_p \). Mass density \( (\rho) \), pressure \( (P) \), and energy density \( (e) \) are varying properties of the material either side of the shock front.
Properties ahead the shock front, in the resting material, are given the affix ‘0’. Using this nomenclature, the three Rankine-Hugoniot equations can be written as:

Conservation of mass:
\[ \rho_0 (v_s - v_{p0}) = \rho (v_s - v_p) \]  \hspace{1cm} Eq. 2.13

Conservation of momentum:
\[ P - P_0 = \rho_0 (v_s - v_{p0}) (v_p - v_{p0}) \]  \hspace{1cm} Eq. 2.14

Conservation of energy:
\[ P v_p - P_0 v_{p0} = \rho_0 (v_s - v_{p0}) \left[ (e - e_0) + \frac{1}{2} \left( v_p^2 - v_{p0}^2 \right) \right] \]  \hspace{1cm} Eq. 2.15

However if the particle velocity ahead of the shock \( v_{p0} \) is zero, and the pressure, \( P_0 \) in the material is ambient and insignificant in comparison with the magnitude of the shock pressure, then it is possible to simplify the above equations to:

\[ \rho_0 v_s = \rho (v_s - v_p) \]  \hspace{1cm} Eq. 2.16

\[ P = \rho_0 v_s v_p \]  \hspace{1cm} Eq. 2.17
\[ e - e_0 = \frac{1}{2} P \left( \frac{1}{\rho_0} - \frac{1}{\rho} \right) \]  

\text{Eq. 2.18}

for a perfect gas, the equation of state is:

\[ P = \rho (\gamma - 1) e \]  

\text{Eq. 2.19}

where \( \gamma \) is the adiabatic constant, and if a compressible metal that has infinite conductivity, then it is possible to derive an expression for the shock velocity and particle velocity by applying a constant magnetic field. Combining Equation 2.17 and 2.1 (Knoepfel, 1970) gives:

\[ \frac{B^2}{2\mu_0} = \rho_0 v_s v_p \]  

\text{Eq. 2.20}

Using empirical data, it has been found that most metals follow the same linear velocity law;

\[ v_s = c_0 + S v_p \]  

\text{Eq. 2.21}

where \( c_0 \) is the speed of sound in the material at normal pressure and \( S \) is a constant of the material related to its compressibility. By combining these two functions an expression is obtained for the particle velocity based upon the applied magnetic field,

\[ \frac{B^2}{2\mu_0} = v_p \rho_0 \left( c_0 + S v_p \right) \]  

\text{Eq. 2.22}

By applying the simplified Rankine-Hugoniot equations it is possible to deduce other unknowns (Goh, 2001). Such work is outside the scope of this thesis and as such is not detailed here.
The above consideration given in Equation 2.22 is in relation to the application of a constant magnetic pressure and in most circumstances this is certainly not the case. Furthermore this consideration assumes an infinite conductor, whereby in reality a material with finite electrical conductivity will be used. The solution in this case will become more complex, with the pressure gradient being applied to a skin depth. The exact calculation of such field/pressure distribution can only be done numerically using a complete magneto-hydrodynamic code. However various numerical results (Knoepfel, 1970) show that Equation 2.22 provides a useful approximation to the particle velocity, and is particularly accurate when the pressure pulse rises and levels off as highlighted in Figure 2.12.

### 2.6.1.1 Shockwaves in Porous Metals

It has previously been shown that shockwaves can be employed to compress conductive region within porous materials and in particular porous metal in pulsed power applications (Nagayama, 1987). Previous work at Loughborough has also detailed the possibility of converting an insulting metallic powder, and in particular aluminium powder, to a conducting material by the means of shock loading (Goh, 2001, Novac et al, 2001).

In general particles of aluminium powder packed together will act as a relatively good insulator due to a thin layer of oxide coating. However, under shock loading, this coating is destroyed and the powder becomes compacted into a relatively good conductor. Previous work detailed the complex electromagnetic phenomena involved when the electrical conductivity is to be measured during the change of the powder from insulator to conductor and the data obtained suggests an almost instantaneous transition mechanism (Gilev, 1994, Gilev and Mihailova, 1997).
Although various hypotheses had been advanced, a basic understanding of the mechanism by which the transition occurred was not however possible until the speed of the transition was continuously and reliably monitored. The results published at Loughborough clearly indicated that the mechanism responsible for destroying the insulating oxide coating is a fast, low pressure, elastic precursor moving ahead of the main high-pressure shock front (Goh, 2001, Novac et al, 2001).

Based on the findings of previous work, the mechanism of magnetic flux-compression inside a phase transition powder material can be viewed as a two-step process, and this phenomenon was first described by Nagayama, (1987).

The conclusions reached during the shock loading experiments on the nature of the mechanism responsible for the phase transition have very important consequences that relate to the design of future pulsed power apparatus, including such articles as powered cascades, used in EMFC experiments (as is discussed in further detail later in this Thesis).

2.6.2 Equation of State using SESAME database

During almost all ultrahigh magnetic field experiments, shockwaves are induced in the material due to the magnetic pressures and as a result the equation of state no longer follows simple perfect gas laws, but rather the Huguenot data. In addition, high energy phenomena means that typical data available for most materials over a standard range is no longer applicable at high temperatures, pressures etc. Several laboratories have achieved empirical and numerical data in such high temperature, pressure conditions, with perhaps the most renowned being the used by National Laboratories in United States (Lyon and Johnson, 1992, Desjarlais, 2001)

The SESAME database (Lyon and Johnson, 1992) maintained by Los Alamos National Laboratories, USA is a computer based library of tables
for thermodynamic properties of numerous materials. This library has been developed as part of a continuing investigation into high energy nuclear physics, and in particular in inertia confinement fusion (ICF) experiments.

The library contains data for more than 150 materials ranging from elements, to metals and compounds. Perhaps the most important aspects of the thermodynamic properties are that they are defined over a large range of temperatures and densities. For most materials in the library the EOSs are formed using various combinations of different theoretical models in different temperature/density regions, whereby the data is interpolated between these regions in an attempt to remain thermodynamically consistent. These models are also supported by empirical methods where possible.

The thermodynamic properties stored in the SESAME database include tables of pressure, P, energy E (and also in many cases the Helmholtz free energy A), each as a function of the density p and the temperature T. Besides these values, there is also prescribed such data as phase transitions, Hugoniot (shock and particle velocities), shear modulus, conductivity etc. Further details regarding material properties and methods used in deriving the models can be found in, "LA-UR-92-3407, SESAME: The Los Alamos National Laboratory Equation of State database" – a guide issued by Los Alamos. Investigation into this information is outside the scope of the current work.

Due to the nature of the work involved, access to, and use of the SESAME database is a privilege obtained via the Los Alamos National Laboratories. It is generally considered that the database is one of the most accurate of its type in the world today, even though its veracity is not commonly published.
2.7 Conclusion

As has been highlighted, only pulsed magnetic systems can produce ultrahigh magnetic flux densities, i.e. those exceeding 100 T. Such high flux densities are employed in solid state physics as well as magnetised target fusion, and more recently have been investigated for purpose as unconventional radio emitters at Loughborough. Two such systems have been developed which can produce such high fields, namely the Single Turn Coil technique and the Flux Compression technique. This thesis investigates the use of both the STC and θ-Pinch EMFC systems to generate these fields, as well as developing further such conditioning devices as cascades.
Ever more often, modern engineering is embracing the usefulness of powerful computers to solve complex analytical problems, and to provide solutions that previously were unachievable through a 'pen and paper' approach. This has led to a deeper understanding of many modern day phenomena, as well as being a fundamental driving force behind efficient product design and development. It would be extremely difficult today to imagine many successful engineering industries that at some level do not employ developmental simulation. This computational development process focuses upon engineering factors such as manufacturing efficiency, product lifespan, product effectiveness etc, all within a virtual simulation environment, thus simultaneously keeping development costs to a minimum, while quickly identifying potential problems and by accelerating innovation allowing for a reduction in overall 'time to market'.

Engineering simulation also finds application at many research institutes and it has recently revealed such unknowns as the behaviour of the geomagnetic poles and explained the necessity for dark matter in current models of the universe. Various computational techniques have been developed to solve many complex engineering problems, with perhaps one of the most well known being the finite element method.

### 3.1 The Finite Element Method

The finite element method is a numerical analysis technique for obtaining approximate solutions to a wide variety of engineering problems and a solution that uses this technique is termed Finite Element Analysis (FEA). The finite element method was first presented by Clough in 1960 and detailed work on plane stress in structural mechanical problems. This work built upon previously published methods (Turner et al, 1956) and was the beginning of the use of FEA in aerospace engineering. Although for many
years this industry, and in particular Boeing, employed FEA to develop stress analysis solutions, the finite element method has in recent years extended to all disciplines. In addition to structural mechanics, engineers use FEA to solve problems including; heat transfer, fluid mechanics, electromagnetics, biomechanics, geomechanics, and acoustics.

The finite element method is used in continuum problems where an unknown variable is to be evaluated (pressure, temperature, displacement etc). By resolving the complete continuum into a number of finite elements it is possible to develop an expression for the unknown variable as a function of each element. This approximating function is often termed an 'interpolation function' and is evaluated between 'nodal points' within each element. Figure 3.1 shows a typical element discretisation and the associated nodal positions. Thus the value of the unknown at node 'B' is a specified function of that at node 'A', depending upon the interpolation function of the element and the element properties.

![Figure 3.1. Finite element discretisation](image)

Although nodes are only shown at the vertices of the elements in Figure 3.1, it is also possible to have nodes at midpoints along the length of the faces. The discretisation shown in Figure 3.1 allows for linear interpolation, when using such "mid-sided" nodes helps develop 'quadratic' relationships. The field variable may therefore be scalar, vector or a higher order tensor. Often polynomials relationships are selected as interpolation
functions in quadratic elements because they are easy to integrate and differentiate.

Clearly, by the nature of this method, the solution is an approximation. How close it is to reality is dependant upon many factors, including the size and number of the elements, as well as the interpolation function and the accuracy of the element properties. In general there are seven definite procedures undertaken in order to derive a finite element solution (Cook, 1974) for a continuum problem, and these are briefly discussed below.

3.1.1 Procedures taken in constructing an FEA solution

3.1.1.1 Discretise the continuum

Firstly the continuum or solution region must be divided into elements and in Figure 3.1 triangular elements have been chosen for this purpose. Such elements may be employed to evaluated stress or temperature distribution, although a variety of shapes may be used depending upon the problem. In some cases, such as evaluating elastic components, it is not uncommon to use a number of alternative elements within one solution continuum. The selection of element types and the number of elements are often matters of engineering judgement. An area where the unknown variable is anticipated to have a high variable gradient across a region is discretised to a finer resolution.

3.1.1.2 Select interpolation functions

The interpolation function is defined as the relationship in 'unknowns' between nodes. If we consider two nodes, A and B in Figure 3.1, and assume that they are part of a structural elastic model, it is clear that a linear interpolation function will result in constant strain (and therefore stress) across the element. As discussed above, if the area of interest experiences a rapidly varying stress then a finer mesh should be used to
capture accurately this transition. However to improve the approximation within each element and to use a lesser number of elements it is also possible to use a 'higher order' interpolation function. This is achieved by allowing variables to vary quadratically, cubically, or with a higher power over the element, with higher-order functions often being facilitated by mid-side nodes along the element.

3.1.1.3 Implement the element properties

Once the interpolation functions, i.e. the relationship from one node to the next, have been established for each element and the mesh has been composed to provide an accurate representation of the solution area, the element properties can be derived. These comprise a series of matrix equations that express the properties of each individual element. Various techniques can be employed to derive these relationships, including: direct method, variational approach (Ritz method), and the method of weighed residuals (Galerkin Method).

The direct method is perhaps the simplest and was certainly the earliest methods for extracting the element properties for a FEA problem. However it only really finds application in simple voltage, structural, heat or fluid flow problems due to the simple linear relationship. It was initially developed for solutions with trussed elements or beams in structural mechanics. Once the elements have been established, it is possible to use direct physical reasoning to establish the element equations in term of the pertinent variables. Thus the displacement experienced at a node of a spring is proportion to the net force applied at that node and the stiffness of the element. Similarly, in a thermal environment the heat flow in a given direction at a node depends on the area, length, temperature difference and the thermal conductivity.

Both the Ritz method and the Galerkin methods are based upon variational calculus and are used to solve the governing partial differential equations (PDEs) of any physical problem, generally finding the conditions
that make some quantity (usually energy) stationary (i.e. a maximum or minimum). From variational calculus the quantity is termed the functional, which usually involves integration of the unknowns in the problem. The Ritz method involves seeking the solution to the governing PDEs by using a trial solution, that generally involves the use of a polynomial series solution for the unknown variables in the problem. Each term in the series is associated with an arbitrary constant which become the unknowns of the problem and can be obtained using the appropriate variational principle and minimising the functional.

The problem in many solutions beyond structural mechanics is that the Ritz Method does not operate directly on the PDE, but rather formulates the problem in terms of the variational principle. An alternative approximating solution is the Galerkin method, often termed the weighed residual method, which is derived directly from the PDEs of the problem without the need for minimising a functional. The PDE for a given problem is usually written as a differential equation with zero on the right-hand-side. Thus

\[ PDE = 0 \quad \text{Eq. 3.1} \]

where PDE represent the left hand side of a partial differential equation. The PDE can be used to provide a measure of the error or 'residual' of the approximation by substituting the trial solution and checking that the right hand side of the equation is as close to zero as possible. Therefore the residual of error can be expressed as:

\[ \text{Residual}(x) = PDE(\text{trial\_solution}) \quad \text{Eq. 3.2} \]

and the best solution is one which minimises the \( \text{residual}(x) \) function. Variation techniques to minimise the residual are used including the 'Collocation method', 'mean square error', and 'weight functions'.

3.1.1.4 Assemble the matrices
To find the properties of the overall system modelled by means of a network of elements, the element properties discussed above are combined into matrix equations that represent the entire system. When developing localised matrices, it is often simpler to define the parameters in a local co-ordinate system. If this is so, the co-ordinate system will have to be transformed to a global co-ordinate system prior to assemblage. These new combined matrix equations have the same form as the individual element matrices, although with more ‘unknowns’. This arises since at any node where elements are interconnected, the value of the field variable is the same for each element sharing that node, thus allowing a complete system of equations to be generated for each individual element equation. As a result of the connectivity of various components, the final matrix will exhibit certain features. Thus, when each element has only a few nodes compared to the overall nodes, and only a few elements share each node, then the final matrix displays ‘bandedness’ or ‘sparseness’. This means that the non-zero terms are clustered about the diagonal of the matrix.

3.1.1.5 Impose boundary conditions

Boundary conditions, or ‘prescribed variables’ are then imposed on the system. Boundary conditions are the nodal loads or constraints of the dependant variables that are known in advance and have a fundamental influence on the behaviour of the system. They can be forces in a structural model, or absorption boundaries in an acoustic model. In order to achieve a unique solution prescribed nodal values are required. In Figure 3.1 for example such boundary conditions may be to impose zero displacement on the outer nodes.

3.1.1.6 Solve the systems of equations

By assembling the matrix equation and including the boundary conditions it is possible to solve for the unknown nodal values in a problem. If the problem is static (in equilibrium) then a set of either linear or non-linear
algebraic equations has to be solved. If the problem is transient (time dependant) then a set of ordinary differential equations have to be solved. In most case computers are used to solve the vast matrix of equations, and various solving techniques have been developed to satisfy alternative problems and computing ability. Linear direct solves are robust solvers, however requiring more memory storage than a sparse solver. However a sparse solver will only be effective for a sparse matrix. As an alternative to the direct solver, iterative solvers such as the Preconditioned Conjugate Gradient (PCG) are available. Variations of the PCG family are the Jacobian, Incomplete factorisation, Multigrid, and Domain decomposition. While the PGC will converge quicker to a solution, most of the computational time is used in constructing the Preconditioner. Eigen solvers can be used for mode problems, and most non-linear analyses rely on Newton-Raphson approximation.

3.1.1.7 Derive additional unknowns for computational results

In many FEA problems the computed field variable at each node is used to establish further unknowns. For example, in a structural problem the computed nodal displacement can be used to evaluate the element stresses and strains. Similarly, within a thermal analysis the nodal temperatures are calculated, establishing the thermal heat fluxes across elements to be derived.

3.1.2 Composing a FEA solution

By employing the steps outlines above, it is possible to derive the solution to a finite element analysis problem. As discussed, most problems consist of a large number of field variables or 'unknowns' and as this leads to a large system of equations it is common practice to use computers to solve such analyses. Examples of such composed solutions are common and also detailed elsewhere (Henwood and Bonet 1996).
3.1.3 Higher order elements

In the most common use of finite element analysis, such as a simple truss example, each member is assumed to exhibit a linear relationship between each node and the interpolation function is thus linear. This means that the strain and therefore the stress evaluated is constant along the element. However in some situations, to achieve good accuracy in areas where the field variable is changing rapidly, it is necessary to develop a finer mesh. As a result it is common practice to use higher order elements, using "mid-sided" nodes to allow for a polynomial variation in the field variable across an element. Polynomial variation also assists in differentiation and integration of the element solution. Figure 3.2 depicts the variation in interpolation function across two elements, one linear, and the other quadratic;

![Figure 3.2. Interpolation functions](image)

Although fewer elements are generally required when using polynomial elements, this does not always reduce the computation time, since more accurate numerical methods, such as Gaussian quadrature (Gaussian-Legendre) need to be employed to evaluate the 'stiffness' matrix.

3.1.4 Non-linearity

Most real life materials exhibit non-linear properties, whereby the characteristics are not reversible when an applied loading is removed, or the material characteristics are dependent upon the solution. Furthermore, unlike linear analyses, non-linear analysis can be path dependent and the material can behave differently depending on the initial conditions and
recent solution history. Structural non-linearities are evident in any form of elasto-plastic behaviour, as well as in problems involving thermal radiation or magnetic hysteresis. Considering the example given by a simple truss solution, most metal will exhibit hysteresis beyond strains of a fraction of a percent of the Young's modulus. Thus in reality the stress-strain relationship in most instances is non-linear.

When evaluating non-linear properties the FEA solution can be determined over a series of closely iterative steps using special solvers. The Newton-Raphson technique is a well-known numerical method for evaluating non-linear behaviour. It operates by using a trial solution, then successfully improving the initial estimate by using a portion of the slope of the non-linear curve to gauge the offset. The resultant curve is an approximation constructed from a series of suitable tangents, as shown in Figure 3.3 for a typical non-linear curve.

![Newton-Raphson non-linear iteration](image)

Figure 3.3. Newton-Raphson non-linear iteration

The method uses the form:

\[ f(x) = 0 \quad \text{Eq. 3.3} \]

where the initial trial solution, \( x_{\text{initial guess}} \) is used. The next trial solution is estimated by using the slope of the curve at point \( x_{\text{initial guess}} \), such that:

\[ x_{i+1} = x_i - \frac{f(x_i)}{\frac{dy}{dx}} \quad \text{Eq. 3.4} \]
Iterations are performed until the solution is attained, to within a specified degree of accuracy, and the right hand side of the non-linear equation approaches zero. This technique clearly only works if the function is differentiable. Within FEA the achieved solution is also dependent upon the trial value and if the trial value is too far from the exact solution, the method may fail to converge. Furthermore if there is a change in the sign of the function, the method fails to gain a solution.

Other methods can also be adopted when evaluating non-linear behaviour and these include such techniques as the 'load incrementation procedure' and the 'iterative procedure'.

3.1.5 Steady state, modal, or transient analysis

Although steady state (equilibrium) analyses are common in simple direct method structural analysis, they are also extremely important in field analysis. Equilibrium field problems (evaluated using the variational principle, or method of weighed residuals) are time independent solutions that evaluate the spatial distribution of the field variable. Such equilibrium analyses are used to evaluate, for example, steady state temperature distributions, or torsion in an elastic structural member.

Alternatively model (Eigenvalue) problems evaluate problems in which the spatial field variable is frequency dependent. Eigenvalue problems encompass such FEA problems as structural vibration or bucking, as well as resonant acoustics and electromagnetic waves.

Transient (propagation) analyses are employed when the field variable is time dependent. They are most common in structural transients or diffusion, or wave propagation problems, when the solution generally reduces to the form:
\[ [M] \left( \frac{d^2 \phi}{(dt)^2} \right) + [C] \left( \frac{d\phi}{dt} \right) + [K] \phi = \{F(t)\} \]  

**Eq. 3.5**

where $\phi$ is the field variable. $[M]$ represents the inertia of the system, while $[C]$ represents the capacitance, or dampening of the transient analysis and $[K]$ is the stiffness matrix. The forcing function $F(t)$ may be harmonic, periodic, aperiodic, or random and in some problem the second order coefficients are zero. In systems where there is no loss of energy, the dampening coefficient is zero. In diffusion problems, such as thermal or electromagnetic, the problems reduce to a first order analysis, as the inertial coefficient $[M]$ is zero.

### 3.2 Using ANSYS code to solve FEA problems

Needless to say, FEA has proved to be an extremely useful tool when considering a broad range of engineering problems. As a result many codes are available as commercial software to facilitate engineering solutions, perhaps the best of these are predominantly transparent, and do not lend themselves to the 'black box' software approach. The advantage of the semi-transparent approach is that it is possible to implement FE solutions while maintaining control over how the program operates. The disadvantage is that these codes are often unfriendly, except to the engineering specialist, and calculated results may be erroneous without a basic understanding of the problem in question. Obviously commercial codes are not wholly transparent (or open source), and there remains a certain amount of propriety regarding the implementation of coding when considering interpolation functions, element properties, and solver capability. However the success, and proven accuracy of many top flight FEA codes allows engineers to rely on them as tools rather than having to develop in-house alternatives.
ANSYS is one such market leader, which was developed in the early 1970s (The Unofficial history of ANSYS, 2006) from a code used to predict transient stresses and displacements of NERVA nuclear reactor rockets due to thermal and pressure loads. Although originally developed for Fortran-77, it has evolved alongside a dramatic rise in computing ability over the past 30 years, and is able to be run on PCs and Unix machines. Today ANSYS is used by many leading engineering firms as a fundamental tool in product development.

As a software suite, ANSYS Multiphysics uses developed elements and interpolation functions that allow the user to develop FEA solution throughout structural mechanics, thermodynamics and electromagnetics (high and low frequency), as well as fluid dynamics, acoustics and explicit structural mechanics*. The ability to transfer information between each alternative solution environment allows the code to be able to represent a "multiphysical" environment, and it is possible to consider a problem that may be dependent upon more than one physical phenomenon.

In general most FEA codes can be dissected into three separate and individual components; Preprocessor, Solver, and Postprocessor.

**Preprocessor**

The purpose of a preprocessor is to generate an input file for the solver that must contain all the relevant data to define the problem. Within the preprocessor it is possible to generate a geometric model, and to implement material properties, perhaps from an external library. Using ANSYS®, it is also possible to import geometric drawings from various types of CAD file configurations, so that complex models may be generated in the most suitable software suite. Mesh generation to

---

* Explicit mechanics are used when solving fast transient structural mechanics, and use Equation 3.5. However while 'implicit' mechanics (as has been discussed) solve for $\Phi$, explicit dynamics solve for $d\Phi/dt$ (velocity), and then extrapolate the other data.
establish the element co-ordinates and associated nodal positions is the most time consuming part of the input file.

**Solver**

Within the solver, the input file is used to generate the various solution matrices. Different loads and boundary conditions are set as well as solver condition, such a convergence criteria for the Newton-Raphson method. Once the field variables have been solved and other associated 'unknowns' have been calculated they are produced as an output file.

**Postprocessor**

The postprocessor use the output file generated by the solver to display graphically the variation in field variable, and their associated components, as well as allowing the user to subsequently evaluate further variables.

These key stages are shown in Figure 3.4.

![Figure 3.4. FE code stages](image)
3.2.1 Implementing the analysis

ANSYS provides two separate ways in which the user can operate the code. The first is the graphical user interface (GUI) shown in Figure 3.5.

This window consists of two main areas. On the right hand side, the user is given a graphics window which allows the constructed problem to be viewed. This window can display either the solid (unmeshed) model or the FE (meshed) model. It can also be used when viewing graphically the output results.

In the left hand region of the window, the individual components as described above are shown. In this instance, extra components such as ‘Design optimisation’ are given, which is an added feature from ANSYS. In Figure 3.5, the ‘Solver’ component is opened to highlight some of the functions of the solution process. During an analysis the user is expected to follow sequentially through each required component, and to view
results in either the General Postprocessor (static or harmonic analysis) or in the Time History Postprocessor (transient analysis).

While the GUI is a user-friendly environment to interact with the FEA code, it can become cumbersome when considering complex problems. As discussed, the FEA code is developed and compiled in Fortran, and as such it is often necessary to implement programming. Therefore as an alternative to using the interactive GUI mode, it is also possible to generate a coded problem and compile the solution. This can be achieved using a "batch mode" analysis, that allows for much greater flexibility when developing engineering solutions. While the program is written in Fortran-77, ANSYS have developed a High Level Language (HLL) that can be used with greater ease and acts as an interface between the user and the lower level language. This type of programming language is called ANSYS Parametric Design Language (APDL) and it can be used to implement a solution while at the same time being able to use common programming functions such as Boolean expressions, arrays, loops, scalar and vector matrix operations. Within APDL the user relies upon the established elements (interpolations functions) etc that have been developed by ANSYS. However, if necessary, it is possible to read in user developed code. This is by far the most flexible method of using the commercial code.

3.2.1.1 Implementing the analysis in batch mode

Appendix A details such batch solution using a simple truss analysis. For reference, the complete batch code used can be found in Appendix B.

3.2.2 Using Multiphysics to solve complex engineering problems

As discussed above, very few engineering problems can in reality, be reduced to one physical phenomenon. The example of the truss member in Appendix A is one in which only a structural features need be taken into
account; however this type of example is generally the simplest and acts to serve as a guide to FE in ANSYS.

The majority of complex engineering problems however span several physical phenomenal, which may all play a vital role in the solution when interacting with each other. For example piezoelectric effects are a function of both electric field and structural displacement. General electric conduction is a function of temperature, and therefore it would be essential to combine both an electric analysis and a thermal analysis to fully represent the system. This can be achieved by employing a complete multiphysical analysis.

Within ANSYS there is the capability to solve engineering problems from various disciplines. Figure 3.6 depicts some of the various fields where there are functions in place to include information pertinent to other physical phenomena. One result of having the facilities to encompass so many engineering disciples is the capability to use a multiphysical approach. As discussed below, there are two alternative approaches to compiling a multiphysical analysis using ANSYS.

3.2.2.1 Coupled Analysis

The first of these multiphysical analyses is a directly coupled field analysis, whereby interpolation functions can be derived that consider variables
from alternative physical disciplines, such as thermo-electric. Various predefined element have been construct in ANSYS in order to facility a coupled physical analysis. By using such element function it is possible to solve an analysis by following the process detail in Figure 3.4. Details of numerous functions and their associated element can be found in ANSYS resources (ANSYS Release 9.0 Documentation, 2004)

3.2.2.2 Sequential Analysis

Sequential analysis is an alternative approach to direct coupling that works on the principle of having various, and separate, 'physical' environments, each representing a different physical phenomenon. The term physical environment relates to an individual preprocessor file created for use in one field, with a sequentially coupled analysis combining these different engineering disciplines to give a global engineering solution, where the input loads to one analysis are dependant upon the output loads of the previous solution.

3.2.2.2.1 One way sequential coupling

One situation in which sequential coupling can be used is where the reaction of the second field does not play a pivotal role on the behaviour of the initial field or can be considered negligible. An example of an analysis where one way coupling would be appropriate would be in a fluid/structural interaction, where the stresses are to be determined in the structure. Solving a fluid analysis would give pressure as a load to a structural analysis. If during the structural analysis, the body is considered to be displaced by a negligible amount, then this could be considered as not affecting the flow rate. Figure 3.7 depict the process of a one-way analysis having two separate physics environments.

It is important to note that each physical environment must be generated with the same number and location of DOFs. – i.e. the same element mesh must be used since the results from one analysis must be directly
transferable as loads to the nodes of the next. Transferable loads must also be consistent, i.e. nodal loads are applied on the nodes, element loads are applied on elements (body loads).

![Diagram](image)

Figure 3.7. One-way sequential Multiphysics analysis

### 3.2.2.2 Full sequential coupling

Full sequential coupling occurs in more complicated problems where the output of one analysis is used to predict the variation in the next, which in turn has an effect on the initial analysis. Full coupling can be directly used when finding equilibrium solution in such situations as electromagnetic induction, or to iterate transient solutions over time. Again, the same mesh must be used in each environment in order to facilitate load transfer, as well as the same regards for type of transfer. Figure 3.8 depict the process of a full sequential analysis having two separate physics environments:
3.2.2.3 Mesh Morphing

An extremely useful tool within ANSYS is its ability to morph the mesh between multiphysical analyses. During a combined physical analysis, it is possible that a structure may displace due to some other physical force (electromagnetic, thermal expansion etc). The process of morphing the mesh takes the calculated nodal displacements from a structural analysis, and updates the co-ordinates in all the relevant physical environments, ready for the next iteration.

3.3 Errors in FEA

As stated initially, a finite element method works by reducing a geometric model to an approximate number of finite elements. Clearly, there is an initial approximation of the model although the result achieved may be considered accurate if the solution is close to real life. FEA is not an exact solution and the scope for error when using it is numerous. Certain key areas for error are:
Modelling errors

Modelling errors occur when the geometry of the problem is not accurately modelled. This can arise in complex geometric problems where the boundary conditions are ill defined.

Mesh errors

Mesh errors can occur if a poor quality mesh is not adopted, and having a suitable mesh is perhaps one of the most important factors when considering FEA. Poor shapes and aspect ratios* can lead to poor results. Mesh density is often critical in key areas of problems, and without adequate resolution problems such as aliasing in harmonic field analysis, and stress concentration can be apparent.

Numerical errors

Numerical errors can be abundant in FEA, with rounding errors the most prolific. Large pivot errors and ill-conditioned matrices, where the coefficients of one row contain varying orders of magnitude can cause sensitivity to small changes in field variable, also causing numerical errors. Inaccurate interpolation functions can give erroneous results and nonlinear material properties can often be difficult to iterate.

3.4 Conclusions

The finite element method is a proven tool when solving engineering problems. Commercial packages such as ANSYS act as development aids without the requirement of the user developing FEA code or interpolation

* the ratio of one side of an element to the other
functions from first hand basis. Furthermore the use of batch mode coding development also allows a user to implement programming routines such as loops and Boolean operatives. As part of an investigative program, the veracity of ANSYS Multiphysics in simulating ultrahigh pulsed power applications will be evaluated.
When generating and investigating the effects of pulsed magnetic fields, a plethora of dedicated experimental equipment is required. Due to the extremely high voltages (some kV) and even higher currents that are often used (> MA) safety is paramount; safety for both the user and the equipment. This is achieved through critical design considerations as well as special measurement techniques.

4.1 Experimental Configuration

Throughout pulsed power experimentation, specifically designed equipment allows the generation and measurement of ultrahigh magnetic fields (> 100 T). This chapter details the components and arrangements used at Loughborough when developing a pulsed magnetic field by the STC and 8-Pinch Flux Compression techniques.

4.1.1 Energy Supply Systems

In most pulsed power applications considerable energy must be available for use within small factions of a second. As discussed in Chapter 2, it is common practice for this to be provided from either large capacitor banks or high-powered explosives.

It is possible to charge large capacitor banks slowly, then discharge them quickly, depending on the inductance of the system. This method is often favoured, as the overall systems are simpler. A large bank can be charged from the local grid through dedicated rectifying and isolating devices and it is this method of energy storage that is used. Figure 4.1 details such a charging arrangement.
Both switches shown in Figure 4.1 are pneumatically driven and both operate in a fail-safe arrangement. If the pneumatics fail the dump automatically closes and the isolator opens, both actuated by gravity.

When charging the bank, the isolator switch is closed and the dump switch is open. The load is therefore isolated from the capacitor by this specialised equipment, which allows the capacitor to be charged at a rate depending upon the charger used, the size of the capacitor, and the total system inductance. Before discharging the capacitor, the isolator switch is opened. Due to the magnitude of the energy stored in the capacitor, it is advisable to maintain this energy for only a short period of time (of the order of seconds). If for some reason the experiment is suspended, it is possible to discharge the capacitor through a special dump system into a dump, which is often a resistive load of water.

The capacitors used at Loughborough are designed specifically to store large amounts of energy for use in high-powered pulsed experiments. In general, a bank can be constructed in two different configurations. When charging in parallel, and discharged in series the result is a high voltage output and the configuration is termed a Marx generator. When charged in parallel and discharged also in parallel, the output is a large current. As discussed in Chapter 2, large currents facilitate large magnetic fields and therefore it is parallel charging/discharging banks that are normally used.
From Figure 4.2 it can be seen that the total capacitance of the bank is:

\[ C_{\text{bank}} = \sum_{n=1}^{N} C_n \]  

so that the total available energy is:

\[ U_{\text{bank}} = \frac{1}{2} C_{\text{bank}} V_0^2 \]  

As discussed, explosive charges are sometimes used to actuate certain components within pulsed power systems. When safety considerations are paramount, this requires dedicated areas to protect the user from explosive effects, and specialised equipment and protective gear to escape from the effects of shock waves as well as the associated debris. For this reason, the adoption of explosives as a primary power source is not followed at Loughborough.

4.1.2 High Voltage Closing Switches

In high-powered pulsed applications there is a need for the switching systems to be able to withstand terawatts of power, while maintaining jitter times of the order of nanoseconds and holding off breakdown due to the large voltages placed across them. Due to these strict criteria, conventional switching mechanisms are not useful and specialised pulsed power switches have been developed. These fall broadly into the
categories of closing and opening switches, with closing switches used to transfer directly the stored energy to a load, and opening switches employed when it is desirable to move the energy from one location to another at a certain time. This is achieved by using a suitable combination of closing and opening switches.

Closing switches are used to deliver the stored energy from a capacitor directly to the load. After the capacitor bank has been fully charged, then isolated, a closing switch seen in Figure 4.3 connects the bank to the load at some predetermined time.

![Figure 4.3 Closing switching](image)

The necessity for effective switching of the stored capacitive energy to the load is fundamental to the efficiency of the energy transfer, as well as the timing of the discharge. As described below, various closing switch techniques are employed to achieve accurate, reproducible, and efficient switching.

**4.1.2.1 Rail Gap Switches**

Possible one of the most commonly employed pulsed power closing switches is the spark gap. This holds off the electric breakdown between two electrodes until the breakdown is instigated either by design or by a triggering mechanism, and the circuit is completed.
Figure 4.4 shows a cross section of a simple spark gap arrangement. A known distance separates the anode and cathode and within the gap is a dielectric - solid, liquid or gas. When the voltage reaches a certain value the dielectric turns from being extremely resistive to conductive, as breakdown occurs and current begins to flow in a process termed self-breakdown. The design of such spark gaps is often bespoke, with empirical data used to set their ratings - often in situ.

There are two problems with this system when used as a closing switch. Firstly, self-breakdown is undesirable in an accurately timed system. Secondly the presence of only one channel for current between anode and cathode means that the impedance is often higher than is desirable, as well as the fact that as large currents flow the surfaces will quickly deteriorate. As a solution to both these problems it is possible to use a triggered rail gap.
In this switch, three long parallel electrodes are housed within a suitable container comprising a dielectric medium. The trigger electrode (in this case a knife-edged trigger) is sited between the two main electrodes, with the gap between each of them determining the operating voltage. The rail gap has the ability to hold off breakdown in the dielectric at its rated voltage and when breakdown is to be initiated, a negative voltage spike is applied to the trigger. As the negative voltage spike is applied the electric field is increased between the trigger and the anode, which eventually causes breakdown to occur. Current flows through a plasma channel between anode and cathode once the medium has become conducting. In the case of a rail gap, due to the geometry of the electrodes, multiple plasma channels are produced, and a higher rate of charge transfer can be passed without degradation of the electrodes when compared to the single channel spark gap.

At Loughborough, Titan Systems Corporation rail gaps are used as closing switches, each single unit being capable of passing currents up to 1.2 MA, and with charge transfer capability up to 10 C. Each switch has an overall inductance of 20 nH. Figure 4.6 shows a picture of such a switch.
In the picture above, the polycarbonate cover is raised, enabling the interior to be viewed but, when operating, this cover is closed and sealed. The switch has the capability to operate over a range of voltage, although for each voltage a specific dielectric medium must be used. The switches at Loughborough are operated as closing switches between the voltage of 10 and 30 kV and at this voltage the recommended dielectric medium is a mixture of 10% oxygen (10% O₂) and 90% Argon (90% Ag). In the configuration shown the trigger electrode is placed at a distance 1/3 from the anode, and 2/3 from the cathode with a pulse supplied to the trigger electrode by a separate TITAN 100 kV trigger generator. To guarantee breakdown, the edge trigger must have a maximum amplitude of 100 kV and a rate of rise time of a minimum of 5 kV/ns. This triggering voltage must also be maintained at the correct DC bias for the gap spacing (Titan Corp, User Manual). With this bias voltage obtained using a 2:1 resistive voltage divider. Furthermore, in order to dc-isolate the trigger switch from the main energy discharge circuit and to couple the trigger signal into the rail-gap switch, two arrangements of series and parallel capacitor are used, as shown in Figure 4.7 for one switch.
In the assembly at Loughborough $R_D$ is a 50 MΩ resistor and $C_S$ is a 1 nF, 70 kV capacitor. The trigger generator can be initiated from either an external voltage pulse between +8 to +12 V with a rise time of less than 10 ns or a push button on the generator. Although the trigger can operate up to 10Hz, it is only used as a single shot device, when the time delay jitter to one standard deviation is less than 1 ns, and for the closing switch it is less than 2 ns.
Figure 4.8 shows the operating curve used to set the gauge pressure of the dielectric medium over the 10 to 30 kV voltage range.

4.1.2.2 Alternative switching mechanisms

Alternative switching methods can also be used, which although somewhat simpler to implement, have certain restrictions. Figure 4.9 details a schematic of one such closing switch.

Figure 4.9(a) shows the cross section of a pin closing switch (not to scale) comprising a guide approximately 300 mm long, used to steer a weight of approximately 1 kg into a small pin. Figure 4.9(b) shows an enlargement of the region highlighted in Figure 4.9(a). During operation the pin passes through the 1 mm copper sheet, and punctures the Mylar insulation underneath to complete the circuit. An electromagnetic keeps the weight at the top of the guide in situ until such time as closing is desired. Prior to operation a safety pin is removed.
This is an extremely simple and effective method for closing pulsed power circuits. However, limitations arise when passing currents exceeding 1 MA, as the area near where the current is transferred can vaporise, and if a plasma channel is not maintained the circuit remains open. Furthermore,
precise timing is impossible, due to the variation in the time taken for the weight to fall and the insulation to puncture.

A further alternative to the rail gap switch is detailed in Figure 4.10. In this design the weight is used to overcome the static friction in a rotating pin on a scissor mechanism. When this friction is overcome, the scissor arms come together to close the circuit. This again forms an extremely simple closing switch although limitations still remain with regards to both timing and maximum current transfer.

![Figure 4.10 Pin closing switch](image)

**4.1.3 Transmission system: Ultra-fast energy delivery**

As discussed previously and shown in Equation 2.2 the peak magnetic field in a STC is a function of the coil current. Similarly, the magnetic pressure exerted in flux compression experiments is a function of the peak magnetic field. As the circuitry detailed above shows, the power supply is derived from a charged capacitor, after the load and transmission system
have been isolated from the mains. It is apparent that the effects of this circuit play an influential role in the efficiency, and that a full understanding of these must be known if operation of the complete system is to be understood.

4.1.3.1 Impedance considerations

A lumped circuit representation of the final stage of a pulsed power network is given in Figure 4.11.

![RLC Circuitry Diagram](image)

Figure 4.11 RLC circuitry

In Figure 4.11, the lumped circuit representation neglects the capacitive effect of the load, transmission line, and switch, as their inductive and resistive properties will be shown to play the dominant role. By concatenating the similar circuit components (i.e. combining the values of resistance, inductance capacitance to obtain a single value for each) the following electrical equation for the circuit becomes:

$$\frac{dL_i(t)}{dt} + R(t)i(t) + \int \frac{1}{C(t)} i(t)dt = 0$$

Eq. 4.3(a)

or
\[
L \frac{di(t)}{dt} + Ri(t) + \frac{1}{C} \int i(t) dt = 0 \quad \text{Eq. 4.3(b)}
\]

if the variation in the lumped inductance and resistance is assumed to be negligible. In reality however, the resistance of the circuit will vary as Joule heat is deposited, and the inductance may vary if any movement occurs in the system, as would happen if STC were used. In such cases the effect of these variations in inductance can be minimised by using ultrafast pulses, so that the experiment is concluded before any significant movement has occurred. In cases such as EMFC experimentation, the variable inductance is an inherent part of the load. Estimation of this variation is best achieved computationally rather than analytically.

If we consider the second order differential equation for transient models given in Chapter 3 (Equation 3.5) it can be shown that by differentiating each side of Equation 4.3 with respect to \( t \), we obtain:

\[
L \frac{d^2 i(t)}{dt^2} + R \frac{di(t)}{dt} + \frac{1}{C} i(t) = 0 \quad \text{Eq. 4.4}
\]

Again from Equation 3.5, it is apparent that the various co-efficients represent inertia, dampering, and stiffness within the system. The natural frequency of the system is:

\[
\omega_n = \sqrt{\frac{K}{M}} \quad \text{Eq. 4.5}
\]

while the viscous dampering factor \( \xi \), is:

\[
\xi = \frac{1}{2\omega_n} \frac{C}{M} \quad \text{Eq. 4.6}
\]

If Equation 3.5 is dividing throughout by the inertia coefficient, the Governing Differential Equation (GDE) can be expressed as:
\[
\frac{d^2i(t)}{dt^2} + 2\xi \omega_n \frac{di(t)}{dt} + \omega_n^2 i(t) = 0 \quad \text{Eq. 4.7}
\]

in which by comparison with Equation 4.4, the natural frequency and the viscous dampening are given by:

\[
\omega_n = \sqrt{\frac{1}{LC}} \quad \text{Eq. 4.8(a)}
\]

\[
\xi = \frac{R}{2} \sqrt{\frac{C}{L}} \quad \text{Eq. 4.8(b)}
\]

respectively. Furthermore if we consider that the general solution to the GDE in Equation 4.7 includes both exponential decay and oscillatory characteristics, then the solution takes the form:

\[
i(t) = Ae^{\lambda t} \quad \text{Eq. 4.9}
\]

where A is an arbitrary constant and \(\lambda\) must be \(-\text{ve}\) for a decay process. Differentiating Eq. 4.9 twice and substituting back into Equation 4.7 gives:

\[
\lambda^2 + 2\xi \omega_n \lambda + \omega_n^2 = 0 \quad \text{Eq. 4.10}
\]

the roots of which are:

\[
\lambda_{1,2} = \omega_n \left[ -\xi \pm \sqrt{\xi^2 - 1} \right] \quad \text{Eq. 4.11}
\]

This gives two constants \(A_1\) and \(A_2\), and by superposition the solution as:

\[
i(t) = A_1 e^{\lambda t} + A_2 e^{\lambda t} \quad \text{Eq. 4.12}
\]
By investigating the value of the viscous dampening factor $\xi$ (0<$\xi$<∞), it is possible to determining the damping of the system. For a value greater than 1, the circuit is overdamped, with the "motion" not being oscillatory, and no period existing. For a value of 1 the system is critically damped.

If $\xi < 1$ the system is underdamped, and the response becomes oscillatory. The term $(\xi^2 - 1)$ becomes negative and by introducing $i = \sqrt{-1}$ Equation 4.11 becomes

$$\lambda_{1,2} = \omega_n \left[ -\xi \pm i\sqrt{1-\xi^2} \right] \quad \text{Eq. 4.13}$$

Substituting this result into Equation 4.12 gives:

$$i(t) = A_1 e^{-\xi_0 t + i\omega_d t} + A_2 e^{-\xi_0 t - i\omega_d t} \quad \text{Eq. 4.14}$$

and by introducing the damped frequency of the systems:

$$\omega_d = \omega_n \sqrt{1-\xi^2} \quad \text{Eq. 4.15}$$

Equation 4.14 becomes:

$$i(t) = e^{-\xi_0 t} \left[ A_1 e^{i\omega_d t} + A_2 e^{-i\omega_d t} \right] \quad \text{Eq. 4.16}$$

using DeMoivre's Theorem, i.e

$$e^{\pm i\theta} = \cos \theta \pm i \sin \theta \quad \text{Eq. 4.17}$$

then

$$i(t) = e^{-\xi_0 t} \left[ A_1 (\cos \omega_d t + i \sin \omega_d t) + A_2 (\cos \omega_d t - i \sin \omega_d t) \right] \quad \text{Eq. 4.18(a)}$$
where $B_1$ and $B_2$ are constants that depend upon the initial conditions $i(0)$ and $di(0)/dt$. Equation 4.18(c) may also be written in terms of a simple constant:

$$i(t) = Ce^{-\xi_0 t} \cos(\omega_d t + \alpha)$$  \hspace{1cm} \text{Eq. 4.19}$$

From this it follows that, with no initial current:

$$i(t) = \frac{V_0}{\omega_d L} e^{-\xi_0 t} \cos(\omega_d t + 90)$$  \hspace{1cm} \text{Eq. 4.20}$$

In order to achieve a fast discharge, with a high peak current, it is important to keep the inductance to a minimum. Several alternative transmission configurations are used in pulsed power applications such as a co-axial, strip, and helical. Perhaps the most commonly used is the strip transmission system, or flat plates of large cross section and low resistance shown in Figure 4.12.

Flat plate transmission lines between the capacitor bank and load allow the ultrafast, efficient delivery of current. The current density and all related effects can be described with sufficient precision by the steady-state, constant current line-density distribution (Knoepfel, 1970) 'Edge
effects' occur, with the bulk of the current density residing in the outer edges of the plates, as discussed for the STC in Chapter 2. Any change in the cross-section or height of the transmission system - such as connection to the load - must therefore be graded slowly, to avoid concentrating the current density in sharp corners and leading to increased Joule deposition and perhaps material melting or vaporisation.

The overall inductance of a flat plate transmission line can be calculated from:

\[ L = \mu_0 \frac{sl}{h} K(s/h) \]  

\textbf{Eq. 4.21}

where \( s \) is the spacing (or gap) between the two plates, \( l \) is the length of the transmission line, \( h \) is the height (or breadth) and \( K(s/h) \) is a correction factor based upon the ratio of the spacing to the height. The magnitude of this factor can be taken from the graph of Figure 4.13.

![Figure 4.13 Inductance and correction factor for parallel plate (Knoepfel p323, 1970)](image)

It can be seen from Equation 4.21 that one way of reducing the inductance of the transmission system is by reducing the gap. Although this may lead to other problems with forces exerted between plates during discharge being exacerbated by reducing the spacing. It is therefore necessary to
restrain the plates and this is achieved at Loughborough by suitable weights being placed on top on the transmission lines. A reduced spacing also causes a higher electric field stress and increases the probability of breakdown. Insulation which is both effective and suitably thin must therefore be used.

In addition, areas of the transmission system where the go and return paths are not in close proximity will introduce inductive effects, and reducing the time rate change of current in the initial moments of the discharge will reduce the effectiveness of experiments.

4.1.3.2 Experimental evaluation of transmission impedance

To use the derived system model given in the Equations of section 4.1.3.1, the resistance and inductance of the transmission network are evaluated by discharging a known capacitance into a known load and recording the variation in current (Novac et al, 1995)

4.1.3.3 Insulating Considerations

As in all high voltage engineering, insulation of the system components is of paramount importance since any breakdown over a region with little impedance could lead to very substantial currents. The resulting Lorenz forces and Joule heating may irreparably damage the system, as well as being dangerous to the user. However, since an inappropriate selection of insulting material or method may also have a detrimental effect on the efficiency of the experiment, consideration must be given to which method of insulation is best suited for the particular application. In most pulsed power systems the application is to prevent shorting of the current path, while simultaneously interfering to minimal extent with the geometric configuration of the system.

It should be noted that during pulsed operations insulators can in general withstand significantly more voltage than at DC. However care must still be
taken to design suitable equipment, with sharp edges avoided whenever possible, as these inevitable lead to an increase in the localised electric field.

### 4.1.3.3.1 Breakdown

Insulators, as discussed in section 4.1.2.1 may be solid, liquid, or gaseous. In most pulsed power applications, liquid or gaseous insulators (such as transformer oil or SF6) are used since, if breakdown does occur, the insulator can be readily repaired. This is unlike solid insulators, which would be irreversibly damaged. Breakdown in a liquid or gaseous insulator will generally occur as a result of the rated electric field value across the insulator being exceeding with such substances with a high breakdown field strength being more capable of holding off larger voltages. Although this is also true for solid insulators, the effects listed below can also cause breakdown in these materials.

- **Intrinsic Breakdown** – The same effect as occurs in gas/liquid insulators, when electrons gain sufficient energy in the electric field to cause a flow of electrons across the potential gap.

- **Streamer Breakdown** – Photoionisation of the material becoming a predominant process in producing electrons. When such an ‘avalanche’ exceeds a certain critical size, breakdown occurs.

- **Thermal Breakdown** – When an insulator is stressed electrically and heat is generated the structure will undergo thermal breakdown if this heat rate exceeds the corresponding rate of loss.

- **Erosion Breakdown** – Areas on an insulator containing a cavity where gas or liquid may have a reduced dielectric strength and these areas may breakdown before the main insulator material.
Current Tracking - Current tracking occurs with repetitively applied fields. Tracking is the gradual formation of permanent conducting paths – usually carbon – along the degraded insulator surface.

Although it is evident that breakdown in solids can occur due to several factors, namely electrical or mechanical failure, thermal softening or ablation, solid insulators provide a mechanical support that gaseous/liquid varieties do not.

4.1.3.3.2 Flashover

Surface flashover is another danger to insulation in high voltage systems. This occurs when the voltage sufficient to cause breakdown over the surface of an insulator rather than through it and it is less well understood. However with suitable precautions the opportunity for this to occur can be reduced.

![Figure 4.14 Flashover](image)

Figure 4.14 shows a cross section of two conducting plates to illustrate what happens when flashover breakdown occurs. The insulation between the two electrodes is holding off a voltage and it is assumed that the insulator has sufficient dielectric strength to prevent breakdown at the specified spacing. What occurs however is an electrical discharge along the surface of the insulator. It should be noted that although shown above for a particular configuration, flashover can occur between any two conductors over an insulating surface so that great care must always be taken in the construction of a pulsed power system.
4.1.3.3.3 Using Mylar in high voltage applications

As discussed earlier the best solution for a transmission network involved in STC and EMFC is to use flat transmission plates and Equation 4.21 shows that the closer the plates are positioned, the lower will be the inductance. Also since the plates must not move during a discharge it is important that the insulating body between them gives suitable mechanical support. Another important factor is the dielectric constant of the insulation between the plates, as a large dielectric constant will lead to unwanted capacitive effects. Mylar sheets are excellent for this application. They are also useful between the driving coil, and the liner in an EMFC experiment, where insulating with either liquid or gas would involve a costly and invasive system.

![Mylar breakdown characteristics graph](Pai, 1995)

Figure 4.15 shows the breakdown behaviour of Mylar in a uniform electric field. When considering the potential for flashover between transmission lines and other parts of the system, it is important to extend the Mylar far beyond the edges of the electrodes. This is illustrated in Figure 4.14.
4.2 Ultrahigh magnetic field system measurements

It is clearly important when generating an ultrahigh magnetic field that the field is accurately measured. Suitable equipment and techniques must be able to cope with a wide bandwidth of frequencies, since transient magnetic fields can often have an exponential increase. Furthermore, the measurement techniques must be able to maintain their integrity under the extreme operating conditions experienced in pulsed power experiments (see Chapter 2), as well as being of a suitable size to operate in the effective volume of the experiment.

Two measurement methods commonly used in pulsed magnetic field systems are based upon an inductive magnetic pick-up probe and the Faraday rotation in an electrooptic device.

4.2.1 Inductive magnetic pick-up probe

This is simplest method of measuring magnetic field and is illustrated by Figure 4.16 in which a time varying magnetic field passes axially though a loop inducing a voltage at the terminals. Although a large gap between the terminals is shown in figure 4.16, this is for clarity only. The time-varying induced voltage is related to the rate of change of magnetic flux density by the expression:
\[ v(t) = (NA + S) \frac{dB}{dt} \]  

where \( N \) is the number of turns in the coil – in the case of Figure 4.16 this is one – and \( A \) is the area enclosed by one turn. \( S \) is the area inevitably formed during manufacture by the leads. The goal is to reduce this as much as possible by careful construction.

By positioning the loop such that the axis is parallel with the magnetic field the time rate of charge of flux density can be recorded by measuring the voltage at the terminals by using, for example, an oscilloscope. In order to obtain the magnetic flux density, the voltage signal must be integrated which is normally achieved by an electronic integrating circuit positioned between the pick-up probe and the measuring device. Care must be taken when considering the bandwidth and response of this integrating device, as the time rate-of-change of magnetic field can vary from zero to as much as \( 10^9 \) T/s in a matter of microseconds. The circuit diagram for such a device is given in Appendix C (similar to that disclosed by Kido et al, 1976).

Care must be taken in the construction of an accurate and useful magnetic pick-up probe since heating will occur in any conductor exposed to a magnetic field. This rate of heating is considered to be:

\[ mc\Delta T \approx \frac{B^2}{2\mu} Al \]  

where \( m \) is the mass, \( c \) is the specific heat, \( \Delta T \) is the associated temperature rise (Knoepfel, 1970), \( A \) is the area and \( l \) is the length of the probe.

During experimental conditions, a conductor may gain sufficient energy to vaporise if the pulsed magnetic flux density reaches between 150 T and 200 T. When the thickness of the pick-up probe is much less than the skin depth, Equation 4.23 can be approximated by:
\[ mc_v \Delta T \approx \frac{1}{2} \left( \frac{d}{s_d} \right)^2 \mu H^2 \]  

\text{Eq. 4.24}

where \( d \) is the thickness and \( s_d \) is the skin depth given by:

\[ s_d = \sqrt{\frac{1}{\pi \cdot f \cdot \mu \cdot \sigma}} \]  

\text{Eq. 4.25}

Equations 4.24 and 4.25 show that to reduce the heating problem either the thickness of the probe or the conductivity must be minimised. It has been shown that a copper coil with a diameter between 0.1 mm and 0.05 mm is sufficient to avoid vaporisation in such ultrahigh pulsed magnetic fields (Knoepfel, 1970).

Another consideration is that in fast transient magnetic fields there is the potential for generating extremely large voltages since the time rate-of-change of magnetic flux density can reach \( 10^9 \) T/s, particularly in EMFC experiments. Assuming a probe is constructed from one turn of wire with a radius of 2 mm and zero additional area Equation 4.22 suggests that the induced voltage at the terminals may exceed 1.2 kV. In such cases an attenuator or shunt resistor must be used before introducing the signal into any recording device.

![Figure 4.17 Cross section of pick-up probe construction](image)

77
Figure 4.17 shows a cross section of a pick-up probe comprising two separate pick-up probes wound on a single glass rod. In many instances, only one probe is used; however the use of two probes connected in opposite senses as detailed in Figure 4.17 allows for any noise in the signal to be recognised and eliminated. In this construction care is taken to position each probe as close a distance as possible to each other, such that the recorded magnetic field is evaluated at the same point.

The pick-up wire generally has a cross-section of 0.1 mm, and is coated with a polyamide that can withstand 2 kV so that a voltage of 4 kV can be withstood between turns. The leads of each probe are twisted tightly together to avoid stray inductive pickup and as shown above run back along the rod. The coils are held in place by epoxy resin, while the leads are restrained from moving by a heat shrink material. The entire construction is placed inside a ceramic outer casing, and air is removed by introducing oil into the narrow cavity to protect against possible shockwaves. At the end of the complete probe, the leads from each sensor are connected to a co-axial cable, which is covered by copper sheeting to protect again interference. The coaxial cable delivers the signal to a recording device.

Each pick-up probe sensor is calibrated in a STC experiment, by comparing the performance to that of a precisely manufactured, multi-turn calibration coil of much larger diameter. Inductive magnetic pick-up probes can be constructed with an error of less than a few percent, and are extremely effective at measuring pulsed ultrahigh magnetic fields in harsh environments such as those experienced in pulsed magnetic arrangements.

4.2.2 Faraday Rotation

As discussed earlier, care must be taken when constructing magnetic pick-up probes to avoid electric interference, and consideration must be given
to the high voltages that might be generated. As an alternative to this, it is possible to measure the magnitude and variation of the magnetic field by using the Faraday effect (Kido et al., 1976).

The Faraday effect is evident when a beam of polarised light passes through a medium, and rotates from the polarisation plane through an angle $\beta$. When the medium is homogenous and the beam passes parallel to the magnetic field lines, the angle of rotation is proportional to the magnetic field, the length of the medium, and the Verdet properties of the material, defined by a constant $V$. Thus

$$\beta = B(t)VL$$

Eq. 4.26

which can be used to record the magnetic field variation by means of the arrangement of in Figure 4.18.

![Figure 4.18 Faraday rotation arrangement](image)

In Figure 4.18 a laser with a uniformly narrow wavelength is used as the light source. The beam is passed through a filter and then a polarising lens. A crystal (the Verdet medium) is placed inside a tube, which is parallel to the magnetic field and by maintaining the orientation of this crystal, keeps the effective length accurate. As the polarised light passes
through this material, it rotates through an angle that is proportional to the magnitude of magnetic field. Thus the rate of change of angle is related to the rate of change of magnetic field.

The light emerging from the crystal is passed through a lens, an iris and a second polariser with the same orientation as the first. This has the effect that the light intensity leaving the second polariser is related to the rotation by:

\[ I_{\text{nt}}(t) = I_{\text{nt}} \cos^2 \beta \quad \text{Eq. 4.27} \]

where \( I_{\text{nt}} \) is the initial intensity of light when no field is present. The varying intensity of the light is transmitted by fibre optic cable to an opto-electric converter, which supplies a voltage that is proportional to the light intensity. If the voltage is recorded over time, on an oscilloscope, the variation in signal is

\[ \text{Sig}(t) = \left[ \cos(A(t)) \right]^2 \quad \text{Eq. 4.28} \]

and

\[ A(t) = 2V \int_0^{t/2} B(t, l) dl \quad \text{Eq. 4.29} \]

The measured magnetic field is the integral of the overall effective length of the crystal with short crystals being used to provide an indication of the variation in magnetic field at a precise location.

Faraday rotation sensors are useful as they are not susceptible to electric interference in the same way as inductive pick-up probes. Errors are however introduced if the crystal is exposed to shockwaves, since the variation in density inside the crystal can lead to a variation in the Verdet constant.
4.3 Voltage sensor

Voltages measurements are required when charging a capacitor banks to enable the energy in the system to be monitored as well as to prevent over charging. Common voltage measuring techniques are employed, such as the use of voltmeters. Such devices are detailed elsewhere.

4.4 Current Sensors

In addition to the accurate measurement of the magnetic field variation, it is necessary to monitor a variation in current that is both large (>1MA) and fast (μs). Two methods are employed; the inductive probe, and the Rogowski coil.

4.4.1 The inductive current sensor

The inductive current sensor works in a manner similar to the inductive magnetic pick-up probe detailed in section 4.2.1 and therefore will not be detailed further here. Again it is the time rate of change of field (or by inference current) that is measured, and thus the signal is required to be integrated. In most systems the signal is actively integrated, as passive components (such as RC circuits) often have a slow response.

4.4.2 The Rogowski Coil

An alternative to the simple inductive probe is the Rogowski coil which is a field-coupled sensor that uses current to induce a voltage in a similar fashion to the inductive probe. Figure 4.19 shows the general construction of a Rogowski coil.
and the equivalent circuit is shown in Figure 4.22.

\[ L \frac{di(t)}{dt} + (R + R_M) i(t) = \frac{L}{N} \frac{di(t)}{dt} \]

Eq. 4.30

where: \( L \) is the coil inductance, \( R \) is the coil resistance, \( R_M \) is a metering resistor from which a voltage across can be measured, \( N \) is the number of turns of the coil, and \( i(t) \) is the measured current and \( i(t) \) the current in the Rogowski coil (Pai, 1995).

The voltage the metering resistance is:

\[ V_M = i(t)R_M \]

Eq. 4.31
and if the pulsed current is an extremely fast transient, the time constant of the discharge is:

\[ t_c \ll \frac{L}{R + R_M} \quad \text{Eq. 4.32} \]

The current in Equation 4.31 can be deduced from Equation 4.30 by neglecting \([(R+R_M)i(t)]\), as the rate of change of current plays the most influential role. Equation 4.30 then becomes:

\[ L \frac{di(t)}{dt} = L \frac{di(t)}{dt} \quad \text{Eq. 4.33(a)} \]

or

\[ \frac{di(t)}{dt} = \frac{1}{N} \frac{dI(t)}{dt} \quad \text{Eq. 4.33(b)} \]

or

\[ i(t) = \int \frac{1}{N} \frac{dI(t)}{dt} dt = \frac{1}{N} I(t) \quad \text{Eq. 4.33(b)} \]

and the metered voltage is given as:

\[ V_M = \frac{R_M}{N} I(t) \quad \text{Eq. 4.34} \]

In this configuration the voltage measured is directly proportional to the current. In order to reduce the voltage seen at the terminals it is important to keep the number of turns large, and the metering resistance small.

If however the time constant of the discharge can be considered as:
\[ t_s >> \frac{L}{R + R_M} \quad \text{Eq. 4.35} \]

Equation 4.30 becomes:

\[ (R + R_M)i(t) = \frac{L}{N} \frac{dl(t)}{dt} \quad \text{Eq. 4.36(a)} \]

hence

\[ i(t) = \frac{L}{N(R + R_M)} \frac{dl(t)}{dt} \quad \text{Eq. 4.36(b)} \]

and \( V_M \) is:

\[ V_M = \frac{LR_M}{N(R + R_M)} \frac{dl(t)}{dt} \quad \text{Eq. 4.37} \]

In this mode the voltage is proportional to the time rate of charge of current. If however a large capacitance in placed in series with the metering resistance as, shown in Figure 4.21

![Figure 4.21 Rogowski coil second equivalent circuit](image)

the voltage equation is:

\[ L \frac{di(t)}{dt} + (R + R_M)i(t) + \frac{1}{C} \int i(t)dt = \frac{L}{N} \frac{dl(t)}{dt} \quad \text{Eq. 4.38} \]
The voltage across the capacitor is now:

\[ V_c = \frac{1}{C} \int i(t) dt = \frac{LI}{CN(R + R_d)} \]

\[ Eq. 4.39 \]

and this passive integrator circuit can be used to measure both the current and its time rate-of-change. However, it is often more useful to use an active integrator on the l-dot signal, as the introduction of the capacitance reduces the response.

A well-constructed Rogowski coil, with equally spaced windings is very accurate at quantifying pulsed currents. A particular benefit is that the transient current may pass anywhere through the loop, and the inductive effect is normalised over the entire area of the loop. As with the inductive probe, care must be taken to insulate the coil and the signal transmission line against external electrical interference.

4.5 Storage Mediums

The primarily storage medium used is an oscilloscope, with signals being recorded on digital devices, with a sufficiently high sampling frequency to obtain an accurate representation of the signal. Such oscilloscopes are detailed elsewhere.

Oscilloscopes used at Loughborough are always isolated from the mains supply and are powered by rectified DC voltages during experimentation. Each item of recording equipment was located in a Faraday cage, to reduce spurious signal noise.

4.6 High Speed Imaging
In many pulsed powered experiments deformation of the structure plays a role in the efficiency and effectiveness of the systems (Matsuda et al., 2002). In such experiments the speed of movement may be in the order of $10^3$ m/s. Under these conditions high speed imaging can be essential as a diagnostic tool, and allows a greater insight to be gained into the dynamics of the system. Two diagnostic techniques that may be used to observe the inherent characteristics of such high energy pulsed experiments are high-speed photography and X-ray imaging.

### 4.6.1 High Speed Photographic Imaging

A specialised camera designed specifically for use in recording movement of explosives or high speed projectiles is valuable in pulsed power experimentation. The Hadland IMACON 486 high speed camera is capable of recording images using shutter speeds of as low as 10 ns ($1/E^8$ secs). An object travelling at 3 k/s would therefore only travelled 0.003 mm in this time, insufficient to cause blurring of the object in most instances. Eight individual exposures can be recorded digitally at a time during a single experiment. Figure 4.22 shows a typical configuration of the IMACON camera and its associated equipment.

Figure 4.22 Hadland IMACON 486 high speed camera configuration
The camera itself can be configured to run through a predetermined exposure program from a PC program connected to the camera by fibre optic cable. This allows the user to set shutter times and speeds, whereby each exposure can be triggered from a rising edge input voltage. As discussed above, eight predetermined exposures can be recorded digitally, before being transmitted to a computer. Each image is digitally recorded in TIFF format. Various lenses can be used in order to focus accurately upon the test specimen.

As shutter speeds are extremely short, it is essential to use flash lighting in many instances to increase the exposure. A similar rising edge input voltage can also trigger this flash lighting. Care must be taken to consider the warm up and duration times of the flashgun in order to achieve suitable exposures. Depending upon the self-luminosity of the experiment, the shutter speeds can also be altered between images to ensure a good exposure. In most instances the duration of a flash pulse is much longer than the entire pulsed power experiment and therefore only one flash pulse is needed. As the response of the lamp is much slower than that of the pulsed power system, the lamp must be ignited well before the experiment begins in order to give suitable time to warm up. This means that a delay pulse trigger generator is needed to co-ordinate the experiment and the flash and camera.

As previously discussed, when used in pulsed power experimentation it is useful to eliminate harmful projectiles and shockwaves. Suitable wood shielding and polycarbonate plates help to isolate the camera equipment from potentially unwanted projectiles. To assess the potential for shockwaves in a particular location in the laboratory, cigarette paper, taped upon the opening of small tubes, was used. These simple devices were positioned in locations of interest prior to an experiment. If after the experiment the paper had been perforated, it was concluded that the force of the shockwaves experienced at that location was too great for the experimental equipment. By using this assessment, every location to be used for equipment was tested prior to installation of said equipment.
4.6.2 Flash X-ray imaging

Using an IMACON high speed camera is an accurate way of capturing the motion of high speed objects, although certain limitations are apparent. When observing materials that have in part become vapourised, it can be difficult to discriminate between solid and gas. Furthermore as has previously been stated it is often the case that large transient currents will be experienced. When these currents heat the metallic structure, the material itself is likely to become photo-emissive with the light produced polluting the images recorded by the camera and obscuring the data. The flash X-ray as a dynamic diagnostic tool is an alternative to the high speed camera and Figure 4.23 shows a typical flash X-ray arrangement.

![Figure 4.23 150 kV Flash X-ray configuration](image)

In this configuration two separate flash X-ray tubes are used, each operated independently by separate Marx generators. When the movement experienced in the time between exposures of the test specimen is sufficiently large such that images taken are not overlapping, it is possible to obtain two exposures on one X-ray film. In such an situation, to minimise the variation at the centre point, the two tubes are placed a suitable distance from the test piece (> 3m) and the X-ray plate is
as close as possible to the test specimen. This also reduces error due to penumbral effects.

A separate timing system is used to accurately time the discharge of each driving Marx generator, and hence the timing of the X-ray flashes. Polycarbonate sheeting is used to protect all the diagnostic equipment. Inside the X-ray film cassette, two image intensifiers are used to enhance the exposure of the X-ray. Care must always be taken so as not to inadvertently obscure the test specimen when using either the high speed camera or X-ray imaging techniques.

4.7 Conclusions

High voltage and high current systems such as those used by ultrahigh pulsed power experiments require specialised equipment. The apparatus detailed above is employed at Loughborough during the course of research investigating the production of pulsed ultrahigh magnetic field experiments.
5. SINGLE TURN COIL TECHNIQUE

As discussed in Chapter 2, the production of pulsed magnetic fields generally falls into either destructive or non-destructive categories, with a similar toroidal topology being adopted in each case. The threshold between the systems is based on the flux density produced, in that systems generating over 100 T are always considered to be destructive while repetitive systems, generating a much lower flux density, are non-destructive.

However in certain circumstances, while the magnetic energy produced is insufficient to cause complete destruction, it may nevertheless cause extensive plastic deformation. Under these conditions the pulsed magnetic system can be considered semi-destructive (Herlach, 1999). Such semi-destructive systems have fundamental application in advanced technologies such as metal forming (Kristiansen, 1993) that employ the very considerable power generated to obtain metal products in a variety of complex shapes. A number of European Universities (mostly in Germany) are collaborating with industrial partners in developing the detailed numerical models required for the optimisation of these industrial processes (Schatzing et al, 2001, Psyk et al, 2004).

This chapter details several STC experiments that were conducted at Loughborough as an essential precursor to future EMFC work. These experiments were however also used to assist in the evaluation of a finite element model that could be implemented in ANSYS, as discussed in later chapters. The experiments detailed here fall into two categories, semi-destructive and destructive, both of which focus upon the use of ultrahigh pulsed currents (in the region of 1 MA) and the corresponding peak flux density produced – a key research interest during this work. Repetitive pulsed system, such as those described in Chapter 2 are outside the scope of the current work.
5.1 Semi-Destructive STC Technique

As mentioned above, in semi-destructive STC configurations the pulsed field must not exceed 100 T, but must be sufficiently large enough to deform plastically the coil. This plastic deformation is principally caused by magnetic pressure produced as a results of current flowing in the coil which as discussed in Chapter 2 has a tendency to occupy the regions of least impedance, namely the outer edges of the coil. The magnitude and exact location of this current is best evaluated by computational methods and from Equation 2.1 and 2.2 it can be seen that the magnitude of the pressure is dependant upon both the transient discharge current and the radius of the coil. Coils with a larger bore than those used in destructive experiments may then be used to evaluate the deformation of the plastic STC, while still maintaining ultrahigh pulsed currents.

5.1.1 Experimental Configuration

For such a typical semi-destructive experiment, a STC constructed from 2 mm pure copper sheet was used, since copper is both particularly malleable and a good conductor. The STC constructed had an inner radius (r) of approximately 10.1 mm and an axial height (h) of approximately 40.7 mm. The feed for the STC was through a nose that tapered out to a height of 200 mm to allow for easy connection to the flat plate transmission system, as illustrated in Figure 5.1.
Aluminium foil was placed between the connection of the STC nose and each transmission plate to ensure a solid connection when clamped. Three sheets of 50 μm Mylar film were placed between the 'go and return' path of the STC, before it was pressed together by a clamp to keep the gap as small as possible and therefore to minimise the load inductance. The Mylar film was also extended out from the edge of the coil so as to prevent flashover.

The flat transmission plates that were used (see section 4.1.3.1) were constructed from two parallel copper plates of 0.25 mm thick and more than 0.6 m wide. These connected the STC to a rail gap switch (Model 40302 – Titan Corp, USA – detailed in section 4.1.2.1), which connected to four parallel capacitors each of 52.64 μF (210.56 μF in total). The flat transmission plates used were similarly separated by three layers of 50 μm Mylar film, and again extended further than the width of each plate to prevent flashover. The flat transmission plates were held in place by weights, as discussed in the previous chapter, and the rail gap trigger electrode was connected to a Model 40230 Titan Corp. 100 kV Marx generator to provide the rising negative edge trigger.

The four capacitors were charged to an initial voltage of 13.7 kV through a charging and isolating system as discussed is Section 4.1.1. After isolating the capacitors from the charging system it was possible to trigger the rail gap by an externally applied rising edge voltage. For safety
purposes, the controls for the charging system, isolation system and the triggering mechanism were operated from an external control room.

The transmission system parameters can be evaluated as described in section 4.3.1.2 of Chapter 4. Each capacitor had an internal inductance of 7.2 nH and a resistance of 1.3 mΩ. By attaching a large load of known value to the transmission system and then discharging a current into the load, the method described in Chapter 4 (Novac et al., 1995) could be used to evaluate the overall system inductance from the current profile. The complete inductance of the transmission system, including the capacitor bank, was determined as 35 nH, while the overall resistance was 2 mΩ.

Long inductive pick-up probes located in tunnels between the parallel plates of the flat plate transmission line were used to monitor the discharge current. A signal proportional to the rate-of-charge of this current was passed through a shielded co-axial cable to eliminate capacitive coupling effects, before being passed directly into a 5 GS/s digital scope and also through an integrator to record the current. The probe itself was located across the width of the transmission plates, housed in a plastic tube and packed with sand so as to protect against the potential threat of shock waves and then calibrated in situ.

A single magnetic pick-up probe was placed at the centre of the axis of the STC to measure the time variation of magnetic flux density. The probe was constructed in a similar fashion as that depicted in Figure 4.19 but with three turns, rather than one, of 0.1 mm diameter wire were wound on a 3 mm diameter glass mandrel. The probe was calibrated in the manner discussed in section 4.2.1 and was assessed as having an error of less than 3%. The tightly twisted wire pair from the probe was passed down the mandrel and then connected to a co-axial cable, shielded with copper sheet to avoid capacitive coupling. The time rate of change of signal from the probe was recorded on a 5 GS/s digital scope and also passed via an integrator, to record the magnetic flux density on a separate channel of the oscilloscope.
The digital scope and the integrators used (see Appendix C) were contained within a Faraday cage to reduce interference. The complete set-up is shown in Figure 5.2.

5.1.2 Results

As discussed above, the primary focus of the research at Loughborough was centred on the production of peak flux densities. As such, it is the peak flux density and corresponding current which are primarily recorded. Further parameters such as temperature of the STC were not considered at this stage and in any event would be difficult to assess.

When the capacitors are fully charged they are isolated from the charger circuit in the control room, where upon a firing signal a signal is sent to the 100 kV Marx generator to trigger the rail gap switch, causing this to breakdown such that the capacitors are discharged into the load. The discharge current and initial variation in magnetic flux density as well as the final deformation of the load are shown below.
5.1.2.1 Current discharge

The current during a typical discharge is shown in Figure 5.3:

![Graph showing current discharge](image)

Figure 5.3. Semi-destructive STC current discharge

The current through the load reaches 1.1 MA in 3.8 μs with the reverse current peaking at -0.78 MA after 11.8 μs and over the first pulse of discharge there is clearly an increase in the period. This is due to the variation in the circuit impedance, caused primarily by a variation in resistance of the STC as Joule energy is deposited and by the variation in inductance as deformation occurs.

5.1.2.2 Magnetic flux density

The variation in magnetic flux density recorded at the centre point of the central axis of the STC during the discharge shown above is given in Figure 5.4.
The central magnetic flux density reaches a peak of just over 26.3 T within 3.8 μs and then decays in an underdamped oscillation — in a similar fashion to the discharge current. The peak magnetic flux density can also be seen to be in phase with the discharge current, meaning that the deformation of the coil during this pulse has not been so excessive as to produce the peak flux density before the peak of the current (see section 2.11 of Chapter 2). Again the period of oscillation is increased as the discharge continues due to changes in circuit parameters.

5.1.2.3 Coil deformation

The deformation of the STC is evident from the recovered test piece. Figure 5.5 shows the deformation produced in the STC by the experiment recorded in Figures 5.3 and 5.4.
Figure 5.5. Pictures of deformed STC
It is apparent from Figure 5.5 that the deformation of the coil is most pronounced at the outer edges. This occurs primarily as a result of the majority of the current distribution occupying these areas. Thermal effects due to Joule deposition may have caused the material to become softer, and with the high electromagnetic stress at these areas, the edge have deformed outwardly. From Figure 5.5(b) it is evident that the axial height of the coil has reduced in order to accommodate changes in the bore. This variation however is gradual from the neck to the outer side. The neck of the coil can be seen to suffer very little deformation as this area was clamped firmly during the discharge.

From Figure 5.5 it is possible to establish that the region that has undergone most deformation is the area diametrically opposite the neck, as highlighted in Figure 5.6.

The central inner radius of the coil (the point where the pick-up probe is placed) was measured on the recovered test specimen as 11.4 mm, giving a marginal increase in the bore of about 1.3 mm at this point. However the radius at the point highlighted by the arrow in Figure 5.6 was measured as 17.1 mm, a growth of just under 7 mm. At this point the axial height was recorded as 34 mm – a reduction of just under 7 mm.

5.2 Destructive STC Technique
The production of ultrahigh magnetic fields exceeding 100 T in STCs can only be achieved using energy pulsed and single-shot apparatus. As discussed in Chapter 2 such experiments are termed destructive, and unlike those described above are often subject to high energy phenomena during the lifetime of the coil. These include shock wave formation within the coil, melting and vaporisation, as well as non-linear diffusion.

The investigation of such destructive pulsed single-turn coils has been undertaken at Loughborough, with a focus on the production of an ultrahigh magnetic flux density. As discussed previously the generation of such a field has application in modern physics, to confirm the verification of certain phenomena predicted to be present in materials subject to pulsed ultrahigh magnetic fields. The simplest and easiest method of generating these fields is the STC.

This section details two such typical experiments, one employing Faraday rotation to measure the axial flux density and the other a pick-up probe to evaluate the central magnetic flux density. Both experiments are subsequently employed as a benchmark for the use of an FEA model at the extreme material range.

5.2.1 Experimental configuration

As discussed in Chapter 2, the production of flux densities in excess of 100 T will result in destruction of the coil. This arises from the pressure difference experienced between the magnetic field within the bore and the outside of the STC, with a much larger pressure pushing outward radially on the coil. As the central field grows this pressure difference increases, causing severe radial deformation and reducing the central flux density. Previous analytical work has shown that even small copper coils are suitable to provide sufficient inertia to ensure that the peak field can be produced before the coils geometry is vastly altered (Forster and Martin,
Two such copper coils are detailed below in Table 5.1. Figure 5.7 shows the STC loads used in destructive tests at Loughborough. This differs from that of Figure 5.1 at the nose, where the tapered point arrives exactly at the STC and is used to minimise the current density in the transmission before arriving at the STC.

<table>
<thead>
<tr>
<th>DESIGN</th>
<th>COIL GEOMETRY</th>
<th>EXTERNAL CIRCUITRY</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Inner Radius (mm)</td>
<td>Outer Radius (mm)</td>
</tr>
<tr>
<td>A</td>
<td>1.5</td>
<td>2.5</td>
</tr>
<tr>
<td>B</td>
<td>1.0</td>
<td>2.0</td>
</tr>
</tbody>
</table>

Table 5.1. Destructive STC parameters

In this system three films of 50 μm Mylar are again used to insulate the go and return plates for both Designs 'A' and 'B' of Table 5.1. Similar copper parallel plates are used for the transmission system between the bank and the load, with care taken to position these as close together as possible and weights are used to prevent displacement during discharge. The Mylar is also suitably extended beyond the width of the transmission system to prevent flashover.
Three capacitors connected in parallel are charged through the isolating system discussed in section 4.1.1. and the pin-connecting switch of section 4.1.2.2 switches the bank to the main transmission line and load. The overall capacitance of the bank is 56.64 \( \mu \)F, with all the other parameters for each experiment being given in Table 5.1.

Long inductive pick-up probes were placed in tunnels in the parallel plate transmission system to record the variation in the capacitor bank discharge current. The probes were contained in a sand filled ceramic cylinder so as to prevent damage from shockwaves, while to reduce electromagnetic coupling the signal was transmitted via co-axial cable, within a copper sheath. The signal was then passed to a 500 MHz, 5 GS/s digital oscilloscope located in a Faraday cage.

The variation in magnetic flux density in Design A was recorded using the Faraday rotation arrangement discussed in section 4.2.2. A SF6, high lead glass crystal from Schott Glass Technologies Inc, Pa, USA used the light provided by a 10 mW HeNe laser. The Verdet constant of the glass employed as the Faraday medium is 17.75 rad/T/m at a wavelength of 632.8 nm. The samples used were approximately 5 mm long with a 1.5 mm square section and were contained inside 2 mm outer diameter plastic tubes. Figure 5.8 (a) highlights the set-up used.

The variation in magnetic flux density in Design B was recorded using a single magnetic pick-up probe system similar to that described in section 4.2.1. Two turns of 100 \( \mu \)m diameter polyimide-insulated wire able to withstand 2 kV was used as a B-dot field sensor, wound on a glass rod 1 mm in diameter and secured in place by epoxy resin (the coil) and shrinkable tubing (the connections). Calibration was performed by comparing the output for a magnetic flux density rising rapidly to more than 10 T in a thick single-turn coil with that given by a standard multi-turn calibration coil of much greater diameter, with the error estimated to be less than 3 %. The power supply was a 17 kJ very fast capacitor bank and
the calibration also confirmed the integrity of the probe under mechanical stress and voltage conditions not too far removed from those experienced in the harsh environment arising of later experimentation.

Figure 5.8. Destructive STC Set-up, (a) Design A, (b) Design B

During experimentation the B-dot sensor was positioned at the centre of a coil inside an ceramic tube 2 mm in diameter. The sensor output was coupled to a 50 Ω semi-rigid coaxial guide via 100 mm to 200 mm of
twisted wire (done so to minimise potential inductive pick-up in the signal). The output signal passed through a 1:10 (20 dB) 1 GHz, 2 W attenuator to 500 MHz, 5 GS/s oscilloscopes situated in a Faraday cage. Figure 5.8 (b) highlights the set-up used.

As can be seen from Figure 5.8 (b) when using the pick-up probe to record the flux density it is possible to introduce image capture facilities inline with the central axis of the STC. This is achieved using the flash X-ray equipment discussed in section 4.5.2. Clearly, a fundamental draw back of using Faraday rotation measurement equipment is that similar imaging diagnostics cannot be introduced along the central axis of the experiment, as is the case for Design A.

5.3 Results

For each design the same general system is used, although as detailed in Figure 5.8 the diagnostic equipment differs. In both system the capacitor bank is fully charged and then isolated from the charging system. The pin switch is activated manually by removing power to the solenoid magnetic (Figure 4.11) in both systems. However when the diagnostic X-ray equipment is used in system B, a signal from the control room in parallel with the switching trigger is passed to the timing unit for the Marx generator. The generator is charged prior to experimentation, such that the timer controls the time of each flash. Results for each system are recorded on a digital oscilloscope

5.3.1 Design A

Due to the fact that Design A employs Faraday rotation, the signal received from the opto-electrical converter is representative of the light intensity of a polarised beam. If the light polarity is in the same plane as the polariser, the signal is at a maximum. As the magnetic field increases, the rate and magnitude of rotation of the polarised light alters, and the
signal observed represents the change in magnetic field, as shown by Equation 4.27. This has the effect of producing a co-sinusoidal reduction of the intensity. Extrapolation of the change of magnetic field must be achieved using Equations 4.26 – 4.29. It is also important to be mindful that the rotational effect is observed through the length of the crystal. The signal received is therefore indicative of the integral of the magnetic flux density along the entire length, meaning that the signal is an average of the flux density along this length. The current is measured directly, and as such does not require any further computational analysis.

5.3.1.1 Current

Figure 5.9 shows the current discharge for the parameters given in the first row of Table 5.1. The current passing through the STC peaks at approximately 900 kA in a time of 1.3 μs. This signal shows a relatively sinusoidal rise to its peak, and then begins to decay.

![Figure 5.9. Design A - Current discharge](image-url)
5.3.1.2. Flux Density

The Faraday signal of the axial magnetic flux density is given in figure 5.10(a), and the extrapolated value of the magnetic flux density is shown in Figure 5.10(b). The frequency of the Faraday signal indicates the rate of change of the magnetic field, which is seen to be greatest in the early
stages and reducing after 0.6 µs. At about 1.5 µs the signal becomes unreliable and the intensity of the signal goes beyond the valid range of the instrumentation, indicating a failure of the measurement system after this point. From the extrapolated data it can be observed that the integrated axial magnetic flux density reaches a peak of just over 140 T in approximately 1.2 µs.

5.3.2 Design B

In contrast to Design A, Design B uses a simple magnetic pick-up loop, similar to that described in Chapter 4, to measure the rate of change of magnetic field. While the overall geometry of the device remains small, this alternative method allows the accurate measurement of the magnetic flux density at a precise locality. The current is recorded in an identical method to that above.

5.3.2.1 Current

Figure 5.11 shows the current discharge for the parameters given in the second row of Table 5.1. The current passing through the STC peaks at just over 860 kA after 1.2 µs, with a sinusoidal rise to the peak current and then begins to decay at about 2 µs.
5.3.2.2 Flux Density

The central variation of magnetic flux density during the discharge of Figure 5.11 is shown in Figure 5.12. A peak of 240 T is recorded in a time of just under 0.8 μs. The field again follows a typical sinusoidal rise, however there is clearly a phase difference between the current and field, with the peak of the field occurring earlier than the peak of the current. From Equation 2.2, it can be concluded that, if the current in the system follows the inner surface of the STC, the peak field should be in the region of 540 T. It is therefore apparent that the mean radius of the current in the STC is increasing, thus reducing the peak field and giving rise to the phase shift between peak current and peak field. This is probably due to both the migration of current through the STC as a result of thermal effects, and the magnetic pressure causing radial expansion. The anomaly of the current surge, most likely due to shorting, shown after approximately 2 μs gives rise to a complementary increase in the central field.
As a good measurement of how well the system performs, it is possible to measure the magnitude of the magnetic flux produced as a function of the initial electrostatic stored energy (so termed the efficacy). The efficacy of the system described by Design B is $4.28 \times 10^{-8}$ Wb/J, which is almost a 25% increase over the nearest figures reported elsewhere (Portugall et al, 1999).

5.3.2.3 Deformation

By using flash X-ray it is possible to capture the deformation of the coil at various stages in the process of the experiment. Figure 5.13 shows two separate pictures, taken from an experiment similar to that of Design B. Figure 5.13(a) shows the STC in its initial position, and Figure 5.13(b) shows the deformation after 0.82 $\mu$s.
In Figure 5.13 the entire coil is not visible due to the necessary Mylar insulation, which obscures part of the upper portion of the coil. What is also apparent is the difficulty of obtaining a uniform cross-section in a solid copper coil when the dimensions are small. Figure 5.13(b) highlights that very little radial deformation has occurred up to the point of peak flux density, with the region directly across from the gap possibly showing the greatest translation. Some necking has also clearly occurred where the cross-section was perhaps initially smaller.

Figure 5.14 details a similar experiment after 1.2 μs, around the time of peak current, and it is apparent that the structure is undergoing a typical
petalling like explosive effect, and has already become unstable. It is probably that after this time only a plasma maintains the circuit, and very little structural mass exists.

5.4 Conclusions

Single turn coil experiments have produced either pulsed ultrahigh magnetic flux densities with destructive consequences, or to cause plastic deformation at lower fields. Magnetic flux density readings have been observed at the central point within the coils as well as along the entire axis. All the experiments detailed above are used in a first attempt to validate a Multiphysics finite element model, with the intention that such a model may be implemented in future STC investigations as well as other pulsed power experiments.
6. FINITE ELEMENT ANALYSIS OF SINGLE TURN COIL SYSTEMS

As discussed in Chapter 3, the use of modelling techniques is becoming more frequently a fundamental prerequisite to understanding and increasing innovation within engineering design, and pulsed power application are not exempt from this. From many years computational codes have been developed in an attempt to predict accurately and to understand further the complex interactions that occur within experiments such as STC and EMFC systems, with the simplest being the filamentary approach (Latef, 1967, Muira and Chikazumi, 1979, Nakao et al, 1985, Muira and Nakao, 1990). Perhaps the most successful model developed to date is however the filamentary model developed at Loughborough (Novac et al [1], 2004). Although this is presently used to advance innovation in such pulsed power systems, certain limitations are apparent. In order to model fully, and therefore to understand and optimise the STCs described in the previous chapter, an alternative modelling technique to filamentary analysis must be developed.

During the period of research undertaken for this thesis, Loughborough had the opportunity of investigating the potential for migrating the current computational analysis of pulsed power system from the filamentary model to a finite element model. This investigative work was conducted using ANSYS®, as extensively described in Chapter 3. Due to financial constraints, the commercial package was only available in a limited version, and for a limited time. Within that time the investigation described below was undertaken to act as an indicator to future potential work in this field. Certain assumptions and simplifications are made where necessary, and a discussion is given of these where appropriate, as well as the potential for overcoming the simplifications.
6.1 Filamentary Analysis of pulsed power systems

Filamentary analysis is not a new technique for analysing electrical systems; it has however proved extremely powerful when predicting the behaviour of pulsed power experiments (Muira and Nakao, 1990, Novac et al [1], 2004). The principal of the filamentary approach, when applied specifically to pulsed power applications, is to resolve a current carrying conductor into a number of equal filaments, each sufficiently small to be considered as carrying a uniform current density. All the individual filaments are considered to be connected in parallel to an overall supply system (capacitor bank and/or transmission system). The resistance of each filament can be deduced from its cross-sectional area and length, while the effective inductance of the filament can be evaluated from sum of the self-inductance and the mutual inductance between each individual filament, each of which are functions of the overall geometry. The response of the system can be calculated by deriving the current flowing in each filament from a matrix of the governing equations. This enables the current and the thermal energy deposited to be deduced, as well as the associated temperature rise, and simple laws of motion can be implemented to approximately determine the filamentary movement – a tolerable approximation in systems where the first term of the Equation 3.5 is dominant.

In the case of the STC technique described in the previous chapter the filamentary approach would initially resolve the coil as shown in cross-section in Figure 6.1.
A simple equivalent circuit of the coil and the transmission system is given in Figure 6.2.

In Figure 6.2 the effective inductance of each filament is, as stated above, a function of both its self and mutual inductances. As the discharge of the current continues, the governing equations for each filament must be solved simultaneously, taking account of variations in resistance due to temperature changes, inductance due to movement, temperature due to Joule heating, and movement due to magnetic pressure etc.

While this model has been extremely effective in certain circumstances, it also has some serious limitations when considering the systems of Chapter 5. Primarily, the model is limited electrically to two dimensions,
meaning that the technique is really only applicable where the 2D approximation is not too severe. In the example of the STC, this approximation may stand as long as the gap produced in the ideal toroid as a result of its connection to the transmission does not play an influential role in the system performance. In more complex geometric models, the technique described above is not applicable and it is therefore limited to consideration of “standard” STCs, limiting development in alternative geometries. In addition, such physical effects as thermal conduction are also not presently calculated. Furthermore, limitations are present when considering the dynamics of the model, which are confined to movement in the radial direction alone (effectively a 1D limitation). Each filament is considered independently without dampening or stiffness considerations (i.e. including only mass and reducing Equation 3.5 to Newton’s second law of motion). In addition, the motion of each filament is evaluated as a lumped mass, translating as a result of an inner magnetic pressure. Other structural effects such as Poisson effects, potential shockwaves etc are difficult to establish.

Although the filamentary approach is an effective tool in many STC systems, it is believed that an alternative method of modelling must be adopted to optimise future pulsed power systems. It is clear that the model presently used in such experiments is insufficient to analyse the semi destructive system as described in Chapter 5.

6.2 Multiphysical FEA model

As discussed in previous chapters, use of the finite element code, allows the continuum (or object to be modelled) to be resolved into suitable finite elements - as opposed to filaments – interpolation functions between each element can be established, as well as element properties which can evaluate conditions such as the stress within the continuum. By using the multiphysical approach described in Section 3.2.2 it is possible to transfer
loads between physical environments and therefore to evaluate effects such as Joule heating due to current flow.

In order to model fully the STC system, three independent transient physical environments must be established: an environment to calculate electrical/magnetic effects, another to evaluate thermal effects, and a further one to evaluate structural/dynamic effects.

6.2.1 Electromagnetic environment

Within a given electromagnetic environment, the model must be capable of resolving the current distribution as well as the magnetic field produced by the STC. Furthermore the discharge current in the transmission system must be evaluated which can be achieved by either of two alternative solutions that can be resolved in one iteration within ANSYS. In principal there are two separate models to analyse. The first model is that of the STC itself. By resolving the STC into discrete elements, the resistance can be evaluated from:

\[ R = \frac{1}{\sigma(T,P)} \frac{I}{A} \]

where the conductivity is a function of both temperature, T and pressure, P. As a first approximation the variation of conductivity due to pressure is neglected, as shockwaves and the effect of magnetoresistance are not considered at present. The variation of inductance of the model can be derived from the energy method, in which the FEA model is supplied with current and the inductance deduced from the magnetic energy produced using:

\[ W = \frac{1}{2} I^2 L \]

Eq. 6.1

Eq. 6.2
These parameters can then be used in a reduced order modelling circuit, the solution of which is used in a Magnetic Vector Potential solution.

Secondly the overall system must be analysed, by means of a lumped circuit representation similar to that of Figure 4.5, and Figure 6.3 is a pictorial representation of the electrical environment used in 3D analysis. Only a portion of the STC is represented, which reduces the number of DOFs – as discussed later in section 6.3.2.1.

Consideration must be given to the accurate modelling of the problem. Care must always be taken to resolve the solid model (the STC) into a suitable finite element mesh, so as to allow characterisation of skin effect. Electromagnetic field penetration into conducting bodies is a function of frequency, permeability, and conductivity and calculating the field and Joule heating losses accurately requires that the finite element mesh is sufficiently fine at the surface of the conductor to capture the surface phenomena. In general, a minimum of one or two elements must be modelled through the depth (see Equation 4.25 in order to evaluate skin depth).

6.2.2 Thermal environment
The predominate purpose of the thermal model is to evaluate temperature effects due to Joule energy deposition. Over a transient time iteration the model must be able to convert the Joule energy into an associated temperature rise by:

\[ \Delta T = \frac{W_{joule}}{mC} \]  \hspace{1cm} \text{Eq. 6.5} 

where \( \Delta T \) is the temperate rise, \( m \) is the mass and \( C \) is the specific heat. Furthermore, the thermal conduction in the material can be evaluated from:

\[ Q = \frac{kA}{l} \Delta T \]  \hspace{1cm} \text{Eq. 6.6} 

where \( Q \) is the heat flux rate through the material, \( k \) is the thermal conductivity, \( A \) is the cross-sectional area, and \( l \) is the length of the region over which the thermal conduction is to be evaluated. Convection from the STC to the surrounding air may also be considered and can be evaluated from:

\[ Q = h |T_f| A (T_s - T_{\text{inf}}) \]  \hspace{1cm} \text{Eq. 6.7} 

where \( T_f \) is the film temperature (the temperature of the fluid immediately between the surface and the free stream fluid, normally taken as an average of \( T_s \) and \( T_{\text{inf}} \)), \( T_s \) is the surface temperature and \( T_{\text{inf}} \) is the free stream fluid temperature – generally assumed to be constant. \( A \) is the surface area, and \( h \) is the convection film co-efficient – which is generally a function of film temperature and therefore requires iteration.

As a general run of thumb radiation effects can be neglected if they constitute less than 5% of the total thermal energy, and these effects have previously been considered not to play an influential role in predicting the
thermal characteristics of a pulsed power system. (Muir and Nakao, 1990, Novac et al [1], 2004)

Variations in temperature due to the effect of latent heat can also be neglected when considering the semi-destructive model, as it is believed that this phase transition is avoided. However this is not the case with the destructive system, in which it is very probable that such phase changes do occur. In such situations the enthalpy of the system is given as a function of the temperature, to account for the latent energy that would be stored or released during a phase change. This is calculated using:

$$H(T) = \int \rho c \cdot dT \quad \text{Eq. 6.8}$$

where $H$ is the enthalpy, $\rho$ is the density and $c$ is the specific heat coefficient.

In a fashion similar to the electromagnetic analysis, it is apparent that to model accurately the thermal system, certain key material properties must be available and they must be at least a function of temperature. These properties include, thermal conductivity, mass density and specific heat and possibly enthalpy.

### 6.2.3 Structural environment

The structural solutions of semi-destructive and destructive analyses perhaps attempt to resolve alternative solutions, with the semi-destructive analysis attempting to model the plastic deformation of the coil, and the destructive analysis attempting to model its movement within the first moments until the peak field occurs. Furthermore, due to the extreme nature of a destructive system, there are inevitable limitations as to what can be modelled.
At this stage a simplified approximate model has been implemented in each solution, in an early attempt to model the characteristics of each. It will however be appreciated that this is simply an approximation and a full investigation is still required into the structural effect within each environment. Indeed it is the belief of the author that it will be beneficial to have a structural model for use in semi-destructive analyses, with a reduced version used in destructive analyses. This investigation is outside the scope of the current work.

Within the structural model, the solution must be able to resolve the non-linear stress/strain relationship that characterises the elastic-plastic deformation occurring in the STC, in particular the semi-destructive STC. While the structural deformation apparent in Figure 5.5 details complex phenomenon, the present investigation is limited to simple mechanical characteristics.

Therefore while ANSYS is capable of evaluating a numerous structural solutions such as the variation in elastic/plastic limits during tension, compression buckling etc, the present analysis is limited to simple mechanical behaviour. This requires the structural environment to be able to implement isotropic non-linear material behaviour for a tensile material, perhaps over temperature in the case of semi-destructive models. The governing equation is given in Equation. 3.5. Details as to mechanical relationships are given in Mechanics of Engineering Materials (Benham and Crawford, 1996) as well as ANSYS Documentation

6.2.4 Combined Multiphysics

In order to gain an accurate and complete model of the pulsed STC system of the previous Chapter, it is necessary to construct a complete finite element model using the sequential multiphysical analysis of section 3.2.2.2.2. In essence an individual physical environment must be created for each physical discipline described above, whereby the results are solved independently and consecutively during a computational solution.
Results obtained from one discipline are passed as loads to the next. Figure 6.4 shows a flow chart detailing the solution process of three separate physical environments in such a manner in ANSYS. For convenience, the abbreviations EMAG, THERM, and STRUCT have been adopted for the three physical environments involved, and they act as prefixes to identify their associated files.

![Multiphysical flow chart](image-url)
From the flow chart of Figure 6.4, and the discussion in Section 3.2.2, it can be seen that the solid and FEA models (discussed in detail below) must be the same for each environment, so as to transfer directly the load from one environment to the next. The crucial material library may be constructed separately using ANSYS Parametric Development Language (ADPL – discussed in Chapter 3) and read in as an input file to all three environments.

In each case a results file and a database are generated for each environment. The database is updated at the end of a solution, while the results file is appended by the newly generated results. This allows for the entire set of results for each environment to be analysed after the iterative process of Figure 6.4 is complete.

### 6.3 Generating the STC model

As detailed above, a particular limitation of the filamentary method is that the model can only be considered in either one or two dimensions at the most. Detailed below are the steps taken to develop 2D and 3D models of the STC arrangement.

#### 6.3.1 Two Dimensional Model of STC

The simplest form of analysis is to consider the STC as a complete toroid. This allows for a 2D cross-section analysis with an axis of symmetry along the centre line of the coil. Clearly this model is an approximation, which cannot consider the effect of the gap in the toroid, as discussed in section 6.1. However, by developing a 2D model, it is possible to analysis the accuracy of the prediction of current generated and the peak flux density at the centre of the coil, as well as allowing for future work making a direct comparison between the effectiveness of an FEA solution and the current...
filamentary model. Such work is currently outside the scope of the current Thesis.

6.3.1.1 Generating the 2D solid model

The solid model representation of the STC must include the coil itself, the surrounding air, and a far field component to model the remote effect of the magnetic field. As explained above this model must be used in all three physical disciplines, although it may not be necessarily employed in its entirety in each solution i.e. there is no need for the far field or surrounding air representations in the structural solution.

In order to reduce the model to 2D, the STC must be considered as a complete toroid, as shown in Figure 2.1, whereby the cross-section may be modelled. However, due to axial symmetry, only one side of the cross section needs to be represented. Furthermore, as symmetry exists along the central axis, only an upper quadrant needs to be modelled. Figure 6.5 details the resulting simplified model.

Figure 6.5. 2D simplification (a) complete model, (b) cross-section (c) simplified cross-section
Lines 15 to 49 of the APDL in Appendix D are used to generate the solid model shown in Figure 6.6. This model is used to represent the 2D FEA model of the semi-destructive STC given in the previous chapter.

![Figure 6.6 Solid Model](image)

### 6.3.1.2 Generating the 2D mesh

As discussed in Chapter 3, the quality of the discretisation of the medium plays a pivotal role in the accuracy of the solution. Here a mesh is developed initially in the EMAG environment, and this element matrix is then re-used in the THERM and STRUCT environments with altered field variables, element properties and interpolation functions. Care must be taken to model accurately movement of the current into the body of the coil, as both magnetic diffusion and Joule heating take place. Parabolic (quadratic) elements are used in all three environments. Lines 90–150 of Appendix D details the Loughborough APDL code used in generating the mesh shown in Figure 6.7. Again this is the model developed to simulate the semi-destructive model of the previous chapter.
Lines 228 - 238 of Appendix D detail the reading of the EMAG matrix and the conversion of the elements of this to the thermal quadratic. In this instance however the farfield elements are nulled (i.e. set such that they are removed from the solution) along with the lumped circuit model. This is also done for the structural environment between lines 272 - and 285, although the air is further nulled in this case. This simplifies the model, reducing the number of unknowns to be evaluated and thus decreasing the simulation time.

6.3.2. Three Dimensional Model of STC

In order to circumvent the limitations manifest in the 2D representations of the semi-destructive STC a complete 3D model must be established. Such a complete model has been generated at Loughborough.

6.3.2.1 Generating the 3D solid model

The typical topology and the way in which the 3D solid model is established is shown in Figure 6.8. Figure 6.8(a) depicts a topological representation of the full STC shown in Figure 5.1, neglecting the tapered nose. This solid model can however be simplified by taking advantage of
the inherent degrees of symmetry, as in the 2D example. Symmetry exists in this model in two of the planes shown in the co-ordinate system in Figure 6.8. Firstly symmetry exists in the x-y plane, and secondly, geometric symmetry exists in the x-z plane, thus reducing the model by discarding from calculations the lower and left hand section of the model as shown in Figure 6.8(b).

Figure 6.8 Simplified STC solid model

Figure 6.8(b) shows the simplified STC solid model used at Loughborough in FEA simulation. Using the geometrically reduced model presented in Figure 6.8, it allows for a reduction in the overall FEA degrees of freedom (unknowns) and hence a reduction in the overall matrix sizes and therefore the computational run-time.

Figure 6.9 below shows the coil with surrounding air used when modelling the semi-destructive system of Chapter 5, and serves to highlight the 3D representation of the STC used in contrast with that detailed in the 2D model of Figure 6.6.
6.3.2.2 Generating the 3D mesh

As already mentioned, the quality of the discretisation of the medium plays a role in the accuracy of the solution. In a similar fashion to that of the 2D model, a mesh is developed initially in the EMAG environment, and this element matrix is then re-used in the THERM and STRUCT environments with altered DOFs. 3D parabolic (quadratic) elements are again used in all three environments, although brick like elements replace simple square ones. A typical code, similar to that given in Appendix D, used to generate a 3D model is given in Appendix E - In this instance the code is again that used to develop the semi-destructive model of the previous chapter. Figure 6.10 shows a typically meshed model, again modelling the coil, the air and the far-field portions.
6.3.3 Material Models

As discussed above, both the semi-destructive and the destructive models may have alternative material models to accommodate the assumptions and simplifications required in each. The destructive model may have a reduced material model when considering the characteristics of the STC in comparison with the semi-destructive model, as in such a model no material flow or loss through vaporisation is believed to occur. Furthermore, as the semi-destructive model does not experience any change phase there is no requirement for high temperature resistive models that may be a requirement of a destructive system, nor is there the requirement to account for the latent energy absorption in the system. Detailed below in Figure 6.11 and 6.12 are the material models used for both the semi-destructive and destructive systems. It will be appreciated at this stage that due to the time constraints within the project, simplifications were required where appropriate. However the models used act as a guide to future more complex models that may be implemented.

6.3.3.1 Semi-Destructive Material Model

Accurate and appropriate material models are fundamental to any analysis. The present material library developed at Loughborough for semi-destructive environments is given in Appendix F. Properties for air and copper are given, although due to the insignificant influence of the variation in air properties with temperature these will be considered to remain constant. On the other hand the variation in electrical resistivity (Ω/m), thermal conductivity (W/(m-K)), density (kg/m$^3$) and specific heat (J/(kg-K)) are all given for copper. Although the models include data that occurs through a phase change, this data is not used in a simulation, as the STC in question does not exceed the melting temperature range. Furthermore the variation in enthalpy is not used in this model. Thermal expansion is also considered to be negligible during the time of the
simulation. Figure 6.11 shows graphically the material models using the units given above, as they are given in data format in Appendix F.

Figure 6.11 Material properties used over temperature in Kelvins (a) resistivity, (Ω/m) (Matula, 1979), (b) thermal conductivity, W/(m-K) (Ho et al, 1972, Simon et al, 1992) (c) density, (kg/m³) (Simon et al, 1992, Hahn, 1970) (d) specific heat, (J/(kg-K)) (White and Collocott, 1984)

Due to the lack of data available for use with pulsed load experiments, a bilinear kinematic hardening model was assumed and the data was iteratively adopted with a Young’s modulus of 1.1E11 N/m², and with a concurrent limit of proportionality and elastic limit approximately between 1.15E8 N/m² and 0.55E8 N/m² depending upon temperature (Ledbetter and Naimon, 1974). In each case a tangent modulus of zero was introduced after the yield point, thus giving the material an elastic-perfectly plastic characteristic (i.e. a tangent modulus of zero after yielding). This
simplified relationship is shown in Figure 6.12 below over the range of temperatures indicated.

![Bilinear kinematic hardening Stress (N/m²) vs Strain (%)](image)

Figure 6.12 Bilinear kinematic hardening Stress (N/m²) v Strain (%)

- 254 K
- 454 K
- 654 K
- 854 K
- 1054 K
- 1250 K

The material was also considered to be incompressible, and have a Poisson's ratio of 0.49 (0.5 was not used as it invalidates the governing equations). As an approximation, dampening in the system was neglected.

The full material library used for semi-destructive STC analysis is given in Appendix F. Material models for both copper and air are represented here.

### 6.3.3.2 Destructive Material Model

Due to the magnitude and rate at which energy is deposited during the production of ultrahigh magnetic fields, a far more complex physical phenomenon exists in a destructive STC experiment than in a semi destructive arrangement. As the coils are exposed to much larger energies it is probable that melting and possibly vaporisation will occur. While the present model can adopt considerations of latent energies, other effects...
such as the structural phase changes are an important limitation. Furthermore the Equation of State for materials exposed to destructive extremes are difficult to ascertain, and extremely complex to implement. As discussed in Chapter 2, it is probable that destructive STC devices will experience shockwave formation within the material, leading to non-linear diffusion characteristics. As in previous modelling methods (Muiru and Nakao, 1990, Novac et al [1], 2004), it has been considered appropriate to make certain assumptions and simplifications when modelling such systems with a focus on peak field prediction. These assumptions for the current destructive model are given below.

The STC itself is assumed to be incompressible. Furthermore it is assumed that in the time scale over which an experiment takes place no significant thermal expansion occurs. In a similar manner, the density, thermal conductivity and specific heat are assumed to remain constant, with a value taken from standard temperature and pressure data at approximately 300 Kelvin. The structural phase change that would be possible is not implemented here, with the structural model maintained from the semi-destructive analysis. Under high forces and temperatures the model will act in a perfectly plastic manner. The electrical resistivity is however included as a function of temperature, with the extreme region being implemented from the SESAME database (see Chapter 2) which allows for both current migration and energy absorption. This variation in resistivity for copper over this further temperature range is shown in Figure 6.13.
It is interesting to note that beyond a certain temperature the electrical resistivity begins to reduce as the metal releases more mobile electrons. Equally the enthalpy of the system is given as a function of temperature in Equation 6.9. The variation in enthalpy of copper is shown graphically in Figure 6.14:
The latent heat of fusion and vaporisation are $205E^3$ K/m$^3$ and $4796E^3$ K/m$^3$ respectively in this model. The ADPL used to generate the material model implemented in this destructive simulations is given in Appendix G and as above properties for both copper (material 1) and air (material 2) being given.

6.3.4 Establishing boundary conditions, loads, and solution options

For an accurate solution, suitable boundary conditions, loads and solution options must be set. Infinite boundary surface flags are set on the outer edges of the far field as well as symmetry with the EMAG environment. Similar symmetry constraints are applied to both the thermal and structural environments.

In relation to the semi-destructive environment, the initial circuit parameters are represented within the EMAG environment. However in order to accommodate the variation in parameters, adjustments are made at a time of 5 µs and again after 8 µs. This allows for the increase in resistance and inductance inherent in the transmission system due to heating and movement.

Surface flags highlight areas of convection between the coil and the surrounding air, however radiation losses are not considered. The simulation is run over a suitable period in order to evaluate the peak field produced, as well as evaluating the deformation of the coil in the semi-destructive environment. Loads between different physics environments are passed directly from results files to databases in each individual time iteration as highlighted in Figure 6.4.

6.4 Results
Detailed below are some of the best results achieved during this particular program of research. Due to the limited time scale only a selected number of results are highlighted from both semi-destructive and destructive STC models, it is however the intention that these results should act as an indicator to potential future work.

6.4.1 Semi destructive simulation results

6.4.1.1 Discharge current

The 2D predicted initial discharge current that passes through the FEA STC model is given in Figure 6.15(a) and is comparing with the results given in Chapter 5.

![Graph showing discharge current comparison](image)

Figure 6.15 Discharge current Comparison with results

As can be seen, the simulated discharge current reaches a peak of 1.05 MA compared to an actual current of 1.09 MA in a similar time, which is an agreement of better than 5%. As can also be seen from Figure 6.15(a), it
is apparent that a slight phase shift is appearing between the actual and simulated currents, due to the time variation of impedance within the real system which is difficult to quantify within the 2D simulated environment.

![Figure 6.16 Simulated Discharge current over 150 μs](image)

Figure 6.16 simulates the discharge current over a much larger period of 150 μs and serves to show the ability to model the decaying underdamped oscillation of the current in the coil.

**6.4.1.2 Central flux density**

The 2D predicted central flux density predicted by the FEA STC model is given in Figure 6.17, where it is compared with the experimental results shown earlier in Chapter 5. Figure 6.18 shows the simulated flux density over a period of 150 μs.

The peak magnetic flux density is predicted as just under 25 T while the experimental value is 26.4 T, with this 5% error also being evident in the prediction of the phase of the first peak. As is clear from Figure 6.17 the magnitude and phase of the flux density in the second reverse peak is not as accurately predicted, due in part no doubt to the currents simulated in Figure 6.15. It is also believed that the increase magnitude and phase shift are associated with the dynamic approximations made for a cylindrical
model. This peak flux density is 16% higher than the experimental, although the time in which it occurs is still accurate to within 5%.

![Graph](image)

**Figure 6.17 2D Magnetic flux density comparison with results**

- **Experimental Flux Density**
- **2D Simulated**

![Graph](image)

**Figure 6.18 2D Simulated magnetic flux density over 150 µs**

- **Experimental Flux Density**
- **2D Simulated**

In a similar manner to Figure 6.16, Figure 6.18 simulates the 2D magnetic flux density produced over a period of 150 µs, and acts to serve as an indicator to the possibility longer simulations.
In contrast to Figure 6.17, Figure 6.19 details the simulated peak flux density using the 3D STC model detailed above. As can be seen, the peak field agrees to within a few percent, and it is possible that this agreement is therefore within the experimental error of the set-up. The 3D model would also appear to be more representative of the system up until the point just after the peak field, as the notable phase shift is less apparent.

![Figure 6.19 3D Magnetic flux density comparison with results](image)

6.4.1.3 Peak temperature

As discussed in the previous chapter the temperature of the STC is a variable that as yet has to be measured. It is difficult therefore to assess the veracity of any simulated thermal results at this stage. However the following results show the 2D simulated temperature.

Reviewing the coil and air in Figure 6.6 it is probable that, while the current migrates through the coil, the temperature stays as a maximum at the top most inner edge – the initial location of the current. Figure 6.20 shows the variation in the 2D simulated temperature over 150 µs at this point, as well
as the temperature at the mid point and inside the central region of the coil, on the inner-side half way down the height.

![Temperature variation graph](image)

As can be seen, the temperature initially begins to climb dramatically up to a peak of approximately 1300 K, well within the melting point of copper. Oscillations in the temperature correspond to the oscillatory nature of the current circulating in the coil and producing Joule heating. As can be seen the rate of rise in temperature appears to decline to zero and then begins to drop after approximately 75 μs, as the heating energy in the coil becomes less that the conduction to the remaining coil and the surrounding air.

6.4.1.4 Coil Deformation

As discussed, simulation of the deformation of the semi-destructive coil can be used as a modelling tool in such processes as metal forming. It is appropriate therefore that the full 3D model is used when evaluating the deformation that is experienced. Figure 6.21 below shows the test
specimens used in the work of the previous chapter and their predicted displacement 150 µs after the start of the capacitor bank discharge.

Figure 6.21. Deformed semi-destructive STC (a) recovered test piece (b) predicted shape - vector displacement in m (c) Von Mises stresses - isocontours in N/m²
The measured and predicted final forms of the STC are compared in Figure 6.21(b), with the photograph of Figure 6.21(a) shows the flanged shape of the STC recovered after the experiment for which the magnetic field history is recorded in Figure 6.18. As is apparent from the results of the simulation that suitable boundary conditions have been applied such that the nose portion of the coil remains stationary during the experiment, and it is the intention that this restricted movement mimics the act of this nose portion being clamped in position.

Due to magnetic diffusion generating a current distribution with peaks located at the outer edge of the STC, the combined electromagnetic stress and thermal effects have caused the material to become plastic and to deform outwardly, mainly at these edges. Figure 6.21(b) is a simulation of the final shape of the deformed STC coil 150 µs after the beginning of the experiment, and this clearly corresponds extremely well with the actual shape of the recovered STC. Measurements show that the actual central inner radius of 11.4 mm is simulated as 11.1 mm. As discussed in the previous chapter the measured radius and axial length at the point highlighted in Figure 6.21(a) are respectively 17.1 mm and 34 mm, which again compare well with corresponding measurements from the simulation of 17.2 mm and 32.8 mm. All other measurements of the actual geometric translations agree with those simulated to within the same degree of accuracy.

The deformation is most pronounced diametrically opposite the gap where the current enters and leaves the STC, and Figure 6.22 shows 3D predictions of the displacement and associated velocity of the radius and axial length at this point. Predictions shows that the edge of the coil has come to a complete rest about 150 µs from the start of the current discharge, and this can be taken as indicative of the coil as a whole.
It can also been seen from Figure 6.22 that when the peak field occurs after 3.8 μs (see Figure 6.12) the outer rim has already expanded by almost 0.1 mm and is travelling at a speed of 100 m/s. The dimensions of the STC are therefore changing very rapidly.

The introduction of a 3D model allows the induced stress distribution within the STC to be observed and potentially allows for the possibility of any structural weaknesses to be highlighted. Figure 6.21(c) presents a Von Mises stress plot when the coil has finally come to rest. However, as discussed above the structural model is based on several assumptions that will not be accurate in the real specimen and it is likely that these approximations will affect the veracity of this computed data. However the information is given here to indicate the potential for future work.

Figure 6.23 presents spatial distributions after 150 μs of the temperature, Joule heating and current density throughout the STC, with the highest temperatures around the inner side of the flanges and where the transmission line meets the coil. The results in this Figure highlight the breadth and depth of information that is available, by pinpointing the magnitude and location of such quantities from the simulation.
6.4.2 Destructive simulation results

In a similar manner to that discussed above, the results below are those achieved within the limited time constraints. Results are given where available, and act as an indication of the potential applicability of the code at this stage for destructive simulations, and it is clear that further work will be required to evaluate the veracity of further design simulations.

6.4.2.1 Design A

6.4.2.1.1 Discharge current
The 2D predicted discharge current of Design A is shown in Figure 6.24. The simulated current is compared with the experimental current up to 2.4 μs, some time after the peak has occurred.

![Figure 6.24 Discharge current comparison with results over 2.4 μs](image)

The simulated current reaches a peak of 912 kA in a time of 1.42 μs, while the experimental data suggest that the peak of 901 kA occurs after 1.35 μs. The agreement in peak current is within 2%, and the accuracy in rise time is within 5%. It will be noted that the profile of the discharge current begins to deviate from that simulated after the peak, probably due to various unexpected system properties due to the high energies involved.

As discussed in Chapter 2, current migration through the coil as the discharge continues is believed to play a role in the peak field that is ultimately produced. Figure 6.25 presents the current density in the cross section of the 2D model after 0.25 μs and at the time of peak current, 1.42 μs.
As can be seen in Figure 6.20, the current initially occupies the inner most upper surface of the coil, as would be expected. The analysis allows the user to observe migration of the current over the cross-section of the coil during the discharge. As can be seen from the Figure, the movement of the coil is also indicated.

6.4.2.1.2 Central flux density

As discussed in Chapter 5, the experimental magnetic flux density recorded by a Faraday rotation method is the integral over the magnetic field experienced over the axial length of the crystal, in this instance 5 mm. Therefore in order to extrapolate this field from the analytical result, it is
essential to mesh the relevant axis with suitable nodes such that the field can be integrated from the results.

Thus it is possible that the integral of the simulated flux is evaluated and compared with the experimental data. Due to the symmetry of the coil, this simulated signal is taken from the axial integration over 2.5 mm of the coil length as only the upper half of the coil is modelled – see Figure 6.5. This is achieved using the following expression:

\[
\text{FluxDensity} = \frac{1}{n_{\text{nodes}}} \sum_{n=1}^{n_{\text{nodes}}} (\text{NodeFlux})_n
\]  
Eq. 6.10

where 'nodes' are the number of nodes along the axis, represented along a length of 2.5 mm from the centre, and (NodeFlux)_n is the simulated flux at each node along this line.

Figure 6.26 compares this simulated integral with the 2D experimentally extracted signal from Figure 5.10 in Chapter 5.

![Figure 6.26 2D Axial flux density](image)
The average peak magnetic flux density is simulated to reach 141 T in a time of approximately 1.15 µs. This compares well with the experimental data, suggesting that the average axial flux density peaks at 140 T in a slightly longer period of 1.2 µs. Both the magnitude and the rise time of the peak field production have been simulated to within 4.2%. As any movement of the coil affects the central flux passing through the crystal, these results suggest that the coils displacement and current migration have both been acceptably simulated.

The analysis used above was also used to evaluate the potential for flux density prediction using a full 3D model. Figure 6.27 shows a comparison of the experimental results with the simulated flux density.

As can be seen from Figure 6.27, the 3D model predicts that the average peak flux density produced in the crystal reaches 129.5 T, at the same time as the experimental data. In this case, the accuracy of prediction is within 7%. Due to the apparent accuracy of the 2D simulation, it can only be assumed that the 3D model is less beneficial in the current model in assessing the peak flux density along the whole of the STC axis. This
however does not negate the benefit of this model, as the accuracy is within an acceptable limit. Thus it is possible to assess further aspects of the experiment that are only available in a 3D analysis, such as investigations of alternative geometric configurations.

In a manner similar to the simulated images of Figure 6.18, the 2D cross-section of the special distribution of flux density is shown in Figure 6.28 after 0.025 μs while the highest axial flux is achieved after 1.15 μs.

Figure 6.28 2D Spatial magnetic flux density in Teslas (a) 0.025 μs (b) 1.15 μs
It is apparent that the simulated peak flux density shown in Figure 6.28 is higher than the peak indicated in Figure 6.25, is due to the fact that the flux density given in Figure 6.25 is the integral of the signal on the central axis. In the simulation the central peak reaches over 162 T in 1.2 μs.

It is important to note that visually the displacement of the coil could be regarded as minimal. However, this displacement, along with the current migration, is a fundamental prerequisite to predict accurately the flux density of any destructive STC system. Figure 6.29 compares experimental axial flux density data with predictions from a model that does not include these factors. The error in peak field prediction and the rise time is quite considerable, at 13% and 23 % respectively.

 ![Figure 6.29 2D Axial flux density comparison with no movement over 1.45 μs](image)

It is interesting to note from Figure 6.29 that the analysis would indicate that movement of the coil would appear to be the main factor affecting the most efficient production peak flux density. Figure 6.29 would appear to suggest that if the movement of a coil is substantially limited, for example by inertial effects due to a large mass, the peak field produced may be
larger. While this characteristic may be known to research establishments investigating STC experiments, the author is currently unaware of any publications to date which indicate this attribute. Indeed this teaching leads away from that disclosed by Forster and Martin (1967)

### 6.4.2.1.3 Peak temperature

In a similar manner to that detailed above the temperature of the coil can also be simulated during the discharge. However approximations with regard to the density and specific heat mean that this value is not exact, although it can be used as a good indicator of the thermal effects within the coil itself. It is also difficult to assess the accuracy of the temperature model, as it is difficult to assess empirically the temperature of the coil during experimentation. At this stage, the results merely indicate the potential for further analysis and investigation to assess the accuracy. Figure 6.30 shows a 2D axially expanded image of the spatial temperature distribution simulated within the coil at the time of peak field.

![Image of temperature distribution](image)

As can been seen Figure 6.30 suggests that the areas initially supporting the largest current density, namely the inner edges, have the largest rise in temperature. Figure 6.31 below shows the variation in temperature at the inner edge at the top of the coil.
It will be seen that there is an initial increase in temperature until the point at which this inner material would vaporise, after which the temperature remains almost constant as latent energy is absorbed.

### 6.4.2.1.4 Coil Deformation

As is evident from Figure 6.29 that the coil deformation and current migration both play an influential role in the overall production of peak field, with the deformation perhaps being the more influential. It is true that when these two factors are neglected the prediction of the field produced increases. Using the simplified structural model detailed above, the deformation can be approximated to perhaps act as an indicator for future designs attempting to increase the efficiency of the STC system. Figure 6.32 indicates the 2D deformation that occurs up to the point when the peak axial magnetic flux density is produced.
It is apparent from Figure 6.32 that the inner top edges of the coil deforms the most over the period up to the point of maximum axial flux density.

### 6.4.2.2. Design B

#### 6.4.2.2.1 Flux Density

The measurement of the flux density produced in Design B differs from that of Design A, in as much as it is the flux produced at the absolute centre of the height axis of the coil that is recorded, as opposed to the average magnetic flux density produced along the entire axis of the Faraday crystal.

Figure 6.33 compares the measured and predicted 3D time variation of the flux density at the central point of the axis of coil.
As can be seen the 3D code shows that the maximum flux density and the time at which it occurs are predicted to within 2% of the experimental data, which is close to the experimental error introduced by the probe. In this instance the 3D model is able to predict accurately the central flux density produced.

**6.4.2.2.2 Coil Deformation**

As discussed above, analysis of the deformation of destructive experiments are limited to within a reasonable timeframe, i.e. up until the structural integrity of the coil begins to breakdown.

The X-ray pictures in Figure 6.34 show the X-rays given in the previous chapter for a coil similar to that producing the flux density given in Figure 6.33, and compares these with overlapping images of a 3D simulation of
this experiment. As discussed in Chapter 5, it is evident that due to the magnetic pressure generated the coil has started to expand radially. However the expansion is not homogenous, with the area highlighted by the arrow 'A' in Figure 6.34(a) travelling furthest in this time. Also obvious from the figure is a widening of the gap in the coil at the connection to the transmission system and some necking of the coil in the lower left section after 820 ns, probably due to initial inhomogeneity in the cross section of the coil.

Figure 6.34. X-ray dynamics Design B (a) images at 0 ns and 820 ns (b) corresponding predicted shapes - scale indicates vector displacement in meters
In Figure 6.34(b), predicted end views of the coil are superimposed on the experimental recordings, and the correlation is again acceptable. The darkened line around the top of the FEA coil after 820 ns is due to the radial expansion at the centre of the coil being slightly greater than it is at the end, something that to be fully observed normally requires two X-ray pictures taken at a right angle. Necking is not apparent in this figure, due to the initially uniform cross section. The author is not aware of any published literature which indicates such deformation.

Figure 6.35 shows the predicted radial and axial length dynamics of the coil at the point highlighted by the arrow 'A' in Figure 6.34(a). At the time of the peak field the outer edges have translated almost 0.34 mm radially, reaching speeds in excess of 1500 m/s.

There are clearly limitations in predictions for the destructive experiment, when large thermal and structural instabilities (shock waves, phase transitions) become significant after a certain time. The X-ray image
obtained 1200 ns from the start of the discharge in Figure 5.14 highlights the explosive petalling effect that is certainly beyond the capabilities of the current 3D model. However, this occurs at a time far beyond that at which the peak field is produced (see Figure 6.33).

6.5. Conclusions

It has been demonstrated that accurate modelling of metallic structures (such as a STC) under heavy transient electromagnetic loading is possible using FEA. In particular, it has been shown that limitations introduced by the present filamentary model have the potential to be overcome with the use of a 3D elastic-plastic modelling environment, essential in a number of further applications.

A major benefit from FEA modelling is the wealth of information that then becomes available. Electromagnetic, thermal and structural data can all be deduced at any given point in time without the dimensional simplifications common in other simplified filamentary. The ability to work in three dimensions allows for quick problem isolation and system innovation, as well as providing a deeper understanding of the system as a whole.

It is clear however that significant limitations still exist when considering such pulsed magnetic fields. There is a need for more accurate material data for use in high power systems. At present certain data is perhaps unreliable which can considerably influence the theoretical predictions and this is an area for future development outside the scope of the present work.
Chapter 2 focused attention on several methods of producing magnetic fields, and concluded that only destructive pulsed magnetic fields can produce ultrahigh magnetic fields (> 100 T). In Chapter 5 ultrahigh magnetic fields were produced by means of an STC configuration and were shown to have an extremely high “efficacy” compared with other published results. By employing similar laboratory equipment and making several modifications to the arrangement shown in Figure 5.2, it is possible to construct a Θ-Pinch EMFC system, hereafter known as an EMFC system. Such a system allows for the investigation of the alternative and perhaps more effective method of ultrahigh field production.

This chapter details work performed at Loughborough to investigate a Θ-Pinch EMFC system and to consider potential enhancements by analysing the geometric configuration of the liner etc, as well as investigating further enhancements such as cascades (detailed in Chapter 2). In particular this Chapter details a series of experiments specifically designed to investigate EMFC systems. The first of these investigated the effectiveness of the Cnare effect EMFC using similar apparatus to that described in previous chapters.

7.1 Cnare Effect

As discussed in Chapter 2, the Cnare effect is the production of a peak magnetic field in an electromagnetically driven system without the requirement for an initial "seed field". The experimental configuration of such a system is not dissimilar to that described in previous chapters, detailing with experimental STCs arrangements. In fact, only relatively minor modifications need to be implemented to establish a suitable arrangement. Since in a Cnare system there is no need to provide a seed
field, the experimental equipment is also further simplified over other EMFC systems that requiring such a facility.

The main difference between the arrangement of the STC experiments, described in Chapter 5 and a Cnare EMFC system is the load itself. Figure 7.1 below shows a EMFC system arranged to produce a peak magnetic field.

![Figure 7.1 EMFC using the Cnare effect](image)

By comparing Figure 7.1 with Figures 2.2 and 5.1, it is apparent that the EMFC arrangement can be considered as an STC provided with a 'liner'. Along the central axis of the STC - hereafter termed the driving coil - and inside the liner there is a ceramic covering arranged to accommodate a probe, of the form described in section 4.2.1. The ceramic covering is intended to protect the probe during experimentation, and it is not an integral part of the system but is positioned so that the magnetic field produced can be recorded.

Again, in a manner similar to that described earlier the switch S is closed to discharge the stored energy from a capacitor bank into the load. This establishes a magnetic field between the driving coil and the inner liner and as the magnetic field diffuses through the liner, inductive currents are produced. The magnitude of these is limited by the finite conductivity of the liner, and some of the magnetic field permeates the liner and establish an inner field. As suggested by the modelling techniques applied at
Loughborough (Novac et al [1], 2004) the Lorenz forces established by the rising currents in the driving coil and the liner produce a force of repulsion between the liner and driving coil and as the liner is of considerably less structurally integrity than the driving coil, this causes a compression of the liner. As the distance between the liner and the driving coil increases, their mutual coupling is reduced. However at the same time the self inductance of the liner is increasing. Previous analytical work using filamentary analysis had suggested that at a certain moment during the implosion of the liner the current begins to reduce and eventually reverses when the liner is considered to be completely decoupled from the driving coil, as its current is produced as a result of a self voltage due to the central field being compressed as the liner implodes (see Chapter 2). In the final moments a large magnetic field is produced at the centre of the coil and this is known as the Cnare effect.

The previous analytical work had predicted the efficiency of various geometric arrangements of driving coil and liner, the outcome of this work suggested a range of geometries suitable to the experimental capabilities at Loughborough.

The work suggested liners with an inner radius ranging from approximately 20 mm to 30 mm would produce the most efficient systems for the energy capabilities available. It also suggested that liners which had an axial length larger than that of the driving coil, deformed in a manner that allowed the central probes to survive for longer, and thus to record higher central magnetic fields (Novac et al [1], 2004)

Table 7.1 details three configurations tested experimentally using the arrangement of in Figure 7.1. The three designs are termed S, M, and L, correlating to Small, Medium and Large.
In each experiment the driving coils are provided by single copper sheet in the same fashion as the STCs of previous chapters. In contrast, each of the liners had been manufactured from 6082 aluminium alloy (99.99\% pure aluminium), since the geometric symmetry of each liner was paramount to a stable implosion. Copper liners, while conductively better, were more difficult to manufacture with a constant radius and wall thickness within the cost limitations of the project. The wall thickness of the aluminium liners could be maintained to a tolerance of less than 10 $\mu$m.

In contrast to the analytical predictions, it was also necessary to manufacture design S with a driving coil that had a larger axial length than that of the liner. This arose because that during experimentation it was discovered that the energy density in the slender neck of the driving coil caused excessive mass loss through vaporisation, resulting in a premature open circuit.

### Table 7.1 Cnare effect geometric arrangements

<table>
<thead>
<tr>
<th>DESIGN</th>
<th>LINER</th>
<th>DRIVING COIL</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Inner Radius (mm)</td>
<td>Wall Thickness (mm)</td>
</tr>
<tr>
<td>S</td>
<td>20.0</td>
<td>0.5</td>
</tr>
<tr>
<td>M</td>
<td>25.0</td>
<td>0.5</td>
</tr>
<tr>
<td>L</td>
<td>31.0</td>
<td>0.5</td>
</tr>
</tbody>
</table>

**7.1.1 Experimental Configuration**

In Cnare type arrangements the stored energy supplying the pulsed power system was obtained from a capacitor bank, see Figure 7.1. This comprised four 52.64 $\mu$F capacitors, connected in parallel as shown in Figure 4.3, with each capacitor having an internal inductance of 7.2 nH,
and a resistance of 1.3mΩ. The capacitor bank had a rating of 30 kV, but for safety 25kV was rarely exceeded. This provided a total stored electrostatic energy of just over 65 kJ and all Cnare experiments were conducted using this level of energy.

The charging and isolation equipment used previously again connected the capacitor bank to the transmission line. The line comprised parallel copper plates tapering at the connection point of the load and connected to this via a Titan Corp, Model 40302 rail gap closing switch. A schematic of the rail gap switch, and its accompanying equipment and load is given in Figure 7.2

As is shown Figure 7.2, the switch was always initially pressurised to a value that was based on the voltage of the system, with a pressure of approximately 22 Psi using a 7:1 mixture of Argon/Oxygen (see Figure 4.10). Before and after experiments, the switch was flushed, so that this mixture was always accurate.
a Titan Corp 100kV Marx generator was used to initiate the switch. The Marx generator was connected to the rail gap via a high voltage cable and a series of capacitors, Cs that conditioned the voltage spike used to initiate the bank. Triggering the Marx generator could provide a 100 kV voltage pulse with less than 1 ns jitter on single shot triggering.

The total resistance and impedance of the transmission system, including the switch and the tapered portion of the transmission plates were 35 nH +/- 1 nH and 2 mΩ. This was estimated by connecting a large load of known value to the transmission system, and discharging the capacitive energy into the load. The current discharge profile, observed by the dI/dt probe indicated in Figure 7.2, was then used to evaluate the impedance by using the analytical approach of section 4.1.3.2. Several discharges enabled the required values to be accurately established.

The driving coil in each Cnare experiment was attached to the transmission line at the tapered position, and held in place mechanically. A thin film of aluminium between the driving coil and the transmission line improved the connection, and reduced the system resistance. At all times the transmission lines were retained in place by weights, usually building bricks to prevent the plates separating due to magnetic forces acting during a discharge. Mylar separated the plates, with sufficient protrusion provided to prevent flashover, as discussed previously. The neck of the driving coil was clamped, such that the feed gap was reduced, and the implosion geometry of the liner was improved. Three 50 μm Mylar sheets filled the gap in the driving coil, and isolated it from the liner.

In early experimentation, and although best engineering care was taken to prevent such an occurrence, it was found that shockwaves developed during the implosions caused an early failure of the flux density probes at the centre of the load. In order to eradicate these shockwaves, the liner was encased in a sealed chamber which was evacuated prior to discharge. Figure 7.3 shows a typical EMFC load.
As a useful indicator the ruler shown in Figure 7.3 is approximately 160 mm in length. The liner chamber was constructed from a cylindrical plastic tube of approximately 0.9 mm thick, arranged such that it fitted neatly within the driving coil. The liner itself was lightly glued to the inner surface of the chamber. The thickness of the glue was negligible, and the gap between the driving coil and the liner was dictated by the thickness of the cylinder. Each end of the chamber was sealed with 2 mm of transparent polycarbonate with small hole at the central axis enabling a magnetic probe to be introduced. A further hole enabled a vacuum tube to be attached, and each aperture was sealed with epoxy resin. The vacuum tube was connected via a gauze filter to a vacuum pump, which was able to evacuate the chamber to approximately 10^{-2} torr (roughly 1.3 N/m^2). A valve positioned on the vacuum tube isolated the chamber from the vacuum pump. This, and the gauze filter prevented the flow of debris, during or post experimentation, into the pump.

As can be seen from in Figure 7.3, the connection to the transmission system to the coil was tapered, so that the energy density was increased only before entering the coil. Due to the experimental arrangement, it was
however necessary to provide a neck portion extending to the cylindrical portion of the driving coil. It can also be seen that the point of connection on the driving coil, which is used to connect to the transmission line, is suitably polished to provide a smooth surface, thus reducing the line resistance.

The experimental set-up used in all Cnare experiments is shown in Figure 7.4. For clarity the external components required by the switch, as shown in Figure 7.2, and the vacuum pump are omitted from the Figure.

As indicated the discharge current is recorded using an inductive probe. In a manner similar to that shown in Figure 5.2, attenuators and integrator are used to condition the signal entering the oscilloscope, with the signal attenuated via a 1:10 (20 dB), 1 GHz 2 W attenuator. The signal was integrated using the integrator shown in Appendix C. Similarly, the magnetic probe signal is also split, before being attenuated or integrated. All probes are connected to the oscilloscopes via 50 Ω co-axial transmissions, with a short section of twisted wire to connecting the probe to the co-axial transmission. The transmissions were further encased in copper sheet approximately 0.5 mm thickness to shield against noise.
The magnetic field probes are positioned at the central axis of the liner chamber such that the turn of wire was at the centre of the axial length of the liner. They comprise one turn of 100 µm diameter polyamide-insulted wire wrapped around a glass mandrel 0.8 or 1.0 mm diameter, retained in place by epoxy and shrink grip. The glass mandrel was sealed within an oil-filed ceramic tube of outer diameter of 2.45 mm. Calibration was performed by comparing the output for a magnetic flux density rising rapidly to more than 10 T in a single-turn coil with that given by a precisely manufactured multi-turn calibration coil of much greater diameter, as discussed previously. Current was provided by a 17 kJ fast capacitor bank, and the calibration also confirmed the integrity of the probe under mechanical stress and voltage conditions approaching those experienced in the harsh environment of the experimental programme. The overall calibration error is estimated to be less than 2%. All probes also shared a common earth, at the capacitor bank. All loops were eradicated to reduce the presence of spurious noise, although small errors could still occur with low levels of background noise on the dB/dt probes.

As in similar STC experiments, precautions were taken to provide a safe environment for the equipment, as well as for personnel. Due to the fact that the driving coil expands and explodes, 30 mm wooden sheeting, reinforced with 2 mm stainless steel was positioned around the load to protect the laboratory from debris.

As discussed in Chapter 4, prior to installing diagnostic equipment, tubes covered with cigarette paper were positioned in the location intended for such equipment. After the experiment, if the shockwaves emanating from the exploding load had perforated the cigarette paper, the position was regarded as unsuitable to house equipment.

Again all charging, isolating, and firing control was conducted from outside the laboratory in the control room as shown in Figure 7.4. Prior to re-entering the laboratory, the room was vented to remove metal vapour, in particular aluminium vapour, resulting from the destroyed liner.
7.1.2 Magnetic Field Production

By using the arrangement detailed above, the designs of Table 7.1 were investigated and their magnetic field production recorded. Table 7.2 details the highest flux density recorded for each design.

<table>
<thead>
<tr>
<th>DESIGN</th>
<th>MAGNETIC FLUX DENSITY (T)</th>
<th>APPROX. MAXIMUM dB/dt (10^8 T/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>S</td>
<td>150</td>
<td>3.0</td>
</tr>
<tr>
<td>M</td>
<td>230</td>
<td>2.5</td>
</tr>
<tr>
<td>L</td>
<td>170</td>
<td>2.5</td>
</tr>
</tbody>
</table>

Table 7.2 Highest Magnetic Flux density produced

As can be seen, design M appears to be most effective at producing a high flux density, design S is capable of producing the highest rate of change of flux density. This is a key aspect of any further high-voltage inductive systems, but is outside the scope of this present thesis.

It is also possible to evaluate the efficacy of each system above by comparing the magnetic flux density produced to the energy initially stored as highlighted in Chapter 2. Figure 7.5 shows a set of data of the dB/dt and the integrated flux density recorded from design M, and Table 2.2 shows the efficacy of such a system, in comparison with other published results.
Figure 7.5 Magnetic flux density recordings, Design M, (a) dB/dt ($10^6$ T/s), (b) Flux density (T)

From Figure 7.5 it is initially apparent that spurious noise in the first few microseconds causes a high frequency oscillation on the dB/dt signal, but this is eliminated when integrated. As the liner begins to collapse, it is clear that the time rate of change of magnetic field experienced by the probe begins to rise dramatically after approximately 8 μs. After about 11.5 μs the probe has probably been destroyed, as the imploding liner
comes into contact with the outer casing of the probe. At this time the integrated signal reaches its maximum of approximately 230 T.

The experiment detailed above is indicative of the best results of peak field production achieved. As mentioned earlier, it is possible to achieve higher magnetic field by the use of an initial seed field, and the use of an initial field was also investigated using design M.

7.2 With seed field

Most EMFC devices work on the principle of compressing an initially present field by some actuator, as detailed in Chapter 2. Such systems however require further experimental equipment over the Cnare effect systems that can complicate the elegance of these simpler systems. However it is possible to produce higher flux densities when comparing each system. A diagram of the field injection system used at Loughborough for injecting design M with a seed field is shown in Figure 2.6, where Helmholtz coils are positioned either side of the driving coil, such that when they are energised they produce an almost constant central magnetic field.

When designing such systems, it is imperative to consider certain key requirements and at Loughborough there were geometric limitations due to the arrangement of the liner and driving coil load. Furthermore there were energy limitations and the initial field was limited to being supplied via a secondary 2400 μF capacitor bank rated at 3.5 kV. This bank therefore could store and discharge an estimated 14.7 kJ of energy. A design requirement of the applied seed field is that the magnetic field produced is not too small, such that the system is not effective. Equally that it is not so large such that turn-around of the liner occurs, before the final implosion volume is reached.
In the present investigation the design of the initial field coils was optimised, using the filamentary analysis numerical program and confirmed using ANSYS®. The solution was a compromise between a greater wire diameter, giving an increased field strength, and the radial length of the initial field coils. Initial field coils with a large radial length dictated that the length of the nose from the transmission to the cylindrical portion of the driving coil would have to be increased, which in turn would increase both the main system inductance and the associated manufacturing difficulties.

The eventual design used 3.1 mm overall diameter enamel insulated copper wire. The calculated inductance of each coil was 271 μH with seven layers each having seven turns and wound on a plastic mandrel 80 mm in diameter and cast in epoxy resin. With an axial distance between the coil centres of 75 mm, the total equivalent resistance and inductance of the initial field coil system were 176 mΩ and 634 μH and the maximum flux density that could be produced at the implosion centre was about 2.5 T. Figure 7.6 below shows a typical flux density variation at the centre point between the initial field coils.

Although not considered here, it is interesting to note the lack of homogeneity of the seed field produced within the bore of the liner indicated by the analytical solution produced by ANSYS. Such lack of
homogeneity may indeed given rise to further non-uniformities in compression, and is an area for further investigation.

To enable many tens of experiments to be withstood with minimum repair, and to provide protection from the electromagnetic influence of the liner during an experiment, each coil is encased in a two layers of 2 mm polycarbonate containing a 2 mm stainless steel electromagnetic shield (Muir et al., 1975). The thickness of the electromagnetic shield was such as to allow injection of the initial field (when the skin depth in steel is 37 mm calculated from the frequency in Figure 7.6) and to protect the coils during the implosion (when the skin depth is evaluated at approximately 1 mm). The coils continued to function after several tens of shots which, together with results from analytical solutions, confirmed that the electromagnetic shield acted as required throughout the experimentation.

A metallic structure is necessary to maintain the two coils at the required position during the initial field injection, when the peak attractive electromagnetic forces can reach $10^4 \text{ N}$ between each coil, and also to limit the outward movement as the driving coil explodes. The complete arrangement can be seen in Figure 7.7.
The two capacitor banks, together with the shields and the metallic structure are all connected to a local common ground of the experiment.

From Figures 7.5 and 7.6 it is apparent that the time taken for the initial field to reach the maximum of 2.5 T is considerably longer than the time taken for an EMFC implosion to occur. As such it was a requirement that further experimental equipment was employed to control the timing of the system – as is further discussed below

7.2.1 Experimental Configuration

Figure 7.7 below is a schematic of the experimental set-up used when employing the initial field coils. For clarity, the functions dictated from the control room or the extra components of the rail gap switch are not shown. In reality, each charger isolation procedure, and the main fire command is controlled via the control room, in a similar fashion to that given above for the Cnare arrangement.

As can be seen by comparing Figure 7.8 and Figure 7.4, the introduction of the initial field makes the experimental arrangement more complex. In this case both banks are initially charged and care must be taken to ensure that the banks reach their maximum charged value simultaneously, so as not to leave either bank fully charged for longer than is necessary. Before charging however, all supplementary equipment is isolated from the mains and placed upon battery power to protect it from spurious noise in the mains supply or power spikes produced by the experiment.

Each bank is isolated prior to a command to a scissor switch, capable of transmitting currents up to 20 kA (as detailed in Figure 4.12) which was used to initiate the initial field system. This causes a discharge to the initial field coils, establishing the initial field (Figure 7.6). The current flowing in the initial field circuit was monitored by a simple current transformer (CT)
such that the signal from the CT produced a rising edge voltage which can in turn trigger a multiple delay pulsed generator. A rising edge trigger from the delay generator then initiates the trigger for the rail gap switch approximately 2 ms later; the current flowing in each circuit as well as the magnetic field produced is recorded as shown in Figure 7.8. After a predetermined time an output trigger could also activate other diagnostic equipment such as X-rays, IMACON camera etc.

At the same time it is possible to use imaging diagnostic equipment to analyse the compression of the liner. Such equipment could be accurately timed in the manner given above, to diagnose key characteristic of the liner as it compresses. Both high-speed camera imaging and X-ray imaging can be employed to observe the dynamics of the implosions. An overview of each system was given in Chapter 4; however for clarity Figure 7.9 shows in more detail the arrangements used. In order to aid the diagnostic techniques, the liner chamber walls were constructed from transparent polycarbonate as discussed previously, to allow both visible (IMACON) and invisible (X-Ray) radiation to permeate readily.
Figure 7.9 Dynamics diagnostic set-ups (a) IMACON High Speed Camera, (b) X-Ray
7.2.2 Magnetic Field Production

Coil design M was investigated using the arrangement given in Figure 7.8. Table 7.3 and Figure 7.10 detail four typical experiments, using an initial field of approximately 2.45 T

<table>
<thead>
<tr>
<th>DESIGN M</th>
<th>INITIAL FLUX DENSITY (T)</th>
<th>MAGNETIC FLUX DENSITY (T)</th>
<th>APPROX. MAXIMUM dB/dt (10^8 T/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(i)</td>
<td>2.45</td>
<td>290</td>
<td>2.2</td>
</tr>
<tr>
<td>(ii)</td>
<td>2.45</td>
<td>285</td>
<td>2.0</td>
</tr>
<tr>
<td>(iii)*</td>
<td>2.45</td>
<td>290</td>
<td>2.2</td>
</tr>
<tr>
<td>(iv)</td>
<td>2.45</td>
<td>301</td>
<td>2.2</td>
</tr>
</tbody>
</table>

* Measured using a three-turn probe, as opposed to a single-turn probe

Table 7.3 Magnetic Flux density with Initial field

![Graph showing magnetic flux density over time](image-url)
As can be seen flux densities in excess of 300 T were produced (experiment (iv)), although the time taken to reach these peaks were marginally longer than in the previous Cnare experiments (approximately 0.2 - 0.4 μs). Furthermore the time rate of change of flux density was less than that in Cnare experiments due primarily to the increase in field at the centre the liner where the difference between the fields across the thickness of the liner is greater than that in a Cnare system. As the liner begins to collapse, the compressed magnetic field induces a repelling action on this inward motion. As explained in Chapter 2, when this initial field exceeds a certain value, it is possible to obtain a turn-around effect. During these circumstances the liner rebounds at a certain implosion diameter. In an ideal experiment, the rebound diameter would equal the working volume diameter. This would allow the measurement means, or the actuating means, within this working volume to remain intact. It is likely that in such a circumstance the peak field would be reached, followed by a gradual decay of the field. This would produce a long period of sustained magnetic field, well suited to solid state physics application.

From Figure 7.10, it is apparent that the rise and subsequent dip in flux density occurs in experiments (iii) and (iv), although it is not clear whether this characteristic is due to a partial turn-around effect, or is a separate phenomenon of the system, such as last minute current migration. The time rate of change of magnetic flux density of experiment (iv) is shown in Figure 7.11.

As can be seen from Figure 7.11, the rate of change of magnetic flux density reaches a positive peak, then starts to decline until it eventually changes sense. This negative extrusion is in contrast to that seen in Figure 7.5, when no initial field exists. It is very probable that after approximately 12 μs the sensor has failed, and the signal is spurious. The efficacy of experiment (iv) is detailed in Table 2.2.
7.2.3 Implosion Dynamics

As shown by Figure 7.11, the dynamics of the implosion may be paramount to the effectiveness of the implosion itself. This has certainly been indicted previously as discussed in chapter 2. Therefore to assess the improvement to the system for the experiments given in Table 7.3, and perhaps to detail the turn-a-round effect it was possible to use the arrangement of Figure 7.9(a).

Figure 7.12 details a concatenation of images taken from various experiments of design M using the IMACON 468 High-speed camera imaging of Figure 7.9(a). Although images are used from numerous experiments it is believed that the consistency of each is sufficiently good to create the above montage. Care was taken to position the vacuum tube connection (as is apparent in the lower left portion of each image) away from any region of interest, such as the feed gap. At a time of 0 µs, back lighting illuminates the liner chamber. The central probe can clearly be seen, together with the connection to the vacuum tube. The outer boundary of the cylindrical image represents the initial radius of the liner. As the implosion progresses, it is evident that the liner begins to
compress. At an early stage however, it is clear that the feed gap appears to be influencing the compression geometry, where at 5.5 μs an undulation has clearly formed on the right hand side of the image of the liner.

![Image of compression process](image_url)

**Figure 7.12 High speed imaging**

If the liner is assumed to be compressing substantially uniformly across its axial height, the increase in thickness of the liner should be correspondent to the reduction in radius. However it is apparent from simple calculations of the mass that the images show that this is not the case. The secondary circular shadow that appears to be following the liner is unexplained, but is believed to be the glue that initially attached the liner to the inner side of the liner chamber.
In the final moments, plasma formation over-exposes the images, even on the lowest shutter speed of 10 ns. By establishing an alternative arrangement, and diffusing the lights further, it is possible to achieve images post-peak field. Figure 7.13 below shows such images obtained from a single experiment.

The initial image in Figure 7.13 show the liner and drive coil at a time of peak field. Subsequent images show the plasma formation and matter ejection as the driving coils break down. This break down is post-peak field, and as such does not influence the experiment. Due to the effects of over-exposure, no quantitative information is believed to be obtained accurately by analysing the images of both Figure 7.12 and Figure 7.13.
In order to circumvent issues regarding over exposure in the visible spectrum, the X-ray arrangement of Figure 7.9(b) was employed. While it is true that there would be the possibility of exposing the photographic paper from erroneous radiation developed in the final stages of the implosion, it was believed that the effect of this erroneous exposure effect would be minimal in comparison to the erroneous exposure developed when using the Imaging camera. As it was only possible to obtain two exposures, each of which had to be recoded on the same photographic paper, a montage taken from several experiments is given in Figure 7.14, again for design M.
Image processing was employed to separate the two images formed on one photographic sheet post experiment. To assist this, care was taken to space the timing of the images such that they did not interfere, as discussed in Chapter 4. In Figure 7.14 the central probe can clearly be seen, together with the attachment to the vacuum tube. Again in a manner similar to that of the IMACON images, as the liner compresses a portion of the liner is occluded during imaging by the vacuum pump connection.

By comparing the images obtained via the IMACON camera and the X-ray imaging, it is apparent that a large portion of the information obtained by the camera is possibly erroneous. Simple calculations, based on the assumption of a uniform compression of the liner, show that the X-ray images are considerable more accurate in describing the compression, as the mass of the liner remains substantially to constant. It is believed that the extra mass shown in the IMACON images is due to mass ejection and vaporisation of the outer surface of the liner.
The geometric perturbation introduced by the feed gap is clearly initially small; it does however appear to become much more pronounced as the liner compresses in the final stages of the implosion. This replicates previously observed phenomena, as highlighted in Figure 2.8. Interestingly, while the outer surface of the liner remains apparently stable, the inner surface exhibits ‘finger’ like perturbations, akin to those describes as magneto-Raleigh-Taylor perturbations (Knoepfel, 1970). It is probably that the maximum flux density achievable is influenced by the existence of these irregularities. As the liner approaches the final flux volume, the shortest path for the current travelling in the liner will be displaced back into the liner, effectively reducing the peak field observed.

From the X-ray images it can be calculated that the liner is travelling at speeds in excess of 2.5 km/s.

In a manner similar to that above, X-ray images were also obtained of the arrangement post-peak field. Figure 7.15 shows three such images, as well as complementary image enhanced versions.

The second row of images in Figure 7.15 has been adjusted to enhance the contrast. The initial image taken at 0 µs shows the driving coil as well as the liner chamber, with the associated probe and vacuum tube. The clamp is also detailed to the right of each image within the Figure. It is possible to observe the small feed gap, present at 0 µs, and fine details on both the probe as well as the vacuum connection.

The second pairing of images are taken at 27.2 µs, well after the peak field has been produced. As can be seen, the driving coil has expanded outwardly. The liner chamber remains in position, probably by inertial effects, and the end caps of the liner chamber have been destroyed at the central portion.
At 48.7 μs after the beginning of the compression, the driving coil has expanded such that necking failure points are beginning to occur. Interestingly, it appears that there is evidence that the structure of the probe may have survived, and this is more apparent in the lower image. This may confirm the possibility of the turn-around effect having occurred.

### 7.3 EMFC using an Insulator-Metallic Phase transition cascade.

The image diagnostic shown in Figure 7.14 highlights the imperfect implosion geometry in the final stages of the EMFC experiment. As discussed in Chapter 2, it is believed that such geometries are inefficient when producing ultrahigh magnetic fields. The main drawback is that at some stage during the implosion, the current induced in the liner reverses and the corresponding electromagnetic force acting on the liner therefore changes in direction. At that time, the resulting decelerating force on the liner is however quite small, due to the increased separation of the coil and the liner. Nevertheless, the absence of a sufficiently strong imploding force triggers an uncontrolled growth of liner outer wall protuberances. This
feature was even more prominent in the presence of an initial magnetic field within the liner, or when a scaled-up geometry was tried and the implosion time was increased. Although studies indicate that an initial field injected differentially will reduce this effect (Novac et al [1], 2004), all experiments reported in the literature have nevertheless been performed with the initial field injected cumulatively i.e. in the same direction as that produced by the single-turn driving coil. Unfortunately, due to the energy limitation of the existing auxiliary bank, experimental validation of this has not yet been possible.

The complete absence of imploding forces towards the end of the implosion is the main reason for the appearance of liner instabilities. This can be overcome in alternative embodiments (such as a Z-pinch arrangement) by the presence of a supplementary stabilising field, however it was not possible here.

As an alternative to the provision of a stabilising field, the unwanted effects present during an implosion can be limited by a cascade of liners, which, when used in explosive experimentation has enabled the highest recorded flux density of 2800 T to be obtained (Bykov et al, 2002). In a cascade implosion each collapsing liner collides with another cold and perfectly symmetric liner, either just as it is about to develop instabilities or as the inner surface is about to evaporate. Part of the kinetic energy is transferred to the cold liner, one that must be initially transparent to Z magnetic fields (to prevent the circulation of θ-currents), and the collision is required to change the state of the cold liner to a homogeneous metallic conductor. The previous technique that used an array of thin axially positioned wires embedded in epoxy resin appears not to be readily applicable in electromagnetic flux compression, due to a lack of any electromagnetic driving force in the final stage of implosion giving rise to rather different liner implosion dynamics.

An elegant alternative approach in which the required change is produced
by using an insulator-metallic phase-transition material, such as aluminum powder, was thought more likely to be successful, and was further investigated.

### 7.3.1 Experimental Configuration

In normal conditions, the very pure (99.99 %) aluminum powder used in Loughborough experimentation (25 μm particle diameter samples prepared with approximately 0.8 g/cm³ mass density) is a relatively good insulator. However as discussed in Chapter 2, under shock loading, the thin oxide coating on the particles that provides the electrical insulation is destroyed and the powder becomes compacted into a relatively good conductor (Nagayama, 1987, Goh, 2001, Novac et al, 2001).

Again as discussed in Chapter 2, details are available of the complex electromagnetic phenomena involved when the electrical conductivity is to be measured during the change of the powder from insulator to conductor, and the data obtained suggests an almost instantaneous transition mechanism (Gilev, 1994, Gilev and Mihailova, 1997). Although various hypotheses have been advanced, a basic understanding of this mechanism was not possible until the speed of the transition was continuously and reliably monitored. The results subsequently obtained clearly indicated that the mechanism responsible for destroying the insulating oxide coating is a fast, low pressure, elastic precursor moving ahead of the main high-pressure shock front (Goh, 2001, Novac et al, 2001).

Based on the findings of the preliminary investigation, the mechanism of magnetic flux-compression inside a phase transition powder material can be viewed as a two-step process, and although this phenomenon was first described by Nagayama (1987) what follows contains a number of novel elements.
In the first step of the process the particle coating is destroyed by an elastic precursor wave that creates a medium of relatively high electrical conductivity. A proportion of the magnetic field is “captured” or “trapped” in the air spaces existing in the rarefied powder and under the action of the following main (higher pressure) shock wave, the powder is compacted and the magnetic field is “expelled”. As a consequence of this, magnetic flux-compression resulting from a highly conductive “piston” (a metallic liner as in experiments reported by Bitchenkov, 1987) will be much more effective than that caused by a low conductivity piston (detonation products from an explosive charge as reported by Nagayama, 1987), explosively-driven magnetic, shock compressed porous metals etc)

The conclusions reached during the shock loading experiments on the nature of the mechanism responsible for the phase transition also have very important consequences that relate to the design of powder cascade experiments to achieve magnetic flux compression.

Firstly, it is obvious that in the absence of the elastic precursor the phase transition, if it still occurs, happens at a later time and is likely to be less efficient. Such conditions could probably only be obtained in vacuum, when no air is present to act as a transmission medium. The initial oxide layer is obviously present even in vacuum experiments. In order to investigate this, electromagnetic flux compression experiments were conducted with aluminium powder cascades under a low-pressure of $10^{-3}$ Torr. The results clearly indicated an extremely low efficiency of the cascade, with the powder acting as a good insulator. The shock precursor in air appears therefore to be essential for the efficient operation of a powder cascade. Secondly, because of the strong attenuation in the elastic precursor wave noted during the measurements, it is expected that the thickness of the cascade will play an important role and that an optimum value is likely to exist.
Electromagnetic flux compression experiments were therefore performed at atmospheric pressure. This simplified the arrangement given previously as there was no requirement for a vacuum pump, or its associated system. Each aluminium powder cascade surrounded a ceramic tube 2.45 mm outer diameter that, as usual, contained the magnetic sensor. As presented in Figure 7.16, the powder is contained in a cylindrical tube
made from transparent 25 μm thick Mylar.

Table 7.4 presents data for the different experimental arrangements. In two instances, design L was employed, since the benefits of such aluminium cascades were anticipated to be most pronounced in this design, due to the previously perceived instabilities that had been encountered.

<table>
<thead>
<tr>
<th>Exp.</th>
<th>DESIGN Employed (Table 9.1)</th>
<th>Outer Diameter (mm)</th>
<th>Probe Diameter (mm)</th>
<th>Thickness of Al (mm)</th>
<th>Axial Length (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1)</td>
<td>L</td>
<td>20.00</td>
<td>2.45</td>
<td>8.75</td>
<td>25.21</td>
</tr>
<tr>
<td>(2)</td>
<td>L</td>
<td>10.00</td>
<td>2.45</td>
<td>8.75</td>
<td>25.20</td>
</tr>
</tbody>
</table>

Table 7.4 Aluminium cascade

Figures 7.17 and 7.18 highlight the recorded flux densities of the experiments detailed in Table 7.4. Figure 7.17 shows that an adequate powder cascade will protect the central probe from damage caused by the imploding liner, throughout the complete magnetic cycle, an effect also evident in Figure 7.18. These results, a premiere in cylindrical magnetic flux-compression, could be of great importance for solid-state measurements in megagauss fields or other special applications, which have the potential to maintain a high flux density for a longer period of time, as well as showing a characteristic up sweep and associated down sweep. As the thickness of the cascade is reduced, as indicted in Table 7.4, the fields obtained are usually higher, but the likelihood of the probe surviving the complete magnetic cycle is clearly reduced. Figure 7.18 shows that an optimised liner-powder cascade working in air will produce much greater fields than a standard liner implosion in vacuum. As can be seen from Figure 7.18, by comparison with a previous experiment that produced lower fields in the order of 150 T the magnetic field now produced has the potential to reach in excess of 245 T.
However when these experiments were replicated with design M, it was found that less substantial results were achieved than with design L, and that only a small increase in peak field produced was produced. Figure
7.19 shows the flux density produced when using Design M with a powder cascade of 1.75 mm thickness and without a powder cascade.

![Figure 7.19: Design M with and without cascade](image)

The obvious similarity in generated fields is believed to be due to the powder cascade being primarily of benefit only when severe final liner perturbations are present. If the liner implosion is of high quality, the effect is much reduced, as can be observed when the peak fields in Figure 7.19 are compared.

As the X-ray pictures of Figure 7.20 clearly show, the powder cascade improves the implosion geometry in the final moments of the experiment. The X-ray images (a) and (b) correspond to the experiments of Figure 7.18. This improvement occurs at exactly the moment the liner instabilities, in the absence of the cascade, would otherwise reach a critical stage, followed by liner breakdown (Figure 7.20(a)).
The results obtained when using aluminium powder cascades show that it is possible to increase the flux density produced in systems that have inherent instabilities in the final stages of implosion. Such systems have potential in reproducible commercial tools, where ultrahigh magnetic fields are required, but costs in producing ideal liners are prohibitively expensive. Furthermore each system can be simplified, as there is no requirement for a vacuum. This may be of particular benefit in many future applications.
where a device is moved from a laboratory experiment to a remote site, since it is able to operate without the requirements of an extremely vacant liner chamber.

Each system produces a flux density profile producing high peak fields and stable implosions, providing very reproducible results. In addition, the powder cascade is able to preserve the sensor integrity well after the peak field is achieved, which could be important in various applications, particularly in solid-state physics experimentation.

### 7.4 EMFC using an Insulator-Metallic Phase transition cascade, and implementing Copper liners

As discussed above, while the use of an ideal copper liner was always preferred over an equivalent aluminium construction, the mechanical tolerances required were not achievable. Preliminary experiments had shown that copper liners were less successful when considering EMFC implosion on the apparatus given above. Unfortunately, similar small size copper liners could not be economically manufactured with sufficiently precise tolerances to prevent the development of liner instabilities during an implosion, leading to a much lower flux density than anticipated.

However, due to the success of the work achieved by using powder cascades, an investigation was made into the possibility of dramatically improved copper liner experiments by the use of an aluminium powder cascade.

#### 7.4.1 Experimental Configuration

The identical experimental configuration was implemented in section 7.3.1, but with a copper as opposed to an aluminium liner being used. As
observed, flux densities up to 300 T were consistently generated in previous work using aluminium liners. Manufacturing tolerances occurring on the nominally 50 mm inner diameter, 0.5 mm wall thickness of liners produced in-house were about 10 μm, and X-rays of a number of these during the flux compression process indicated a stable implosion, but with some small instabilities appearing on the inner wall of the liner during the final stages (Figure 7.20(a)). Unfortunately, as discussed above, high quality copper liners having the same dimensions are extremely difficult to manufacture and are accordingly prohibitively expensive.

Copper liners were therefore manufactured in-house with the nominal dimensions given in Table 7.5, careful measurements indicated that the tolerances were unfortunately much greater than those of the aluminium liners, and were up to 100 μm in the wall thickness. The very disappointing peak flux densities of between 100 T and 220 T achieved with these liners during experiments similar to those in which aluminium liners were used are obviously a consequence of the serious lack of precision in their manufacture. Furthermore, X-ray pictures revealed extremely severe perturbations of the liner surface during all implosions.

The geometric measurements of design M of Table 7.1 were employed to investigate the potential improvement in peak flux density production using copper liner.

<table>
<thead>
<tr>
<th>Exp No.</th>
<th>Liner (copper)</th>
<th>Driving coil (copper)</th>
<th>Aluminium powder cascade</th>
<th>Peak flux density (T)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>inner radius (mm)</td>
<td>wall thickness (mm)</td>
<td>height (mm)</td>
<td>inner radius (mm)</td>
</tr>
<tr>
<td>1</td>
<td>25.00</td>
<td>0.50</td>
<td>20.03</td>
<td>26.25</td>
</tr>
<tr>
<td>2</td>
<td>25.08</td>
<td>0.45</td>
<td>19.99</td>
<td>26.53</td>
</tr>
<tr>
<td>3</td>
<td>25.05</td>
<td>0.40</td>
<td>19.92</td>
<td>25.43</td>
</tr>
<tr>
<td>5</td>
<td>25.05</td>
<td>0.40</td>
<td>19.97</td>
<td>26.30</td>
</tr>
</tbody>
</table>

Table 7.5 Aluminium cascade with Copper liners
In each of the experiments recorded in Table 7.5, two magnetic pick-up probes were employed, as indicted in Chapter 4. In each case three-turn coils of 50 µm polyamide insulated copper wire wound on a 1 mm diameter glass rod. One of the coils is positioned centrally on the liner axis and the other such that an axial separation of 1 mm exists between adjacent coil edges.

7.4.2 Experimental Results

Table 7.5 summarises the principal results of the copper liner experimental programme. Experiment 1 of Table 7.5 shows the best result obtained with a copper liner (no powder cascade). As can be seen the flux density produced does not compare well with the fields in excess of 300 T produced by an aluminium liner of similar design (Figure 7.10). Experiment 2 of Table 7.5 was obtained while iterating an ideal cascade thickness.

Experiments 3 and 5 are nominally identical EFC experiments using powder cascades, with what is believed to be the optimum thickness for the present arrangement.

Figures 7.21 and 7.22 show the magnetic flux density produced by Experiments 3 and 5. As the measurement was obtained by using two probes, both the positive and the negative senses are shown to indicate the agreement up until peak field.

Figure 7.23 and 7.24 show X-ray images taken for the Experiment detailed in Figures 7.21 and 7.22.
Figure 7.21 Flux Density produced by Experiment 3 of Table 7.5

Figure 7.22 Flux Density produced by Experiment 5 of Table 7.5
As can be seen the flux densities produced are much higher than anticipated by the experiment without a powder cascade, and in particular when considering the implosion geometry given in the X-ray pictures.

The most important outcome of this experimental research was that flux densities up to about 350 T can be produced, despite the X-ray pictures showing clear evidence that substantial perturbations always appear in the copper liner geometry. The distorted geometry emphasises that, without a
powder cascade, the compression efficiency is very poor, as is evidenced by the results in Table 7.5.

The results in Figures 7.21 – 7.24 suggest that a two-step flux-compression process is taking place, which has never been observed in previous EFC experiments. A first attempt to explain qualitatively this rather complex phenomenon was published by Novac [3] et al, 2004 and is re-iterated here. Initially the flux-compression process is similar to that of a conventional EFC experiment, with the liner being compressed by electromagnetic forces. As seen from Figure 7.23 and 7.24, considerable perturbations from an ideal cylindrical shape progressively develop. When the liner begins to interact mechanically with the powder cascade it generates shock waves, initiating the change in phase from an insulator to a conducting state. Once a circular conductive region has been established, a circular current is induced in a direction opposite to that of the liner current, clearly changing the magnetic field polarity detected by the magnetic probes as evident in Figures 7.21 and 7.22. The current path probably travels together with the shock-driven inner conductive phase boundary through the aluminium powder towards the implosion centre, performing the second step of the flux-compression process. More flux-compression is possibly provided later by the now conductive powder being compacted by the collapsing liner. During this last process, due to the highly mismatched shock impedances, shock-waves can travel a few times in powder backwards and forwards between the ceramic tube and the liner. Also during the period, when flux-compression is provided by the powder cascade, the magnetic field is no longer characterised by the usual exponential growth observed during conventional EFC experimentation.

7.5 Conclusions
It has been successfully demonstrated that ultrahigh magnetic fields can be generated by electromagnetic flux compression using a fast capacitor bank, without the use of a powder cascade. Magnetic flux densities up to 300 T and pulses with a rate of change in excess of $3 \times 10^8$ T s$^{-1}$ have been produced with good repeatability, using about 60 kJ of energy from the main capacitor bank. The outcome of the work suggests that when a fast high current bank is available, it is advantageous to use electromagnetic flux compression, as an alternative to the single-turn coil technique, to push the magnetic field boundary well beyond 300 T without major investment.

However it has been demonstrated that the use of an optimised aluminium powder cascade can greatly improve the results of an electromagnetic flux compression process in which significant liner instabilities are developed. Using this technique, flux densities of about 350 T have been generated, using a capacitor bank of similar energy.

This technique has shown that such system may be constructed without the requirement for vacuum, or indeed good implosion geometry. This lends itself extremely well to the development of rapid manufacture, or remote systems, where the laboratory arrangements are limited. Interestingly, the new technique that showed for the first time in magnetic flux-compression in an imploding cylindrical geometry both a significant up and a down sweep of the field pulse. Such a system may have considerable implications in solid state physics, where the length of pulse duration in the ultrahigh region is useful. Further detailed it the possible capture of the turn around effect, believed to occur within such systems, having the potential to add to the knowledge and understanding of such pulsed ultrahigh magnetic field systems.
As discussed earlier, FEA model using ANSYS has been developed for the simulation and prediction of peak field production during STC experiments. The work detailed the assumptions made and the potential future possibilities. As part of the current program of work the potential for using a similar FEA model to predict the peak flux density produced in EMFC experiments was also investigated. Again this work was conducted under a strict time scale and acts only as a preliminary indicator to future potential work.

During the course of the investigation preliminary results were obtained, however due to the massive deformation occurring in EMFC experiments, it was difficult to model such implosions using the current finite element approach. As the deformation during an implosion continues, it is clear that the accuracy of the model is reduced, and as such it has not yet been possible to develop an accurate finite element model in ANSYS for the current EMFC experiments.

Furthermore the complex perturbations exhibited on the liner seen in Figure 7.20(a) have proved impossible to model using the current analysis. The phase change complications of the aluminium cascade certainly can also not be accurately represented using the current FEA tool.

However in contrast, it has been possible process to develop a model that may assist in the production of the experimental arrangement used in such environment. In particular the auxiliary magnetic field coils, and the interaction with the driving coil / liner arrangement have all been accurately modelled using an FEA code. Appendix H details the 2D analytical code used to develop such a model. It is believed that further work on the model will assist in the future development of peripheral experimental equipment,
as well as enhancing material design and such interesting future work as seed field homogeneity within the liner immediately prior to implosion.
9. PUBLICATIONS PRODUCED DURING THE COURSE OF THIS RESEARCH

Throughout the course of this research, there has been the opportunity to publish work in several recognised journals in the field, as well as present work at numerous international conferences. This work has been presented both in poster format and orally.

Below details a list of publications to date.

9.1 Academic Journal Publications


9.2 Conference Publications


11. Novac B M, Smith I R, Rankin D F and Hubbard M, 'Flux compression dynamic transformers as pulsed voltage sources'


at the 15th IEEE International Pulsed Power Conference, Monterey CA, USA, June 2005


10. CONCLUSIONS

It has been shown to be possible to produce pulsed ultrahigh magnetic fields using either the STC technique or a Θ-pinch electromagnetically driven flux compression device. Flux densities of about 350 T have been generated, using a capacitor bank with an energy of approximately 70 kJ.

The work described here has included an accurate finite element model, which may be implemented as an alternative solution to the widely used filamentary model when considering STCs under heavy electromagnetic loading. Furthermore, it has been shown that the limitations introduced by the current filamentary model may to be overcome by the use of a 3D elastic-plastic modelling environment, essential in a number of future applications.

As explained, the work presented in this thesis was conducted under a limited licence agreement and as such it acts as an indicator to future development in this area. However, it is apparent that a major benefit from FEA modelling is the wealth of information that potentially becomes available. Electromagnetic, thermal and structural data can all be deduced at any given point in time without the dimensional simplifications common in other simplified filamentary models. The ability to work in three dimensions allows for quick problem isolation and system innovation, as well as providing a deeper understanding of the system as a whole. It is interesting to note that the structural movement of the coil in the simulation environment appears to play the most influential role in the flux density recorded along the axis of the coil. This knowledge, in conjunction with previous work may, lead to further improvements in future coil design.

It is clear however that significant limitations still exist when considering ultrahigh pulsed magnetic fields in STCs. At this stage approximations have been considered with regards to structural data and there is a need for more accurate material data for use in high power systems. At present
certain data is perhaps unreliable, which can considerably influence the theoretical predictions, and this represents an area for future development outside the scope of this current work. Furthermore, the veracity of solution unknowns, such as temperature, is yet to be investigated, and this may influence other parameters.

In addition to the aforementioned work, detailed experimental work has validly shown the success of alternative geometric configurations when using EMFC techniques. Furthermore, the significant instabilities that are present in such implosions have been demonstrated to be removed by means of a metallic insulator-conductor phase transition cascade, activated by the elastic precursor to a shockwave.

This cascade technique has shown that systems may be constructed without the requirement for vacuum, or indeed good implosion geometry. This lends itself extremely well to the development of rapid manufacture, or remote systems, where elaborate laboratory facilities are limited. Interestingly the new technique has shown, for the first time in magnetic flux-compression in imploding cylindrical geometry, both a significant up and a down sweep of the field pulse. Such a system may have considerable implications in solid state physics, where the length of the pulse duration in the ultrahigh region is useful. Further details of the possible capture of the turn around effect, believed to occur within such systems, has the potential to add to the knowledge and understanding of such pulsed ultrahigh magnetic field systems.
From the findings of this thesis a greater understanding of STC and EMFC techniques has emerged. The use of a finite element model to simulate the STC technique has shown to be fit for purpose within such high energy experiments. However it is the intention that the work presented should act as a precursor to future developments in this area. Below is detailed a list of future work in relation to both the STC and EMFC systems described in this thesis.

- Further development of the STC finite element model including development and evaluation of an accurate material model, with the structural environment including effects from dampening and potential pressure effects within the STC, with a focus on predicting shockwave behaviour.

- Experimental verification of further system variables, such as thermal transients and structural effects within STC systems.

- Experimental investigation into STC system, whereby the coil geometry and/or the material is modified to limit movement, with a focus on optimum peak flux density production.

- Expansion of finite element modelling to other of pulsed power systems, with a focus on assessing accuracy in modelling conditioning components.

- Comparative evaluation of current finite element model with the existing filamentary model.

- Investigation and development of an understanding of the influence of the spatial distribution of the seed field within the liner in EMFC experiments, with a focus on optimising the system.
- Modification of an EMFC system comprising cascade to a system which may be used outside of the laboratory, and test the effectiveness.
REFERENCES


ANSYS release 9.0 Documentation (2004), ANSYS, Inc. Southpointe, 275 Technology Drive Canonsburg, PA 1531. USA


Production of Automotive Parts. 2nd European Pulsed Power Symposium, Hamburg, Germany: 82-86.


100 kV Trigger Generator Model 40168. Titan Corporation user manual. L3 Communications, Titan System, 4855 Ruffner Avenue, Suite A San Diego, CA 92111 (858) 499-0284. USA.


APPENDIX A

Implementing an analysis in batch mode

214
Appendix A

By considering the following two-dimensional beamed (trussed) structure, it is possible to evaluate the forces and stresses within the assembly.

In Figure A.1 the cross-section of each beam is 320 mm$^2$ (3.2*10$^{-4}$ m$^2$) and the Young's Modulus (E) is 70 GPa. The force at node '3' is 500 N. The length of element [3] can be calculated as 0.455 mm, and angles 'a' and 'b' as 33.34$^\circ$ and 56.56$^\circ$ respectively. The fundamental equation of this finite element solution is:

$$[K][u] = [F]$$  

Eq. A.1

where [K] is the stiffness matrix, [u] the displacement vector, and [F] the applied load vector. This solution is considered to be "small deflection theory" or linear analysis. Small deflection theory assumes that the displacement calculated for the applied load can be extrapolated to any other value of load, and that the stiffness of the structure does not change for any value of applied load. This assumption for many situations is regarded as accurate.
In the example of the loaded truss it is possible to implement the solution to this by using APDL, and compiling the program. Figure A.1 details the code used to generate the output file of the preprocessor. In the figure, each line is given a numerical reference, but this is used for clarity here, and is not replicated in the code to be compiled.

```
1 | Douglas Rankin
2 | Loughborough University
3 | 2D Direct Method Example
4 | Thesis inclusion June 2005
5 |
6 |
7 |
8 | /TITLE, 2-D DIRECT METHOD EXAMPLE
9 | ********************************************
10 | | ENTERS THE PREPROCESSOR
11 | | SELECTS ELEMENT 1 AS LINK1
12 | | SET REAL CONSTANT 1, AREA
13 | | DEFINES THE YOUNGS MOD
14 | | SETS UP NODES
15 | | USE ELEMENT TYPE 1
16 | | USE MATERIAL 1
17 | | BUILD ELEMENTS BETWEEN NODES
18 | | FINISH PREPROCESSING
19 |
20 | ********************************************
```

Figure A.1. APDL preprocessor

From the code above it is clear in line 14 that the element selected for the analysis is an ANSYS developed element. 'LINK1' is a 2D truss element that represents uniaxial tension or compression. Ux and Uy are the degrees of freedom available. There is no ability to considered bending in the element, but this is outwith the example given above. Consideration must be given to the sequential method in which the nodes and element are created to give the correct numbering sequence.
**Appendix A**

<table>
<thead>
<tr>
<th>28</th>
</tr>
</thead>
<tbody>
<tr>
<td>***</td>
</tr>
<tr>
<td>29</td>
</tr>
<tr>
<td>*</td>
</tr>
<tr>
<td>30</td>
</tr>
<tr>
<td>S</td>
</tr>
<tr>
<td>31</td>
</tr>
<tr>
<td>L</td>
</tr>
<tr>
<td>32</td>
</tr>
<tr>
<td>T</td>
</tr>
<tr>
<td>33</td>
</tr>
<tr>
<td>E</td>
</tr>
<tr>
<td>34</td>
</tr>
<tr>
<td>S</td>
</tr>
<tr>
<td>35</td>
</tr>
<tr>
<td>E</td>
</tr>
<tr>
<td>36</td>
</tr>
<tr>
<td>L</td>
</tr>
<tr>
<td>37</td>
</tr>
<tr>
<td>S</td>
</tr>
<tr>
<td>38</td>
</tr>
<tr>
<td>E</td>
</tr>
<tr>
<td>39</td>
</tr>
<tr>
<td>F</td>
</tr>
<tr>
<td>40</td>
</tr>
<tr>
<td>I</td>
</tr>
<tr>
<td>41</td>
</tr>
<tr>
<td>N</td>
</tr>
<tr>
<td>42</td>
</tr>
<tr>
<td>*</td>
</tr>
<tr>
<td>43</td>
</tr>
<tr>
<td>*</td>
</tr>
<tr>
<td>44</td>
</tr>
<tr>
<td>S</td>
</tr>
<tr>
<td>45</td>
</tr>
<tr>
<td>L</td>
</tr>
<tr>
<td>46</td>
</tr>
<tr>
<td>T</td>
</tr>
<tr>
<td>47</td>
</tr>
<tr>
<td>E</td>
</tr>
<tr>
<td>48</td>
</tr>
<tr>
<td>S</td>
</tr>
<tr>
<td>49</td>
</tr>
<tr>
<td>E</td>
</tr>
<tr>
<td>50</td>
</tr>
<tr>
<td>L</td>
</tr>
<tr>
<td>51</td>
</tr>
<tr>
<td>S</td>
</tr>
<tr>
<td>52</td>
</tr>
<tr>
<td>E</td>
</tr>
</tbody>
</table>

**Figure A.2. APDL solver**

Figure A.2 details the APDL that is used to establish the solver. This code follows sequentially on from the previous file and so the numbering is continued. As can be seen, the analysis type is set up, along with the boundary conditions and loads. The solver is also programmed to print out the nodal solutions as well as the element solutions. Finally the Frontal solver is selected, and the problem is solved. From the 'jobname.out' file a wealth of information is detailed about the analysis, including pivot values, co-efficient values, and computational time. Also the nodal and element solutions are given. Figure A.3 shows this section of the output file.

From the data in Figure A.3 it is possible to see the nodal displacements (Ux, Uy) for each individual node. Furthermore, the force in each element (MFORX) is given as well as the axial stress (SAXL) and the axial strain (EPELAXL). By comparison Figure A.4 pictorially details the results from a hand-worked solution. All values are in S.I units (MKS) and differ only slightly from those in the calculated results, with those derived by ANSYS being more accurate since more rounding errors were included in the worked example. It is also interesting to note that, while running a 2.8 GHz P4 computer with 768 MB RAM, the problem was established and then solved in 0.453 seconds.
2-D DIRECT METHOD EXAMPLE

***** ANSYS - ENGINEERING ANALYSIS SYSTEM RELEASE 9.0 *****
ANSYS Multiphysics 00254611 VERSION=INTEL NT 15:24:31 JUN 14, 2005 CP= 0.453

2-D DEGREE OF FREEDOM SOLUTION ***** TIME = 1.0000
LOAD STEP = 1 SUBSTEP = 1 CUM. ITER = 1

NOTE - ALL VECTOR DOFS ARE IN NODAL COORDINATE SYSTEMS:

NODE UX UY
1 0.00000 0.00000
2 0.00000 -0.55969E-05
3 -0.12929E-04 -0.58788E-04

MAXIMUMS

VALUE -0.12929E-04 -0.58788E-04
1

***** ANSYS - ENGINEERING ANALYSIS SYSTEM RELEASE 9.0 *****
ANSYS Multiphysics 00254611 VERSION=INTEL NT 15:24:31 JUN 14, 2005 CP= 0.453

2-D DIRECT METHOD EXAMPLE

***** ELEMENT SOLUTION ***** TIME = 1.0000
LOAD STEP = 1 SUBSTEP = 1 CUM. ITER = 1

EL= 1 NODES= 1 2 MAT= 1 LINK1
NFORCE= -500.00
SAXL= -0.15625E+07 EPELAXL= -0.000022 EPETHAXL= 0.000000 EPSWAXL= 0.000000 EPINAXL= 0.000000
EL= 2 NODES= 1 3 MAT= 1 LINK1
NFORCE= -760.00
SAXL= -0.23750E+07 EPELAXL= -0.000034 EPETHAXL= 0.000000 EPSWAXL= 0.000000 EPINAXL= 0.000000
EL= 3 NODES= 3 2 MAT= 1 LINK1
NFORCE= 909.72
SAXL= 0.29429E+07 EPELAXL= 0.000041 EPETHAXL= 0.000000 EPSWAXL= 0.000000 EPINAXL= 0.000000

Figure A.3. FEA nodal and element solution

Figure A.4. Worked resultant local forces

Once the solution is complete it is possible to view the results in the postprocessor. Figure A.5 details the code used to output an image of the displacement vector sum from the results file.
Again here the numbering continues, as the program here is included in the whole complied code. The first results of the solver are read into the postprocessor (in this instance there is only one set, as the analysis is static). The JPEG file output parameters are set, and the title is included. Figure A.6 shows an output JPEG detailing the vector displacement of the system.

On the image, the initial shape along with the deformed shape is given. Unless stated to do otherwise the postprocessor will scale the displacement in order to give the user a clearer picture of what movement would occur. In this case the displacement is scaled by a factor of approximately 318.
Figure A.6. Graphical output of displacement vector sum in metres
APPENDIX B

Batch code
/TITLE, 2-D DIRECT METHOD EXAMPLE

!************************************************************
/PREP7

ET, 1, LINK1
R, 1, 3.2E-4
MP, EX, 1, 70E9
N, 1, 0, 0, 0
N, 2, 0, 0.25, 0
N, 3, 0.38, 0, 0
TYPE, 1
MAT, 1
E, 1, 2
E, 1, 3
E, 3, 2
FINI

!************************************************************

/SOLU

ANTYPE, STATIC

NSEL, S,, 1
D, ALL, ALL, 0
NSEL, S,, 2
D, ALL, UX, 0
NSEL, S,, 3
F, ALL, FY, -500

ALLSEL, ALL
OUTPR, NSOL, 1
OUTPR, ESOL, 1

EQSLV, FRONT
SOLVE
FINI

!************************************************************
Appendix B

/POST1
SET,FIRST

/SHOW, JPEG
/GFILE, 800
JPEG, QUAL, 100

/PLOPTS, INFO, 1
/PLOPTS, LEG1, 1
/PLOPTS, LEG2, 1
/PLOPTS, FRAME, 1
/PLOPTS, TITLE, 1
/PLOPTS, MINM, 1
/PLOPTS, LOGO, 1
/PLOPTS, WINS, 1
/PLOPTS, WP, 0
/PLOPTS, DATE, 1
/PLOPTS, FILE, 1

/RGB, INDEX, 100, 100, 100, 0
/RGB, INDEX, 80, 80, 80, 13
/RGB, INDEX, 60, 60, 60, 14
/RGB, INDEX, 0, 0, 0, 15

/TITLE, DISPLACEMENT SUM
FINI
SUM, 1, 1.0

SAVE
APPENDIX C

Integrator circuit
Figure C.1: Inductive magnetic pick up probe integrator circuit
APPENDIX D

2D STC FEA Batch Code
Douglas Rankin  
Loughborough University  
2D Semi-destructive STC  
Thesis inclusion Copyright July 2005

/TITLE, 2-D Semi-destructive STC

!*******************************************************************

! SET UP SOLID MODEL

/PREP7  
! ENTERS THE PREPROCESSOR

INRAD=10.125E-3
OUTRAD=12.125E-3
HEIGHT=20.35E-3
BOXH=40E-3
BOXW=50E-3
FF=6E-3

RECTNG, INRAD, OUTRAD, 0, HEIGHT  
RECTNG, 0, BOXW, 0, BOXH  
RECTNG, 0, BOXW+FF, 0, (BOXH+FF)  
AOVLAP, ALL  
NUMCMP, ALL

K, 12, (BOXW/2), (BOXH), 0  
K, 13, ((BOXW+FF)/2), ((FF)+(BOXH)), 0  

L, 4, 12  
L, 12, 7  
L, 12, 13  
L, 13, 10  
L, 10, 7  
L, 7, 12  
AL, 3, 2, 13, 5, 15, 14  
AL, 15, 18, 17, 16  
AOVLAP, ALL  
NUMCMP, ALL

FINI  
! FINISH PREPROCESSING

!*******************************************************************
Appendix D

! ESTABLISH 'EMAG' ENVIRONMENT

! ENTERS THE PREPROCESSOR

/PREP7
SHPP,OFF
PIVCHECK,OFF

ET,1,PLANE53,4,,1
ET,2,PLANE53,,1
ET,3,INF110,,1,1
ET,4,CIRCU124,0
ET,5,CIRCU124,1
ET,6,CIRCU124,2
ET,7,CIRCU124,6

R,1,((OUTRAD-INRAD)*(2*HEIGHT))
R,2,0.5E-3
R,3,20E-9
R,4,210.56E-6,13.717E3
R,5,1

N,1,16E-2,BE-2,O
N,2,20E-2,BE-2,O
N,3,20E-2,2.1E-2,O
N,4,16E-2,2.1E-2,O

MPREAD,MATLIB_2D_SEMISTIC,TXT

N,1,16E-2,8E-2,0
N,2,20E-2,8E-2,0
N,3,20E-2,2.1E-2,0
N,4,16E-2,2.1E-2,0

FARFIELD=1
DENSX=5
DENSY=20
LINES=6
LINES2=10

TYPE,3
MAT,2
LESIZE,9,,1
LESIZE,14,,1
LESIZE,16,,1

! SET REAL CONSTANTS

! X-SECTIONAL AREA

! RESISTANCE

! INDUCTANCE

! CAPACITANCE, Vo

! SCALING

! IMPORT MATERIAL LIBRARY

! GENERATE NODES FOR CIRCUIT

! SET UP MESH VARIABLES

! SET FARFIELD MESH
Appendix D

101 LESIZE, 8, 3, 1
102
103 TYPE, 1 ! SET STC MESH
104 MAT, 1
105 LESIZE, 1, 3, DENSX, 5
106 LESIZE, 3, 3, DENSX, 0.2
107 LESIZE, 2, 3, DENSY, 0.2
108 LESIZE, 4, 3, DENSY, 5
109
110 TYPE, 2 ! SET AIR MESH
111 MAT, 2
112 LESIZE, 11, 3, LINES, 2
113 LESIZE, 12, 3, LINES, 2
114 ALLSEL, ALL
115 LSEL, S, 3, 13, 15, 3
116 LESIZE, ALL, 3, DENSX
117 LSEL, S, 3, 5, 7, 2
118 LESIZE, ALL, 3, DENSY
119 ALLSEL, ALL
120 LSEL, S, 3, 4, 12, 0
121 LOCAT, ALL
122 ALLSEL, ALL
123 LESIZE, 6, 3, LINES, 0.02
124 LESIZE, 18, 3, LINES2
125 LESIZE, 17, 3, LINES2
126 LESIZE, 10, 3, LINES2
127 ALLSEL, ALL
128
129 TYPE, 1 ! MESH THE STC
130 MAT, 1
131 REAL, 1
132 AMESH, 1
133 ALLSEL, ALL
134
135 TYPE, 3 ! MESH THE FARFIELD
136 MAT, 2
137 ASELS, S, 3, 5, 1
138 AMESH, ALL
139 ALLSEL, ALL
140
141 TYPE, 2 ! MESH THE AIR
142 MAT, 2
143 LOCAT, 3, 2
144 LOCAT, 5, 13
145 AMESH, 2
146 AMESH, 6
147
148 LSEL, S, 3, 19, 21, 1 ! REMOVE CONCATENATED LINES
149 LDELE, ALL
150 ALLSEL, ALL
151
NC=NODE(((OUTRAD-INRAD)/2)+(INRAD), (HEIGHT/2), 0)

TYPE, 4
REAL, 2
E, 1, 2

TYPE, 5
REAL, 3
E, 3, 4

TYPE, 6
REAL, 4
E, 1, 4

TYPE, 7
REAL, 5

E, 2, 3, NC
ALLSEL, ALL

ASEL, S,, 1
NSLA, S, 1
CP, 1, CURR, ALL
CP, 2, EMF, ALL
ALLSEL, ALL

ASEL, S,, 1
ESLA, S
CM, COIL, ELEM
ALLSEL, ALL

LSEL, S,, 18
LSEL, A,, 15
LSEL, A,, 7
NSLL, S, 1
SF, ALL, INF
ALLSEL, ALL

NSEL, S, LOC, X, 0
D, ALL, AZ, 0
ALLSEL, ALL

NSEL, S, LOC, Y, 0
DSYM, SYMM, Y
ALLSEL, ALL

PHYSICS, WRITE, EMAG
FINT
SAVE

230
ALLSEL, ALL  ! ALTER CIRCUIT PARAMETERS
RMODIF, 2,1,1E-3
RMODIF, 3,1,1E-9
ALLSEL, ALL
PHYSICS, WRITE, EMAG2  ! WRITE EMAG 2
FINI  ! FINISH PREPROCESSING
SAVE

!*******************************************************************

ESTABLISH 'THERM' ENVIRONMENT

! ENTERS THE PREPROCESSOR

PHYSICS, READ, EMAG  ! READ EMAG PARAMETERS
LSCLEAR, ALL  ! CLEAR LOADS, BUT MAINTAIN
PHYSICS, CLEAR  ! SOLID/MESH

ET, 1, PLANET77,,1  ! ALTER MESH ELEMENTS
ET, 2, PLANET77,,1
ET, 3, 0
ET, 4, 0
ET, 5, 0
ET, 6, 0
ET, 7, 0

MPREAD, MATLIB_2D_SEMISTIC.TXT  ! IMPORT MATERIAL LIBRARY

LSEL, S,,2,4,1  ! SET CONVECTION LINES
SFL, ALL, CONV, 50,,293
ALLSEL, ALL

NSEL, S, LOC, Y, 0  ! SET AXIS OF SYMMETRY
DSYM, SYMM, Y
ALLSEL, ALL

TUNIF, 293  ! UNIFORM TEMP
Appendix D

254  PHYSICS, WRITE, THERMAL  ! WRITE THERMAL
255
256  FINI  ! FINISH PREPROCESSING
257  SAVE
258
259
260
261
262
263
264
265
266
267
268  ! ESTABLISH 'STRUCT' ENVIRONMENT
269
270  /PREP7  ! ENTERS THE PREPROCESSOR
271
272  PHYSICS, READ, EMAG  ! READ EMAG PARAMETERS
273  LSCLEAR, ALL  ! CLEAR LOADS, BUT MAINTAIN
274  PHYSICS, CLEAR  ! SOLID/MESH
275
276  ALPHA_DAMP=0  ! SET RAYLEIGH-TAYLOR
277  BETA_DAMP=0.0
278
279  ET, 1, PLANE183,,, 1
280  ET, 2, 0
281  ET, 3, 0
282  ET, 4, 0
283  ET, 5, 0
284  ET, 6, 0
285  ET, 7, 0
286
287  MREAD, MATLAB_2D_SEMISTC, TXT  ! IMPORT MATERIAL LIBRARY
288
289
290  ASEL, S,,, 2  ! SET AREA OF MESH
291  ASEL, A,,, 6
292  CM, AIR_MORPH, AREA
293  ALLSEL, ALL
294
295  ALPHAD, ALPHA_DAMP  ! SET DAMPENING
296  BETAD, BETA_DAMP
297
298  DL, 1, SYMM  ! SET AXIS OF SYMMETRY
299  ALLSEL, ALL
300
301  PHYSICS, WRITE,STRUCT  ! WRITE STRUCT
302
303  FINI  ! FINISH PREPROCESSING
304  SAVE

232
RUN SIMULATION
START_TIME=0
FINAL_TIME=1.8e-5
INCREMENTS=0.5e-7
ITTERATIONS=(FINAL_TIME-START_TIME)/INCREMENTS
TIME=START
*DO,I,1,ITTERATIONS
TIME=TIME+INCREMENTS

!-------------------------EMAG-----------------------------I
!----------------------------------------------------------1
/PREP7
LSCLEAR,ALL
PHYSICS,CLEAR
PHYSICS,READ,EMAG
FINISH

/ASSIGN,ESAV,EMAG,ESAV
/ASSIGN,EMAT,EMAG,EMAT
/ASSIGN,RST,EMAG,RMG

*IF,I,EQ,1,THEN
/SOLU
ALLSEL,ALL

TOFFST,O
TREF,293
TUNIF,293

ANTYPE,TRANS
OUTRES,ALL,ALL
TIME,TIME
NSUBST,1
KBC,0
RESCONTROL,,NONE
NROPT,FULL,,ON
Appendix D

356  SOLCONTROL, 0
357  NEQIT, 1
358  CNVTOL, VLTG, ... , -1
359  NCNV, 0
360  
361  SOLVE
362  SAVE, EMAG, DB ! SAVE EMAG, DB
363  
364  FINISH
365  
366  *ENDIF
367  
368  
369  
370  *IF, I, GT, 1, AND, TIME, LT, 5E-6, THEN ! NEXT PERIOD
371  
372  /SOLU ! ENTER SOLVER
373  
374  ALLSEL, ALL
375  
376  TOFFST, 0 ! SET TEMPS
377  TREF, 293
378  
379  ALLSEL, ALL ! APPLY THERMAL LOADS
380  ESEL, S, TYPE, 1
381  NSLE, S, ALL
382  LORREAD, TEMP, LAST, ... THERM, RTH
383  ALLSEL, ALL
384  
385  ANYTYPE, TRANS, REST ! SET ANALYSIS OPTIONS
386  OUTRES, ALL, ALL
387  TIME, TIME
388  NSUBST, 1
389  KBC, 0
390  RESCONTROL, , NONE
391  NROPT, FULL, , ON
392  SOLCONTROL, 0
393  NEQIT, 1
394  CNVTOL, VLTG, ... , -1
395  NCNV, 0
396  
397  SOLVE
398  SAVE, EMAG, DB ! SAVE EMAG, DB
399  
400  FINISH
401  
402  *ENDIF
403  
404  
405  
406  *IF, I, GT, 1, AND, TIME, GE, 5E-6, THEN ! NEXT PERIOD

234
/*ENDIF*/

/ENTER PREPROCESSOR

ALLSEL, ALL

*/IF, TIME, GE, 8E-6, THEN

RMODIF, 2, 1, 2.6E-3

RMODIF, 3, 1, 24E-9

*/ELSE

RMODIF, 2, 1, 1.3E-3

RMODIF, 3, 1, 24E-9

*/ENDIF

FINISH

/ENTER SOLVER

ALLSEL, ALL

TOFFST, 0

TREF, 293

ALLSEL, ALL

ALLSEL, ALL

ESEL, S, TYPE, '1

NSLE, S, ALL

LDREAD, TEMP, LAST, ALL, THERM, RTH

ALLSEL, ALL

ANTYPE, TRANS, REST

ANTYPES, TRANS, REST

OUTRES, ALL, ALL

TIME, TIME

NSUBST, 1

KBC, 0

RESCONTROL, 'NONE

NROPT, 'FULL, 'ON

SOLCONTROL, 0

NEQIT, 1

CNVTOL, 'VLTG, 'VLT, '1

NCNV, 0

SOLVE

SAVE, EMAG, DB

FINISH

*/ENDIF

/ASSIGN, ESAV

/ASSIGN, EMAT

/ASSIGN

!*----------------------------------------------------------!

235
Appendix D

!----------------------------------------------------------!

!-------------------------THERM----------------------------!

PEND7

LSCLEAR, ALL

PHYSICS, CLEAR

PHYSICS, READ, THERMAL

FINISH

/ASSIGN, ESAV, THERM, ESAV

ASSIGN, EMAT, THERM, EMAT

ASSIGN, RTH, THERM, RTH

*IF, I, EQ, 1, THEN

! FIRST ITERATION

/SOLU

! ENTER SOLVER

ALLSEL, ALL

TOFFST, 0

TREF, 293

TUNIF, 293

ESEL, $, TYPE, $1

LDREAD, HGEN, LAST, EMAG, RMG

ALLSEL, ALL

ANYPE, TRANS

OUTRES, ALL, ALL

TIME, TIME

NSUBST, I

KEO, 0

RESCONTROL, NONE

SOLVE

SAVE, THERM, DB

! SAVE THERM.DS

FINISH

*ENDIF

*IF, I, GT, 1, THEN

! NEXT PERIODS

236
Appendix D

```
509  /SOLU          ! ENTER SOLVER
510
511  ALLSEL,ALL
512
513  TOFFST,0         ! SET TEMPS
514  TREF,293
515
516  ESEL,GS,TYPE,1    ! LOAD JOULE ENERGY
517  LDREAD,HGEN,LAST,,EMAG,RMG
518  ALLSEL,ALL
519
520  ANTYPE,TRANS,REST  ! SET ANALYSIS OPTIONS
521  SOLCONTROL,ON
522  OUTRES,ALL,ALL
523  TIME,TIME
524  NSUBST,1
525  KBC,0
526  RESCONTROL,,NONE
527
528  SOLVE
529  SAVE, THERM, DB   ! SAVE THERM. DB
530
531  FINISH
532
533  *ENDIF
534
535  /ASSIGN, ESAV      ! RE-ASSIGN FILES
536  /ASSIGN, EMAT
537  /ASSIGN
538
539  !-----------------------------------------------!
540  !-----------------------------------------------!
541
542
543
544
545
546
547
548  !---------------------------------------------STRUCT------------------------------------------!
549  !---------------------------------------------!
550
551  /PREP7             ! ENTER PREPROCESSOR
552  LSCLEAR,ALL
553  PHYSICS,CLEAR
554  PHYSICS,READ,STRUCT ! LOAD STRUCT ENVIRONMENT
555  FINISH
556
557  /ASSIGN, ESAV, STRUCT, ESAV ! ASSIGN FILES
558  /ASSIGN, EMAT, STRUCT, EMAT
559  /ASSIGN, RST, STRUCT, RST
```

237
Appendix D

560  *IF, I, EQ, 1, THEN             ! FIRST ITERATION
561
562 /SOLU                             ! ENTER SOLVER
563
564 ALLSEL, ALL
565
566 TOFFST, 0                         ! SET TEMPS
567 TREF, 293
568 TUNIF, 293
569
570 ESEL, S, TYPE, ,, 1              ! LOAD TEMPERATURE
571 LDREAD, TEMP, LAST,,, THERM, RTH
572 NSLE, S, ALL                     ! LOAD LORENS
573 LDREAD, FORC, LAST,,, EMAG, RMG
574
575 ALLSEL, ALL
576
577 ANTYPE, TRANS                    ! SET ANALYSIS OPTIONS
578 NLGEOM, ON
579 SSTIF, ON
580 PRED, ON
581 NCNV, 0
582 NEQIT, 30
583<br>584 0.5 Cutcontrol, PLSLIMIT, 0.5
585 NROPT, FULL,, ON
586 NLDIAG, NRRES, ON
587 CNVTOL, F, 0.005, 0.001
588 CNVTOL, U, 0.05, 2, 0
589 OUTRES, ALL, ALL
590 TIME, TIME
591 NSUBST, 1
592 KEC, 0
593 RESCONTROL,, NONE
594
595 SOLVE                             ! SAVE STRUCT.BD
596 SAVE, STRUCT, DB
597 FINISH
598
599 *ENDIF
600
601
602 *IF, I, GT, 1, THEN             ! NEXT PERIODS
603
604 /SOLU                             ! ENTER SOLVER
605
606 PARSAY, ALL                      ! SAVE ALL PARAMETERS
607 RESUME, STRUCT, DB               ! RESUME DB
608 PARRES                           ! RESUME PARAMETERS
609
610
ALLSEL, ALL

T0FFST, 0
TREF, 293

ESEL, S, TYPE, 1
LDREAD, TEMP, LST, THERM, RTH

NSLE, S, ALL
LDREAD, FORC, LST, EMAG, RMG

ALLSEL, ALL

ANTYPE, TRANS, REST
NLGEOM, ON
SSTIF, ON
FRED, ON
NCNV, 0
NEQIT, 30

CUTCONTROL, PLSLIMIT, 0.5
NROPT, FULL, ON
NLDIAG, NRRES, ON

CNVTOL, F, 0.005, 0, 0.01

CNVTOL, U, 0.05, 2, 0

OUTRES, ALL, ALL
TIME, TIME
NSUBST, 1
KBC, 0
RESCONTROL, NONE

SOLVE
SAVE, STRUCT, DB
FINISH

*ENDIF

!----------------------------------------------------------!

!----------------------------------------------------------!

!-------------------------MORPH----------------------------!

/PRF7

ALLSEL, ALL
ICDELE

ALLSEL, ALL
DAMORPH,AIR_MORPH,,2  
ALLSEL,ALL  
FINISH  
/ASSIGN,ESAV  
/ASSIGN,EMAT  
/ASSIGN  
!-----------------------------------------------!
!-----------------------------------------------!
*ENDDO  

!*******************************************************************

TIME HISTORY POST PROCESS  
/PREP7  
LSCLEAR,ALL  
PHYSICS,CLEAR  
PHYSICS,READ,EMAG  
FINISH  
/ASSIGN,ESAV,EMAG,ESAV  
/ASSIGN,EMAT,EMAG,EMAT  
/ASSIGN,RST,EMAG,RMG  
/POST26  
FILE,EMAG,RMG  
PMTTRAN,'COIL',,,,,,'COIL'  
FINISH  

-------------------------------

SAVE  
*IIF,1,EQ,2,THEN  

-------------------------------
Appendix D

RE-ASSIGN FILES

*ENDIF
APPENDIX E

3D STC FEA Batch Code
APPENDIX E

! Douglas Rankin
! Loughborough University
! 2D Semi-destructive STC
! Thesis inclusion July 2005

/TITLE,3-D Semi-destructive STC

!*******************************************************************

! SET UP SOLID MODEL

/PREP7

INRAD=10.125E-3
OUTRAD=12.125E-3
HEIGHT=20.35E-3
GAP=0.5E-3
CLAMP=7E-3

K,1,0,0,0
K,2,0,0,HEIGHT

PCIRC,0,INRAD,0,90
PCIRC,0,INRAD,90,180
PCIRC,0,OUTRAD,0,90
PCIRC,0,OUTRAD,90,180

Y_OUT=GAP+(OUTRAD-INRAD)
X_OUT=SQRT((OUTRAD*OUTRAD)-(Y_OUT*Y_OUT))
RECTNG,X_OUT,(X_OUT+CLAMP),0,Y_OUT

ETOL,1E-7

Y_IN=GAP
X_IN=SQRT((INRAD*INRAD)-(Y_IN*Y_IN))
RECTNG,X_IN,(X_OUT+CLAMP),0,Y_IN
SAVE
AOVLAP,ALL
NUMCP,ALL
SAVE
ADELE,2,3,1
ADELE,5,6,1
ADELE,8,9,1

RECTNG,X_OUT,(X_OUT+CLAMP),0,Y_OUT
RECTNG,X_IN,(X_OUT+CLAMP),0,Y_IN
AOVLAP,ALL
NUMCMP,ALL
ALLSEL,ALL
BTOL

FINI ! FINISH PREPROCESSING

*******************************************************************************

ESTABLISH 'EMAG' ENVIRONMENT

/PREP7
SHPP,OFF
FIVCHECK,OFF

ET,1,SOLID97,4
ET,2,SOLID97
ET,3,INFIN111,1
ET,4,CIRCU124,0
ET,5,CIRCU124,1
ET,6,CIRCU124,2
ET,7,CIRCU124,7,2
ET,8,MESH200,6,0

R,1,((OUTRAD-INRAD)*{2*HEIGHT}) ! X-SECTIONAL AREA
R,2,0.8E-3 ! Resistance
R,3,24E-9 ! Inductance
R,4,210.56E-6,13.717E3 ! Capacitance, Vo
R,5,1 ! Scaling factor ?

MPREAD,MatLib_2D_SEMISTIC,TXT ! IMPORT MATERIAL LIBRARY

N,1,6E-2,1E-2,1E-3
N,2,8E-2,1E-2,1E-3
N,3,8E-2,0.1E-2,1E-3
N,4,6E-2,0.1E-2,1E-3

FARFIELD=1
DENSX=20
DENSY=10
MSHAPE,0,2D
MSHKEY,1

244
Appendix E

TYPE, 8
ESIZE, 0, 8
AMESH, 1

LESIZE, 14, 3
LESIZE, 13, 3
LESIZE, 15, 8
AMESH, 4

LESIZE, 22, 1
LCCAT, 22, 23
ESIZE, 0, 8
AMESH, 2
LDELE, 33
ALLSEL, ALL

LESIZE, 30, 1
LESIZE, 31, 1
LESIZE, 25, 1
AMESH, 6

LESIZE, 32, 8
LESIZE, 29, 3
LCCAT, 31, 23
AMESH, 7
LDELE, 33
ALLSEL, ALL

LESIZE, 26, 3
LESIZE, 27, 3
LESIZE, 26, 1
AMESH, 3

LESIZE, 28, 3
LESIZE, 21, 3
AMESH, 5

L, 1, 2
LESIZE, 33, 8
TYPE, 1
MAT, 1
ASEL, ALL
VDRAG, ALL, 33

IVSEL, S, 4, 5, 1
IVSEL, A, 7
VSEL, S, 1, 3
VSEL, A, 6

ESLV, 8
TYPE, 2
MAT, 2
EMODIF, ALL
ALLSEL, ALL.

TYPE, 2
MAT, 2
ESIZE, 0, 4
ASEL, S, 11, 15, 4
ASEL, A, 17, 20, 3
ASEL, A, 21
ASEL, A, 24, 26, 1
ASEL, A, 28
ASEL, A, 31, 33, 1
VEXT, ALL, 0, 0, 0, 2, 2, 2

TYPE, 3
MAT, 2
ESIZE, 0, 1
ASEL, S, 34, 42, 4
ASEL, A, 47, 51, 4
ASEL, A, 56, 59, 3
ASEL, A, 63, 67, 4
ASEL, A, 69, 75, 3
VEXT, ALL, 0, 0, 0, 1.3, 1.3, 1.3

ET, 8, 0

NA=NODE([(X_OUT+CLAMP), (GAP+((OUTRAD-INRAD)/2)), (HEIGHT/4))]
NB=NODE(-(OUTRAD-INRAD), 0, (HEIGHT/4))

TYPE, 4
REAL, 2
E, 1, 2
! RESISTOR Element creation
! Use real constant 2
! Generate element between nodes 1 and 2

TYPE, 5
REAL, 3
E, 3, 4
! INDUCTOR Element creation
! Use real constant 3
! Generate element between nodes 3 and 4

TYPE, 6
REAL, 4
E, 1, 4
! CAPACITOR Element creation
! Use real constant 4
! Generate element between nodes 1 and 4

TYPE, 7
REAL, 5
E, 2, 3, NA, NB
! 3D COUPLER Element creation, with connection to COIL
! Generate element between nodes 2 and 3 (circuit)
! and N1 and N2 (coil)

ALLSEL, ALL
ASEL,S,AREA,,25
NSLA,S,1
CP,1,CURR,ALL     ! Couple the CURR dof
CP,2,VOLT,ALL     ! Couple the EMF dof
ALLSEL,ALL

ASEL,S,22
NSLA,S,1
CP,3,CURR,ALL     ! Couple the CURR dof
CP,4,VOLT,ALL     ! Couple the EMF dof
ALLSEL,ALL

ESEL,S,MAT,,1
CM,COIL,ELEM
ALLSEL,ALL

ASEL,S,76,84,4
ASEL,A,89,93,4
ASEL,A,98,101,3
ASEL,A,105,109,4
ASEL,A,111,117,3
SFA,ALL,,INF
ALLSEL,ALL

/SOLU

! FLUX PARALLEL CONDITION
ASEL,S,LOC,Y,0
DA,ALL,ASYM

! FLUX NORMAL CONDITION
ASEL,S,LOC,Z,0
DA,ALL,SYMM

ALLS
D,4,VOLT,0

PHYSICS,WRITE,EMAG
FINISH
SAVE

FINI                  ! FINISH PREPROCESSING
SAVE

********************************************************************
Appendix E

! ESTABLISH 'THERM' ENVIRONMENT

/PREP7 ! ENTERS THE PREPROCESSOR

PHYSICS,READ,EMAG ! READ EMAG PARAMETERS
LSCLEAR,ALL ! CLEAR LOADS, BUT MAINTAIN
PHYSICS,CLEAR ! SOLID/MESH

ET,1,SOLID70
ET,2,SOLID70
ET,3,0
ET,4,0
ET,5,0
ET,6,0
ET,7,0
ET,8,0

MPREAD,MATLIB_2D_SEMISTIC,TXT ! IMPORT MATERIAL LIBRARY

TUNIF,293

ASEL,S,,,8,18,5
ASEL,A,,,21
ASEL,A,,,24,20,2
ASEL,A,,,30,32,2
ASEL,A,,,33
SFA,ALL,CONV,50,293
ALLSEL,ALL

NSEL,S,LOC,Y,0
DSYM,SYMM,Y
ALLSEL,ALL

NSEL,S,LOC,Z,0
DSYM,SYMM,Z
ALLSEL,ALL

PHYSICS,WRITE,THERMAL ! WRITE THERMAL

FINI ! FINISH PREPROCESSING
SAVE

**********************************************************************************
! ESTABLISH 'STRUCT' ENVIRONMENT

/PREP7

! ENTERS THE PREPROCESSOR

PHYSICS,READ,EMAG

! READ EMAG PARAMETERS

LSCLEAR,ALL

! CLEAR LOADS, BUT MAINTAIN

PHYSICS,CLEAR

! SOLID/MESH

ALPHA_DAMP=0

! SET RAYLEIGH-TAYLOR

BETA_DAMP=0.0

ET,1,SOLID185 145

ET,2,0

ET,3,0

ET,4,0

ET,5,0

ET,6,0

ET,7,0

ET,8,0

MREAD,MATLIB_2D_SEMISTC,TXT ! IMPORT MATERIAL LIBRARY

VSEL,S,TYPE,,2

CM,AIR_MORPH,VOUJ

ALLSEL,ALL

ASEL,S,,4,5,1

ASEL,A,,7

NSLA,S,1

DSYM,SYMM,Z

ALLSEL,ALL

ASEL,S,,22

NSLA,S,1

DSYM,SYMM,Y

ALLSEL,ALL

!ASEL,S,,25,26,1

ASEL,S,,26

NSLA,S,1

D,ALL,ALL,0

ALLSEL,ALL

ALPHAD,ALPHA_DAMP

BETAD,BETA_DAMP
PHYSICS,WRITE,STRUCT ! WRITE STRUCT
FINI ! FINISH PREPROCESSING
SAVE

******************************************************************************
******************************************************************************

! RUN SIMULATION

START_TIME=0
FINAL_TIME=1.8e-4 10.0002 10.0001
INCREMENTS=0.2e-6
ITERATIONS={(FINAL_TIME-START_TIME)/INCREMENTS}
TIME=START_TIME

*DO,I,1,ITERATIONS
  TIME=TIME+INCREMENTS
  !-------------------------EMAG-----------------------------!
  !----------------------------------------------------------!
  /PREP7
  LSCLEAR,ALL
  PHYSICS,CLEAR
  PHYSICS,READ,EMAG
  FINISH
  /ASSIGN,ESAV,EMAG,ESAV
  /ASSIGN,EMAT,EMAG,EMAT
  /ASSIGN,RST,EMAG,RMG

  *IF,I,EQ,1,THEN
  ! FIRST ITERATION
  /SOLU
  ALLSEL,ALL ! select everything
  TOFFST,0
  TREF,293
  TUNIF,293

  !-------------------------EMAG-----------------------------!
  !----------------------------------------------------------!

250
SFA, ALL, MCI, IN
ALLSEL, ALL
ASEL, S, 22
SFA, ALL, MCI, OUT
ALLSEL, ALL
D, 4, VOLT, 0

!-----------------------

ANTYPE, TRANS        ! Transient analysis
OUTRES, ALL, ALL     ! Output all results
TIME, TIME           ! Time of analysis
NSUBST, 1            ! Number of substeps
KBC, 0               ! Ramped solution
RESCONTROL, ,NONE    ! No multiframe restart
NROPT, FULL, ,OFF    !    
SOLCONTROL, 0        !    
NEQIT, 1             !    
CNVTOL, VLTG, , , , -1
NCNV, 0

SOLVE                ! Solve problem
SAVE, EMAG, DB       ! Save emag.db

FINISH               ! Finish in /sou

*ENDIF

*IF, I, GT, 1, AND, TIME, LT, SE-6, THEN

/SOLU
ALLSEL, ALL

TOFFST, 0
TREF, 293

!-----------------------

ASEL, S, AREA, , 25
SFA, ALL, MCI, IN
ALLSEL, ALL
ASEL, S, 22
SFA, ALL, MCI, OUT
ALLSEL, ALL
D, 4, VOLT, 0

!-----------------------

ALLSEL, ALL          ! select everything
ESEL, S, TYPE, , 1

251
NSLE, S, ALL
LDREAD, TEMP, LAST, , THERM, RTH
ALLSEL, ALL
ANTYPE, TRANS, REST  ! Transient restart

OUTRES, ALL, ALL  ! Output all results
TIME, TIME  ! Time of analysis
NSUBST, 1  ! Number of substeps
KEC, 0  ! Ramped solution
RESCONTROL, , NONE  ! No multi-frame restart
NROPT, FULL, OFF
SOLCONTROL, 0
NEQIT, 1
CNVTOL, VLTG, , , -1
NCNV, 0

SOLVE  ! Solve problem
SAVE, EMAG, DB  ! Save emag.db
FINISH  ! Finish in /solut

*ENDIF

*IF, I, GT, 1, AND, TIME, GE, 5E-6, THEN

/PREP7
ALLSEL, ALL

*IF, TIME, GE, 3E-6, THEN
  RMODIF, 2, 1, 1.6E-3
  RMODIF, 3, 1, 28E-9
*ELSE
  RMODIF, 2, 1, 1.1E-3
  RMODIF, 3, 1, 28E-9
*ENDIF

FINISH

/SOLU

ALLSEL, ALL  ! select everything
TOFFST, 0
TREF, 293
TUNIF, 293

!---------------------
ASEL, S, AREA, , 25
Appendix E

SFA, ALL,, MCI, IN
ALLSEL, ALL
ASEL, S,, 22
SFA, ALL,, MCI, OUT
ALLSEL, ALL
D, 4, VOLT, 0
!------------------

ALLSEL, ALL  ! select everything
ESEL, S, TYPE,, 1
NSLE, S, ALL
LDREAD, TEMP, LAST,,, THERM, RTH
ALLSEL, ALL
ANTYPE, TRANS, REST  ! Transient restart

OUTRES, ALL, ALL  ! Output all results
TIME, TIME  ! Time of analysis
NSUBST, 1  ! Number of substeps
KBC, 0  ! Ramped solution
RESCONTROL,, NONE  ! No multi frame restart
NROPT, FULL,, OFF
SOLCONTROL, 0
NEQIT, 1
CNVTOL, VLTG,,, -1
NCNV, 0

SOLVE  ! Solve problem
SAVE, EMAG, DB  ! Save emag.db

FINISH  ! Finish in /solu

*ENDIF

/ASSIGN, ESAV  ! RE-ASSIGN FILES
/ASSIGN, EMAT
/ASSIGN

!----------------------------------------------------------

!------------------------- THERM -----------------------------
!----------------------------------------------------------

/ PREP7  ! ENTER THE PREPROCESSOR
LSCLEAR, ALL

253
Appendix E

PHYSICS,CLEAR
PHYSICS,READ,THERMAL
! READ THERMAL ENVIRONMENT
FINISH

/ASSIGN, ESAV, THERM, ESAV
/ASSIGN, EMAT, THERM, EMAT
/ASSIGN, RTH, THERM, RTH

*IF, I, EQ, 1, THEN

! ASSIGN OUTPUT FILES

! FIRST ITERATION

/SOLU

ALLSEL, ALL

TOFFST, 0
TREF, 293
TUNIF, 293

ESEL, S, TYPE, , 1
LDREAD, HGEN, LAST, ..., EMAG, RMG
ALLSEL, ALL

ANTYPE, TRANS

! Transient analysis

OUTRES, ALL, ALL

! Output all results
TIME, TIME

! Time of analysis
NSUBST, 1

! Number of substeps
KRC, 1

! Ramped solution
RESCONTROL, NONE

! No multi frame restart
SOLVE

! Solve problem
SAVE, THERM, DB

! save therm.db
FINISH

! Finish in /solu

*ENDIF

*IF, I, GT, 1, THEN

/SOLU

ALLSEL, ALL

TOFFST, 0
TREF, 293

ESEL, S, TYPE, , 1
LDREAD, HGEN, LAST, ..., EMAG, RMG
ALLSEL, ALL

ANTYPE, TRANS, REST

! Transient restart
SOLCONTROL, ON

254
OUTRES, ALL, ALL ! Output all results
TIME, TIME ! Time of analysis
NSUBST, 1 ! Number of substeps
KBC, 1 ! Ramped solution
RESCONTROL, "NONE" ! No multiframe restart
SOLVE ! Solve problem
SAVE, THERM, DB ! save therm.db

FINISH ! Finish in /solu

*ENDIF

/ASSIGN, ESAV ! RE-ASSIGN FILES
/ASSIGN, EMAT
/ASSIGN

!---------------------------------------------------------------------!
!---------------------------------------------------------------------!

!------------------------STRUCT---------------------!
!/PREP7
LSCLEAR, ALL
PHYSICS, CLEAR
PHYSICS, READ, STRUCT
FINISH

/ASSIGN, ESAV, STRUCT, ESAV ! ASSIGN FILES
/ASSIGN, EMAT, STRUCT, EMAT
/ASSIGN, RST, STRUCT, RST

*IF, I, EQ, 1, THEN ! FIRST ITERATION

/SOLU ! ENTER SOLVER

ALLSEL, ALL
TOFFST, 0
TREF, 293
TUNIF, 293

ESEL, S, TYPE, 1
NSLE, S, ALL
LOREAD, FORC, LAST, \ldots, EMAG, RMG

255
LDREAD, TEMP, LAST, \ldots, THERM, RTH
ALLSEL, ALL

ANTYPE, TRANS

! Transient analysis

NLGEOM, ON
SSTIF, OFF
PRED, ON
NCNV, 0
NEQIT, 100
CUTCONTROL, PLSLIMIT, 0.5

OUTRES, ALL, ALL
TIME, TIME
NSUBST, 1
KRC, 0
RESCONTROL, , NONE
SOLVE
SAVE, STRUCT, DB

! Output all results
! Time of analysis
! Number of substeps
! Ramped solution
! No multiframe restart
! Solve problem
! Save struct.db

FINISH
! Finish in /solu

*ENDIF

*IF, I, GT, 1, THEN

/ SOLU

PARSAV, ALL
RESUME, STRUCT, DB
PARRES
ALLSEL, ALL

TOFFST, 0
TREF, 293

ESEL, S, TYPE, , 1
NSLE, S, ALL
LDREAD, FORC, LAST, \ldots, EMAG, RMG
LDREAD, TEMP, LAST, \ldots, THERM, RTH
ALLSEL, ALL

ANTYPE, TRANS, REST

! Transient restart

NLGEOM, ON
SSTIF, OFF
FRED, ON
NCNV, 0
NEGIT, 100
CUTCONTROL, FLSLIMIT, 0.5

OUTRES, ALL, ALL ! Output all results
TIME, TIME ! Time of analysis
NSUBST, 1 ! Number of substeps
KBC, 0 ! Ramped solution
RESCONTROL, NONE ! No multiframe restart
SOLVE ! Solve problem
SAVE, STRUCT, DB ! save struct.db

FINISH ! Finish in /solu

*ENDIF

!----------------------------------------------------------!
!----------------------------------------------------------!

!----------------------------------------------------------!-MORPH----------------------------!
!----------------------------------------------------------!

/FREET    ! ENTER PREPROCESSOR
ALLSEL, ALL
ICDELE ! DELETE INITIAL CONDITIONS
ALLSEL, ALL
DVMORPH, AIR_MORPH, , 2 ! MORPH COMPONENTS
ALLSEL, ALL
FINISH

/ASSIGN, ESAVE ! RE-ASSIGN FILES
/ASSIGN, EMAT
/ASSIGN

!----------------------------------------------------------!
!----------------------------------------------------------!

*ENDDO

**************************************************************************
APPENDIX F

Semi Destructive Materials Library
MATERIAL PROPERTIES OF COPPER, NON DESTRUCTIVE

PERMEABILITY

\[
\begin{align*}
MF,MUX,1,1
\end{align*}
\]

CONDUCTIVITY

\[
\begin{align*}
MFTEMP,\ldots, \quad \text{temperature is in degrees K} \\
MFTEMP,1,1.0 \\
MFTEMP,2,31.0 \\
MFTEMP,3,61.0 \\
MFTEMP,4,91.0 \\
MFTEMP,5,121.0 \\
MFTEMP,6,151.0 \\
MFTEMP,7,181.0 \\
MFTEMP,8,211.0 \\
MFTEMP,9,241.0 \\
MFTEMP,10,271.0 \\
MFTEMP,11,301.0 \\
MFTEMP,12,331.0 \\
MFTEMP,13,361.0 \\
MFTEMP,14,391.0 \\
MFTEMP,15,421.0 \\
MFTEMP,16,451.0 \\
MFTEMP,17,481.0 \\
MFTEMP,18,511.0 \\
MFTEMP,19,541.0 \\
MFTEMP,20,571.0 \\
MFTEMP,21,601.0 \\
MFTEMP,22,631.0 \\
MFTEMP,23,661.0 \\
MFTEMP,24,691.0 \\
MFTEMP,25,721.0 \\
MFTEMP,26,751.0 \\
MFTEMP,27,781.0 \\
MFTEMP,28,811.0 \\
MFTEMP,29,841.0 \\
MFTEMP,30,871.0 \\
MFTEMP,31,901.0
\end{align*}
\]
MPTEMP, 32, 931.0
MPTEMP, 33, 961.0
MPTEMP, 34, 991.0
MPTEMP, 35, 1021.0
MPTEMP, 36, 1051.0
MPTEMP, 37, 1081.0
MPTEMP, 38, 1111.0
MPTEMP, 39, 1141.0
MPTEMP, 40, 1171.0
MPTEMP, 41, 1201.0
MPTEMP, 42, 1231.0
MPTEMP, 43, 1261.0
MPTEMP, 44, 1291.0
MPTEMP, 45, 1321.0
MPTEMP, 46, 1351.0
MPTEMP, 47, 1381.0
MPTEMP, 48, 1411.0
MPTEMP, 49, 1441.0
MPTEMP, 50, 1471.0
MPTEMP, 51, 1501.0
MPTEMP, 52, 1531.0
MPTEMP, 53, 1561.0
MPTEMP, 54, 1591.0
MPTEMP, 55, 1621.0
MPTEMP, 56, 1651.0
MPTEMP, 57, 1681.0
MPTEMP, 58, 1711.0
MPTEMP, 59, 1741.0
MPTEMP, 60, 1771.0
MPTEMP, 61, 1801.0
MPTEMP, 62, 1831.0

MPDATA, RSVX, 1,, 2.000000e-011
MPDATA, RSVX, 1,, 9.349245e-011
MPDATA, RSVX, 1,, 1.023582e-009
MPDATA, RSVX, 1,, 2.887478e-009
MPDATA, RSVX, 1,, 4.921354e-009
MPDATA, RSVX, 1,, 6.985160e-009
MPDATA, RSVX, 1,, 9.041285e-009
MPDATA, RSVX, 1,, 1.109139e-008
MPDATA, RSVX, 1,, 1.313714e-008
MPDATA, RSVX, 1,, 1.518020e-008
MPDATA, RSVX, 1,, 1.722223e-008
MPDATA, RSVX, 1,, 1.926489e-008
MPDATA, RSVX, 1,, 2.130985e-008
MPDATA, RSVX, 1,, 2.335877e-008
MPDATA, RSVX, 1,, 2.541331e-008
MPDATA, RSVX, 1,, 2.747514e-008
MPDATA, RSVX, 1,, 2.954592e-008
MPDATA, RSVX, 1,, 3.162730e-008
MPDATA, RSVX, 1,, 3.372097e-008
MPDATA, RSVX, 1,, 3.582856e-008

I data is in units of ohm-m
MPDATA,RSVX,1,,3.795176e-008
MPDATA,RSVX,1,,4.009223e-008
MPDATA,RSVX,1,,4.225162e-008
MPDATA,RSVX,1,,4.443160e-008
MPDATA,RSVX,1,,4.663383e-008
MPDATA,RSVX,1,,4.885998e-008
MPDATA,RSVX,1,,5.111170e-008
MPDATA,RSVX,1,,5.339067e-008
MPDATA,RSVX,1,,5.569854e-008
MPDATA,RSVX,1,,5.803698e-008
MPDATA,RSVX,1,,6.040765e-008
MPDATA,RSVX,1,,6.281221e-008
MPDATA,RSVX,1,,6.525233e-008
MPDATA,RSVX,1,,6.772967e-008
MPDATA,RSVX,1,,7.024589e-008
MPDATA,RSVX,1,,7.280266e-008
MPDATA,RSVX,1,,7.540164e-008
MPDATA,RSVX,1,,7.804448e-008
MPDATA,RSVX,1,,8.073266e-008
MPDATA,RSVX,1,,8.346844e-008
MPDATA,RSVX,1,,8.625288e-008
MPDATA,RSVX,1,,8.908784e-008
MPDATA,RSVX,1,,9.197499e-008
MPDATA,RSVX,1,,9.491599e-008
MPDATA,RSVX,1,,9.791250e-008
MPDATA,RSVX,1,,1.009662e-007
MPDATA,RSVX,1,,2.101076e-007
MPDATA,RSVX,1,,2.130905e-007
MPDATA,RSVX,1,,2.160734e-007
MPDATA,RSVX,1,,2.190563e-007
MPDATA,RSVX,1,,2.220392e-007
MPDATA,RSVX,1,,2.250220e-007
MPDATA,RSVX,1,,2.280049e-007
MPDATA,RSVX,1,,2.309878e-007
MPDATA,RSVX,1,,2.339707e-007
MPDATA,RSVX,1,,2.369536e-007
MPDATA,RSVX,1,,2.399365e-007
MPDATA,RSVX,1,,2.429193e-007
MPDATA,RSVX,1,,2.459022e-007
MPDATA,RSVX,1,,2.488851e-007
MPDATA,RSVX,1,,2.518680e-007
MPDATA,RSVX,1,,2.539560e-007

! ISOLINEAR THERMAL CONDUCTIVITY

MPTEMP,1,1.0
MPTEMP,2,101.0
MPTEMP,3,201.0
Appendix F

MPTEMP, 4, 301.0
MPTEMP, 5, 401.0
MPTEMP, 6, 501.0
MPTEMP, 7, 601.0
MPTEMP, 8, 701.0
MPTEMP, 9, 801.0
MPTEMP, 10, 901.0
MPTEMP, 11, 1001.0
MPTEMP, 12, 1101.0
MPTEMP, 13, 1201.0
MPTEMP, 14, 1301.0
MPTEMP, 15, 1358.0
MPTEMP, 16, 1458.0
MPTEMP, 17, 1558.0
MPTEMP, 18, 1658.0
MPTEMP, 19, 1758.0
MPTEMP, 20, 1858.0
MPTEMP, 21, 1958.0
MPTEMP, 22, 2058.0

MPDATA, KXX, 1,, 5.053978e+001
MPDATA, KXX, 1,, 4.385918e+002
MPDATA, KXX, 1,, 3.629671e+002
MPDATA, KXX, 1,, 3.858533e+002
MPDATA, KXX, 1,, 3.823387e+002
MPDATA, KXX, 1,, 3.765923e+002
MPDATA, KXX, 1,, 3.731180e+002
MPDATA, KXX, 1,, 3.663313e+002
MPDATA, KXX, 1,, 3.589750e+002
MPDATA, KXX, 1,, 3.518016e+002
MPDATA, KXX, 1,, 3.452565e+002
MPDATA, KXX, 1,, 3.391606e+002
MPDATA, KXX, 1,, 3.323938e+002
MPDATA, KXX, 1,, 3.273861e+002
MPDATA, KXX, 1,, 1.695315e+002
MPDATA, KXX, 1,, 1.728239e+002
MPDATA, KXX, 1,, 1.756459e+002
MPDATA, KXX, 1,, 1.780271e+002
MPDATA, KXX, 1,, 1.799953e+002
MPDATA, KXX, 1,, 1.815771e+002
MPDATA, KXX, 1,, 1.827978e+002

! data is in units of W/(m-K)

MPDATA, KXX, 1,, 5.053978e+001
MPDATA, KXX, 1,, 4.385918e+002
MPDATA, KXX, 1,, 3.629671e+002
MPDATA, KXX, 1,, 3.858533e+002
MPDATA, KXX, 1,, 3.823387e+002
MPDATA, KXX, 1,, 3.765923e+002
MPDATA, KXX, 1,, 3.731180e+002
MPDATA, KXX, 1,, 3.663313e+002
MPDATA, KXX, 1,, 3.589750e+002
MPDATA, KXX, 1,, 3.518016e+002
MPDATA, KXX, 1,, 3.452565e+002
MPDATA, KXX, 1,, 3.391606e+002
MPDATA, KXX, 1,, 3.323938e+002
MPDATA, KXX, 1,, 3.273861e+002
MPDATA, KXX, 1,, 1.695315e+002
MPDATA, KXX, 1,, 1.728239e+002
MPDATA, KXX, 1,, 1.756459e+002
MPDATA, KXX, 1,, 1.780271e+002
MPDATA, KXX, 1,, 1.799953e+002
MPDATA, KXX, 1,, 1.815771e+002
MPDATA, KXX, 1,, 1.827978e+002

! DENSITY

[---------]

MPTEMP, 1,, 1.400
MPTEMP, 2,, 1.104
MPTEMP, 3,, 1.204
MPTEMP, 4,, 1.304
MPTEMP, 5, 404.0
MPTEMP, 6, 504.0
MPTEMP, 7, 604.0
MPTEMP, 8, 704.0
MPTEMP, 9, 804.0
MPTEMP, 10, 904.0
MPTEMP, 11, 1004.0
MPTEMP, 12, 1104.0
MPTEMP, 13, 1204.0
MPTEMP, 14, 1250.0
MPTEMP, 15, 1358.0
MPTEMP, 16, 1391.0
MPTEMP, 17, 1424.0
MPTEMP, 18, 1457.0
MPTEMP, 19, 1490.0
MPTEMP, 20, 1523.0

MPDATA, DENS, 1,, 9.028155e+003  ! data is in units of kg/m^3
MPDATA, DENS, 1,, 9.014886e+003
MPDATA, DENS, 1,, 8.978478e+003
MPDATA, DENS, 1,, 8.935182e+003
MPDATA, DENS, 1,, 8.889740e+003
MPDATA, DENS, 1,, 8.842551e+003
MPDATA, DENS, 1,, 8.793617e+003
MPDATA, DENS, 1,, 8.742936e+003
MPDATA, DENS, 1,, 8.690509e+003
MPDATA, DENS, 1,, 8.636336e+003
263
MPTEMP, 10, 901.0
MPTEMP, 11, 1001.0
MPTEMP, 12, 1101.0
MPTEMP, 13, 1201.0
MPTEMP, 14, 1300.0
MPTEMP, 15, 1356.0
MPTEMP, 16, 1456.0
MPTEMP, 17, 1556.0
MPTEMP, 18, 1656.0
MPTEMP, 19, 1756.0
MPTEMP, 20, 1856.0
MPTEMP, 21, 1956.0
MPTEMP, 22, 2056.0
MPTEMP, 23, 2156.0
MPDATA, C, L, , 1.296101e-002
MPDATA, C, L, , 1.712736e+002
MPDATA, C, L, , 3.553745e+002
MPDATA, C, L, , 3.836240e+002
MPDATA, C, L, , 3.955715e+002
MPDATA, C, L, , 4.061073e+002
MPDATA, C, L, , 4.152834e+002
MPDATA, C, L, , 4.234257e+002
MPDATA, C, L, , 4.311336e+002
MPDATA, C, L, , 4.392805e+002
MPDATA, C, L, , 4.490136e+002
MPDATA, C, L, , 4.617538e+002
MPDATA, C, L, , 4.791357e+002
MPDATA, C, L, , 5.030266e+002
MPDATA, C, L, , 5.161615e+002
MPDATA, C, L, , 5.161615e+002
MPDATA, C, L, , 5.161615e+002
MPDATA, C, L, , 5.161615e+002
MPDATA, C, L, , 5.161615e+002
MPDATA, C, L, , 5.161615e+002
MPDATA, C, L, , 5.161615e+002
MPDATA, C, L, , 5.161615e+002
MPDATA, C, L, , 5.161615e+002
MPDATA, C, L, , 5.161615e+002
MPDATA, C, L, , 5.161615e+002
MPDATA, C, L, , 5.161615e+002
MPDATA, C, L, , 5.161615e+002

! MODULUS OF ELASTICITY
!-----------------------
MP, EX, 1, 1.1E11

! BILINEAR KINEMATIC MODEL
!-----------------------
TB, BKIN, 1, 6
MPTEMP, , , , , , , , , , , ,
TBTEMP, 254.0, 1
TB DATA, 1
TKDATA, 1, (1.288065e+011*0.9E-3)
MPTEMP, , , , , ,
TBTEMP,454.0,2
TB DATA, 1, (1.168304e+011*0.9E-3)
MPTEMP, , , , , ,
TBTEMP,654.0,3
TB DATA, 1, (1.045589e+011*0.9E-3)
MPTEMP, , , , , ,
TBTEMP,854.0,4
TB DATA, 1, (9.125362e+010*0.9E-3)
MPTEMP, , , , , ,
TBTEMP,1054.0,5
TB DATA, 1, (7.691439e+010*0.9E-3)
MPTEMP, , , , , ,
TBTEMP,1250.0,6
TB DATA, 1, (6.185884e+010*0.9E-3)

! POISSON'S RATIO
!-----------------------
MP,NUXY,1,0.499

! COEFFICIENT OF THERMAL EXPANSION
!----------------------------------
MP,ALPX,1,0

!*******************************************************************
!*******************************************************************
MATERIAL PROPERTIES OF AIR
! PERMEABILITY
!---------------
MP,MURX,2,1

! CONDUCTIVITY
!-------------
MP,RSVX,2,0

! ISOLINEAR THERMAL CONDUCTIVITY
!--------------------------------
MP,KXX,2,0.02

! DENSITY
!-----------------

MP,DENS,2,1.29

! SPECIFIC HEAT COEFFICIENT
!-------------------------

! MODULUS OF ELASTICITY
!----------------------

MP,EX,2,100

! POISSON'S RATIO
!-----------------

MP,NUXY,2,0.4999

! COEFFICIENT OF THERMAL EXPANSION
!---------------------------------

MP,ALPX,2,0

!************************************************************************

! EOF
APPENDIX G

Destructive Materials Library
MATERIAL PROPERTIES OF COPPER, DESTRUCTIVE

PERMEABILITY

\[ \mu_r(x, l, l) \]

CONDUCTIVITY

\[ \sigma(x, l, l) \]

\begin{tabular}{l}
\hline
\text{MPTEMP} & \text{2, 31.0} \\
\text{MPTEMP} & \text{3, 61.0} \\
\text{MPTEMP} & \text{4, 91.0} \\
\text{MPTEMP} & \text{5, 121.0} \\
\text{MPTEMP} & \text{6, 151.0} \\
\text{MPTEMP} & \text{7, 181.0} \\
\text{MPTEMP} & \text{8, 211.0} \\
\text{MPTEMP} & \text{9, 241.0} \\
\text{MPTEMP} & \text{10, 271.0} \\
\text{MPTEMP} & \text{11, 301.0} \\
\text{MPTEMP} & \text{12, 331.0} \\
\text{MPTEMP} & \text{13, 361.0} \\
\text{MPTEMP} & \text{14, 391.0} \\
\text{MPTEMP} & \text{15, 421.0} \\
\text{MPTEMP} & \text{16, 451.0} \\
\text{MPTEMP} & \text{17, 481.0} \\
\text{MPTEMP} & \text{18, 511.0} \\
\text{MPTEMP} & \text{19, 541.0} \\
\text{MPTEMP} & \text{20, 571.0} \\
\text{MPTEMP} & \text{21, 601.0} \\
\text{MPTEMP} & \text{22, 631.0} \\
\text{MPTEMP} & \text{23, 661.0} \\
\text{MPTEMP} & \text{24, 691.0} \\
\text{MPTEMP} & \text{25, 721.0} \\
\text{MPTEMP} & \text{26, 751.0} \\
\text{MPTEMP} & \text{27, 781.0} \\
\text{MPTEMP} & \text{28, 811.0} \\
\text{MPTEMP} & \text{29, 841.0} \\
\text{MPTEMP} & \text{30, 871.0} \\
\text{MPTEMP} & \text{31, 901.0} \\
\text{MPTEMP} & \text{32, 931.0} \\
\hline
\end{tabular}

! temperature is in degrees K
Appendix G

data is in units of ohm-m
Appendix G

MPDATA, RSVX, 1,, 2.954592e-008
MPDATA, RSVX, 1,, 3.162730e-008
MPDATA, RSVX, 1,, 3.372097e-008
MPDATA, RSVX, 1,, 3.582856e-008
MPDATA, RSVX, 1,, 3.795176e-008
MPDATA, RSVX, 1,, 4.009223e-008
MPDATA, RSVX, 1,, 4.225162e-008
MPDATA, RSVX, 1,, 4.443160e-008
MPDATA, RSVX, 1,, 4.663383e-008
MPDATA, RSVX, 1,, 4.885998e-008
MPDATA, RSVX, 1,, 5.111170e-008
MPDATA, RSVX, 1,, 5.339067e-008
MPDATA, RSVX, 1,, 5.569854e-008
MPDATA, RSVX, 1,, 5.803698e-008
MPDATA, RSVX, 1,, 6.040765e-008
MPDATA, RSVX, 1,, 6.281221e-008
MPDATA, RSVX, 1,, 6.525233e-008
MPDATA, RSVX, 1,, 6.772967e-008
MPDATA, RSVX, 1,, 7.025899e-008
MPDATA, RSVX, 1,, 7.280266e-008
MPDATA, RSVX, 1,, 7.540164e-008
MPDATA, RSVX, 1,, 7.804488e-008
MPDATA, RSVX, 1,, 8.073286e-008
MPDATA, RSVX, 1,, 8.346844e-008
MPDATA, RSVX, 1,, 8.625880e-008
MPDATA, RSVX, 1,, 8.908784e-008
MPDATA, RSVX, 1,, 9.197499e-008
MPDATA, RSVX, 1,, 9.491599e-008
MPDATA, RSVX, 1,, 9.791250e-008
MPDATA, RSVX, 1,, 1.009662e-007
MPDATA, RSVX, 1,, 2.101076e-007
MPDATA, RSVX, 1,, 2.130905e-007
MPDATA, RSVX, 1,, 2.160734e-007
MPDATA, RSVX, 1,, 2.190563e-007
MPDATA, RSVX, 1,, 2.220392e-007
MPDATA, RSVX, 1,, 2.250220e-007
MPDATA, RSVX, 1,, 2.280049e-007
MPDATA, RSVX, 1,, 2.309878e-007
MPDATA, RSVX, 1,, 2.339707e-007
MPDATA, RSVX, 1,, 2.369536e-007
MPDATA, RSVX, 1,, 2.399365e-007
MPDATA, RSVX, 1,, 2.429193e-007
MPDATA, RSVX, 1,, 2.459022e-007
MPDATA, RSVX, 1,, 2.488851e-007
MPDATA, RSVX, 1,, 2.518680e-007
MPDATA, RSVX, 1,, 2.539560e-007
MPDATA, RSVX, 1,, 1.6666E-6
MPDATA, RSVX, 1,, 2.0E-6
MPDATA, RSVX, 1,, 2.2222E-6
MPDATA, RSVX, 1,, 1.6666E-6
MPDATA, RSVX, 1,, 1E-6

! data is in units of ohm-m
! ISOLINEAR THERMAL CONDUCTIVITY
!-----------------------------------

MP,KXX,1,402

! DENSITY
!----------

MP,DENS,1,8930

! SPECIFIC HEAT COEFFICIENT
!--------------------------

MP,C,1,516

! ENTHALPY
!------------

MTTEMP,1,0
MTTEMP,2,1320
MTTEMP,3,1350
MTTEMP,4,2830
MTTEMP,5,2860
MTTEMP,6,20000
MPDATA,ENTH,1,,0
MPDATA,ENTH,1,,6.1E9
MPDATA,ENTH,1,,7.7E9
MPDATA,ENTH,1,,1.36E10
MPDATA,ENTH,1,,3.76E10
MPDATA,ENTH,1,,4.64E10

! MODULUS OF ELASTICITY
!---------------------

MP,EX,1,1.1E11

! BILINEAR KINEMATIC MODEL
!------------------------

TB,BKIN,1,6
MTTEMP,1,6
TBTEMP,254.0,1
TBDATA,1,(1.288065e+01+0.9E-3)
MPTEMP,.     .     .     .     .     .
TBTEMP,454.0,2
TBDATA,1,(1.168304e+011*0.9E-3)
MPTEMP,.     .     .     .     .     .
TBTEMP,554.0,3
TBDATA,1,(1.045589e+011*0.9E-3)
MPTEMP,.     .     .     .     .     .
TBTEMP,654.0,4
TBDATA,1,(9.125362e+010*0.9E-3)
MPTEMP,.     .     .     .     .     .
TBTEMP,754.0,5
TBDATA,1,(7.691439e+010*0.9E-3)
MPTEMP,.     .     .     .     .     .
TBTEMP,854.0,6
TBDATA,1,(6.185884e+010*0.9E-3)

! POISSON'S RATIO
!-----------------------
MP,NUXY,1,0.499

! COEFFICIENT OF THERMAL EXPANSION
!----------------------------------
MP,ALPX,1,0

!*******************************************************************
!*******************************************************************
MATERIAL PROPERTIES OF AIR

! PERMEABILITY
!---------------
MP,MURX,2,1

! CONDUCTIVITY
!--------------
MP,RSVX,2,0

! ISOLINEAR THERMAL CONDUCTIVITY
!-------------------------------
MP,KXX,2,0.02
Appendix G

! DENSITY
!----------

MP,DENS,2,1.29

! SPECIFIC HEAT COEFFICIENT
!----------------------------

! MODULUS OF ELASTICITY
!-----------------------

MP,EX,2,100

! POISSON'S RATIO
!----------------

MP,NUXY,2,0.4999

! COEFFICIENT OF THERMAL EXPANSION
!-----------------------------------

MP,ALPX,2,0

*******************************************************************

EOF
APPENDIX H

2D Flux Compression FEA Batch Code
! SET-UP VARIABLES
!----------------------

! SIMULATION TIME
!------------------

! HELMHOLTZ COILS
!-----------------
START_TIME_INIT=0
FINAL_TIME_INIT=2.0E-3
INCREMENTS_INIT=0.01E-3
ITERATIONS_INIT=(FINAL_TIME_INIT/INCREMENTS_INIT)

! FLUX COMPRESSION
!-------------------
START_TIME=2E-3
FINAL_TIME=2.012E-3
INCREMENTS=4E-9
ITERATIONS=(FINAL_TIME-START_TIME)/INCREMENTS

! GEOMETRY
!---------------------------------------------------

! INITIAL COILS
!---------------------------------------------------
INRAD=40E-3
OUTRAD=61.7E-3
HEIGHT=10.85E-3
GAP=26.65E-3
SHEATH=2E-3
SINRAD=37.00E-3
SOUTRAD=70.855E-3

! LINER
!----------------------------~----------------------
LINRAD=25.0E-3
LOUTRAD=25.5E-3
LHEIGHT=10E-3

! COIL
!----------------------------~----------------------
CINRAD=26.5E-3
COUTRAD=28.1E-3
CHEIGHT=8.5E-3

! INNER AREA SURROUND
!----------------------------~----------------------
BOXH=22.5E-3
BOXW=45E-3
BOXW1=35E-3

! OUTER AREA SURROUND
!----------------------------~----------------------
BOXH2=100E-3
BOXW2=120E-3

! MESHING PARAMETERS
!~~~~~~~~~~~~~~~~~~~~~~~~~~~~
!~~~~~~~~~~~~~~~~~~~~~~~~~~~~
LDENSX=4
LDENSY=50
CDENSX=5
CDENSY=50
INNER=8
MIDDLE=10
DENSX=10
DENSY=10
SDENSY=3
SDENSiX=20

! STRUCTURAL DAMPENING

ALPHA_DAMP=0
BETA_DAMP=0

! MODELLING

! EMAG ELEMENT SELECTION

/FPREP7
ET,1,PLANE53,,1  ! LINER
ET,2,PLANE53,4,,1  ! STC
ET,3,PLANE13,,1,1  ! AIR
ET,4,PLANE53,3,,1  ! INITIAL COILS
ET,5,PLANE13,,1  ! STEEL SHEILD
ET,6,CIRCU124,0  ! RESISTOR
ET,7,CIRCU124,1  ! INDUCTOR
ET,8,CIRCU124,2  ! CAPACITOR
ET,9,CIRCU124,6  ! 3D MASSIVE CONDUCTOR
ET,10,CIRCU124,5  ! STRANDED COIL

! FLUX CIRCUIT REAL CONSTANTS (OPEN CIRCUIT INIT)

R,1,((OUTRAD-CINRAD)*(2*CHEIGHT))  ! X-SECTIONAL AREA
R,2,9999999999  ! Resistance (open)
R,3,3E-9  ! Inductance
R,4,52.64e-6,24.5E3  ! Capacitance, Vo
R,5,1  ! Scaling factor
R,6,((OUTRAD-LINRAD)*(2*LHEIGHT))

R,7,((OUTRAD-LINRAD)*(2*HEIGHT))  ! X-SECTIONAL AREA
R,8,100E-3  ! Resistance
R,9,92E-6  ! Inductance
Appendix H

R,10,2.400E-6,3.5E3
R,11,1
R,12,4.709E-4,49,,0.785

! IMPORT MATERIAL LIBRARY
!---------------------------------------------------
mpread,matlib.txt
!---------------------------------------------------

! GEOMETRIC MODELS
!---------------------------------------------------

!------FLUX CIRCUIT---------!
N,1,0,0,0 ! Generate node 1 for circuit (top-left)
N,2,0,0,0 ! Generate node 2 for circuit (top-right)
N,3,0,0,0 ! Generate node 3 for circuit (bottom-left)
N,4,0,0,0 ! Generate node 4 for circuit (bottom-right)

! ------INITIAL CIRCUIT--------!
N,5,0,0,0 ! Generate node 1 for circuit (top-left)
N,6,0,0,0 ! Generate node 2 for circuit (top-right)
N,7,0,0,0
N,8,0,0,0 ! Generate node 3 for circuit (bottom-left)
N,9,0,0,0 ! Generate node 4 for circuit (bottom-right)

! FLUX COMPRESSION INNER AREA
!---------------------------------------------------
RECTNG,LINRAD,LOUTRAD, (BOXH2-LHEIGHT),(BOXH2+LHEIGHT)
RECTNG,CINRAD,COUTRAD, (BOXH2-CHEIGHT), (BOXH2+CHEIGHT)
RECTNG,0,BOXW, (BOXH2-BOXH), (BOXH2+BOXH)
K,13,{(3*LINRAD)/4},{{BOXH2-BOXH}},0 !------altered to get gap
K,14,{(3*LINRAD)/4},{{BOXH2+BOXH}},0 !------taller box set to 3/4
K,15,BOXW1,{{BOXH2-BOXH}},0
K,16,BOXW1,{{BOXH2+BOXH}},0

L,3,14
L,2,13
L,5,15
L,8,16
L,9,13
L,13,10
Appendix H

! INITIAL FIELD AND OUTER AREA
!---------------------------------------------------

RECTNG, SINRAD, SOUTRAD, (BOXH2-GAP+1E-3), (BOXH2-GAP+SHEATH+1E-3)
RECTNG, SINRAD, (SINRAD+SHEATH), (BOXH2-GAP+1E-3+SHEATH), ((BOXH2-GAP+1E-3) - (SOUTRAD-SINRAD))
RECTNG, INRAD, OUTRAD, (BOXH2-GAP), (BOXH2-GAP-(2*HEIGHT))

RECTNG, SINRAD, SOUTRAD, (BOXH2+GAP-1E-3), (BOXH2+GAP-SHEATH-1E-3)
RECTNG, SINRAD, (SINRAD+SHEATH), (BOXH2+GAP-1E-3-SHEATH), ((BOXH2+GAP-1E-3) + (SOUTRAD-SINRAD))
RECTNG, INRAD, OUTRAD, (BOXH2+GAP), (BOXH2+GAP+ (2*HEIGHT))

RECTNG, 0, BOXW2, 0, (2*BOXH2)

ALLSEL, ALL
AOVLAP, ALL
NUMCMP, ALL

! MODELLING
!---------------------------------------------------

! FLUX COMPRESSION INNER AREA
!---------------------------------------------------

TYPE, 1
REAL, 6
MAT, 1

LESIZE, 1, \ldensx
LESIZE, 3, \ldensx
LESIZE,2,,LDENSY, 1-3
LESIZE,4,,LDENSY, 1-3
AMESH,1

TYPE,2
REAL,1
MAT,2

LESIZE,5,,CDENSX
LESIZE,7,,CDENSX
LESIZE,6,,CDENSY, 1-3
LESIZE,8,,CDENSY, 1-3
AMESH,2

!- INNER
---------------------------------------------------

TYPE,3
MAT,3

LESIZE,11,,INNER,2
LESIZE,12,,INNER,2
ALLSEL,ALL
LSEL,S,,1,3,2
LSEL,A,,4
LCCAT,ALL

ALLSEL,ALL
LESIZE,10,,LDENSY,-2
LESIZE,15,,LDENSX
LESIZE,16,,LDENSX

ALLSEL,ALL
LSEL,S,,10
LSEL,A,,15
LSEL,A,,16
LCCAT,ALL
AMESH,3

ALLSEL,ALL
LDELE,54
LDELE,55
---------------------------------------------------

ALLSEL,ALL
LESIZE,14,,INNER,2
LESIZE,13,,INNER,2
ALLSEL,ALL
LSEL,S,,5,7,1
LCCAT,ALL
ALLSEL, ALL

LESIZE, 9,, CDENSY,-2
LESIZE, 17,, CDENSX
LESIZE, 18,, CDENSX

ALLSEL, ALL
LSEL, S,, 18
LSEL, A,, 9
LSEL, A,, 17
LOCAT, ALL
AMESH, 4

ALLSEL, ALL
LOELE, 54
LOELE, 55

!---------------------------------------------------

ALLSEL, ALL
LSEL, S,, 13, 14, 1
LSEL, A,, 8
LOCAT, ALL

ALLSEL, ALL
LSEL, S,, 11, 12, 1
LSEL, A,, 2
LOCAT, ALL
ALLSEL, ALL

LESIZE, 19,, MIDDLE
LESIZE, 20,, MIDDLE
AMESH, 5

LOELE, 54
LOELE, 55

!*********************************************************

! HELMHOLTZ AND OUTER AREA
!---------------------------------------------------------------

! HELMHOLTZ COILS
!---------------------------------------------------------------

TYPE, 4
REAL, 12
MAT, 2
LESIZE, 24,, DENSX
LESIZE, 26,, DENSX
! STEEL SHIELD

TYPE, 5
MAT, 4
LESIZE, 25, . . . , DENSY,
LESIZE, 27, . . . , DENSY,
AMESH, 6
LESIZE, 31, . . . , DENSX
LESIZE, 33, . . . , DENSX
LESIZE, 32, . . . , DENSY,
LESIZE, 34, . . . , DENSY,
AMESH, 7

LESIZE, 38, . . . , SDENSX
LESIZE, 39, . . . , SDENSX
AMESH, 8
LESIZE, 40, . . . , SDENSY,
LESIZE, 41, . . . , SDENSY,
LESIZE, 42, . . . , SDENSY,
AMESH, 9
LESIZE, 47, . . . , SDENSY
LESIZE, 48, . . . , SDENSY
LESIZE, 49, . . . , SDENSY,
AMESH, 12

LESIZE, 28, . . . , SDENSX
LESIZE, 29, . . . , SDENSX
AMESH, 10
LESIZE, 38, . . . , SDENSX
LESIZE, 39, . . . , SDENSX
AMESH, 13
LESIZE, 40, . . . , SDENSY,
LESIZE, 41, . . . , SDENSY,
AMESH, 14

! OUTER AREA

---------------------------------
Appendix H

|TYPE, 3|
|MAT, 3| SMRTSIZE, 1| AMESH, 14|

! CIRCUIT CONSTRUCTION, AND SET-UP
-------------------------------

! FLUX COMPRESSION CIRCUIT
---------------------------

NC = NODE(((OUTRAD-CINRAD)/2)+(CINRAD)), (BOXH2), 0)

TYPE, 6 ! RESISTOR Element creation
REAL, 2 ! Use real constant 2
E, 1, 2 ! Generate element between nodes 1 and 2

TYPE, 7 ! INDUCTOR Element creation
REAL, 3 ! Use real constant 3
E, 3, 4 ! Generate element between nodes 3 and 4

TYPE, 8 ! CAPACITOR Element creation
REAL, 4 ! Use real constant 4
E, 1, 4 !{5} ! Generate element between nodes 1 and 4
E, 1, 4
E, 1, 4
E, 1, 4

TYPE, 9 ! 3D COUPLER Element creation, with connection to
COIL
REAL, 5 ! Use real constant 5
E, 2, 3, NC ! Generate element between nodes 2 and 3 (circuit)
and
ALLSEL, ALL

! INITIAL FIELD CIRCUIT
-----------------------

NU = NODE(((OUTRAD-INRAD)/2)+(INRAD)), (BOXH2+GAP+HEIGHT, 0)
NL = NODE(((OUTRAD-INRAD)/2)+(INRAD)), (BOXH2-GAP-HEIGHT, 0)

TYPE, 6 ! RESISTOR Element creation
REAL, 8 ! Use real constant 2
E, 5, 6 ! Generate element between nodes 1 and 2

TYPE, 7 ! INDUCTOR Element creation
REAL, 9 ! Use real constant 3
E,8,9  ! Generate element between nodes 3 and 4
TYPE,8  ! CAPACITOR Element creation
REAL,10  ! Use real constant 4
E,5,9  !(S)  ! Generate element between nodes 1 and 4

TYPE,10  ! 3D COUPLER Element creation, with connection to
COIL
REAL,11  ! Use real constant 5
E,6,7,NU  ! Generate element between nodes 2 and 3 (circuit)
and
E,7,8,NL

! COUPLING EQUATIONS
!---------------------------------------------------
ASEL,S,,6
NSLA,S,1
CP,1,CURR,ALL  ! Couple the CURR dof
CP,2,EMF,ALL  ! Couple the EMF dof
ALLSEL,ALL

ASEL,S,,7
NSLA,S,1
CP,3,CURR,ALL  ! Couple the CURR dof
CP,4,EMF,ALL  ! Couple the EMF dof
ALLSEL,ALL

ASEL,S,,2
NSLA,S,1
CP,5,CURR,ALL  ! Couple the CURR dof
CP,6,EMF,ALL  ! Couple the EMF dof
ALLSEL,ALL

! COMPONENTS
!---------------------------------------------------
ASEL,S,,2
ESLA,S
CM,COIL,ELEM
ALLSEL,ALL

ASEL,S,,1
ESLA,S
CM,LINER,ELEM
ALLSEL,ALL

ASEL,S,,6,10,1
ESLA,S
CM, STEEL, ELEM
ALLSEL, ALL

ASEL, S, 7
ESLA, S
CM, HELMHOLTZ, ELEM
ALLSEL, ALL

ASEL, S, 11, 13, 1
ESLA, S
ICM, STEEL_UP, ELEM
ALLSEL, ALL

! BOUNDARY CONDITIONS
!-----------------------------------------

ALLSEL, ALL
LSEL, S, EXT
NSLL, S, 1
D, ALL, AZ, 0
ALLSEL, ALL

! WRITE PHYSICS INITIAL FIELD (FLUX OPEN)
!-----------------------------------------
PHYSICS, WRITE, EMAG
FINISH

! WRITE PHYSICS FLUX COMP (FLUX CLOSED)
!-----------------------------------------

/PREP7
ALLSEL, ALL
RMODIF, 2, 1, 2E-3
ALLSEL, ALL

ALLSEL, ALL
PHYSICS, WRITE, EMAG2
FINISH

! THERMAL MODELLING
!*************************************************************

/PREP7
LSCLEAR, ALL
PHYSICS, CLEAR

ET, 1, PLANE77, 1
ET, 2, PLANE77, 1
ET,3,O
ET,4,O
ET,5,O
ET,6,O
ET,7,O
ET,8,O
ET,9,O
ET,10,O

! MATERIAL MODELS
-----------------------------------------------

! IMPORT
----------!

rnpread,matlib.txt

! BOUNDARY CONDITIONS
-----------------------------------------------

LSEL, S,,1,8,1
!SEL, ALL, CONV, 50,,293
ALLSEL, ALL

TUNIF, 293

! WRITE THERMAL PHYSICS
-----------------------------------------------

PHYSICS, WRITE, THERMAL
FINISH

! Write new thermal environment
! Finish in solution

! STRUCTURAL MODELLING
-------------------------------

/ PREP7
LSCLEAR, ALL
PHYSICS, CLEAR

ET,1, PLANE183,,1
ET,2, PLANE183,,1
ET,3,0
ET,4,0
ET,5,0
ET,6,0
ET,7,0
ET,8,0
ET,9,0
ET,10,0

! MATERIAL MODELS
!---------------------------------------------

!---------------- IMPORT ----------------

tmpread,matlib,txt

!---------------------------------------------

! BOUNDARY CONDITIONS
!---------------------------------------------

ASEL,S,,3,5,1
CM,AIR_MORPH,AREA
ALSEL,ALL
ESEL,S,,3
CM,AIR_MORPH_ELEM,ELEM
ALSEL,ALL

ASEL,S,,1,2,1
NSLA,S,1
D,ALL,UY,0
ALSEL,ALL

ALPHAD,ALPHA_DAMP
BETAD,BETA_DAMP

ALSEL,ALL
LSEL,S,EXT
NSLL,S,1
ID,ALL,ALL,0
ALSEL,ALL

! WRITE STRUCTURAL PHYSICS
!---------------------------------------------

ALSEL,ALL
PHYSICS,WRITE,STRUCT
FINISH
SAVE

/PREP7
ALSEL,ALL
TIME=START_TIME_INIT
*DO,1,1,ITERATIONS_INIT
TIME=TIME+INCREMENTS_INIT

! INITIAL FIELD ITERATIONS
!~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~
!~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~

/PREP7
LSCLEAR,ALL
PHYSICS,CLEAR
PHYSICS,READ,EMAG
FINISH
Appendix H

!--------------------------------------EMAG---------------------------------------
-----!

/ASSIGN, ESAV, EMAG, ESAV
/ASSIGN, EMAT, EMAG, EMAT
/ASSIGN, RST, EMAG, RMG

*IF, I, EQ, 1, THEN

/SOLU
ALLSEL, ALL       ! select everything
TOFFST, 0
TREF, 293
TUNIF, 293
ANTYPE, TRANS    ! Transient analysis
TRNOPT, FULL,...
NROPT, FULL,..., ON
OUTRES, ALL, ALL ! Output all results
TIME, TIME       ! Time of analysis
NSUBST, 1        ! Number of substeps
KBC, 0           ! Ramped solution
RESCONTROL, NONE ! No multiframe restart
SOLCONTROL, 1
NEQIT, 1
CNVTOL, VLTG,...,-1
CNVTOL, A
CNVTOL, CSG
NCNV, 0

SOLVE            ! Solve problem
SAVE, EMAG, DB   ! Save emag.db

FINISH           ! Finish in /solu

*ENDIF

*IF, I, GT, 1, THEN

/SOLU
TOFFST, 0
TREF, 293
ALLSEL, ALL       ! select everything
ANTYPE, TRANS, REST ! Transient restart
TRNOPT, FULL,...
NROPT, FULL,..., ON
OUTRES, ALL, ALL ! Output all results
TIME, TIME       ! Time of analysis
NSUBST, 1        ! Number of substeps
KBC, 0           ! Ramped solution
RESCONTROL, NONE ! No multiframe restart
SOLCONTROL,1
NEQIT,1
CNVTOL,VLTC,,,-1
CNVTOL,A
CNVTOL,CSG
NCNV,0

SOLVE ! Solve problem
SAVE, EMAG, DB ! Save emag.db

FINISH ! Finish in /solu

*ENDIF

/ASSIGN, ESAl
/ASSIGN, EMAT
/ASSIGN

!--------------------------------------THERMAL-----------------------------------
------!

!--------------------------------------THERMAL-----------------------------------
------!

/PREl
LSCLEAR, ALL
PHYSICS, CLEAR
PHYSICS, READ, THERMAL
FINISH

/ASSIGN, ESAl, THERM, ESAl
/ASSIGN, EMAT, THERM, EMAT
/ASSIGN, RTH, THERM, RTH

*IF, I, EQ, 1, THEN

/SOLU
ALLSEL, ALL
TOFFST, 0
TREF, 293
TUNIF, 293
ESEL, S, TYPE,, 1
ESEL, A, TYPE,, 2
NSLE, S, ALL

! LDREAD, HGEN, LAST,,, EMAG, RMG
ALLSEL, ALL
ANTYPE, TRANS ! Transient analysis
SOLCONTROL,1
OUTRES, ALL, ALL  ! Output all results
TIME, TIME  ! Time of analysis
NSUBST, 1  ! Number of substeps
KBC, 0  ! Ramped solution
RESCONTROL, NONE  ! No multiframe restart

SOLVE  ! Solve problem
SAVE, THERM, DB  ! save therm.db
FINISH  ! Finish in /solu

*ENDIF

*IF, I, GE, 1, THEN

/ SOLU
ALLSEL, ALL
TOFFST, 0
TREF, 293
ESEL, S, TYPE,, 1
ESEL, A, TYPE,, 2
NSLE, S, ALL
LDREAD, HGEN, LAST,,, EMAG, RMG
ALLSEL, ALL
ANTYPE, TRANS, REST  ! Transient restart
SOLCONTROL, ON
OUTRES, ALL, ALL  ! Output all results
TIME, TIME  ! Time of analysis
NSUBST, 1  ! Number of substeps
KBC, 0  ! Ramped solution
NCNV, 0
RESCONTROL, NONE  ! No multiframe restart

SOLVE  ! Solve problem
SAVE, THERM, DB  ! save therm.db

FINISH  ! Finish in /solu

*ENDIF

! ASSIGN, ESAY
! ASSIGN, EMAT
! ASSIGN
!--------------------------------------------------------------------------------­­------!

! STRUCTURAL

291
!--------------------------------------------------------------------------------­
------!

/PREP7
LSCLEAR, ALL
PHYSICS, CLEAR
PHYSICS, READ, STRUCT
FINISH

/ASSIGN, ESAV, STRUCT, ESAV
/ASSIGN, EMAT, STRUCT, EMAT
/ASSIGN, RST, STRUCT, RST

*IF, I, EQ, 1, THEN

/SOLU
ALLEL, ALL
TOFFST, 0
TREF, 293
TUNIF, 293
ESEL, S, TYPE, 1
ESEL, A, TYPE, 2
NSLE, S, ALL
!
LDREAD, FORC, LAST, EMAG, RMG
!
LDREAD, TEMP, LAST, THERM, RTH
ALLEL, ALL
ANTYPE, TRANS ! Transient analysis
NLGEOM, ON
SOLCONTROL, ON
NCNV, 0
NEQIT, 30
NROPT, FULL, ON
CUTCONTROL, PLSLIMIT, 1
CNVTOL, F, 0.005, 0, 0.01
CNVTOL, U, 0.05, 2, 0
OUTRES, ALL, ALL ! Output all results
TIME, TIME ! Time of analysis
NSUBST, 1 ! Number of substeps
KBC, 0 ! Ramped solution
RESCONTROL, NONE ! No multiframe restart
NLDIAG, NRRE, ON
NLDIAG, EFLG, ON

SOLVE ! Solve problem
SAVE, STRUCT, DB ! save struct.db

FINISH ! Finish in /solu
Appendix H

*ENDIF

*IF, I, GT, 1, THEN

SOLU
PARSAV, ALL
RESUME, STRUCT, DB
PARRES
ALLSEL, ALL
TOFFST, 0
TREF, 293
ESEL, S, TYPE,, 1
ESEL, A, TYPE,, 2
NSLE, S, ALL
LDREAD, FORC, LAST,,//, EMAG, RMG
LDREAD, TEMP, LAST,,//, THERM, RTH
ALLSEL, ALL
ANYTYPE, TRANS, REST ! Transient restart
NLGEOM, ON
SOLCONTROL, ON
NCNV, 0
NEQIT, 30
NROPT, FULL,, ON
CUTCONTROL, FSLIMIT, 1
CNVTOL, F,, 0.005, 0, 0.01
CNVTOL, U,, 0.05, 2, 0
OUTRES, ALL, ALL ! Output all results
TIME, TIME ! Time of analysis
NSUBST, 1 ! Number of substeps
KBC, 0 ! Ramped solution
RESCONTROL, NONE ! No multiframe restart
NLDIAG, NRRE, ON
NLDIAG, EFLG, ON

SOLVE ! Solve problem
SAVE, STRUCT, DB ! save struct.db
FINISH ! Finish in /solu

*ENDIF

! MORPHING
!--------------

/ PREP7
FLUX COMPRESSION ITERATIONS

*ENDDO
TOFFST, 0
TREF, 293
ALLSEL, ALL    ! select everything
ESEL, S, TYPE, 1
ESEL, A, TYPE, 2
NSLE, S, ALL
LDREAD, TEMP, LAST, THERM, RTH
ALLSEL, ALL
ANTE, TRANS, REST    ! Transient restart
TRNOPT, FULL, , , ,
NROPT, FULL, , ON
OUTRES, ALL, ALL    ! Output all results
TIME, TIME    ! Time of analysis
NSUBST, 1    ! Number of substeps
KBC, 0    ! Ramped solution
RESCONTROL, NONE    ! No multiframe restart
SOLCONTROL, 1
NEQIT, 1
CNVTOL, VLTG, , , , -1
CNVTOL, A
CNVTOL, CSG
NCNV, 0

SOLVE    ! Solve problem
SAVE, EMAG, DB    ! Save emag.db
FINISH    ! Finish in /solu

/ASSIGN, ESAV
/ASSIGN, EMAT
/ASSIGN

!--------------------------------------------------------------------------------------!
!--------------------------------------THERMAL---------------------------------------!
!--------------------------------------------------------------------------------------!

/FRP7
LSCLEAR, ALL
PHYSICS, CLEAR
PHYSICS, READ, THERMAL
FINISH

/ASSIGN, ESAV, THERM, ESAV
/ASSIGN, EMAT, THERM, EMAT
/ASSIGN, RTH, THERM, RTH

/SOLU

ALLSEL, ALL
TOFFST, 0
TREF, 293
ESEL, S, TYPE, , 1
ESEL, A, TYPE, , 2
NSLE, S, ALL
LDREAD, HGEN, LAST, , , EMAG, RMG
ALLSEL, ALL
ANTYPE, TRANS, REST ! Transient restart
SOLCONTROL, ON
OUTRES, ALL, ALL ! Output all results
TIME, TIME ! Time of analysis
NSUBST, 1 ! Number of substeps
KBC, 0 ! Ramped solution
NCNV, 0
RESCONTROL, NONE ! No multiframe restart
SOLVE ! Solve problem
SAVE, THERM, DB ! save therm.db

FINISH ! Finish in /sou

/ASSIGN, ESAVE
/ASSIGN, EMAT
/ASSIGN

!---------------------------------------------------------------

--------!

*IF, TIME, LE, 2.0006E-3, THEN

! STRUCTURAL
!---------------------------------------------------------------

--------!

/PREP7
LSCLEAR, ALL
PHYSICS, CLEAR
PHYSICS, READ, STRUCT1
FINISH

/ASSIGN, ESAVE, STRUCT, ESAVE
/ASSIGN, EMAT, STRUCT, EMAT
/ASSIGN, RST, Struct, RST
/SOLU
PARSAV,ALL
RESUME,STRUCT, DB
PARRES
ALLSEL, ALL

TOFFST,0
TREF,293
ESEL,S,TYPE,,1
ESEL,A,TYPE,,2
NSLE,S,ALL
LDREAD, FORC, LAST,, EMAG, RMG
LDREAD, TEMP, LAST,, THERM, RTH
ALLSEL, ALL
ANTYPE, TRANS, REST   ! Transient restart
NLGEOM, ON
SOLCONTROL, ON
NCNV, 0
NEQIT, 30
NROPT, FULL, ON
CUTCONTROL, PLSLH1IT, 1
CNVTOL,F,,0.005,0,0.01
CNVTOL,U,,0.05,2,0
OUTRES, ALL, ALL   ! Output all results
TIME, TIME   ! Time of analysis
NSUBST, 1   ! Number of substeps
KBC, 0   ! Ramped solution
RESCONTROL, NONE   ! No multiframe restart
NLDIAG, NRRE, ON
NLDIAG, EFLG, ON

SOLVE   ! Solve problem
SAVE, STRUCT, DB   ! save struct.db
FINISH   ! Finish in /solu

! MORPHING

/PREP7
ALLSEL, ALL
ICDELE
ALLSEL, ALL
DAMORPH, AIR_MORPH,, 2   ! Morph AIR-IN
ALLSEL, ALL
FINISH

/ASSIGN, ESAVE
/ASSIGN, EMAT
/ASSIGN

!-----------------------------------------------

-----!

*ENDIF

*IF, TIME, GT, 2.0006E-3, THEN

!-----------------------------------------------

-----!

/PREP7
LSCLEAR, ALL
PHYSICS, CLEAR
PHYSICS, READ, STRUCT2
FINISH

/ASSIGN, ESAV, STRUCT, ESAV
/ASSIGN, EMAT, STRUCT, EMAT
/ASSIGN, RST, STRUCT, RST

/SOLU

PARSAV, ALL
RESUME, STRUCT, DB
PARRRES
ALLSEL, ALL
TOFFST, 0
TREF, 293
ESEL, S, TYPE,, 1
ESEL, A, TYPE,, 2
NSLE, S, ALL
LDREAD, FORC, LAST,,, EMAG, RMG
LDREAD, TEMP, LAST,,, THERM, RTH
ALLSEL, ALL
ANTYPE, TRANS, REST     ! Transient restart
NLGEOM, ON
SOLCONTROL, ON
NCNV, 0
NEQIT, 30
NROPT, FULL,, ON
CUTCONTROL, PLSLIMIT, 1  ! 0000000000
CNVTOL, F,, 0.005, 0, 0.01
CNVTOL, U,, 0.05, 2, 0
OUTRES, ALL, ALL     ! Output all results
TIME, TIME           ! Time of analysis
NSUBST, 1           ! Number of substeps
KRC, 0              ! Ramped solution
RESCONTROL,, NONE   ! No multiframe restart

298
NLDIAG, NRRE, ON
NLDIAG, EFLG, ON

SOLVE  ! Solve problem
SAVE, STRUCT, DB  ! save struct.db

FINISH  ! finish in /solu

! MORPHING
!------------------
/PREP7
ALLSEL, ALL
ICDELE
ALLSEL, ALL
DMORPH, AIR_MORPH,, 2  ! Morph AIR-IN
ALLSEL, ALL
FINISH

/ASSIGN, ESAV
/ASSIGN, EMAT
/ASSIGN
!------------------------------------------------------------------------------------------------------------------------
-----!
*ENDIF*

*ENDDO

/PREP7
LSCLEAR, ALL
PHYSICS, CLEAR
PHYSICS, READ, EMAG
FINISH

!------------------------------------------------------------------------------------------------------------------------EMAG------------------------------------------------------------------------------------------------------------------------
-----!
/ASSIGN, ESAV, EMAG, ESAV
/ASSIGN, EMAT, EMAG, EMAT
/ASSIGN, RST, EMAG, RMG

/POST26
FILE, EMAG, RMG
PMGTRAN, 'LINER', 'LINER'
PMGTRAN, 'COIL', 'COIL'
PMGTRAN, 'STEELLOW', 'STEELLOW'
PMGTRAN, 'HELMHOLTZ', 'HELMHOLTZ'
FINISH
Appendix H

/ASSIGN, ESAV
/ASSIGN, EMAT
/ASSIGN

!---------------------------------------------------------------
------!